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**Shifting narratives:
from multiple stellar populations in globular clusters
to sustainability**

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“Je me rends compte qu’en fait tout est là, depuis toujours—cet enfant, ses yeux rêveurs avec cette passion au creux de ses mains, cet enfant qui essaie maladroitement d’exprimer au reste du monde ses sentiments.

Et si tout se déroulait de la même façon simplement parce qu’on les observe continuellement avec le même regard? Et si les réponses avaient toujours été là, devant nous, mais qu’il fallait juste apprendre à contempler les choses avec un œil nouveau? Et si en fin de compte au moment où l’on se sent le plus perdu, il manquait juste parfois une légère impulsion sur un petit détail pour que tout change.”

- Adrian Ström, un nouveau regard

“I realize that, in fact, everything has always been here—this child, their dreamy eyes, the passion cradled in their hands, this child who clumsily tries to share their feelings with the rest of the world. And what if everything unfolded in the same way simply because we keep observing it through the same lens? And what if the answers had always been right here, in front of us, and all we needed was to learn to see them with fresh eyes? And what if, in the end, at the very moment when we feel most lost, all that is missing is a slight nudge on a small detail for everything to change?”

- Adrian Ström, a new perspective

*To the child with dreamy eyes,
holding a passion cradled in their hands,
who observed the beauty of Saturn's rings for the first time.*

Abstract

In this thesis, I explore narratives surrounding multiple stellar populations in globular clusters (GCs) and sustainability. For a long time, GCs were believed to host a single stellar population and were often described and modelled as spherical, non-rotating systems. This perspective has evolved with the discovery of multiple stellar populations (MSPs), characterized by different abundances of light elements. “Enriched” populations show an enhancement of certain elements, such as nitrogen and sodium, and depletion in others, such as carbon and oxygen, compared to the “pristine” stars typically found in the field of the Galaxy. Many theories have been proposed to explain the origins of MSPs, yet none fully reproduce all the observed signatures.

Using nuclear reaction network simulations, I investigate the conditions of temperature and time required for the nucleosynthesis of the chemical elements relevant to the MSP phenomenon. I find that only a narrow range of temperature and time can reproduce the abundances in light elements, in good agreement with previous works. Building on these results, I explore a specific theory proposing that the nucleosynthesis of enriched material occurs within an accretion disk around a stellar-mass black hole. Using the slim-disk model and nuclear reaction simulations, my findings suggest that this scenario is feasible only for parameter ranges not currently observed in black holes, such as sub-solar masses and very low viscosity.

I also challenge the view that globular clusters are spherically symmetric systems. I developed a robust method to measure the ellipticity of GCs, tested it extensively on mock data, and applied it to 26 Milky Way GCs. My analysis reveals that 14 of these clusters are flattened to a statistically significant level. Furthermore, I investigate the shapes of MSPs within these clusters and find that at least one population deviates from spherical symmetry in 13 GCs. Interestingly, pristine populations are often more flattened than enriched populations. I examined potential causes for the flattening, including rotation and velocity anisotropy, finding that rotation could be the main driver of the shape in some clusters, while for others follow-up observations and detailed dynamical modelling are required to reach definitive conclusions.

These findings highlight the need to rethink our assumptions and update our long-standing models for globular clusters, especially as increasingly complex features emerge from new data. This approach goes beyond just astrophysics; as astronomers, we have a responsibility to constantly question and reassess the practices and narratives in our field and beyond, particularly when it comes to urgent global issues like the climate crisis. In this spirit, I also discuss two sustainability initiatives within teaching and research, which show how meaningful change can take place. Our constantly improving understanding of globular clusters teaches us the importance of challenging old ideas and adapting our methods to address new problems.

With this thesis, I embrace this lesson and push for a shift in narrative, both for research and societal challenges.

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List of Acronyms

AGB	Asymptotic giant branch
BH	Black hole
EDA	Early accretion disk
FRMS	Fast rotating massive star
GC	Globular clusters
HST	Hubble Space Telescope
IPCC	Intergovernmental Panel on Climate Change
KDE	Kernel density estimate
LOS	Line-of-sight
MCMC	Markov Chain Monte Carlo
MSPs	Multiple stellar populations
PCA	Principle component analysis
PM	Proper motion
RV	Radial velocity
SMS	Super-massive star
SNe	Supernovae
VMS	Very massive star
YMC	Young Massive Cluster

Declaration of published work

This doctoral thesis is the result of the research I conducted during my PhD at the University of Vienna within the framework of the Vienna International School of Earth and Space Science. My work resulted in one first-author publication and several conference proceedings and talks. In addition to the published material, this dissertation also presents unpublished results, some of which (for example Chapter 4) will be expanded and published in the future. The list below outlines which parts of this Thesis are based on published work.

- The work presented in Chapter 2 and Chapter 3 has been published as Fréour et al. (2024) “Investigating black hole accretion disks as potential polluter sources for the formation of enriched stars in globular clusters” in collaboration with Alice Zocchi, Glenn van de Ven and Elena Pancino. It was presented at the French Society of Astronomy & Astrophysics (SF2A) 2022 (Fréour, 2022) and at the Austrian Early Career Conference 2024 (Fréour and Zocchi, 2024).
- The work presented in Sect. 5.4 has been carried out in collaboration with Tadeja Veršič, Gwenaél Van Looveren and Paula Granero Ordoñez. It resulted in a conference proceeding (Fréour et al., 2022, “The PLEES Index: Climate Change Changes Needs”), a public presentation followed by a panel discussion¹, a blog post², a talk in the Astronomers for Planet Earth Symposium 2022³, and an invited talk for the Lecturers Without Borders NGO⁴.

¹<https://visess.univie.ac.at/activities/big-picture-talks-and-events/>

²<https://blog.univie.ac.at/en/research/effectively-communicating-climate-change-the-plees-index/>

³<https://www.youtube.com/watch?v=2mHfnMtqQHk>

⁴<https://www.youtube.com/watch?v=IZ8Zett8rEs>

Chapter 1

INTRODUCTION

“Sometimes while gazing at the night’s sky, I imagine stars looking down making wishes on the brightest of us.”

- Richelle E. Goodrich

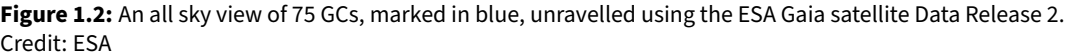
Globular clusters and their multiple stellar populations

The term globular cluster (GC) originates from the Latin word *globulus* - small sphere - and is attributed to William Herschel, who described, in his *Catalogue of a Second Thousand New Nebulae and Clusters of Stars* (Herschel, 1789), his observations of Nebulae realised with his twenty-feet reflector. The name *globular cluster* describes the common picture that we have of these objects: densely packed and spherical agglomeration of stars, often containing hundreds of thousands to millions of stars. The first observation of a GC, ω Centauri, is attributed to ancient astronomers such as Ptolemy who catalogued it as a star. ω Cen was re-classified as a non-stellar object only in 1677 by Edmond Halley and finally designated as a GC by James Dunlop in 1826. Due to its size and proximity, ω Cen, shown in Fig. 1.1, is one of the most studied GC in the Milky Way.



Figure 1.1: The globular cluster ω Cen captured with OmegaCAM, the wide-field imager for the Cassegrain focus of the VLT Survey Telescope located in Paranal, Chile. Credit: ESO

The Milky Way (MW) contains more than 150 GCs, arranged in a nearly spherical halo. Figure 1.2 shows the position of 75 MW GCs as observed with the ESA Gaia satellite. Their age usually range between 10 Gyr and 13 Gyr (Dotter et al., 2009; Marín-Franch et al., 2009), with a peak formation around 12.5 Gyr ago, corresponding to a redshift of $z \sim 5$. The star formation rate of the Universe peaked at redshift $z \sim 1.9$ (Madau and Dickinson, 2014), when most GCs were already formed, thus they provide tight constraints on the formation of galactic halos (see, e.g., Salaris and Weiss 2002 for the MW). Among



the oldest objects in the Universe, they present a unique laboratory for studying various astrophysical phenomena. For example, RR Lyrae stars present in the old populations of stars in GCs make them very useful for distance calibration and to provide insights into the age of the Universe (Krauss and Chaboyer, 2003). They also host a high number of X-ray sources. The formation of these sources is attributed to the high stellar encounter rate resulting from the high density in the cores of GCs (Pooley et al., 2003), making them particularly interesting for studying stellar interactions.

GCs also play a role in reconstructing a galaxy's evolutionary history and tracing ancient mergers (West et al., 2004). Mergers between galaxies are a natural part of galaxy evolution and often involve the total disruption of the smaller galaxy, known as *satellite galaxy*. Contrary to the satellite galaxy, GCs can survive these mergers and be used to recover the merger history of their host galaxy.

While broadly used to understand galaxy formation and evolution, the formation of GCs is still a matter of debate. There are two main families of models (see Forbes et al. 2018 for a review on this topic). The first links GCs formation to specific conditions in low-mass dark matter halos during or prior to reionization. In this context, GCs could have formed shortly after the Big Bang from gravitationally bound gas clouds (Peebles and Dicke, 1968) embedded in dark matter halos (Kravtsov and Gnedin, 2005). Trenti et al. (2015) suggested that mini dark matter haloes, gas-rich but star-free, could have merged, creating a shock-wave leading to a high compression of the gas and subsequent star cluster formation. The dark matter content would then be expelled during the assembly of the host galaxy. The second family of models relies on the idea that young massive clusters (YMCs) with characteristics similar to GCs are observed to form in gas-rich environments with high star formation rates and gas pressure (Portegies Zwart et al., 2010). Such conditions can exist at high-redshift. High turbulent pressures in the disk of galaxies could be suitable for the formation of gravitationally bound clusters and enable the creation of massive giant molecular clouds (GMCs), which can collapse to form massive clusters as suggested by Harris and Pudritz (1994). Some MW GCs are suspected to be the remnant nuclear star clusters (NSCs) of disrupted dwarf galaxies (Pfeffer et al., 2021); an example is ω Cen, whose complex stellar populations and metallicity spread suggest that it is a former NSC (Bekki and Freeman, 2003; Lee et al., 1999).

Astronomers have long considered GCs to be the manifestation of a single and homogeneous stellar population, and have modelled them as such for decades. The simple picture that describes these objects as spherically symmetric, non-rotating and isotropic clusters of stars with the same age and the same metallicity has been increasingly challenged over the past decades thanks to much improved observations, which are able to unveil their complexity. One of the most intriguing and still unsolved puzzles in GCs is the presence of multiple stellar populations (MSPs). These populations appear as separate sequences in color-magnitude diagrams (CMDs), and they also show very specific patterns in the distribution of stellar abundances, the two most studied ones being the anti-correlation between carbon (C) and nitrogen (N), and between oxygen (O) and sodium (Na). MSPs are the main focus of this thesis.

In this Chapter we provide an overview of the multiple stellar populations phenomenon. In Sect. 1.1 we summarize the chemical differences between MSPs, which constitutes the main observational evidence for their presence. In Sect. 1.2 we introduce existing theories explaining the origin of MSPs and the different issues they face. In Sect. 1.3 we present the main properties of MSPs and the relation between MSPs and global properties of the host GC. The questions addressed in this Thesis are described in Sect. 1.4.

1.1 Signatures of multiple stellar populations in globular clusters

The first photometric discovery of the presence of MSPs was made by James Anderson, in its PhD thesis (Anderson, 1997, 2002). Using a set of images obtained with the Advanced Camera for Surveys (ACS) and the Wide Field and Planetary Camera 2 (WFPC2) onboard the Hubble Space Telescope (HST), they highlighted the presence of several main-sequence turnoffs and subgiant branches in ω Cen. While ω Cen is a very complex object, with more than 8 populations identified (Villanova, 2013), which show some differences in metallicity, other clusters also exhibit MSPs, usually linked to a spread in helium

content or light elements rather than metallicities (see for e.g. Busso et al., 2007; Piotto et al., 2015). Such a spread can be directly identified by considering a suitable combination of filters.

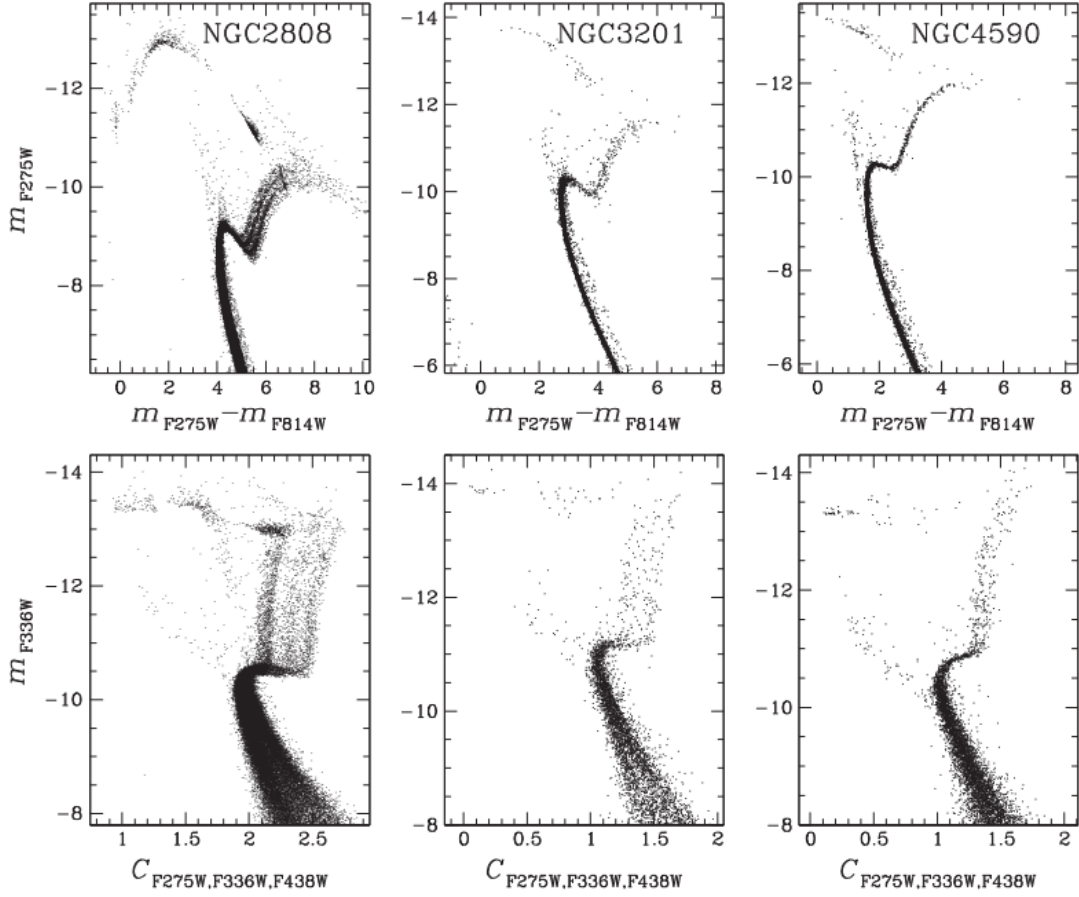


Figure 1.3: Top panels: m_{F275W} versus $m_{F275W} - m_{F814W}$ CMDs of NGC 2808, NGC 3201, and NGC 4590. Bottom panels: m_{F336W} versus $C_{F275W,F336W,F438W} = (m_{F275W} - m_{F336W}) - (m_{F336W} - m_{F438W})$ diagrams for NGC 2808, NGC 3201, and NGC 4590. While the three populations of NGC 2808 are already visible in the top panel, the two populations present in NGC 3201 and NGC 4590 are only unravelled using the $C_{F275W,F336W,F438W}$ index introduced by Milone et al. (2013). This figure has been taken from Piotto et al. (2015).

In the top panels of Fig. 1.3, we show the m_{F275W} versus $m_{F275W} - m_{F814W}$ color-magnitude diagrams (CMDs) of NGC 2808, NGC 3201, and NGC 4590. Three separate sequences are visible above the main sequence turn-off in the red-giant branch of NGC 2808, corresponding to three different populations associated with variations in helium and C, N, and O abundances, but only a single sequence is visible for NGC 3201 and NGC 4590. When using the $C_{F275W,F336W,F438W} = (m_{F275W} - m_{F336W}) - (m_{F336W} - m_{F438W})$ index introduced by Milone et al. (2013) and plotting it versus m_{F336W} , two separate populations become apparent in the red giant branches of these clusters, as shown in the bottom panels of Fig. 1.3. Overall, two main stellar populations have been identified: “pristine stars” with pristine chemical abundances, similar to field stars located in the halo of the MW, and “enriched stars”, showing enhancement in N, Na, and sometimes in aluminium (Al), and depletion in C, O, and sometimes in magnesium (Mg). Pristine stars are often referred as 1P/P1 (first population/population 1) or 1G (first generation) and enriched stars as 2P/P2 or 2G. Here, we prefer to use the terminology *pristine* or *P1* and *enriched* or *P2* to avoid a bias toward any scenario for the formation of MSPs involving multiple generations of stars. In Fig. 1.3, P1 are located in the left sequence of the CMD while P2 are found in the right sequence, corresponding to higher nitrogen abundance and lower oxygen and carbon abundances.

1.1.1 Light elements

Already in the 70s, C and N abundances in stars within GCs were of particular interest. Osborn (1971) found highly enhanced CN bands in one star of NGC 5904 (M5) and in one of NGC 6254 (M10). Cohen (1978) was one of the first to report the discovery of statistically significant Na variations in the galactic GCs NGC 5272 (M3) and NGC 6205 (M13). Shortly afterward, Peterson (1980) identified substantial star-to-star variations in sodium abundances within three red giant branch (RGBs) stars in NGC 6205 reaching an order of magnitude difference. Evidence that giant stars with the highest sodium abundance also exhibit low oxygen values (Pilachowski et al., 1983) and that giant stars with a high nitrogen abundance are also enhanced in sodium (Norris and Pilachowski, 1985) arose. Denisenkov and Denisenkova (1989, 1990) mentioned evolutionary mixing to explain these chemical peculiarities. Sodium could be synthesized through the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction in red giants, at the same location inside the star where N is created and O destroyed, thus resulting in an overabundance of both sodium and nitrogen and in a depletion of oxygen. Some GCs also exhibit an Si-Al correlation as well as a Mg-Al anti-correlation. The extent of the Mg-Al anti-correlation is broader at low metallicity and for massive GCs (Carretta et al., 2009b; Pancino et al., 2017). Langer and Hoffman (1995) suggested that Al could be considerably enhanced through very deep mixing and the activation of the MgAl reaction chain within bright giants. However, additional observations (Gratton et al., 2004) provided evidence against this type of evolutionary model as main sequence stars were found to also exhibit abundance variations (Cannon et al., 1998).

The observed abundance trends in light elements are consistent with H-burning through the activation of the CNO cycle, NeNa and MgAl chains (Langer et al., 1993), requiring temperatures around 80 MK (Prantzos et al., 2007). These correlations and anti-correlations are very strong signatures of the presence of MSPs (Carretta et al., 2009b) and are ubiquitous among GCs older than 2 Gyrs (Martocchia et al., 2017, 2018a; Mucciarelli et al., 2014; Mucciarelli et al., 2008). In Fig. 1.4 we show the main relations between the abundances of some relevant chemical elements in NGC 6752: the top-left panel shows the anti-correlation between oxygen and sodium with data from Carretta et al. (2007), the top-right and bottom-left panels show the anti-correlation between magnesium and aluminium and magnesium and silicon, respectively, with data from (Carretta et al., 2012), and the bottom-right panel shows the anti-correlation between carbon and nitrogen with data from Carretta et al. (2005). The enriched stars are located in the upper-left corner of each panel, corresponding to a depletion of the chemical element indicated in the x -axis and to an enhancement of the chemical element indicated in the y -axis with respect to the pristine stars, located in the lower-right corner of each panel.

1.1.2 Heavy elements

While the light element abundance patterns are ubiquitous among GCs hosting MSPs, abundance variations in heavy elements seem to occur on a case-by-case basis. For instance, a K-Na correlation has been detected in a few GCs, for example NGC 4833 (Carretta, 2021), NGC 2808 (Mucciarelli et al., 2015), and NGC 6715 (Carretta, 2022). Carretta and Bragaglia (2021) also found an excess of Ca (and to some extent Sc) with respect to field star abundances in 8 out of 77 GC (NGC 4833, NGC 6715, NGC 6402, NGC 5986, NGC 5824, ω Cen, NGC 2419, and NGC 2808), confirming the findings of Cohen and Kirby (2012) and Mucciarelli et al. (2012) for NGC 2419, and of Carretta (2015) for NGC 2808. In NGC 2419, Cohen and Kirby (2012) found that the abundances of potassium and scandium are significantly anti-correlated with magnesium, while other elements such as silicon and calcium are just weakly anti-correlated with Mg. Except for scandium, they found that the abundances of iron-peak elements show no variation from one star to another. Such observations discard supernovae (SNe) as enrichment source, as they would induce a spread in iron-peak elements. In general, the presence of such an enhancement in heavy elements is a challenge for many scenarios on the formation of MSPs as heavier elements such as K require higher temperature $T > 180$ MK to be created, quite far from the temperature $T \approx 80$ MK required to recover the abundances in light elements.

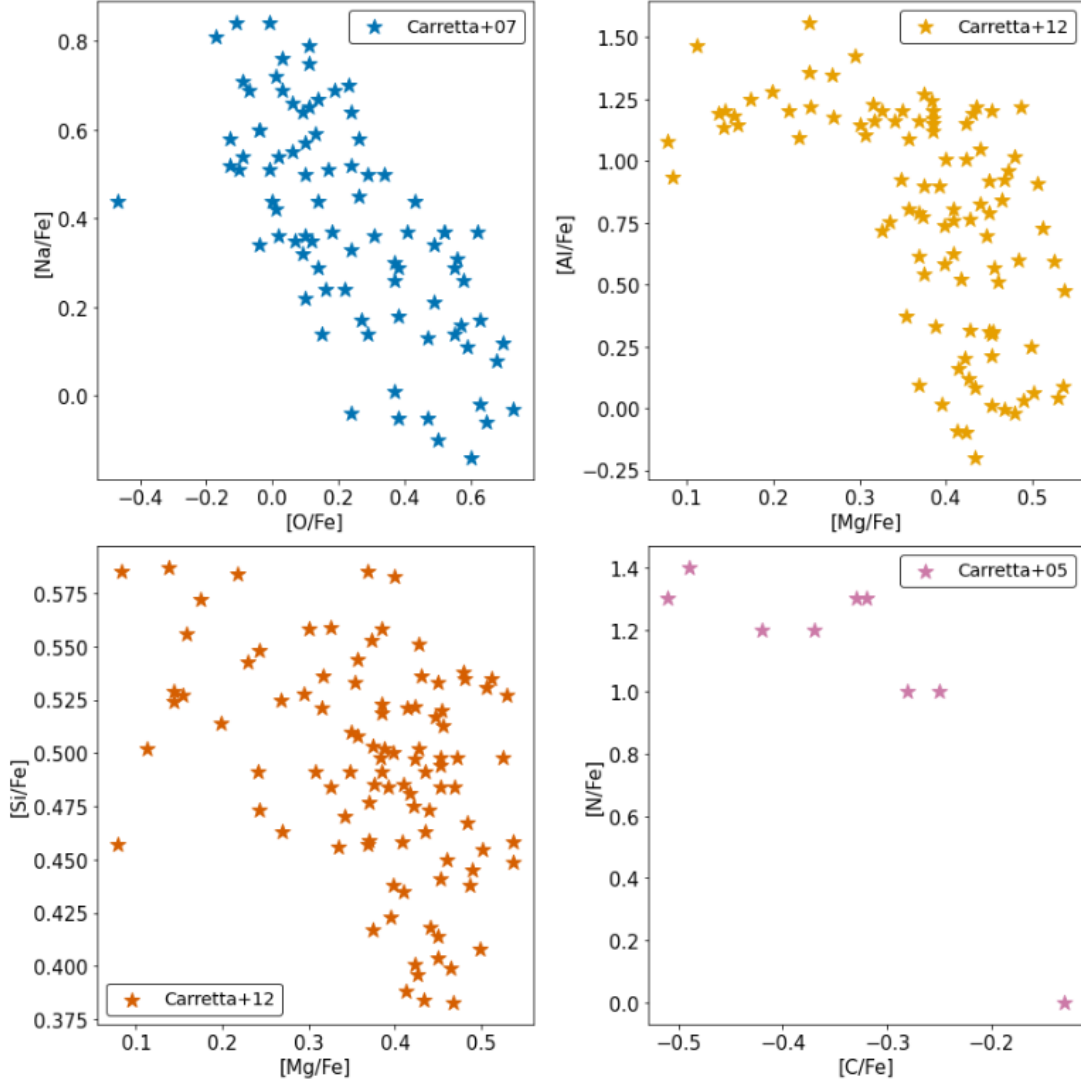


Figure 1.4: Light element abundance patterns in NGC 6752. The top-left panel shows the anti-correlation between oxygen and sodium, based on data from Carretta et al. (2007). The top-right and bottom-left panels illustrate the anti-correlations between magnesium and aluminium, and Magnesium and Silicon, respectively, using data from (Carretta et al., 2012). The bottom-right panel shows the anti-correlation between carbon and nitrogen, with data from Carretta et al. (2005).

1.2 Theories for the formation of MSPs

All these observations put strong constraints on the models of the formation of MSPs. Such models should be general enough to account for the ubiquity of MSPs in GCs but should be stochastic enough to take into account the cluster-to-cluster variations in the MSP features. Most of the scenarios explaining the origin of MSPs involve a type of polluter. The basic idea is that enriched stars are formed from a mix of pristine material, similar to the one composing pristine stars, and enriched material, polluted by a certain source enriched in N, Na, and Al. Among these scenarios, there are two sub-types: the single-epoch scenarios, where pristine and enriched stars form simultaneously, and the multi-epoch scenarios, where pristine stars form first, followed by the formation of the enriched stars. In this section we introduce the main theories for the formation of MSPs. The scenarios are commonly labelled by the source generating the enriched material.

1.2.1 Asymptotic Giant Branch stars

Already 40 years ago Asymptotic Giant Branch (AGB) stars have been found to show abundance peculiarities in some chemical elements (Cottrell and Da Costa, 1981). Some 20 years later, Ventura et al. (2001) proposed that low-mass stars might have been polluted by the envelope of AGB stars, leading to the observed abundances; p -capture elements can indeed be synthesized during the hot-bottom burning phase in AGBs.

In the AGB scenario, the cluster undergoes a first star formation event. Pristine stars are formed. After a few million years, supernovae explosions occur, cleaning the center from the remaining gas. The pristine stars evolve, and low- to intermediate-mass stars enter the AGB phase. Such stellar evolutionary phase is characterized by two dredge-up, mixing the material from the core region into the outer layers, resulting in a change in the surface composition and by the activation of the hot bottom burning phase cycling the CNO elements. This evolutionary phase is also characterised by a significant mass loss through winds. These winds are thus enriched in N, Na, and depleted in C thanks to the interplay between the dredge-up and the hot bottom burning. Due to its very low velocity (Loup et al., 1993), the expelled material is trapped in the gravitational well of the GC. The GC re-accretes pristine material from the intra-cluster medium, with which the enriched material is diluted. Finally, the material cools and a new star formation event occurs, producing enriched stars (D’Ercole et al., 2008).

This scenario is the most popular to explain the formation of MSPs in GCs. It can nicely explain the anti-correlation between C and N and between Mg and Al (Prantzos et al., 2007). The dilution with pristine material makes it possible to reproduce the O-Na anti-correlation (a correlation is expected, otherwise). In the AGB scenario, enriched stars form in a denser environment, and are more centrally concentrated. The model also faces several challenges, the biggest one being the mass-budget problem. Current observations of GCs have revealed a higher percentage of enriched stars than pristine stars, reaching more than 70% of enriched stars in some clusters (e.g., NGC 104, NGC 2808, NGC 7078, Leitinger et al. 2023). Therefore, GCs should have been much more massive in the past in order to have enough pristine stars in the AGB phase to generate the enriched material necessary to the formation of the second population. To overcome this issue, an early mass loss of pristine stars or a modified IMF are required. The temperature reached by AGB stars is also too low to enable the formation of heavy elements such as K (Iliadis et al., 2016) and too high ($T \gtrsim 100$ MK) to reproduce the observed isotopic ratios of Mg (Denissenkov and Hartwick, 2014), requiring a narrow range of temperature around 80 MK, as shown by Prantzos et al. (2007).

1.2.2 Fast rotating massive stars

Decressin et al. (2007) suggested fast-rotating massive stars (FRMS) as a polluter creating the enriched material. Like for the AGB scenario, the cluster undergoes a first star formation event. The first massive stars to form are fast rotators, rotating at the critical limit. Due to their high mass, between $20 M_{\odot}$ and $120 M_{\odot}$, they undergo hydrogen burning in their cores. Their fast rotation mixes the material, whose composition resembles the observed chemical abundance patterns of MSPs, and brings it to the surface. These stars experience heavy mass loss as equatorial wind, orbiting around the massive star like a Keplerian disc. Clumps in the disc mix with the remaining pristine gas, forming enriched stars.

This scenario, like the AGB scenario, is an example of multi-epoch (or multi-generation of stars) scenario. The main difference is that the age difference between the two populations is much larger in the AGB scenario, because low- and intermediate-mass stars have to reach the AGB phase for the material to be enriched. In the FRMS scenario, SNe coexist with the formation of enriched stars, but the velocity of the gas in the explosion is high enough that it can escape the cluster. This is required to avoid an iron spread between the two populations. The wind from FRMS remains trapped in the gravitational potential, like the wind from AGB stars. This scenario also suffers from the mass-budget problem. To overcome this issue, Charbonnel et al. (2014) suggested a modification of the IMF, pristine stars would form with a top-heavy IMF, implying that a high fraction would already have died by today.

1.2.3 Supermassive stars

Denissenkov and Hartwick (2014) suggested supermassive stars (SMS), also referred to as very massive stars (VMS), as a possible polluter source for the enriched material. Stars more massive than $10^3 M_{\odot}$ would reach temperatures high enough to activate the CNO cycle and p -capture reactions. In this scenario, the cluster undergoes a first star formation event, leading to a generation of pristine stars. The most massive ones sink toward the center, where the SMS is then formed through runaway collisions of massive stars. The SMS expels a high fraction of enriched material through wind and instabilities. As in other scenarios, the enriched population forms from the mix between enriched and pristine material.

The SMS scenario is a multi-epoch scenario and also faces the mass-budget problem. To avoid such an issue, Gieles et al. (2018) suggested a single star formation episode. A fraction of the pristine population accretes the enriched material generated by the SMS when still in the protostar stage, forming enriched stars. The SMS gets continuously replenished through stellar collision. Consequently, the material ejected during its lifetime can be an order of magnitude bigger than the SMS mass and alleviate the mass-budget problem. Recently, Milone et al. (2023) reported the detection of MSPs in the main sequence branch of 47 Tuc; the extent of the oxygen spread in the observed M-dwarf spans the same range as in red giants, leading the authors to conclude that the formation of MSPs should be independent of stellar mass. Such an argument would contradict the above scenario as accretion of gas at the protostar stage should follow a Bondi-type accretion (Bondi, 1952) where the accretion rate is proportional to the mass of the object squared.

Nevertheless, SMSs remain hypothetical objects so far. The James Webb Space Telescope (JWST), which has the main science goal of shedding light into the formation of the first structures in the Universe and the birth and assembly of galaxies, has rekindled discussions and search for SMSs. Of particular interest is the star-forming object GN-z11, at redshift $z = 10.6$, observed by the NIRSpec spectrograph on JWST, which shows very bright Nitrogen emission lines (Bunker et al., 2023), and a super-solar N/O ratio (Cameron et al., 2023). A few theories have been suggested to explain the Nitrogen abundance of this object, among which the potential observation of a super-massive star polluting its surrounding (Charbonnel et al., 2023). The decade to come will surely bring new insight into the existence of SMSs.

1.2.4 Early-disk accretion

The early accretion disk (EDA) scenario (Bastian et al., 2013) is one of the few single-epoch scenarios for the formation of the different populations. Through their accretion disk, low-mass protostars would sweep-up material previously enriched by the ejecta from FRMS and interactive binaries, forming enriched stars. The accretion efficiency being proportional to stellar mass, such a scenario would also suffer from the recent conclusion drawn by Milone et al. (2023) that the oxygen range required to reproduce the observations of the M-dwarfs in the bottom of the main sequence of 47 Tuc was similar to the one in RGB stars. Moreover, as highlighted in Bastian and Lardo (2018), the protostar should be fully convective to efficiently mix the material within the star, requiring the accretion timescale to be very short, thus the accretion process to be very efficient. Another timescale constraint comes from the lifetime of the disc: according to simulations (Wijnen et al., 2016), it appears not to be long enough to accrete the required material.

1.2.5 Accretion disk around stellar mass black holes

Breen (2018) suggested black hole accretion disks as potential sites for the formation of the enriched material. Studying the nucleosynthesis of N and Na, they demonstrated that a sufficient amount of enriched material could be created in only ~ 3 Myr, given a reasonable number of black holes, set to 100, and an accretion rate $\dot{M} \approx 10^4 \dot{M}_{\text{Edd}}$, assuming a super-Eddington accretion flow, overcoming the mass-budget problem. One advantage of such a theory is that black hole accretion disks can have more versatile properties than stars, depending on the optical depth, the viscosity, and the state of the black hole, resulting in broad ranges of densities, temperatures, and radial velocities (for a review of black hole accretion disks, see Abramowicz and Fragile 2013). A temperature profile for the accretion disk covering a broad range could be an advantage for the creation of the enriched material. If the accretion

disk has a radial temperature profile between 200 MK and 50 MK, it would be possible to synthesize not only Na, O, C, N, Mg, and Al, but also heavier elements like K. The diverse range of physical properties exhibited by accretion disks could account for the variety of properties of stellar populations in different globular clusters. We investigate this scenario in more detail in Chapter 3.

1.2.6 Other theories

Another scenario involving the yield of massive stars was suggested by de Mink et al. (2009). Binary interaction between two massive stars could release a high fraction of enriched material in the medium. As for the FRMS scenario, the enriched material expelled through winds would mix with pristine material and form the population of enriched stars. One advantage of this scenario is the variability of the yield expelled by the binary which depends on their mass and their time of interaction. This could explain the cluster-to-cluster variations in abundances. The mass-budget problem could be alleviated assuming that the fraction of massive binaries is very high in the first million years after the cluster formation and that most of the envelope of the donor is expelled in the ISM.

The reverse population order scenario (Marcolini et al., 2009) switched the classical view by suggesting that enriched stars were actually the “normal” population while pristine stars formed in a second time in the outer part of the GC after dispersion of the peculiar gas through Type II supernovae. This scenario relies on several assumptions. It assumes that GCs form in a specific region of the halo that has been pre-enriched by SNe II. Enriched stars form first, in the inner part of the proto-GC where the gas has been enriched unevenly by a single SNe Ia and AGB star material, while stars with pristine compositions are formed later after SNe II explosions mix the enriched gas with the surrounding interstellar medium. However, this scenario requires specific conditions which are not expected to exist at the present epoch (Conroy, 2012).

Another family of models relies on an early star formation period (eSF) benefitting from specific conditions at high redshift such as a high density and turbulent environment, resembling those occurring today in starburst galaxies. In these scenarios, the enriched material is generated by massive stars (Elmegreen, 2017; Wünsch et al., 2017). Turbulent conditions and density in the early universe support an efficient stripping of winds from massive stars, allowing this material to cool and collapse in the cluster center, forming enriched stars. Depending on the specific model variant, these scenarios may face the mass-budget problem or rely on particular assumptions about the mass loss of pristine stars, which need to be thoroughly tested through simulations to assess their feasibility (see Bastian and Lardo (2018) for more details).

Many other scenarios have tried to shed light on the origin of MSPs (see for example Hopkins 2014 or Winter and Clarke 2023): most of them involve a polluter source (AGB, FRMS, and SMS, for example) generating the enriched material and some type of dilution with pristine gas. They are often referred to as “self-enrichment” scenarios. So far, no scenario has been able to reproduce all the observations. In Fig. 1.5, taken from Bastian and Lardo (2018), the main scenarios are listed in the first column, namely the AGB (Sect. 1.2.1), the FRMS (Sect. 1.2.2), the VMS (Sect. 1.2.3), the EDA (Sect. 1.2.4), the reverse order and the eSF period (Sect. 1.2.6). The main constraints coming from observations are indicated in the other columns. The near ubiquity and the age trend refer to the presence of MSPs in MW GCs older than a few Gyr and in extragalactic environments (see, e.g., Schiavon et al. 2013). More details on the age limit is given in Sect. 1.3.1, together with information on the apparent correlation between fraction of enriched stars and cluster mass, and between spread in helium and cluster mass. The abundances in light elements and the Mg-Al correlation present in some GCs have been discussed in Sect. 1.1. The Li-correlation refers to the fact that enriched stars are expected to be Li free if they form from the ejecta of pristine stars generated at high temperature as lithium is efficiently destroyed above 2.5 MK. This is not the case, and some clusters host enriched stars with a similar Li abundance than pristine stars (D’Orazi et al., 2010). The variety/stochasticity relates to cluster-to-cluster variations in the properties of MSPs and the discreteness refers to the fact that, in some clusters, the MSPs can be separated in discrete groups, these two points are discussed in Sect. 1.3.2. The mass-budget problem refers to the main issue faced by many scenarios (see for e.g. Sect. 1.2.1). The YMCs column relies on the idea that YMCs are proto-GCs, resembling GCs in their early stages. As such, they could provide additional constraints, such as on the time it takes a cluster to become gas free (Bastian et al., 2014). The red crosses in Fig. 1.5

show where models are failing to reproduce the observations, with the asterisk showing where this could be alleviated under some type of tuning. The green check-mark indicate where the models can reproduce the observations, with asterisks highlighting where certain assumptions are required.

	(near) Ubiquity (§2)	Abundances (§5.1)	Li correlations (§5.1.2)	Variety/stochasticity (§5.1.3)	Mg-Al (§5.1.5)	Discreteness (§5.2)	Mass budget (§5.2)	f_{enriched} correlation with GC mass (§5.4)	He spread correlation with GC mass (§5.5)	YMCs (§5.6)	Age Trend (§5.6.1)
AGB	✗	✗*	✗*	✗	✓*	✗*	✗*	✗	✗*	✗	✗
FRMS	✗	✗*	✗	✗	✗	✗	✗*	✗	✗	✗	✗
VMS	✗	✗*	✗	?	✗*	✗	✓*	✓*	✓*	✓	✗
EDA	✗	✗*	✗	✗	✗	✗	✗*	✗	✗	✓*	✗
Reverse Order	✗	✗*	✗	?	?	✗	✓*	✗	✗	✗	✗
eSF Period	✗	✗*	✗	✗	✗	✗	✗*	✗	✗	✓	✗

Figure 1.5: Table summarizing the different theories and whether they reproduce the observations. This figure has been taken from Bastian and Lardo (2018).

Future successful theories should be independent of the location where the GC formed. They should take into account the mass of the GC as a driving factor for the presence of MSPs and the fraction of enriched stars. They should also include a high degree of stochasticity as MSPs in GCs are characterized by a high variety in their patterns (e.g. spatial distribution of the populations discussed in Sect. 1.3.3). This is an issue for most current theories (Bastian et al., 2015).

1.3 Properties of multiple stellar populations

Abnormal chemical abundances, in particular in light elements, are ubiquitous among GCs hosting MSPs. However, not all GCs host MSPs. Their presence depends on some global properties of the host GC, such as its mass. Furthermore, not only do pristine and enriched stars show different chemical compositions, they also have different kinematical properties.

1.3.1 Link with cluster mass and age

The mass of the GC is a key parameter in the context of MSPs, because many aspects of this phenomenon appear to be connected to this quantity. Indeed, the extent of the spread in light elements and in helium correlates with cluster mass (Carretta et al., 2010, Milone et al., 2015). As mentioned by Bastian and Lardo (2018), this is an extra difficulty for scenarios where the enriched stars formed from a dilution of the pristine gas with enriched material (e.g. AGB, FRMS, SMS), as low-mass clusters are expected to retain less (pristine) gas than high-mass clusters (Krause et al., 2016), therefore leading to less dilution, and thus to a broader spread in chemical abundances, contrary to what is observed. The fraction of enriched stars also correlates with cluster mass (Milone et al., 2017), ranging from 80% in high mass clusters (e.g., NGC 2808, 47 Tuc) to 40% in low mass clusters (e.g., NGC 6362). Mass could also play a role in dictating the presence or absence of MSPs: all the GCs without MSPs have a mass $M < 10^5 M_{\odot}$, but some higher mass GCs exhibit a single populations (Milone et al., 2020).

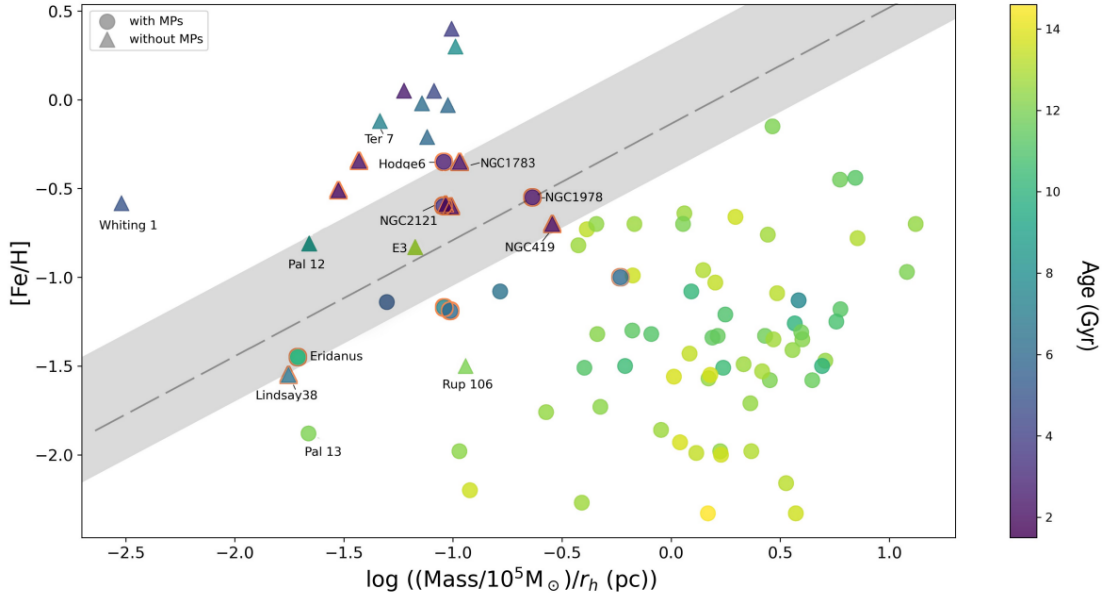


Figure 1.6: Logarithmic compactness versus metallicity of GCs with (circle) and without (triangle) MSPs. The symbols are colored according to the age. The dashed-line shows the apparent threshold to the onset of MSPs, and the grey area represents the error. Clusters with red edges are located more than 50 kpc away from the Galactic center. The figure is taken from Huang et al. (2024).

There are some hints that age could also play a role. Clusters younger than ~ 2 Gyr do not host MSPs, NGC 1978 being the youngest cluster with MSPs, while intermediate-age clusters older than ~ 6 Gyr all show evidence of MSPs (Martocchia et al., 2018a). However, because most massive young clusters have a mass close to the threshold of $10^5 M_\odot$, the age limit might just be actually another effect of the cluster mass (Milone et al., 2020). More recently, Wang et al. (2023) refined the initial mass lower limit suggested by Milone et al. (2020) for the presence of MSPs. They found that this initial mass threshold is $\log M_{\text{initial}} = 4.98$ in young GCs (close to 2 Gyr) and $\log M_{\text{initial}} = 5.26$ in old GCs (above 10 Gyr).

By combining their findings on the presence of a simple stellar population in the low mass GC Whiting 1 with literature studies, Huang et al. (2024) proposed a limit, here shown as the dashed line in Fig. 1.6, to determine which GCs are hosting MSPs based on their age, compactness, and metallicity. By comparing the logarithmic compactness, defined as the ratio between the cluster initial mass and its half mass radius, and the metallicity of GCs, they found that, for a given compactness, more metal-poor GCs tend to have MSPs; conversely, for a given metallicity, more compact GCs tend to host MSPs, leading them to visually define the dashed line in Fig. 1.6.

1.3.2 Ubiquitous though cluster-specific

As mentioned in Sect. 1.3.1, all the GCs older than 2 Gyr host MSPs, making them ubiquitous. However, their properties vary a lot from cluster to cluster. In Fig. 1.4 the distribution of stars seems continuous, but some clusters exhibit a bi-modal distribution of their stellar populations, with a pristine and an enriched population clearly separated and clustered around certain values (e.g., see Marino et al. 2008 for M4). More than two discrete sub-groups are also found in some GCs: for example, Carretta (2015) discovered five sub-populations in NGC 2808, two among the pristine stars, one intermediate population, and two enriched populations. This discreteness of MSPs became apparent thanks to a number of high precision spectroscopic and photometric surveys, which are increasingly providing tighter constraints on MSPs.

Using high-precision photometric observations with the filters F275W, F336W, F438W, and F814W, Milone et al. (2017) introduced chromosome maps, multiple pseudo-colour diagrams which make it possible to easily distinguish between the different populations. Based on these maps, they defined

two distinct types of GCs: Type I are GCs for which the MSPs appear clearly separated in two main groups in the chromosome map, the pristine stars and the enriched stars; Type II are GCs for which the separation is more complex, with more than two groups of stars.

Other aspects such as the spatial distribution of MSPs, and some kinematical properties are cluster-specific.

1.3.3 Spatial distribution and kinematics of MSPs

GCs are old stellar systems, and their relaxation time (which is a way to measure the effect of the scattering process between stars) is typically shorter than their age. This means that during their evolution, GCs have undergone a number of relaxation times: we indicate as “dynamically young” those for which this number is small, and “dynamically old” those for which it is large. Such a dynamical age is therefore an indication of how much relaxation processes have influenced the system. Therefore, if any kinematic and structural differences between the MSPs would have been imprinted at the birth of the cluster, there is higher chance to observe such differences in dynamically young clusters, which might still retain part of their initial conditions. In dynamically old GCs, some differences might also survive, in particular in the outer parts, where interactions are rarer. Overall, with cluster evolution the MSPs are expected to become more mixed, both kinematically and structurally. Studying structural and kinematical properties of MSPs, highlighting similarities and differences, could therefore provide additional information to constrain their formation mechanisms.

To quantify the spatial distribution of the two populations, we introduce the A^+ parameter, representing the area enclosed between the cumulative radial distributions of different types of stars, which can be used to quantify how much the spatial distribution of such stars differ from one another. It was initially developed by Alessandrini et al. (2016) to study the concentration of blue straggler stars, and Dalessandro et al. (2019) extended it to the MSPs framework, defining it as:

$$A^+(R) = \int_{R_{\min}}^R [\varphi_{P1}(R') - \varphi_{P2}(R')] dR', \quad (1.1)$$

where R is the distance from the cluster center, and φ_{P1} and φ_{P2} are the cumulative radial distributions of pristine and enriched stars, respectively. The radial distributions of pristine and enriched populations behave differently in different GCs. In some cases, for example in NGC 104 (Milone et al., 2011), NGC 2808 (Simioni et al., 2016), NGC 5272 (Massari et al., 2016) and NGC 5927 (Dondoglio et al., 2021), enriched stars are more centrally concentrated than pristine stars, as expected based on most of the proposed theories for the formation of MSPs. For example, in the case of the AGB scenario (see Sect. 1.2.1), the ejecta of P1 (pristine) stars in their AGB phase sink toward the cluster center and P2 (enriched) stars form from these ejecta, more centrally concentrated; the populations are expected to mix quickly at the center of the cluster due to higher dynamical interactions, but some differences might survive in particular in the outer part of the cluster. For instance, using N-body simulations with an initially more concentrated P2, Vesperini et al. (2013) found that many galactic GCs should still show these differences in concentration of their multiple stellar populations. Other clusters, such as NGC 6723 and NGC 362 (Lim et al., 2016), NGC 7078 (M15, Larsen et al., 2015), and NGC 3201 and NGC 6101 (Leitinger et al., 2023), show the opposite trend in the distribution of their populations, with more concentrated pristine stars, challenging most of the formation scenarios (see Sect. 1.2). Finally, in other clusters (e.g., NGC 6362, Dalessandro et al., 2014), enriched and pristine stars are well mixed and have similar distributions. Therefore, this is another cluster-specific property of MSPs.

While GCs have been long modelled using spherically symmetric, isotropic, non-rotating models (King, 1966), there is increasing observational evidence that these systems deviate from this simple picture. The presence of rotation has been detected in several GCs (Bellazzini et al., 2012; Bianchini et al., 2018; Dalessandro et al., 2024; Lane et al., 2010; Leitinger et al., 2024; Martens et al., 2023; Sollima et al., 2019). Rotation can be detected along the line-of-sight (LOS), by using LOS velocity measurements, and on the plane of the sky, by using proper motion data. The ordered-to-random motion parameter A/σ , defined as the ratio between the rotation amplitude A and the central velocity dispersion σ , is commonly used to quantify the importance of internal rotation in shaping stellar systems such

as galaxies (Binney, 2005; Emsellem et al., 2011) and globular clusters (Bianchini et al., 2013, 2018). There are indications that clusters with a high degree of internal rotation also exhibit a more flattened shape (Fabricius et al., 2014; Kamann et al., 2018). More information are given in Chapter 4 where we investigate the ellipticity of GCs and of their MSPs in relation to their internal kinematics.

Velocity anisotropy is another dynamical factor contributing to the cluster shape. When considering proper motion data, it is defined as:

$$\beta = 1 - \frac{\sigma_{\text{tan}}^2}{\sigma_{\text{rad}}^2}, \quad (1.2)$$

where σ_{rad}^2 and σ_{tan}^2 are the velocity dispersions along the radial and tangential component, respectively. If $\beta = 0$, the cluster is isotropic, if $\beta > 0$, the cluster is radially anisotropic, and if $\beta < 0$, the cluster exhibits tangential anisotropy. Figure 1.7, taken from Leitinger et al. (2024), shows the anisotropy profiles of dynamically young (top panel) and dynamically old (bottom panel) Galactic GCs. In their analysis, they used the normalised anisotropy $\tilde{\beta} = \beta/(2 - \beta)$, which can only take values in the range $[-1, 1]$. The lines are color-scaled according to the concentration parameter A^+ (see Eq. 1.1): positive values, coloured in blue, correspond to a more centrally concentrated pristine population, while negative values, coloured in red, correspond to a more centrally concentrated enriched population. Unsurprisingly, deviation from isotropy and differences in concentration are still very visible in dynamically young GCs, showing overall a higher anisotropy and a different spatial distribution for their MSPs than dynamically old GCs. The differences are more evident in the outer part of the GCs. In 47 Tuc (Richer et al., 2013) and NGC 2808 (Bellini et al., 2015), enriched stars tend to have a more radially anisotropic velocity distribution than pristine stars. Like with the other properties introduced above, for example the radial distribution, such a trend is far from being universal and many GCs show isotropic velocity distribution for both populations (e.g. Cordoni et al., 2020).

Both rotation and velocity anisotropy can provide strong constraints for the formation mechanism of MSPs. Using a set of N-body simulations with various initial conditions reflecting different formation scenarios, Hénault-Brunet et al. (2015) demonstrated that distinct rotational patterns of pristine and enriched stars serve as a unique kinematic marker, particularly in the outer regions of clusters. They examined multi-epoch scenarios, where pristine stars form first and enriched stars form later from a mix of pristine and polluted material (as in the AGB, FRMS, or VMS scenarios, see Sect. 1.2.1, Sect. 1.2.2, and Sect. 1.2.3 respectively), and accretion scenarios, where a single star formation event occurs and enriched stars form through the accretion of material during their early proto-star stage (e.g., the EDA scenario; Sect. 1.2.4). They found that in multi-epoch scenarios, P2 stars are expected to rotate faster than P1 stars. In contrast, for the accretion scenarios, P2 stars are predicted to rotate more slowly and exhibit radial anisotropy. They concluded that rotational patterns could serve as evidence to distinguish between these scenarios. These results have been further corroborated by Lacchin et al. (2022). They used 3D hydrodynamics simulations to follow the formation of P2 stars from a mix of AGB ejecta from a rotating P1 and of pristine gas accreted by the cluster. Their findings indicate that faster rotation of P2 is expected under this formation scenario.

1.3.4 Binariness

In a few GCs, the number of binary stars in the enriched population appears lower than in the pristine stars. This has been observed for example in NGC 6362 (Dalessandro et al., 2018) and in NGC 6121 (D’Orazi et al., 2010), when studying the outer part of the clusters using spectroscopy. Milone et al. (2020) used multi-band HST photometry to infer the binary fraction of the two populations, probing the inner part of the clusters: in 4 out of 5 GCs (NGC 6121 being the exception, in good agreement with D’Orazi et al. 2010), they did not detect any difference between the number of binaries in pristine and enriched stars. Such photometric method only probe the inner part of the GCs, where the density is high and consequently the number of binaries is predicted by numerical simulations to be lower due to higher disruptions (Hong et al., 2015; Vesperini et al., 2011). Lucatello et al. (2015) monitored the radial velocities of stars in 10 Galactic GCs. They found $4.9\% \pm 1.3\%$ fraction of binaries in pristine stars and only $1.2\% \pm 0.4\%$ among enriched stars. They concluded that this difference cannot be due to incompleteness, which would affect the percentages in a similar way, but would rather indicate

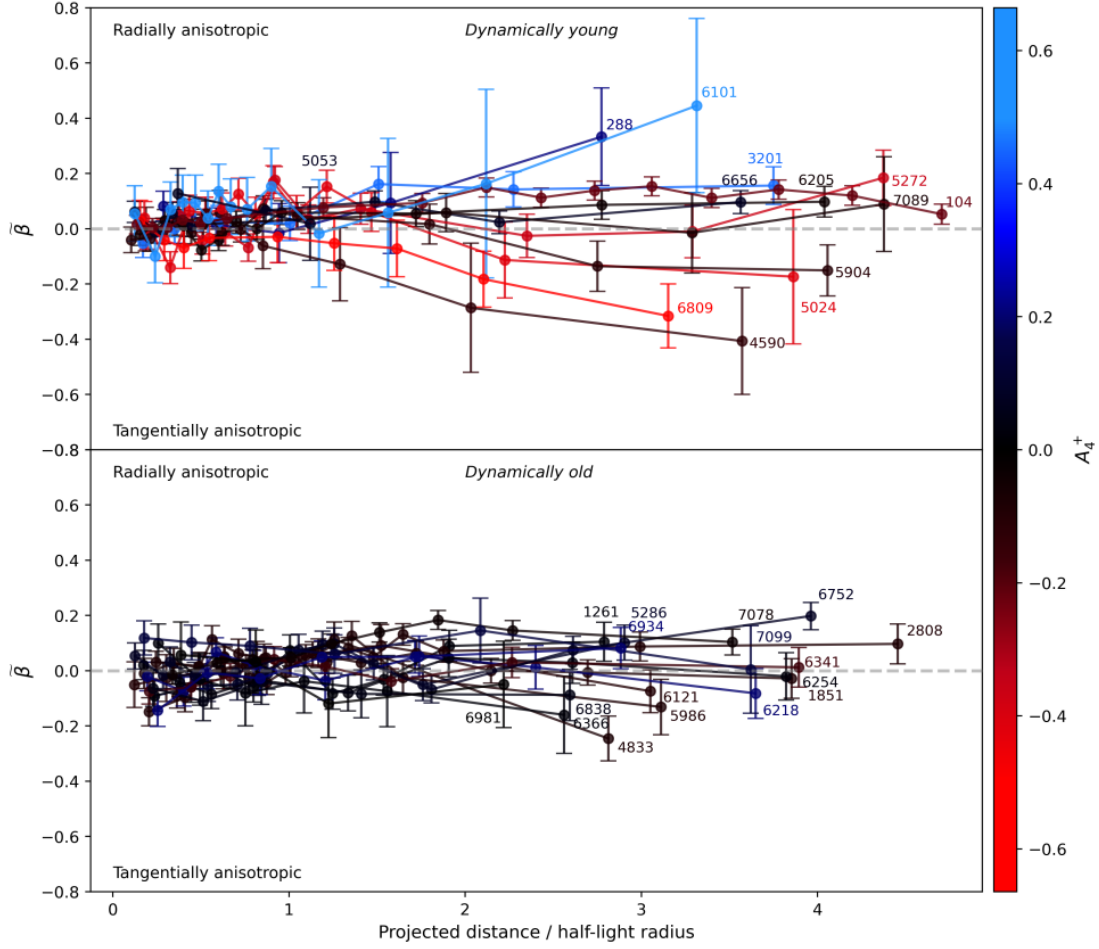


Figure 1.7: Anisotropy profile of dynamically young (top panel) and dynamically old (bottom panel) Galactic GCs. The profiles are color-scaled according to the concentration parameter A_3^+ , with positive values (red lines) indicating a more centrally concentrated P1 and negative values (blue lines) indicating a more centrally concentrated P2. This figure has been taken from Leitinger et al. (2024).

differences in the environment where the two populations form and evolve. They suggested that enriched stars might have formed in a denser environment, leading to more binary disruptions, but that other mechanisms could impact the number of binaries, such as differences in kinematics, in the spatial structures, or in chemical composition.

