



universität
wien

MASTERARBEIT / MASTER'S THESIS

Titel der Masterarbeit / Title of the Master's Thesis

Are Tidal Dwarf Galaxies the birth sites of kinematically
decoupled cores in Dwarf Galaxies?

verfasst von / submitted by

Bernhard Baumschlager, BSc

angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien, 2018 / Vienna 2018

Studienkennzahl lt. Studienblatt /
degree programme code as it appears on A 066 861
the student record sheet:

Studienrichtung lt. Studienblatt /
degree programme as it appears on Astronomie
the student record sheet:

Betreut von / Supervisor: Univ.-Prof. Dipl.-Phys. Dr. Gerhard Hensler

Acknowledgements

First of all I want to thank my supervisor Gerhard Hensler for the opportunity to work on this new and exciting theory and for his guidance throughout the development of this thesis. With pleasure I thank Patrick Steyrleithner for the time he invested to introduce me to the `FLASH` code and for providing me comparison data from simulations of his Master's thesis. I also benefited a lot from the numerous discussion with him and Matthias Kühtreiber. My thank goes to Silvia Plöckinger and Simone Recchi for the helpful suggestions about the project and its numerical realisation.

I'm very grateful for the generous support from my parents during my years at university, without your help it would have been hardly possible to make it!

The software used in this work was in part developed by the DOE NNSA-ASC OASCR Flash Center at the University of Chicago. The computational results presented have been achieved [in part] using the Vienna Scientific Cluster (VSC).

Contents

1	Introduction	1
1.1	Kinematically Decoupled Cores	1
1.1.1	Rate of occurrence	3
1.1.2	Formation scenarios of KDCs	3
1.1.3	Implications on the formation of KDCs in Dwarf Galaxies	5
1.2	Tidal Dwarf Galaxies	6
1.2.1	Formation of Tidal Dwarf Galaxies	6
1.2.2	Properties of TDGs	7
1.2.3	Contribution to the dwarf galaxy population	8
1.3	The Hypothesis: Formation of KDCs in TDGs	9
2	Chemodynamical galaxy evolution models	11
2.1	FLASH code	11
2.1.1	Adaptive Mesh Refinement	12
2.2	Hydrodynamics	14
2.2.1	Solver	15
2.3	Timestep	16
2.3.1	Hydrodynamic timestep	17
2.3.2	Particle timestep	17
2.4	Self-Gravity	17
2.4.1	Multigrid Poisson solver	18
2.4.2	Coupling hydrodynamics with gravity	20
2.5	Cooling	20
2.5.1	Implementation	22
2.6	Stars	22
2.6.1	Star Formation	23
2.6.2	Initial Mass Function	25
2.6.3	Feedback	27
2.7	3D Orbit	32
2.7.1	Tidal field	32
2.7.2	Ram pressure	33

3	Simulations	35
3.1	Initial data	35
3.1.1	Data extraction	36
3.1.2	SPH-to-Grid mapping	37
3.2	Simulation Setup	38
3.2.1	Initial gas distribution	38
3.2.2	Initial stellar population	39
3.2.3	Boundary conditions	39
3.2.4	Simulation runs	39
4	Results	43
4.1	Structural evolution of TDGs	43
4.1.1	Mass assembly	43
4.1.2	Star formation	46
4.1.3	Cluster mass function	49
4.1.4	Stellar distribution	51
4.2	Chemical evolution of TDGs	52
4.3	Dynamical evolution of TDGs	56
4.3.1	Stellar rotation curve	56
4.3.2	Stellar kinematic maps	57
4.3.3	Gas dynamics	61
4.3.4	Kinometry	62
4.3.5	The dynamics of TDGs	64
4.3.6	Counter rotating stars	68
4.4	The influence of the IMF description	71
4.4.1	Star formation and stellar feedback	72
4.5	Environmental influences	76
4.5.1	Orbit	76
4.5.2	Tidal field	77
4.5.3	Ram pressure	78
4.5.4	Tidal arm	80
5	Discussion	85
5.1	Star Formation	85
5.2	IMF description	87
5.3	Self-regulated star formation recipe	88
5.4	Environmental influences	88
5.5	Distinguishing primordial DGs from TDGs	89
5.5.1	Structural differences	89
5.5.2	Metallicity	90
5.5.3	Dynamics	91

5.6 Counter rotating stars and KDCs in TDGs	95
6 Outlook	97
A Summery of model properties	99
Abstract English	103
Abstract Deutsch	105
Bibliography	107
List of Figures	119
List of Tables	121

Chapter 1

Introduction

1.1 Kinematically Decoupled Cores

For a long period of time elliptical galaxies (E) were assumed to be featureless stellar systems with smooth light distributions. This picture has changed at the end of the 1970's when the first substructures like gas emission-lines (Malin and Carter, 1980), isophote twists (Leach, 1981) or low rotation velocities and anisotropic velocity dispersions (Illingworth, 1977) were detected in Es. These substructures are indicative for a vibrant assembly history, including events like galaxy-galaxy interactions, mergers or gas accretion. Such interactions are most likely also imprinted in the kinematics of Es, especially in their central regions (e.g. Kormendy, 1984; Jedrzejewski and Schechter, 1988; Hernquist and Barnes, 1991). Among these peculiarities are fast rotating cores, misalignments of the rotational axis of the core and main body or even counter rotating cores (CRC). All of these kinematic substructures in the cores of galaxies, with typical sizes of $0.1 \leq R/R_e \leq 1.5$, are commonly summarised by the term kinematically decoupled cores (KDC). Figure 1.1 illustrates a selection of three exemplary rotation curves of KDC harbouring galaxies derived from long slit observations. In the top left panel the counter rotating core of NGC 3608 can be seen. NGC 4494 (top right) shows a strong bump in its rotation curve, indicative for two aligned but distinct rotational components (Jedrzejewski and Schechter, 1988, Figures 1 & 2). The bottom panel shows the rotation curve of the Virgo cluster dwarf elliptical (dE) VCC 1183, clearly visible is its counter rotating core (Toloba et al., 2014, Figure 1).

Krajnović et al. (2006) derived a classification scheme of the dynamics of early type galaxies (ETG) based on 2D kinematic maps obtained by integral-field spectroscopy. This scheme allows to distinguish between single and multiple rotational components (SC and MC, respectively) and groups galaxies according to some basic properties of their kinematic maps. Following this method Emsellem et al. (2007) defined a KDC as MC with either a sudden change in the kinematic position angle ($> 20^\circ$) or a low-level rotation in the outer regions.

The first discoveries of KDCs in luminous early type galaxies (ETG) date back to the early

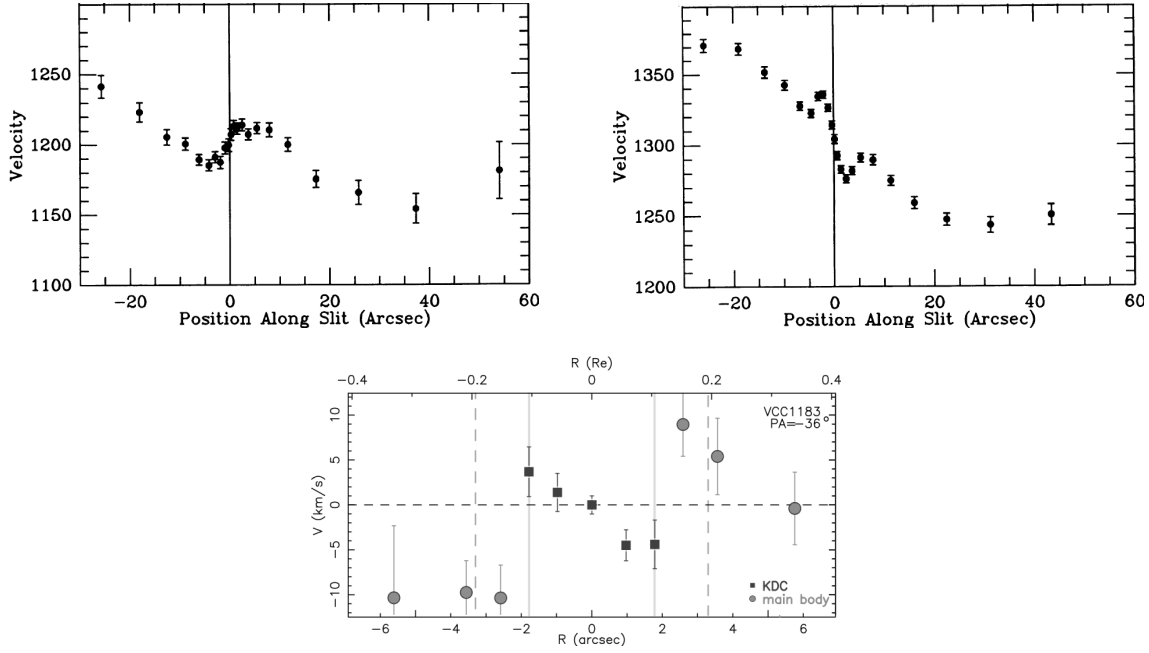


Figure 1.1: Examples of observed rotation curves of KDC hosting ETGs; Top left: NGC 3608 shows a counter rotating core; Top right: NGC 4494 harbours a strong bump in the rotation curve; The velocities are heliocentric and given in km s^{-1} in the top figures, adopted from Jedrzejewski and Schechter (1988, Figures 1 & 2). Bottom: The dE VCC 1183 hosts a counter rotating core (Toloba et al., 2014, Figure 1).

1980's, when Efsthathiou et al. (1982) discovered the first KDC in NGC 5813, showing a rapid rotating core and low rotation velocity at larger radii. Another enigmatic E is IC 1459 for which Franx and Illingworth (1988) reported a fast counter-rotating stellar core ($v_{\text{core}} \approx 170 \text{ km s}^{-1}$) but also a gas disk co-rotating with the main body. Within the last decade the number of detected KDCs in ETGs has dramatically increased, due to improved observational techniques (i.e. larger telescopes and integral-field units) and the availability of large surveys on ETGs like the ATLAS^{3D} project (Cappellari et al., 2011). In addition to the odd kinematic structures, some KDCs show a decoupling in the stellar population, being younger and more metal-rich, with respect to the main body. This was for example reported for NGC 2865 (Hau et al., 1999) or NGC 1700 (Kleineberg et al., 2011).

NGC 770 a low-luminosity elliptical galaxy ($M_V = -18.9$), residing in the borderlands between luminous and dwarf ellipticals, hosts a CRC with a radius almost comparable to the effective radius, $\sim 4 \text{ arcsec}$ and 5.3 arcsec , respectively (Geha et al., 2005).

De Rijcke et al. (2004) presented, for the first time, observational prove of the existence of KDCs in dwarf galaxies (DG), FS76 and FS373 in the NGC 5044 respectively NGC 3258 group. In both dEs the rotation directions of the KDC and the main body are aligned but a pronounced bump is present in the central region. The dE VCC 510 displays a small-scale CRC, which extends to roughly 2 arcsec - approximately 10% of the effective radius (Thomas et al., 2006). Toloba et al. (2014) reported on the detection of CRCs in two dEs in the Virgo cluster, namely, VCC 1183 and VCC 1453. Furthermore, an age and

metallicity segregation, with younger and more metal-rich stars in the KDC compared to the main body, was found in both galaxies, similar to the population decoupling reported for several KDCs in luminous ETGs.

1.1.1 Rate of occurrence

First estimates on the frequency of KDCs in ETGs from Harsoula and Voglis (1998) predicted that 1/3 of luminous elliptical galaxies are hosts of KDCs, confirming Franx and Illingworth (1988) who concluded that a significant fraction of ETGs might harbour unresolved kinematic peculiarities. Due to improved observational techniques, like integral-field spectroscopy, which is in favour of detecting KDCs (Toloba et al., 2014), the rate of occurrence is nowadays estimated to about 50% in luminous ETGs. Within the SAURON sample of 48 elliptical and S0 galaxies, 67% of the slow rotating and 25% of the fast rotating galaxies harbour a KDC (Emsellem et al., 2007). Krajnović et al. (2011) found that 47% out of 260 ETGs of the volume-limited ATLAS^{3D} sample show kinematically peculiar structures. In the regime of DGs Toloba et al. (2014) estimated that approximately 6-8% of dEs host a KDC. McDermid et al. (2006) argued that, due to the fading of a stellar population, some KDCs might not be observable for more than 2 – 5 Gyr after their formation. Considering the fading effect and missing integral-field spectroscopy of dEs, the numbers above are most likely only lower limits of the real fraction of galaxies with KDCs, especially for dEs. Furthermore, if no KDC is detected does not exclude its existence, as observations are always measuring both components at once, therefore a low luminosity KDC could be hidden underneath a brighter co-rotating stellar component.

1.1.2 Formation scenarios of KDCs

During the last decades a variety of processes for the formation of KDCs in luminous ETGs have been proposed. These processes usually involve some kind of strong interaction with the host galaxies' environment, either in the form of gravitational interaction of close neighbouring galaxies or by the interplay of a galaxy with intergalactic gas. In the case of gravitational interactions a large variety of configurations have been tested, including both short and long term interactions between two or more galaxies.

Hau and Thomson (1994) simulated a close encounter between two elliptical galaxies with a mass ratio of 2:1. Both galaxies initially follow a none-rotating Hernquist (1990) potential, with a small exponential disk superimposed on the primary. The fly-by encounter induced a slow rotation in the primary halo and the rotation direction only depends on the orbit inclination of the secondary. Therefore, Hau and Thomson concluded that the formation of any kind of kinematic misalignment, including counter rotation, is possible by this scenario. Moore et al. (1996) defined the term *galaxy harassment* as multiple close and fast encounters between galaxies, a process known to be able to transform the small spiral galaxies into dEs. Considering the findings of Hau and Thomson (1994), harassment

could provide a mechanism to transform a spiral galaxy into a KDC harbouring dE.

The probably most extensively studied gravitational triggered formation process is the merging of galaxies with its wide range of possible initial parameter and object combinations. The merging of a dE with an E leads to a core-within-a-core structure in the merger remnant, if the core radius of the dE is small enough compared to the E so that it can survive the event (Kormendy, 1984). Balcells and Quinn (1990) performed N-body simulations of dE-E mergers and found that the denser core of the dE can survive the merger event, but only in the case of retrograde merger orbits KDCs can be formed. Using N-body SPH simulations of a merger of two gas rich disk galaxies with equal masses and initially anti-parallel spin direction Hernquist and Barnes (1991) found a counter rotating gas disk in their merger remnant. If star formation would be enabled, Hernquist and Barnes assumed that a counter rotation would also be produced in the stellar component. In extension to the above, Balcells and González (1998) investigated major merger simulation of spiral galaxies with unequal masses and found that their simulations produce larger KDCs compared to the Hernquist and Barnes (1991) model. Furthermore, they concluded that the Balcells and Quinn (1990) dE-E model easily produces the general properties of Es but fails in the population decoupling as reported for some Es by e.g. Hau et al. (1999), whereas the disk-disk merger scenario would naturally explain it. The probably most extensive numerical study on the formation of kinematic properties (slow/fast rotation) of ETGs was performed by Bois et al. (2011), who simulated a set of 70 binary disk mergers with varying gas fraction and mass ratios from 1:1 to 6:1. Within this large set of simulations KDCs are only formed in ETGs which are classified as slow rotators and are therefore produced in mergers with mass ratios close to equal (1:1 - 3:1) and retrograde merger orbits. These results agree well with the findings of Bendo and Barnes (2000) who concluded that kinematic substructures, including CRCs, can only be formed by equal mass mergers. Contrary to the previous studies Tsatsi et al. (2015) showed that a KDC can also be formed as a result of an initially prograde merger of two disk galaxies. During their simulation the orbital spin flips, resulting in a retrograde merger orbit, shortly before the final coalescence. The outflow along the tidal arms produces an reactive thrust, caused by reactive Mestchersky (1902) forces, resulting in the orbital spin flip. This additional merger scenario might help to explain the high fraction of ETGs which harbour a KDC.

Accretion of intergalactic gas from intergalactic filaments provides a further mechanism to form KDCs. To mimic the inflow along filaments onto a spiral galaxy, Thakar and Ryden (1998) simulated the inflow of gas from a rectangular column with a retrograde angular momentum with respect to the disk galaxy. Their experiments result in a galaxies with two large but counter rotating disks, a rare but known phenomenon (e.g. NGC 4550, Rubin et al., 1992). Furthermore, they found that the size of the counter rotating disk mostly depends on the angular momentum of the accreted gas, therefore material with small angular momentum could settle to the disks centre and form a KDC.