1.4 This thesis

Any attempt to explain the MSP phenomenon requires to consider the chemistry involved in the formation of the enriched material. In Chapter 2, we investigate the conditions in temperature and time required to generate the enriched material. Such investigation provides constraints on the nucleosynthesis independently of any formation theory. This chapter sets the framework for Chapter 3, in which we apply our results to test the scenario from Breen (2018), who proposed that the enriched material could be synthesized in accretion disks around stellar mass black holes. Using a nuclear reaction network and an accretion disk model, we infer the physical parameters of the accretion disk-stellar mass black hole system compatible with the nucleosynthesis of the enriched material. Moving beyond the chemistry of MSPs, we study the shape of GCs and their MSPs in Chapter 4 by modelling their ellipticity. After the implementation and careful testing of several methods, we present comprehensive

1. Introduction

measurements of global ellipticity and of ellipticity for population 1 (P1, pristine stars) and population 2 (P2, enriched stars) in 26 Galactic GCs.

On the one hand, GCs are a beautiful example of sustainable systems, sustaining their diversity in stellar populations for several billion years. On the other hand, in only a few decades, human activities have resulted in a drastic loss of the biodiversity with a 73% decline in the vertebrate wildlife populations in just 50 years¹. This Thesis has been started in October 2021. On the 27th of February 2021, the Working group II (WG II) of the Intergovernmental Panel on Climate Change (IPCC) released the 6th assessment report tackling the impacts, adaptation and vulnerability of socio-economic and natural systems to climate change. Hans-Otto Pörtner, co-chair of IPCC's WG II, said *"The scientific evidence is unequivocal: climate change is a threat to human well-being and the health of the planet. Any further delay in concerted global action will miss a brief and rapidly closing window to secure a liveable future"*. Given the emergency of the social and climate crisis, every organization, every discipline, every individual, has a role to play. Scientists, and in particular astronomers, have a unique perspective on the Earth. In Chapter 5 we reflect on the role of astronomers in tackling the climate crisis and present specific projects and initiatives where astronomy skills contribute to climate action in an interdisciplinary framework. Finally, we present our conclusions in Chapter 6.

¹<https://www.worldwildlife.org/press-releases/catastrophic-73-decline-in-the-average-size-of-global-wildlife-populations-in-just-50-years-reveals-a-system-in-peril>

Chapter 2

NUCLEOSYNTHESIS OF THE ENRICHED MATERIAL

“Somewhere, something incredible is waiting to be known”

- Carl Sagan

Declaration of published work

This chapter includes text already published in Fréour et al. (2024). As a result, there may be partial overlap with this publication.

Introduction

As introduced in Chapter 1, the origin of the multiple stellar populations (MSPs) remains an unresolved puzzle despite the many existing theories. The chemical anomalies in light elements (He, C, N, O, Na, Al, and sometimes Mg) and sometimes in heavier elements such as Si or K exhibited by a substantial fraction of stars in most GCs challenge our current understanding on their formation. In general, the “enriched population”—characterized by enhancements in N, Na, and Al and depletion in C, O, and Mg relative to the “pristine population”—is thought to form from a mixture of pristine and enriched material. The pristine gas has a composition identical to that of the pristine population of stars, while the enriched gas shares the abundance characteristics of the enriched population. The main question, then, is to determine the type of objects capable of producing this enriched material. So far, several candidates have been proposed, among them are Asymptotic Giant Branch stars (see Sect. 1.2.1), fast-rotating massive stars (Sect. 1.2.2), super-massive stars (Sect. 1.2.3), and interactive binaries (Sect. 1.2.4). None of them can account for all the properties of MSPs (Sect. 1.2.6). One of the challenge they face is the temperature T required to generate the observed abundance patterns (Iliadis et al., 2016). While the temperatures required to initiate the depletion of O and formation of N from the CNO cycle are close to the temperature activating the NeNa chain, the MgAl chain requires higher temperatures to lead to an enhancement in Al and a depletion in Mg. Si and K are created at even higher temperatures. Such broad range of temperatures is rarely reachable in a single stellar object over a short period of time. Therefore, understanding the physical conditions in temperatures and in densities, as well as the timescales required to generate the enriched material is crucial to constrain the polluter source. In this chapter, we study how these physical parameters influence the formation of C, N, O, Na, Al, Mg, Si, and K by means of dedicated nuclear reaction network simulations. The results presented in this chapter are independent of any theory or polluter source involved in the formation of the enriched stars. We solely focus on the physics of the nucleosynthesis of the enriched material.

In Sect. 2.1, we introduce the main equations of a nuclear reaction network and the codes used in our simulations. In Sect. 2.2, we present the data needed to establish the initial chemical abundances required to initiate the reaction network. In Sect. 2.3 and 2.4, we define relevant timescales for the analysis and explore the conditions in temperature, density, and time leading to the observed anti-correlations. In Sect. 2.5, we present the dilution model between pristine and enriched gas and compare the results of our simulations with observations. In Sect. 2.6, we define the concept of enrichment threshold, particularly useful for the analysis presented in Chapter 3. Finally, we summarise the analysis and the main results in Sect. 2.7.

2.1 Nuclear reaction networks

Nuclear reaction networks are mathematical models used to simulate the complex interactions of nuclear reactions occurring within stars, stellar explosions, and other astrophysical environments such as neutron star mergers or X-ray bursts. These networks track the evolution of nuclear species by accounting for various nuclear processes such as fusion, fission, and beta decay.

2.1.1 Theory

The theoretical framework behind nuclear reaction networks is based on the principles of nuclear physics, including nuclear binding energies, reaction rates, and conservation laws. By integrating these principles into a network of equations, we can model the evolution of nuclear abundances over time under different astrophysical conditions.

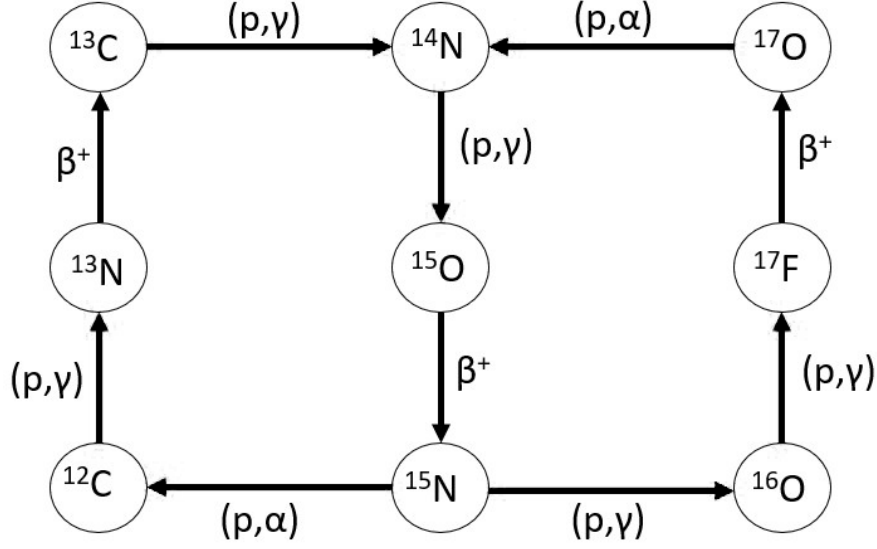


Figure 2.1: Schematic representation of the CNO cycle. The chemical species involved in the reaction are written inside the circles. The type of reaction is written side to the arrow. β^+ stands for beta decay, (p, γ) for proton-capture, and (p, α) for proton-alpha reaction. This figure is adapted from Gratton et al. (2019).

The rate of change of the abundance Y_i of a nuclear species i with respect to time t can be described by:¹

$$\frac{dY_i}{dt} = \sum_j \lambda_j (-R_{ji} + P_{ji}) N_{ji} \prod_{k \in \mathbb{R}_j} Y_k^{N_{ik}}, \quad (2.1)$$

where λ_j represents the reaction rate coefficient associated with species j , $(-R_{ji} + P_{ji})$ denotes the net change in the abundance of species i due to reactions involving species j , R_{ji} representing the number of particles of species i that are consumed and P_{ji} denoting the number of particles of species i that are produced in the nuclear reaction with j . N_{ji} represents the stoichiometric coefficient associated with species i in reactions involving species j , and $\prod_{k \in \mathbb{R}_j} Y_k^{N_{ik}}$ quantifies the contribution of species k to the production or destruction of species i (Hix and Thielemann, 1999).

As an example, let us consider the CNO cycle illustrated in Fig. 2.1, and in particular the case of ^{12}C , which is involved in two reactions:



The first one (Eq. 2.2) is a proton-capture reaction where an atom of ^{12}C captures a proton, transforming in ^{13}N alongside with the emission of a γ -ray. It contributes negatively to the change in ^{12}C abundance, proportionally to the quantity of ^{12}C initially present. The second reaction (Eq. 2.3) is also a proton-capture reaction with ^{12}C as a product and not a reactant: as ^{15}N is destroyed, ^{12}C is created. The equation governing the evolution of the abundance of ^{12}C is thus:

$$\frac{dY_{\text{C12}}}{dt} = \lambda_2 Y_{\text{N15}} Y_p - \lambda_1 Y_{\text{C12}} Y_p, \quad (2.4)$$

¹A detailed derivation of this equation is given in Lippuner and Roberts (2017).

where Y_{N15} , Y_{C12} , and Y_p are the abundances of ^{15}N , ^{12}C , and hydrogen, and λ_1 and λ_2 are the reaction rate coefficients corresponding to Eq. 2.2 and 2.3. The reaction rate coefficients λ are available in reaction rate libraries. They can be determined theoretically or experimentally. Usually, libraries are constructed using both types of data because some rates are hard to determine experimentally. For example, among widely used libraries, STARLIB (Sallaska et al., 2013) gathers rates determined experimentally, when possible, and theoretically otherwise. The Pynucastro code that will be introduced in Sect. 2.1.3 uses mainly the REACLIB database² (Cyburt et al., 2010) providing a continuously updated reaction rate library based on experimental or theoretical work. The NACRE collaboration (Angulo et al., 1999; Xu et al., 2013) compiles tabular data, together with lower and upper bounds as proxy for uncertainties and analytical formula.

For a given reaction, the main factor impacting the reaction rates is the temperature. As an example, the reaction rate corresponding to the proton capture reaction from Eq. 2.2 is given by:

$$\lambda_1 = 2.00 \times 10^7 T_9^{2/3} \exp(-13.692 T_9^{1/3} - (T_9/0.46)^2) \times (1 + 9.89 T_9 - 59.8 T_9^2 + 266 T_9^3) \\ + 1.00 \times 10^5 T_9^{3/2} \exp(-4.913/T_9) + 4.24 \times 10^5 T_9^{3/2} \exp(-21.62/T_9), \quad (2.5)$$

where T_9 is the temperature in Giga Kelvin. For this reaction, the rate goes from 1.18×10^{-19} at $T = 10$ MK to 2.18×10^{-5} at $T = 100$ MK (Angulo et al., 1999) showing the strong dependency of the rate on the temperature.

Another important feature to notice is the link between density and mean lifetime of particles. The abundance of a given species over time is described by a differential equation that depends on its interactions with other chemical elements, as shown in Eq. 2.1. If we consider two particles j and k , then the mean lifetime of particle j against destruction by particle k is (Hix and Meyer, 2006):

$$\tau_k(j) = \frac{1}{\lambda_{j,k} n_k}, \quad (2.6)$$

where $\lambda_{j,k}$ is the reaction rate between j and k , depending on the temperature, and n_k is the number density of particle k . Thus, a higher density of particle k leads to a lower mean lifetime for particle j . In the reaction network simulations, this translates into the same final abundance when increasing (decreasing) the density by a certain factor and simultaneously decreasing (increasing) the simulation time by the same factor, as highlighted by Prantzos et al. (2007). Running two simulations with densities ρ_1 and $\rho_2 = 100 \times \rho_1$ for a time t_1 and $t_2 = 0.01 \times t_1$, respectively, leads thus to the same results. Considering the coupling between density and time, we maintain a constant value for the density, hereafter indicated as ρ , and investigate the evolution of the mass ratio of chemical elements with respect to time. The main drivers in our simulations are thus the temperature and the timescale.

In astrophysics, many different reaction networks are available. The choice depends on the context of the problem. Nuclear reaction networks are crucial for simulating the processes occurring within stars and during stellar evolution. These networks are often embedded in stellar evolution models to accurately represent the synthesis of elements and the energy generation mechanisms in stars (see for example the MESA code, Paxton et al., 2011). They can also be coupled to hydrodynamical simulations to accurately describe various scenarios such as supernovae or X-ray burst (see, e.g., FLASH Ricker et al., 1999). Only a few nuclear reaction networks are publicly available and provided without being embedded in a specific type of astrophysical object, such as TORCH (Timmes, 1999), Libnucnet (Meyer and Adams, 2007), Skynet (Lippuner and Roberts, 2017), or Pynucastro (Smith Clark et al., 2022). For a detailed review on nuclear astrophysics and the broad range of application, we refer the reader to Schatz et al. (2022).

This section focuses on the formation of the enriched material specific to MSPs in GCs, and is aimed at identifying the conditions in temperature and time suitable for the creation of N, Na, Al, Si, and K, independently of the astrophysical context. We ran our simulations using the TORCH and Pynucastro codes, that will be introduced, respectively, in Sect. 2.1.2 and Sect. 2.1.3.

²<https://reaclib.jinaweb.org/>

2. Nucleosynthesis of the enriched material

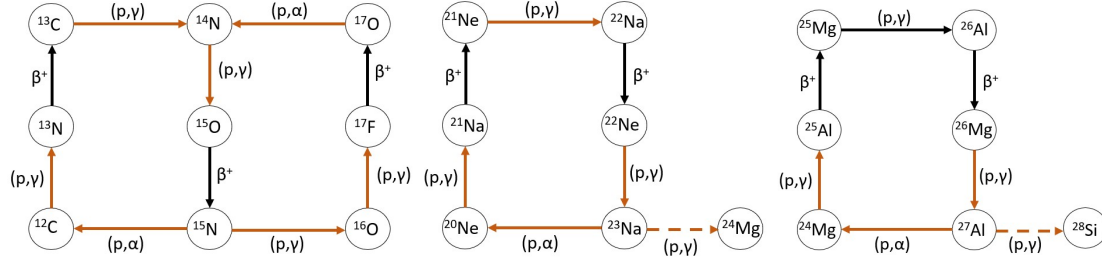


Figure 2.2: The CNO cycle, the Ne-Na cycle, and the Mg-Al cycle. The orange arrows show the reaction rates that we modified to run our simulations. The dashed lines represent the reaction involving a species outside of a specific reaction chain. The figure is adapted from Salaris et al. (2002) and Gratton et al. (2019).

2.1.2 TORCH

TORCH (Timmes, 1999) is a 513-isotope network coded in Fortran77 and publicly available³. In its standard setup, the TORCH code makes it possible to vary initial temperature, density, time, and chemical composition of the gas. The mass ratios of 14 chemical elements can be specified. We modified the code to add the initial mass ratios of sodium, aluminium, argon, potassium, calcium and scandium to the initial gas composition.

TORCH offers different burning modes, and in our simulations we tested two of them. The “hydrostatic” mode occurs at constant temperature and density; it represents the slow and stable nuclear burning happening in objects in which the thermodynamic conditions do not change rapidly, computing separately the adiabatic changes in the fluid and the results of nuclear burning over each time step. The “self-heat at constant density” mode allows the temperature to increase with the energy released by the various reactions.

We tested both modes, varying the temperature between 50 MK and 190 MK. For the range of density considered, we do not find any difference between the two modes. It is only when the density exceeds 10 g cm^{-3} and for long duration of the simulation that the temperature significantly changes. Therefore, we used the “hydrostatic” mode of TORCH.

Reaction rates are also important parameters to consider as they can influence the yields in some chemical elements. For example, Izzard et al. (2007) studied the effect of reaction rate uncertainties on the outcome of nucleosynthesis in AGB stars. They found that the yields of several light elements of particular interest for the MSP phenomenon were uncertain. Most of all, they found variations of two orders of magnitude in the yields in ^{26}Al and ^{23}Na , and of more than one order of magnitude in ^{24}Mg and ^{27}Al . As a consequence, we modified the rates of the reactions indicated by the orange arrows in Fig. 2.2 with updated values. We used the NACRE II library (Xu et al., 2013) for chemical elements with mass number A smaller than 16 and the STARLIB library (Sallaska et al., 2013) for the others. Only the abundance of Na is greatly affected by the change in the reaction rates, mainly due to the fact that the reaction rate of $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ from STARLIB is ~ 800 times smaller than the initial one in TORCH (big variations of this rate were already noticed by Prantzos et al. 2007). It is important to note that we did not change the reaction rates of $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ and $^{26}\text{Mg}(p,\gamma)^{26}\text{Al}$, because ^{26}Al has several excitation states, making these reactions more complicated. Ventura et al. (2018) emphasized the importance of accurately determining the $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ reaction rate, because ^{26}Al decays in ^{26}Mg , an isotope of particular interest for enriched stars. Consequently, we expect that changing these reaction rates slightly could shift the region found in the parameter space but would not modify our main result.

2.1.3 Pynucastro

Pynucastro (Smith Clark et al., 2022) is an open-source project providing a user-friendly interface to solve nuclear reaction network equations in python. The reaction network is characterized by a set of differential equations similar to Eq. 2.1, forming a stiff system of equations characterized

³https://cococubed.com/code_pages/net_torch.shtml

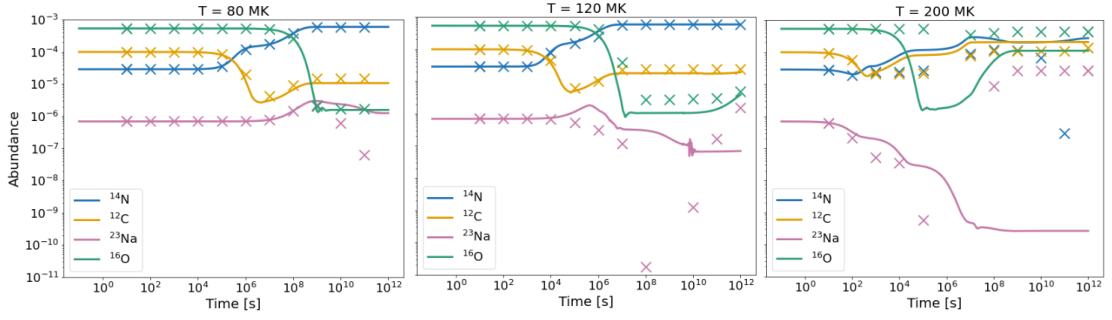


Figure 2.3: Comparison of the yields in C in orange, N in blue, O in green, and Na in pink, using TORCH (crosses) and Pynucastro (full lines) at constant density of 1 g cm^{-3} for three different temperatures indicated on top of each panel, $T = 80$ MK (left panel), $T = 120$ MK (middle panel), and $T = 200$ MK (right panel)

by variables that can vary at very different rates, making it particularly challenging to solve due to numerical instabilities. Therefore, specific numerical methods need to be employed to solve such differential equations. We used the Backward Differentiation Formula (BDF) integration method (Byrne and Hindmarsh, 1975) from the SciPy module. To set up the reaction network, a first step consists in carefully selecting the chemical elements of interest. For this purpose, we selected all the isotopes involved in the CNO cycle, NeNa, MgAl and K chain. Additionally, we included all isotopes that are reactant or products associated with any of the elements listed. To ensure that the network is stable and accurately captures the evolution of the chemical elements of interest, we run several tests, varying the number of isotopes included in the network. We selected a total of 132 chemical elements, to best compromise between accuracy and relevance.

2.1.4 Selection of the reaction network code

In this section we briefly discuss the differences between the TORCH and Pynucastro codes and we provide the main motivation behind our choice of network. A detailed comparison of the codes is beyond the scope of this thesis. We focus on four chemical elements of particular interest for the MSP phenomenon: C, N, O, and Na. In Fig. 2.3, we show the results of TORCH (crosses) and Pynucastro (curves) for these four chemical elements for a temperature of $T = 80$ MK (left panel), $T = 120$ MK (middle panel), and $T = 200$ MK (right panel). There is good agreement between the two codes for ^{14}N and ^{12}C regardless of the temperature. The yields in ^{16}O also match except when the temperature is $T = 200$ MK where Pynucastro predicts a sudden decrease of the abundance which is not the case with TORCH. Finally, there is a difference with respect to the yields in ^{23}Na for time $t > 10^5$ s. This difference is stronger at higher temperatures. Such a difference could be explained partly because of the different reaction rate libraries used, NACRE II (Xu et al., 2013) and STARLIB (Sallaska et al., 2013) for TORCH and REACLIB (Cyburt et al., 2010) for Pynucastro, with larger differences in the reaction rates of sodium as mentioned in Sect. 2.1.2.

Overall the yields at temperature lower than 100 MK, which are the temperatures of interest for the formation of the light elements, are similar between the two codes. We decided to use Pynucastro for the rest of this work because of its user-friendly design. Being implemented in Python, it is built with classes and libraries that make it particularly flexible and simple to adapt to our needs. This structure allows us to tailor the code for our specific purposes, limiting our study to the chemical elements of interest in the scope of MSPs.

2.2 Chemical abundance data for NGC 6752 and NGC 4833

We aim at studying the conditions in temperature and time suitable for the formation of the enriched material in GCs, while keeping the density fixed. The first step to set up our simulations is to define an

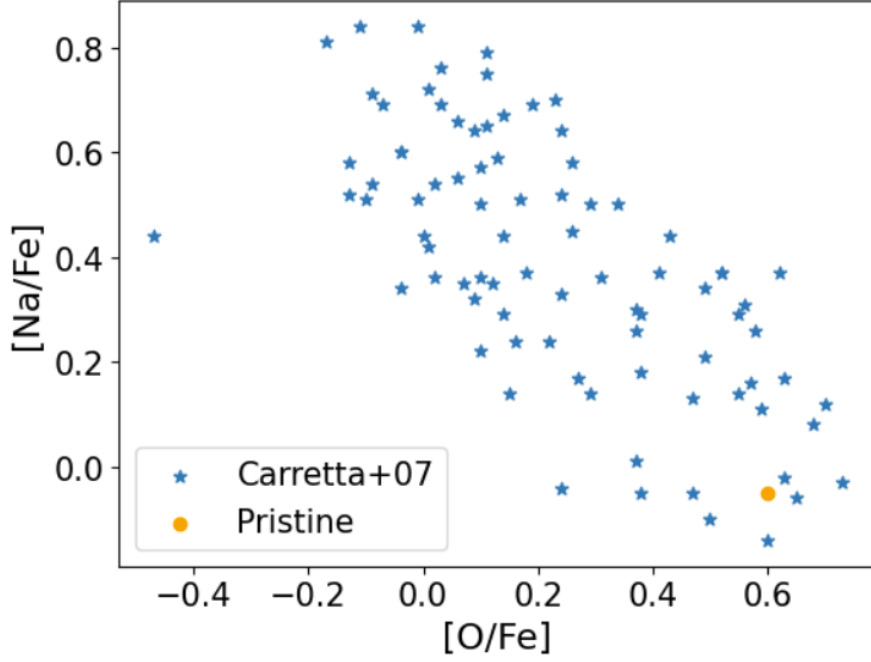


Figure 2.4: Chemical abundances in oxygen and sodium of stars in NGC 6752, based on observations from Carretta et al. (2007). The orange dot shows the pristine composition in O and Na that we determined visually.

initial set of abundances (given as mass ratios) for the relevant elements. To determine suitable values for this purpose, we used the pristine composition of two globular clusters: NGC 6752 and NGC 4833.

NGC 6752 has been widely studied over the past few years (Carretta, 2013; Lapenna et al., 2016; Lee, 2018; Martins et al., 2021; Mucciarelli et al., 2017, 2019). It is one of the few globular clusters for which measurements of abundances for C, N, Na, O, Al, Mg (including its isotopes), Si and K are available (Carretta et al., 2005, 2007, 2012; Yong et al., 2003). For these chemical elements, we visually estimated an average value for the pristine mass ratio, as shown in Fig. 2.4. For helium, we used a mass fraction of 0.246 (Milone et al., 2013), and for iron we used $[\text{Fe}/\text{H}] = -1.5$, which corresponds to $M_{\text{Fe}} = 4.7 \times 10^{-5}$ (Gratton et al., 2005). For the other elements (Ar, Ca, Sc, and Ni), we proceeded as follows. Firstly, we took the solar mass fraction of chemical element X from Table 4 in Lodders (2021). Then, as done by Prantzos et al. (2007), following Goswami and Prantzos (2000), we recovered the abundance of element X at the metallicity of NGC 6752. These abundances are given as $[\text{X}/\text{Fe}]$, the ratio of the abundance of element X to the iron abundance, normalised with respect to the solar composition:

$$[\text{X}/\text{Fe}] = \log_{10} \left[\frac{f(\text{X})}{f(\text{Fe})} \right] - \log_{10} \left[\frac{f(\text{X}_{\odot})}{f(\text{Fe}_{\odot})} \right]. \quad (2.7)$$

Here, $f(\text{X})$ can be either a number density or a mass ratio. The conversion between number density N_{X} and mass ratio M_{X} is done through the atomic mass m_{X} :

$$M_{\text{X}} = m_{\text{X}} N_{\text{X}}. \quad (2.8)$$

Then, we apply the following formula to convert from abundance to mass ratio:

$$M_{\text{X}} = 10^{[\text{X}/\text{Fe}]} \frac{M_{\text{Fe}} M_{\text{X}_{\odot}}}{M_{\text{Fe}_{\odot}}}. \quad (2.9)$$

Using the same method, we also computed the initial abundances in NGC 4833. This globular cluster has a lower metallicity than NGC 6752 ($[\text{Fe}/\text{H}] \approx -2.015$, see Carretta et al., 2014). The first extensive abundance analysis was carried out by Carretta et al. (2014), unsurprisingly highlighting the

Table 2.1: This table provides the pristine mass ratio used as input in the nuclear reaction code. The chemical elements are listed in the first column and their corresponding mass ratio in the second (NGC 6752) and third column (NGC 4833).

Element	NGC 6752 M_X	NGC 4833 M_X
H	0.745	0.745
He	0.246	0.246
Li	$1.6 \cdot 10^{-9}$	
^{12}C	$1.0 \cdot 10^{-4}$	$2.4 \cdot 10^{-5}$
^{13}C	$1.0 \cdot 10^{-6}$	$2.4 \cdot 10^{-6}$
^{14}N	$2.9 \cdot 10^{-5}$	$4.6 \cdot 10^{-5}$
^{16}O	$1.0 \cdot 10^{-3}$	$3 \cdot 10^{-4}$
^{20}Ne	$1.0 \cdot 10^{-4}$	$7.3 \cdot 10^{-5}$
^{22}Ne	$1.6 \cdot 10^{-5}$	$5.7 \cdot 10^{-6}$
^{23}Na	$1.1 \cdot 10^{-6}$	$4.4 \cdot 10^{-7}$
^{24}Mg	$4.7 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$
^{25}Mg	$3.4 \cdot 10^{-6}$	$2.8 \cdot 10^{-6}$
^{26}Mg	$3.4 \cdot 10^{-6}$	$2.8 \cdot 10^{-6}$
^{27}Al	$2.0 \cdot 10^{-6}$	$9.7 \cdot 10^{-7}$
^{28}Si	$6.1 \cdot 10^{-5}$	$1.8 \cdot 10^{-5}$
^{36}Ar	$1.0 \cdot 10^{-5}$	$1.0 \cdot 10^{-5}$
^{39}K	$1.0 \cdot 10^{-7}$	$3.0 \cdot 10^{-8}$
^{40}Ca	$4.3 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$
^{45}Sc	$1.4 \cdot 10^{-9}$	$3.6 \cdot 10^{-10}$
^{54}Fe	$2.7 \cdot 10^{-6}$	
^{56}Fe	$4.7 \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$
^{58}Fe	$1.4 \cdot 10^{-7}$	
^{58}Ni	$4.3 \cdot 10^{-6}$	

presence of multiple stellar populations in NGC 4833. They derived abundances of Na, O, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Y, Ba, La, and Nd in 73 red giants. They detected the classical anti-correlation patterns between Mg and Na, Al, and Si, and a correlation between Mg and O. Interestingly and contrary to NGC 6752, Roederer and Thompson (2015) detected a statistically significant anti-correlation between K and Mg but no statistically significant anti-correlation or correlation between K and other chemical elements. Carretta (2021) analyzed the chemical composition of 59 stars. They confirmed the anti-correlation between K and Mg, and detected an anti-correlation between K and O, as well as a correlation between K and Na, and K and Si. The stars with a high potassium abundance also show slightly higher Ca and Sc abundances. NGC 4833 is therefore one of the few globular clusters hosting such relation between these heavy elements, together with NGC 2419 (Cohen and Kirby, 2012), NGC 2808 (Carretta, 2015; Mucciarelli et al., 2015), and NGC 6715, NGC 6402, NGC 5296, NGC 5824, and NGC 5139/ ω Centauri (Carretta and Bragaglia, 2021).

The adopted pristine mass ratios are presented in Table 2.1. The chemical elements are listed in the first column. The second and third columns represent the pristine mass ratio for NGC 6752 and NGC 4833 respectively.

These initial abundances will serve as inputs for the nuclear reaction network.

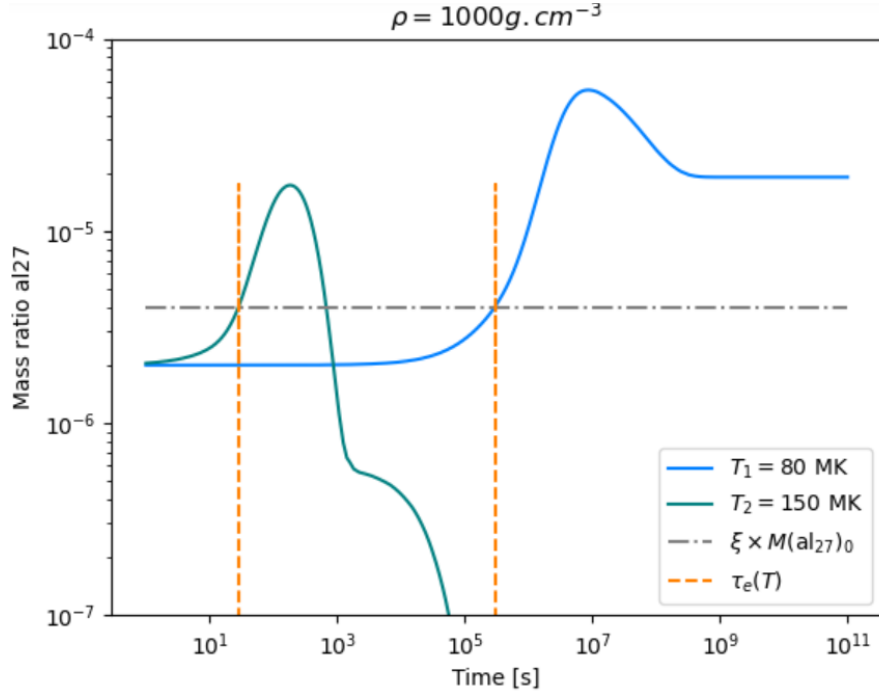


Figure 2.5: Illustration of the concept of enrichment timescale. The green and blue lines represent the ^{27}Al mass ratio obtained from nuclear reaction simulations at temperatures of $T = 80 \text{ MK}$ and $T = 150 \text{ MK}$, respectively. The horizontal dash-dotted line represents the threshold set to determine the enrichment, with a factor $\xi = 2$. In this case, ^{27}Al is considered enriched if $M_{\text{Al}} > 2 \times M_{\text{Al}_0}$. The two orange dashed lines correspond to the enrichment timescales, represented by their respective x-values.

2.3 Formation and destruction of the chemical elements of interest

In nuclear physics, a widely used timescale is the burning time, τ^{burn} , characterizing the timescale on which an individual chemical element is destroyed (Hix and Meyer, 2006):

$$\tau^{\text{burn}} = \frac{Y_i}{\dot{Y}_i}, \quad (2.10)$$

where Y_i is the nuclear abundance of species i and $\dot{Y}_i = dY_i/dt$ is the time variation of this abundance, introduced in Eq. 2.1. The burning time is proportional to the inverse of the density ρ and the reaction rate λ :

$$\tau^{\text{burn}} \propto (\lambda \rho)^{-1}. \quad (2.11)$$

However, for our purpose we are particularly interested in the timescale required for a chemical element to be enhanced with respect to the initial (or pristine) value. Thus, we define the enrichment timescale, τ_e :

$$\tau_e \equiv t(M_X > \xi M_{X_0}), \quad (2.12)$$

where the parameter ξ sets a threshold for the definition of the timescale.

The enrichment timescale of a chemical element X is determined by ξ , by the initial mass ratio, M_{X_0} , and by the temperature of the simulation, the latter playing a crucial role in obtaining the desired mass ratio, M_X , in the nuclear reaction network. Figure 2.5 illustrates the definition of τ_e . We plot the evolution of the mass ratio of ^{27}Al for two temperatures. Then, we set the enrichment threshold $\xi = 2$.

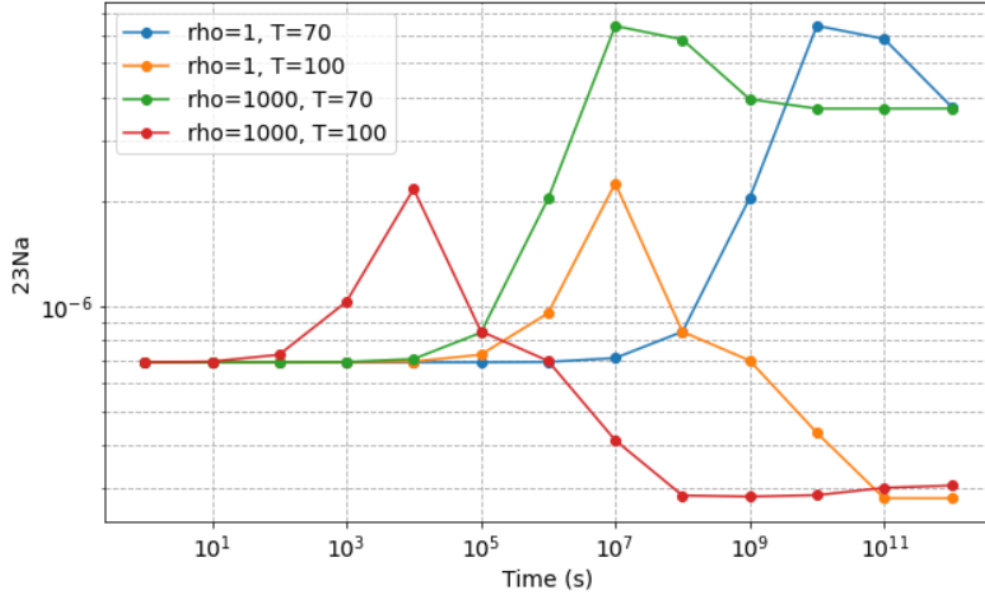


Figure 2.6: Time evolution of the mass ratio of ^{23}Na for different sets of temperature (in million Kelvin) and density (in g/cm^3). For a given temperature, the curves are shifted along the x-axis by a factor equal to 1000, the ratio of the two densities considered.

Finally, we determine the enrichment timescale of ^{27}Al for each simulation by identifying the point in time when the ^{27}Al mass ratio surpasses ξ -times the pristine mass ratio. If $\xi = 2$, as in the case of Fig. 2.5, the enrichment timescale is thus the time necessary to obtain a mass ratio for the chemical element X greater than two times the initial mass ratio, M_{X_0} . Similarly, we define a depletion timescale in Eq. 2.13, using the same parameter ξ . This timescale is used to inspect the conditions in temperature and time required to obtain the observed anti-correlations between chemical elements in MSPs:

$$\tau_d \equiv t(M_X < \frac{1}{\xi} M_{X_0}). \quad (2.13)$$

The role of ξ is further detailed in Sect. 2.6.

2.4 Exploring the role of temperature, density, and time

Using the initial chemical abundances given in Table 2.1, we vary the temperature T between 50 and 250 MK and the time t between 10^{-6} and 10^{14} s. For each pair of temperature and time, we obtain the final mass ratios for the 132 chemical elements. The density is kept constant to 1000 g cm^{-3} . This value has been chosen arbitrarily and has only a small impact on the results, because of the coupling between time and density mentioned at the beginning of Sect. 2.1. If we would decrease the density, for instance to get a better agreement with wind from massive stars, the primary impact would be a rightward shift of the results shown in Fig. 2.5 toward larger timescales. This is illustrated in Fig. 2.6 where the mass ratio of ^{23}Na is plotted as a function of time, for four choices of temperatures and densities.

Using the definition of the enrichment and depletion timescales from Sect. 2.3 with $\xi = 2$ and the initial abundances of NGC 6752, we ran the nuclear reaction simulations probing a wide range of temperature and time. We plot in Fig. 2.7 the region of parameter space in temperature and time required to obtain the specified anti-correlations, key characteristic of MSPs. In the top panel, from left to right we plot the time (x -axis) and temperature (y -axis) values making it possible to obtain an anti-correlation between carbon and nitrogen, between oxygen and sodium, and between magnesium and aluminium. In the lower-left panel, we show the region in this parameter space where we can obtain the anti-correlation between magnesium and potassium. The lower-middle panel and the lower-right

2. Nucleosynthesis of the enriched material

panel respectively show the intersection of the parameter space reproducing the observed abundance patterns in light elements and in all the elements studied. For the light elements, only a very narrow range of temperatures allows the simultaneous production of N, Na, Al, and Si and destruction of C, O, and Mg, in good agreement with Prantzos et al. (2007), as shown in the lower-middle panel. The empty lower right panel implies that, across the entire temperature range examined and over a time range spanning 14 orders of magnitude, potassium cannot be produced alongside the observed anti-correlations in light chemical elements. These results, independent of the polluter type and of the formation scenario of MSPs, suggest a different origin for the heavy element patterns, pointing toward either multiple polluter types or a single polluter able to reach lower temperatures close to 70 MK as well as $T > 150$ MK in a short amount of time (Iliadis et al., 2016).

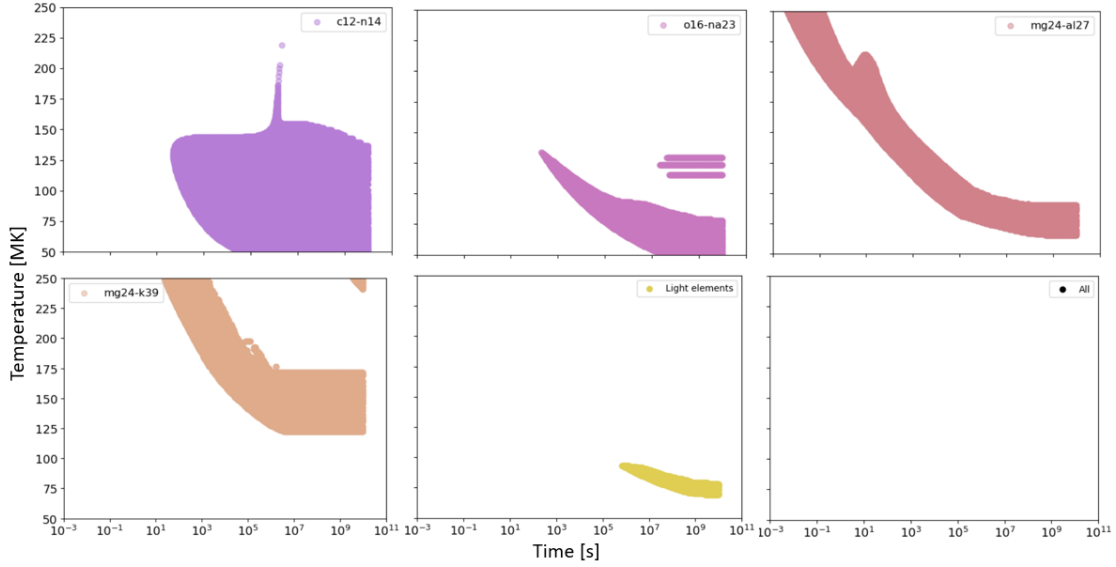


Figure 2.7: Temperature and time generating the observed anti-correlations ^{12}C - ^{14}N (upper-left), ^{16}O - ^{23}Na (upper-middle), ^{24}Mg - ^{27}Al (upper-right), and ^{24}Mg - ^{39}K (lower-left). The lower middle and right panels represent the intersection of the parameter space reproducing the observed abundance patterns in light elements (middle) and in all the elements studied (right). Only a small region in temperature and time makes it possible to reproduce the light element patterns. At such temperature and time, ^{39}K can not be enhanced.

We also tested the impact of using different initial abundances, specifically those from NGC 4833, in the nuclear reaction network. We find no differences in the parameter space reproducing the observed abundance patterns in the chemical elements studied. Therefore, in the rest of this chapter we only use the initial abundances of NGC 6752.

2.5 Comparison with observations

A widely accepted explanation for the emergence of MSPs in globular clusters involves the intervention of a polluter, which generates and expels enriched material containing a specific chemical element in a mass ratio denoted as M_e . This enriched material subsequently mixes with the surrounding pristine gas, characterized by a mass ratio of M_p , leading to the formation of an enriched star. The final composition of the resulting star can be computed (see also Prantzos et al., 2007):

$$M_f = (1 - \omega) M_p + \omega M_e, \quad (2.14)$$

where ω is the fraction of enriched material.

An advantage of the mixing description adopted here is that simulations of the enriched material (providing the quantity M_e) and observations (allowing us to get an estimate of M_p) are easily linked by Eq. 2.14 and ω is the only parameter needed to describe the mixing process. The distribution of the

mixing weight ω will depend on the type of polluter and on the formation scenario considered for the enriched stars.

Comparing the results of simulations with observations can be challenging as the simulated quantities are different from the observable ones. Indeed, observations of chemical abundances can be measured through the stellar flux, directly linked to the equivalent width of spectral lines. Chemical abundances can then be inferred from flux observations using the curve of growth, linking the equivalent width to the number of absorbing atoms in the atmosphere (the column number density N_X) and thus to the abundance of elements in stellar atmospheres (see Gray 2005 for more information). These abundances are often expressed normalized with respect to the solar composition (see Eq. 2.7) and the mass ratio of the chemical elements, direct output of our simulations, are hidden inside this formulae.

Here we want to compute the mass ratio M_{X_f} of each element after mixing pristine and enriched gas in our simulations following Eq. 2.14, and to compare this with the observed values to understand how the different input parameters (temperature, density and time) and the mixing weight ω could reproduce the observations. In order to make the comparison between simulation and observation feasible, we adopted a two-step approach.

Firstly, in order to understand under which conditions the gas from the polluter can be enriched in X_1 and depleted in X_2 (for example enriched in Na and depleted in O) with respect to the pristine composition, we study the quantity $[X_2/Fe]_e - [X_2/Fe]_p$ versus $[X_1/Fe]_e - [X_1/Fe]_p$. This provides a quick visual way to assess the conditions in temperature and time making it possible to reproduce the observed abundance patterns.

Secondly, with the aim of comparing the simulated composition of enriched stars with the observed one given by $[X/Fe]$, we should divide the mass ratio of element X by the mass ratio of iron, take the logarithm and normalize with respect to the Sun:

$$[X/Fe]_f = \log_{10} \left[\frac{(1 - \omega) M_{X_p} + \omega M_{X_e}}{M_{Fe}} \right] - \log_{10} \left[\frac{M_{X_\odot}}{M_{Fe_\odot}} \right]. \quad (2.15)$$

This formula is only valid if the iron content for primordial and enriched material is similar. This is a reasonable hypothesis because the reaction channel impacting iron should not be activated at the temperatures considered. However, the recent findings of a metallicity spread among pristine stars in several GCs (Lardo et al., 2022; Milone et al., 2017) could impact this formula. If such a spread is confirmed in many clusters, it will be necessary to adapt this approach.

In the following, we will first focus on the Mg-Al anti-correlation and Mg isotopic ratios (Sect. 2.5.1) as these elements provide a strong constraint for many theories, as mentioned by Denissenkov and Hartwick (2014). We will also look for regions of the parameter space reproducing the observations in oxygen and sodium (Sect. 2.5.2), and in nitrogen and carbon (Sect. 2.5.3).

2.5.1 Aluminium and magnesium

The spread in Mg values differs from cluster to cluster. While most of the GCs in the Milky Way have a narrow range of magnesium abundance, implying a small (or absent) anti-correlation with Al, a few galactic GCs contain stars with extreme depletion in Mg ($[Mg/Fe] < 0$). For instance, this is the case for NGC 2419 (Mucciarelli et al., 2012) and NGC 2808 (Carretta et al., 2014). Carretta et al. (2009a) suggested that massive and metal-poor GCs tend to show a more extended Al-Mg anti-correlation. This result was corroborated by Mészáros et al. (2015) and Pancino et al. (2017). In addition to its anti-correlation with aluminium, magnesium is also interesting with respect to the ratios of its isotopes. Yong et al. (2003) found a mild anti-correlation between ^{24}Mg and Al and a positive correlation between ^{26}Mg and Al. This means that enriched stars have simultaneously a lower abundance in magnesium and a higher fraction of ^{26}Mg . As for ^{25}Mg , the isotopic ratio seems to be the same for the two populations. A similar trend has also been detected in red giant stars in NGC 5139 (ω Cen, Da Costa et al. 2013). To constrain the nature of the polluter it is thus important to simultaneously study the Al-Mg anti-correlation, the relation between Al and Mg isotopes and the Mg isotopic ratios as a function of magnesium abundance. To reproduce the observations, we would need a depletion in magnesium by approximately an order of magnitude together with a high percentage of ^{26}Mg and a small percentage of ^{24}Mg , in order to have an

2. Nucleosynthesis of the enriched material

efficient transfer of Mg isotopes between pristine and enriched gas in the mixing phase. The pristine isotopic ratio of magnesium is taken as 87% of ^{24}Mg , 6.5% of ^{25}Mg and 6.5% of ^{26}Mg (see Tab. 2.1), also written as 87:6.5:6.5, while the extreme enhanced stars can reach isotopic ratios of 60:5:35 (Yong et al., 2003).

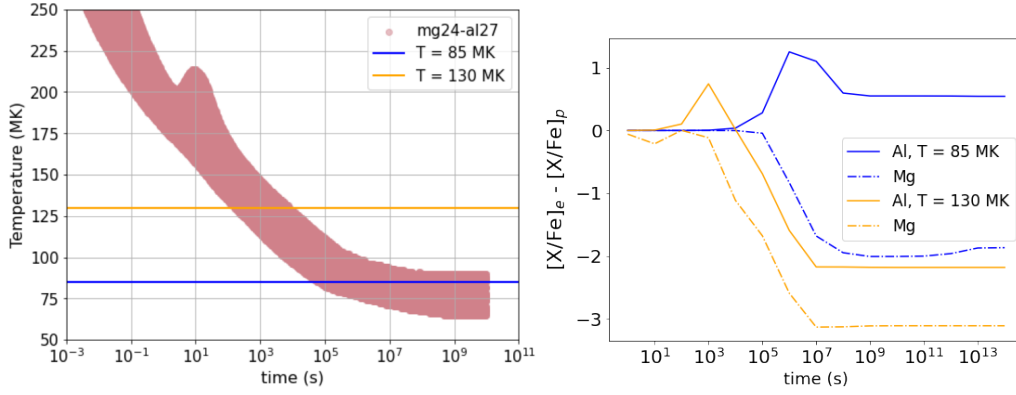


Figure 2.8: *Left panel:* Temperature and time generating the observed anti-correlations ^{24}Mg - ^{27}Al (see also the top right panel of Fig. 2.7). The blue and orange lines represent a temperature of 85 MK and 130 MK respectively. *Right panel:* The abundance output of the nuclear reaction network ($[X/\text{Fe}]_e$) normalized with respect to the primordial abundance ($[X/\text{Fe}]_p$) is plotted as a function of time for aluminium (solid line) and magnesium (dashed line). The blue curve has been obtained with a temperature of 85 MK and the orange one with a temperature of 130 MK. The density is set to 1000 g cm^{-3} .

As a starting point, we use the results presented in Fig. 2.7 where we have already constrained the values in temperature and time required to create the anti-correlation between aluminium and magnesium. Not only are we interested in the temperature and time that make it possible to have an enrichment in aluminium and a depletion in magnesium, but we also need the duration of the enrichment to be long enough to allow for enough material to be generated by any polluter type. Therefore, we introduce a new quantity, the duration of the enrichment:

$$\Delta\tau_e = \min_{t > \tau_e} t(M_X < \xi M_{X_0}) - \tau_e, \quad (2.16)$$

where τ_e is the enrichment timescale defined in Eq. 2.12, and M_{X_0} is the initial mass ratio of the chemical element X . The duration of the enrichment can be visualized in Fig. 2.8. In the left panel, the region of parameter space in temperature and density required to obtain the anti-correlation between Al and Mg is plotted, similar to Fig. 2.7. We added a blue and an orange horizontal line at $T = 85 \text{ MK}$ and $T = 130 \text{ MK}$, respectively. At a temperature of 85 MK, Al is enhanced and Mg depleted from $t = 9 \times 10^4 \text{ s}$ until the end of the simulation, but the anti-correlation is only present between 10^2 and 10^4 s at a temperature of 130 MK. This is also visible in the right panel of Fig. 2.8, showing the evolution of the mass ratio normalized with respect to the pristine abundance as a function of time for Al (continuous line) and Mg (dash dot line) at the two chosen temperatures. At $T = 130 \text{ MK}$, Al is enriched after 10^2 s , reaching a peak in enrichment at about 10^3 s and decreasing toward being depleted after 10^4 s . Contrarily, at $T = 85 \text{ MK}$, aluminium gets enriched after 10^5 s , reaches a peak at 10^6 s and decreases to a plateau at an enrichment level of $[\text{Al}/\text{Fe}]_p + 0.6$. Therefore, temperatures around 85 MK are particularly interesting, with enrichment and depletion becoming stable after some time, in good agreement with previous results from Prantzos et al. (2007).

We investigated further the evolution of the Mg isotopic ratios in a narrow range of temperatures ($75 \leq T \leq 85 \text{ MK}$). We included ^{26}Al in the ^{26}Mg isotopic ratio because ^{26}Al decays in ^{26}Mg through the emission of a γ -ray after 1 Myr. The results are plotted in Fig. 2.9. The evolution of the ^{24}Mg , ^{25}Mg , and ^{26}Mg isotope ratios, and the Mg and Al mass ratio are plotted as a function of time for different temperatures, represented by lines of different colors. The color scheme goes from light orange for a temperature of 75 MK to dark orange for 85 MK. We also included the results of a simulation carried out at a higher temperature, 130 MK in black, for comparison. As expected, temperatures between 75 MK

and 85 MK allow a stable enhancement in aluminium and depletion in magnesium, which is not the case at a temperature of 130 MK. As previously mentioned, ^{26}Mg is of particular interest for the problem of MSPs in GCs. At a temperature between 75 MK and 85 MK, it takes about a 10^6 s for the percentage to be more than 50%. However, when looking at panel showing the time evolution of the mass ratio in magnesium, one can see that magnesium is quickly depleted by a factor 100. Thus, when the mixing will occur, the contribution of enhanced material in Mg (and its isotopes) will be very limited. The fact that enriched stars have simultaneously a lower abundance in magnesium and a higher fraction of ^{26}Mg requires the nucleosynthesis to occur in very specific conditions, at $t \approx 10^7$ s for $\rho = 1000 \text{ g.cm}^3$ and $75 < T < 85$ MK in our simulations.

We have shown that within the range of temperatures $75 \leq T \leq 85$ MK, an enrichment in aluminium and a depletion in magnesium are possible and stable for a long timescale. Mg isotopic ratios can be close to 30:20:50 after 10^6 s. Such a composition, when mixed with pristine material, could make it possible to recover the extreme enhanced abundances if the nucleosynthesis occurs when magnesium is not too depleted yet, to allow for an efficient mixing. Our results are consistent with the ones from Prantzos et al. (2007), within ≈ 5 MK. This slight difference in temperature could be explained by the use of a different reaction rate library. They used the reaction rates from Angulo et al. (1999) for $A < 20$ and from Iliadis et al. (2001) for $A \geq 20$ while we used the REACLIB database Cyburt et al. (2010), providing up-to-date reaction rates. The next step is to use Eq. 2.15 to compute the chemical abundances for stars with different mix of pristine and enriched material, and compare them to observations.

The concept of mixing weight is illustrated in Fig. 2.10, showing the observed magnesium and aluminium abundances from Gruyters et al. (2014) as black stars together with the results of the mix between pristine and enriched material obtained through our computations as colorful points. The mixing weight ω varies from 0 (only pristine composition) to 0.5 (stars with half pristine and half enriched material). The three symbols correspond to different sets of temperature and time. For the left-pointing triangles, the enriched composition has been taken at $T = 85$ MK and $t = 10^6$ s, corresponding to the peak of the enrichment visible in Fig. 2.8. The right-pointing triangles have been obtained with an enriched composition at $T = 85$ MK and $t = 10^{11}$ s, where the enrichment in aluminium has a plateau. Finally, the circles have been obtained through a mixing with the enriched material generated at $T = 130$ MK and $t = 10^{11}$ s; with these conditions, aluminium is depleted: this is visible in Fig. 2.10, with decreasing aluminium abundance as ω increases (increasing contribution from the enriched material). The right-pointing triangles are systematically above the left-pointing triangles, as expected, because the abundance in aluminium in the enriched material is larger at 10^6 s. The extreme abundances, corresponding to the stars in the upper left corner, can even be recovered with a mix of 40% pristine and 60% enriched material generated at $T = 85$ MK and $t = 10^6$ s.

2.5.2 Sodium and oxygen

In this section, we focus on oxygen and sodium. We ran similar simulations as in Sect. 2.5.1 to quantify the values of the mixing weight ω making it possible to recover the enhancement in sodium and depletion in oxygen observed in GCs. Figure 2.11 shows, on the left panel, the observed oxygen and sodium abundances from Carretta et al. (2007) as black stars. Similarly to Fig. 2.10, the results of the mix between pristine and enriched material are shown as colorful points with each symbol corresponding to a given set of temperature and time. On the right panel, the evolution of the sodium and oxygen mass ratio normalized with respect to the pristine level are plotted as a function of time for $T = 85$ MK (blue lines) and for $T = 130$ MK (orange lines).

Contrary to Mg-Al, it is not possible to obtain O-Na yields compatible with observations. Regardless of the value of ω , the largest sodium abundances cannot be recovered. One possible explanation is the level of enrichment visible in the right panel of Fig. 2.11. At $T = 85$ MK and $t = 10^6$ s, sodium can be enriched to ≈ 3 times more than the pristine value: even with a high mixing weight, this is not sufficient to reproduce the extremely enriched stars. These results are different and not compatible with the one presented in Prantzos et al. (2007), probably due to the fact that we used a more recent reaction rate for $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ (private communication with Nicolas Prantzos and Christian Iliadis).