Ram pressure stripping (RPS) is one of the major drivers of the transformation from gas rich dwarf irregular (dIrr) galaxies to gas poor dEs (e.g. Lin and Faber, 1983; Boselli et al.,

2008). As purely hydrodynamic interaction of a galaxies interstellar medium (ISM) with the surrounding medium (i.e. intergalactic medium, IGM), it is supposed to remove the ISM rather than changing its spin direction or influencing the stellar component at all. Therefore, Toloba et al. (2014) concluded that RPS does not provide a reasonable way to form kinematically decoupled structures in galaxies.

But also alternative scenarios for the formation of KDCs, which do not require direct environmental interactions, are discussed in the literature. As examples the formation from a primordial collapse (e.g. Barnes and Efstathiou, 1987; Harsoula and Voglis, 1998) or projection effects of non-circular orbits (e.g. Statler, 1991) shall be mentioned. In the case of NGC 5982 Statler (1991) proposed the possibility that projection effects of non-circular stellar orbits within a triaxial potential could cause the kinematic peculiarities. A suggestion strengthened by observations of Oosterloo et al. (1994). Van den Bosch et al. (2008) concluded that the KDC in NGC 4365 is also caused by projection effects.

1.1.3 Implications on the formation of KDCs in Dwarf Galaxies

De Rijcke et al. (2004) suggested that the merger scenario is unlikely for dwarf galaxies as in groups and clusters of galaxies the relative velocities are too high and the galaxy density in the field is too low. Alternatively de Rijcke et al. proposed harassment as the key driver for the formation of KDCs in dwarfs, as both of their dwarfs are located in groups of galaxies, where the distances between galaxies and the relative velocities are small enough to provide enough time for the interaction to convert a sufficient amount of angular momentum. With simulations of a fly-by interaction between a dE and a large E, González-García et al. (2005) have shown that counter rotating features only appear under rather restrictive conditions, i.e. only little too no dark matter (DM) is allowed to be bound to the dE and near head on collision orbits are required. These counter rotating features appear at too large radii compared to observed KDCs in dEs, therefore they cannot be classified as KDCs. Following this argument Thomas et al. (2006) conclude that in the case of VCC 510 harassment is not the formation mechanism. KDCs in cluster dwarf galaxies are most likely not the result of galaxy harassment within the cluster or the accretion of gas, due to the lack of cold gas within clusters (Toloba et al., 2014). Therefore, Toloba et al. proposed that the KDCs in the Virgo-Cluster dwarfs were formed in lower density environments like pairs or groups of galaxies, either through wet dwarf-dwarf mergers or gas accretion. These KDC-harboursing dwarfs were then subsequently falling into the Virgo cluster, although there is no evidence from the direct environment that they were formed within a group. Although the dwarf-dwarf merge scenario is commonly assumed to be unlikely it cannot be ruled out as close low luminosity companions have been detected around blue compact dwarf galaxies (e.g. Rich et al., 2012).

As alternative to the above mentioned formation scenarios, the possibility of KDCs being formed in tidal dwarf galaxies (TDG) is examined within this thesis.

1.2 Tidal Dwarf Galaxies

1.2.1 Formation of Tidal Dwarf Galaxies

Within the standard model of cosmology, the Λ cold dark matter (Λ CDM) paradigm, the halos of galaxies form hierarchically from bottom up. Therefore, small DM halos form first, from the initial density fluctuations in the early universe, and subsequently build up mass via accretion and merging. Within the DM halos baryonic matter is able to cool, condense and form stars, resulting in the formation of galaxies with various morphologies ranging from elliptical (E), lenticular (S0) to spiral (S) galaxies, as characterised by the Hubble sequence. In this scenario dwarf galaxies (DG) are objects formed in the lowest mass halos, which show a rather quiet merger history. Within this thesis the gas poor dwarf elliptical and dwarf spheroidal galaxies are referred to as dEs, similar to the combination of gas poor (E & S0) galaxies into the class of early type galaxies (ETG). But not all galaxies follow the morphological Hubble sequence.

In “The Atlas of Peculiar Galaxies” (Arp, 1966) 338 galaxies, which are morphologically distinct from the sequence, are compiled. Some of these galaxies have close companions which might be connected by gaseous bridges, show asymmetries, distortions and general irregular shapes or exhibit long stretched arms emerging from the galaxies’ main body. The formation process of these peculiarities, especially the expanded arms, was explained by Toomre and Toomre (1972) who showed that the arms are formed due to tidal forces during the gravitational interaction of galaxies. Due to the formation process these arms are commonly called tidal tails or arms.

Zwicky (1956) was the first to speculate about DG-sized objects being associated with long extensions emerging from larger galaxies. Detailed observation of interacting galaxies and their tidal tails revealed that the arms do not only consist of old stars ejected from the parent galaxies, areas with bluer colours, indicative for young stars, inhabit the redder arms. Furthermore, $H\alpha$ and FUV emission, as tracers of recent star formation as well as molecular gas, the reservoir for star formation, have been detected (e.g. Mirabel et al., 1991, 1992; Braine et al., 2000, 2001, 2004). These star forming knots, at least the most massive one with masses above $10^8 M_{\odot}$, are called tidal dwarf galaxies (TDG) (e.g. Duc, 2012). Figure 1.2 shows composite images of three interacting respectively post-interacting galaxy systems, the emission from HI from VLA (blue) and FUV from GALEX (pink) is superimposed onto optical images (image from Lelli et al., 2015). In the left panel the collisional galaxy NGC 5291 with its extended HI-ring is displayed, the disturbed lenticular galaxy NGC 4694 is illustrated in the top right panel and the bottom right panel shows the late stage merger NGC 7252, also known as the “Atoms for Peace”, with its extended tidal arms. The pink FUV knots along the gaseous tidal debris are indicative of recent star formation and mark the positions of TDGs.

The formation of TDGs during mergers of galaxies provides an alternative way of DG formation compared to the hierarchical structure formation in the Λ CMD cosmology. With

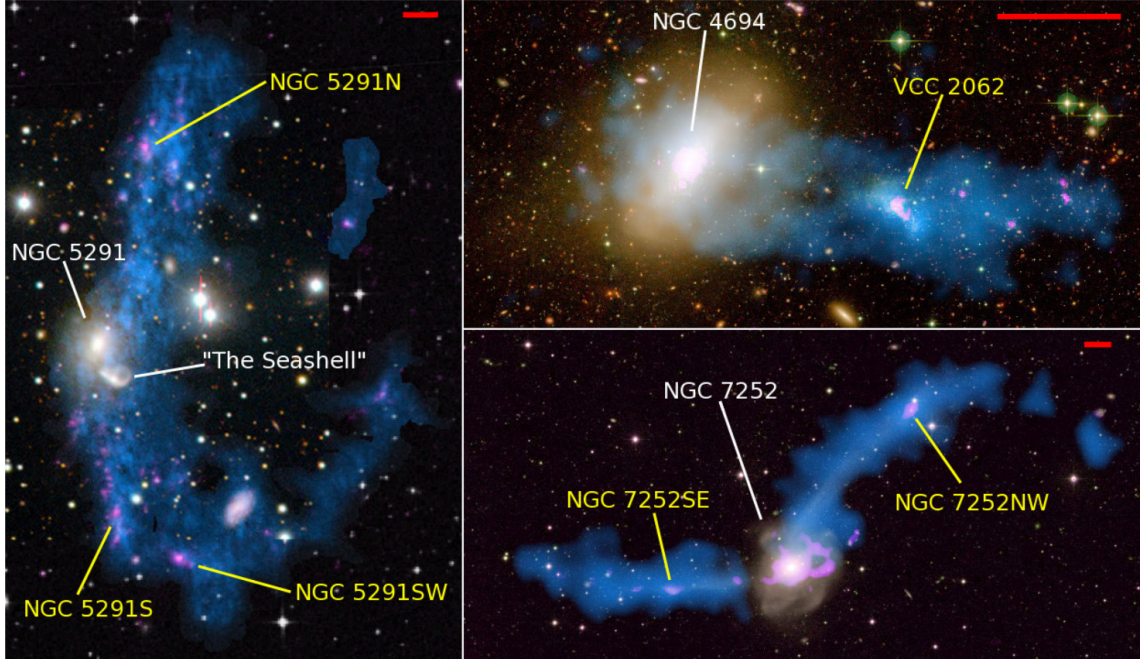


Figure 1.2: Composite images of post-/interacting systems, H I emission from VLA (blue) and FUV emission from GALEX (pink) are overlain onto optical images. The systems shown are the collisional galaxy NGC 5291 (left), NGC 4694 (top right) is a remnant of an old merger and NGC 7252 (“Atoms for Peace”, bottom right) is a late-stage merger. The TDGs are labelled in yellow and the red bar in the top right corner of each panel corresponds to a distance of 10 kpc. Figure taken from Lelli et al. (2015).

two competing theories at hand, a single detailed scenario for the formation of TDGs within the tidal arm has not been fully established, yet. The first of them is the formation out of stellar concentrations which are massive enough to bind gas from the tidal arm, as was found in the simulations of Barnes and Hernquist (1992). Whereas, Elmegreen et al. (1993) suggest that TDGs form from massive gas clouds and therefore provide a scenario in the completely different way compared to the first one.