2. Nucleosynthesis of the enriched material

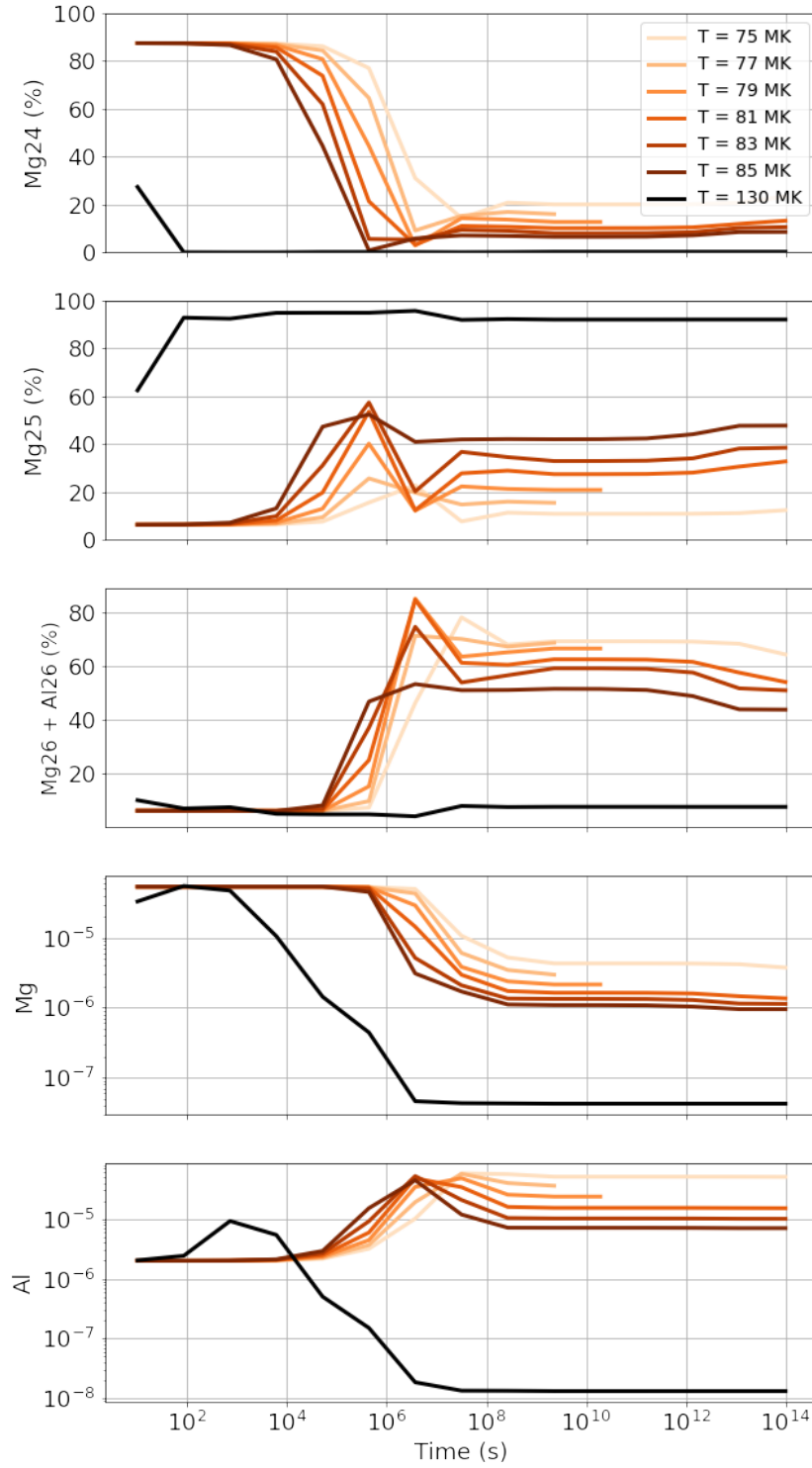


Figure 2.9: From top to bottom, evolution of the ^{24}Mg , ^{25}Mg , and ^{26}Mg isotope ratios, and of the Mg and Al mass ratios as a function of time for different temperatures, represented by the different colors. Note that magnesium isotopes seem to be initiated with a different percentage at $T = 130$ MK. This is not the case, the appeared difference is due to the almost instantaneous destruction of ^{24}Mg and ^{26}Mg , in less than 1 s, at such a high temperature.

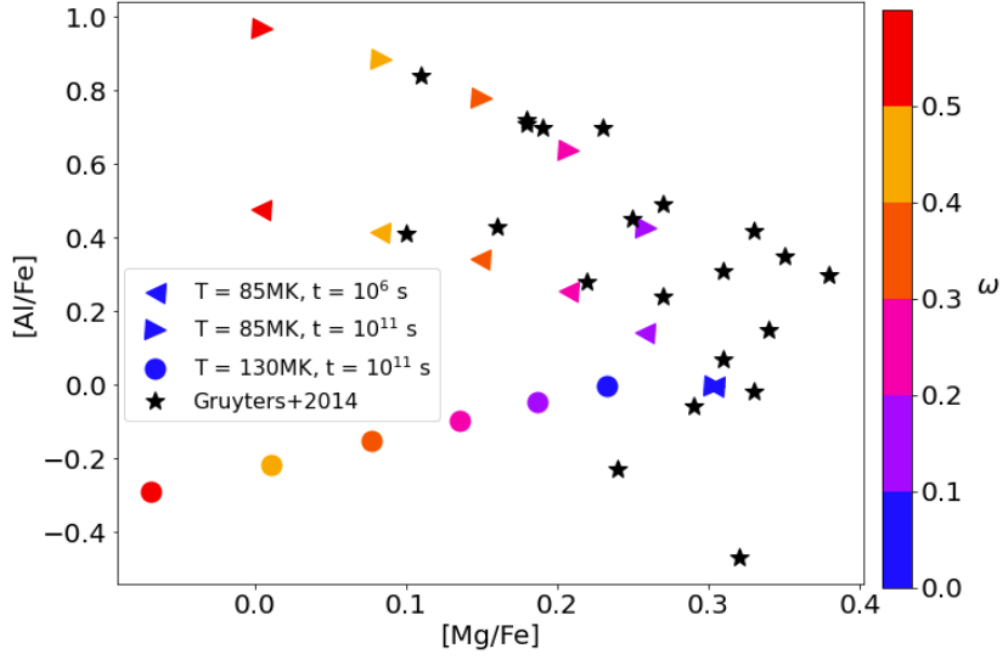


Figure 2.10: Comparison between the mixing model (colorful points) and the observed abundances in magnesium and aluminium (black stars) taken from Gruyters et al. (2014). The mixing weight ω varies from 0 (only pristine material, in blue) to 0.5 (50% of pristine and 50% of enriched composition, in red). Three sets of time and temperature are considered, indicated in the legend box on the lower left corner.

2.5.3 Nitrogen and carbon

The last chemical elements that we studied are carbon and nitrogen. The impact of the mixing weight is plotted in the left panel of Fig. 2.12, with a similar color scheme to Fig. 2.10 and Fig. 2.11. We consider values of the mixing weight up to 0.7, equivalent to stars made of 30% pristine and 70% enriched material. Stars extremely enhanced in nitrogen and depleted carbon can be recovered with $\omega = 0.7$ and at a temperature of 85 MK. At a temperature of 130 MK, the extreme abundance of nitrogen can be recovered but the depletion in carbon is not sufficient. This is illustrated in the right panel of Fig. 2.12: the orange dash-dot curve represents the mass ratio of carbon, normalized to the pristine abundance, with enriched material generated at 130 MK. The curve is negative, indicating that carbon is indeed depleted relative to its initial abundance. However, it is less depleted than the material generated at 85 MK (blue dash-dot curve).

2.6 Enrichment threshold

The simulations conducted on six chemical elements in Sect. 2.5 highlighted the difficulty in reproducing the observed anti-correlation patterns in globular clusters hosting multiple stellar populations. While the observed abundance ranges for aluminium and magnesium can be reproduced by mixing 50% of enriched material generated at $T = 85$ MK and $t = 10^{11}$ s, nitrogen and carbon require a higher fraction of enriched material (70%). However, even with a high mixing weight, the extreme abundances observed in oxygen and sodium remain unattainable. One way to address this issue is to study the extent of enrichment by exploring the role of the enrichment threshold parameter, ξ . In this section, we aim to demonstrate the influence of ξ on the achieved enrichment *after dilution* and to compare it with observations. Therefore, we focus on the combined impact of ξ and the mixing weight, ω . The effect of ω has already been discussed in Sect. 2.5, as well as in previous studies (e.g., Di Criscienzo et al. 2018; Prantzos et al. 2007).

2. Nucleosynthesis of the enriched material

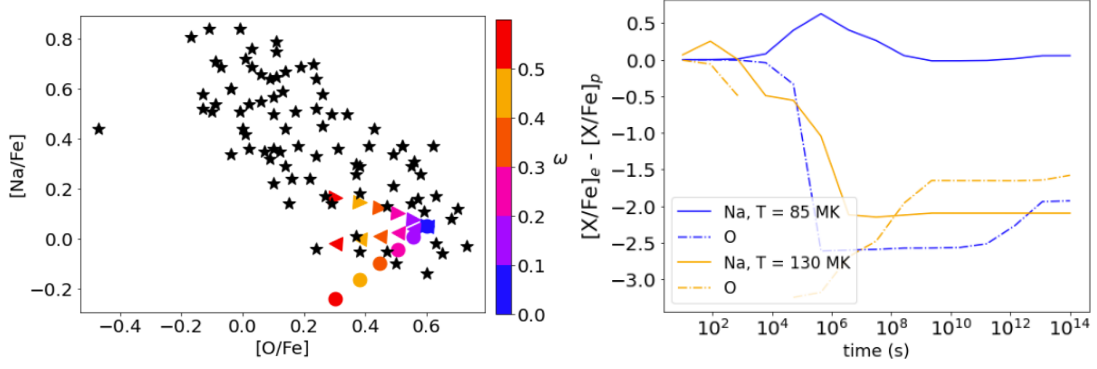


Figure 2.11: *Left panel:* Comparison between the mixing model (colorful points) and the observed abundances in oxygen and sodium (black stars) taken from Carretta et al. (2007). The mixing weight ω varies from 0 (only pristine material, in blue) to 0.5 (50% of pristine and 50% of enriched composition, in red). Three sets of time and temperature are considered, indicated in the legend box on the lower left corner. *Right panel:* The abundance output of the nuclear reaction network ($[X/Fe]_e$) normalized with respect to the primordial abundance ($[X/Fe]_p$) is shown as a function of time for sodium (solid lines) and oxygen (dashed lines). The blue curves have been obtained with a temperature of 85 MK and the orange ones with a temperature of 130 MK. The density is set to 1000 g cm^{-3} .

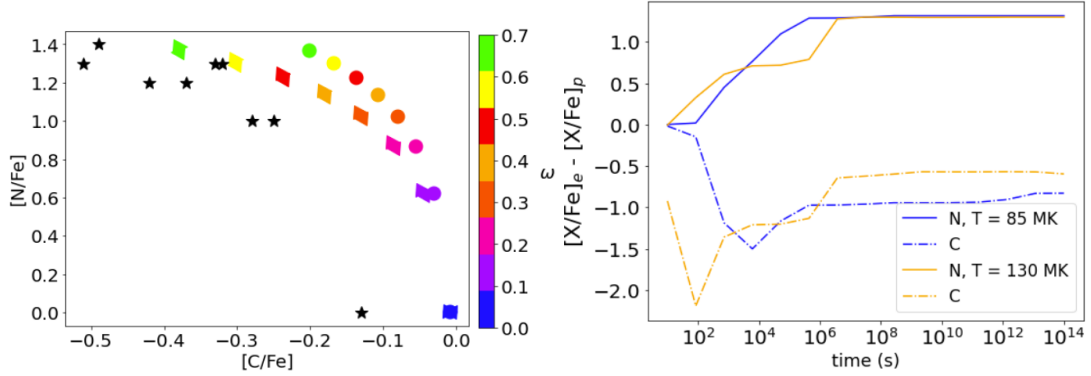


Figure 2.12: Same as Fig. 2.11 for carbon and nitrogen.

We used four distinct values for ω , going from $\omega = 0.1$, where the final star is mainly made of pristine material, to $\omega = 0.7$, where the star is mainly made of enriched material. For each value of the mixing weight ω , we vary the enrichment threshold ξ from $\xi = 1$ (the enriched material has the same composition as the pristine), to $\xi = 17$ (enrichment of the material seventeen times higher than the pristine composition). Such an upper bound for ξ has been chosen arbitrarily, for illustrative purposes. In Fig. 2.13 we plot the observed abundances in NGC 6752 of O and Na (upper-left, Carretta et al., 2007), Al and Mg (upper-right, Gruyters et al., 2014), O and K (lower-left, Carretta et al., 2007; Mucciarelli et al., 2017), and C and N (lower-right, Carretta et al., 2005), represented as black stars. The final abundances obtained are plotted as colored circles. Each point was calculated using Eq. 2.14, with the pristine mass ratio taken as initial abundance of NGC 6752 (see Sect. 2.2) and the enriched mass ratio as ξ times the pristine mass ratio. We used the same value of ξ for both chemical elements in the same panel. For example, the orange points correspond to an enrichment threshold of $\xi = 13$ for Na and a depletion threshold of $\xi = 13$ for O. An important observation from Fig. 2.13 is the variation in abundance ranges among different chemical elements. For example, the observed range for oxygen spreads more than 1 dex (with $\Delta[\text{O}/\text{Fe}] \sim 1$), whereas for magnesium it covers only 0.3 dex (with $\Delta[\text{Mg}/\text{Fe}] \sim 0.3$). Consequently, while a value of $\xi = 2$ (represented by blue dots, indicating that the enriched material has a mass ratio twice its pristine value) can reproduce the extreme magnesium and

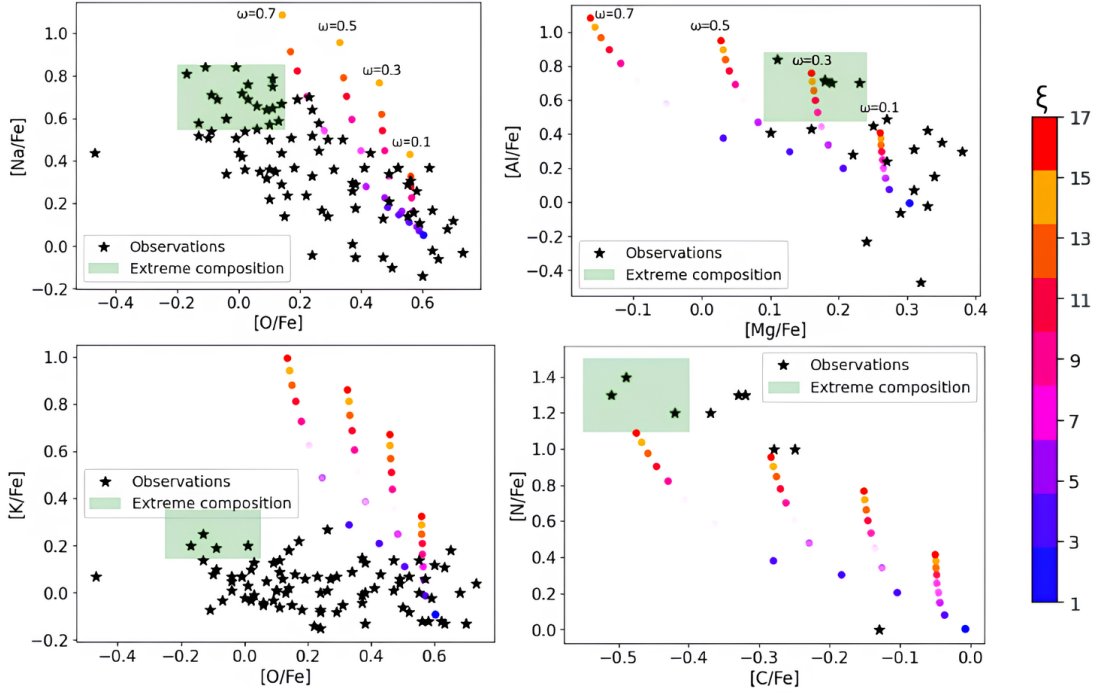


Figure 2.13: Chemical abundance of O versus Na (upper-left), Mg versus Al (upper-right), O versus K (lower-left), and C versus N (lower-right). Black stars represent the observed abundances of C and N (Carretta et al., 2005), O and Na (Carretta et al., 2007), Al and Mg (Gruyters et al., 2014), and K (Mucciarelli et al., 2017). The green rectangles indicate the location of the most extreme abundances. The colored circles represent the abundances obtained using the reaction network ($T = 80$ MK and $\rho = 1000 \text{ g cm}^{-3}$) and the dilution model introduced in Eq. 2.14, with $\omega = 0.1, 0.3, 0.5$, and 0.7 ; the circles are colored according to the enrichment level specified by the parameter ξ . While the extreme potassium abundances can be reproduced with only a small ξ , other chemical elements like oxygen require large mixing weights and enrichment levels to reproduce the extreme population.

potassium compositions with a mixing weight of $\omega = 0.5$, replicating the extreme oxygen abundance necessitates a significantly higher value of ξ even with a substantial mixing weight.

However, it is important to keep in mind that the output of our simulation, the mass ratio, is strongly influenced by the temperature. Consequently, the enrichment level ξ and the enrichment timescale are constrained by the temperature. Figure 2.14 illustrates how the enrichment timescale for aluminium changes with the parameter ξ for different temperatures, represented by the colored lines and ranging from 50 MK (light yellow) to 250 MK (black line). When $\xi = 8$, the minimum value for the enrichment timescale is $\tau_e = 10$ s. Such a value of ξ only makes it possible to recover the extreme composition in Mg and Al, assuming a mixing weight $\omega > 0.5$ (see Fig. 2.13, pink dots). Overall, ξ should be smaller than 3 to give an enrichment timescale $\tau_e < 1$ s, and the temperature should also have specific values ($T > 150$ MK). As shown in Fig. 2.13, only the extreme Mg abundance can be recovered with $\xi = 3$ (blue dots). The main conclusion drawn from Fig. 2.13 is that as the enrichment level increases, the corresponding timescale also increases for all temperatures. However, it is important to note that for certain temperatures (e.g., $T > 200$ MK), achieving a high enrichment level (e.g., $\xi = 4$) is not possible within the duration of the simulation $\Delta t = 10^{14}$ s. This time translates to 3.2 Myr and has been set as the upper time bound in our simulations, as the enriched material must be generated very quickly due to the observational constraint on the age difference (approximately 1 ± 20 Myr, Martocchia et al., 2018b) between pristine and enriched stars.

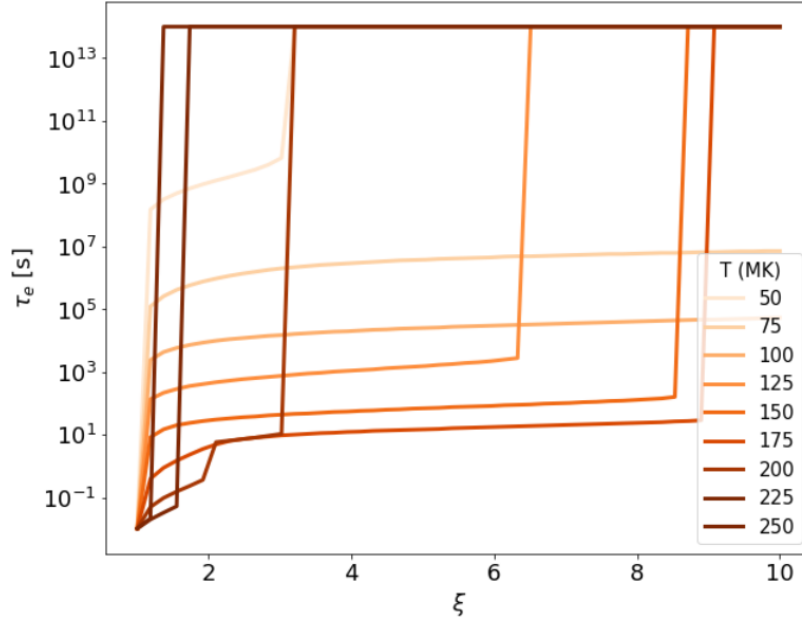


Figure 2.14: Illustration of the evolution of the enrichment timescale τ_e as a function of the parameter ξ . The lines are colored according to the temperature (in MK). The higher is ξ , the more enriched is the final composition in the corresponding chemical element, here ^{27}Al . The enrichment timescale is directly dependent on the temperature.

2.7 Summary

In this section we have focused on the enriched material involved in the formation of the multiple stellar populations present in many globular clusters. In Sect. 2.1, we introduced the main equations of a nuclear reaction network, and the two codes used to compute chemical abundances, TORCH (Timmes, 1999) and Pynucastro (Smith Clark et al., 2022). The main parameters to consider are the temperature, the density, the time, and the initial abundances presented in Sect. 2.2. In Sect. 2.3, we defined the enrichment timescale, τ_e , as the timescale required for a chemical element to be enhanced with respect to its initial abundance. This timescale is parametrised according to the enrichment threshold ξ , which quantifies the level of enrichment of a chemical element with respect to its initial abundance, discussed in Sect. 2.6. The impact of the time and the temperature on the formation of enriched material are illustrated in Sect. 2.5, and set into context with real observations of C, N, O, Na, Al, and Mg. Particular emphasis is given to the isotopic ratios of magnesium in Sect. 2.5.1 as their ratio differs in pristine and enriched stars.

We find that a very small range of temperature and time (equivalent to density) could lead to the simultaneous $^{12}\text{C} - ^{14}\text{N}$, $^{16}\text{O} - ^{23}\text{Na}$, and $^{24}\text{Mg} - ^{27}\text{Al}$ anti-correlation patterns. However, the $^{24}\text{Mg} - ^{39}\text{K}$ anti-correlation observed in some GCs requires a different region of the parameter space. Our results, independent of the polluter source, are in very good agreement with previous works (Iliadis et al., 2016; Prantzos et al., 2007) and suggest that the enriched material is either coming from multiple polluters at different temperatures or from a single polluter having a large temperature range, for example, black hole accretion disks. The chapter set the basis for the analysis carried out in Chapter 3.

Chapter 3

ACCRETION DISKS AROUND STELLAR MASS BLACK HOLES AS A POTENTIAL NUCLEOSYNTHESIS SOURCE

“Black holes are where God divided by zero.”

- Albert Einstein

Declaration of published work

This chapter includes text already published in Fréour et al. (2024). As a result, there may be partial overlap with this publication.

Introduction

Our exploration of the conditions in temperature and time necessary for enhancing a subset of chemical elements highlights the limitations of the single polluter model. The most extensively studied pollution sources include Asymptotic Giant Branch stars (Sect. 1.2.1), fast-rotating massive stars (Sect. 1.2.2), and supermassive stars (Sect. 1.2.3). These stellar objects, however, encounter significant challenges in generating heavier chemical elements, such as potassium, which require temperatures exceeding 200 MK. Two possible solutions to this limitation are to either invoke multiple polluters generating the enriched material simultaneously or to consider a single polluter capable of reaching a broad range of temperatures.

Breen (2018) suggested that light elements could be created in accretion disks around black holes, with the appropriate conditions (see also Sect. 1.2.5). These chemical elements could then be expelled through outflows from the accretion disk, mix with the surrounding pristine gas and form the enriched stars in globular clusters. A sufficient amount of enriched material could be created in only ~ 3 Myr, depending on the initial number of black holes and on their accretion rate, overcoming the mass-budget problem. Several questions should be considered to reckon whether black hole accretion disks could be the pollution source for the enriched material in globular clusters. Can the required temperatures be reached in an accretion disk? What are the different timescales involved in the formation and accretion of the material? Are they compatible with observations?

In Chapter 2, we have introduced the reaction network that we employed, and we have analyzed the effects of temperature and time on the yields of C, N, O, Na, Al, Mg, and K in nucleosynthesis. In this chapter, we explore the hypothesis that accretion disks around stellar mass black holes could be a source of enriched material involved in the formation of MSPs in GCs. In Sect. 3.1, we review literature on nucleosynthesis in accretion disks. In Sect. 3.2, we discuss various accretion disk models and introduce the main equations of the model selected. We present our approach for assessing the feasibility of enriched material formation within an accretion disk surrounding a stellar mass black hole in Sect. 3.3. We present our results in Sect. 3.4 and discuss their implications on the scenario described by Breen (2018) in Sect. 3.5. Our conclusions are presented in Sect. 3.6.

3.1 Nucleosynthesis in accretion disks around black holes

Several studies have primarily focused on investigating heavy element nucleosynthesis within black hole accretion disks. Chakrabarti et al. (1987) explored the conditions under which nucleosynthesis could occur inside *thick* accretion disks around black holes. They showed that at the center of a thick disk, products of the PP-chain (proton-proton chain), the CNO cycle, and *rp*-process (rapid proton process) could be created. They found that the amount of these elements produced was strongly dependent on the physical parameters of the disk, such as the mass of the black hole and the viscosity parameter, with smaller masses boosting the nucleosynthesis of such elements. This is promising as such reactions produce elements lighter than $Z=40$. Far from the center, thick accretion disks resemble thin discs (Shakura and Sunyaev, 1973).

Using the formalism presented in Chakrabarti and Mukhopadhyay (1999), Mukhopadhyay and Chakrabarti (2000) investigated three different types of accretion flow: hot, moderately hot and cooler flows. These categories are defined based on the maximum temperature achievable in each model, which in turn depends on various parameters of the accretion disk model, such as mass accretion rate and density. For example, in the hot accretion flow case, the temperature can reach up to $47 \cdot 10^9$ K while it stays below $0.8 \cdot 10^9$ K for the cooler flow. Depending on the inputs of their accretion disk model (a total of seven variables), they find that the nucleosynthesis of some chemical elements is possible.

Hu and Peng (2008) investigated the nucleosynthesis in advection-dominated accretion flow (ADAF) and outflow regions around a $10 M_{\odot}$ black hole. They found that for a heating factor $f \approx 0.001$, representing the fraction of the viscously dissipated energy, significant amounts of ^{26}Al , ^{51}Cr , ^{53}Mn , and ^{55}Fe could be created in the accretion disk.

These results suggest that nucleosynthesis could occur in accretion disks around black holes and be an effective way to increase the abundance of certain chemical elements in the interstellar medium. As

we focus on the issue of multiple stellar populations in globular clusters, our attention is only directed towards specific (light) elements.

3.2 Disk model

Accretion disks are described by three quantities: their geometry (vertically “thin” versus “thick” disks), the mass accretion rate (sub-Eddington versus super Eddington accretion rates) and their optical depth (opaque versus transparent).

Regarding the geometry, thin disks are characterized by a height H that is very small compared to the radial extent r ($H/r < 1$), and their properties can therefore be described mainly as depending on radial coordinates. Thick disks have $H/r > 1$. There can be some simplifications in the physics through assumptions as $H \approx r$, but this requires more careful considerations.

The mass accretion rate is expressed with respect to the Eddington mass accretion rate, defined as the accretion rate for which the accreting black hole radiates at the Eddington luminosity given by:

$$L_{\text{Edd}} = \frac{4\pi G m m_p c}{\sigma_T} \quad (3.1)$$

For a stellar-mass black hole, this quantity is derived based on the balance between radiation pressure and gravitational force. Thus, it mainly depends on the mass of the black hole m .

The optical depth of accretion disks is very important because it quantifies the mechanisms of energy transfer within the gas. Opaque disks are optically thick, meaning photons are absorbed and re-emitted multiple times before escaping: energy is transported primarily by radiation diffusion and convection. Opaque disks are often found in systems with high accretion rates, close to the Eddington limit. Transparent disks are optically thin, allowing photons to escape without significant re-absorption: energy is primarily transferred by advection and outflows rather than radiation. Transparent disks are common in systems with low accretion rates, well below the Eddington limit.

A summary of the main accretion disk models and their properties is shown in Fig. 3.1. The x -axis represents the optical depth, with optically thin disks on the left and optically thick disk on the right. The y -axis shows the mass accretion rate, where a value of 1 corresponds to the Eddington mass accretion rate. Sub-Eddington flows are located on the bottom of the figure while Super-Eddington flows are positioned toward the top. Finally, the red dashed line indicates $H = r$. Geometrically thin disks lie below this line while geometrically thick lie above it. In Sect. 3.2.1 and 3.2.2, we focus on two geometrically thin disk models: the Shakura-Sunyaev disk (also known as α -disk) and the slim disk.

3.2.1 Shakura-Sunyaev and Novikov-Thorne disk models

The Shakura-Sunyaev (S-S) disk model (Shakura and Sunyaev, 1973) is one of the most commonly used analytical model to describe accretion disks. Using a few assumptions, Shakura and Sunyaev (1973) showed that it is possible to solve analytically the system of thin disk equations. The S-S model is stable for sub-Eddington mass accretion rates ($\dot{m} \ll \dot{m}_{\text{Edd}}$). The disk is geometrically thin (and is therefore referred to as a “thin disk” model), and optically thick. The accretion disk is divided in three domains, depending on different physical conditions. In the inner part, the radiation pressure and the electron scattering are dominant. In the middle part, electron scattering is still the main source of the opacity, but gas pressure dominates. Finally, in the outer part of the disk, the temperature and density are low. The gas pressure still dominates but the main contributor to the opacity is free-free absorption.

The Novikov-Thorne (N-T) model (Novikov and Thorne, 1973) is the relativistic generalization of the S-S model. The black hole is considered to be a rotating Kerr black hole. Relativistic correction terms are added to the Newtonian equations. These corrections are particularly important close to the inner edge of the rotating Kerr black hole where the gravitational pull is big. Far away from the center, N-T equations are equivalent to the S-S equations. In our case, we are mainly interested in the material close to the inner edge of the black hole, where outflows arise.

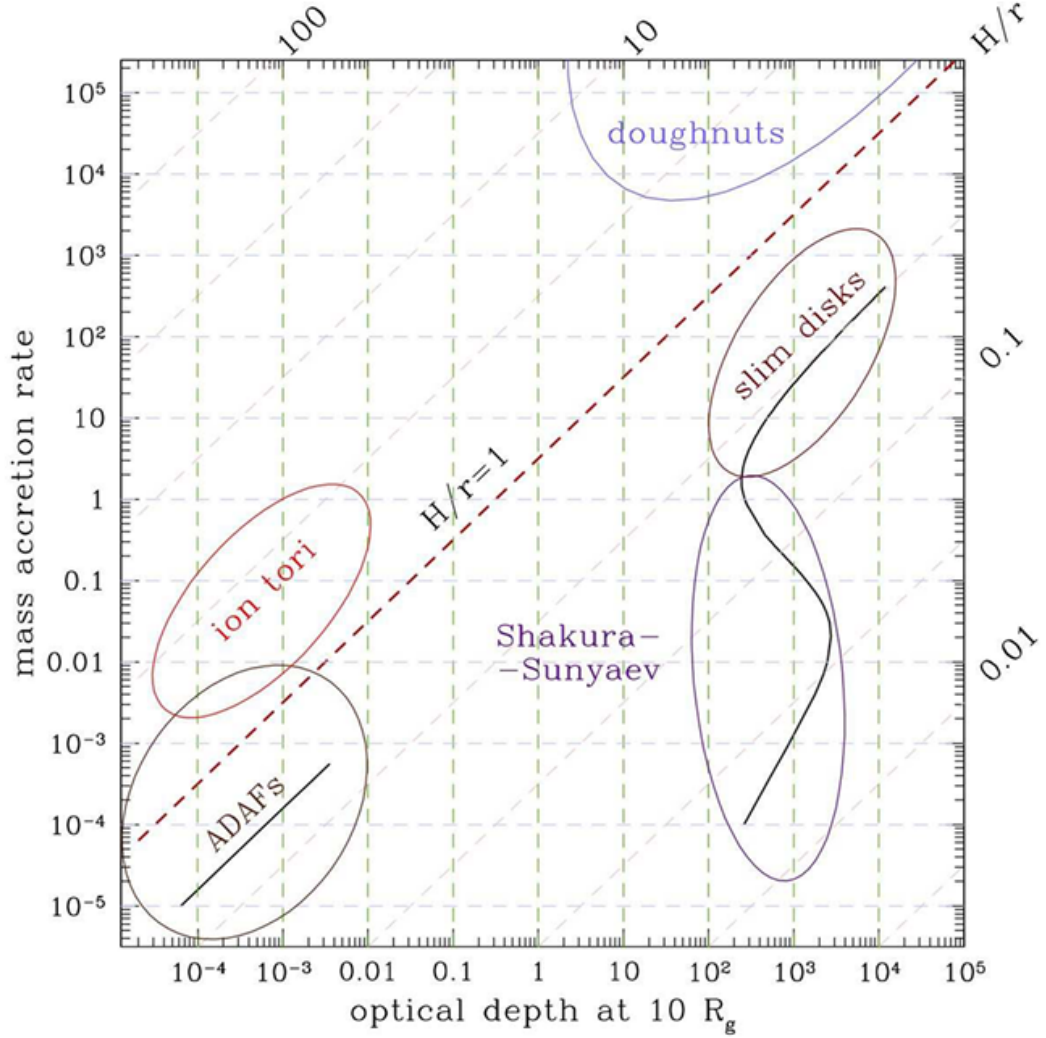


Figure 3.1: Several accretion disk models are shown in a optical depth, mass accretion rate, and geometry plane. This figure has been taken from Abramowicz and Fragile (2013).

3.2.2 Slim disk

Breen (2018) emphasized the necessity of a super-Eddington accretion flow to generate a sufficient amount of enriched material within a limited time-frame. This requirement stems from the need for the material to be produced in a matter of a few million years, aligning with the observational constraints observed in gas-free young massive clusters. The slim disk model, originally introduced by Abramowicz et al. (1988) serves as a valuable expansion of the S-S model in scenarios involving a super-Eddington accretion flow, as visually represented in Fig. 3.1. For accretion rates $\dot{m} \approx 0.1 \dot{m}_{\text{Edd}}$, the S-S disk may become unstable due to the radiation pressure contribution to the viscous torque (Janiuk et al., 2002; Lightman and Eardley, 1974; Shakura and Sunyaev, 1976). For mass accretion rates close to or larger than the Eddington limit, the disk becomes thick and advection comes in the balance as an extra cooling mechanism. In this case, the slim disk can be used as an alternative disk model. In this model, a portion of the photons produced within the disk becomes unable to exit its surface because they are confined by the inward flow of matter. This critical radius, at which this confinement happens, is commonly referred to as the “trapping radius,” r_{trap} . This radius marks the transition point between the inner region, in the slim disk regime, and the outer region, where cooling is radiation-dominated

and the accretion disk can be described by the standard S-S model. Such a radius is only dependent on the mass accretion rate.

We describe the slim accretion disk by using the detailed expressions presented by Watarai (2006). Aspects that are of particular importance to our discussion include the temperature, density, and radial velocity of the flow, v_r . The relevant equations used to describe these three quantities are characterized by two groups of equations, denoted by the subscripts *in* and *out*, depending on the position within the accretion disk, with respect to the trapping radius. Solving the equations within the trapping radius gives the following expressions for the radial velocity v_r , the surface density Σ and the temperature T :

$$\begin{aligned} |v_{r_{in}}| &\approx 3.17 \times 10^9 f \left(\frac{\alpha}{0.1} \right) \left(\frac{r}{r_g} \right)^{-1/2} \text{ cm s}^{-1}, \\ \Sigma_{in} &\approx 2.36 \times 10^3 f^{-1} \left(\frac{\alpha}{0.1} \right)^{-1} \left(\frac{\dot{m}}{100} \right) \left(\frac{r}{r_g} \right)^{-1/2} \text{ g cm}^{-2}, \\ T_{in} &\approx 2.52 \times 10^7 f^{1/8} \left(\frac{m}{10} \right)^{-1/4} \left(\frac{r}{r_g} \right)^{-1/2} \text{ K}, \end{aligned} \quad (3.2)$$

where α is the viscosity of the gas, $r_g = 2GM/c^2$ is the Schwarzschild radius, and $m = M/M_\odot$ and $\dot{m} = \dot{M}/(L_{\text{Edd}}/c^2)$ are the normalized mass and mass accretion rate, expressed in unit of solar mass and Eddington accretion rate, respectively. These equations are slightly different from the canonical self-similar solutions (see, e.g., Wang and Zhou 1999), because of the treatment of energy transport. In Watarai (2006), the ratio of the advective cooling rate to the viscous heating rate, f , is not constant and is given by:

$$f(\dot{m}, r) = 0.5 \left(D^2 x^2 + 2 - Dx \sqrt{D^2 x^2 + 4} \right), \quad (3.3)$$

where D is a numerical coefficient taken to be equal to 2.18, and $x = (r/r_g)/\dot{m}$. The quantities outside the trapping radius are similar to the solutions from Shakura and Sunyaev (1973):

$$\begin{aligned} |v_{r_{out}}| &\approx 5.96 \times 10^{12} \left(\frac{\alpha}{0.1} \right) \left(\frac{\dot{m}}{100} \right)^2 \left(\frac{r}{r_g} \right)^{-5/2} \text{ cm s}^{-1}, \\ \Sigma_{out} &\approx 1.26 \left(\frac{\alpha}{0.1} \right)^{-1} \left(\frac{\dot{m}}{100} \right)^{-1} \left(\frac{r}{r_g} \right)^{3/2} \text{ g cm}^{-2}, \\ T_{out} &\approx 4.79 \times 10^7 \left(\frac{m}{10} \right)^{-1/4} \left(\frac{\dot{m}}{100} \right)^{1/4} \left(\frac{r}{r_g} \right)^{-3/4} \text{ K}. \end{aligned} \quad (3.4)$$

It is important to highlight that the density is provided as (projected) surface density. The conventional conversion formula from 2D surface density to a 3D density profile is as follows:

$$\Sigma = \int_{-H}^H \rho dz. \quad (3.5)$$

Here, H represents the height of the disk. To go from 2D to 3D density, we opted for the simplified vertical one-zone approximation commonly used in the standard disk model: $\Sigma = 2H\rho$; this choice is further discussed in Sect. 3.6. Finally, the viscous timescale can be defined as the time needed for the material at a given radius, R , to be accreted onto the compact object:

$$\tau^{\text{visc}} = \frac{R}{v_r}. \quad (3.6)$$

3.3 Method

The first step consists in coding the accretion disks' equations introduced in Sect. 3.2. The outputs of the disk model are the density, temperature, and radial velocity of the accretion flow. The temperature

Accretion disk model		
Input	Range explored	Output
m	$[10^{-4}, 10^8] M_{\odot}$	$T = f(m, \dot{m}, R, \alpha)$
$\dot{m}$	$[10^{-4}, 10^5] \dot{M}_{Edd}$	$\rho = f(m, \dot{m}, R, \alpha)$
R	$[3, 300] R_{sch}$	$v_R = f(m, \dot{m}, R, \alpha)$
α	$[10^{-4}, 1]$	
Reaction network		
Input	Range explored	Output
T	$> 2 \times 10^6$ K	$M_X = f(M_{X_0}, T, t)$
t	$[10^{-6}, 10^{14}]$ s	
Quantity of Interest		
Viscous timescale: $\tau_{visc} = R/v_r$		
Enriched timescale: $\tau_e = f(M_X)$		

Table 3.1: This table provides an overview of the methodology employed to obtain the quantities of interest presented in the last section. The first section provides the input parameters, the ranges explored, and the outputs of the accretion disk model. The second section presents the inputs, their range, and the outputs of the reaction network used. These two steps lead to the computation of important timescales: the viscous timescale only depends on the accretion disk model, while the enriched timescale depends on the evolution of the mass ratio of chemical element X , which is dependent on the temperature and thus on both the disk model and the reaction network.

is used as an input for the reaction network, as all the reaction rates are temperature dependent as described in Sect. 2.1.1. By varying the parameters of the black hole and its accretion disk (black hole mass, m , mass accretion rate, $\dot{m}$, radial distance to the black hole, R , viscosity of the gas, α), we obtained different densities, temperatures, and radial velocities for the gas. The second step consists in using these temperatures and densities as input of the reaction network, we can compute the enrichment timescale and compare it to the viscous timescale in order to determine whether accretion disks can host the required nucleosynthesis of different (light) chemical elements. The nuclear reaction network used is Pynucastro, previously introduced in Sect. 2.1.3. The network is initialised using the chemical abundances of NGC 6752 presented in Sect. 2.2.

Table 3.1 summarizes the method followed to obtain the quantity of interest represented by the viscous and enrichment timescales from the inputs of the accretion disk model. The range of mass, mass accretion rate, radius, and viscosity investigated is given in the second column of Table 3.1. The range of black hole masses and accretion rates is very broad, covering 11 and 8 orders of magnitude, respectively. To ensure the completeness of our investigation, we sampled our parameter space using a two-step method designed to optimally cover it. First, we divided the space into a regular grid $[l \times 10^i, l \times 10^{i+1}]$ for i varying between 0 and $\log_{10}(u/l) - 1$, where l and u are the lower and upper bound of the interval. Then, within each grid cell, we use Latin hypercube sampling (McKay et al., 1979) to take 100 points randomly sampled. A Latin hypercube is a sampling method that ensures each variable in a set is sampled uniformly across its range, and each sample is independent of the others. We have a total of $11 \times 8 \times 2 \times 4 = 704$ different intervals within our four-dimensional (4D) parameter space. Within each interval, we randomly sampled 100 values for each parameter. We thus obtained a total of $704 \times 100 \times 4 = 281,000$ values of $(m, \dot{m}, r, \alpha)$. We used these values as inputs for the analytical model of the accretion disk and obtained 281,000 tuples of (T, ρ, v_r) . For the nuclear reaction network, we only used the tuple with $T > 2$ MK as no nucleosynthesis of the chemical elements of interest can occur

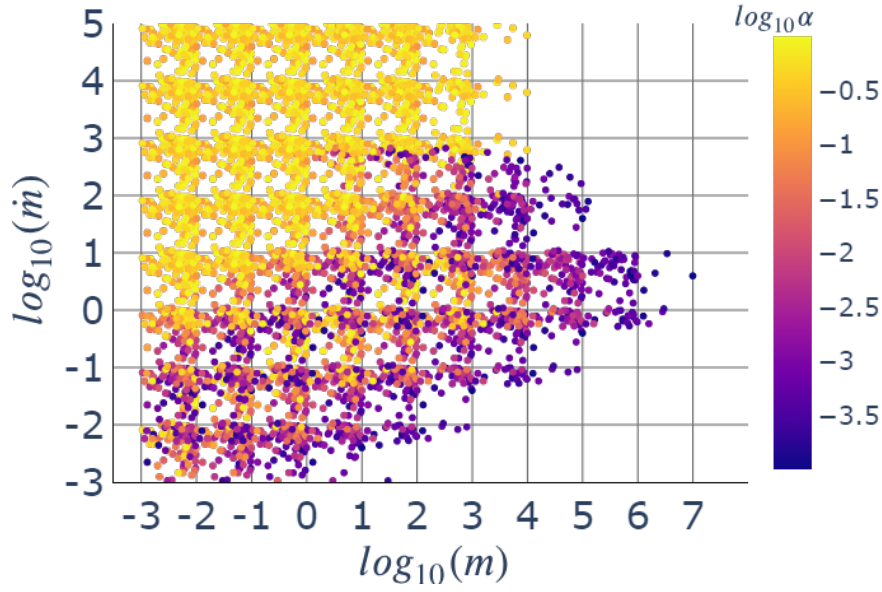


Figure 3.2: Parameter space exploration for the black hole and accretion disk system. A total of 25,730 points are plotted (out of the initial 281,000), representing approximately 9% of the samples $(m, \dot{m}, r, \alpha)$ that yield temperatures exceeding the threshold of 2 MK required as input into the nuclear reaction network. The points are displayed in a logarithmic scale on the m versus $\dot{m}$ plane and color-scaled based on α values.

for smaller temperatures. We are left with a total of 25,730 values. For each value we run the nuclear reaction code, solving a stiff system of equations (see Sect. 2.1). The results are presented in Sect. 3.4.

3.4 Results

In this section, we present the results of our simulations, focusing on the parameters of the accretion disk–black hole system that enable the production of N, Na, Al, and K, which are elements enhanced in the enriched stars of MSPs.

In the following, we study the ratio $\tau_{nuc} = \tau_{visc}/\tau_e$. If $\tau_{visc} < \tau_e$, then $\tau_{nuc} < 1$, and the material in the accretion disk is accreted before nucleosynthesis can occur. If $\tau_{nuc} > 1$, the enrichment timescale is larger than the viscous timescale, and nucleosynthesis could occur in the accretion disk before the gas is accreted. The results of our simulations are plotted in Fig. 3.2 and Fig. 3.3.

Figure 3.2 shows the entire range of parameter values leading to a temperature high enough for nucleosynthesis to occur ($T > 2$ MK), in the logarithmic plane, m versus $\dot{m}$, and color-scaled according to α . Some combinations of parameters, such as a high black hole mass and low accretion rate, result in temperatures that are too low to allow for nucleosynthesis. Conversely, accretion disks around black holes with sub-solar masses can reach $T > 2$ MK for a broad range of accretion rates and viscosity.

We ran the simulation for different enrichment thresholds (values of ξ , see Sect. 2.3 for a definition of ξ and Sect. 2.6 for details on its role). In the left panel of Fig. 3.3, we show the values of $(m, \dot{m}, r, \alpha)$ resulting in an enrichment of ^{14}N , ^{27}Al , and ^{39}K larger than two times the pristine value ($\xi = 2$). Only very light black holes with $m < 1^1$ and very small viscosity parameter $\alpha < 0.003$ make the enrichment of ^{27}Al and ^{39}K possible. Regarding ^{14}N , a few models around $m \approx 1$ and moderate mass accretion rate $1 < \dot{m} < 100$ make the enrichment possible. By increasing the enrichment threshold from 2 to 4, the number of points in the right panel of Fig. 3.3 corresponding to ^{14}N and ^{27}Al significantly decreases.

¹Both m and $\dot{m}$ are dimensionless parameters defined with respect to the solar mass and the Eddington mass accretion rate respectively (see Sect. 3.2).

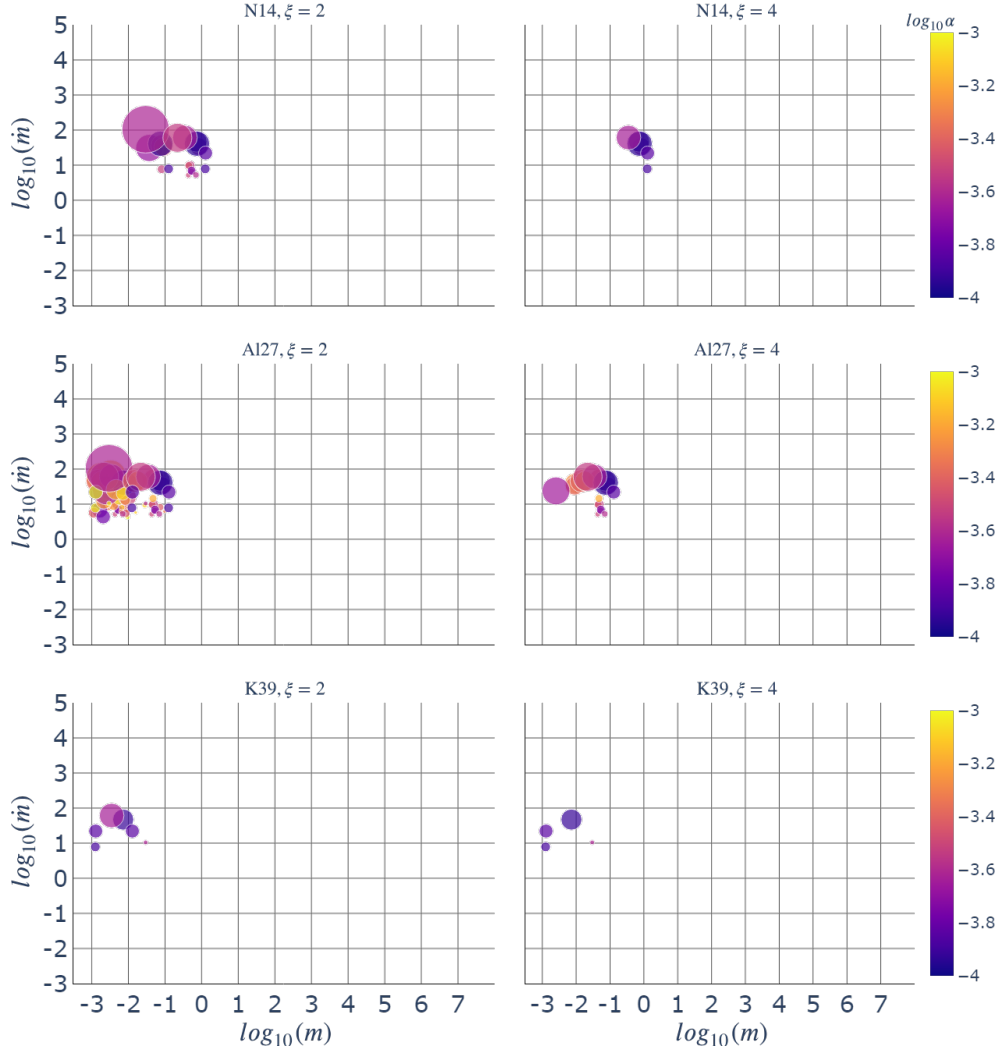


Figure 3.3: Identification of $(m, \dot{m}, r, \alpha)$ values resulting in an enrichment of ^{14}N , ^{27}Al , and ^{39}K larger than two ($\xi = 2$, left panel) and four ($\xi = 4$, right panel). The size of the points corresponds to the distance from the center of the black hole, r . Only 20 (upper-left), 82 (middle-left), and 6 (lower-left) out of the 25,730 points enable an enrichment by a factor of 2, translating into 0.07%, 0.3%, and 0.02% of the initial sample. When $\xi = 4$, the number of points becomes 6 (upper-right), 19 (middle-right), and 4 (lower-right), translating into 0.02%, 0.07%, and 0.015% of the initial sample. The largest distance to the black hole making an enrichment possible occurs for a value of $r = 61 r_g$, visible in the top and middle left panels.

This means that only a few $(m, \dot{m}, r, \alpha)$ values can generate a material four times enhanced in nitrogen and aluminium with respect to the pristine value.

We further investigated the potential formation of ^{14}N and ^{27}Al focusing on the duration of the enrichment, $\Delta\tau_e$ (see Sect. 2.5.1). Here, the role of $\Delta\tau_e$ can be visualized in Fig. 3.4, showing the evolution of ^{14}N and ^{27}Al mass ratios as a function of time for two different successful runs plotted in shades of blue. $\Delta\tau_e$ corresponds to the time length when the different colored curves are above the enrichment thresholds represented by the dashed and dot-dashed lines. We compute the duration of the enrichment $\Delta\tau_e$ for each of the points shown in Fig. 3.3. For ^{27}Al , $\Delta\tau_e$ barely exceeds 100 seconds and never exceeds 500 seconds in the 113 successful runs. Regarding ^{14}N , once the mass ratio is exceeding the threshold, it stays at a constant value until the end of the simulation.

3. Nucleosynthesis in accretion disk around stellar mass BH

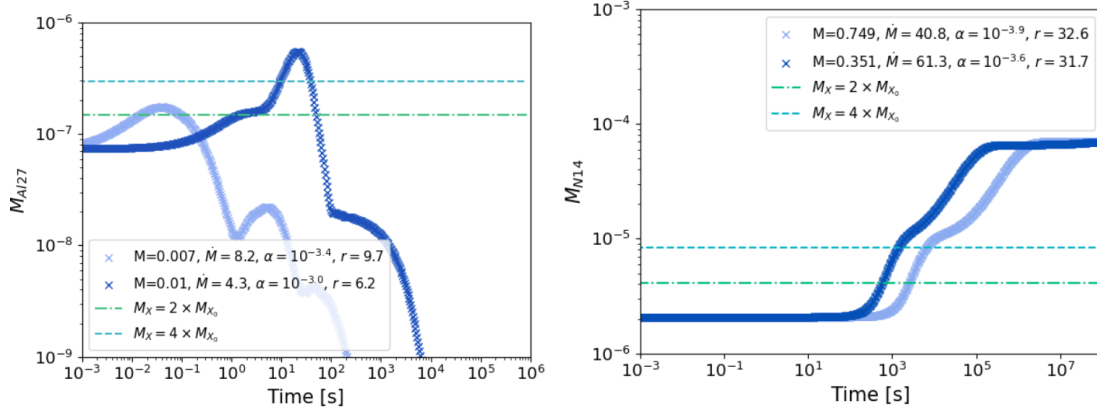


Figure 3.4: Variation of ^{27}Al and ^{14}N mass ratio over time for two runs where the enrichment timescale exceeds the viscous timescale. The labels detail the parameters of the black hole and accretion disk systems. The mass, M , is expressed in $M_\odot$, the mass accretion rate in terms of the Eddington rate, $\dot{M}_{\text{Edd}}$, and the radius in unit of the Schwarzschild radius. The two enrichment thresholds corresponding to $\xi = 2$ and $\xi = 4$ are represented by the dash-dot and the dotted lines, respectively. While the ^{27}Al mass ratio only remains above the threshold for a brief duration, the enrichment in ^{14}N is rather stable and remains at a high level until the end of the simulation.

3.5 Accretion disks around stellar mass black holes as a potential polluter source?

The results presented in Section 3.4 indicate the potential for nucleosynthesis of ^{14}N , ^{27}Al , and, interestingly, ^{39}K within an accretion disk surrounding sub-solar mass black holes using the slim disk model. These possibilities arise when there is an accretion rate close to the Eddington value, and an extremely low viscosity parameter. In the following section, we delve into a more detailed discussion regarding the impact of enrichment duration on the ejection of enriched material and examine the feasibility of such values for m and α .

Given the small duration of the enrichment in ^{27}Al (less than a few hundred seconds), even if a tiny black hole with mass $M = 0.01 M_\odot$ and an accretion disk with an extremely low viscous parameter ($\alpha < 10^{-3}$) would exist, the ejection of the newly formed ^{27}Al would have to occur in an incredibly fine-tuned way in order to pollute the surrounding medium. We find similar results also while examining the duration of the enrichment for ^{39}K , even when setting a smaller value for the enrichment ($\xi = 2$, justified by the range of $[\text{K}/\text{Fe}]$ abundances being much smaller than the range of $[\text{Al}/\text{Fe}]$, as shown in Fig. 2.13).

The low value for the viscous parameter α is a very challenging constraint for the nucleosynthesis. While numerical simulations suggest a value close to $\alpha \approx 0.02$ (Hawley et al., 2011), observations are better represented with $\alpha \approx 0.1$ (King et al., 2007). In any case, the values required to enrich the gas in ^{14}N , ^{27}Al , and ^{39}K are almost two orders of magnitudes smaller than what is suggested by numerical simulations.

The last parameter putting strong constraints on the nucleosynthesis is the black hole mass, which also tends to be very small, although the mass required for the nucleosynthesis of ^{14}N , close to $1 M_\odot$, is more plausible compared to the cases of ^{27}Al and ^{39}K . When considering a modeling approach based on X-ray observations, a black hole with a mass of $1.3 M_\odot$ still falls within the range of very low likelihood in the distribution function of black hole masses in the Milky Way, as indicated by Özel et al. (2010). Given our results on the black hole mass required for the nucleosynthesis, primordial black holes (PBHs) would be of particular interest. They are hypothetical astronomical objects, which would have formed shortly after the Big Bang, and are thought to have originated from the extreme density fluctuations during the early universe. They can possess a very wide range of masses, as suggested by Escrivà et al. (2022) and Carr et al. (2023). For instance, the thermal-history-induced mass spectrum of PBHs peaks at $M \approx 1 M_\odot$ and has a lower tail reaching $M = 10^{-8} M_\odot$. Using numerical simulations, Musco et al. (2023) also found that the PBH mass function during the quantum chromodynamics epoch

would peak at $M \approx 1 M_{\odot}$, with the lower mass tail extending until $10^{-3} M_{\odot}$. PBHs are dark matter candidates (Carr and Kuhnel, 2021) and evidence for their existence has recently been claimed using LIGO/Virgo gravitational-wave data (Franciolini et al., 2022). If such primordial black holes exist, they could be relevant to globular clusters as they are among the oldest structures in the Universe. However, there are still many uncertainties around these objects such as: how long they survive across cosmic time; whether they can have an accretion disk and, if yes, what would be a suitable model to describe them; and whether they could have a much lower viscosity parameter, α , that is compatible with the value found in this work. The research on PBHs will surely benefit from upcoming gravitational wave telescopes such as Einstein and LISA (Franciolini et al., 2023).

3.6 Conclusion

We have explored the possibility of accretion disks around stellar mass black holes to be the polluting source of the enriched material at the origin of the phenomenon of multiple stellar population in globular clusters, following up on Breen (2018).

In this study, we used the slim disk model, presented in Sect. 3.2.2, with the framework outlined in the work by Watarai (2006). This optically and geometrically thick model proves to be particularly suitable for scenarios involving super-Eddington mass accretion rates. Here, advection emerges as a significant cooling mechanism and cannot be neglected any more. Unlike the Shakura and Sunyaev (1973) model, presented in Sect. 3.2.1, the slim disk model introduces less restrictive assumptions, notably not imposing a Keplerian gas rotation profile. Using this disk model, we probed a very wide range of parameters for the black hole and accretion disk system, varying the black hole mass m , the mass accretion rate $\dot{m}$, the viscosity parameter α , and the radius r over many orders of magnitude. Each combination of $(m, \dot{m}, \alpha, r)$ leads to a temperature T , density ρ , and radial velocity v_R of the accretion flow. We then use T and ρ as input to the nuclear reaction network and obtain mass ratios for 132 chemical elements. We focused on some of the chemical elements in over-abundance in the enriched stars of GCs, namely ^{14}N , ^{23}Na , ^{27}Al , and ^{39}K .

We defined the enrichment timescale as the time needed for a chemical element to be enriched with respect to the pristine value, using the parameter ξ to quantify the level of enrichment. Subsequently, we compared the enrichment timescale to the viscous timescale, which characterizes the lifetime of the gas before accretion onto the black hole, and which depends on the radius and radial velocity of the flow. We generated 281,000 sets of values for the parameters $(m, \dot{m}, \alpha, r)$, and we extracted 25,730 (T, ρ) pairs with temperature high enough for the nucleosynthesis to happen ($T > 2 \text{ MK}$) as detailed in Sect. 3.3. Among these pairs, only 82 lead to an enrichment timescale for ^{27}Al smaller than the viscous timescale, using an enrichment threshold of $\xi = 2$: this means that ^{27}Al can be twice more enriched than the pristine mass ratio before the gas is accreted by the black hole in only $\approx 0.3\%$ of the simulated points (see Sect. 3.4). The number of points reduces to 20 for ^{14}N , to 6 for ^{39}K , and to 0 for ^{23}Na . The few quadruplets making an enrichment in ^{27}Al and ^{39}K possible correspond to very light black holes $m < 0.01 M_{\odot}$ and very low values for the viscosity parameter, $\alpha < 10^{-3}$. Even under the assumption that stars consist entirely of enriched material, it is important to note that such a low enrichment threshold ($\xi = 2$) will still be unable to reproduce extreme $[\text{Al}/\text{Fe}]$ values. The enrichment in ^{14}N requires a larger black hole mass, around $1 M_{\odot}$, but a very low viscosity parameter (as obtained for ^{27}Al and ^{39}K). Such low value ($\alpha < 10^{-3}$) is disfavoured by current observations and hydrodynamical simulations, as discussed in Sect. 3.5. We conclude that, given current observations and numerical simulations on black hole mass and viscosity, accretion disk around stellar mass black holes, as described by the slim disk model, cannot generate the enriched material involved in the formation of enriched stars in GCs.

However, it is essential to acknowledge a potential limitation in our approach. To derive the volume density of the gas, an input for the nuclear reaction network, we employed a straightforward technique of dividing surface density by scale height. This method is typically employed under the one-zone approximation, which remains valid for geometrically thin accretion disks where the vertical variations of primary variables are averaged due to a significantly smaller scale height compared to the radial distance ($H \ll r$). However, this assumption does not hold true as $H \approx r$, which is the case in the slim

3. Nucleosynthesis in accretion disk around stellar mass BH

disk model. Nevertheless, given that the density is intricately linked with time in the nuclear reaction network and because the enrichment timescale generally exceeds the viscous timescale by several orders of magnitude, we anticipate that our results remain robust despite this assumption. Conducting further hydrodynamical simulations in conjunction with a nuclear reaction network within accretion disks could offer additional insights and constraints regarding the potential for nucleosynthesis.

Chapter 4

ELLIPTICITY OF MULTIPLE STELLAR POPULATIONS IN GLOBULAR CLUSTERS

“There is an astonishing imagination, even in the science of mathematics.”

- **Voltaire**

Introduction

Moving away from the outdated belief that GCs are composed of a single stellar population, in this Chapter we tackle another misconception about globular clusters, i.e., the assumption that they are spherically symmetric. The first evidence that shapes of GCs deviate from spherical symmetry can be traced back to more than a century ago, when Pease and Shapley (1917) manually counted the number of stars in different sectors of photographs taken by the 60-inch reflector at Mount Wilson. They concluded that several clusters, including M 13 (NGC 6205), had an elongated shape and were elliptical rather than spherical. Since then, several studies have focused on studying the shape of GCs (Chen and Chen, 2010; Frenk and Fall, 1982; Geyer et al., 1983; White and Shawl, 1987), confirming that many of them are indeed flattened.

Studying the relations between the flattening and other kinematical and structural properties of GCs can provide constraints on the mechanisms causing it. This could also be important for the MSPs, because it could bring a new insight into the puzzle of their existence. For example, if one population is systematically flatter than the other, this could discard the scenarios predicting no kinematical differences between the two populations (see Chapter 1).

In this Chapter, we present the first detailed analysis of the ellipticity of GCs and their multiple populations in 26 MW GCs. After defining the ellipticity in Sect. 4.1 and presenting a literature review on this topic in Sect. 4.2, in Sect. 4.3 we describe the different steps of data preparation, with special attention to the classification of MSPs, carried out by Leitinger et al. (2023). In Sect. 4.4 we discuss three different methods that could be used to measure the ellipticity of stellar distributions, and in Sect. 4.5 we carefully test them to select the most robust and accurate one. We present our results on the ellipticity of GCs as a whole in Sect. 4.6 and of their MSPs in Sect. 4.7. In Sect. 4.8 we delve deeper into the shape and kinematics of specific clusters. Finally, in Sect. 4.9 we summarize our conclusions and provide an outlook on possible follow up investigations.

4.1 Definition

The ellipticity, also commonly referred as flattening, quantifies the deviation of a system from spherical symmetry. It can be described using the following quadratic equation:

$$F(x, y) = Ax^2 + Bxy + Cy^2 + Dx + Ey + H = 0, \quad (4.1)$$

where x and y are the Cartesian coordinates, and A, B, C, D, E , and F are numerical coefficients, which can be used to compute some useful quantities defining the ellipse. Equation 4.1 is characterizing an ellipse if $4AC - B^2 > 0$. Given this constraint, we can obtain the equation of the ellipse:

$$\frac{(x - x_0)^2}{a^2} + \frac{(y - y_0)^2}{b^2} = 1, \quad (4.2)$$

where the location of the ellipse center is given by (x_0, y_0) and a and b are the axis of the ellipse, usually a is the semi-major axis and b is the semi-minor-axis, all dependent on the coefficients in Eq. 4.1. Finally, the ellipticity, e , and the angle between the x -axis and the semi-major axis of the ellipse, Φ , can be computed as follows:

$$e = 1 - \frac{b}{a} \quad (4.3)$$

$$\Phi = \frac{1}{2} \arctan \left(\frac{B}{A - C} \right). \quad (4.4)$$

In the following we will refer to e as the *ellipticity* or the *flattening*, and to Φ as *angle* or *position angle* of the ellipse. In the case of GCs, which are 3D objects, we aim at reconstructing their 2D shape, in the plane of the sky. In this context, the ellipticity is a projected quantity.

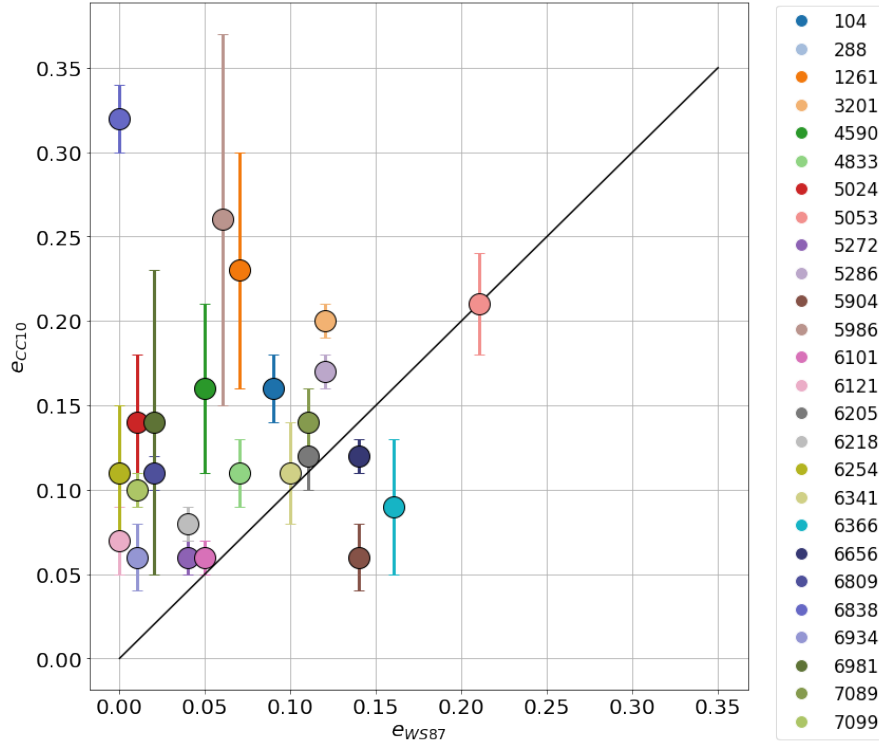


Figure 4.1: Ellipticities of the 26 GCs studied here, as reported by White and Shahl (1987) and Chen and Chen (2010), respectively on the abscissa and on the ordinate.

4.2 State of the art

The ellipticity of GCs can be measured through different methods. A commonly used method involves the computation of iso-density contours of the stellar distribution, and fitting ellipses, usually using Least-Square, to the contours. Such a method has been used by Geyer et al. (1983) who computed the ellipticity variations of 20 Galactic cluster, and four Magellanic Cloud clusters, and by Cordoni et al. (2020) who derived ellipticity profile for 7 MW GCs. This method has the advantage to provide an ellipticity profile as a function of the radial distance from the cluster center. However, computing isodensity contours is not always straightforward and can depend on the available observations. White and Shahl (1987) noted that they were unable to directly estimate isodensity contours because the Palomar and ESO plates available at the time lacked the density-wedge information needed for the calibration of the isodensitracer. To address this limitation, they used a surface photometry method that involved blurring digitized images of blue-sensitive photographic plates from the Palomar and ESO/SRC surveys. Based on these blurred images, they computed isophote contours to which they fitted ellipses. Another commonly used method relies on the number-count of point sources. For example, Chen and Chen (2010) analysed the spatial distribution of Two Micron All Sky Survey (2MASS) point sources with such a technique. They attributed a clustering parameter to each star in their sample, quantifying the local stellar density. The total number density was then calculated by summing the values of all the stars within a grid. They fitted an ellipse to the isodensity contour meeting three times the sky density fluctuation. A downside of this method is its sensitivity to the grid size, as discussed in Chen and Chen (2010). More recently, Dalessandro et al. (2024) used a combination of discrete contours and principle component analysis (PCA). We discussed their method and results in more detail in Sect 4.7.2.

Interestingly, these analyses yielded very different results, and consequently different conclusions.

In Fig. 4.1 we compare the ellipticities reported by White and Shahl (1987) with the ones determined by Chen and Chen (2010). The latter seem to obtain systematically more flattened GCs. The biggest difference can be seen for NGC 6838: Chen and Chen (2010) report an ellipticity of 0.32, whereas White

and Shawl (1987) find it to be round. White and Shawl (1987) concluded that the flattening of clusters can be linked to internal kinematical factors, such as rotation or velocity anisotropy, whereas Chen and Chen (2010) suggested that tidal effect from the external Galactic potential might impact the shape of GCs located in the Galactic bulge. The discrepancy between the results of these two works is likely due to the use of different observations and of different methods. Indeed, on the one hand, the observations used by White and Shawl (1987) cover the inner parts of GCs, where a lower flattening is expected due to internal relaxation; moreover, they use optical wavelengths, which can be sensitive to interstellar dust extinction. On the other hand, the 2MASS data analysed by Chen and Chen (2010) probe the outer parts of GCs, more sensitive to tidal effects; the probabilistic star-counting technique they adopted could be affected by the size of the grid.

The first work on the ellipticity of MSPs can be attributed to Cordoni et al. (2020) who computed the ellipticity profiles of the pristine (P1) and enriched (P2) populations in seven Galactic GCs. While NGC 6254 and NGC 5904 exhibit a more elliptical P2, NGC 104 shows a more flattened P1, and no statistically significant trend could be inferred for the rest of their sample. This is a first hint that none of the population behaves in a universal way in term of flattening. As part of a 3D kinematic analysis, Dalessandro et al. (2024) studied the ellipticity of the two populations in 16 Galactic GCs and found a correlation between ellipticity and rotation. The samples studied by Cordoni et al. (2020) and Dalessandro et al. (2024) have four GCs in common. Their results are incompatible for three out of the four GCs. The different methods adopted to compute ellipticities in these works could partly explain these discrepancies. We further discuss this point in Sect. 4.6.2 where we compare our results with past literature.

This overview on the investigation of flattening of GCs and of their MSPs highlights the importance of providing a robust method which could provide consistent results also when used on different datasets. This will be the focus of Sect. 4.4.

4.3 Data preparation

In this section, we describe the few steps of data preparation necessary to obtain a classification of the MSPs. These steps are detailed in Leitinger et al. (2023). These data have been kindly provided to us by Ellen Leitinger.

4.3.1 Photometric data

Two different photometric datasets have been used to extract positions and magnitudes of stars in the sample of GCs considered in this Thesis. The first one, the Stetson catalogue (Stetson et al., 2019), is one of the most extensive photometric catalogues publicly available. It provides wide-field ground-based Johnson-Cousins data in the U, B, V, R, and I filters for stars in 48 Galactic GCs. The second is composed of space-based HST UV Globular Cluster Survey data (Nardiello et al., 2018; Piotto et al., 2015), obtained using UV/blue filters and the Wide Field Camera 3 (WFC3) UVIS/IR imager. While HST data typically only covers the very central regions of GCs (up to a few arcminutes), the ground-based photometric data from (Stetson et al., 2019) allows us to probe the GCs to a larger extent, out to more than 10 arcmin for some clusters. An example is NGC 104, illustrated in Fig. 4.2, where the blue points show stars from Stetson’s catalogue, while the red points at the center correspond to the stars in the HST UV Globular Cluster Survey catalogue. Such an extended coverage, up to 15 arcmin from the center of NGC 104 for example, is particularly useful to understand the shape of dynamically old GCs which retain their dynamical differences mainly in the outer part (see Sect. 1.3.3 for more details).

4.3.2 Differential reddening correction

Interstellar dust affects observations, through scattering and absorption; its effect is stronger at lower (bluer) wavelengths than at higher (redder) wavelengths. This effect is called differential reddening and impacts observations, especially for objects with a large amount of interstellar dust along the line of sight. Differential reddening can cause a broadening of the main sequence, and therefore correcting

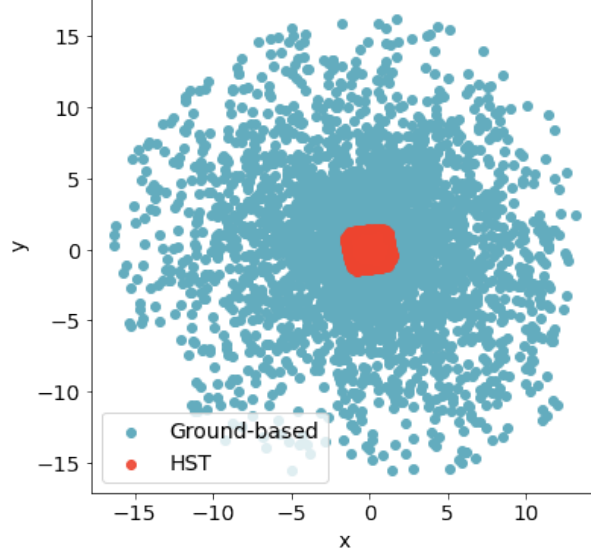


Figure 4.2: Spatial distribution of stars with photometric data in the globular cluster NGC 104. Blue points represent the stars in the ground-based catalogue from Stetson et al. (2019), while red points at the center correspond to stars in the HST UV Globular Cluster Survey catalogue (Nardiello et al., 2018; Piotto et al., 2015).

for this effect is very important to distinguish between multiple stellar populations in globular clusters (Milone et al., 2012b). Pancino et al. (2024) computed DR maps for the 48 GCs presented in the Stetson catalogue (Stetson et al., 2019). These maps have been used to obtain differential reddening values for each star in the dataset using the nearest neighbours method. The DR of a star is computed by taking the median value of its k nearest neighbours, where the choice of k depends on the GC under consideration.

4.3.3 Completeness analysis and membership

Assessing data completeness is crucial to accurately quantify the ellipticity, as Stetson et al. (2019) pointed out, the incompleteness of some datasets in certain regions can lead to erroneous estimate of the flattening and complicate a comprehensive comparison of results. The completeness analysis is done in two steps. The first consists in determining a spatial completeness correction, to ensure that we have a uniform coverage of the clusters. To do this, each cluster is divided in concentric rings spaced by 1.0 arcsec. Along each ring, 360 artificial points are distributed. For each artificial point, the distance to its nearest neighbour is computed. If the distance is smaller than a given threshold, usually close to 1 arcsec but varying from cluster to cluster, the point is considered as covered. The spatial completeness factor is then defined as the ratio between the number of points covered and the total number of points along the annulus. The points located outside of the outermost annulus allowing for a spatial completeness larger than 50% are discarded.

The second step consists of applying a photometric completeness correction to account for data gaps due to missing photometry. This step is carried out after a photometric cleaning process, aiming at removing non-members and non-RGB stars. For Stetson’s data, the membership assessment is done using proper motions, after cross-matching the stars in common with the GAIA DR3 catalogue (Gaia Collaboration et al., 2021). The HST UV Globular Cluster Survey data already includes a membership probability parameter. The idea is then to account for the stars eliminated during the photometric cleaning process by assigning a weight to the remaining stars. Similarly to the spatial completeness analysis, the cluster is divided into annuli. A completeness factor, defined as the ration between the number of stars in the annuli after photometric cleaning and before is attributed to each annuli. The final completeness factor is the product of the spatial and photometric completeness factor. More information on these steps are available in Leitinger et al. (2023).

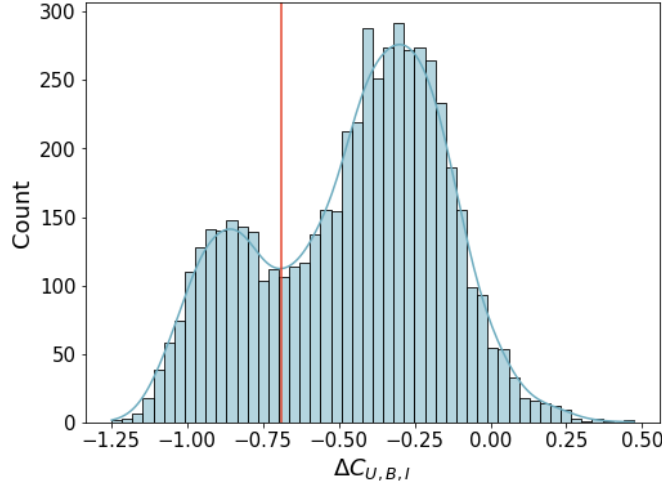


Figure 4.3: $\Delta C_{U,B,I}$ distribution of stars in NGC 104. The red vertical line has been determined manually to match the location of the dip in the histogram, representing the boundary between P1 (in the left) and P2 (in the right) stars. Data are from the ground-based catalogue Stetson et al. (2019) and the HST UV Globular Cluster Survey catalogue (Nardiello et al., 2018; Piotto et al., 2015). They have been kindly provided by Ellen Leitingner.

4.3.4 Classification of the multiple stellar populations

After correcting the dataset for differential reddening and completeness, both spatially and photometrically, we can classify the stars in several groups based on a combination of filters adequately selected. To do so, several methods can be used such as chromosome maps based on HST photometry (Milone et al., 2015) or the $C_{U,B,I} = (U - B) - (B - I)$ pseudo-colour (Monelli et al., 2013). In this Chapter, we used the $C_{U,B,I} = (U - B) - (B - I)$ pseudo-colour index. The method used to separate stellar populations by using the $C_{U,B,I}$ index is described in Milone et al. (2017). First, stars are grouped in bins according to their brightness in the V-band. For each bin the mean value of the V magnitude and the 4th and 96th percentile of the $C_{U,B,I}$ distribution are computed.

Then, the CMD is verticalized, following the procedure describe by Milone et al. (2017), and the normalised distribution $\Delta C_{U,B,I}$ is computed in the following way:

$$\Delta C_{U,B,I} = \frac{C_{U,B,I} - X_{blue}}{X_{red} - X_{blue}}, \quad (4.5)$$

where X_{red} and X_{blue} are the red and blue verticalized fiducial lines representing the 4th and 96th percentile of the pseudo-color distribution. The histogram in Fig. 4.3 shows the distribution of the pseudo-colour $\Delta C_{U,B,I}$. The central dip in the histogram represents the approximate boundary between P1, located left from the red line, with lower $\Delta C_{U,B,I}$ and P2, in the right side of the red line. A Gaussian mixture model with two components is fitted to the $\Delta C_{U,B,I}$ distribution, to assign to each star the probability with which it belongs to the two populations. In the following analysis, we will consider only stars with a probability greater than 70% of belonging to one population as part of that population. Therefore, at this stage, we have a complete sample of stellar positions, in right ascension and declination, and the corresponding classification as P1 or P2 for 26 MW GCs. Finally, we need to convert from the equatorial coordinate system to the Cartesian space in order to model the projected 2D ellipticity. To do so, we use the coordinate conversion formula from van de Ven et al. (2006) taking into account projection effects for objects close to the equatorial plane and with a large angular diameter.

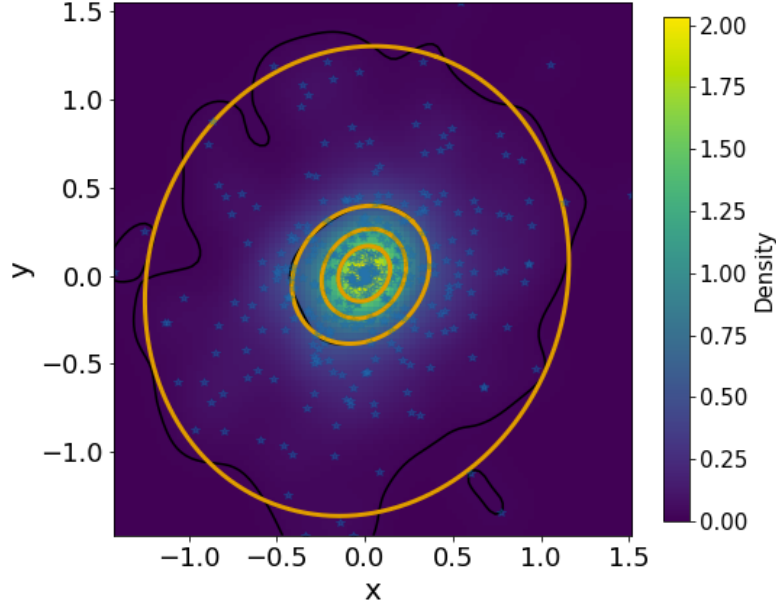


Figure 4.4: Mock data of a GC are plotted as blue stars. We fit ellipses (in orange) to different density contours (in black). The density is estimated using KDE and is plotted from yellow (high density) to dark blue (low density).

4.4 Methods

In this section, we discuss three different methods that we have explored to measure the ellipticity of GCs. In the first method, described in Sect. 4.4.1, we smooth the spatial distribution of stars in the GCs using a two-dimensional kernel density, and fit ellipses to different contour levels; this approach makes it possible to extract an ellipticity profile as a function of the distance to the cluster center, and is similar to the one employed by Cordoní et al. (2020). In the second method, presented in Sect. 4.4.2, we apply a probabilistic approach using Bayesian inference with a Gaussian likelihood to estimate the ellipticity. Finally, we investigate principal component analysis (PCA) in Sect. 4.4.3, a data-driven method that identifies the major and minor axes of the clusters based on the variance of the data. Each method has its own set of advantages, assumptions, and limitations, that we further discuss in Sect. 4.5.

4.4.1 Method 1: contour fitting of kernel density

This method is composed of two steps. First, we used Kernel Density Estimation (KDE, Scott 2015) to estimate the density of stars in the Cartesian space. This non-parametric method is useful to determine the probability density of a dataset; in our case, it creates a smooth and continuous function representing the density of stars. Second, we define a set of contour levels ranging from 10% to 90% of the maximum density value, and we fit ellipses to each contour using a Least-Square method (Halir and Flusser, 1998).

This method is illustrated in Fig. 4.4. To test this and to illustrate this approach, we generated mock data of a GC, corresponding to the blue stars plotted in in Fig. 4.4. We estimated the surface density using KDE: this is shown in shades from yellow (high density, at the cluster center) to purple (low density, in the outskirts) in the figure. Then, we selected several density contours, indicated with black lines in Fig. 4.4. Using the quadratic equation of the ellipse given by Eq. 4.1, we fit an ellipse to each contour level, by using the algorithm presented by Halir and Flusser (1998). The errors on the parameters are estimated by randomly generated 100 mock GCs with a similar ellipticity and position angle. We fit an ellipse to each perturbed contour, and for both the ellipticity e and the position angle Φ we determine the mean and standard deviation at each contour. The best-fit ellipses are represented by the orange lines in Fig. 4.4. We also compute the mean ellipticity and mean angle by averaging over all the contours.

This provide us with a single value for the ellipticity and position angle of the GC, which can then be compared with the results of the methods presented in Sect. 4.4.2 and Sect. 4.5.3. We assess of the robustness and precision of this method in Sect. 4.5.1.

4.4.2 Method 2: Markov Chain Monte Carlo

Using Bayesian inference brings the advantage of providing a straightforward way to estimate the error on the parameters, in our case e and Φ . Bayesian statistics uses a prior and a likelihood function to estimate the probability distribution of a set of parameters, the posterior distribution. For our application, we choose uniform priors for the parameters, $0 < e < 1$ and $0^\circ < \Phi < 180^\circ$, and we use a Gaussian likelihood function:

$$p(x|\Theta) = \frac{1}{2\pi\sqrt{\det \Sigma_R}} \exp \left[-\frac{1}{2}(x - \mu)^T \Sigma_R^{-1} (x - \mu) \right] \quad (4.6)$$

where

$$\Sigma_R = R \begin{pmatrix} a & 0 \\ 0 & a(1-e) \end{pmatrix} R^T \quad (4.7)$$

is the covariance matrix of the data to which we applied a rotation by an angle φ given by the rotation matrix R :

$$R = \begin{pmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{pmatrix}. \quad (4.8)$$

We add a uniform background to the likelihood, using the following function:

$$\Lambda_{\text{back}} = \frac{1}{(x_{\text{max}} - x_{\text{min}})(y_{\text{max}} - y_{\text{min}})}, \quad (4.9)$$

where x_{max} , x_{min} , y_{max} , and y_{min} are the bounds of the distribution of stars in Cartesian coordinates. Therefore, the total likelihood is the weighted mixture of the Gaussian and uniform likelihoods:

$$\Lambda_{\text{total}} = (1 - \lambda_{\text{outlier}}) \cdot p(x|\Theta) + \lambda_{\text{outlier}} \cdot \Lambda_{\text{uniform}}. \quad (4.10)$$

The free parameter λ_{outlier} accounts for outlier stars and is an additional fitting parameter, together with e and Φ . We use the Markov Chain Monte Carlo (MCMC) method implemented within the emcee package (Foreman-Mackey et al., 2013) to sample the posterior distribution defined using the the likelihood and priors functions described above. MCMC is a powerful statistical technique used in Bayesian inference for sampling complex probability distributions. It relies on the Markov property, where the probability of transitioning to a new state depends only on the current state, enabling the generation of a sequence of correlated samples. We test this method in Sect. 4.5.2.

4.4.3 Method 3: Principle component analysis

PCA is a method aiming at reducing the number of dimensions in large datasets in order to extract the most important information (Pearson, 1901). In our case, we are working with the stellar positions in the Cartesian coordinate system, so 2D data. Therefore, PCA is not used here to reduce the dimensions but rather to find the axes with the most information encoded.

The dataset of stellar position is represented by the matrix $\mathbf{D}$:

$$\mathbf{D} = \begin{pmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \vdots & \vdots \\ x_n & y_n \end{pmatrix}. \quad (4.11)$$

4. Ellipticity of MSPs in GCs

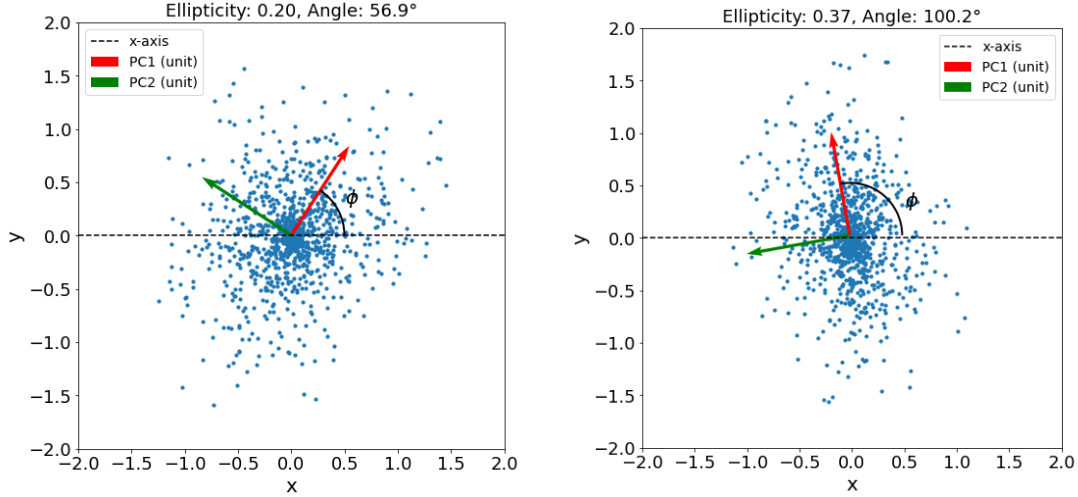


Figure 4.5: Principle component analysis of a mock dataset representing 1000 stars in a globular cluster with an imposed ellipticity $e = 0.2$ and an angle $\theta = 60^\circ$ in the left panel, and in a cluster with $e = 0.4$ and $\theta = 100^\circ$ in the right panel.

Each row (x_i, y_i) represents the position of a star in a 2D Cartesian coordinate system with the origin in the center of the cluster. We implement PCA using the singular value decomposition (SVD), which decomposes $\mathbf{D}$ into three matrices:

$$\mathbf{D} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T. \quad (4.12)$$

In this decomposition $\mathbf{U}$ is an $N \times N$ orthogonal matrix, where N is the length of the data matrix $\mathbf{D}$, in our case the number of stars in our dataset. $\mathbf{\Sigma}$ is a diagonal matrix with the singular values σ_1 and σ_2 , which are related to the square roots of the eigenvalues of the covariance matrix of the data. $\mathbf{V}^T$ is a 2×2 orthogonal matrix, where each column represents the principal direction (eigenvector) of the data. The singular values σ_1 and σ_2 represent the spread of the data along each principal component. The square of each singular value gives the variance along each principal component, which is proportional to the eigenvalues of the covariance matrix. This decomposition thus provides the principal directions of the data and their associated variances.

In PCA, the eigenvector associated with the largest eigenvalue (or the largest singular value σ_1) is the direction along which the variance is maximized. This direction is identified as the major axis of the data distribution. Conversely, the eigenvector associated with the smallest eigenvalue (or the smallest singular value σ_2) corresponds to the minor axis. The ellipticity and the inclination angle are then computed as:

$$e = 1 - \frac{\sigma_2}{\sigma_1} \quad (4.13)$$

$$\theta = \arctan\left(\frac{v_{1y}}{v_{1x}}\right), \quad (4.14)$$

where v_{1x} and v_{1y} are the components of the eigenvector associated with the largest singular value (or eigenvalue), indicating the direction of maximum variance.

The concept of PCA is illustrated in Fig. 4.5 for two mock GCs with different ellipticity and orientation. The principle components are indicated by the red (semi-major axis) and green (semi-minor axis) vectors. We assess of the robustness and accuracy of this method in Sect. 4.5.3.

4.5 Testing the codes

In this section, we will test the three different methods described in Sect. 4.4 on mock GCs, varying three parameters: the number of stars N , the true ellipticity e_{true} , and the true angle of the ellipse Φ_{true} . We will also test the robustness of the methods with respect to the presence of outlier stars. These tests are particularly important to ensure that the method selected provides accurate and meaningful information on the global ellipticity of GCs and of their MSPs. We generated mock positions of stars following a King profile (King, 1966). Then, we applied a transformation to the dataset to impose an ellipticity and an angle. Each test is realised several times, depending on the speed of the method, on slightly different mock GCs with the same imposed ellipticity and position angle. We fix the seed of the random generator of stars to make our tests reproducible. The mean value and the error bars on the parameters are obtained by averaging and taking the standard deviation of the realisations (for the KDE and PCA methods) or by direct computation (for MCMC).

4.5.1 KDE and contour fitting

The first test that we run aims at quantifying the impact of the number of stars on the error on the ellipticity profile, for two different values of the true ellipticity. We present the results in Fig. 4.6, where the ellipticity profile is shown in the top row as a function of the distance from the cluster's center for two values of true ellipticities, 0.1 (left panel) and 0.2 (right panel). We consider three choices for the number of stars: $N = 100$ (represented in blue in the figure), $N = 500$ (in yellow), and $N = 1500$ (in pink). The resulting position angles are shown in the bottom row of Fig. 4.6, with similar panels and colours as for the ellipticity. When considering a small number of stars ($N = 100$), the code overestimates the ellipticity, with an ellipticity predicted to be close to 0.2 instead of 0.1 in the left panel and close to 0.25 instead of 0.2 in the right panel. The error bars on the parameters are large, and the results are consistent within the error bars. When the number of stars increases, the errors decrease significantly and the code accurately recovers the true value of the ellipticity. When both e_{true} and the number of stars are small, the position angle at varying distances from the center is not accurately recovered, as illustrated in the bottom left panel of Fig. 4.6, where the mean value of the angle is overestimated by 25° . The error-bars are also very large: this can be explained by the fact that the rounder the ellipse, the harder it is to define and constrain its position angle. If $N = 500$ or $N = 1500$ and $e_{\text{true}} = 0.2$, the profile of the position angle is very accurately recovered, as shown by the pink and orange points in the bottom-right panel of Fig. 4.6.

The second test that we run is a robustness check. We manually add a few outlier stars (1% of the total number of stars) and inspect the profiles recovered. We present the results in Fig. 4.7 for a mock GC with 1500 stars, $e_{\text{true}} = 0.2$, and $\Phi_{\text{true}} = 45^\circ$. In the left panels, we show where the outliers have been added, along the major axis of the ellipse in the top panel, and along the minor axis of the ellipse in the bottom panel. In the right panels, we show the corresponding ellipticity profiles recovered. Adding 1% of outlier stars has a strong impact on the recovered ellipticity. The ellipticity is biased toward higher values when the outliers are added in the direction of the major axis (see the top panel of Fig. 4.7), and toward smaller (rounder) values when the outliers are added along the minor axis (see the bottom panel of Fig. 4.7).

Finally, we want to test the ability of the method to recover the *mean* ellipticity and *mean* position angle of mock GCs with random parameters. To do so, we uniformly sampled 200 times the number of stars N between 50 and 1500, the true ellipticity e_{true} between 0.01 and 0.3, the true angle Φ_{true} between 0° and 180° , and the tidal radius r_t between twice the core radius r_c and 10 arcmin. We used these parameters as inputs to mimic the distribution of stars in a globular cluster.

We define the error on the ellipticity err_e as the difference between true ellipticity, e_{true} and recovered ellipticity, e_{rec} . Similarly, we define the error on the angle as $err_\Phi = \Phi_{\text{true}} - \Phi_{\text{rec}}$. The quantities e_{rec} and Φ_{rec} are the same as e and Φ : here we add the subscript to emphasize the difference between true ellipticity and the one recovered by the method, in the context of error computation. Figure 4.8 shows the error on the ellipticity (left panel) and on the angle (right panel) as a function of the true ellipticity, for different number of stars, coloured from blue (low N) to yellow (high N). On the left panel, we can see that the ellipticity is constantly overestimated when $e_{\text{true}} < 0.05$. This means

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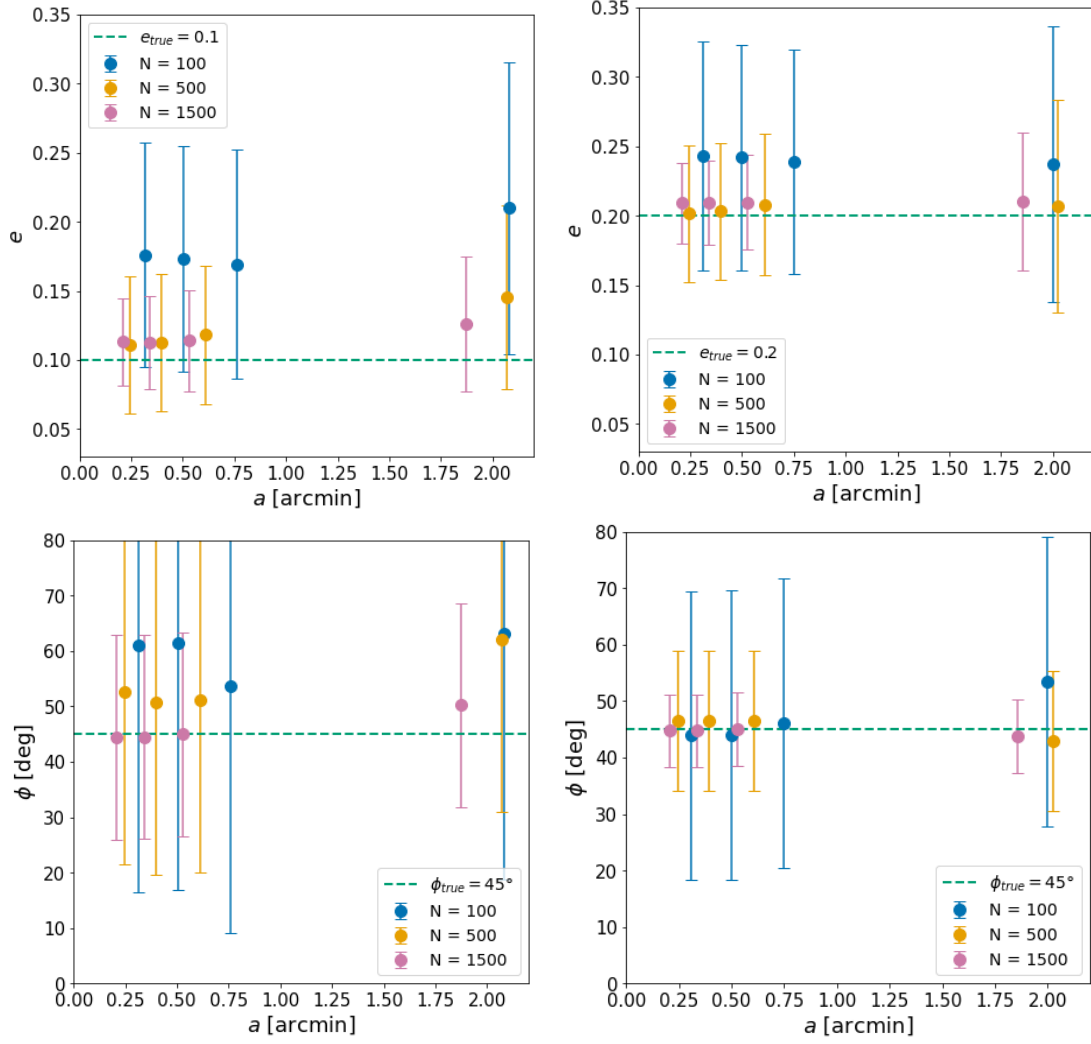


Figure 4.6: *Top panels:* Ellipticity profile recovered for mock datasets composed of a different number of stars. The true ellipticity is marked by the dashed line; $e_{\text{true}} = 0.1$ in the left panel and $e_{\text{true}} = 0.2$ in the right panel. *Bottom panels:* Position angles recovered at various radial distances from the center of mock clusters, for different numbers of stars and for the ellipticity values marked in the top panels. The blue, yellow, and pink points represent mock GCs with 100, 500, and 1500 stars respectively.

that the KDE method tends to flatten the GCs which are close to spherical. When $e_{\text{true}} > 0.1$, the main source of bias for the code is the number of stars. Dark blue points correspond to $N < 200$ stars in the GC. Such a small number of stars prevents the KDE method from recovering the true ellipticity of the cluster even for flattened systems. The right panel of Fig. 4.8 shows that the error on the angle Φ is mainly linked to the ellipticity, with almost spherical clusters having very large errors.

In this section, we have established that by fitting ellipses to KDE contours it is possible to recover the ellipticity and position angle profiles of a system with a true ellipticity $e_{\text{true}} > 0.1$ and with a sufficient number of stars. However, this method has strong limitations when it comes to dealing with outliers, with small numbers of stars, and with round stellar distributions.

4.5.2 Markov Chain Monte Carlo

In this section, we test the ability of MCMC to recover the mean ellipticity and mean position angle of stars in a mock GC. We run the same tests as in Sect. 4.5.1, but in this case we run each test only on

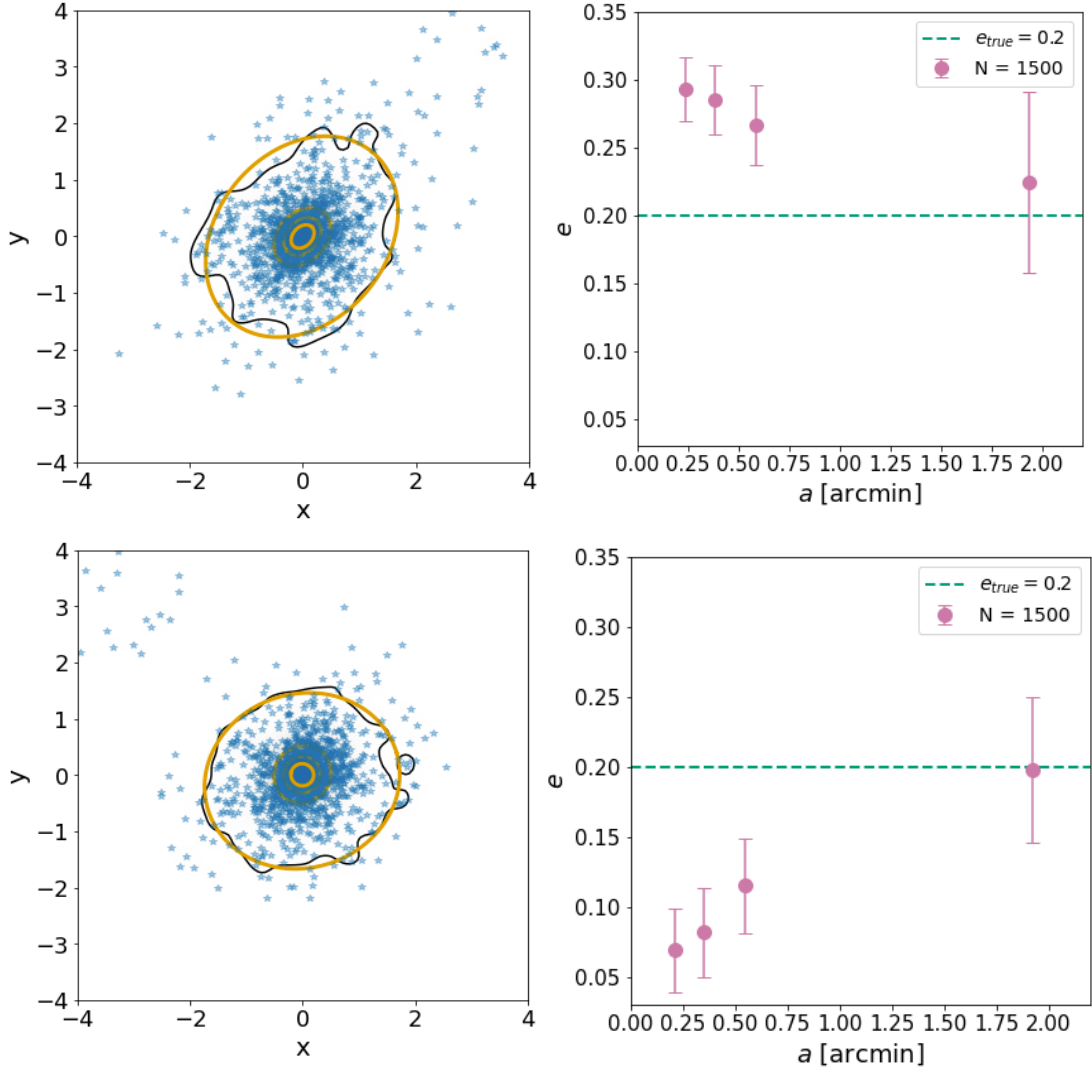


Figure 4.7: Left panels: Mock GCs containing 1500 stars (blue stars). Outliers have been included, and are visible in the upper right and upper left corner of the Cartesian plane in the top and bottom panels, respectively. The ellipticity profile is computed by fitting ellipses (in orange) to different isodensity contours (in black). Right panels: Ellipticity profiles of the mock GCs as a function of the distance from the cluster centre. The true ellipticity ($e_{\text{true}} = 0.2$) is shown as a green dashed line.

a single GC, instead of using many realizations, due to the high demands of time and computational resources required by this method. To set-up the tests, we first need to choose a number of walkers, each of which will explore the parameter space in parallel according to the posterior probability distribution. We set the number of walkers to 100.

The results are shown in Fig 4.9, where we plot the recovered ellipticity (x -axis) and the recovered angle (y -axis) for two different true ellipticities, 0.1 in the left panels and 0.2 in the right panels, using different colours corresponding to different numbers of stars in the mock GCs. The difference between top and bottom panels lies in the initial condition used to define the starting point of each walker in the parameter space: we initialized the ellipticity to $e_i = 0.3$ and to $e_i = 0$ in top and bottom panels, respectively. The impact of the initial ellipticity on the results is striking. On the one hand, when $e_i = 0.3$ (top panels of Fig. 4.9), the code struggles to recover the true value, regardless of the number of stars in the mock GC. On the other hand, when $e_i = 0$ (bottom panels), both the ellipticity and the angle are accurately recovered when $e_{\text{true}} = 0.2$. However, for both initial conditions, this method

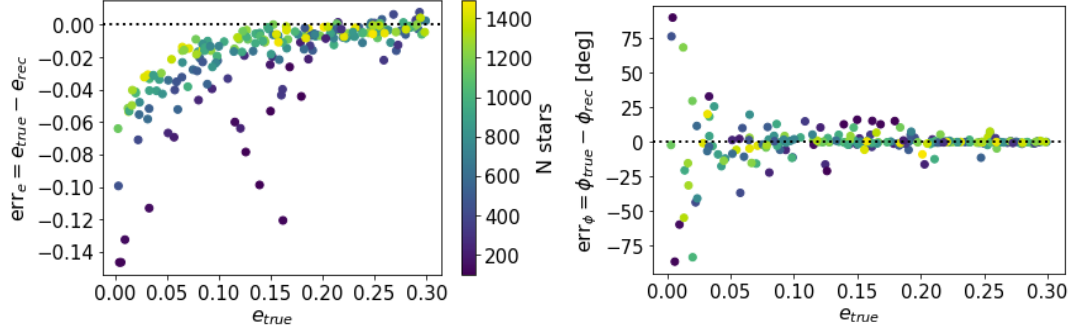


Figure 4.8: Impact of the true ellipticity on the errors in the ellipticity (left panel) and on the angle (right panel) for the KDE method. The points are color-scaled according to the number of stars in the mock GCs.

performs poorly when the ellipticity is 0.1. In such a case, the ellipticity is systematically overestimated for $N = 100$ and $N = 500$.

Then, we also tested the robustness of the code to the presence of outlier stars. Like in Sect. 4.5.1, we add 15 outliers to a GC with a true ellipticity of 0.2 and 1500 stars. For this test, we initialise the ellipticity to 0. We expect our implementation to be robust thanks to the presence of a background likelihood, accounting for potential outliers, in the total likelihood (see Sect. 4.4.2). The results are presented in Fig. 4.10. In the right panel outliers have been added along the major-axis of the ellipse, while in the left panel they have been added along the minor-axis. As expected, the code is robust to the presence of outliers, with relatively small deviation from the true parameters, both for the ellipticity and for the angle.

Due to the high computational time of this method, we did not run the last test carried out in Sect. 4.5.1 where we randomly sampled several parameters of the GC.

In this section, we have established that Bayesian inference using MCMC performs relatively well to recover the ellipticity and angle, when the ellipticity of the walkers is initialized to a value $e_i = 0$, and when a sufficient number of stars is available. However, the error bars associated with the estimated parameters are very large, larger than those obtained in Sect. 4.5.1, and the computing time is very long. The advantage of such method is its robustness to outlier stars which only slightly impact the recovered ellipticity and position angle.

4.5.3 Principle component analysis

So far, we have tested two methods to extract the ellipticity and the corresponding position angle of GCs. Overall, we found the results very sensitive to the number of stars in the dataset, and to the ellipticity, with the methods struggling to accurately recover the shape of clusters with a small ellipticity, and a sensitivity to outliers for the KDE method. Therefore, results can be biased. In this section, we test the PCA method introduced in Sect. 4.4.3, running similar tests as in Sects. 4.5.1 and 4.5.2.

First, we tested the ability of PCA to recover the mean ellipticity and the mean position angle of mock GCs. We randomly sampled 1000 times¹ the true ellipticity e_{true} , the true position angle Φ_{true} , the total number of stars N and the tidal radius r_t within the same ranges listed Sect. 4.5.1.

The histograms in Fig. 4.11 show the distribution of the error on the ellipticity (left panel) and on the angle (right panel). The median value is indicated by the black dashed line, and the 4th and 96th percentiles by the red and blue dashed line, respectively. The angle is very accurately recovered, with a median error close to zero, and with 90% of the mock clusters included between -5° and $+5^\circ$. The ellipticity is also accurately recovered with an error between -0.07 and $+0.01$ in 90% of the clusters. However, there are some cases in which the ellipticity is strongly over-estimated.

To understand the reason for this over-estimation, in Fig. 4.12 we show the errors as a function of the number of stars considered. In the left panel, the error on the ellipticity seems to depend on the

¹We can do this because the PCA method is very fast.

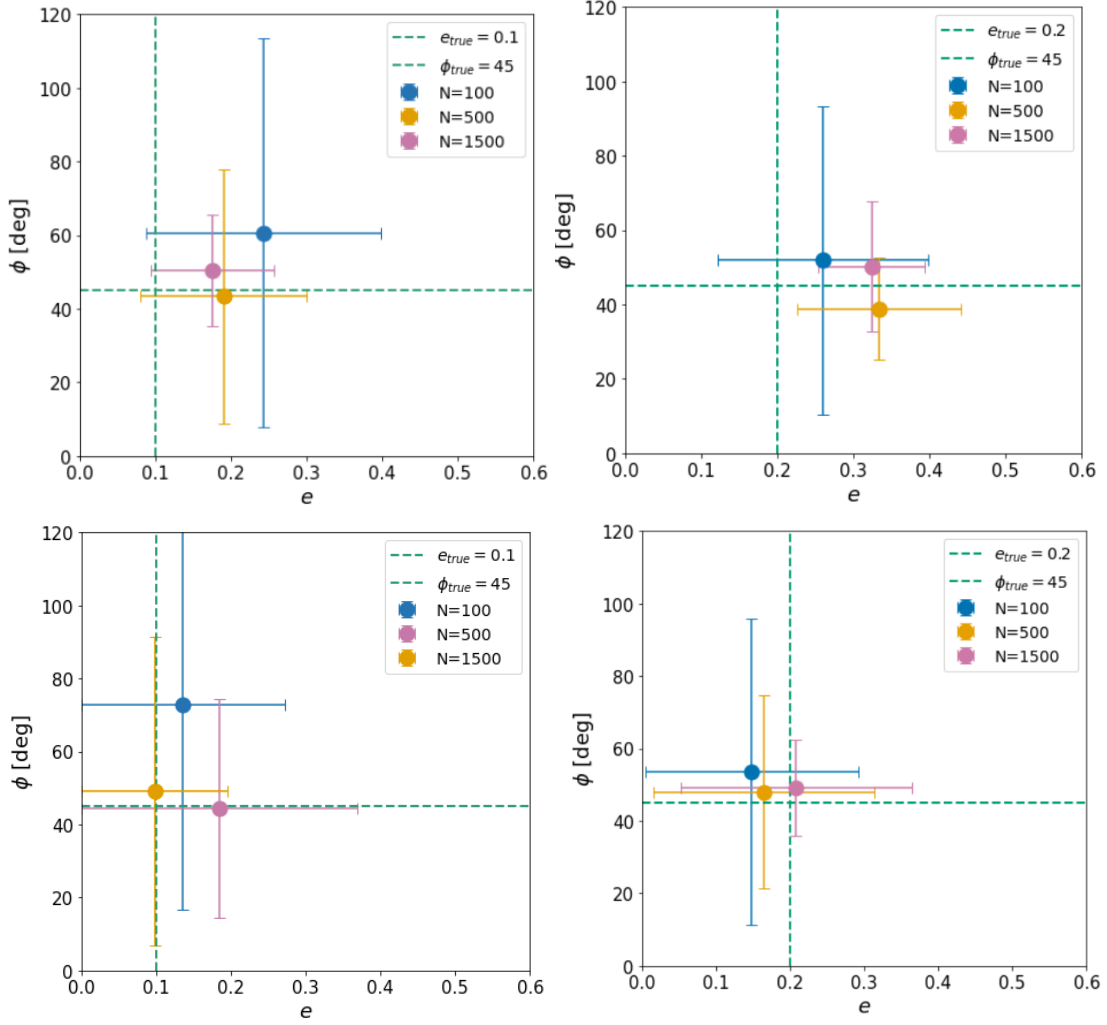


Figure 4.9: Recovered ellipticity e and angle Φ for mock GCs with different ellipticities: $e_{\text{true}} = 0.1$ in the left panels and $e_{\text{true}} = 0.2$ in the right panels. Each point corresponds to a different value of the total number of stars in the GC. The dashed lines show the true values of the ellipticity and the angle. Top and bottom panels represent the results obtained when initialising the walkers to $e_i = 0.3$ and to $e_i = 0$, respectively.

number of stars; mock GCs with less than 200 stars show the biggest error on the recovered ellipticity. On the contrary, the number of stars does not influence the error on the angle. Errors above $|150|^\circ$ should not be considered as they arose because of the constraint $0^\circ < \Phi < 180^\circ$. Angles close to 180° are sometimes estimated to be close to 0, generating an unrealistically large error.

The top panels of Fig. 4.13 show the errors as a function of the true ellipticity, color-scaled by the number of stars. On the left panel, the ellipticity is constantly overestimated when $e_{\text{true}} < 0.05$. This means that the PCA tends to flatten the GCs which are close to spherical, introducing a systematic bias. When $e_{\text{true}} > 0.1$, the main source of bias for the code is the number of stars: this is evident by looking at the behaviour of GCs with $N < 200$ stars, indicated with blue points in the figure. A small N impacts the ability of the PCA to recover the true ellipticity of the cluster even for flattened systems. On the right panel, the error on the angle Φ is mainly linked to the ellipticity, with clusters close to spherical showing very broad errors. In the bottom panels of Fig. 4.13 we show the errors as a function of the true angle, coloured according to the ellipticity; the value of the angle has no impact on the error on the ellipticity and on the recovered angle.

We also run a robustness test, whose results are shown in Fig. 4.14. As we already did in Sects. 4.5.1 and 4.5.2, we added 1% outliers along the major- and minor-axis of the mock GCs, to study their impact

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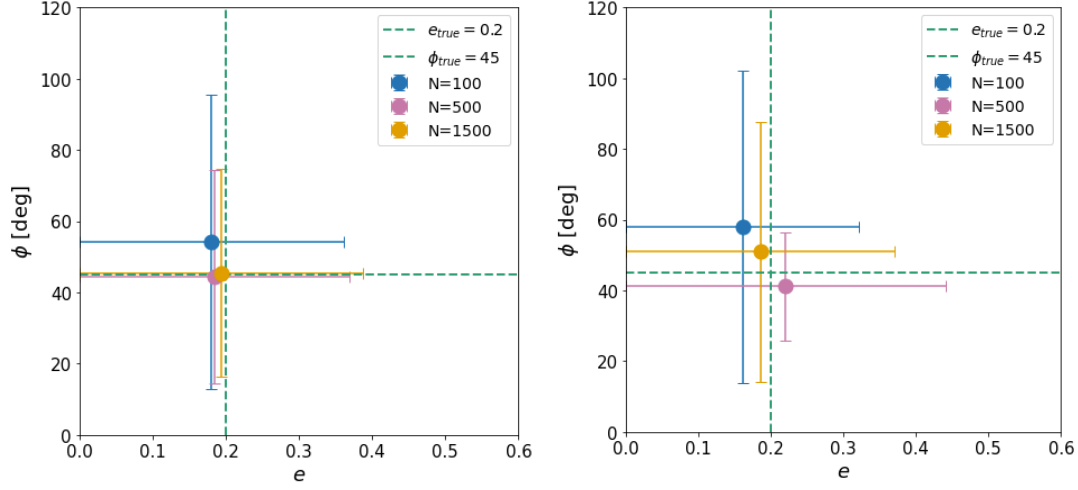


Figure 4.10: This figure is similar to the bottom right panel of Fig. 4.9. The main difference is the presence of 1% outlier stars, added along the major-axis (left panel) and minor-axis of the ellipse (right panel), as shown on the left panels of Fig. 4.7.

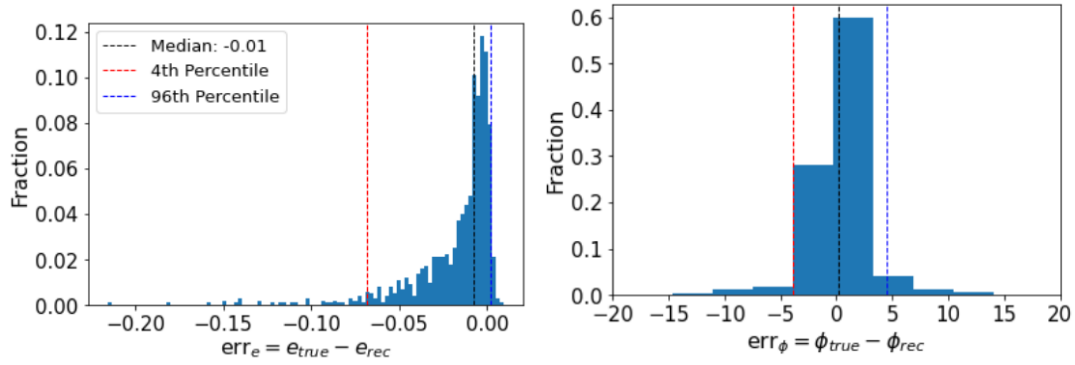


Figure 4.11: Histograms showing the distribution of the error between the true and recovered ellipticity (left panel) and the true and recovered angle (right panel). The black dashed lines indicate the median value of the error and the red and blue dashed lines indicate the 4th and 96th percentiles, respectively.