Wetzstein et al. (2007) investigated numerical resolution effects on the formation of TDGs in galaxy collision models. They found that TDGs are always formed at lowest resolutions, due to particle noise, but never within high resolution pure N-body simulation. Furthermore just the inclusion of a dissipative component is not sufficient for the formation of TDGs in high resolution simulation, although it is required but it also has to be extended and massive enough. Therefore, the results from Wetzstein et al. (2007) favour a formation scenario out of collapsing gas as proposed by Elmegreen et al. (1993).

1.2.2 Properties of TDGs

Due to their origin from tidally expelled material from the discs of their parent galaxies, TDGs are supposed to contain only very little DM, if at all. TDGs are not able to capture DM, as their escape velocity is much lower than the assumed velocity dispersion of the parents DM halos (e.g. Bournaud, 2010; Lelli et al., 2015). As a consequence from the expected absence of DM the mass-to-light (ML) ratio is expected to be close to one (e.g.

Barnes and Hernquist, 1992; Wetzstein et al., 2007), in agreement with observations (e.g. Duc and Mirabel, 1994). Despite their different formation mechanism, TDGs show similar sizes and masses as normal primordial dEs, with effective radii in the order of 100 pc and masses of the stellar content between $10^6 \leq M_*/M_\odot \leq 10^{10}$ and therefore follow the same mass-radius (MR) relation (Dabringhausen and Kroupa, 2013, and references therein). Duc et al. (2004) proposed a more restrictive lower mass cut of $10^{8-9} M_\odot$ for young tidal objects to be classified as TDGs, as also other objects like super star clusters (SSC) are able to form within the tidal debris of interacting galaxies. The luminosity range typical for observed TDGs is $-14 < M_B < -18$ (e.g. Mirabel et al., 1992; Duc and Mirabel, 1994; Weilbacher et al., 2003), a luminosity range that is also comparable to the primordial population of DGs (e.g. Mo et al., 2010).

TDGs show a bimodal distribution in the stellar ages, with no more than 50% of stars originate from the parent galaxies and have ages of a few Gyr. Superimposed on this old population is a young population of stars which formed in a starburst at the time the TDG is formed, followed by a normal star formation rate (SFR) as expected for DGs with comparable size (e.g. Elmegreen et al., 1993; Hunter et al., 2000). Observationally derived SFRs of TDGs range from $10^{-4} M_\odot \text{ yr}^{-1}$ to $10^{-1} M_\odot \text{ yr}^{-1}$ (e.g. Duc and Mirabel, 1998; Lee-Waddell et al., 2014; Lisenfeld et al., 2016).

The confirmed TDGs show an offset from the mass-metallicity (MZ) relation of dwarf galaxies. This effect is a result of the formation mechanism of TDGs, as they emerge from pre-enriched material of their high mass parent galaxies, therefore the location of DGs along the MZ relation is thought to be a reliable method to distinguish between TDGs and primordial DGs (e.g. Duc and Mirabel, 1994, 1998; Croxall et al., 2009; Sweet et al., 2014). However, chemical evolution models of TDGs (Recchi et al., 2015) show that the bimodal distribution of DGs can be explained by different ages and therefore initial metallicities of TDGs. Old TDGs, formed in the early universe, originate from less enriched material, therefore the self enrichment within the TDGs becomes the dominant mode of enrichment, these TDGs potentially form the observed MZ relation of DGs. Whereas, young TDGs, with ages less than a few Gyr, form from substantially pre-enriched material and are those DGs which significantly deviate from the MZ relation. Thus selecting TDGs based on their metallicity is only valid for recently formed TDGs.

1.2.3 Contribution to the dwarf galaxy population

To quantify the fraction of TDGs among the population of DGs it is necessary to have reliable estimates on the following parameters: (1) The number of TDG forming mergers, i.e. wet mergers and therefore involve at least one spiral galaxy (N_{wet}). (2) The average number of TDGs formed per merger event (N_{TDG}). (3) The fraction of TDGs which survive long enough to be discovered today (S). (4) The number of TDGs which disperse from the parent galaxies, so that they can be found in the field.

Due to the absence of a supporting DM halo, TDGs are suspected to be very vulnerable to

internal and external disruptive effects like stellar feedback, ram pressure and tidal forces (e.g. Ploekinger, 2014). But observations and simulation have shown that TDGs can indeed be long lived objects and can survive for several billion years. Recchi et al. (2007) performed 2D simulations of TDGs and found that these objects can survive an initial starburst for several 100 Myr and might turn into long lived dwarf spheroidal galaxies. Within a large set of galaxy merger simulation Bournaud (2010) found that half of the formed TDGs with masses greater than $10^8 M_\odot$ survive for a Hubble time. The oldest confirmed TDGs have been found by Duc et al. (2014) with approximated ages of about 4 billion years. More recent detailed chemodynamical simulations on the survivability of TDGs have shown that, despite their lack of DM, TDGs can survive disruptive events like starbursts or the tidal field of the parent galaxies and reach ages of more than 3 Gyr (Ploekinger et al., 2015). Kaviraj et al. (2012) estimated, for values of $N_{wet} = 3$, $N_{TDG} = 0.22$ and $S = 0.5$, that $\sim 6\%$ of DGs in clusters have a tidal origin, requiring that the present day production rate is comparable to the early universe. Most of the observational predictions are derived from galaxy mergers in the local universe and the theoretical estimates are based on simulation resembling the properties of these local galaxies. In simulations of gas rich major mergers, comparable to mergers in the early universe, a much higher number of TDGs can be produced (e.g Barnes and Hernquist, 1992; Fouquet et al., 2012). For the mass range $8.5 \leq \log(M/M_\odot) \leq 9.5$ Wen et al. (2012) suggest that $\sim 3\%$ of the local DGs are old TDGs and no more than $\sim 10\%$, if higher production and merger rates in the early universe are taken into account. The most extreme estimates on the fraction of TDGs predict that all DGs have a tidal origin. If 1-2 TDGs are formed per merger, with a typical lifetime of 10 Gyr, then the number of TDGs can account for the whole DG population in the universe (Okazaki and Taniguchi, 2000). A similar result was obtained by Dabringhausen and Kroupa (2013) based on the MR relation along which TDGs and primordial DGs are indistinguishable.

1.3 The Hypothesis: Formation of KDCs in TDGs

Within this thesis a novel theory (Hensler, private communication) on the formation of KDCs in dEs is investigated, which does not only describe the formation of the KDC but simultaneously also explains the population decoupling, i.e. the age respectively metallicity segregation, as found by Toloba et al. (2014) in two Virgo cluster dEs.

In this hypothesis KDC harbouring dEs are old TDGs, which have decoupled from their parent galaxies and lost their gas during their further evolution.