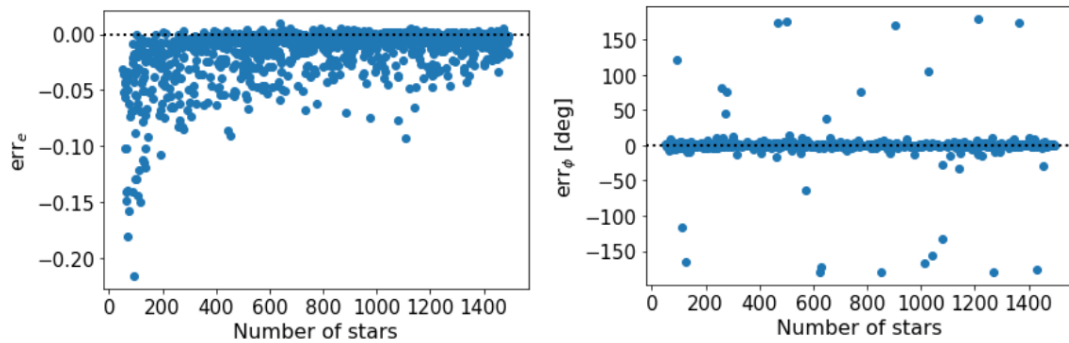


Figure 4.12: Impact of the number of stars on the errors on the ellipticity (left panel) and on the angle (right panel).

on the PCA method. Contrary to MCMC, PCA is not robust to the presence of outliers. Adding a few outliers in the direction of the semi-major axis of the GC lead to an overestimation by 0.1 of the true

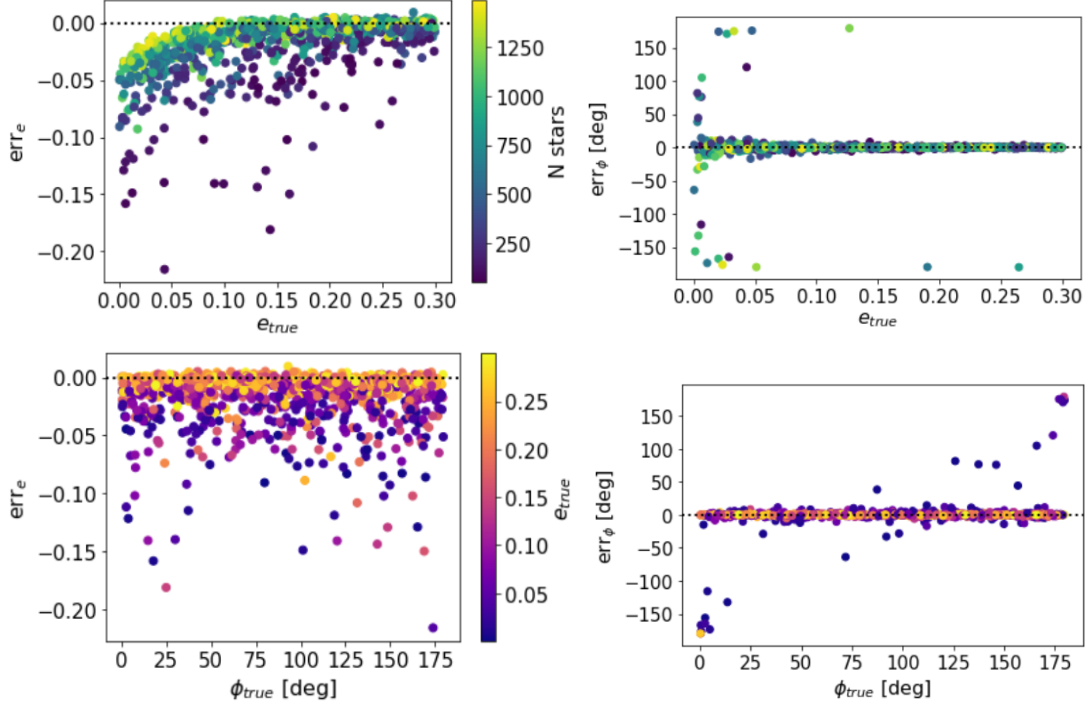


Figure 4.13: *Top panels:* the errors on the ellipticity (left panel) and on the angle (right panel) are shown as a function of the values of true ellipticity. The points are coloured according to the number of stars in the mock GCs. *Bottom panels:* the errors on the ellipticity (left panel) and on the angle (right panel) are shown as a function of the values of true angle. The points are coloured according to the true ellipticity of the mock GCs.

ellipticity (right panel). In that case the true angle is accurately recovered and the associated error-bars quite small. When the outliers are added along the semi-minor axis of the ellipse (left panel), one of the two parameters is systematically wrong. For $N = 100$, the angle is over-estimated by more than 30° . For $N = 1500$, the angle is accurately recovered but PCA tends to flatten the GC and recovers an ellipticity of 0.05. For all the three values of N , the error-bars associated with the angle are large. These findings can be explained by the mathematics behind the PCA, which relies on a variance estimate via the L^2 norm. Such a norm is very sensitive to outliers since it squares the distances.

To conclude, the number of stars and the ellipticity are the main drivers of errors in recovering ellipticity and angle with the PCA method, similarly to what we found for the KDE method (Sect. 4.5.1). When there are less than 200 stars in the mock GC, the ellipticity is considerably overestimated while the angle remains well recovered. The code also overestimates the flattening of clusters with a small ellipticity, close to spherical, and struggles to estimate the angle when $e_{\text{true}} < 0.05$. Finally, PCA is very sensitive to outliers because of the use of the L^2 norm in the variance estimate. One of the main advantage of the PCA method is its speed. Therefore, we decided to adapt the PCA to make it robust to outliers and to correct for the biases present in small datasets.

4.5.4 Robust PCA and bias correction

The robust PCA uses a distinct approach to compute the covariance matrix, relying on the Minimum Covariance Determinant (MCD) method (Rousseeuw, 1984). This method identifies a subset of the data with the smallest possible covariance determinant, which measures the spread of the distribution. By minimizing this determinant, the method selects the subset of data that is most tightly clustered, thus reducing the influence of outliers on the final covariance estimate. We use the scikit-learn class `MinCovDet`² to compute the covariance matrix using the MCD method. Then, as done in Sect. 4.5.3, we

²<https://scikit-learn.org/stable/modules/generated/sklearn.covariance.MinCovDet.html>

4. Ellipticity of MSPs in GCs

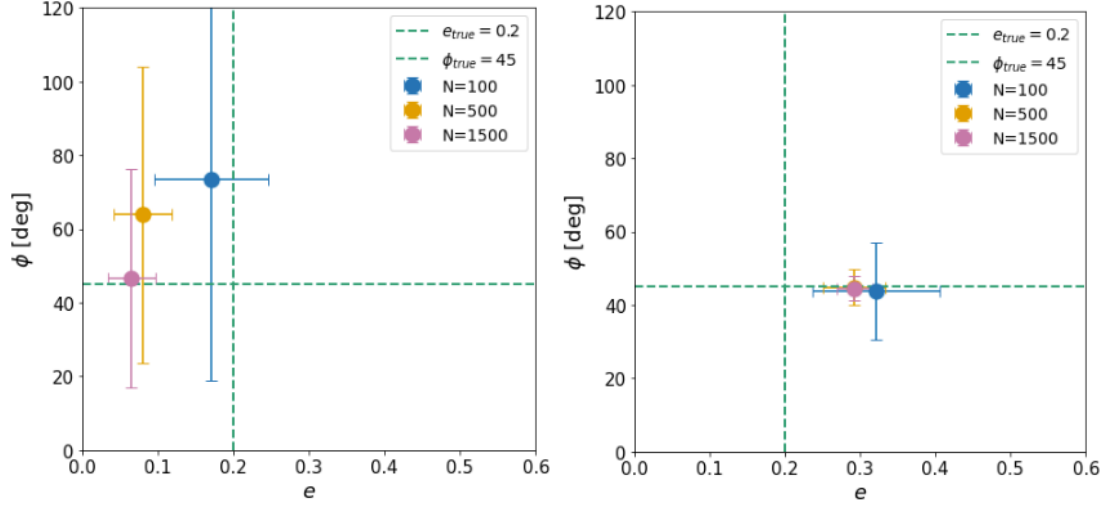


Figure 4.14: Recovered ellipticity e and angle Φ for two mock GCs with $e_{true} = 0.2$ and $\Phi_{true} = 45$ deg shown as green dashed line. 10% outliers are added to the data in the upper left corner (left panel) and upper right corner (right panel).

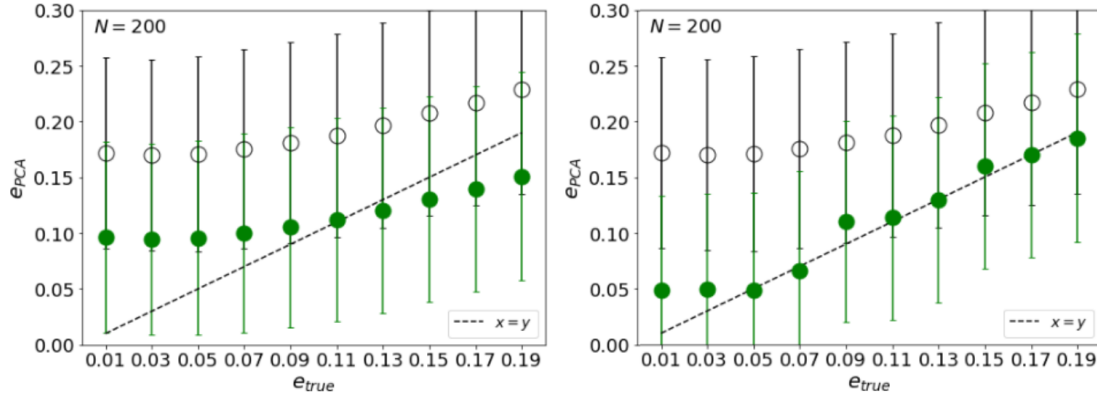


Figure 4.15: Comparison between the bias correction using 2-degree polynomial (left panel) and random forest regression (right panel) for a set of mock GCs with ellipticity varying from 0.01 to 0.2 and 200 stars. In each panel the x -axis shows the true ellipticity and the y -axis the ellipticity recovered using the PCA method without correction (empty dark circles) and with correction (green circles). The dashed line represents the identity.

compute the eigenvalues and eigenvectors of the covariance matrix and estimate the ellipticity and angle of the data.

Our aim is to construct a bias correction function using a set of mock data, to correct for the systematic biases linked to small datasets ($N \simeq 100$) and to the overestimation of the ellipticity. To do this, we proceeded as follows. We fixed the angle to $\Phi_{true} = 45^\circ$ because, contrary to the ellipticity, changing its value does not impact the results. We generated mock data of GCs with true ellipticity varying from $e_{true} = 0.01$ to $e_{true} = 0.3$ with steps of 0.01, and a total number of stars N going from $N = 50$ to $N = 1500$ in steps of 50. For each pair of parameters (e_{true}, N) , we created 100 different GCs using a random distribution of stars following a King (1966) model. Using the robust PCA algorithm, we computed the ellipticity e_{rec} as the mean value of the ellipticity of the 100 realisations, and the associated error by taking the standard deviation. The problem is now a classical regression problem where we seek to find the true ellipticity (target) of an elliptical distribution of stars given a total number of stars and the (biased) recovered ellipticity (features). Several methods can be used to solve such a problem. Among the ones we tried are the polynomial regression (where the relationship between

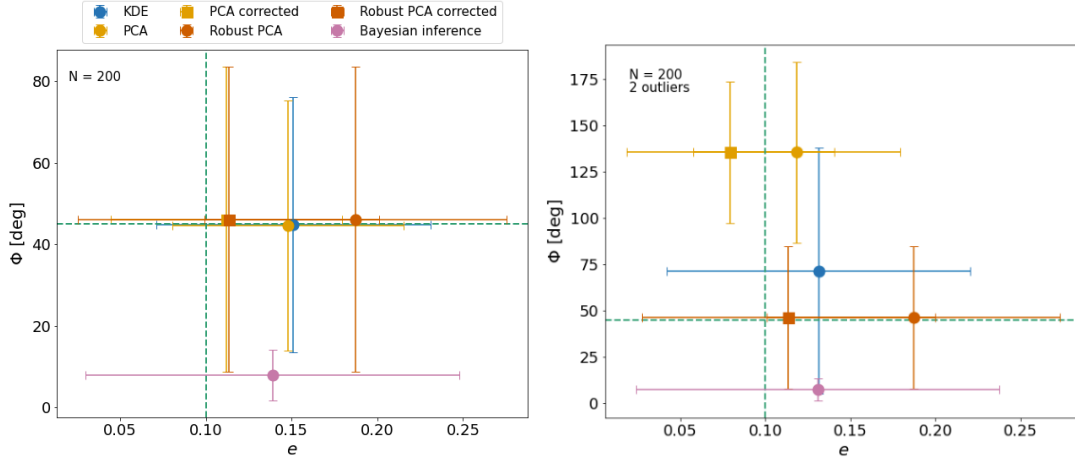


Figure 4.16: Comparison between the different methods to model the ellipticity and the angle for 100 mock GCs with $N = 200$ stars. The true parameters are plotted with the green dashed line. In the bottom panel, we just add two outliers in the direction of the semi-minor axis of the ellipse.

the input variables and the output is a n -degree polynomial) and the random forest regression (which creates multiple decision trees, each learning slightly different patterns from the data by using random subsets of data and features, and then averages their predictions to produce a final output). In Fig. 4.15 we compare these two methods. The true ellipticity of the mock GCs is shown on the x -axis and the ellipticity recovered using the robust PCA method is shown on the y -axis. The dashed line represents the identity. The empty circles show the results before bias correction and the filled green circles after correction using a 2-degree polynomial (left panel) and random forest regression (right panel). The green circles in the right panel lie close to the identity, providing thus the most accurate bias correction.

4.5.5 Comparison between the methods

In this section, we compare the results of the KDE, MCMC, PCA, and robust PCA methods on both mock and real data. First, we generate 100 mock GCs with $e_{\text{true}} = 0.1$, $\Phi_{\text{true}} = 45^\circ$, and $N = 200$ stars. We use each method to recover the ellipticity and the angle³. We repeat the same test, using the same parameters and the same mock GCs, but adding two outliers along the minor axis. The results are shown in Fig. 4.16. In both panels, the recovered ellipticity is shown on the x -axis and the recovered angle on the y -axis. The KDE method is shown in blue, the Bayesian inference using MCMC in pink, the PCA in yellow and the robust PCA in orange, with squared symbols obtained after bias correction. The comparison between the left and right panels of Fig. 4.16 illustrates the impact of outliers on the ellipticity and angle obtained with PCA. By adding only 1% of outliers (2 stars) along the semi-minor axis of the clusters, the robustness of the methods can easily be assessed. Again, we can see that KDE and PCA are very sensitive to the presence of a few outliers. The recovered angle is shifted, with the semi-major axis of the ellipse closer to the direction of these outliers. The MCMC method is robust but not accurate, struggling to converge toward the true ellipticity for a small number of stars. Finally, our implementation for the robust PCA after bias correction is both accurate, with an error on the true ellipticity of 0.015 for $N = 200$, and robust, with the orange square maintaining the same position in both panels of Fig. 4.16.

To emphasize the importance of testing codes on mock data and highlight the potential for erroneous results when this step is omitted, we apply the KDE, PCA, and robust PCA methods to extract the ellipticity of the two populations in NGC 1261. The data is presented in Fig. 4.17. Red and blue dots represent stars classified as pristine (P1) and enriched (P2), respectively. Stars shown in purple were included only in the computation of the total ellipticity, as their probability of belonging to either population is

³As mentioned in Sect. 4.5.2, the MCMC method is slow, therefore we only run it on a single mock GC.

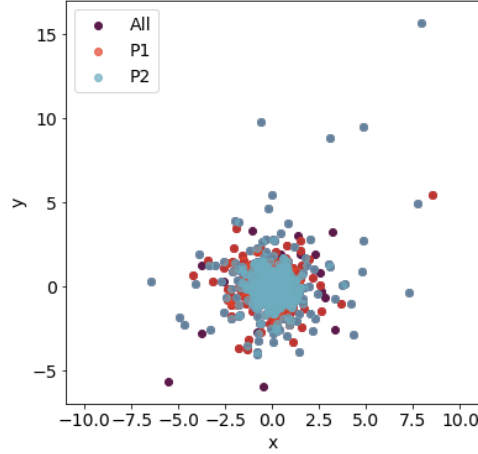


Figure 4.17: The data from NGC 1261. P1 stars are plotted in red and P2 stars in blue. Some outliers are present, particularly in the enriched population.

$< 70\%$. This cluster is particularly interesting as it includes a few stars located further away from the cluster center, visible in the upper-right corner of Fig. 4.17.

In Fig. 4.18 we show the ellipses fitted to the different density contours estimated with KDE. The left panels show the fit to the isodensity contours of P1 stars, and the right panels the fit to contours of P2 stars. In the top panels, we have masked one outlier star among the P1 and three among the P2. The mean ellipticity of P1 is $e_{1,KDE} = 0.11 \pm 0.02$ with the outliers and $e_{1,KDE} = 0.08 \pm 0.02$ after removal of one outlier; the ellipticity of P2 is $e_{2,KDE} = 0.16 \pm 0.01$ with the outliers and $e_{2,KDE} = 0.14$ without. Similarly, we determine the mean ellipticity and angle using both the PCA and robust PCA methods. The results are presented in Fig. 4.19. The top two rows illustrate the PCA results: the first row shows the ellipticity and angle recovered when masking the outliers, while the second row shows the recovered parameters when all stars are considered. The bottom row presents the robust PCA results, including only the panel where all stars are used, as this method is robust and produces similar outcomes with or without masking. The results for P1 and P2 stars are shown in the left and right panels respectively. Masking the outlier among P1 stars results in a shift of angle by 77° , visible in the first two left panels of Fig. 4.19. Masking the outliers among P2 stars results in a rounder cluster recovered by using the PCA method, with the ellipticity going from 0.21 ± 0.09 when all the stars are considered and to 0.14 ± 0.05 when the three outliers are masked, as shown in the first two right panels of Fig. 4.19. When considering the enriched population (right panel) and including all stars, the results from the PCA (middle panel) differ considerably from those of the robust PCA (bottom panel). However, after removing the three outliers (top panel), the results from the PCA change significantly and resemble the one of the robust PCA. This highlights the importance of developing and testing robust and accurate methods to model the ellipticity of GCs and their MSPs.

4.6 Global ellipticity of GCs

The careful methodology tests described in Sect. 4.5 ensure the robustness and accuracy of the ellipticity and position angle measurements that we will present in this section, obtained for the 26 GCs in our sample by using the robust PCA method. For each cluster, we obtain three values of ellipticity and angle: the global ellipticity e and position angle Φ for the entire cluster, the ellipticity e_1 and position angle Φ_1 for the pristine population, and the ellipticity e_2 and position angle Φ_2 for the enriched population.

To compute the global ellipticity and position angle, we randomly sampled 90% of all the stars in each GC 100 times. We then use the mean value and standard deviation of the ellipticities and position angles obtained for each of these realisations as measurement and corresponding error estimates for

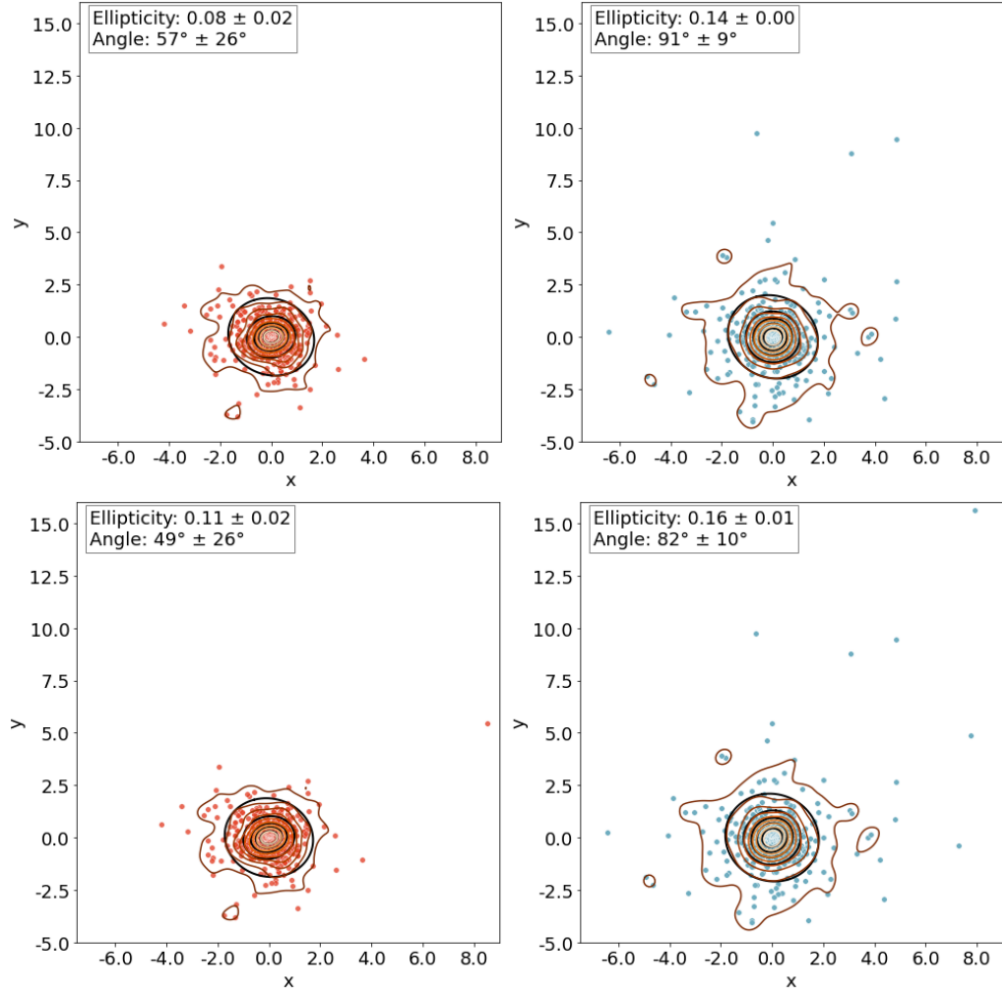


Figure 4.18: Estimate of the ellipticity of P1 (left panel) and P2 stars (right panel) through the fitting of ellipses to the contours of the KDE. In the top row we masked 1 outlier for P1 and 3 outliers for P2. The bottom row shows the results when considering all the stars.

these quantities. We present our results on the global ellipticity of GCs in Sect. 4.6.1 and we analyse the relation between flattening and kinematics of the clusters in Sect. 4.6.2.

4.6.1 Results

In this section we present the ellipticity and position angle values obtained for the 26 Galactic GCs in our sample, by using the robust PCA method described in Sect. 4.5.4 and tested in Sect. 4.5.5. We compare these values with those that can be found in the literature, and we put them into relation with other relevant global properties of GCs in Sect. 4.6.2. The results of our analysis are presented in Table 4.1, where we provide the values of ellipticity e , together with ellipticity measured by White and Shawl (1987) and Chen and Chen (2010) (e_{WS87} and e_{CC10} , respectively). In our analysis, we will refer to GCs as *round* or *spherical* when they have $e = 0$ within 3σ , where σ is the uncertainty on the ellipticity, and as *flattened* or *elliptical* otherwise. According to this criterion, among our 26 GCs we find 14 flattened GCs.

In the left panel of Fig. 4.20 we compare our ellipticity measurements with those provided by White and Shawl (1987). Overall, our values are in good agreement with theirs, within 3σ , except for four GCs, namely NGC 6838, NGC 6366, NGC 6656, and NGC 7089. Particularly striking is the situation of NGC 6838

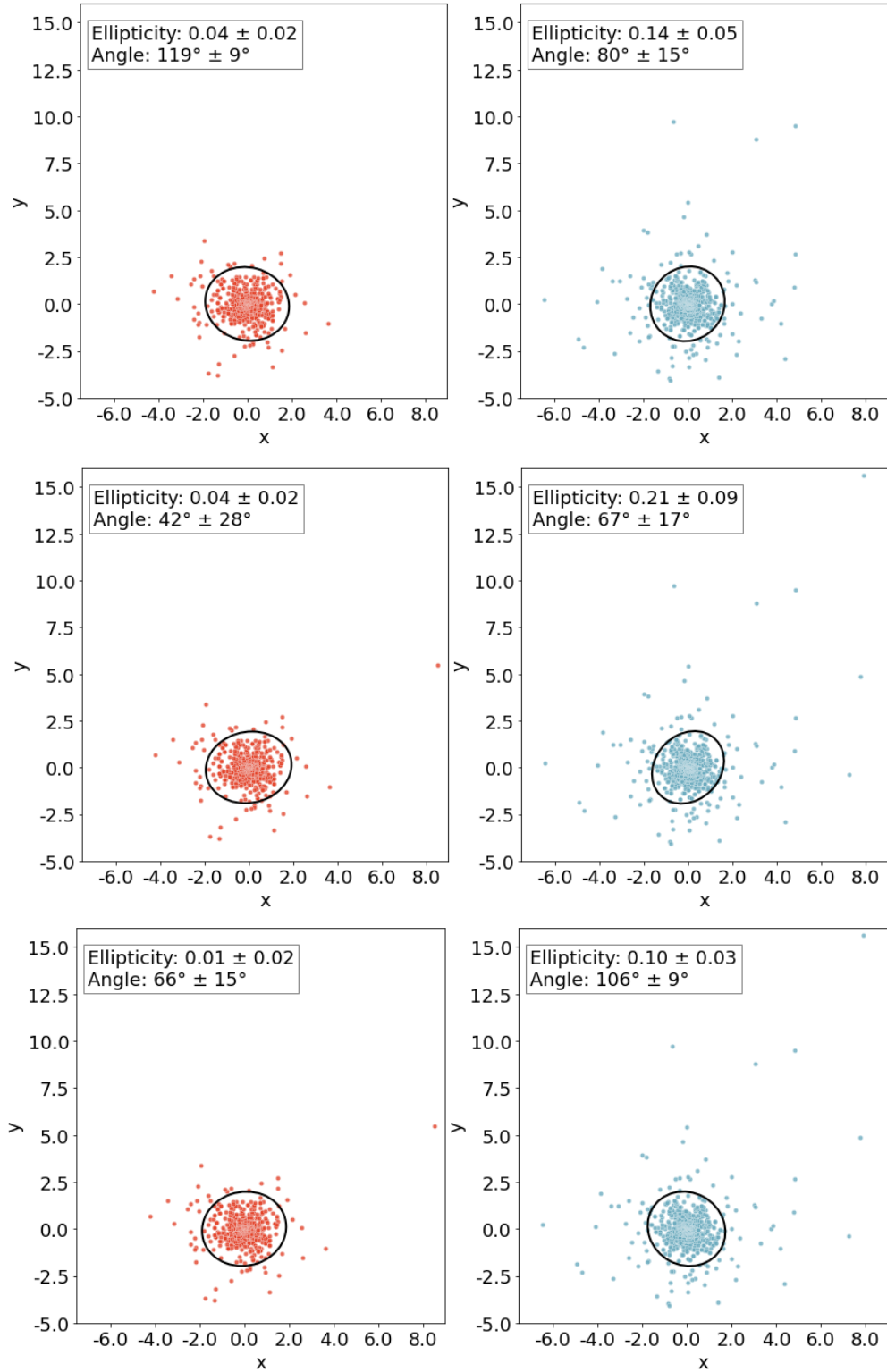


Figure 4.19: Estimate of the ellipticity of P1 (left panel) and P2 stars (right panel) with the PCA method (in the top panels including all stars and in and middle panels masking outliers) and with the robust PCA method (bottom row).

and NGC 6366: the first appears to be round in White and Shawl (1987), but we find it to be very flattened, and for the second the situation is reversed. In the right panel of Fig. 4.20 we also compare our results with those by Chen and Chen (2010). Overall, their analysis yielded larger ellipticities, less in agreement with our findings. The case of NGC 6838 is once again particularly interesting, as Chen and Chen (2010) found it very flattened, while White and Shawl (1987) found it round; our measurement appears to be somewhat in between of those estimates. Chen and Chen (2010) suggested that the high flattening of NGC 6838 might be related to its recent crossing through the Galactic disk some 16 Myr ago (Vande Putte and Cropper, 2008), much shorter than the relaxation time of the cluster (Harris, 1996).

We also investigate if our results change when considering only HST data, thus probing the very center of the clusters, usually up to ~ 2 arcmin, as opposed to 5 to 15 arcmin with the ground based data. In Fig. 4.21, we show the ellipticity recovered using all data versus the one obtained by using only HST data. We find a good agreement between the ellipticities. The ellipticities of all the clusters except three agree within the error-bars, and most of them fall on the identity line. Investigating any potential variation in the ellipticity with the distance to the cluster center could be done in the few GCs differing from the identity line in Fig. 4.21, namely NGC 6254, NGC 288, and NGC 6101. Such an analysis should be carried out carefully as obtaining an ellipticity profile requires some type of radial binning or contour fitting which decreases the number of stars in each bin or contour, therefore making the fit particularly sensitive to outliers and bias.

Cluster	N_{min}	e_{tot}	e_{harris}	e_{chen}	Flattening
104	1326	0.08 ± 0.01	0.09	0.16 ± 0.02	Yes
288	214	0.07 ± 0.02		0.06 ± 0.01	Yes
1261	432	0.10 ± 0.01	0.07	0.23 ± 0.07	Yes
3201	265	0.11 ± 0.02	0.12	0.20 ± 0.01	Yes
4590	202	0.02 ± 0.02	0.05	0.16 ± 0.05	No
4833	417	0.15 ± 0.02	0.07	0.11 ± 0.02	Yes
5024	785	0.05 ± 0.01	0.01	0.14 ± 0.04	Yes
5053	79	0.21 ± 0.03	0.21	0.21 ± 0.03	Yes
5272	658	0.06 ± 0.02	0.04	0.06 ± 0.01	3σ
5286	873	0.10 ± 0.01	0.12	0.17 ± 0.01	Yes
5904	497	0.15 ± 0.02	0.14	0.06 ± 0.02	Yes
5986	659	0.09 ± 0.01	0.06	0.26 ± 0.11	Yes
6101	239	0.06 ± 0.03	0.05	0.06 ± 0.01	$< 3\sigma$
6121	189	0.00 ± 0.02	0.00	0.07 ± 0.02	No
6205	576	0.10 ± 0.01	0.11	0.12 ± 0.02	Yes
6218	280	0.03 ± 0.02	0.04	0.08 ± 0.01	No
6254	456	0.08 ± 0.03	0.00	0.11 ± 0.04	$< 3\sigma$
6341	421	0.12 ± 0.02	0.10	0.11 ± 0.03	Yes
6366	220	0.00 ± 0.02	0.16	0.09 ± 0.04	No
6656	323	0.05 ± 0.02	0.14	0.12 ± 0.01	$< 3\sigma$
6809	265	0.03 ± 0.02	0.02	0.11 ± 0.01	No
6838	115	0.16 ± 0.03	0.00	0.32 ± 0.02	Yes
6934	234	0.03 ± 0.01	0.01	0.06 ± 0.02	3σ
6981	182	0.05 ± 0.03	0.02	0.14 ± 0.09	No
7089	756	0.05 ± 0.01	0.11	0.14 ± 0.02	Yes
7099	174	0.05 ± 0.04	0.01	0.10 ± 0.01	No

Table 4.1: This table compares our ellipticity measurements with those provided in White and Shawl (1987) and Chen and Chen (2010). The cluster number is given in the first column. In the second column, we provide the number of stars used in our computations (corresponding to 90% of the total number of stars available). The ellipticities from our analysis, White and Shawl (1987), and Chen and Chen (2010) are provided in the next three columns. We qualify the clusters as flattened or not in the last column.

4. Ellipticity of MSPs in GCs

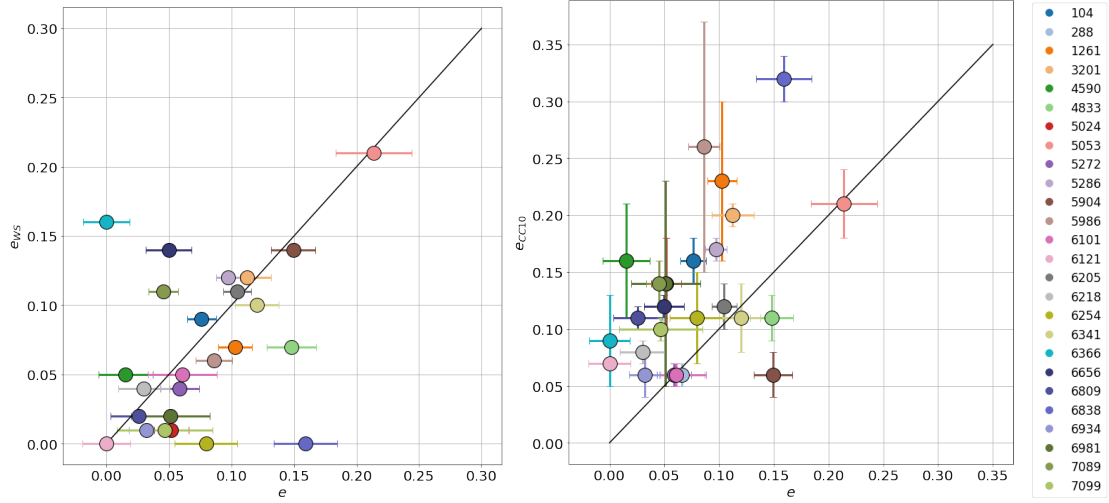


Figure 4.20: The ellipticities of the 26 Galactic GCs in our sample, measured by using the robust PCA method, are here compared with the estimates from the literature, provided by White and Shaw (1987) (left panel) and Chen and Chen (2010) (right panel). The solid lines indicate equal ellipticities; each GC is represented by a coloured point (see legend on the side), and error bars are indicated.

4.6.2 Ellipticity and dynamics

In this section, we explore the factors that influence the shapes of GCs.

The first quantity that we investigate is the relaxation time. It can be defined as the time scale on which encounters between stars, leading to energy exchange, produce major changes in the structure of the cluster, without disturbing its dynamical equilibrium (Meylan and Heggie, 1997). Our results are shown in Fig. 4.22, where we put into relation the ellipticity that we measure for the 26 MW GCs in our sample and the relaxation time at the half-mass radius taken from Harris (1996)⁴. A trend is visible in the figure: clusters with longer relaxation times (dynamically young) are in general more elliptical, and those with short relaxation time (dynamically old) are more round. An evident exception is NGC 6838, which is very flattened, even if it appears to be dynamically old. As mentioned in Sect. 4.6.1, its high flattening might be related to its recent crossing through the Galactic disk.

These findings indicate the importance of understanding the origin of the deviation from spherical symmetry of GCS. Three physical properties can impact the shape of a GC. The first parameter is the rotation. If a cluster is rotating, the rotation can cause the cluster to become flattened in the plane of rotation. Secondly, velocity anisotropy can lead to deviations from spherical symmetry when motion is preferentially aligned in a specific direction. Finally, tidal effects from the galaxy can distort GCs depending on their orbit. This could result in a flattening potentially observable in the outer part of the cluster.

To identify the primary driver behind the observed flattening in GCs—whether it is internal rotation, velocity anisotropy, or tidal effects—we first consider the role of rotation. In Fig. 4.23 we plot the ellipticity we recovered (shown on the x -axis) and the 3D ordered-to-random motion parameter A/σ from Leitinger et al. (2024) (shown on the y -axis). This parameter quantifies the importance of rotational motion (described by the quantity A , defined as the rotational amplitude) with respect to random motions (described by σ , representing the velocity dispersion). Leitinger et al. (2024) computed A using the L^2 norm of the mean tangential velocity and of the amplitude of the LOS velocity signal. They also calculated the velocity dispersion using the L^2 norm of the velocity dispersion along the line-of sight and along the tangential direction. We find a general trend suggesting that clusters that rotate more are also more elliptical. We note three GCs that deviate from this trend: on the one hand, NGC 6838 and NGC 4833, located in the lower-right corner of the plot, are among the most flattened ones but are

⁴The relaxation time is taken from the updated Harris catalogue available online: <https://physics.mcmaster.ca/~harris/Databases.html>

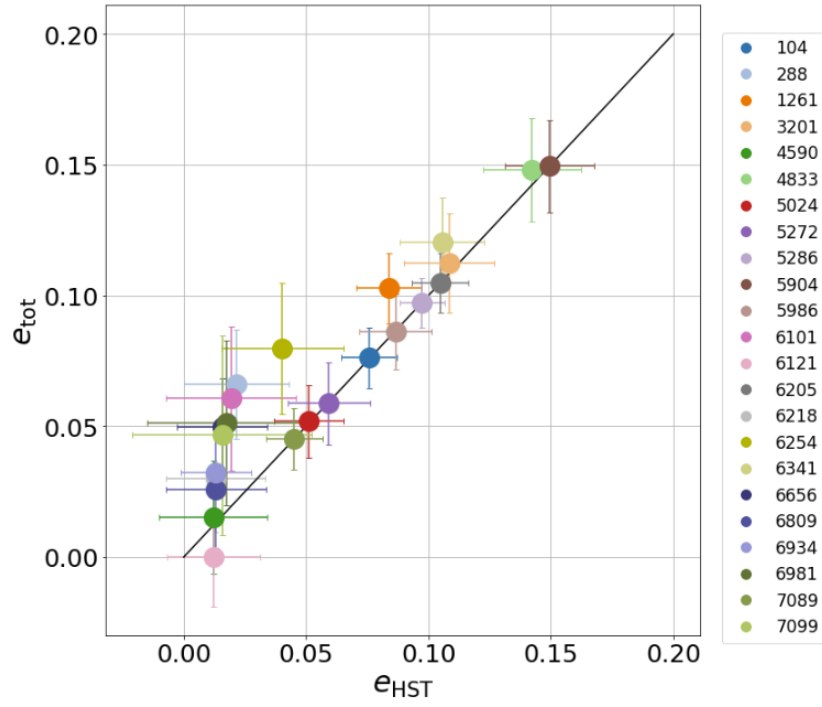


Figure 4.21: Comparison between the ellipticity obtained when using only HST data (typically covering only the center of the GCs) and when using all the data, including the ground based photometry, which extends up to 5 to 15 arcmin, depending on the clusters.

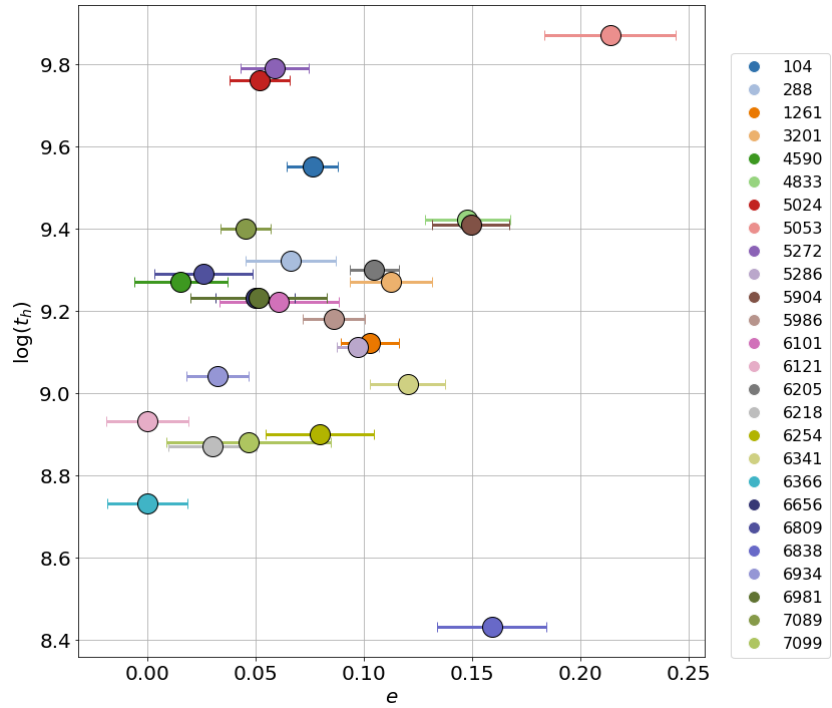


Figure 4.22: The ellipticity e of 26 Galactic GCs, obtained using the robust PCA method, is shown here against the relaxation time at the half-mass radius from Harris (1996).

4. Ellipticity of MSPs in GCs

not rotating; on the other hand, NGC 104 has a very strong rotation, even though its ellipticity is not as extreme.

To further evaluate the impact of rotation on the shape of GCs, we employed the V/σ diagram, a tool frequently used for elliptical galaxies (Brough et al., 2017; Cappellari et al., 2007; Emsellem et al., 2011). The relation between projected rotation signature and flattening is derived from the tensor virial theorem (Binney, 1978) and for an edge-on system is given by:

$$\left(\frac{V}{\sigma}\right)_{ed} = k_1 \sqrt{\frac{e}{1 - k_2 e}}, \quad (4.15)$$

where the subscript ed indicates the edge-on case, V is the maximum rotation velocity along the line-of sight, e is the ellipticity, and k_1 and k_2 are constants that account for the intrinsic properties of the system, including its geometry and kinematics. In our analysis, we assume $k_1 = 0.831$ and $k_2 = 0.896$ (Bianchini et al., 2013; Cappellari et al., 2007). The quantities presented in Eq. 4.15 need to be corrected to account for the inclination of the GCs. This can be done as follows:

$$\left(\frac{V}{\sigma}\right)_{ed} = \left(\frac{V}{\sigma}\right)_{obs} \frac{\sqrt{1 - \delta \cos^2 i}}{\sin i} \quad (4.16)$$

$$e_{intr} = 1 - \sqrt{1 + e(e - 2)/\sin^2 i}, \quad (4.17)$$

where i represents the inclination angle and δ the anisotropy of the GC. The quantity e_{intr} indicates the intrinsic ellipticity or inherent shape of the cluster, excluding projection effects.

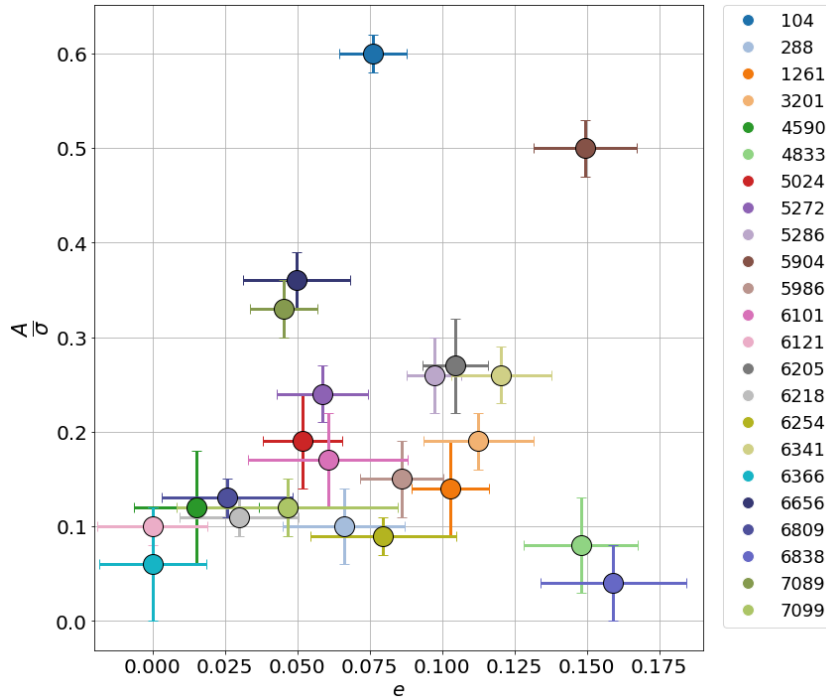


Figure 4.23: Ellipticity as a function of the ordered-to-random motion parameter $\frac{A}{\sigma}$, a proxy of rotation taken from Leitinger et al. (2024)

The above equations are only valid for the *projected* rotation signature, along the line-of sight. Therefore, we cannot directly use the 3D A/σ quantity shown in Fig. 4.23. Instead, we use the amplitude of the rotation along the line-of-sight A_{LOS} , kindly provided by Ellen Leitinger, and the central 1D velocity dispersion σ_0 from the Baumgardt (2022) catalog⁵.

⁵<https://people.smp.uq.edu.au/HolgerBaumgardt/globular/lclusters/parameter.html>

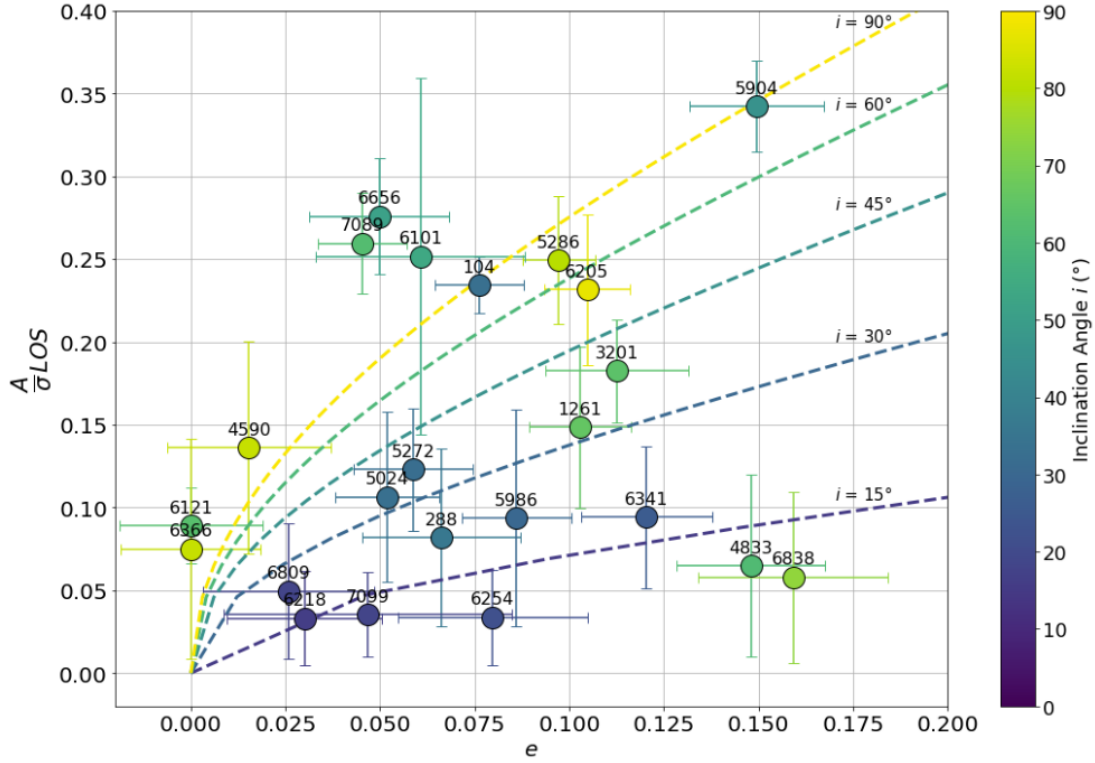


Figure 4.24: This plot shows the rotation strength as a function of the measured flattening. The name of each GC is indicated close to the corresponding point, colored according to the inclination angle of the cluster. Low inclinations are plotted in blue while high inclinations are colored in yellow. The dashed lines indicate the relation for isotropic oblate rotators viewed at different inclination angles.

In Fig. 4.24 we show the quantity $(A/\sigma)_{LOS} = A_{LOS}/\sigma_0$ as a function of the ellipticity. Each point represents a GC and is colour-scaled according to its inclination angle, taken from Leitinger et al. (2024). The dashed lines show the *corrected* relation between A/σ_{LOS} and e for different inclinations, for an isotropic system ($\delta = 0$), as described by Eqs. 4.16 and 4.17. Each GC should lie in the corresponding coloured line *if they behave as isotropic oblate rigid rotators*. Any deviation from the line of isotropic rotators at a given inclination could be attributed to the influence of differential rotation and/or pressure anisotropy. If a GC lies above the line, it might indicate radial anisotropy ($\delta > 0$), whereas lying below the line could suggest tangential anisotropy ($\delta < 0$). This interpretation directly comes from Eq. 4.17 where replacing δ by a positive value will shift $(V/\sigma)_{obs}$ to higher values for a given inclination and edge-on $(V/\sigma)_{ed}$. If the flattening is due to either rotation or anisotropy, then no GC should lie above the yellow line, corresponding to the edge-on case. By inspecting Fig. 4.24, we can identify a few groups of GCs. The majority appear to have the ellipticity and rotation strength consistent with what is expected in this framework, given their inclination. Some clusters (namely NGC 4833 and NGC 6838) appear to be more flattened than expected, possibly suggesting that additional mechanisms like tangential anisotropy and tides play a role in determining their shape. Finally, some clusters (namely NGC 104, NGC 7089, NGC 6656, and NGC 5904) seem to be more round than expected, given their rotation: in this case, radial anisotropy might play a role.

To identify the GCs for which the flattening cannot be explained as being due to rotation in this approach, it is necessary to consider the uncertainties on all the quantities that play a role in determining their position in a plot like that in Fig. 4.24, not only on A/σ_{LOS} and e , but also on the inclination angle i . Figure 4.25 is the same as Fig. 4.24, but in this case each GC is represented by an ellipse whose axes correspond to the uncertainties in rotational velocity and ellipticity, and whose colour gradient represents the range of inclination angles defined by their uncertainty, from the lower to upper bounds, as estimated by Leitinger et al. (2024). We divided the GCs arbitrarily in two groups, shown in separate

4. Ellipticity of MSPs in GCs

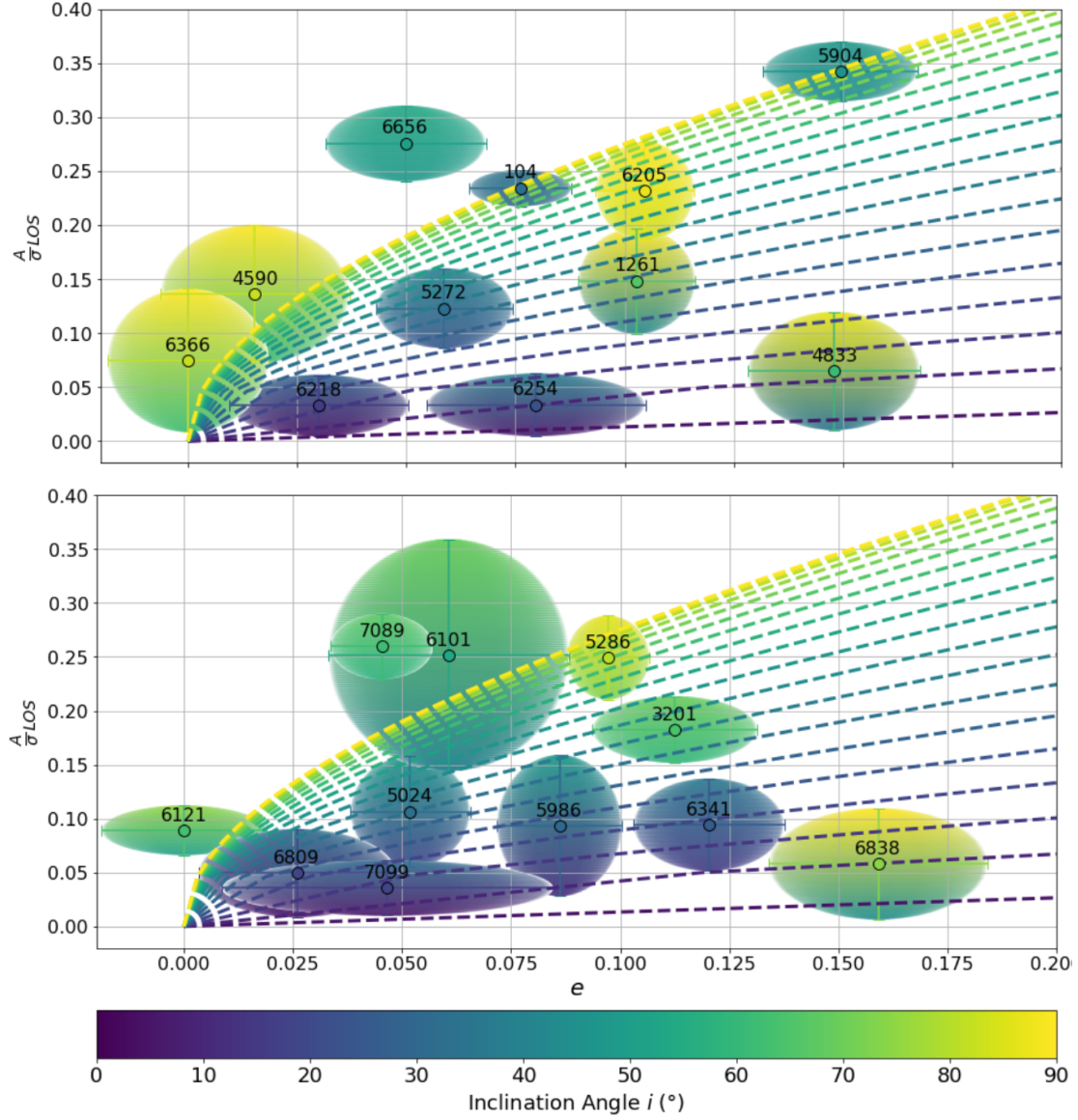


Figure 4.25: This plot shows the same quantities as Fig. 4.24, the rotation strength as a function of the measured flattening. For each GC, we plot an area of uncertainty in A/σ_{LOS} and e represented by the ellipse surrounded each circle. The ellipse is colored according to the inclination angle of the cluster, with a gradient going from the lower bound of i , the value of i minus its uncertainty, to its upper bound, the value of i plus its uncertainty. We arbitrarily separated the GCs in two groups, shown in separate panels, to limit the overlap between clusters.

panels in the figure, to avoid overlaps as much as possible and to make it possible to accurately visualize all GCs. This approach allows for a quick identification of the GCs that are located in positions that are not consistent with those expected in this framework.

NGC 6656 (upper panel) and NGC 7089 (lower panel) are located above the yellow line, suggesting that they are rotating faster than expected, for systems with their low flattening. This might suggest that another (or more) mechanism are contributing to the cluster shape and counter-acting the effect of rotation. NGC 104 and NGC 5904 (upper-panel) both lie on the edge-on line, above their expected location. Their positions above the $\delta = 0$ line, combined with their inclination could hint at radial anisotropy. In fact, NGC 104 exhibits radial anisotropy toward the outer region (Cordoni et al., 2020; Leitinger et al., 2024; Libralato et al., 2022; Milone et al., 2018). This leads us to conclude that the

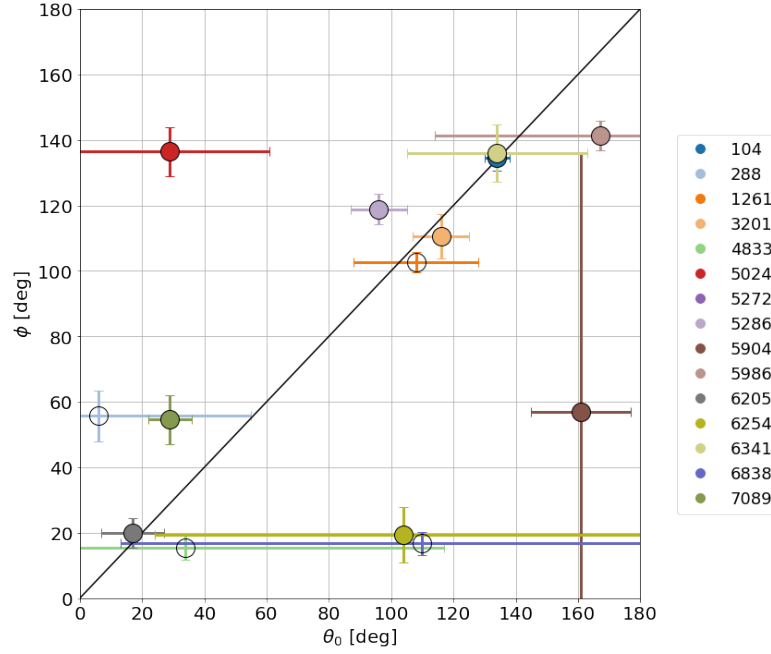


Figure 4.26: Comparison between the position angle of the rotation axis from Leitinger et al. (2024) and the position angle measured in this work. The black line indicates the identity: in this case, this represents an alignment between the semi-minor axis of the ellipse and the rotation axis of the cluster. Empty symbols denote clusters flagged as non-rotating in Leitinger et al. (2024). We only include here the clusters that we flagged as elliptical.

flattening of NGC 104 could be linked to both rotation and radial anisotropy. We note that our results for this cluster are in very good agreement with Bianchini et al. (2013) who provided a similar diagram as Fig. 4.24 for three GCs: ω Cen, NGC 7078, and NGC 104. Using the ellipticity estimates by White and Shawl (1987), they found a similar location for NGC 104 in a diagram of this type, which they explain as being a combined effect of internal rotation and pressure anisotropy. We further discuss this cluster in Sect. 4.8.1. The case of NGC 5904 is interesting as it shows isotropy (Libralato et al., 2022) or slight tangential anisotropy (Leitinger et al., 2024), at odds with what would be expected for a system in its position in Fig. 4.25. Finally, NGC 4833 (upper panel) and NGC 6838 (lower panel) are located below their expected position, being very flattened and non-rotating (Bianchini et al., 2018; Leitinger et al., 2024; Vasiliev, 2019). Their positions below the $\delta = 0$ line suggest that tangential anisotropy could be the primary cause of the flattening, and indeed tangential anisotropy has been uncovered by Leitinger et al. (2024) in their outskirts. These two clusters are dynamically old, and their tangential anisotropy might have been even stronger in the past.

To further investigate the effect of rotation, we compare the position angle of the ellipse with the angle of the rotation axis. We recall that, based on our definition, the position angle of the ellipse Φ is the angle between the x -axis, coinciding with the right ascension coordinate on the plane of the sky, and the semi-major axis of the ellipse, in the anti-clockwise direction. The position angle of the rotation axis, θ_0 , is defined by Leitinger et al. (2024) as the angle between the declination coordinate on the plane of the sky and the rotation axis of the cluster.

If the flattening of a cluster is due to rotation, we expect that the cluster is flattened perpendicularly to the axis of rotation. Due to how θ_0 and Φ_0 are defined, this means that they should be equal. In Fig. 4.26, we show the position angles we measure and compare them to the rotation axis position angles from Leitinger et al. (2024). Here, we only consider the 14 clusters flagged as elliptical in Sect. 4.6.1. The empty circles correspond to clusters classified as non-rotating in Leitinger et al. (2024). The black line indicates the identity: a cluster falling on this line would suggest that its flattening could be due to rotation. Eight clusters have such an alignment within the error bars, including NGC 104 (see Sect. 4.8.1), and NGC 3201 and NGC 1261 (see Sect. 4.8.2).

4.7 Ellipticity of the multiple stellar populations

Now that we have assessed the global shape of GCs, we delve deeper into the flattening of their MSPs. To obtain the ellipticity and angle of the two populations, we first filter out stars with ambiguous classification, considering as part of a population only stars with a probability $> 70\%$ of belonging to that population. We then randomly sample a number of stars corresponding to 90% of those belonging to the smaller population 100 times; to avoid introducing bias caused by differences in the number of stars sampled between populations P1 and P2. We detail our results on the ellipticity of the MSPs in Sect. 4.7.1 and we analyse the relation between flattening and various parameters of the MSPs in Sect. 4.7.2.

4.7.1 Results

In this section, we present the ellipticity of MSPs and their position angle. While the value of the position angle of the ellipse taken alone has no physical meaning, the comparison between the orientation angles of the ellipses representing the two populations can provide valuable insights into their formation and evolution. This comparison, never done in the literature so far, is important because it allows us to assess the degree of alignment (or misalignment) between the two populations, which can give clues on the main mechanisms shaping their dynamics and spatial distribution, and on their interplay during the evolution of the cluster. Throughout this section, we will often refer to the difference in ellipticity, Δe , and to the difference between the position angles, $\Delta\Phi$, defined as:

$$\Delta e = e_1 - e_2 \quad (4.18)$$

$$\Delta\Phi = \Phi_1 - \Phi_2 \quad (4.19)$$

Because of these definitions, positive values of Δe and $\Delta\Phi$ indicate a more elliptical and more inclined pristine population, negative values a more elliptical and more inclined enriched population.

In Table 4.2 we present a summary of our results: for each cluster, we list its global ellipticity (see Sect. 4.6), the ellipticity of its pristine (P1) and enriched (P2) population, the difference in ellipticity and in position angle, a flag indicating whether the GC can be considered round (as defined in Sect. 4.6.1), and which population, if any, can be considered as flat based on the same criterion.

By comparing the last two columns of this table, we can see that, for many clusters, one population tends to drive the global ellipticity. However, there are two round clusters showing surprising results, namely NGC 6121 and NGC 6809. The population 1 of NGC 6121 is highly flattened. Its population 2 is also very elliptical but the error bars are large therefore we did not flag it as elliptical. We note that the two populations have a position angle inclined at almost 90 degrees from one another; this misalignment explains why this cluster appears round, when considering all the stars. NGC 6809 is also intriguing, as this cluster is round but shows a flattened P2, and a round P1. The difference in position angle between the two populations is also close to 90 degrees. We also note that two flattened clusters show spherical populations: NGC 4833 and NGC 7089. For the former, this is especially striking, whereas for the latter the discrepancies between global flattening, which is very small, and MSPs flattening is not so large.

We compare the ellipticities of P1 and P2 in Fig. 4.27. We do not include in the plot the clusters that have round populations, and therefore we are left with 13 clusters, including those that have at least one population flattened at a statistically significant level. Eight of these clusters have a more flattened P1, while four have a more flattened P2. One cluster, NGC 5986, lies exactly on the identity line in the figure, because its populations are equally elliptical.

We also analyse the difference in absolute value between the position angle of the two populations. In Fig. 4.28 we plot the difference in angle and in ellipticity between the two populations for the same clusters shown in Fig. 4.27. There is a scatter in the difference in the angles. Such a scatter is surprising because one might expect a stronger alignment in the orientations of the two populations as they belong to the same GC. We note that half of the clusters have large error-bars associated to $\Delta\Phi$. Overall, five clusters exhibit a significant misalignment in the ellipses associated with each population, with the difference in angle deviating from zero beyond the error bars. NGC 6121 and NGC 6809 are close to

NGC	e	e_1	e_2	Δe	$\Delta\Phi$ [deg]	Global shape	Flag MSPs
104	0.08 ± 0.01	0.24 ± 0.02	0.02 ± 0.03	0.22 ± 0.04	-22 ± 44	E	P1
288	0.07 ± 0.02	0.02 ± 0.05	0.02 ± 0.04	0.00 ± 0.07	-	E	-
1261	0.10 ± 0.01	0.01 ± 0.02	0.10 ± 0.03	-0.09 ± 0.04	-40 ± 17	E	P2
3201	0.11 ± 0.02	0.02 ± 0.04	0.20 ± 0.04	-0.18 ± 0.06	38 ± 30	E	P2
4590	0.02 ± 0.02	0.04 ± 0.02	0.02 ± 0.04	0.02 ± 0.05	-	S	-
4833	0.15 ± 0.02	0.06 ± 0.05	0.03 ± 0.04	0.03 ± 0.06	-	E	-
5024	0.05 ± 0.01	0.02 ± 0.02	0.07 ± 0.02	-0.04 ± 0.03	-106 ± 11	E	P2
5053	0.21 ± 0.03	0.25 ± 0.05	0.08 ± 0.08	0.17 ± 0.09	33 ± 81	E	P1
5272	0.06 ± 0.02	0.21 ± 0.03	0.01 ± 0.03	0.20 ± 0.04	51 ± 90	S	P1
5286	0.10 ± 0.01	0.08 ± 0.02	0.09 ± 0.03	-0.01 ± 0.03	6 ± 10	E	P1
5904	0.15 ± 0.02	0.20 ± 0.03	0.14 ± 0.06	0.07 ± 0.07	120 ± 76	E	P1
5986	0.09 ± 0.01	0.27 ± 0.02	0.13 ± 0.03	0.14 ± 0.03	-51 ± 8	E	P1 & P2
6101	0.06 ± 0.03	0.03 ± 0.03	0.02 ± 0.05	0.02 ± 0.06	-	S	-
6121	0.00 ± 0.02	0.23 ± 0.05	0.16 ± 0.07	0.07 ± 0.08	80 ± 19	S	P1
6205	0.10 ± 0.01	0.03 ± 0.03	0.02 ± 0.04	0.01 ± 0.05	-	E	-
6218	0.03 ± 0.02	0.02 ± 0.03	0.16 ± 0.07	-0.14 ± 0.08	-	S	-
6254	0.08 ± 0.03	0.02 ± 0.02	0.12 ± 0.04	-0.10 ± 0.05	-	S	-
6341	0.12 ± 0.02	0.10 ± 0.03	0.02 ± 0.04	0.08 ± 0.05	-3 ± 27	E	P1
6366	0.00 ± 0.02	0.12 ± 0.06	0.03 ± 0.04	0.08 ± 0.07	-	S	-
6656	0.05 ± 0.02	0.23 ± 0.05	0.04 ± 0.04	0.19 ± 0.06	64 ± 74	S	P1
6809	0.03 ± 0.02	0.07 ± 0.04	0.18 ± 0.05	-0.11 ± 0.07	96 ± 15	S	P2
6838	0.16 ± 0.03	0.14 ± 0.09	0.04 ± 0.05	0.10 ± 0.11	-	E	-
6934	0.03 ± 0.01	0.03 ± 0.03	0.04 ± 0.07	-0.01 ± 0.08	-	S	-
6981	0.05 ± 0.03	0.08 ± 0.07	0.02 ± 0.04	0.06 ± 0.08	-	S	-
7089	0.05 ± 0.01	0.02 ± 0.03	0.02 ± 0.04	0.00 ± 0.04	-	E	-
7099	0.05 ± 0.04	0.04 ± 0.05	0.12 ± 0.08	-0.09 ± 0.10	-	S	-

Table 4.2: This table provides, for each GC, whose NGC number is indicated in the first column, our global ellipticity measurements (second column), the ellipticity of the pristine population, e_1 (third column), the ellipticity of the enriched population, e_2 (fourth column), the difference in ellipticity (fifth column), and the difference between the position angle of the ellipses (sixth column). This difference is listed only for clusters showing at least one flattened population. Finally we mark the clusters we have identified as round in Sect. 4.6.1 with (S - spherical) and the others with (E - elliptical) in the second to last column, and we specify which of the two populations is flattened in the last column; we use a dash to indicate clusters for which none of the population is flattened.

having an orthogonal alignment of their two populations, falsely making them appear round when considering all the stars in the analysis. Other clusters such as NGC 3201, NGC 1261, or NGC 5986 show a difference close to 45° . Two clusters show an alignment of the ellipse of their two populations: NGC 5286, which also exhibits a similar ellipticity between P1 and P2, and NGC 6341.

4.7.2 Ellipticity and dynamics of MSPs

Now that we have a better picture of the distribution of ellipticities and their position angle for the two populations, we can carry out a similar analysis as that presented in Sect. 4.6.2 to understand the link between flattening and various physical quantities.

We start by investigating the difference in spatial concentration between the two populations, which could drive the difference in ellipticity. In such a case, we expect the most centrally concentrated population to also be the rounder one, due to more intense dynamical interaction in this region. In Fig. 4.29 we show the concentration parameter A^+ from Leitinger et al. (2023), defined as in Eq. 1.1, as a function of the difference in ellipticity between P1 and P2. A^+ is defined as the area enclosed between the cumulative radial distributions of the two populations. A positive value of A^+ indicates a more centrally concentrated P1, while a negative value corresponds to a more centrally concentrated P2. As

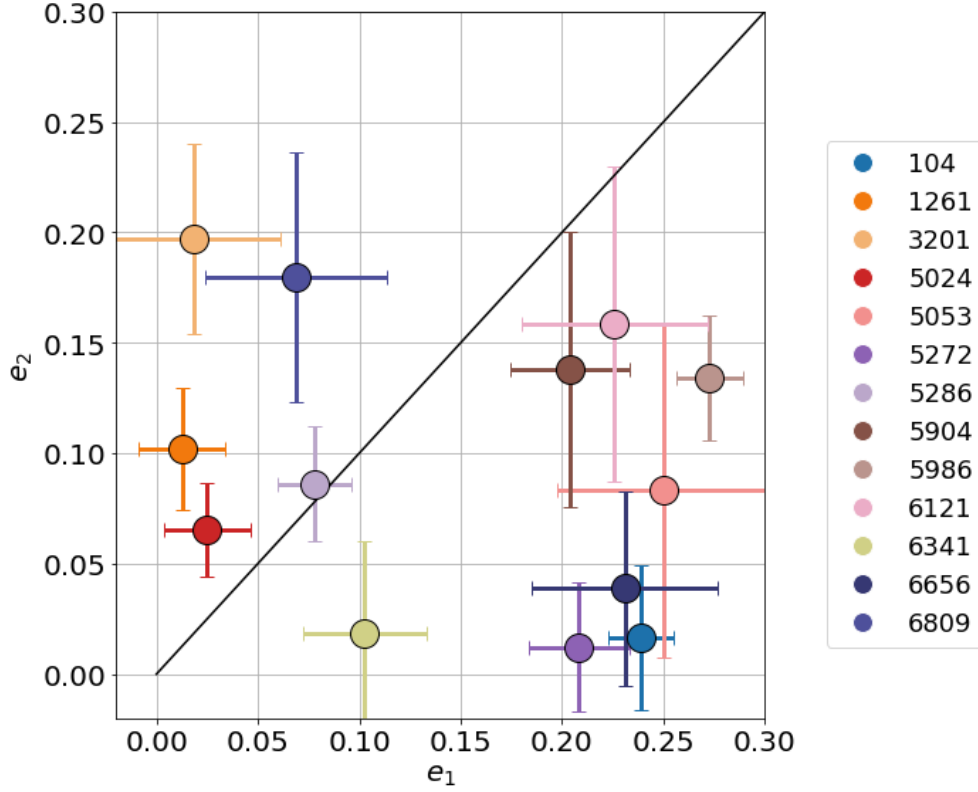


Figure 4.27: The ellipticity measured for the enriched P2 is shown here versus the ellipticity of the pristine P1, for the 13 clusters for which we detect a flattening in at least one population at a statistically significant level. The solid line indicates equal ellipticities. The colors of points indicate specific clusters as indicated in the legend.

already done in Fig. 4.27, we do not include in the plot the clusters that have round populations. By inspecting the figure, we can see a trend indicating that the most centrally concentrated population is also the least elliptical. For example, for NGC 3201, P1 is the most centrally concentrated population, and P2 is the most elliptical. At the opposite end of the plot we find NGC 104 and NGC 5272, in which P2 is the most centrally concentrated population, and P1 the most elliptical. This could indicate that velocity anisotropy or tidal effects might play an important role in the flattening of the populations in these clusters. We note two outliers with respect to the general trend observed in Fig. 4.29, NGC 6809 and NGC 5024, both exhibiting a P2 more elliptical and more centrally concentrated than P1. Some clusters have spatially mixed populations and show a higher ellipticity of P1 (e.g. NGC 5053); in fewer cases, P2 seems to be more elliptical (e.g. NGC 1261).

Moving to the link between flattening and rotation, we show values of A/σ_{LOS} as a function of the recovered ellipticity for the pristine P1 (top panel) and the enriched P2 (bottom panel) in Fig. 4.30. The colourful lines are similar to the one shown in Fig. 4.24, displaying the theoretical location of an isotropic oblate rotator in the e versus V/σ plot given its inclination, also plotted in colour. The amplitude of the rotation for the two populations, A_1 and A_2 , has been kindly provided by Ellen Leitinger (Leitinger et al., 2024), together with the inclination angle of each population, describing the inclination of the rotation axis of each population with respect to the observer, with $i = 0^\circ$ corresponding to a face-on view and $i = 90^\circ$ corresponding to an edge-on view. To compute the A/σ_{LOS} , we also need the central velocity dispersion of the two populations. Because such data is not available, we used the same value as in Sect. 4.6.2, i.e., the central velocity dispersion computed using all the stars in the clusters. This approximation is discussed in Sect. 4.9.

In Fig. 4.30, we can divide the clusters in three main groups. The first group gathers clusters having the ellipticity and rotation strength of their population consistent with what is expected for an isotropic oblate rotator, given their inclination. In the top panel, some of these clusters have low rotation

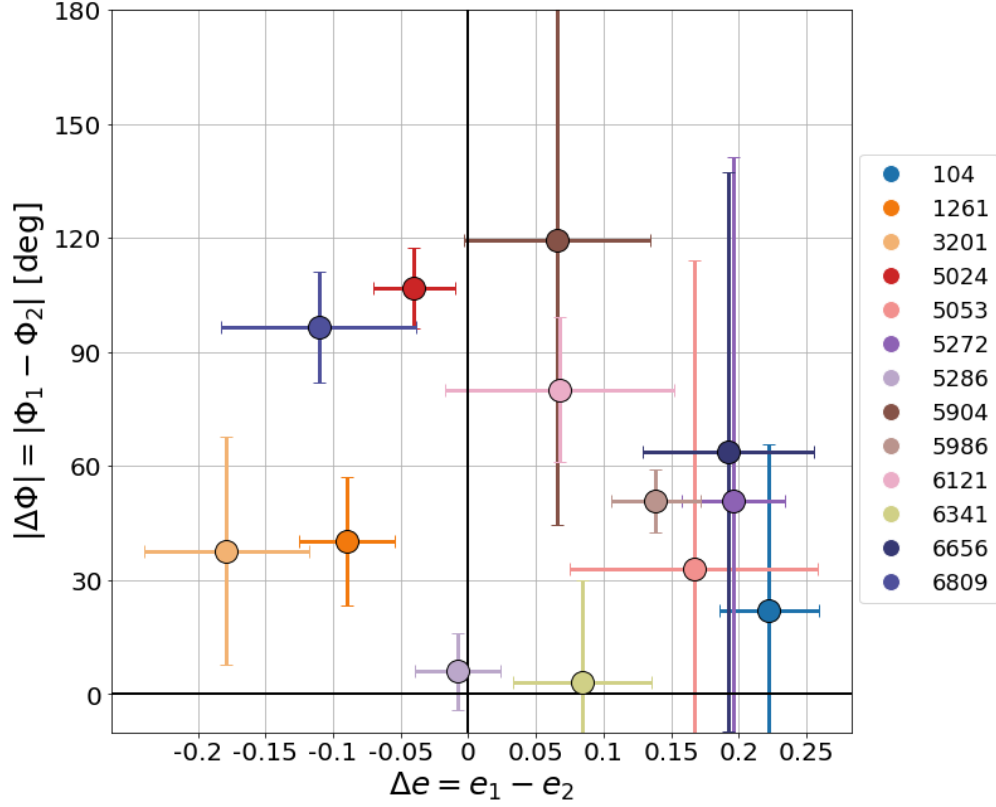


Figure 4.28: The absolute value of the difference in position angle for the ellipses representing the two MSPs is shown here against the difference in ellipticity. The black lines indicate same ellipticities and position angles. We do not include in this figure the clusters in whom both populations are round within 3σ .

and low flattening (the labels indicating their name are not shown because they are too crowded; they are NGC 6254, NGC 5024, NGC 3201, NGC 288, and NGC 6218). Other clusters, namely NGC 104, NGC 6121, NGC 5272, and NGC 5904 have a flattening > 0.2 and a rotation strength also consistent within this framework, given their inclination between 10° and 50° . In the bottom panel, we also have clusters exhibiting low rotation and low flattening of their population 2 such as NGC 288 and NGC 6341, and others like NGC 5286 or NGC 6121 displaying a higher flattening and a rotation strength of their population 2, consistent with what is expected for an isotropic oblate rotator. The second group that we identify gathers clusters more elliptical than what we would expect based on their rotation. This is the case of the population 1 of NGC 6341, in the top panel of Fig. 4.30, and of the population 2 of NGC 6218, NGC 6254, NGC 6809, and NGC 3201. This might suggest that others properties, such as anisotropy, affect these populations. In the third group we list clusters that are more rotating than expected based on their ellipticity. The population 1 in NGC 7089 and the population 2 in NGC 104 are remarkable example of such a behaviour.

To further investigate this, by also taking into account the errors on the inclination angle of the two populations, we use the same figure style already proposed in Fig. 4.25. In Fig. 4.31 and Fig. 4.32 we plot the values of A/σ_{LOS} as a function of the ellipticity for the pristine P1 and for the enriched P2, respectively. The dimensions of the ellipses drawn around each cluster account for the uncertainties on A/σ_{LOS} and on the ellipticity, whereas their color gradient indicates the uncertainty on the inclination angle, taken from Leitinger et al. (2024). We do not include in these figures the clusters for which the error in inclination angle is larger than 30° . Again, we arbitrarily divide the clusters in two groups (shown separately in two panels in each figure) to prevent any overlap and to make the figures easier to inspect.

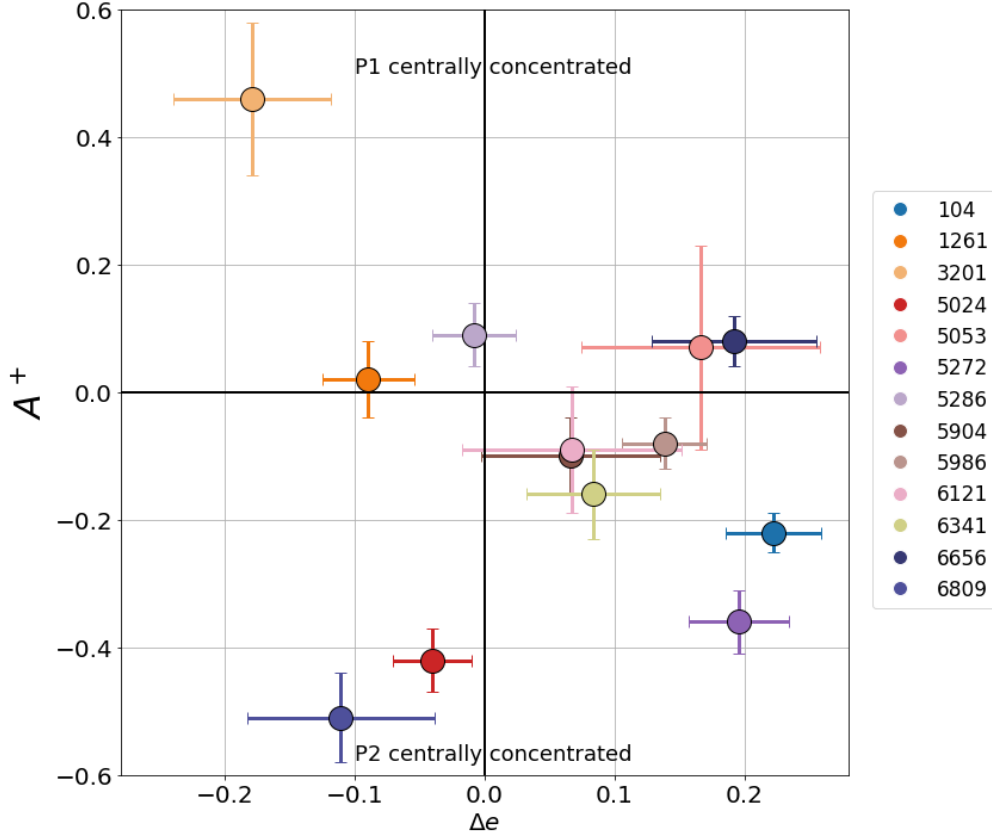


Figure 4.29: The concentration parameter A^+ from Leitinger et al. (2023) is shown against the difference in ellipticity between the two populations, $\Delta e = e_1 - e_2$. We do not include in this figure the clusters in whom both populations are round within 3σ . A general trend is visible, with the more flattened population often corresponding to the least concentrated one.

In the top panel of Fig. 4.31, we see that the position of most clusters in the plot is consistent, within the uncertainties, with the corresponding theoretical line, given their inclination. In particular, P1 of NGC 104 shows an ellipticity which could be entirely explained by its rotation. In the bottom panel, most clusters are also located where we would expect to find them, with the exception of NGC 7089, which has a very round but strongly rotating P1. For P2, shown in Fig. 4.32, the situation is very similar, but we notice some exceptions: P2 of NGC 104 (in the bottom panel) and P2 of NGC 5272 (in the top panel) have a strong rotational signature but a very round shape, given their inclination angle, suggesting that other mechanisms might counter-act the effect of rotation.

Finally, we compare our results with the works from Cordoni et al. (2020) and Dalessandro et al. (2024).

We have 6 GCs in common with Cordoni et al. (2020): NGC 104, NGC 288, NGC 5904, NGC 6121, NGC 6254, and NGC 6838. Our results are in very good agreement for NGC 104 (more flattened P1), NGC 288 (round), and NGC 6254 (more flattened P2). For NGC 6838, they found rather spherical populations at the center of the cluster, with increasing ellipticity toward the outer region. Even though our results suggest a more flattened P1 for this cluster, the large error bars associated with this measurement make the results still compatible. For NGC 6121, they found a P1 close to round and a P2 slightly elliptical while we detected a significant flattening in P1. Interestingly, for NGC 5904 they find that the ellipticity of P1 increases toward the outer part, while that of P2 decreases, both converging toward a flattening of 0.13 at about 8 arcmin from the cluster center; for this cluster, we find a very flattened P1 ($e_1 = 0.2 \pm 0.03$) and a quite elliptical P2 ($e_2 = 0.14 \pm 0.06$), consistent with the values

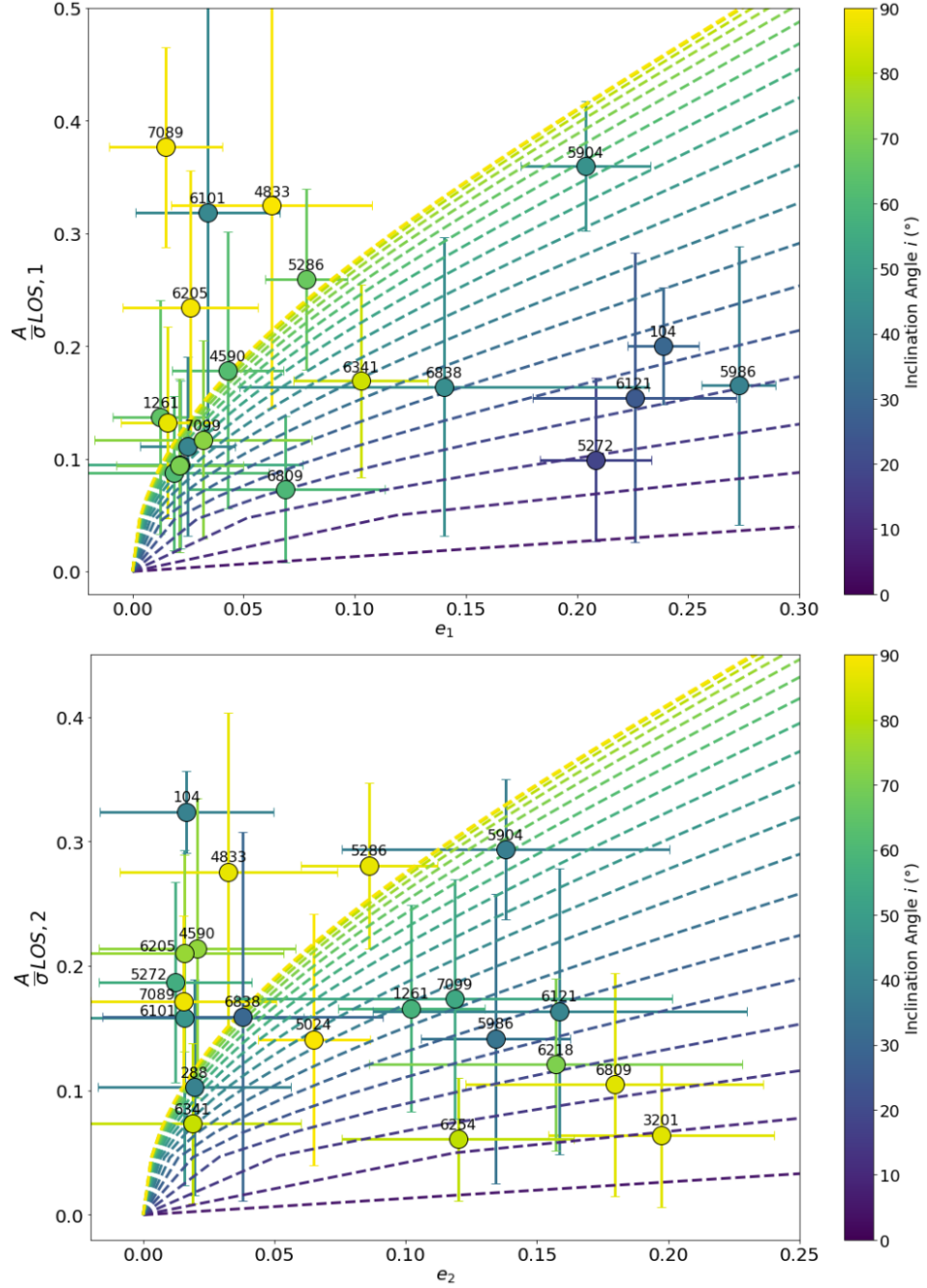


Figure 4.30: This plot shows the same quantities displayed in Fig. 4.24, namely the rotation strength as a function of the measured flattening for the pristine population (top panel) and for the enriched population (bottom panel). The name of each GC is indicated close to the corresponding point, except for the conglomeration of clusters with low ellipticity and low A/σ_{LOS} in the top panel where we removed the labels. These clusters are NGC 6254, NGC 5024, NGC 3201, NGC 288, and NGC 6218. The points are colored according to the inclination angle of the cluster. Low inclinations are plotted in blue while high inclinations are colored in yellow. The dashed lines indicate the relation for isotropic oblate rotators viewed at different inclination angles.

they reported. Our results are compatible and suggest the necessity, for certain clusters, to obtain an ellipticity profile. This point is further discussed in Sect. 4.9.

4. Ellipticity of MSPs in GCs

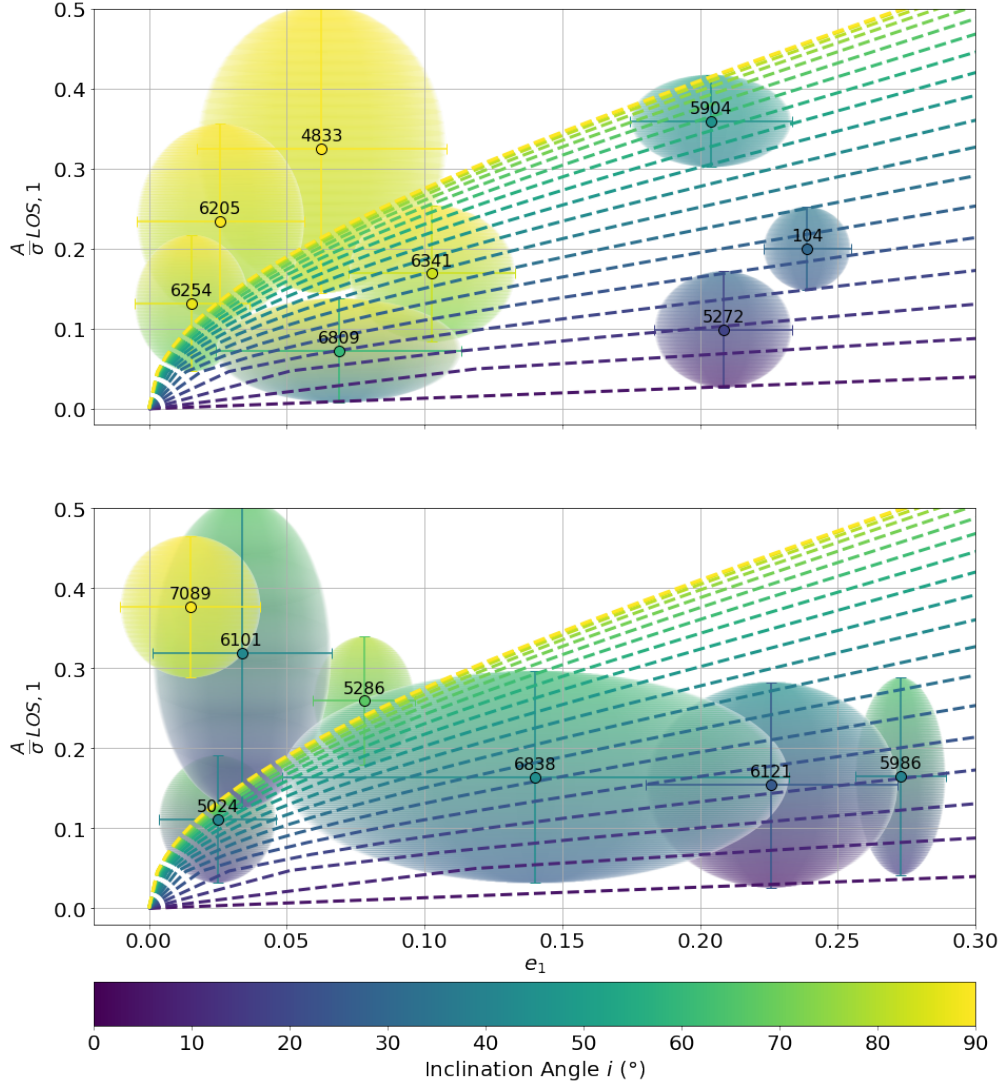


Figure 4.31: This plot shows similar results as Fig. 4.25 for the pristine population. For each GC, we plot an area of uncertainty in A/σ_{LOS} and e represented by the ellipse surrounded each circle. The ellipse is colored according to the inclination angle of the cluster, with a gradient going from the lower bound of i to its upper bound. We arbitrarily separated the GCs in two groups to limit the overlap between clusters.

We also have 9 GCs in common with Dalessandro et al. (2024): NGC 104, NGC 288, NGC 1261, NGC 3201, NGC 5272, NGC 5904, NGC 5986, NGC 6205, and NGC 6254. Figure 4.33 shows a comparison of the ellipticity values they reported versus those we obtained for P1 (left panel) and P2 (right panel). Overall, we find a significant difference between the two sets of ellipticities, with their estimates being typically more flattened than ours. We find incompatible results for several clusters. For example, in NGC 104 we find a very elliptical P1 and a round P2, in good agreement with Cordoni et al. (2020), while Dalessandro et al. (2024) found a P2 considerably more flattened than the P1. Similarly, for NGC 3201 we find a flattened P2 and a round P1, while Dalessandro et al. (2024) recovered a more elliptical P1 than P2.

The reasons for these discrepancies could be found in the different approaches we adopted to measure the flattening of these systems. To do this, Dalessandro et al. (2024) first binned the stars radially, separating them according to the 10th, 50th, and 90th percentiles of the stellar distribution. They computed the shape tensor iteratively starting from a spherical grid for each bin. Then, they rotate

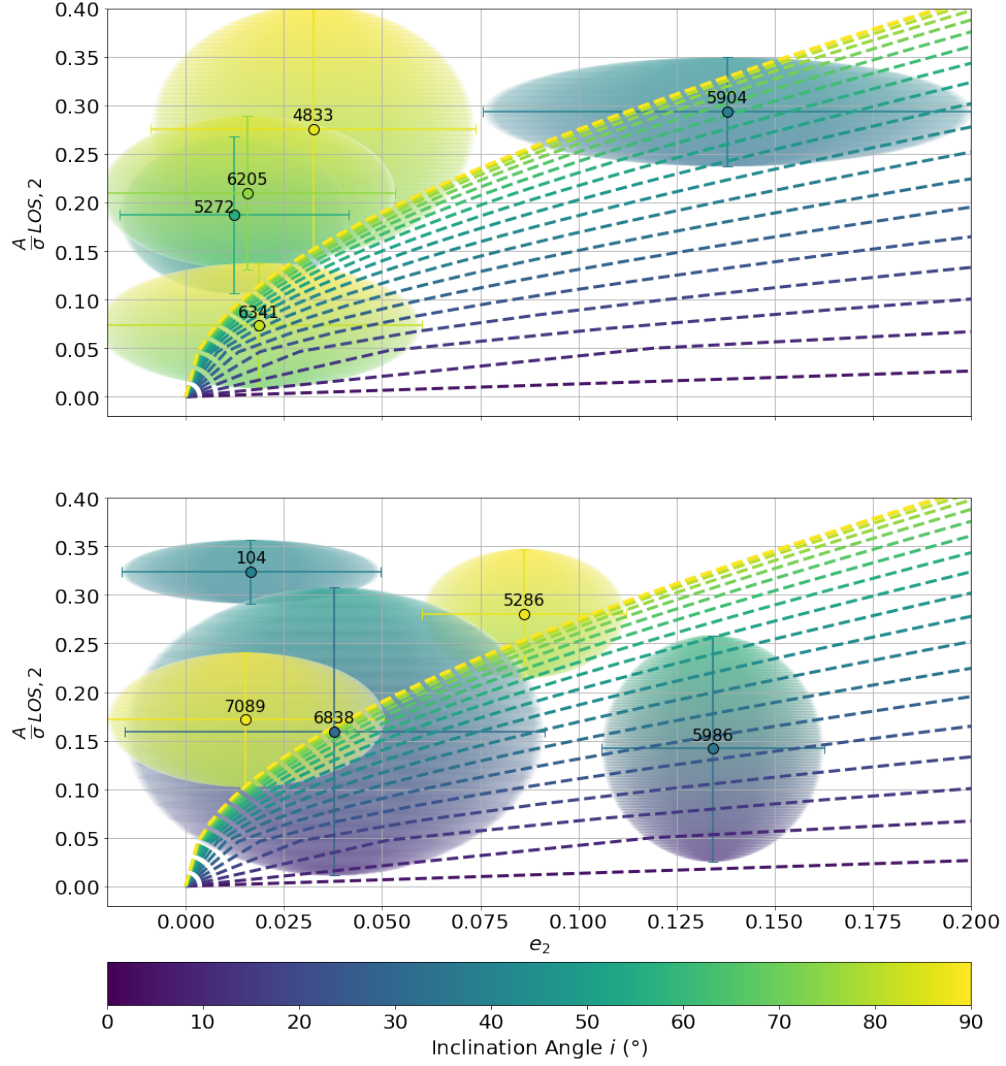


Figure 4.32: This plot shows similar results as Fig. 4.25 for the enriched population. For each GC, we plot an area of uncertainty in A/σ_{LOS} and e represented by the ellipse surrounded each circle. The ellipse is colored according to the inclination angle of the cluster, with a gradient going from the lower bound of i to its upper bound. We arbitrarily separated the GCs in two groups to limit the overlap between clusters.

the star's coordinate and compute iteratively its distance from the cluster centre using an ellipticity-dependent formula. They binned the stars again in this new coordinate system and re-computed the shape tensor. The eigenvalues and eigenvectors of the shape tensor define the ellipticity of GCs in a similar way as the PCA (see Sect. 4.4.3). Such a method suffers from the same problem as the PCA, namely its sensitivity to outliers. We took this into account when building the robust PCA method, which is the one we used to compute the ellipticities discussed in this section, but Dalessandro et al. (2024) did not explicitly mention any correction of this type.

At this stage, we have an overall picture of the ellipticity of MSPs in 26 GCs. We find that the pristine population often drives the global ellipticity of the cluster, with a flattening > 0.2 in 7 MW GCs, while the enriched population reaches this degree of flattening in only 2 MW GCs (namely NGC 3201 and NGC 6809).

By means of N-body simulations, Mastrobuono-Battisti and Perets (2016) studied the morphological and kinematical evolution of a disk P2 embedded in a more spherical P1, and found that P2 formed in flattened configurations tend to drive the global ellipticity of the cluster. As a consequence, a positive

4. Ellipticity of MSPs in GCs

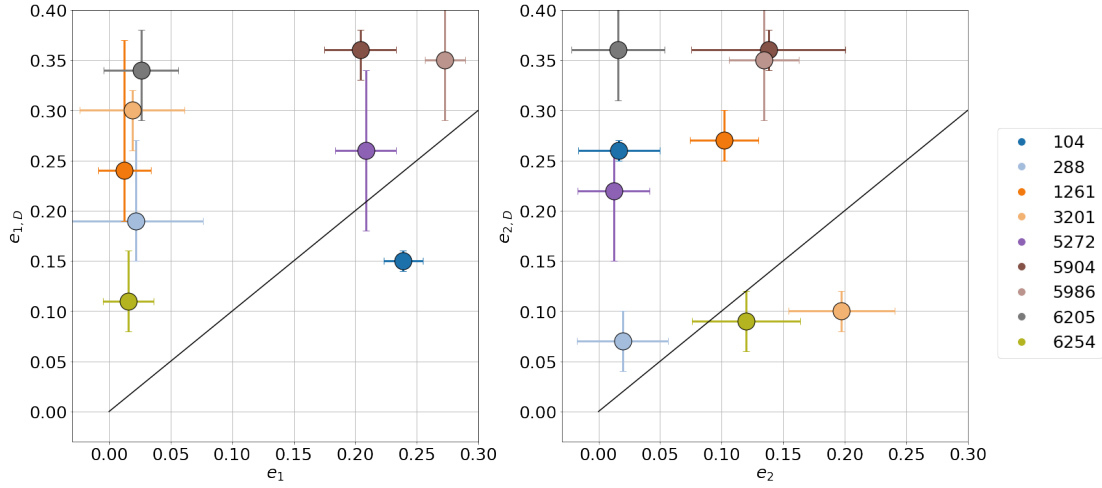


Figure 4.33: Our values of the ellipticity of P1 (left panel) and P2 (right panel), shown in the abscissae, are compared with the ones reported by Dalessandro et al. (2024), and shown in the ordinate, for the 9 clusters in common in our samples (see also the legend on the right). The black lines indicate the identity.

correlation between the global ellipticity and the fraction of P2 stars would be expected under such an initial configuration. They also specified that the flattening may still be detectable today, even after 12 Gyr of evolution. Over time, relaxation processes would smooth out these features, but they are expected to remain more pronounced in clusters with longer relaxation times (i.e., dynamically young GCs), leading to a positive correlation between GC relaxation time and ellipticity. We already noticed such a trend between relaxation time and global flattening, as shown in Fig. 4.22. We further investigated the first correlation suggested by Mastrobuono-Battisti and Perets (2016), but we found no correlation between the global ellipticity and the fraction of P2 stars given by Leitinger et al. (2024). The Pearson correlation coefficient we compute for this relation is actually negative, with a value of -0.11, suggesting a small anti-correlation between the fraction of enriched stars and the global ellipticity. Therefore, our findings argue against a very disky initial P2. However, as pointed out by Hénault-Brunet et al. (2015), numerical simulations are often initiated with a spherical cluster, and different initial conditions with that regard should be investigated before drawing any conclusion (see Sect. 1.3.3 for more discussion on this article).

4.8 An insight into specific clusters

The results presented in Sect. 4.6 and Sect. 4.7 highlight an interesting complexity in the interplay between kinematics and shape in some clusters. In this section, we explore these results in greater depth for NGC 104 (Sect. 4.8.1), NGC 3201 and NGC 1261 (Sect. 4.8.2), NGC 6121 and NGC 6809 (Sect. 4.8.3), and NGC 7089 (Sect. 4.8.4).

4.8.1 NGC 104

We start by discussing one of the most studied GC, NGC 104, the second brightest Galactic GC after ω Cen. This is one of the few clusters for which strong rotation has been measured (Bellazzini et al., 2012; Bianchini et al., 2018; Kamann et al., 2018; Kimmig et al., 2015; Lane et al., 2010; Sollima et al., 2019; Vasiliev, 2019). As part of our analysis, we also computed the position angle of its elliptical shape: we find an alignment between the semi-minor axis of the ellipse and the rotation axis of the cluster measured by Leitinger et al. (2024), suggesting that rotation might be the main mechanism responsible for its flattening. We provide more details in Sect. 4.6.2, with a comparison between the position angle of the ellipse and of the rotation axis of some clusters, among them NGC 104.

Regarding its MSPs, Martens et al. (2023) found no difference in the rotation strength between the two populations, while Leitinger et al. (2024) found that P2 was rotating faster than P1 at a $3.5\text{-}\sigma$ level, around a similar rotation axis. Leitinger et al. (2024) pointed out that this difference in rotation might not be representative of the initial conditions of the cluster, as NGC 104 has undergone 2.5 relaxation time, which could have already altered the kinematics imprinted at birth; they also found radial anisotropy in the outer region of the cluster, with P2 showing a slightly stronger anisotropy, and a more centrally concentrated second population, in agreement with past literature (Cordero et al., 2014; Milone et al., 2012a).

Cordoni et al. (2020) derived ellipticity profiles for the two populations of this cluster and found that P1 is significantly more elliptical than P2, especially at the center of the cluster, in good agreement with our measurement of a stronger flattening for P1 than P2, and in tension with the results from Dalessandro et al. (2024). For the flattened population, the pristine P1, we compared the position angle of the ellipse with the angle of the rotation axis from Leitinger et al. (2024). We find an alignment within 2σ (σ here refers to the uncertainty on the rotation angle) between the semi-minor axis of P1 and the rotation axis, suggesting that its flattening might be due to rotation.

The fact that P2 in NGC 104 is round while rotating faster than P1 indicates that some other effects might have an impact on shaping the morphology of this cluster. Anisotropy might be the best candidate here, as P2 stars are more radially anisotropic than P1 stars. We do not expect tidal effects to have a strong impact, because they would not contribute greatly to the flattening in the centre of the cluster, where most P2 stars are found.

4.8.2 NGC 3201 and NGC 1261

We analyse these clusters together because they have similarities in their ellipticity. They both exhibit a very flattened P2 and a round P1, and have a difference in the angle between the ellipses representing the two populations of about 40° . Their global shape is similar, with an ellipticity close to 0.1, and they show very similar total A/σ_{LOS} . However, we note that, while NGC 3201 has been classified as rotating (Bellazzini et al., 2012; Ferraro et al., 2018; Kamann et al., 2018; Leitinger et al., 2024; Martens et al., 2023), the case of NGC 1261 is debatable, with no rotation signal found by Leitinger et al. (2024) and Sollima et al. (2019), and a 2σ significance level of rotation unravelled by Ferraro et al. (2018). When comparing the semi-minor axis of the ellipse with the rotation axis of these clusters⁶ we find a very good agreement, suggesting that their flattening could be linked to rotation (see Fig. 4.26).

The fact that, in these clusters, one of the populations is significantly more elliptical than the other suggests that the two populations might be affected differently by the dynamical mechanisms able to shape the morphology of these systems. NGC 3201 is among the clusters exhibiting the most centrally concentrated P1. Therefore, the flattening of P2 could be link to external forces, like tidal effects from the galaxy. The presence of tidal tails around this cluster would confirm such a speculation, requiring follow-up observations in the outer part. The case of NGC 1261 is more complicated, because the two populations are spatially mixed. This cluster is characterised by isotropy (Leitinger et al., 2024), and it is dynamically old, therefore we would not expect any significant difference between the flattening of the two populations.

4.8.3 NGC 6121 and NGC 6809

These clusters are very interesting because we classified them as round in Sect. 4.6.1, but they both have at least one flattened population. They both have a rather low 3D rotation velocity (see Fig. 4.23). From a rotation perspective, NGC 6121 is a debated cluster. While some studies detected rotation at a statistically significant level by using line-of-sight velocities (Bellazzini et al., 2012; Lane et al., 2010; Leitinger et al., 2024), other detected rotation at a non-statistically significant level (Bianchini et al., 2018; Kamann et al., 2018; Kimmig et al., 2015), or not at all (Sollima et al., 2019; Vasiliev, 2019) by using proper motion data. There is statistically significant signs of rotation in NGC 6809 (Bianchini et al., 2018; Gaia Collaboration et al., 2018; Leitinger et al., 2024).

⁶Leitinger et al. (2024) provided an estimate of the angle of the rotation axis also for clusters that they classified as non-rotating.

4. Ellipticity of MSPs in GCs

When considering all the stars in NGC 6121, we find no flattening at all, but when we consider the individual MSPs we find a significant ellipticity ($e_1 = 0.23 \pm 0.05$ and $e_2 = 0.16 \pm 0.07$). The most intriguing aspect is the orientation of the ellipses between the two populations, at almost 90° . While this nicely explains why the cluster appears round when considering all the stars together, it is very puzzling that the flattening of the MSPs is not aligned along the same direction. This is illustrated in Fig. 4.34, where we show the distribution of the stars in NGC 6121 used to model the ellipticity of P1 (in red) and P2 (in blue). For NGC 6809, we find a more flattened P2 ($e_2 = 0.18 \pm 0.05$) and also in this case we report a difference in the position angle of the ellipses describing the MSPs of about 90° . The orientation of the semi-minor axis of the ellipse representing P2 is the same, within error bars, as the orientation of the rotation axis, suggesting that rotation could play a role in the flattening.

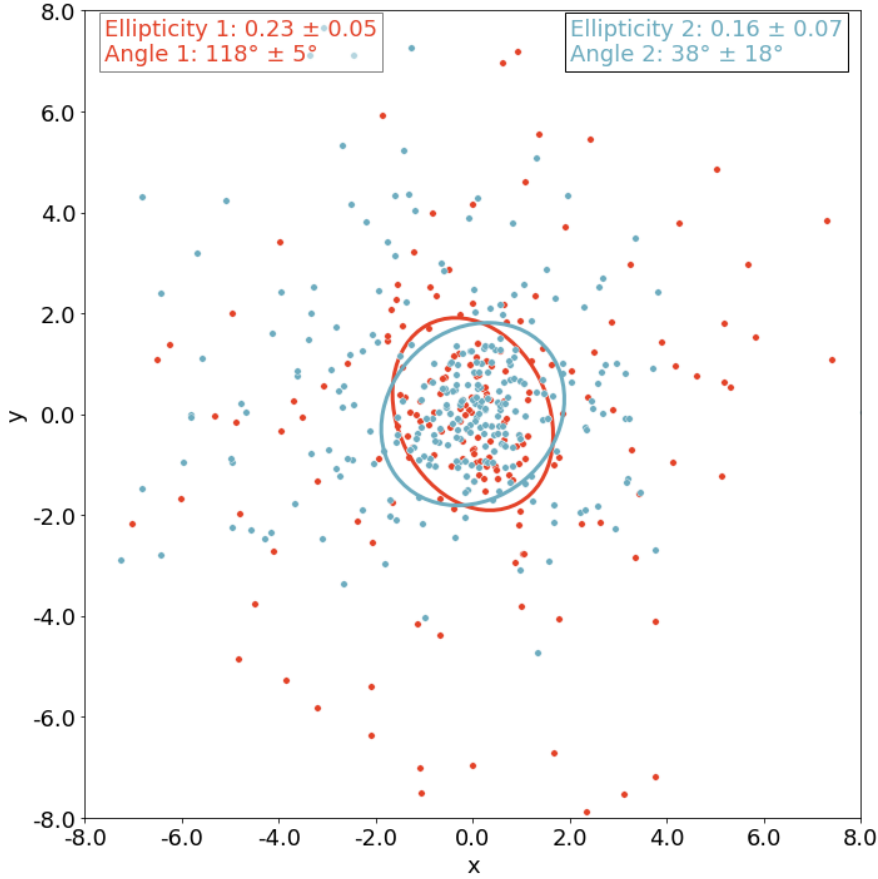


Figure 4.34: Spatial distribution of stars belonging to P1 (in red) and P2 (in blue) in the globular cluster NGC 6121. The recovered ellipses are also shown for P1 and P2, with a red and blue line, respectively. Both populations have a significant flattening, and are aligned along perpendicular axes.

4.8.4 NGC 7089

NGC 7089 is a rotating GC (Bianchini et al., 2018; Kamann et al., 2018; Kimmig et al., 2015; Leitinger et al., 2024; Martens et al., 2023; Sollima et al., 2019; Vasiliev, 2019). Using the 3D A/σ , Leitinger et al. (2024) identified a difference in rotation between P1 and P2 at a 2σ level, with P1 rotating faster than P2. Martens et al. (2023) did not find any statistically significant difference in the v/σ evaluated at the half-light radius, and along the line-of sight. Leitinger et al. (2024) found a slight radial anisotropy in the outer region of this cluster for both populations, and no difference in the spatial distribution of P1 and P2. This cluster also exhibits tidal tails (Jordi and Grebel, 2010). Kuzma et al. (2016) reported that NGC 7089 is embedded in a nearly spherical and diffuse stellar envelope extending at about 5 times its

tidal radius. Such an envelope and the presence of an iron and neutron capture elements spread in the MSPs lead the authors to conclude that it could originate from the stripped nucleus of a dwarf galaxy. For this cluster and its two populations, we recover a very round shape, with an ellipticity smaller than what we would expect based on the value of A/σ_{LOS} (see Fig. 4.24). This might suggest that other mechanisms could be acting to counter-act the flattening effect of rotation in NGC 7089.

4.9 Conclusions and future work

In this Chapter, we have used photometric ground based observations (Stetson et al., 2019) combined with HST data (Nardiello et al., 2018; Piotto et al., 2015) to model the flattening of GCs and of their MSPs.

To do this, we have implemented and investigated three methods that provide a measurement of the flattening and of the position angle of the elliptical shape representing the cluster. The first method relies on a kernel density estimate of the distribution of stars and an ellipse fitting to different isodensity contours. This approach has the advantage of providing an ellipticity profile, and is particularly interesting for clusters for which we expect a variation of the flattening with the radial distance. However, the method is sensitive to outliers, which can considerably alter the results. The second method is a Bayesian inference technique using MCMC, which includes a background density to account for the presence of outlier stars. While this approach is robust, it lacks accuracy due to the failure of the MCMC to converge. The third method investigated is PCA, which captures the direction along which the variance of the data is minimum and maximum, providing very fast results but sensitive to outliers. Thus, all the methods that we have tested are either not robust or not accurate. Therefore, we further developed and improved the fastest of these methods, the PCA, to make it robust to the presence of outliers. After carefully testing it on mock data, we applied the robust PCA to the 26 MW GCs in our sample.

We report statistically significant deviation from spherical symmetry for 14 GCs. For some clusters, the flattening is perpendicular to the orientation of the rotation axis, suggesting that rotation could be the main dynamical mechanism causing it. We also find a statistically significant flattening of one or the two populations in 13 clusters, with a higher ellipticity often attributed with the pristine population. One cluster, NGC 4833 is flattened when we consider all the stars but hosts two populations that appear round. In such a case, we will need simulations including different scenarios for the formation of MSPs, to understand which one might evolve to show the behaviour observed in this cluster.

Our approach has some limitations that should be addressed. First of all, our current implementation of the robust PCA only allows for the computation of a single value for the ellipticity and the position angle for the entire stellar population under consideration. However, the ellipticity could vary with the distance from the cluster center. For example, Geyer et al. (1983) computed ellipticity profiles for 20 Galactic globular clusters; they found that ellipticity variations with radial distance are a common phenomenon and detected significant variations in a few clusters, none of which are however present in our sample. Lanzoni et al. (2018) found a radial variation in NGC 5904, with no ellipticity in the center to $e = 0.14$ at a distance of 140 arcsec. Smaller variations in flattening in this cluster have also been detected by White and Shawl (1987) and Stetson et al. (2019).

Secondly, when analysing the link between flattening and rotation for both the global ellipticity and the ellipticity of MSPs, we have used the central 1D velocity dispersion σ_0 from the Baumgardt (2022) catalogue to evaluate the ratio A/σ . The central velocity dispersion of the two populations might differ from the global one and from one another (e.g., see Martens et al. 2023), but we do not expect such differences to be bigger than a factor of 1.5. However, estimating A/σ using the central velocity dispersion of each population could slightly shift the position of the clusters in the A/σ versus flattening diagram presented in Sect. 4.7.2. A follow-up analysis should be carried out to confirm the results presented in this thesis.

Finally, to really understand if rotation is driving the observed flattening, we need simulations with a variety of initial conditions, including different spatial setups and rotational strengths, for both P1 and P2. For the more unusual cases, we will also need simulations that explore different scenarios for the MSPs to figure out which ones might evolve to match the behaviour observed in this Thesis. These steps are key to getting a clearer picture of what is shaping these systems.

Chapter 5

SUSTAINABILITY IN ASTROPHYSICAL RESEARCH

*"We are all weavers of the grand tapestry of history.
As we cast our minds back and consider those who lived at moments of great consequence, we naturally feel that
if we had lived then, we would have been among those who made the noble choices rather than
those who stumbled along, head down, changing nothing.
Well, this is our chance."*

- Christina Figueres, The future we choose

"When educating the minds of our youth, we must not forget to educate their hearts."

- Dalai Lama

Introduction

The evidences are clear and indubitable, climate change is caused by humans (Intergovernmental Panel on Climate Change (IPCC), 2021). Global warming is intensifying, triggering unprecedented changes and threatening the equilibrium of the Earth's system and its inhabitants (IPCC, 2021). The consequences on the ecosystems are catastrophic, with, among other, a drop of 69% on the species populations of vertebrates since 1970 (Almond et al., 2022). So are the consequences on humans, in particular on vulnerable populations and minorities (IPCC, 2023a), with a very likely increase in inequalities between and within countries (Taconet et al., 2020). In a world everyday more divided, where the 1.5% of the richest grab 47.5% of the total wealth¹, where 712 million people were living below the 2.15\$ poverty line in 2022², where about 2.33 billion people were facing moderate or severe food insecurity in 2023³, are we failing as a society? How can academia face the biggest challenge of humankind? What is our role as astronomers and as teachers?

Although my scientific research focuses on globular clusters and their multiple stellar populations, I have dedicated part of my PhD to create and teach a course on Sustainability in Academia and to develop an interdisciplinary project to communicate on climate change. This chapter is a bridge between two worlds. It is an intent to leave the ivory tower. This chapter is the result of seeds planted by many meetings over time: some have instantly taken root in my mind as self-evident, some have required careful considerations and planning, others yet remain to sprout. There is only one absolute certainty: the next pages would have never existed without the many discussions with my students and my colleagues. This chapter is about collective intelligence, and the bright perspectives it offers.