During gravitational interactions, i.e. fly-by or mergers, of gas rich galaxies material is expelled to form the typical extended tidal arms. The ejected gas and stars stream along the bent arm, with higher velocities at the front side compared to the back side. The gas within these arms can form overdens regions which eventually collapse to form TDGs. Assuming a constant mass during the collapse, then conservation of angular momentum leads to a spin up of the TDG, which is proportional to the ratio of the initial and fi-

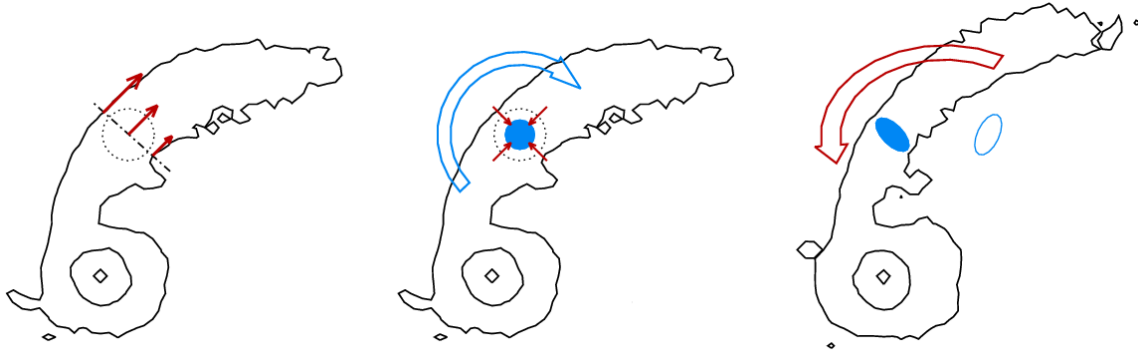


Figure 1.3: The formation of KDCs in TDGs. Left: Stream velocity along the tidal arm, the dotted circle indicates the location of the proto-TDG. Middle: Gravity triggers the collapse of the TDG and conservation of angular momentum results in a retrograde rotation of the TDG. Right: The tidal torque exerted on the TDG causes a change in the rotation direction of the TDG, thereby the gaseous component feels a stronger torque due to its viscosity. See text for details.

nal radii. Therefore, already a relative velocity difference of 2.0 km s^{-1} at a distance of 10.0 kpc from the centre of the forming TDG yields a rotational velocity of 10.0 km s^{-1} at $r_{TDG} = 2.0 \text{ kpc}$ after the collapse. The collapse out of the streaming gas of the tidal arm leads to a retrograde rotation of the TDG with respect to the sense of rotation of the tidal arm.

As TDGs are born in close proximity to their parent galaxies they feel their gravitational potential and are thus exposed to the resulting tidal field, which exerts the so-called tidal torque on the TDGs. Due to the viscosity of gas the tidal torque has a stronger impact on the gaseous component than the stellar component and causes the inversion of its rotational direction. The basic principles of the theory are sketched in Figure 1.3.

The old stellar component, expelled from the interacting galaxies, and captured to the TDG by gravity, constitute the main body of the KDC harbouring TDG. On the other hand the subsequently formed and therefore younger and metal-enriched stars build the core of the TDG with an inverted rotation direction and thus the KDC. This scenario naturally explains the observed population decoupling, with younger and metal-enriched stars at the centre of the TDG. This formation scenario is in agreement with the findings of Ploekinger et al. (2015), who showed that an initially retrograde rotating TDG can form a counter rotating gaseous component.

Here, numerical simulations of young TDGs, embedded in the tidal arm, are carried out in order to study their dynamical evolution. The initial data for these simulations are taken from a galaxy collisions simulation from Yang et al. (2014). In Chapter 2 an overview of the applied simulation code and its methods as well as some of the additional modules which deal with the main physical processes that drive galaxy evolution are described. Chapter 3 deals with the initial data and the setup of the numerical simulations. The results are presented in Chapter 4 and a final discussion is provided in Chapter 5.

Chapter 2

Chemodynamical galaxy evolution models

In order to investigate the possible formation of KDCs in TDGs, fully three-dimensional chemodynamical simulations of TDGs, embedded in the tidal arms of the interacting galaxies, are carried out. These simulations include the dynamics of self-gravitating gas, radiative cooling of gas in dependency of the chemical composition, the formation of stars and feedback from stars. Stars influence the interstellar gas in several ways, during star formation gas is converted into star what reduces the amount of gas within a galaxy. But on the other hand, during feedback events from stars the ISM gets heated and metal enriched material is returned back to the gas reservoir. The included feedback processes are ionising UV-radiation, stellar winds, AGB-stars as well as Type Ia and Type II supernovae. As TDGs are born in the vicinity of interacting galaxies they get disturbed by the gravitational potential of the parent galaxies, therefore the effects of an external gravitational potential are included in the presented simulations.

In the following sections the used hydrodynamic simulation code FLASH and its adaptive mesh infrastructure is described, furthermore, the key ingredients for galaxy evolution simulations and their numerical treatment are presented. These ingredients cover gas dynamics, self gravity, cooling of gas, star formation and stellar feedback as well as the effects of an external gravitational potential, which is particularly important for the evolution of TDGs.

2.1 FLASH code

The FLASH code was developed by Fryxell et al. (2000), at the Center for Thermonuclear Flashes (FLASH Center¹). It was founded in 1997 at the University of Chicago under contract to the US Department of Energy as part of its Accelerated Strategic Computing Initiative (ASCI). The aim of the Center is to advance the knowledge about astrophysical phenomena involving thermonuclear flashes, related to compact stars. These include

¹<http://flash.uchicago.edu>

X-ray bursts, classical novae and Type Ia supernovae. The `FLASH` code is highly parallelized, using the Message-Passing Interface (MPI) for inter process communication and adaptive mesh refinement (AMR) to improve the resolution of the domain where needed. Furthermore, it is equipped with several modules dealing with physical processes such as hydrodynamics or self gravity and additionally it is possible to include particles. Through its modular structure `FLASH` can be extended to a large variety of astrophysical problems, which makes it also a powerful tool for simulations of galaxies. The simulations presented within this thesis made use of an advanced version of `FLASH3`, which was extended for the treatment of stellar particles, gas cooling and an external gravitational potential by Ploekinger (2014); Ploekinger et al. (2014, 2015).

2.1.1 Adaptive Mesh Refinement

Simulations of a large variety of astrophysical problems, ranging from the internal processes of stars to the evolution of galaxies, require a high spatial resolution while covering a large domain. Running this kind of simulations on an uniform grid (UG) would require a lot of computational resources. To overcome this issue and to make the computations more efficient a technique called adaptive mesh refinement (AMR) can be used.

Within this method the simulation grid is not static at a fixed spatial resolution, instead it increases the resolution of the simulation domain where it is required. Thus it provides the necessary resolution and at the same time it keeps the computational costs low.

In order to provide this functionality `FLASH` uses the `PARAMESH`-package from MacNeice et al. (2000), a block-structured adaptive mesh. Within this kind of AMR-method the computational domain is split into blocks, each containing a fixed number of cells along each spatial direction. If one of the existing blocks is getting refined, the newly created child blocks have to fulfill certain criteria. A child block must have half the side length of its parent. By this the child blocks completely fill the parent block and cannot overlap each other or neighboring blocks. In $ndim$ -dimensions the parent block is thus divided into 2^{ndim} child blocks, of which each consists of the same number of grid cells as their parent block. Therefore, the resolution is improved by a factor of two from one level of refinement to the next. Furthermore, only jumps of one level of refinement between two neighboring blocks are allowed.

The different blocks form a tree data-structure, where the leafs are the active child blocks. This tree-structure tracks the position of the blocks within the simulation domain. The upper panel of Figure 2.1 illustrates the AMR-principles, based on a two-dimensional example grid, with its resulting tree data-structure (lower panel).

The refinement criteria used by `FLASH` is based on the description of Löhner (1987). The computed error estimate is a dimensionless value and can thus be applied to any grid variable. Furthermore, it provides the advantage of being a completely local indicator, hence no communication between different processes is needed to decide whether or not a block has to be refined. The estimator proposed by Löhner is a modified second derivative,

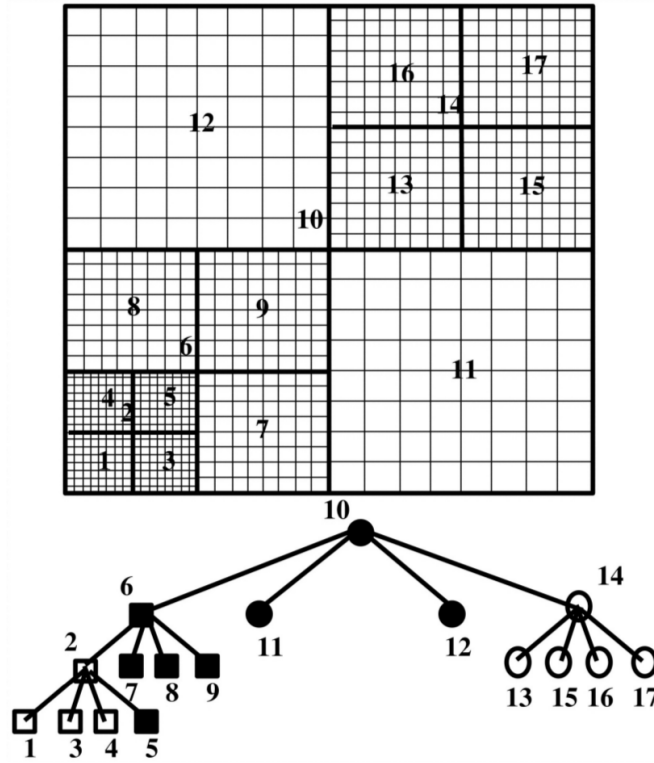


Figure 2.1: The upper panel shows an example of a simple 2D block structure (outlined in bold) covering a fixed domain. The interior 8×8 cells are shown within each block. The size of a cell varies between two refinement levels by a factor of two. The lower panel shows the resulting tree structure, where different symbols indicate the processor on which a block would be located on a four processor machine. Figure 2 from Fryxell et al. (2000)