I will start by defining sustainability and discussing the ethical duty of researchers in Sect. 5.1. Then, I will focus on the role of astronomers, discussing the impact of climate change on astronomy, our unique view on Earth, and the power of collective action through Astronomers for Planet Earth (A4E) in Sect. 5.2. Finally, I will delve deeper into specific interdisciplinary projects combining sustainability and astronomy by presenting the course “Sustainability in academia” that I have created and taught at the University of Vienna (Sect. 5.3) and the “PLEES index” research project, carried out in the framework of the Vienna International School of Earth and Space Science⁴ (Sect. 5.4).

5.1 Introduction to sustainability in research

The earliest evidence of global warming can be traced back to Arrhenius (1897), who predicted that the burning of fossil fuels could enhance the natural greenhouse effect and lead to global warming. He estimated that doubling atmospheric CO₂ could increase global temperatures significantly. In 1957, Charles David Keeling began measuring atmospheric CO₂ concentrations at the Mauna Loa Observatory in Hawaii, demonstrating a clear increase in CO₂ levels over time.

We have therefore been aware of human-induced climate change for decades, and we have had years to adapt our behaviour, develop new policies, and mitigate our impact on the planet. The 2024 Emissions Gap Report from the United Nations Environmental Program titled *“No more hot air ... please! With a massive gap between rhetoric and reality, countries draft new climate commitments”* revealed the huge gap between our current actions and the policies. This is shown in Fig. 5.1. On the left panel, the global greenhouse gas (GHG) emissions are plotted as a function of years. Limiting the temperature increase to +1.5°C by the end of the century is very unlikely if not impossible, and limiting it to +2°C is unlikely. The emissions gap between the current policies scenario and the nationally determined contributions (NDC)⁵, corresponding to climate action plans submitted by countries and outlining their commitments to reduce GHG emissions, is shown on the right panel of Fig. 5.1. The difference between

¹<https://elements.visualcapitalist.com/wp-content/uploads/2024/07/global-wealth-report.pdf>

²<https://pip.worldbank.org/home>

³<https://www.who.int/news/item/24-07-2024-hunger-numbers-stubbornly-high-for-three-consecutive-years-as-global-crises-deepen-un-report>

⁴<https://visess.univie.ac.at/>

⁵An “unconditional contribution” refers to actions that countries can implement using their own resources and capacities, while a “conditional contribution” involves measures that countries would pursue if they receive international support or if certain other conditions are fulfilled.

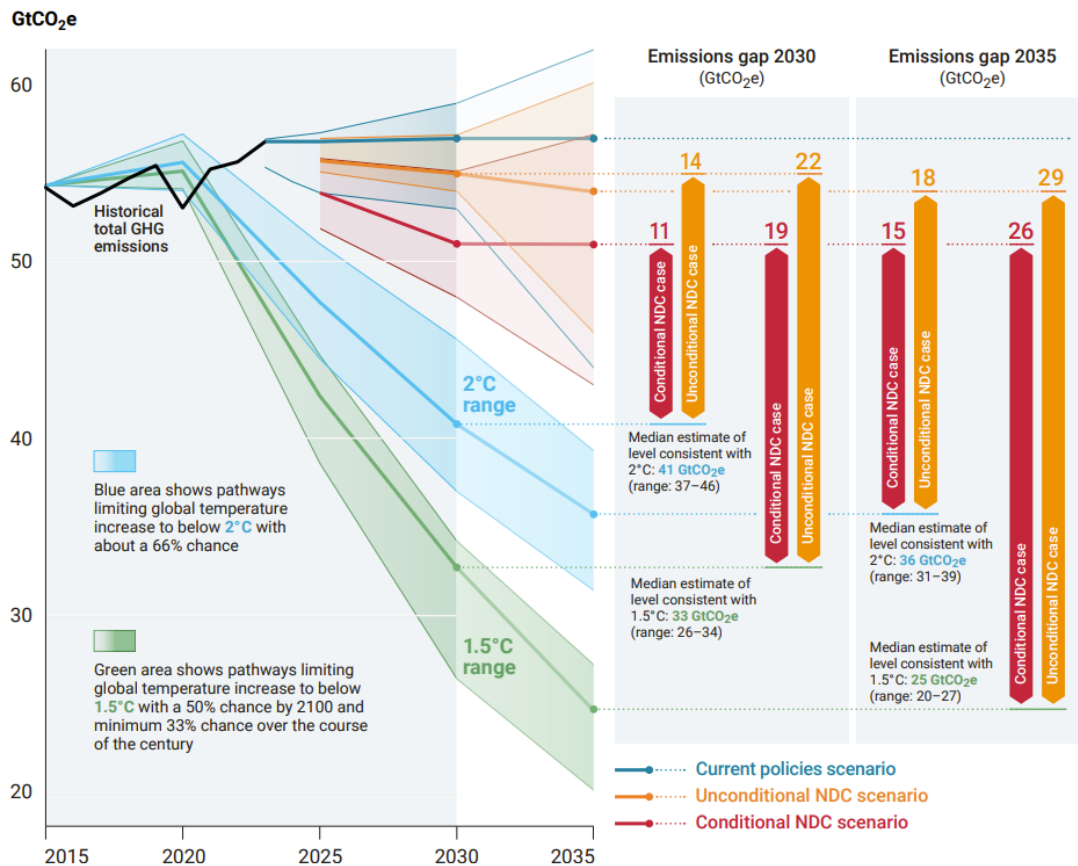


Figure 5.1: Global Greenhouse Gas emissions under different scenarios (left panel) and the emissions gap between policies and actions in 2030 and 2035 (right panel). This figure has been taken from United Nations Environment Programme (2024). In the left panel, the coloured curves show different pathways resulting in a range of temperature increase by the end of the century. In the right panel, the arrows represent the emission gap between the current policies and the conditional (red) and unconditional (orange) nationally determined contributions. The figure can be interpreted as followed: to align with the goal of limiting global warming to below 2°C, annual emissions in 2030 must decrease by 14 GtCO₂e compared to the levels projected under current unconditional NDCs.

commitment and implemented policies is huge, while immediate and ambitious actions are needed. For decades, climate research has provided critical insights into the consequences of human actions and offered guidance for policymakers. However, as Fig.5.1 reveals, these efforts alone are insufficient, as scientific warnings are often ignored. This raises a pressing question about the role of research in addressing this crisis and what else researchers can and should do to drive meaningful change.

5.1.1 The concepts of sustainability and sustainable development

Sustainability has been defined by the United Nations Brundtland Commission (1987) as “meeting the needs of the present without compromising the ability of future generations to meet their own needs”. There are three pillars to sustainability: society, economy, and ecology. The visual representations associated with this concept are multiple, and source of controversy (see Purvis et al., 2019 for a review on the origin of these representations). Two of the most widely used are shown in Fig. 5.2. Cato (2008) refers to the left panel as the *classical view*, in which the economy, environment and society interact but are not interdependent. The right panel is identified as the *green economics paradigm*, conveying the crucial notion that economy should be a tool for society to prosper, which is only possible if society evolves together with the environment on which it relies.

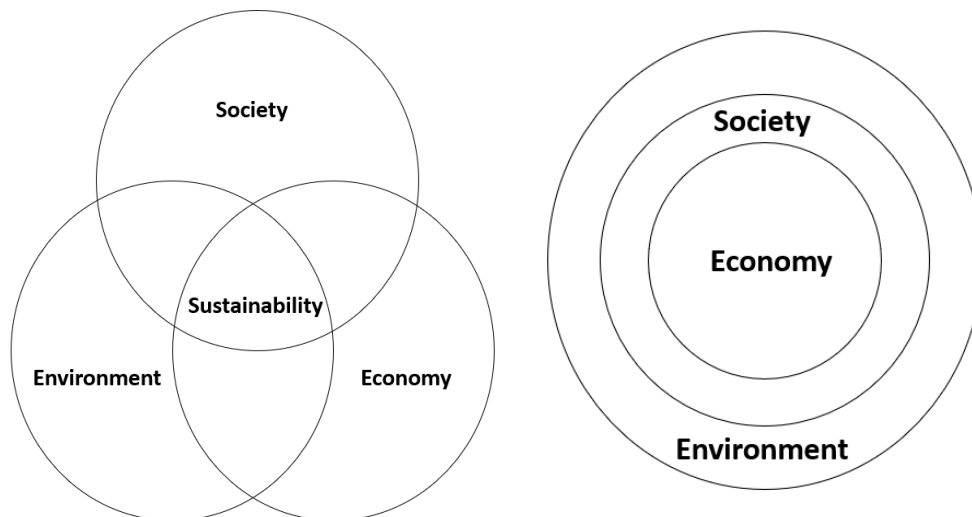


Figure 5.2: Two representations of the pillars of sustainability. On the left, the circles of economy, society and environment are of equal size, contributing equally to sustainability. On the right panel, environment is the base on which society lies, and economy is a part of society. This figure is taken from Cato (2008).

Sustainable development refers to the process toward achieving sustainability. The year 2015 probably marks the greatest achievement in the battle for a more equal, fair and sustainable world: not only was the Paris agreement adopted by 196 countries as an outcome of the Conference of Parties in Paris (COP21), but also all United Nations Member States adopted the 2030 Agenda for Sustainable Development. For the first time 17 sustainable development goals (SDGs) were defined, and the signatories committed to work together, in a global partnership, to achieve human rights for all. In 2016, the former director of the Stockholm resilience center Johan Rockström and the board member Pavan Sukhdev introduced the famous *wedding cake* model⁶, shown in Fig. 5.3.

This representation of the SDGs, highlighting the three pillars of sustainability, aims at emphasizing the pivotal role of the biosphere (the environment), the basic layer of the cake. If the biosphere is altered, threatened, shaken, the entire system could collapse; oppositely, if the economy is endangered, the impacts on the society and the biosphere are minimal.

The human-induced climate change, the biodiversity loss, and the recrudescence of wars are threatening sustainable development more than ever. In the midst of these crises, every discipline has a role to play, whether through advancing research, teaching the new generations, communicating to the general public, or collaborating with stakeholders to advance concrete solutions.

5.1.2 Ethical considerations in research

Ethics is the branch of philosophy asking the practical question “*What choices should we make?*”, what is morally right and wrong⁷, leading to reflection on values, principles and beliefs. It is defined as “*a system of moral principles, the rules of conduct recognized in respect to a particular class of human actions or a particular group, culture, etc.*”⁸. The first declaration on research ethics was adopted in 1964 in Helsinki, specific to medicine, with the aim of regulating research on humans. Research ethics is relevant for each research area, whether quantitative or qualitative, whether it deals with social or natural science. Weinbaum et al. (2019) investigated the common ethical principles between scientific disciplines through an extensive literature review and found ten of them: duty to society; beneficence; conflict of interest; informed consent; integrity; nondiscrimination; non-exploitation; privacy and confidentiality; professional competence; and professional discipline. They define the ethical principle of duty to society as “*Researchers and research must contribute to the well-being of society*” and the

⁶<https://www.stockholmresilience.org/research/research-news/2016-06-14-the-sdgs-wedding-cake.html>

⁷<https://www.britannica.com/topic/ethics-philosophy>

⁸<https://www.dictionary.com/>

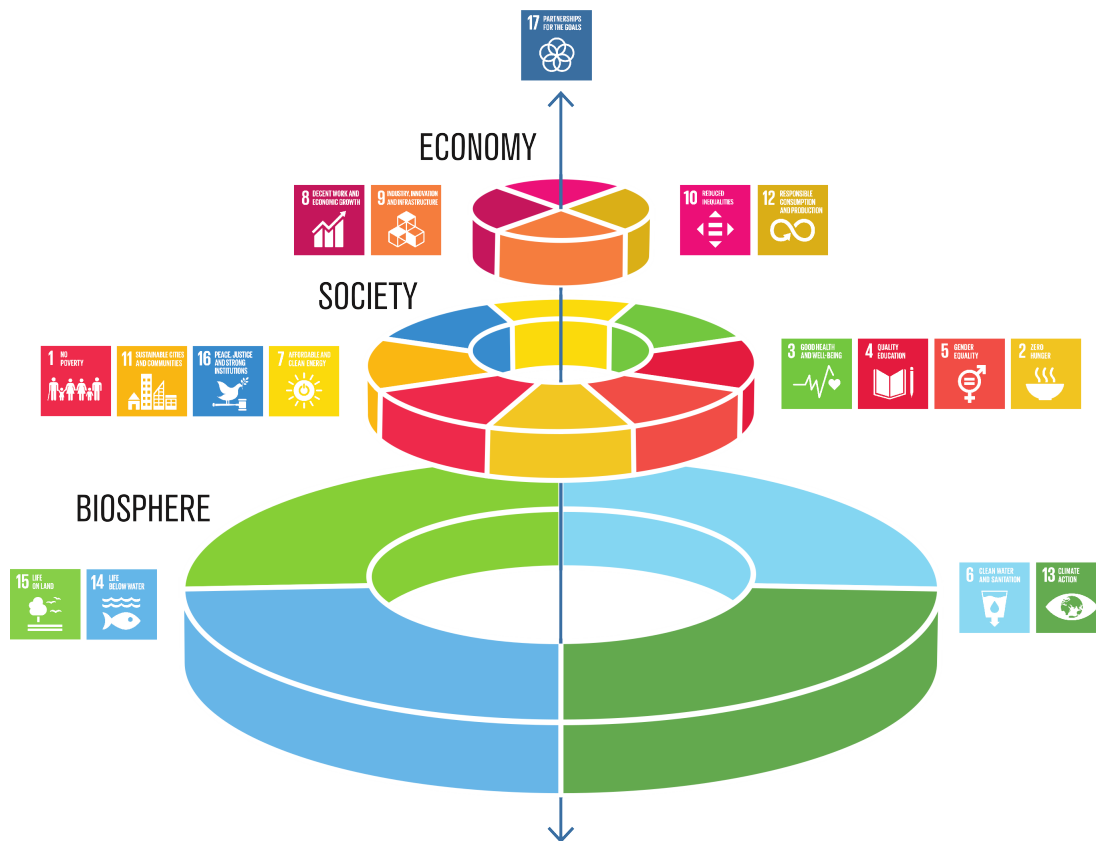


Figure 5.3: The wedding cake representation of the 17 sustainable development goals (more details on each goal can be found here: <https://sdgs.un.org/goals>). The bottom layer represents the biosphere, which supports the next layer: society. On top of society, the third layer, the economy, can flourish. Finally, the 17th SDGs *Partnerships for the Goals*, is the “cherry on top”. Credit: Azote for Stockholm Resilience Centre, Stockholm University.

principle of beneficence as “Researchers should have the welfare of the research participant in mind as a goal and strive for the benefits of the research to outweigh the risks”.

Since then some questions specific to astronomy have arisen. In which sense is astrophysics research contributing to the well-being of society? Do we, as astronomers, reflect on positive versus negative impacts of our research on society? The night sky can be observed from anywhere (modulo light pollution which is already an issue): who has not been amazed stargazing, and wondering about the mystery of life? Undoubtedly astrophysics generates curiosity, and sparks excitement toward science. It is one of the few scientific disciplines remaining highly attractive to students (Valls-Gabaud and Boksenberg, 2009). It is a bridge between cultures and countries, and it requires strong international collaborations regardless of the geopolitical context. It investigates meaningful questions, sometimes close to philosophy, such as “where do we come from?”, “what is time?”, “what was before us and what will be left after?”. So in a sense astrophysics research is contributing to the well-being of society, bringing fascination and fostering collaboration in a time of great challenges.

A serious effort is needed in the astrophysics community, to properly address the second question. IPCC Working Group II Co-Chair Hans-Otto Pörtner said: “The scientific evidence is unequivocal: climate change is a threat to human well-being and the health of the planet. Any further delay in concerted global action will miss a brief and rapidly closing window to secure a livable future”. The climate crisis is just the tip of the iceberg: the global crisis is way deeper than imagine, with the biodiversity crisis, the 6th mass extinction, and the extreme poverty to name but a few. In this context, are we, astronomers, levelling with the gravity of the current situation? What story will we tell the society in a few decades?

Various works have calculated and presented the mean carbon footprint of astronomers. Martins et al. (2021) estimated a 28 tCO₂/year annual carbon footprint for astronomers working at the French

institute IRAP. Knödlseider (2023) computed a lower limit for the carbon footprint of astronomical research infrastructures and obtained the impressive number of 60 tCO₂/year/astronomer⁹. To limit the increase in mean global surface temperature by the end of the century and avoid irrevocable changes and destruction, we need immediate actions (see Fig. 5.1). Including an environmental aspect in the ethical considerations of researchers seems to be a logical step to face the global challenges of the 21st century. Such a practice would stimulate and encourage discussions to quantify the impact of astronomical research on society when devising a new research project or a new observing facility. What would the discovery of another exoplanet mean, if 200 million of people lose their home and have to migrate due to climate change¹⁰?

On December 5th 2022, the CNRS ethics committee COMETS published the report *"Integrating environmental issues into research practices – An ethical responsibility"*¹¹. The first recommendation of the committee is *"Recognising that consideration of the environment is an integral part of research ethics; affirming in this respect the responsibility of research players to consider their activity in the light of environmental issues; this responsibility concerns not only the footprint of research practices but more generally the negative or positive environmental impact that the choice of a particular research subject and a particular way of addressing it (the research path) can have on the environment in the broadest sense, whether in the short, medium or long term."* Research on animals has been regulated since 1986, with specific bans adopted later on. The regulation followed on from various scandals and protests, with scientists advocating for animal welfare and respect. Perhaps time has come to also adopt ethical rules taking into account the environment, to ensure that advances in science are not made at the price of life destruction. Some might argue that such regulation would go against academic freedom¹²: if regulations on research topics and methods were to be set for the sake of sustainability, this would indubitably restrict research freedom and lead to resistance and indignation from a part of the research community. If done at this stage, it could be counter-productive, and well ahead of its time. Instead, fostering discussions and reflections, inventing new metrics (both for institution ranking and citations) and including the environmental impact within research ethics charts and proposal or grant criteria should be top priority. Astronomy organizations have an important role to play and a responsibility to institutionalize the value of sustainability (Burtscher et al., 2021).

5.2 Synergies with astrophysical research

5.2.1 Impact of climate change on astronomy

Climate change is impacting and will impact everyone everywhere. Astronomers will surely not be spared. Using data from the Very Large Telescope (VLT) located in Cerro Paranal in the Atacama desert (Chile) and past and projected climate data, Cantalloube et al. (2020b) suggested four impacts of climate change on our profession. Firstly, the increase in temperature at Paranal will lead to recurrent temperatures in excess of the cooling system abilities, resulting in *dome seeing* (Tallis et al., 2020). This turbulent phenomenon is created by temperature differences in the immediate surroundings of the instrument and can alter the functioning of adaptive optics. Secondly, turbulence will also increase in the surface layer located in the first tens meter above the ground. This has already started, as shown in Fig. 2 from Cantalloube et al. (2020b), with the seeing, a measure of the optical turbulence, increasing significantly since the '90s. A possible explanation of this phenomenon could be a modification of the global atmospheric circulation due to changes in the temperature gradient because of human induced climate change. The third consequence is the so-called *wind-driven halo effect*, specifically

⁹For comparison, a one-way flight from Paris to New York emits approximately 1 tCO₂/person. According to the Paris Agreement, the mean carbon footprint of each human should be below 2 tCO₂ per year by 2050 to limit the rise in global mean temperature to 1.5°C. However, such a temperature target is now unreachable as 2024 is set to be the first year to hit +1.5°C (Cuff, 2024). Consequently, the average carbon footprint per person will need to be reduced even further to mitigate future warming.

¹⁰see Brown (2008) for more detail on migrations due to climate change.

¹¹<https://comite-ethique.cnrs.fr/en/comets-opinion-integrating-environmental-issues-into-the-conduct-of-research-an-ethical-responsibility/>

¹²A universal definition of academic freedom does not exist; here we use the following definition: *"freedom of teachers and students to teach, study, and pursue knowledge and research without unreasonable interference or restriction from law, institutional regulations, or public pressure"*; see <https://www.britannica.com/topic/academic-freedom>.

impacting exoplanet imaging, which requires high angular resolution and high contrast observations. It occurs when the adaptive optics correction is slower than the atmospheric turbulence variation (Cantalloube et al., 2020a). This phenomenon, in Paranal, is due to the southern sub-tropical jet stream, and occurs more regularly during strong El Niño events. El Niño episodes are likely to intensify due to global warming, therefore increasing the wind-driven halo effect. Finally, extreme weather events will increase in every part of the world (IPCC, 2023c). Cyclones, droughts, floods, heavy precipitations, and extreme temperatures, among others, could further impact the ability of observing, and decrease the observing time available of the telescopes. They could also directly damage the observatories, the access roads, and the telescopes (see Kooten et al. 2024 for a review on this topic). The impact of these events will of course depend on the location of the observatories, and on the type of instrument used. Securing observing time is already now a difficult task: the impact of climate change on observations will surely sharpen the competition to get observing time. Raising awareness within the community is crucial to develop adaptation strategies and avoid putting further stress on a selection process that is already very selective.

5.2.2 A unique perspective on the Earth

From the landing of Apollo 11 on the Moon with the famous quote “*That’s one small step for man, on giant leap for mankind*”, to the most distant picture ever taken of the Earth by Voyager 1 on February 14, 1990, known as “the pale blue dot”, to the beautiful pictures taken by astronauts aboard the International Space Station (ISS), we have all had the opportunity to see the Earth wonderful, yet so fragile. However, as astronomers, we have another perspective, a unique one. Carl Sagan wrote, about the pale blue dot: “*From this distant vantage point, the Earth might not seem of any particular interest. But for us, it’s different. Consider again that dot. That’s here. That’s home. That’s us. [...] It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we’ve ever known.*” (Sagan, 1994). These words outline the uniqueness of our perspective on the Earth, and our duty to protect it.

We, as astronomers, know how rare life on a planet is. Even though 7360 exoplanets¹³ have been confirmed, the conditions under which life can develop are very fine-tuned. It requires the host-star to be stable enough, as strong solar winds can disrupt a planet’s atmosphere. The planet should be located at a suitable distance from the host star, have an atmosphere with the right composition, have a stable orbit and climate over geological time and an appropriate size. We, as astronomers, know that there is no planet B. So far, life has not been observed in any other place in the Universe, despite the billions of stars and planets. Enrico Fermi nicely pointed out this paradox (known as Fermi’s paradox), saying “*But where is everybody?*” (Jones, 1985) while having lunch with his co-workers Emil Konopinski, Edward Teller, and Herbert York. The latest reported that Fermi “*followed up with a series of calculations on the probability of earth-like planets, the probability of life given an earth, the probability of humans given life, the likely rise and duration of high technology, and so on. He concluded on the basis of such calculations that we ought to have been visited long ago and many times over*”. Many theories have been formulated to answer this paradox (see Cirkovic, 2018 for a review), for example the *zoo hypothesis* (intelligent extraterrestrial lives exist and are observing us without intending any contact) or the *great filter hypothesis* (there are barriers in the development of an intelligent species which are challenging to overcome, and might lead to self-extinction). Haqq-Misra and Baum (2009) proposed an alternative explanation to the paradox. They argue against intelligent civilization formation being very rare or inevitably destroying themselves. Instead, they formulated the *sustainability solution*. Intelligent civilizations may have existed, but their exponential growth defeated them, through resource exhaustion or self-destruction. Some may still exist, having understood the concept of sustainability and slow growth, therefore slowing down the development of technologies and resource use, including also space exploration, which makes them undetectable.

¹³Number as of December 5, 2024: <https://exoplanet.eu/home/>

5.2.3 Astronomers for planet Earth

Astronomers for Planet Earth (A4E) is a grass-roots movement born simultaneously at the San Francisco State University and at the European Astronomical Society (EAS) annual meeting in Lyon in 2019, under the impulsion of a few astronomers to act, very conscious about the climate crisis and the role we could play. More than 2000 members located in 80 different countries are currently part of the movement. A4E has several missions. Firstly, it aims at sharing the unique perspective that astronomers have on the Earth, and the science of Earth's warming climate. Secondly, discussions on solutions are also a top priority of the movement. Thirdly, it provides a platform for the members to interact, and a sense of community based on common values, together with resources to communicate on and teach climate change. Last but not least, it bridges the gap with society by providing information and outreach material on the climate crisis. All this work is carried out voluntarily.

It is impossible to quantify the devotion of the members over the past few years. In this section, I will outline some of the work carried out with regards to conferences. Conferences are at the very center of academic practices. Researchers are encouraged to travel to showcase their results and build international collaboration. Travelling to conferences likely impacts research visibility, as revealed by Berné et al. (2022), who found a correlation between scientific visibility as measured by the h-index (publication rate) and air travel in France. Wynes et al. (2019) also studied the relation between article citations and air travel. They found a weaker trend worldwide, with differences between different parts of the world. Regardless of the impact of conferences on scientific research, the carbon footprint of air-travel should be addressed, as they contribute to the human-induced climate change.

Burtscher et al. (2020) estimated for the first time the carbon footprint of travel to a large astronomical meeting, the EAS yearly meeting in 2019. Hosted in Lyon, this event gathered 1240 astronomers. Burtscher et al. (2020) compared the carbon footprint of this meeting with the one in 2020, which was fully online due to the COVID-19 pandemic: not only did the number of participants increase significantly thanks to the more inclusive online format, but also the carbon footprint was estimated to be 3,000 times smaller than for the in-person EAS 2019. Gokus et al. (2024) quantified the global emissions associated with travel of astronomers to conferences and workshops using data from 362 meetings. They found that the total distance travelled by the community over a year is 1.5 times the distance between the Earth and the Sun, for an average carbon footprint of 1 tCO₂ per participant per meeting. Gokus et al. (2024) quantitatively investigated three types of alternative meetings: hubs, hybrid, and fully online meetings. “The Future of Meetings” (TFOM)¹⁴ is actively working on improving the quality of such meetings (Moss et al., 2022). A successful example of online meeting is the fully online A4E symposium organised in 2022 (Wagner et al., 2023): more than 500 A4E members based all over the world gathered virtually over a week to discuss topics related to astronomy and sustainability.

All the articles mentioned in the previous paragraph have been written by members of A4E. This is a non-exhaustive list of works which reflects only the very tip of the iceberg. Many more activities are carried out on a daily basis, through teaching, outreach, and research by members and non-members of A4E. Rector (2024) gathers a very complete state of the art on the role of astronomers in the climate crisis: in their Chapter 1 they write: *“Thinking about climate change is often overwhelming. It can feel that one person can't make a difference”*. As further discussed in their Chapter 12.3, this is precisely the strength of A4E: a community sharing the same values, the preservation of life on Earth, the fight for a fairer world, acknowledging our special role as astronomers, a community at the service of society, sharing resources to increase our impact. The availability of these resources and the support of the community are one of the drivers that lead me to create and teach a course on sustainability in academia.

5.3 Teaching sustainability in academia

Education shapes the minds of the future. It instils values, thoughts, methods in students, providing them with tools to apprehend the world in which they grow. As the forestry engineer Baba Dioum, once said *“in the end we will conserve only what we love, we will love only what we understand, and we will understand only what we are taught”*. With this in mind and with the strong conviction that, regardless

¹⁴<https://thefutureofmeetings.wordpress.com/about/>

of their field of study, students can make a change, I offered an elective course named *Sustainability in academia*. In this section, I describe the course content, the learning methods, and the outcome of the course.

5.3.1 Academia and its pivotal role in the transition

Academia is defined by the Cambridge dictionary as the *Teaching, studying, and scientific work that happens in colleges and universities*. Higher education as provided by colleges and universities is a very powerful platform for individual and collective transformation. The challenges we are facing now require more than ever in depth reasoning, innovative transformations, and collaboration. Žalėnienė and Pereira (2021) identified a few key roles higher education can play. Firstly, interdisciplinarity is necessary to tackle the global challenges. Universities can bridge the gap across disciplines and develop projects incorporating sustainability principles. Secondly, not only higher education practices impact students and academic staff, but they can also reach the general public through outreach events. Thirdly, higher education shape the future decision makers, workers, citizens. Instituting sustainability values which will grow within people is a very important step. Finally, universities are a microcosm, requiring buildings, energy, food, and interaction between different stakeholders. They can lead by example, using green energy, efficient isolation, biodiversity hubs, encouraging everyone to get involved in sustainable projects like common gardening area or biodiversity hubs, initiating many activities that can be replicated.

Despite the pivotal role that academia has to play in the transition, several barriers impede change to take place. Urai and Kelly (2023) draw a parallel between these barriers and the one impeding climate action, namely lack of time, overwork, and inertia, trapped by a system based on overproduction and competition. They suggested that the main obstacle to transformation lies at the very heart of academic culture. Short term contracts, pressure to publish leading to fast science, work overload, mental illness, and precarity are unfortunate realities of academia. In such environment, no time nor energy is left to deal with the outside world and tackle the challenges we are facing.

So, how can we break this spiral? Urai and Kelly (2023) argue that we first need to change our own perception of our job and of academia. Inspired by the *Doughnut economics*, concept introduced by Kate Raworth (Raworth, 2017), they introduced the *doughnut academia*, illustrated in Fig. 5.4 with two concentric circles. The inner social foundation represents what should be provided by universities, such as for example secured job and careers, with sufficient resources and not precarious, or service to society, to make an impact outside the *ivory tower*, providing high quality education, free of the influence of lobbyists. The outer human and planetary ceiling represent resources that universities should not overshoot, such as the human load, decent workload and space for any employee to think and work stress-free, or the planetary impact, embedding our research work in a bigger context and limiting the exponential use of resources on the pretext of more and more science. These boundaries are currently being overshoot in many institutions.

Following up on this assessment, Urai and Kelly (2023) suggested *seven way to think like a 21st-century scientist*, to start shifting our mindset and work toward a more sustainable academic world. Among the seven ways, four are of particular interest for Sect. 5.3.2. Firstly, we should *change the goal*, from seeing universities as business, with students as the main consumers, to seeing universities through the academic doughnut perspective, a place where we can thrive, bring benefit to the society, grow as persons, have an impact, and make a change. Secondly, we should *get savvy with the systems*, stop seeing ourselves as cogs in a machine but rather as gardeners of the academic system, feed it, nurture it, cherish it. Thirdly, we should *see the big picture*. Instead of viewing our work as separated from the world around us, we should see it as embedded in the society and the planet, for a greater good. Finally, we should *create to regenerate*, and handle the precious resource that is time differently, starting with slow science instead of racing for publications, talks, and travelling always more. Even though education is a long term investment, with a slow impact (between 10 and 30 years, Otto et al. 2020), it plays a crucial role in the shift of mindset, and teaching is very important to the transformation of academia. Bowen (2018) suggested that the impact of higher education on an adult last for most of their life (between fifty to sixty years on average).

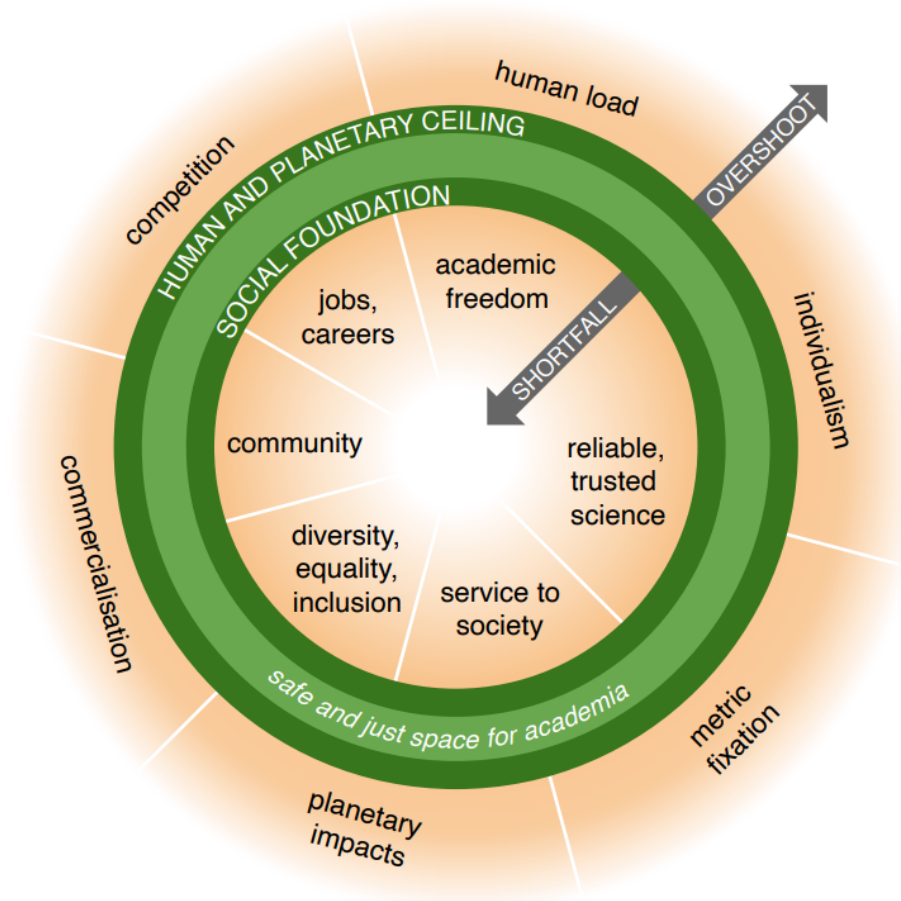


Figure 5.4: The doughnut academia, taken from Urai and Kelly (2023). This figure has been inspired by the doughnut economics (Raworth, 2017). The inner social foundation represents what should be provided by universities. The outer human and planetary ceiling represent resources that universities should not overshoot.

5.3.2 Course content

Convinced that the global crisis concerns every human being, regardless of their job, origin or location, that academics have an ethical duty regarding current and future generations, and that students should be made aware of the global situation, to comprehend it, reflect on solutions and feel empowered, I have created the course *Sustainability in academia*. This course has been offered at the Department of Astrophysics of the University of Vienna, as part of the new curriculum for bachelor and master students in the autumn semester 2023. It falls in a module called Science and Society, which addresses topics that include gender equality, diversity, climate change, and sustainability. Thanks to its success and the very positive feedback received from the students, the course was extended to a broader audience in the spring semester 2024, including students coming from astrophysics, informatics, biology, environmental science, and business school. I kept a similar course structure throughout the two semesters, and I adapted the content to take into account the variety of background. The course accounts for 2 ECTS which corresponds to 9 hours of lectures across the semester. The learning objectives were:

1. explain the concept of sustainability and the state of climate change;
2. discuss the different issues regarding sustainability in academia;
3. propose, evaluate and prioritise the solutions to improve sustainability in academia;
4. debate and defend a position, and form compromise.

Apart from the introductory lecture and the final assessment, I have decided to divide the course into three blocks. The first part is about *Sustainability in higher education*. It starts by representing the state of the art of higher education in the world, to reflect that attending university is a privilege. For instance, the average years of schooling is strongly correlated with the GDP per capita (Ritchie et al., 2023). Emphasis is also made on the fact that climate change is still absent of many curricula, 47% of national curricula make no reference to it (UNESCO, 2021). Then, using the results presented in Helmers et al. (2021), I introduced the notion of carbon footprint and incorporated data on the global carbon footprint of universities. The objective is to offer students a perspective on the scale of emissions in various categories at the university level, specifically classified into three main sectors: energy, mobility, and other. Energy and mobility are the main contributors to overall emissions. I also delved into the challenges slowing down change in higher education transformation. On the one hand, universities must adapt to external pressures and expectations arising from heightened competition, accreditation requirements, funding considerations, and more. On the other hand, simultaneously, they have to be accountable to society, generating public value for both present and future students, as well as other stakeholders (Argento et al., 2020; Žalėnienė and Pereira, 2021), creating an apparent conflict and inertia in the transition. Finally, I emphasized the role of teaching in creating the next generation of leaders and empowering students into action, using resources from UNESCO¹⁵.

In the third lecture, I tackled *Sustainability in research*. During the fall 2023, I delved into the carbon footprint of astrophysical research (Jahnke et al., 2020; Martin et al., 2022) as the students were all from the bachelor or master in astronomy. During the summer semester 2024, I included information on the carbon footprint of biophysics laboratories (Giuglaris and Seze, 2023), and gave ample time to students to reflect on the emission of their research field. I emphasized the contribution of mobility to the footprint of researchers, and the correlation between CO₂ emissions from flights and the academic position of travellers (Stevens et al., 2020). I also explored the impact of travelling on scientific work and publications (Berné et al., 2022; Wynes et al., 2019).

The fourth lecture was the most crucial in the series. I explored various stakeholders in higher education (Chapleo and Sims, 2010) to offer students insights into potential actors and their roles, placing them at the centre of the transition as key stakeholders. This enabled the students to consider the problem of sustainable transition from various angles. I also presented solutions existing in several universities to increase sustainability such as the student initiative Green Campus, addressing sustainability issues at the University of Cape Town¹⁶. Some of the teaching methods employed in this session have been inspired by the climate fresk workshop¹⁷ and are presented in Sect. 5.3.3, together with the final assessment.

5.3.3 Pedagogical approach

Throughout the lectures, I focused on creating a positive course environment, conducive to discussion, to make students feel safe and comfortable to speak up. The climate crisis triggers various emotional responses, all different from individual to individual, which should be acknowledged and expressed to move from feeling to acting. In general, I tried to apply the 3 H model for teaching “*head, heart, hands*”. *Head* refers to the cognitive aspect (i.e., how students think), encouraging them to analyse and reflect on an issue. *Heart* refers to the affective aspect, emotions and feelings, how do they feel about a specific task or question. Finally, *hands* refer to action and practicality. The integration of these three dimensions emphasizes the importance of nurturing not only intellectual growth but also emotional intelligence and the ability to apply acquired knowledge in real-world scenarios. As my main objectives for the course were to foster discussions and empower students into taking action, ample time was devoted to interactions. At the beginning of each lecture a quiz would either recap the previous lecture or introduce a few concepts to be explored on that day.

Throughout the course, students had to defend and discuss their position on different questions relating to sustainability. These frequent debates prepared them for the final assessment, which took the format of a Model United Nations (MUN) debate. Such a format was elected to shift from the usual

¹⁵<https://unesdoc.unesco.org/ark:/48223/pf0000246888>

¹⁶<https://acdi.uct.ac.za/green-campus-initiative>

¹⁷<https://climatefresk.org/>

competition present in debates to a collaboration-oriented mindset, an aspect crucial to tackling the current challenges humanity is facing.

The set-up was different between the two semesters, therefore so were the teaching methods used. In the winter semester 2023 (WS23) the attendance was possible in-person only and for students in astronomy while in the summer semester 2024 (SS24) I designed the lectures to be hybrid to follow-up on the request of several students and I opened the attendance to the entire faculty. Teaching in hybrid is very different and more challenging than in person or online only. Consequently, I separated the teaching methods into two different sections (Sect. 5.3.4 and Sect 5.3.5).

5.3.4 Winter semester 2023

Most of the teaching methods used during this semester involved in person discussions in small groups. During the fourth lecture on stakeholders and solutions, I employed a teaching method inspired by the Climate Fresk workshop which worked very well. I gave the students colorful post-its, assigning a different color to each stakeholder, and asked them to brainstorm practical solutions for each stakeholder. They then placed their post-its on the blackboard, populating a graph that showed “easiness of implementation versus impact.” This technique is commonly used during the debriefing part of the Climate Fresk workshop. Having the students place their post-its on the blackboard added some physical movement and helped visualize the various groups of solutions. This exercise is suited to different learning styles: visual learners could focus on the post-its and their positions on the graph, auditory learners benefited from discussing where to place the post-its with peers, and kinaesthetic learners engaged through the physical activity of moving around the room.

As mentioned in Sect. 5.3.3 the final assessment was a MUN debate where students had to play a role, defend a position and form compromise with the others in order to efficiently collaborate and reach an agreement to solve an issue. During WS23 the focus of the debate was astrophysical research as all students were enrolled in this field. Students formed groups of two or three and selected a country that they would represent during the MUN debate. The goal was to debate two problems:

1. How can higher education in astronomy be made more inclusive and sustainable?
2. How can conference/workshop organizers ensure that participation in astronomy conferences/-workshops are inclusive, representative and maintain a minimal carbon footprint?

Countries represented were Chile, China, the Netherlands, South Africa, Turkey, and the USA. The outcomes of the question number one were:

- create yearly/regular reports from each institution about environmental/inclusivity/sustainability status, to increase transparency and communication on that matter;
- make it mandatory for all universities to offer climate change courses;
- heated discussion on data sharing and public availability.

A more clear agreement was reached to answer the second question:

- develop a new tool for all countries to use for hybrid conferences, also including opportunities for interaction, as desired by South Africa, and tailored for astronomical use;
- enhance the efforts to reduce travelling when going to in person conferences. This could be made by developing local conference hubs, in each continent, with some joint online sessions. Some speakers could be broadcasted all over the locations;
- pledge to increase percent of online-only conferences: 25% was proposed by the USA as an example (not fixed/hard number), but this could be difficult to achieve in some cases.

Overall, the students really stick to their role. By carrying preliminary research on the country they represented, they got to understand the political and environmental context and propose accurate discussion points and positions. This exercise gave them an insight into international negotiations, and the challenges of reaching an agreement between countries with diverse cultures, politics, and history.

5.3.5 Summer semester 2024

The hybrid format that I offered in the SS24 is more challenging in many aspects and required careful adaptation of my teaching methods in order to include online participants as much as in-person ones.

5. Sustainability in astrophysical research

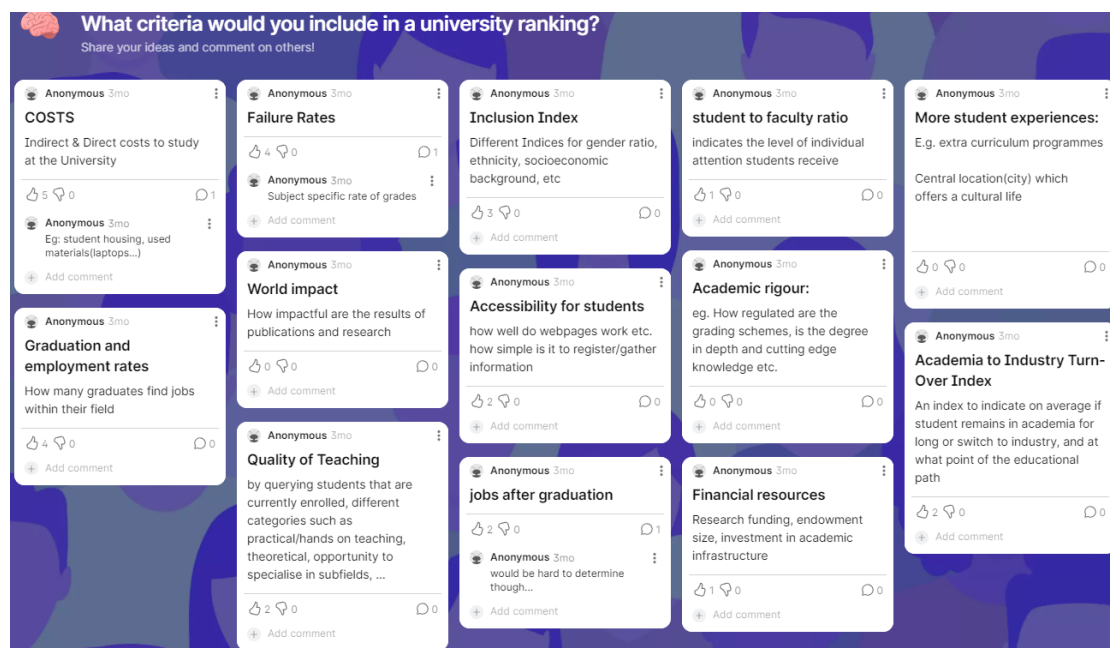


Figure 5.5: Answers from the students to the question *What criteria would you include in a University ranking?*.

A tool that I broadly used to foster discussions in hybrid mode is Padlet¹⁸. Different set-up are possible depending on the type of exercises. The advantage is that students can simultaneously modify the document, add arrows, vote for an answer that they support. As an example, during the second lecture where we talked about sustainability in higher education, we went through the Times Higher Education ranking of Universities and studied the criteria for the ranking¹⁹, to follow-up on the recent news that the University of Zurich stopped providing data for the ranking. I asked the students to pair-up and think about the criteria they would include in a university ranking, using Padlet. Their answers are shown in Fig. 5.5. In only ten minutes they managed to define thirteen criteria that they would include to take into account sustainability, fairness of access, diversity, and inclusion among other in the ranking. This exercise was the starting point of a very fruitful discussion, and helped students to determine key areas where improvement are needed. For instance, when referring to the cost of studies, we mainly mention the direct price (tuition fees principally). However, the real price of studying is considerably increased, especially in Europe where tuition fees are low in many countries, when taking accommodation, transportation, incidental living costs. Access to higher education is linked to parent's income as explained by Bonneau and Grobon (2022) using statistics in France. I used Padlet to work on other questions such as “Should research teams be given a carbon budget?” Overall, I have noticed that asking open questions is more efficient to foster discussions and encourage students to be creative than YES/NO questions, which are nevertheless good to force students to choose their party.

For the MUN debate, unlike in the past semester (see Sect. 5.3.4), I decided to focus the discussion at the university level. This decision was further motivated by the students' diverse backgrounds, which are ideal for a fruitful discussion. The debate question was: “How can the University of Leeds transition to carbon neutrality while fostering long-term sustainability and incorporating environmental awareness into the mindset of students and staff?” The set-up resembled a university council. Students had to choose between representing a department (astrophysics, biology, environmental science, business school, informatics) or a person (student representative, dean, chair, secretary for the debate). Each role came with a description of specific behavior (for example, the dean was reluctant to change, while the student representative was very proactive about creating a more sustainable working environment).

¹⁸<https://padlet.com/>

¹⁹https://www.timeshighereducation.com/sites/default/files/breaking_news_files/the_2021_world_university_rankings_methodology_24082020final.pdf

Each participant had to prepare a paper beforehand to present their solutions. The chair was responsible for setting the agenda and moderating the debate and the secretary for taking detailed notes and handing over a report. The structure of the debate was very different from the past semester as I did not intervene at all, letting the students fully autonomous during the two hours of discussion. Autonomously they reached an agreement and wrote a proposal that included solutions such as establishing a committee responsible for curriculum development to create mandatory interdisciplinary courses on sustainability across all departments. My main takeaway from teaching this semester to an interdisciplinary audience is the power of collective intelligence. I have seen that students can effectively learn, understand, and take action when they are provided with the space and security to do so.

5.3.6 Feedback from students

In order to further improve the course, and to assess the effectiveness of my teaching methods, I asked students to fill in a feedback form at the end of each semester. The top panels of Fig. 5.6 present the results of students enrolled in the WS23 (left panel) and in the SS24 (right panel) to the three following questions:

- Using a scale from 1 (disliking) to 10 (liking), please rate your satisfaction with the MUN debate as an assessment format.
- On a scale from 1 (not comfortable at all) to 10 (very comfortable), how comfortable did the course environment make you feel, and was it conducive to meaningful discussions?
- Overall, on a scale from 1 (not satisfied at all) to 10 (very satisfied), how satisfied are you with the course?

Overall the students really enjoyed the course environment and felt safe to speak-up. This aspect is crucial when dealing with sustainability and climate change as these topics drive a lot of emotions (Neckel and Hasenfratz, 2021). Although already high in the WS23, the overall satisfaction with the course and the MUN debate increased in the SS24, with a mean value of satisfaction with the course going from 8.6 to 9.7. The increase of student satisfaction is likely linked to a better communication and construction of the course from my side regarding the learning objectives (LO), as shown in the bottom panel of Fig. 5.6, representing their answers to the question “On a scale from 1 (not adequately prepared) to 10 (very well prepared), please rate how effectively the course has equipped you to achieve the learning objective *X*”, with *X* going from 1 to 4, representing the LO previously introduced in Sect. 5.3.2. Students enrolled in the SS24 (right panel) considered being better prepared than students enrolled in the WS23 (left panel) for the four LOs, with a difference in the mean value of about one point for each of the LO.

It also worth noting that one student enrolled in the WS23 found it challenging to engage in discussions, particularly during the MUN debate. This student also attributed a low grade to the completion of the LOs.

The increase in student satisfaction and learning effectiveness between the two semesters could have several explanations. Firstly, I took into account the feedback from the previous semester and adapted some teaching methods or parts of the course that were less effective. Secondly, with a semester of experience teaching the course by myself for the first time, I undoubtedly felt more comfortable with both the topic and my role as a teacher during the second semester, thus transferring knowledge more efficiently. Finally, I am strongly convinced that interdisciplinarity helped stimulate fruitful discussions among students, despite the hybrid mode of the second semester. More than interdisciplinarity, interculturality also played a crucial role. In the SS24, a few exchange students were also present, coming from the USA, Bangladesh, India, and Australia.

5.3.7 Final lecture

To tackle the global crisis, we need not only to inform students but also to empower them to use their knowledge in the real world and take action. With this in mind, and to wrap up the semester of courses nicely, I opened the last lecture to suggestions from students. During both semesters, they expressed a desire to invite guest speakers.

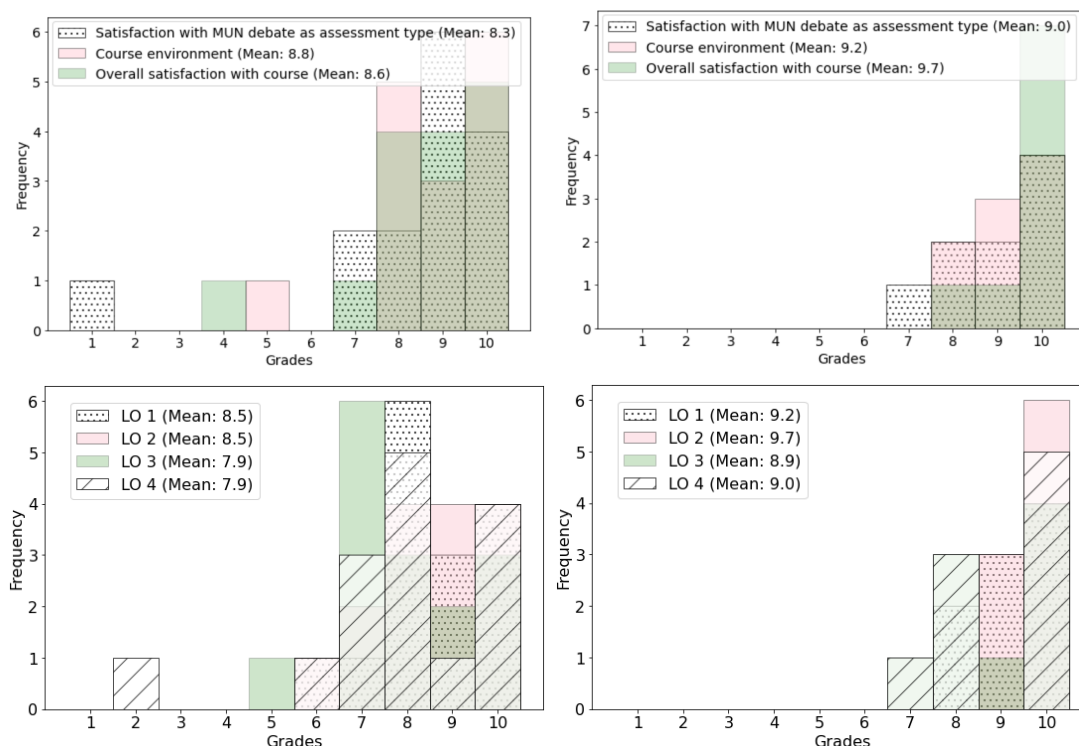


Figure 5.6: Distribution of answers from the students to questions on the satisfaction with the course (top panels) and on the accomplishment of the learning objectives (bottom panels). The answers of the students from the first semesters are plotted on the left panels and the answers of the students from the second semester on the right panels.

The Conference of Parties 28 (COP28)²⁰ took place from November 30, 2023, to December 13, while my course was ongoing in the WS23. Therefore, two guest speakers were invited to share their experiences attending a COP, one of whom attended COP28 in Dubai. The students particularly benefited from this final lecture. They actively interacted with the external speakers, asking many relevant questions, demonstrating good competence in the course topics, and showing high interest and motivation to understand international negotiations.

In the SS24, at the students' request, I invited the student assistant of the Sustainability Office of the University of Vienna to present their office, their work, the university's carbon emissions strategy, and the role students could play in the bigger picture. The discussion was very dynamic and fruitful, with students showing a strong interest in understanding how they could become more active. Two of them really became active and reached out for guidance and supervision in their journey to work for a more sustainable world.

5.3.8 Challenges and barriers to action in students

Teaching the course "Sustainability in Academia" was enriching for me. I am particularly interested in understanding the causes of inaction, and the many discussions and reflections that arose during the two semesters provided me with some insights into the challenges and barriers to action that students face, and later, that society as a whole faces.

One particularly striking moment was when I asked students during an informal discussion, "Do you feel empowered within the university context?" To my surprise, not only did they not feel empowered, but they also believed they had no say in their studies or opportunities to act. If students graduate from university feeling like passive participants in the educational system, how can we expect society—which

²⁰<https://unfccc.int/cop28/5-key-takeaways>

education helps to shape and instil values—to act and change the trajectory of a flawed system? Interestingly, the causes of inaction in students are very similar to the one presented in Sect. 5.3.1 (Urai and Kelly, 2023). After feelings of powerlessness, the second most cited reason is the lack of time. Many students have to take part-time jobs to fund the cost of higher education (see Sect. 5.3.5), leaving them with neither the time nor the mental space to address the climate crisis. The third reason, partly linked to the second, is an impression of disconnection between their field of study and the global crisis. In particular for students coming from Science, Technology, Engineering, and Mathematics (commonly referred to as STEM disciplines) not directly linked to climate change, it appears hard to combine their drive for their field with being useful to society in a context of crisis. Here, I did not intent to quantify the sources of inaction, and they are surely not complete. These are just some of the many plausible causes mentioned by the students across the semesters.

5.3.9 Solutions to these challenges

Ending this section on challenges and barrier to inaction without suggesting avenue for solutions would be the antithesis of empowerment. Therefore, I will introduce here some potential ways to deal with each of the aforementioned issues.

The first solution is to “*teach with inspiration, not fear*” (Bennett, 2024). Students are the next generation of leaders, politicians, economists, researchers, workers, doctors. Regardless of their field and position, they will have an impact on the world not only through their job but also through their interaction with other human beings. That is one of our duty as teachers to instil humanitarian values and to empower them into shaping the future they want to see. Presenting only the causes and consequences of climate change, without going through *realistic* solutions, tailored to the audience, is one of the main cause for inaction. Some statistics to point out this fact are given in the UNESCO website²¹. One of the key figures presented in the website revealed that while 40% of teachers feel confident teaching the cognitive aspects of climate change, only 20% can effectively explain how to take action. Offering dedicated training to teachers, and giving them the time and mental space to effectively follow these training could be a solution to help teaching with inspiration.

To solve the issue of lack of time, slot should be arranged in the curricula. Courses on sustainability could be made mandatory in every discipline in universities. This has already been done in some institutions²². Involving local stakeholders, NGOs, politics, in these courses would be a way to bridge the gap with the real world and to go from providing knowledge to students to encouraging them to apply their knowledge.

Finally, the last point on the apparent disconnection between the study field and the crisis can be overcome incorporating climate change in already existing courses, as mentioned by Leal Filho et al. (2023). Encouraging interdisciplinary research projects could also be a solution. Many pieces of knowledge are transferable from a discipline to another and the benefit of interdisciplinary teamwork is no longer to be proved. Curious to apply my analytic and programming skills to communicate on climate change, I founded an interdisciplinary project, the PLEES index, together with three colleagues from astronomy and Earth science.

5.4 An example of interdisciplinary project: The PLEES index

Recently, the Working Group III from the IPCC released the third and final report on the impacts of climate change, adaptation and vulnerability of countries (IPCC, 2023b), revealing that Paris agreement’s initial target to limit the rise in mean global temperature to 1.5°C above pre-industrial level was likely unreachable. While the 2°C target is still possible, they urge to act before it is too late.

A way to trigger a fast change in society relies on reaching the social tipping point. Malcolm Gladwell describes it as “*that magic moment when an idea, trend, or social behaviour crosses a threshold, tips, and spreads like wild-fire*” (Gladwell, 2000). Otto et al. (2020) show that information feedback could very rapidly trigger this social tipping point. For example, informing consumers on the carbon footprint

²¹<https://www.unesco.org/en/sustainable-development/education>

²²<https://universitetslararen.se/2023/10/24/climate-course-to-be-compulsory-in-barcelona/>

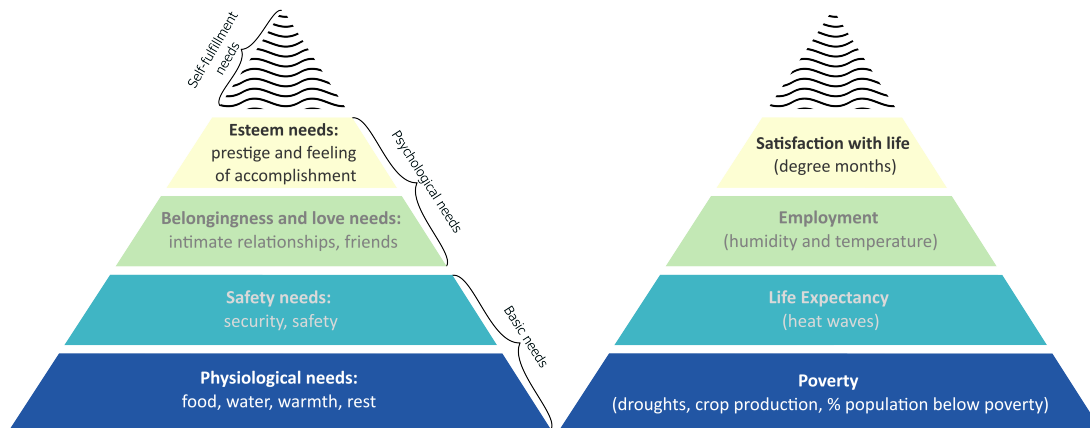


Figure 5.7: The pyramid on the left shows the hierarchy of needs proposed by Maslow (1943). The pyramid on the right shows the structure of the PLEES index, which is inspired by the Maslow pyramid and uses quantifiable properties to provide a way to measure the achievement of each level in the pyramid. The top two levels of the left pyramid are merged together in the right one, for simplicity.

of their lifestyle choice and their purchases, could lead to awareness, followed by a change in their way of consuming, potentially leading to the decarbonisation of society. Such social dynamics have already been observed on various topics such as the legalization of women suffrage or gay-marriage²³. One way to get closer to the social tipping point is to inform people on the effect of climate change on their life. Different indexes already exist to quantify the impact of climate change on countries. For instance, the *Notre Dame-Global Adaptation Index*²⁴ aims to estimate the adaptation of each country to climate change, yearly, in order to help decision makers build resilient policies. Introduced more recently, the *Children's Climate Risk Index*²⁵ deals with the exposure of children to the climate crisis. To date, no index fully addresses the social, psychological, and economical impact of climate change, for different global warming scenarios and different timescales. With the aim to raise awareness about the impact of climate change on developed countries, we constructed the Poverty, Life Expectancy, Employment, and Satisfaction (PLEES) index, based on the hierarchy of needs developed by Abraham Maslow. This index takes into account the psychological, social, and economical impact of climate change worldwide and can be projected under different scenarios of climate change. This research project is a collaborative effort conducted under the Vienna International School of Earth and Space Sciences. In this section, I will detail the Poverty (P) and Employment (E) indices, as defining them was part of my task within this collaboration. The remaining indices, LE and S, are provided in Appendix A.

5.4.1 Methods

Maslow (1943) argued that human motivation is driven by needs, and identified five hierarchical levels of human needs. These levels are often depicted in a pyramid (see the left panel of Fig. 5.7): the lowest level comprises basic physiological needs, such as breathing and eating; once these primary needs are satisfied, individuals can progress up the pyramid to higher levels, culminating in the achievement of personal satisfaction and feeling of accomplishment. As basic needs are fulfilled, higher needs and desires emerge. Using the representation of this hierarchy as a pyramid, we first linked each level of the pyramid to an indicator. The mapping is schematically shown in Fig. 5.7, where we compare a representation of Maslow's hierarchy of needs (on the left) to the corresponding pyramid illustrating the quantifiable and measurable quantities that we use to construct the PLEES index (on the right). For example, we defined the poverty as the basis of the PLEES pyramid, equivalent to the physiological need in Maslow's hierarchy. Then, each indicator is linked to one or more climate related phenomena based on a careful correlation analysis. The connection between each need, the index we created

²³<https://www.bloomberg.com/graphics/2015-pace-of-social-change/>

²⁴<https://gain.nd.edu/our-work/country-index/rankings/>

²⁵<https://data.unicef.org/resources/childrens-climate-risk-index-report/>

Need	Index	Indicator	Correlated variable
Physiological	Poverty (P)	Poverty rate	Consecutive dry days, cereal crop production
Safety	Life expectancy (LE)	Life expectancy	Number of extreme heat day
Belongingness	Employment (E)	Unemployment rate	Heavy labor productivity loss due to heat
Esteem	Satisfaction (S)	Satisfaction with life index	Gross Domestic Product, Degree month

Table 5.1: This table provides an overview of the setup of the PLEES index. The first column lists the four needs from Maslow's hierarchy that we considered. The second column shows the corresponding indices we created. The third column presents the existing indicators that serve as the basis for our calculations. In the final column, we list the variables impacting each indicator.

based on already existing indicators, and the variables impacting them is shown in Table 5.1. The PLEES index is the sum of the P, LE, E, and S indices and has values between 0 and 4. We compute it for each country with available data and project it under different Representative Concentration Pathways (RCPs) scenarios.

RCPs are scenarios of concentrations of anthropogenic greenhouse gas emissions as a function of time, adopted by the IPCC to understand the effects of different efforts to curb further emission. Among others, they provide information on the global temperature changes (sea and land), sea level changes and extreme weather events. Under the *intermediate scenario - RCP4.5*, which is the most probable one given the current policies, emissions should peak around 2040 and decline after. The global temperature at the end of the century is predicted to increase by an amount between 2°C and 3°C. According to the *pessimistic scenario RCP8.5*, minimal efforts will be made to transform the energy sector from the traditional one, powered by fossil fuel, and personal and freight mobility will still be dominated by motorised vehicle with internal combustion engines burning fossil fuel. The added unconstrained emission will cause a larger increase of the average global temperature, sea level rise and extreme weather events compared to RCP4.5²⁶. All will result in high levels of adaptation costs to cope with higher temperatures, droughts, floods and increasing sea levels affecting the coastal cities by the turn of the century and beyond. According to this scenario, the average temperatures are expected to continue to increase for the duration of the model predictions, until the 26th century. The mean global temperature at the end of the century could exceed +5°C with respect to pre-industrial mean surface temperature. Other scenarios exist, but we decided to focus on the two mentioned above to show the most likely pathway and the worst case scenario as an incentive to take immediate action.

5.4.2 Construction of the P index

The first level of Maslow's hierarchy of needs corresponds to physiological needs, like eating, drinking, and sleeping. To construct the P index, we used a methodology similar to the one used by Krishnamurthy et al. (2014), who developed an experimental Hunger and Climate Vulnerability Index (HCVI). They defined the HCVI as a combination of exposure (*Exp*), sensitivity (*Sens*), and adaptive capacity (*AC*), with the vulnerability index calculated as:

$$V = Exp \times Sens \times AC. \quad (5.1)$$

Droughts affect agricultural yields and, consequently, food security (Gornall et al., 2010; Gregory et al., 2005; Lobell et al., 2008). Krishnamurthy et al. (2014) found a positive correlation of 0.412 between the frequency of droughts and exposure to hunger, identifying droughts as the primary climate phenomenon linked to food insecurity. Cereal crop production has the highest correlation coefficient with the sensitivity component (-0.611), while the poverty rate shows the highest correlation with adaptive capacity (0.799). Therefore, to compute the *P* index, we selected one indicator per component:

²⁶RCP8.5 predicts an average temperature increase of 4.4°C and relative sea rise of 0.63 m by 2080-2100 over baseline values set between the years 1986-2005.

the number of droughts (Consecutive Dry Days, CDD) for exposure, cereal crop production (CCP) for sensitivity, and the total population below the poverty line (PR) for adaptive capacity. To normalize each component for each country i to a value between 0 and 1, we define them as follows:

$$Exp_i = \frac{CDD_i}{365} \quad (5.2)$$

$$Sens_i = \frac{CCP_i}{\max_j CCP_j} \quad (5.3)$$

$$AC_i = 1 - \frac{PR_i}{100} . \quad (5.4)$$

Our final index, P , is defined as the average of the three components:

$$P_i = \frac{(1 - Exp_i) + (1 - Sens_i) + AC_i}{3} . \quad (5.5)$$

Values of P range from 0 to 1; a P value close to 0 is associated with countries with a high poverty rate and exposed to heat waves as probed by a high number of CCDs.

Richardson et al. (2018) adapted the HCVI index from Krishnamurthy et al. (2014) to enable future projections under different climate change scenarios. To do so, they treated each component of the index (exposure, sensitivity, and adaptive capacity) independently. For exposure, they used the output of climate models on the average length of extreme weather events such as droughts. Projecting indicators such as the sensitivity (in our case cereal crop production) and adaptive capacity (poverty rate) is more challenging as the outcome depends on how society adapts to climate change. Therefore, Richardson et al. (2018) used adaptation scenarios for these projections, quantifying different level of improvements in fields such as agricultural production or national infrastructure. The sensitivity and adaptive capacity can then be projected using the following formula:

$$x_{2050} = x_{\text{baseline}} - \ln \left(\frac{2 + p - x_{\text{baseline}}}{2 - x_{\text{baseline}}} \right) , \quad (5.6)$$

where x_{baseline} is the baseline value of sensitivity or adaptive capacity for a given country, and p is a scaling factor quantifying the level of adaptation ($p = 0.1$ for a low level and $p = 0.2$ for a high level of adaption).

Our projected P^{RCP_j} index is then the average contribution of each component projected under a given RCP, either through direct use of the output of climate models (for the consecutive dry days), or through adaptation scenarios for the cereal crop yields and the poverty rate (Eq. 5.6). In Fig. 5.8 we show the time evolution of the P index averaged by continent using the RCP4.5 and high level of adaptation scenario. A small P index indicates high exposure to droughts, high sensitivity to food insecurity due to low crop production, and limited adaptive capacity due to high poverty rates. Europe, in green, and Africa, in blue, have the highest (0.7 in 2020) and lowest (0.29 in 2020) P index, respectively. Between 1975 and 2020, the P index is constant in most of the continents, except for Africa where one can notice a slight improvement in the index, due to a decrease in the poverty rate. Between 2020 and 2080, the P index considerably decreases in every continent. This can be explained by a worldwide increase in droughts and higher vulnerability to food insecurity due to a decrease in crop yields.

5.4.3 Construction of the E index

The third level of Maslow's hierarchy of needs addresses love and social belonging. To construct the E index, we followed a methodology similar to that used for the P index, as described in Sect. 5.4.2.

We used the unemployment rate (UR) as an indicator of a country's adaptive capacity. Exposure and sensitivity are merged into a single component, measured by labor productivity loss due to heat. This indicator, computed by Parsons et al. (2021) for current conditions and projected under various global warming scenarios ($+1^\circ\text{C}$, $+2^\circ\text{C}$, $+3^\circ\text{C}$, and $+4^\circ\text{C}$), encompasses exposure by using heat exposure data, specifically the Wet Bulb Globe Temperature, a heat stress metric that incorporates both temperature

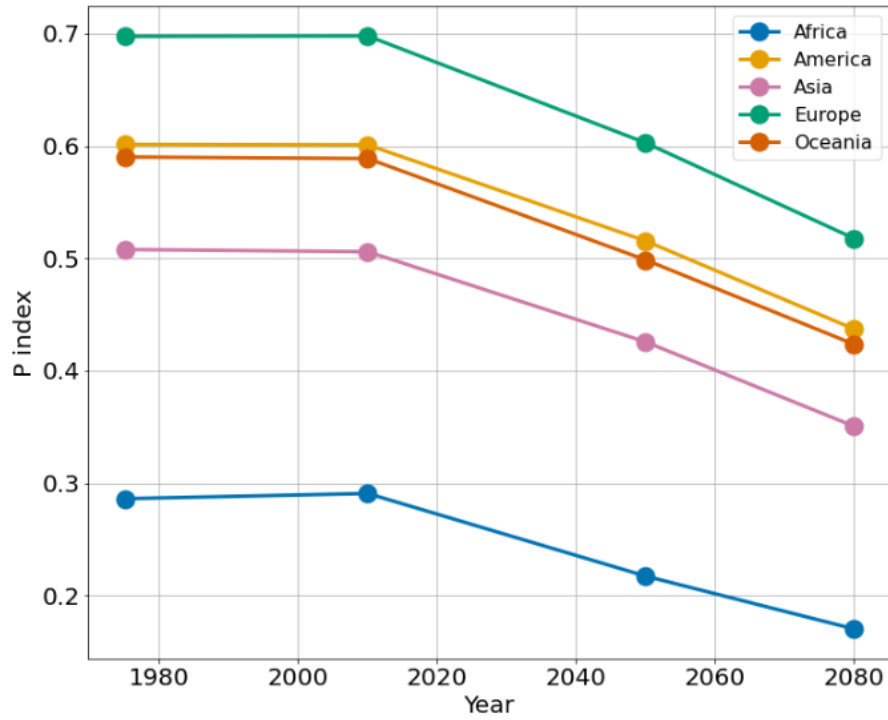


Figure 5.8: Evolution of the P index, averaged by continent, as a function of time (in years) for the RCP4.5 scenario. The blue line corresponds to Africa, the pink one to Asia, the orange one to Oceania, the yellow one to America, and the green one to Europe.

and humidity impacts on the human body. The sensitivity component is represented by the proportion of workers in the primary sector. Parsons et al. (2021) calculated heat-induced lost working hours on a global grid of latitude (360 points) and longitude (720 points) over a 12-hour workday, totaling 259,200 values. We linked each grid point to its corresponding country and summed the hours lost for each. To facilitate cross-country comparisons, we retrieved the number of workers in agriculture, forestry, fisheries, and construction for each country. By dividing the total hours lost due to heat by the working population, we derived the number of working hours lost (HL) per person in each country. Assuming a 12-hour workday and 365 days per year, the maximum of annual working hours is 4380.

Similarly to Eq. 5.5, we define the E index:

$$E_i = \frac{2}{3} \times \frac{4380 - HL_i}{4380} + \frac{1}{3} \times \left(1 - \frac{UR_i}{100}\right). \quad (5.7)$$

The more the hours lost due to heat, the higher the exposure/sensitivity of the country, and the lower the E index. The projection of E under different RCP scenarios is similar to the projection of the P index. For the exposure/sensitivity component HL , we use a different dataset from Parsons et al. (2021). For RCP4.5 and RCP8.5 in 2080, we used data corresponding to +2°C and +4°C temperature increases, respectively. For the unemployment rate, we use the adaptation formula from Eq. 5.6 as future employment rates depend on multiple factors, including each country's adaptation pathway. In Fig. 5.9, we show the time evolution of the E index averaged by continent using the RCP4.5 and high level of adaptation scenario. A higher E index indicates lower vulnerability, meaning that the country has fewer productivity losses due to heat and a relatively lower unemployment rate, suggesting a more resilient labour market and stronger adaptive capacity.

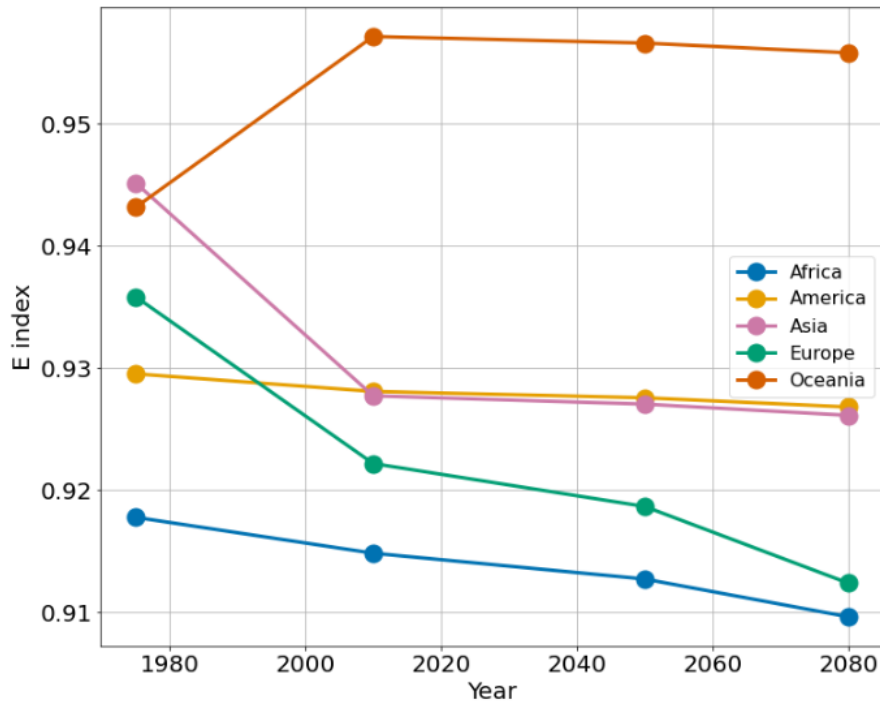


Figure 5.9: Evolution of the E index, averaged by continent, as a function of time (in years) for the RCP4.5 scenario. The blue line corresponds to Africa, the pink one to Asia, the orange one to Oceania, the yellow one to America, and the green one to Europe.

5.4.4 Data

The poverty rate data was extracted from the World Bank²⁷, using the poverty headcount ratio at 5.50\$ per day to quantify the percentage of people earning less than 5.50\$ per day. To avoid capturing yearly trends and missing data, we averaged the poverty rate between 2010 and 2020. The number of CDD, a proxy for droughts, is defined as the “maximum number of consecutive days with precipitation below 1 mm in a year” and was extracted from the Copernicus Climate Data Store²⁸. The cereal crop yields have been extracted from the Food and Agriculture Organization of the United Nations²⁹. Similarly to the poverty rate, we averaged the yields between 2010 and 2020.

The first dataset required to compute the E index is the unemployment rate, retrieved from the International Labour Organization database³⁰. To avoid capturing yearly trends and missing data, we averaged the total unemployment rate (expressed as a percentage of the total labour force) over five years, between 2012 and 2016. Data on the number of people working in agriculture, forestry, fisheries, and construction were taken from the Food and Agriculture Organization of the United Nations database³¹ and, when not available there, from the OECD³² database. Hours lost due to heat are from Parsons et al. (2021)³³.

²⁷<https://data.worldbank.org/indicator/SI.POV.UMIC>

²⁸We used the climate model EC-Earth3 with ensemble numbers r1i1p1f1, r4i1p1f1, and r6i1p1f1, averaged over the three ensemble numbers for each grid point available at <https://cds.climate.copernicus.eu/datasets/sis-extreme-indices-cmip6?tab=overview>

²⁹<https://www.fao.org/faostat/en/#data/QCL>

³⁰https://rshiny.ilo.org/dataexplorer46/?lang=en&segment=indicator&id=UNE_2EAP_SEX_AGE_RT_A

³¹<https://www.fao.org/faostat/en/#data/OEA>

³²<https://data.oecd.org/emp/employment-by-activity.html>

³³<https://zenodo.org/record/5594470#.Y3dcIseZO5c>

5.4.5 Results

We compute the final PLEES index as the sum of each index P, LE, E, and S, for each country for the present time and we project it under two different RCP scenarios, RCP4.5 and RCP8.5, and two different timescales, 2050 and 2080. The results are shown in Fig. 5.10. The top panel shows the current value of the PLEES index while the other panels show the PLEES index projected under RCP4.5 (left) and RCP8.5 (right) respectively, and for two different timescales 2050 (middle) and 2080 (bottom). In the top panel, Northern and Western European countries, Northern America, and Australia all have a PLEES index exceeding 3.5. In contrast, most African countries are displayed in turquoise, equivalent to an index of around 2.5. When accounting for the impact of climate change and projecting the index, one can see how the color of each country is changing. Most of the countries show a significant decrease in the PLEES index. The impact is even more evident for RCP8.5, revealing that countries worldwide will go down the pyramid of needs and experience a strong loss in life comfort due to climate change. Such a decrease in the PLEES index will be all the way stronger than the countries are high in the PLEES pyramid.

To better visualise the variation of the PLEES index with time, we compute the difference between each time epoch. The results are shown in Fig. 5.11. The top panel shows the difference in PLEES index between 1975 and 2020, the middle and bottom panels the difference between 2020 and 2050 for RCP4.5 and RCP8.5 respectively. Blue colors indicate a positive difference, meaning that countries are moving higher in the pyramid of needs, while red colors indicate a decrease in the PLEES index. While many countries in Africa and South America saw an increase in their life quality, as probed by the PLEES index, between 1975 and 2020, most countries will experience losses in life comfort in the future, regardless of the RCP scenario. European countries and the US will not be spared, as attested by the dark red color in the bottom panel of Fig. 5.11. A few countries in Asia and Eastern Europe stand out, in blue in the three panels, namely Russia, Mongolia, Kyrgyzstan, and Nepal. The increase in the PLEES index for these countries can be explained by a milder weather due to a warmer climate. The increase in global mean temperature will lead to a significant decrease in the heating degree days in these countries where winter is particularly tough. Such a decrease will raise the Satisfaction index *S* (see Appendix A for more details).

5.4.6 Conclusion

In this section, we have presented the construction of the Poverty, Life Expectancy, Employment, and Satisfaction (PLEES) index. This index is based on Maslow's hierarchy of needs and is structured to reflect the levels of human needs, with each component connected to measurable indicators impacted by climate. By incorporating poverty, life expectancy, employment, and life satisfaction, which are critical to assessing a country's well-being and (lack of) vulnerability, we built the first index taking into account the social, psychological, and economic impact of climate change worldwide. The PLEES index varies between 0 and 4. Wealthier European countries, Northern America, and Australia show a very high PLEES index, close to the maximum value of 4, while African countries have a smaller index (around 2.5). The design of the index allows projections under different climate scenarios (RCPs). Our analysis suggest that most countries will see their life quality, as probed by the PLEES index, significantly decrease in the future due to the consequences of climate change. This decrease is more pronounced for the RCP8.5 scenario, predicting a global temperature increase of about +5° by the end of the century.

This index is a visual tool, easy to distribute in social media, aiming to inform people about climate change, targeting in particular more developed countries, with the financial and political means to generate a positive change, showing that their life comfort is at risk. We believe that popularising the idea of social tipping point is a good way to show that big changes can happen very quickly if citizens act together. The PLEES index could be an alternative to the broadly used human development index³⁴ allowing for projections under different climate change scenarios and socio-economic pathways.

Our approach has some limitations which should be addressed in future refinement of the index. First of all, the index oversimplifies the complex socio-economic dynamics by reducing them to a single value. Different countries may score similarly in the PLEES index but have vastly different underlying

³⁴<https://hdr.undp.org/data-center/human-development-index#/indicies/HDI>

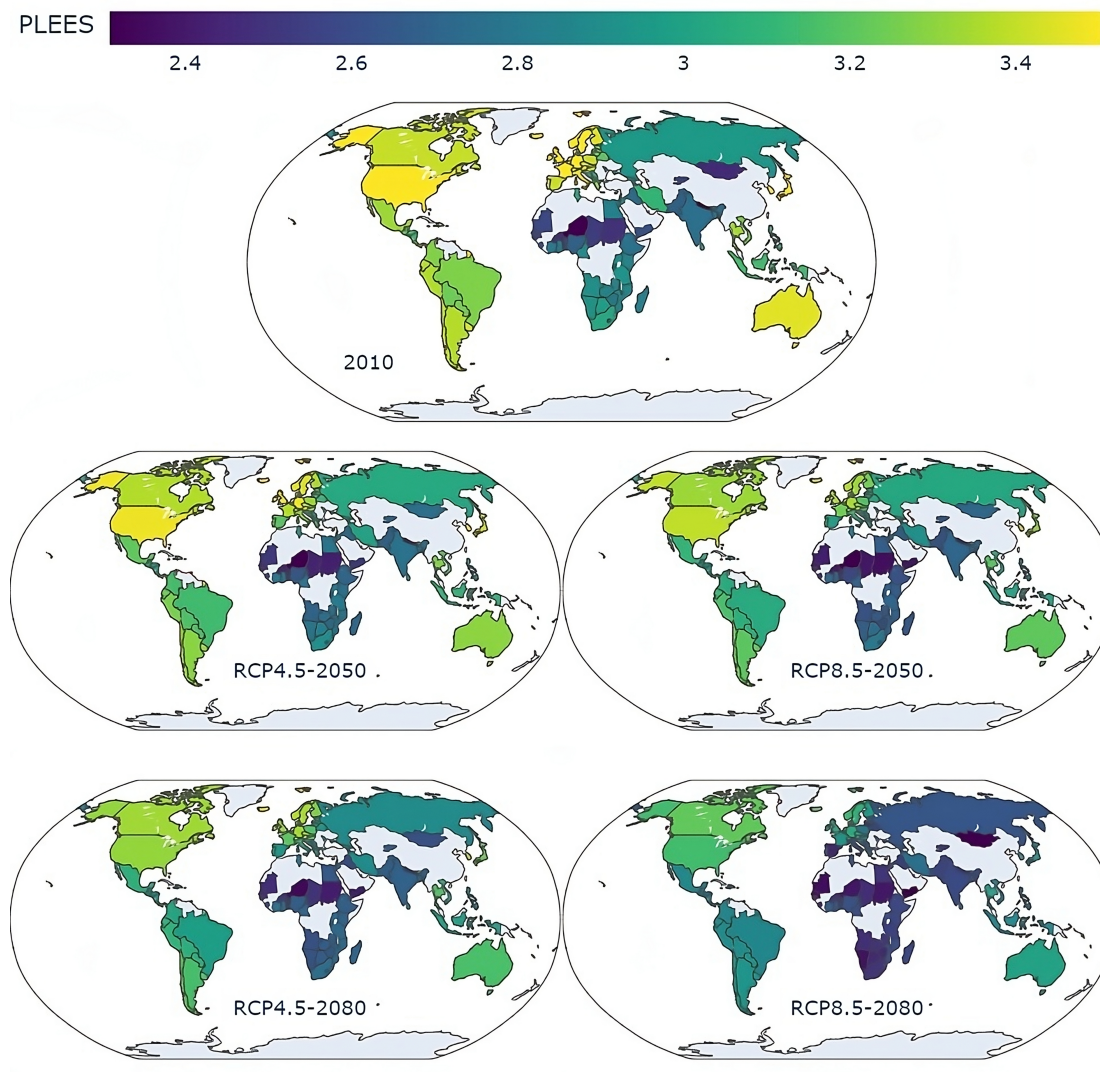


Figure 5.10: World maps of the PLEES index obtained for the present (top panel), and future, as projected under RCP 4.5 (left panels) and RCP 8.5 scenarios (right panels) in 2050 (middle panels) and 2080 (bottom panels). The color scale is the same in all maps. A PLEES index close to the maximal possible value (4) is colored in yellow while a low value (close to 1) is colored in dark blue.

issues. Although we selected the variables most strongly correlated with each index (i.e., droughts affecting vulnerability to hunger for example), other factors also influence these indices and were not included in the analysis. Incorporating these additional factors and conducting a more comprehensive correlation analysis for each index could improve the accuracy of the projections. Averaging the indices over each country fails at capturing the internal variations in extended countries such as the US or Russia. The use of a smaller spatial grid could better capture these local variations. The climate crisis will not only affect us through extreme weather events and their consequences, such as decreased crop yields, but will also force millions of people to migrate within or outside their countries (Almulhim et al., 2024). Military conflicts could also arise in developing countries due to climate change (Ko et al., 2024). Such consequences will surely impact the quality of life in many countries.

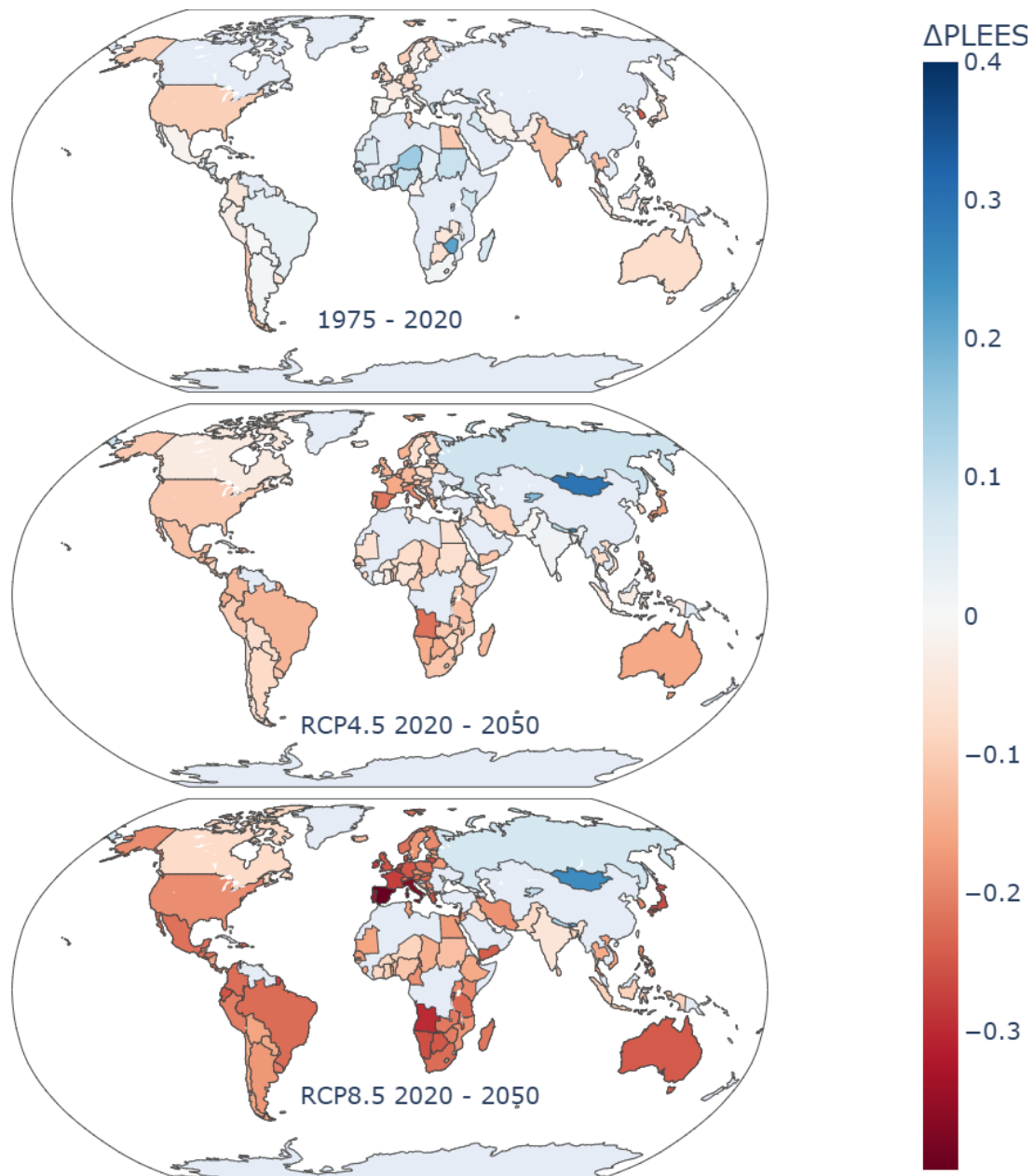


Figure 5.11: World maps of the Δ PLEES defined as the difference between the PLEES index in 1975 and in 2020 (top panel), between 2020 and 2050 (middle panel) and between 2020 and 2080. The color scale is similar in all the maps. A Δ PLEES in blue indicates an increase in the PLEES index with time, while a red color indicates a decrease of the PLEES index with time.

5.5 Take-away message

I opened this Chapter with a few facts on wealth distribution, hunger and biodiversity loss, and I asked the following questions: are we failing as a society? How can academia face the biggest challenge of humankind? What is our role as astronomers and as teachers? These tough questions have to be reflected upon if we ought to envision a sustainable future, both individually and collectively (see Sect. 5.1). Academia, by producing knowledge and transmitting it to the next generation, has a key role to play in the climate and social crisis. More than ever, the challenges faced require inter- and

trans-disciplinary collaboration and partnership between the generations. Academia can provide the adequate structure for such collaborations to arise.

As astronomers, we are embedded in the academic world. By redefining academic success beyond traditional metrics like the h-index, embracing slow science, and enhancing communication between astronomy and society through our unique perspective on Earth (see Sect. 5.2), we could drive meaningful change and be a catalyst for systemic evolution.

In this Chapter, I have presented several initiatives aiming at using our position and knowledge as astronomers to tackle the crisis. By ideating and teaching the course “Sustainability in Academia” (Sect. 5.3) I engaged students from diverse disciplines, encouraging them to reflect on a more sustainable academic future. Additionally, Sect. 5.4 is an example of how our research skills can be applied beyond astrophysics to address global issues, such as effective climate communication.

One key takeaway from these efforts is the need for interdisciplinary collaboration and the power of collective actions. As a community, we have the ability not only to envision a more sustainable future, but also to actively create it. This could start by transforming the academic world, where academia does not respond to the growing demands of a capitalist system, but leads by example, putting sustainable practices into action.

Chapter 6

THESIS CONCLUSIONS

“You cannot get through a single day without having an impact on the world around you. What you do makes a difference, and you have to decide what kind of difference you want to make.”

- Jane Goodall

Thesis summary

For a long time globular clusters have been thought to be simple objects, spherical, non-rotating systems composed of a single, densely packed stellar population. However, the continuous advancement of technology have allowed us to unravel the complexity of globular clusters. Multiple stellar populations were detected in all GCs older than ~ 2 Gyr. With each new observation and modelling effort, the complexity of these populations has become increasingly evident. While one population, the one identified as “pristine”, has a chemical composition similar to that of stars in the Milky Way field population, another (or more than one, identified as “enriched”) population exhibits chemical anomalies, being enhanced in some specific chemical elements such as nitrogen and sodium, and depleted in others, such as oxygen and carbon. Many theories were proposed to shed light on the origin of these MSPs, each one focusing on a specific polluter to explain the presence of variations in chemical abundances. These theories are constantly challenged by new photometric and kinematic data (i.e., showing the presence of rotation or anisotropy), which put tighter constraints on the formation scenarios. To date, none of the proposed theory has been able to explain all observations (Chapter 1). However, most models agree that one or more polluter sources are needed, to produce the material necessary to form or to pollute the enriched stars.

By means of nuclear reaction network simulations, I explored the conditions necessary for the formation of these chemical signatures in Chapter 2. I found that only a narrow range of temperature and time can reproduce the abundances of light elements, in good agreement with previous works. This chapter sets the basis for the analysis carried out in Chapter 3 where I investigated the scenario proposed by Breen (2018), which suggests that the nucleosynthesis of enriched material could occur in accretion disks around stellar-mass black holes. Using a slim disk model, I assessed whether the temperature and timescales required to produce the enriched material could be achieved within such disks, given black hole parameters such as mass and accretion rate. My findings indicate that only very low-mass black holes could fulfil these conditions under the assumptions of the slim disk model used in this work.

Moving beyond the chemistry, I delved deeper into the shape of GCs, going beyond the common assumption that they are spherically symmetric systems (Chapter 4). Modelling the structural parameters of GCs required meticulous methods to avoid biases in the results. To this end, I developed and tested a robust and efficient method for determining the ellipticity of GCs and their MSPs. Applying this method to 26 Milky Way GCs, I uncovered significant differences in the flattening of MSPs across several clusters. While for some clusters the flattening appears to be linked to rotation, for others follow-up observations are needed to understand its origin, especially when differences in flattening and orientation are found between the individual MSPs.

Finally, in Chapter 5, I addressed the topic of sustainability in research. The constant pressure to publish more, travel extensively, and work longer hours to remain competitive in a demanding and tight field often leaves researchers with little time or energy to face one of the greatest challenge of humankind, the climate crisis. In this Chapter, I reflected on the ethical responsibility of researchers and emphasized the unique perspective we, as astronomers, have on Earth, i.e, the understanding that there is no “planet B”. I described a course I developed on sustainability in academia, sharing the insights gained through interactions with students and their reflections on the issue. Additionally, I highlighted an interdisciplinary project carried out with other PhD students in VISESS, in which we applied skills developed through astrophysical research to create the PLEES index, a tool designed to communicate on climate change. This initiative showcases how we, as scientists, can leverage our expertise to contribute meaningfully to addressing the climate crisis.

Connecting the dots

While the research topics and methods discussed in this thesis are diverse and seem disjoint at first glance, they share similar fundamental conclusions. To tackle a complex problem, whether it is the puzzle of the presence of multiple stellar populations in globular clusters or the climate and social crisis that we are currently facing, we need to approach it from multiple angles. For GCs and their MSPs, this

means understanding the origin of their chemical differences as well as their kinematical and structural differences, and bridging observations, simulations, and modelling. For the climate crisis, this means collaborating beyond fields, beyond borders, across generations.

One of the key lessons globular clusters offer the real world is the need for old beliefs, and the methods tied to them, to evolve. GCs are not all spherical, they are not all non-rotating, and most of them definitely do not host single populations. Yet, even now, they are still often modelled using isotropic, non-rotating assumptions. In the case of GCs, evolving these outdated views was relatively straightforward. The shift in our understanding of GCs came from new and improved observations and the clear, visual evidence they provided, such as the discovery of MSPs and of the richness and complexity of kinematic properties they display. Now, there is growing momentum to develop more sophisticated dynamical models (for example including rotation, pressure anisotropy, and a realistic effect of tides) and refine numerical simulations. For the climate crisis, the situation is more complicated. The science is clear, the evidence is everywhere. Yet, the actions taken so far remain insufficient, and the number of climate sceptics is still surprisingly high, and is even growing in some countries, for example in France¹.

For both problems, unravelling the origin of MSPs and finding solutions for urgent climate action, we have not found an answer yet. To find such answers, we must embrace creativity: in the first case, to reconstruct the past, and in the second, to reimagine the future. We need to invent new narratives, to propose a long-lasting story-line, learning from the past. For multiple stellar populations in globular clusters, this might mean combining current theories, which alone face high challenges to reproduce the observations, but which might bring new insights when taken together. This also suggests to think outside the box, for instance by exploring different initial conditions for the numerical simulations of globular clusters. This might be achieved by providing rigorous and robust methods in a transparent way to tell the full story behind results. This might be addressed by more collaboration between observers, modellers, and simulators, and more data and resource sharing. For the climate and social crisis, this might mean combining the knowledge and initiatives done all around the world to develop a more fair and sustainable way of living. This could be addressed, like for GCs and their MSPs, by thinking outside the box, by for instance creating new communication and empowerment tools. This might mean more collaborations between people, in and across countries. Last but not least, this might suggest rethinking our relationship with the living world, and our way of living in a fast-paced world.

Future avenues

There are several ways to expand this work.

The results obtained in Chapter 3 are highly dependent on the model used for the black hole accretion disk. Exploring different models could provide more insight into the possibility of accretion disks to host the nucleosynthesis reactions producing the chemical elements involved in the formation of MSPs. Running hydrodynamical simulations coupled to a nuclear reaction network to track the time evolution of the mass ratio of chemical elements could also complement the analytical work carried out in Chapter 3, and rule out—or not—accretion disk around stellar mass black holes as polluter sources for the enriched material involved in the formation of enriched stars.

The method presented in Chapter 4 to model the ellipticity of GCs is robust and could be applied to more GCs. Obtaining flattening measurement of a significant fraction of MW GCs would be interesting to better constrain the causes of the flattening. Some GCs might have an ellipticity varying with the distance to the cluster centre. To accurately capture this trend, the method could be extended and combined with binning of stars to obtain an ellipticity profile. This is feasible but requires careful considerations and robustness checks to ensure the reliability of the recovered profiles. From the modelling point of view, it would be crucial to take into account the kinematic complexity of these systems, including for example rotation and pressure anisotropy in dynamical models of globular clusters. Moreover, a careful exploration of the time evolution of these systems is needed to identify which mechanisms play a significant role in shaping the properties of present-day globular clusters. Initialising numerical simulations with different ellipticities, rotations, and anisotropies (among other properties), and tying

¹<https://www.ipsos.com/en/obscop-2022>

them to a specific formation scenario for MSPs would provide valuable information on the kinematics and morphology that could be observed with existing and future facilities, and potentially rule-out some theories and encouraging the development of new ones.

Finally, by using our unique position, as astronomers, we can reach a broader audience. We could use this to support our colleagues climate scientists, who have been calling for help for decades and have not been heard so far, in communicating on climate change. We could shift the narrative on climate change, basing it on the beauty of planet Earth, its fragility, and its uniqueness, and communicate the benefits of what a sustainable future for all would bring. Exploring in more detail such a novel narrative and evaluating the expected impact that it could have on society could be an avenue to understand what could encourage immediate climate action.

The 20th century has been marked by remarkable technological progress that substantially improved the quality of life, stimulated our curiosity about the universe, and generated considerable knowledge. As we look to the rest of the 21st century, one of its greatest achievements may lie in our ability to invent new narratives and redefine what once seemed inevitable.

Appendix A

Additional information on the PLEES index

In this section, we first introduce the notion of shared socio-economic pathways (SSPs) and we detail the computations of the Life expectancy (LE) and Satisfaction (S) indices used in the PLEES index (see Sect. 5.4), defined as $PLEES = P + LE + E + S$, with the P and E indices defined in Sects. 5.4.2 and 5.4.3, respectively. The structure of the index is presented in pyramidal form on the right in Fig. 5.7.

Shared socio-economic pathways (SSPs)

A SSP is a collection of global pathways that describe alternative futures of socio-economic development implying different challenges in climate change adaptation and mitigation. They are used to inform greenhouse gas emission scenarios. In Fig. A.1 five different SSPs are shown in a mitigation versus adaptation graph. The most optimistic path, SSP 1, is located in the lower left part: it assumes gradual changes to global policies towards a sustainable economy, an inclusive development with emphasis on respecting environmental boundaries and human well-being, and moving consumption to lower material growth, resource and energy use. In this pathway, the challenges to mitigate and adapt to climate change are low as the society is *taking the green road*. The intermediate path is captured by SSP 2 scenario, also referred as *middle of the road*. In the business-as-usual scenario corresponding to SSP 5, there are great national variations in the success rate of adopting global climate policies, and the transition to a sustainable future is very slow, with CO₂ concentration increasing throughout this century. The highest global temperature increase by 2100 is expected under such a SSP. The society relies on competitive markets and technological innovations as a path forward and rapidly consumes fossil fuels, resulting in great technological progress but resource exhaustion and very high CO₂ emissions. This SSP is therefore located on the upper left corner of Fig. A.1, facing high challenges for mitigation, as energy demand is high and climate action is delayed, and low challenges for adaptation thanks to technological advances and high economic growth. In this work we focus on SSP 2 combined with the global warming scenario RCP4.5, which is very realistic given the current global political trends, and SSP 5 combined with RCP8.5 as an example of the worst case scenario (see Sect. 5.4).

LE index

The second level of the pyramid corresponds to the feeling of security and safety. We used the life expectancy as an indicator of the level of security and safety of a country, quantifying the general health situation of a population. In order to determine the life expectancy, we follow the method presented by Hauer and Santos-Lozada (2021). In this method a population is divided in different age groups, each spanning 5 years from 5 up to 100 years, with ages 0 to 5 being further divided in 0-1 and 1-4. The probability of a person dying in a certain age group x is then given by:

$$q_x = \frac{m_x \times n}{1 + (n - a_x) \times m_x} \quad (\text{A.1})$$

where n is the width of the age interval, m_x is the mortality rate of the group, and a_x the average number of years spent in the group. The probability of a person dying q_x is then used to determine the number of people left in each category:

$$l_x = 100000 \times \prod_{i=0}^x (1 - q_i) \quad (\text{A.2})$$

A. Additional information on the PLEES index

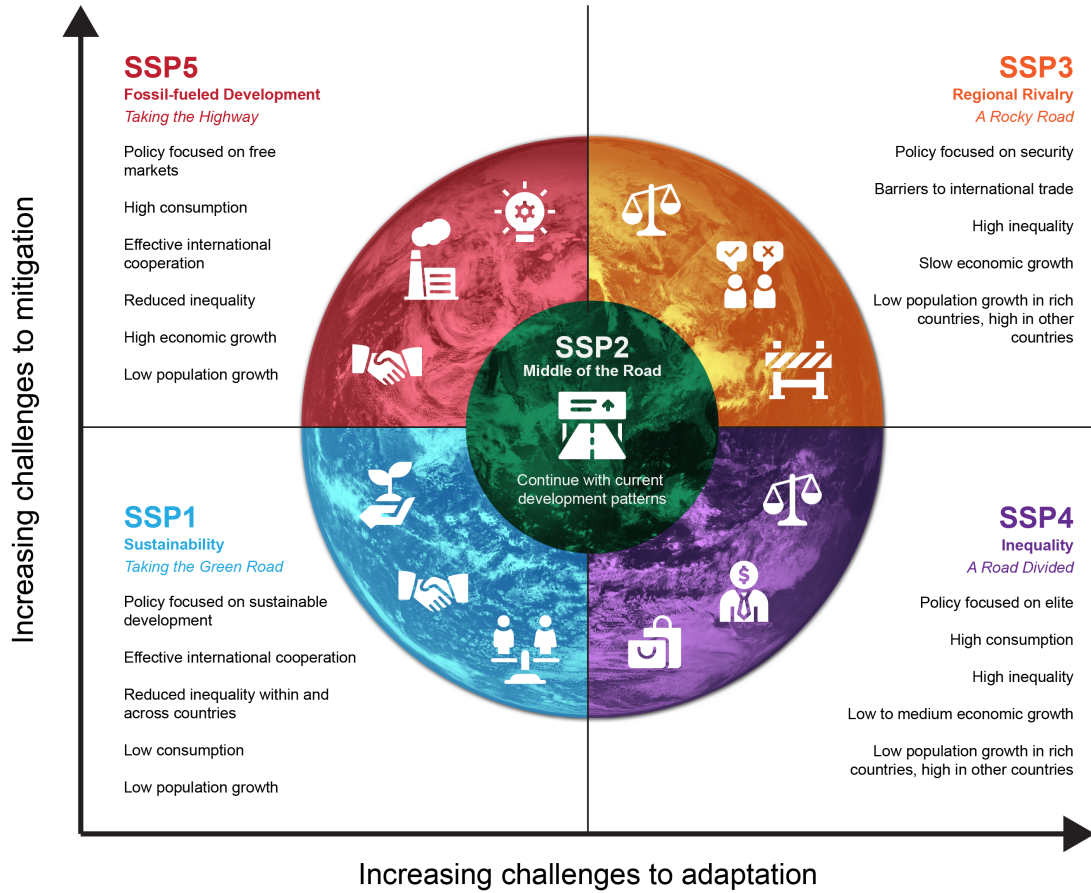


Figure A.1: This plot shows the five shared socio-economic pathways in a challenges for adaptation versus challenges for mitigation graph. Source: climate data (Understanding Shared Socio-economic Pathways (SSPs) - <https://climatedata.ca/resource/understanding-shared-socio-economic-pathways-ssps/>), 2024.

where the factor 100000 is just a normalization factor initialising the number of people in each category. The next step is to calculate the person-years lived, which is defined as:

$$L_x = n \times l_x + (n - a_x) \times l_{x-1} \quad (\text{A.3})$$

Here the index $x - 1$ indicates the number of people in the previous age category, who only live up to the average age of category x . The total person-years lived is then given by:

$$T_x = \sum_{i=x}^{100} L_i. \quad (\text{A.4})$$

With this we can finally calculate the life expectancy at birth by dividing the total person-years lived at age 0 by the number of people at age 0, which we set to 100000 earlier:

$$LE_{base} = T_0 / 100000 \quad (\text{A.5})$$

These equations can be used to calculate the life expectancy for present day countries. We left out the country index i for clarity of the equation.

The next step is to assess the impact of climate change on the life expectancy, in order to project the LE index to the future. Forzieri et al. (2017) compared the excess mortality due to different natural phenomena, such as heat waves or droughts, for European countries. They show that heat waves are

responsible for the vast majority of climate related deaths. As such we only consider excess fatalities due to extreme heat. The number of fatalities is calculated through the following equation:

$$R_{Fat} = H \times ExpLE \times V, \quad (A.6)$$

where H represents the hazards, $ExpLE$ the population exposed to the hazard and V the vulnerability of the location. In order to add the excess mortality to the baseline mortality, Eq. A.6 needs to be rewritten as a mortality rate:

$$m_{ex} = \frac{R_{Fat}}{ExpLE} = H \times V = \frac{H_s}{H_{base}} \times V, \quad (A.7)$$

where the hazards are quantified by the number of extreme heat days (EHDs) according to the baseline (H_{base}) or different SSP scenarios (H_s). The combined mortality ($m_x + m_{ex}$) is then used in Eq. A.1 and the steps until Eq. A.5 are repeated to calculate LE_{EHD} , the life expectancy taking into account the impact of EHDs. This allows us to compute the life expectancy:

$$LE_i = 1 - \frac{LE_{i,base} - LE_{i,EHD}}{10}, \quad (A.8)$$

where $LE_{i,base}$ is the life expectancy in country i without taking into account effect of extreme heat, and $LE_{i,EHD}$ is the life expectancy obtained when considering the effect of extreme heat days. When the LE_i index is close to one, the heat waves have little impact on the life expectancy of that country. When the index is close to zero, the heatwaves cause the life expectancy to be reduced by a decade.

The mortality rate for a given age group and the average number of years spent in it have been extracted from the UN abridged life tables¹. To compute the vulnerability V , we followed the method from Hauer and Santos-Lozada (2021) and used the Global Burden of Disease data base². For the baseline, we considered the fatalities due to extreme weather averaged over the years 2010-2019, divided in age categories and countries. The number of warm days is used to project the life expectancy, as a proxy for heat waves. Like for the CDD (see Sect. 5.4.2), it has been extracted from the CDS, using the climate model EC-Earth3 with ensemble numbers r1i1p1f1, r4i1p1f1, and r6i1p1f1 (corresponding to different initial conditions for the model). For each grid point, we averaged over the three ensemble numbers.

Life satisfaction

The fourth level of Maslow's hierarchy of needs represents *esteem needs*: to quantify the corresponding level in the PLEES pyramid, we use a proxy of life satisfaction. Life satisfaction is subjective and is usually estimated using self-reporting questionnaires (e.g. Margolis et al., 2019). Maddison and Rehdanz (2011) were the first to study the correlations on a global scale between climate and satisfaction with life, spanning several climatic regions. Using data from the World Values Survey³ and historical climate data, they identified the strongest correlation between self-reported life satisfaction, gross domestic product per-capita (GDPPC) and climate, as described in terms of degree months (DM). This variable quantifies the deviation of monthly mean temperature from a base temperature of $T_b = 18.5^\circ\text{C}$, at which it is not necessary to either heat or cool buildings for people to feel comfortable indoors. They found the following relation between life satisfaction, $\ln(GDPPC)$ and DM :

$$LS_j^k = \alpha + \beta \ln(GDPPC_j^k) + \gamma DM_j^k + \delta \ln(GDPPC_j^k) DM_j^k = \alpha + ls_j^k, \quad (A.9)$$

where α , β , γ , and δ are constants. They depend on the regression model used and reflect the variables used in the correlation analysis (see Maddison and Rehdanz (2011) for more detail). The index k generalizes the equation for a k -th time step, meaning that once we have the information on the DM and $GDPPC$ at a specific year for each country j , we can compute the life satisfaction. This is the principle of our projection method.

¹<https://population.un.org/wpp/Download/Standard/CSV/>

²<https://vizhub.healthdata.org/gbd-results/>

³<https://www.worldvaluessurvey.org/wvs.jsp>

To compute LS_j we need information on DM .

HDD and CDD are computed according to the formulas present in Spinoni et al. (2015). The information in the online interactive Atlas⁴ can be downloaded as a map with a 1 degree resolution. To compute the degree months we downloaded the maps and we assigned a mean value of HDD and CDD to each country using geographical country masks. To convert that into months we use: $DM = CDM + HDM = (CDD + HDD)/12$. We use this variable to project the life satisfaction according to different climate scenarios. It is important to note that the definition of DM by Maddison and Rehdanz (2011) and in the IPCC report are not the same. However, we do not expect them to differ substantially.

We use the projections of gross domestic product (GDP) in 2005 dollars from the International Institute for Applied Sciences Analysis (IIASA). These projections depend on the SSP, and we focused on SSP2 and SSP5 as previously mentioned. The data was downloaded in May 2022 from an online repository⁵. Two predictions are included, that of IIASA and OECD⁶. We compared the interpretations of OECD and IIASA and found negligible differences. The information for the GDP and population is presented in 5 year time steps from 2010-2100. We use the value of the population and GDP in the middle of the climate data: 2030, 2050 and 2090.

⁴<https://tinyurl.com/fbevwm4p>

⁵<https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10#intro>

⁶Organisation for Economic development and Cooperation.

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“And in the middle of the night, stargazing into the immensity while the breeze ruffled their skin, they unraveled the mystery of the universe.

It was never about the Big Bang. It was never about the stars.

It is about love. Love for oneself, for each other, and for the world.

It is about daring. Daring to be vulnerable, to say ‘I love you’, ‘I am sorry’, ‘I made a mistake’, daring to break the rules when they are unfair, daring to drop the mask, daring to surf the waves of life.

It is about accepting. Accepting our differences, our flaws, our experiences, to, together, write the manifesto of our survival.

It is about embracing the interconnectedness of our souls on the canvas of our lives.”

Zusammenfassung

In dieser Dissertation untersuche ich Narrative rund um multiple Sternpopulationen in Kugelsternhaufen (Globular Clusters, GCs) und Nachhaltigkeit.

Lange Zeit wurde angenommen, dass GCs nur eine einzige Sternpopulation beherbergen, und sie wurden häufig als kugelförmige, nicht-rotierende Systeme beschrieben und modelliert. Diese Perspektive hat sich mit der Entdeckung multipler Sternpopulationen (Multiple Stellar Populations, MSPs) geändert, die durch unterschiedliche Häufigkeiten leichter Elemente gekennzeichnet sind. „Angereicherte“ Populationen zeigen eine erhöhte Menge bestimmter Elemente wie Stickstoff und Natrium, sowie eine Verringerung anderer Elemente wie Kohlenstoff und Sauerstoff, im Vergleich zu den „ursprünglichen“ (engl. „pristine“) Sternen, die typischerweise im Feld der Galaxie zu finden sind. Viele Theorien wurden vorgeschlagen, um die Ursprünge von MSPs zu erklären, doch keine reproduziert alle beobachteten Merkmale vollständig.

Mithilfe von Netzwerksimulationen für Kernreaktionen untersuche ich die Temperatur- und Zeitbedingungen, die für die Nukleosynthese der chemischen Elemente, die für das MSP-Phänomen relevant sind, erforderlich sind. Ich stelle fest, dass nur ein enger Bereich in Temperatur und Zeit die Häufigkeiten der leichten Elemente reproduzieren kann, was gut mit früheren Arbeiten übereinstimmt.

Aufbauend auf diesen Ergebnissen untersuche ich eine spezifische Theorie, die vorschlägt, dass die Nukleosynthese des angereicherten Materials innerhalb einer Akkretionsscheibe um ein stellares Schwarzes Loch erfolgt. Mithilfe des Slim-Disk-Modells und Kernreaktionssimulationen deuten meine Ergebnisse darauf hin, dass dieses Szenario nur für Parameterbereiche möglich ist, die derzeit bei Schwarzen Löchern nicht beobachtet werden, wie beispielsweise Massen unterhalb der Sonnenmasse und sehr niedrige Viskosität.

Ich hinterfrage auch die Vorstellung, dass Kugelsternhaufen sphärisch symmetrische Systeme sind. Ich habe eine robuste Methode entwickelt, um die Elliptizität von GCs zu messen, diese ausführlich mit simulierten Daten getestet und auf 26 GCs in der Milchstraße angewendet. Meine Analyse zeigt, dass 14 dieser Sternhaufen signifikant abgeflacht sind. Darüber hinaus untersuche ich die Formen von MSPs innerhalb dieser Sternhaufen und finde heraus, dass mindestens eine Population in 13 GCs von der sphärischen Symmetrie abweicht. Interessanterweise sind ursprüngliche Populationen oft stärker abgeflacht als angereicherte Populationen. Ich habe mögliche Ursachen für die Abflachung untersucht, darunter Rotation und Geschwindigkeitsanisotropie, und festgestellt, dass Rotation in einigen Sternhaufen der Haupttreiber für die Form sein könnte, während in anderen Fällen weitere Beobachtungen und detaillierte dynamische Modellierungen erforderlich sind, um endgültige Schlussfolgerungen zu ziehen.

Diese Ergebnisse unterstreichen die Notwendigkeit, unsere Annahmen zu überdenken und unsere langjährigen Modelle für Kugelsternhaufen zu aktualisieren, insbesondere da immer komplexere Merkmale aus neuen Daten hervorgehen. Dieser Ansatz geht über die Astrophysik hinaus; als Astronomen tragen wir die Verantwortung, die Praktiken und Narrative in unserem Fachgebiet und darüber hinaus ständig zu hinterfragen und neu zu bewerten, insbesondere angesichts dringender globaler Herausforderungen wie der Klimakrise. In diesem Sinne diskutiere ich auch zwei Nachhaltigkeitsinitiativen in Lehre und Forschung, die zeigen, wie bedeutende Veränderungen möglich sind. Unser ständig besseres Verständnis von Kugelsternhaufen lehrt uns, alte Ideen infrage zu stellen und unsere Methoden anzupassen, um neue Probleme anzugehen.

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