normalized to the average of the gradient over the width of one cell. The criterion actually used by FLASH in one dimension can be calculated by

$$E_i = \frac{|u_{i+2} - 2u_i + u_{i-2}|}{|u_{i+2} - u_i| + |u_i - u_{i-2}| + \epsilon [|u_{i+2}| + 2|u_i| - |u_{i-2}|]}, \quad (2.1)$$

where u_i is the value of the refinement test variable in the i^{th} cell. When this criterion is extended to multiple dimension, all cross derivatives have to be computed and it becomes

$$E_{i_X i_Y i_Z} = \left\{ \frac{\sum_{pq} \left(\frac{\partial^2 u}{\partial x_p \partial x_q} \right)^2}{\sum_{pq} \left[\frac{1}{2\Delta x_p} \left(\left| \frac{\partial u}{\partial x_p} \right|_{i_{p+1}} + \left| \frac{\partial u}{\partial x_p} \right|_{i_{p-1}} \right) + \epsilon \frac{|\overline{u_{pq}}|}{\Delta x_p \Delta x_q} \right]^2} \right\}^{\frac{1}{2}}, \quad (2.2)$$

where the sums are carried out over the coordinate directions and $|\overline{u_{pq}}|$ is the average of the values of $|u|$ over several neighboring cells in the p and q direction. The partial derivatives in Eq. 2.2 are actually finite-difference approximations calculated at the centre of the i_X, i_Y, i_Z -th cell. The ϵ -term of the denominator, with $\epsilon = 10^{-2}$ as default value, acts as a filter to prevent refinement in regions of small ripples.

In order to mark a block for refinement, the refinement criteria has to be fulfilled for only one cell within that block ($E_{i_x i_y i_z} > CTORE$). On the other hand, to mark a block for derefinement all cells within a block and its siblings from the same parent block have to fulfill the derefinement criteria ($E_{i_x i_y i_z} < CTODE$). In principle PARAMESH would allow to advance the solution with different timesteps for different levels of refinement, within FLASH this feature is not used. Taking the above mentioned restrictions into account and assuming the computational domain is covered by a single block on the first level of refinement, the resolution at any given level of refinement can then be calculated by

$$\Delta x = \frac{D}{n_{cells} 2^{(l_{ref}-1)}}, \quad (2.3)$$

where D is the size of the computational domain, n_{cells} the number of cells in one direction of a block and l_{ref} the level of refinement of interest.

In terms of parallelization, PARAMESH follows the single program multiple data (SPMD) approach. Meaning that the same code is performed on all processors but the program flow is modified by the local data of each processor. Each block is surrounded by a given number of guard cells, which get filled from the neighboring blocks or, in case the block boundary coincides with the boarder of the simulation domain, from the user-provided boundary conditions. The blocks are redistributed after every refinement/derefinement step according to a Morton space-filling curve, to keep the workload of the different processors balanced and reduce the required amount of inter-processor communication.

2.2 Hydrodynamics

Hydrodynamic, also known as fluid dynamic, describes the motion and properties of a fluid (liquid or gas). In order to determine this motions, FLASH uses the Euler equations for compressible and inviscid fluids (Equations 2.4 - 2.6). These equations correspond to the Navier-Stokes equations for a fluid with zero viscosity and without heat conduction.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (2.4)$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \nabla P = \rho \mathbf{g} \quad (2.5)$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P) \mathbf{v}] = \rho \mathbf{v} \cdot \mathbf{g} \quad (2.6)$$

Equation 2.4, the first Euler equation, is the equation of mass conservation, it is based on the condition that the temporal change in density ρ has to be equal to the flux $\rho \mathbf{v}$ of mass through a given surface, where $\mathbf{v}$ is the velocity. The second Euler equation (2.5) expresses the conservation of momentum, similar to Equation 2.4. It also takes the gradient in pressure P and external forces i.e. gravity, caused by the gravitational acceleration $\mathbf{g}$

into account. The third equation (2.6) is the equation of energy conservation, where

$$E = \varepsilon + \frac{1}{2} |\mathbf{v}|^2, \quad (2.7)$$

is the total energy per unit mass, the sum of the specific internal energy ε and the kinetic energy per unit mass. If the internal energy is dominating the kinetic energy, then the calculation of the internal energy via Equation 2.7 can lead to unphysical results caused by truncation errors. In order to avoid this unwanted behaviour, FLASH is able to evolve the internal energy (Equation 2.8) independently.

$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot [(\rho \varepsilon + P) \mathbf{v}] - \mathbf{v} \cdot \nabla P = 0 \quad (2.8)$$

This is controlled by the parameter *eintSwitch*, which is defined such that Equation 2.8 is used if $\varepsilon < \text{eintSwitch} \cdot \frac{1}{2} |\mathbf{v}|^2$. Through out this work *eintSwitch* = 1 is used for stability reasons. To solve the Euler equations an additional equation linking pressure, density and temperature respectively internal energy is needed. This kind of equation is called equation of state (EOS) and describes the physical state of the fluid. Equation 2.9 shows the used gamma-law EOS for an ideal gas, where γ is the adiabatic index.

$$P = (\gamma - 1) \rho \varepsilon \quad (2.9)$$

FLASH is capable of solving the Euler equations in one, two and three dimensions and provides different EOSs.

2.2.1 Solver

In Cartesian coordinates the Euler equation in conserved form can be written in vector notation as:

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{F} = 0, \quad (2.10)$$

with

$$\mathbf{U} = \begin{pmatrix} \rho \\ \rho \mathbf{v} \\ \rho E \end{pmatrix}, \quad \mathbf{F}(\mathbf{U}) = \begin{pmatrix} \rho \mathbf{v} \\ \rho \mathbf{v} \mathbf{v} + P \\ (\rho E + P) \mathbf{v} \end{pmatrix}, \quad (2.11)$$

where $\mathbf{v} = (u, v, w)$ is the three dimensional velocity vector, $\mathbf{U}$ and $\mathbf{F}$ are the state and flux vector, respectively. By splitting the velocity vector into its components Equations 2.11 can be written as:

$$\mathbf{U} = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{pmatrix}, \quad \mathbf{F}(\mathbf{U})_x = \begin{pmatrix} \rho u \\ \rho u^2 + P \\ \rho uv \\ \rho uw \\ (\rho E + P)u \end{pmatrix}, \quad \mathbf{G}(\mathbf{U})_y = \begin{pmatrix} \rho v \\ \rho uv \\ \rho v^2 + P \\ \rho vw \\ (\rho E + P)v \end{pmatrix}, \quad \mathbf{H}(\mathbf{U})_z = \begin{pmatrix} \rho w \\ \rho uw \\ \rho vw \\ \rho w^2 + P \\ (\rho E + P)w \end{pmatrix}. \quad (2.12)$$

Substituting Equations 2.12 into Equation 2.10 gives

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}(\mathbf{U})_x}{\partial x} + \frac{\partial \mathbf{G}(\mathbf{U})_y}{\partial y} + \frac{\partial \mathbf{H}(\mathbf{U})_z}{\partial z} = 0 \quad (2.13)$$

(e.g. Toro, 2009). Within the finite volume approach, two adjacent cells, which are sharing a common interface, can be interpreted as Riemann problem. A Riemann problem is an initial-value problem where two initially constant states of a fluid are separated by an interface, i.e.

$$\mathbf{U}_l = \begin{pmatrix} \rho_l \\ \rho_l \mathbf{v}_l \\ \rho E_l \end{pmatrix}, \quad \mathbf{U}_r = \begin{pmatrix} \rho_r \\ \rho_r \mathbf{v}_r \\ \rho E_r \end{pmatrix} \quad (2.14)$$

at the left and right side of the interface. Therefore, Riemann problems are set up and solved at each cell interface. The solution of the Riemann problem $\mathbf{U}_{RP}$ is then used to calculate the flux through an interface $\mathbf{F}_{i+1/2} = \mathbf{F}(\mathbf{U}_{RP})$, where the subscript $i + 1/2$ denotes the interface between cell i and $i + 1$.

FLASH provides two different hydrodynamic solvers, which are extended versions of the general Riemann problem, namely the piecewise-parabolic method (PPM) and the Monotone Upstream-centred Scheme for Conservation Laws (MUSCL) Hancock solver. The directionally split third-order PPM uses second-order Strang time splitting, whereas the MUSCL Hancock scheme is directionally unsplit and provides second-order accuracy both in time and space. Furthermore, different Riemann solver, such as the Roe, HLL or HLLC solver, as well as various slope limiters are provided.

For the simulations presented within this thesis the unsplit MUSCL Hancock scheme in combination with the HLLC Riemann solver and van Leer slope limiter is used.

2.3 Timestep

A large variety of physical processes influence the evolution of galaxies, such as the motion of gas or stars, cooling of the interstellar medium or the formation of stars. Each of these processes occurs on its own typical timescale, for example cooling is a much faster process than the advection of gas. Choosing the minimal timestep of all relevant processes would lead to a very small timestep and thus to very long computation times. To avoid this problem only the minimum between the hydrodynamic and particle timestep is considered as simulation timestep. Details on the computation of the hydrodynamic and particle timestep can be found below. Processes acting on shorter timescales are treated as sub-grid models, with their own timestep, e.g. the energy loss due to radiative cooling is calculated by an iterative Newton-Raphson scheme (see Section 2.5).

2.3.1 Hydrodynamic timestep

For stability reasons the timestep of hyperbolic differential equations, such as the Euler equations, cannot be arbitrary large. In order to assure stability the Courant-Friedrichs-Lewy (CFL) condition is used to calculate the timestep:

$$\Delta t_{hyd} = c_{cfl} \frac{\Delta x}{S_{max}^n}, \quad (2.15)$$

where Δx is the size of a grid cell and

$$S_{max}^n = \max \{|u_i^n| + a_i^n\} \quad (2.16)$$

is the maximum wave speed (flow (u_i^n) + sound (a_i^n) speed) at the n^{th} timestep within all cells of the computational domain, including boundary cells. The CFL-factor c_{cfl} is a constant between zero and one, where values closer to one result in a more efficient scheme. This condition ensures that no wave can propagate further than Δx (e.g. Toro, 2009). The minimal timestep of all cells, independent of the refinement level, according to the CFL condition, is used as hydrodynamic timestep Δt_{hyd} . For the simulations presented here c_{cfl} is set to 0.1, this results in typical hydrodynamic timesteps in the range of 10^3 to 3×10^4 yr.

2.3.2 Particle timestep

Within FLASH particle calculations are performed on a block-base, therefore all calculations related to particles are performed for all particles within a block rather than a single grid cell. If a particle leaves a block it might need to be mapped to a different processor, during this off-processor mapping FLASH only allows particles to be moved to the direct neighbour block. Therefore, the timestep needs to be limited in a way such that a particle cannot travel further than Δx_b , the size of an AMR-block. In addition to that the accuracy of the results decreases with increasing timestep. The particle timestep is calculated by:

$$\Delta t_{part} = c_{part} \frac{\Delta x_b}{v_{max}}, \quad (2.17)$$

where v_{max} is the maximal velocity of all particles and $c_{part} = 0.5$, as standard value, is a safety factor to ensure that a particle cannot over shoot a neighbouring block of a lower refinement level.

2.4 Self-Gravity

Astrophysical problems typically deal with self gravitating objects, like stars and galaxies or the formation of the large scale structure of the universe due to gravity. In either case

Poisson's equation for the gravitational potential,

$$\nabla^2 \phi(\mathbf{x}) = 4\pi G \rho(\mathbf{x}), \quad (2.18)$$

for a density distribution $\rho(\mathbf{x})$ has to be solved. FLASH provides different gravity solvers depending on the grid geometry and external boundary conditions. In the following sections the multigrid Poisson solver in general and the additional steps required for the applied isolated boundary condition are outlined.

2.4.1 Multigrid Poisson solver

The direct multigrid Poisson solver for oct-tree adaptive meshes (Ricker, 2008) was developed to be incorporated into the framework of FLASH. It is based on the method described by Huang and Greengard (2000), modified to operate on finite volume meshes. This scheme allows the treatment of individual AMR blocks as independent uniform grids on which Poisson's equation is solved. As such any Poisson solver that can handle homogeneous Dirichlet boundary conditions can be used, within FLASH a fast sine transform is implemented. If inhomogeneous Dirichlet boundary conditions, i. e. given value boundaries, are present a boundary value elimination is applied. The algorithm needs three basic operations, taking residuals, restricting from the fine to coarse level and prolongation from the coarse level to the faces of fine level blocks. The residual $R(\mathbf{x})$ at a certain grid cell at position $\mathbf{x}$ is defined as:

$$R(\mathbf{x}) \equiv 4\pi G \rho(\mathbf{x}) - \nabla^2 \tilde{\phi}(\mathbf{x}), \quad (2.19)$$

where $\nabla^2 \tilde{\phi}(\mathbf{x})$ is the finite difference Laplacian applied to the numerical approximation of the gravitational potential. The restriction operator is applied when quantities are mapped from a higher level of refinement ($l+1$) to a coarser level (l) and is therefore calculated as:

$$\left(\mathcal{R}_l \tilde{\phi}\right) \equiv \frac{1}{2^d} \sum_{c=1}^{2^d} \tilde{\phi}^{l+1}, \quad (2.20)$$

where the sum is carried out over all grid cells of level ($l+1$) which are located within one cell at level (l). It is applied to the interior grid cells of a block. The prolongation operator $\mathcal{I}_l$ is only used to define boundary values for the single block Poisson solver and therefore is only applied to the edges of a block. To prolong values from a lower level (l) to the next higher level ($l+1$) quartic interpolation is used:

$$\left(\mathcal{I}_{l+1} \tilde{\phi}\right) \equiv \sum_{p,q,r=-2}^2 \alpha_{pqr} \tilde{\phi}_{i+p,j+q,k+r}^l, \quad (2.21)$$

where the coefficients α_{pqr} are given through the interpolation scheme and the sum is carried out over the adjacent cells at $l_{ref} = l$.

With these three operators the algorithm can be described by the following six steps:

1. Restrict the source function $4\pi G\rho$ to all levels of refinement by using Equation 2.20, starting at the highest refinement level l_{max} . And compute the discrete L_2 norm for each block.
2. Interpolation step: Loop over all refinement levels from $l = 1$ to l_{max} .
 - 2.1. Solve $\nabla^2 \tilde{\phi} = 4\pi G\rho$ for all blocks on level l using the single block Poisson solver, with homogeneous Dirichlet boundary conditions.
 - 2.2. Compute the residuals according to Equation 2.19.
 - 2.3. For every block that has child blocks, prolong the face values for $\tilde{\phi}$ onto them (Equation 2.21).
3. Restrict the residuals to all levels, from $l = l_{max}$ to 1, using R instead of $\tilde{\phi}$ in Equation 2.20. And calculate the discrete L_2 norm of the residuals for each block.
4. Check if the ratio of the residuals norm (step 3) and the source norm (step 1) is smaller than the desired accuracy, if not proceed with the correction step.
5. Correction step: Loop over all refinement levels from $l = 1$ to l_{max} .
 - 5.1. Solve $\nabla^2 C = R$, where C is the correction of the gravitational potential and is calculated by the single block Poisson solver.
 - 5.2. Update the residuals with $R = R - \nabla^2 C$ for all blocks.
 - 5.3. Correct the solution on all leave blocks of level l so that $\tilde{\phi} \rightarrow \tilde{\phi} + C$
 - 5.4. For every block that has child blocks, prolong the face values for C onto them (Equation 2.21).
6. If a correction was applied return to step 3.

In order to account for the isolated boundary conditions of the physical simulation box, a correction on $\tilde{\phi}$ has to be applied. Therefore, a multipole Poisson solver is used to define the gravitational potential on the physical boundaries of the simulation box for the multigrid solver. Typically 5-6 V-cycles iterations are needed to achieve the required accuracy for the first call of the multigrid solver and an additional 3 iterations for the correction due to the isolated boundary conditions.

The parallelization of the gravity solver is achieved through the distribution of blocks on different processors by the AMR-package. On a coarse level of refinement the blocks are only distributed to a few processors, this results in the main scaling bottleneck, as processors allocated to higher refined blocks have to wait until the coarse level calculations are completed (Ricker, 2008).

2.4.2 Coupling hydrodynamics with gravity

The Euler equations of hydrodynamics couple with gravity through the momentum and the energy equation, where the gravitational source terms are $\rho \mathbf{g}$ and $\rho \mathbf{v} \cdot \mathbf{g}$, respectively (see right hand sides of Equations 2.5 and 2.6). As different hydrodynamic schemes incorporate the gravitational source term in different manners, only the gravitational potential ϕ is provided by the gravity solver. From which the gravitational acceleration can be calculated by:

$$g_{x,ijk} = \frac{(\phi_{i-1,j,k} - \phi_{i+1,j,k})}{2 \Delta x}, \quad (2.22)$$

where $g_{x,ijk}$ is the gravitational acceleration in the x-direction of a grid cell and Δx is the grid spacing, and analogue for the other coordinate-directions. The incorporation of the gravitational accelerations for the unsplit MUSCLE Hancock scheme follows the description of Truelove et al. (1998). Where the velocities at the left and right sides ($S = L$ or R) of the interface $i + 1/2$, separating cells i and $i + 1$, are modified according to:

$$v_{S,i+1/2} \rightarrow v_{S,i+1/2} + \frac{\Delta t}{2} \frac{(g_{S,i+1/2}^+ + g_{S,i+1/2}^-)}{2}, \quad (2.23)$$

where $(g_{S,i+1/2}^+ + g_{S,i+1/2}^-)/2$ is the characteristic-averaged value of $g_{S,i+1/2}$, the superscripts denotes the $v + a$ and $v - a$ characteristic respectively.

2.5 Cooling

Cooling of gas is, besides gravity, one of the major drivers of structure formation, from the formation of larger scale structures in the universe down to molecular clouds which eventually form stars. Depending on the temperature, chemical composition and ionisation fraction the cooling rate and the associated processes are strongly varying. The dominant cooling mode, for a hot plasma in collisional ionisation equilibrium, is radiative cooling due to metal line transitions. At temperatures greater than a few times 10^7 K cooling occurs mainly by bremsstrahlung (Boehringer and Hensler, 1989; Dalgarno and McCray, 1972). For lower temperatures the cooling rate is determined by collisional excitation of fine structure levels of neutral and ionised atoms. By the inclusion of molecular gas, the cooling rate at low temperature would be increased (e.g. Dalgarno and McCray, 1972).

In order to accurately describe the radiative cooling for all temperatures, Ploeckinger (2014) divided the cooling function into two different temperature regimes. For the temperature range $10^4 < T [\text{K}] < 10^8$ the cooling tables from Boehringer and Hensler (1989) for H, He, C, N, O, Ne, Mg, Si, S and Fe are used. For temperatures below 10^4 K the cooling functions from Dalgarno and McCray (1972) and Schure et al. (2009) are evaluated, taking into account the cooling due to C, N, O, Si, S and Fe. To account for the composition dependent ionisation the ion fractions for ionisation equilibrium are taken from Arnaud and Rothenflug (1985) and Arnaud and Raymond (1992, for iron).

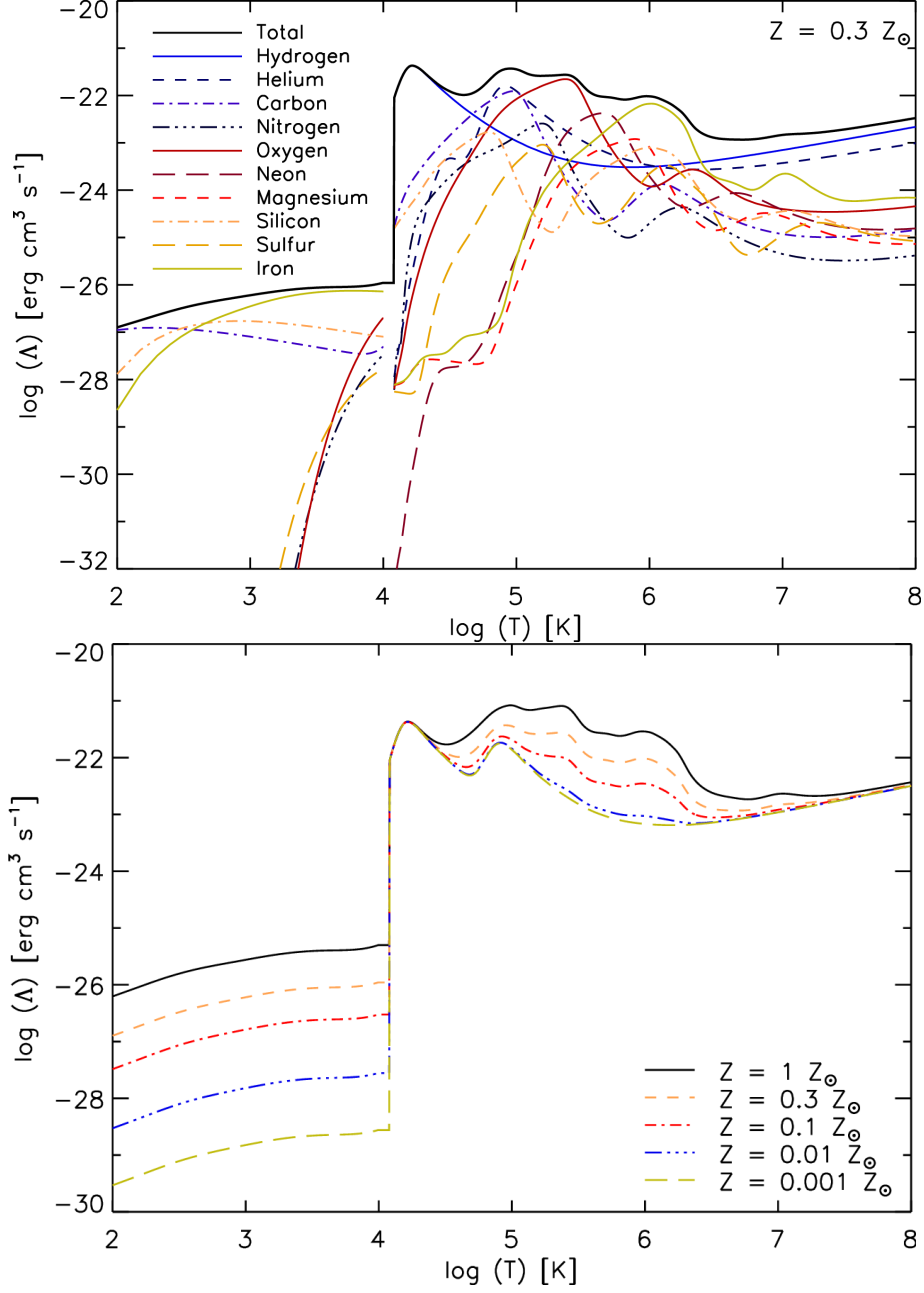


Figure 2.2: Top: Combined radiative cooling rate coefficient $\Lambda(T)$ for $Z = 0.3 Z_{\odot}$ with the contribution of the 10 different species considered for cooling. Bottom: Combined radiative cooling rate coefficient for $Z = 1.0, 0.3, 0.1, 0.01$ & $0.001 Z_{\odot}$

Figure 2.2 illustrates the combined cooling coefficient $\Lambda(T)$ and the contributions of the considered elements for a metallicity of $Z = 0.3 Z_{\odot}$ in the temperature range $10^2 \leq T$ [K] $\leq 10^8$ in the top panel and the combined cooling coefficient for several values of Z in the bottom panel. The loss of energy due to the effect of radiative cooling is given by

$$\frac{\partial \varepsilon}{\partial t} = -n^2 \Lambda(T), \quad (2.24)$$

where ε is the internal energy density and n the particle number density.

2.5.1 Implementation

To calculate the energy loss due to radiative cooling, an implicit Newton-Raphson solver is used, in case it does not converge fast enough a bisection routine is used. One Newton-Raphson iteration step is calculated by

$$\varepsilon_{n+1}^{new} = \varepsilon_{n+1}^{old} - \frac{f(\varepsilon)}{f'(\varepsilon)}, \quad (2.25)$$

with

$$f(\varepsilon) = \varepsilon_{n+1} - \varepsilon_n + \Delta t_{cool} \frac{n_H^2}{\rho} \Lambda(T, f_i) \quad (2.26)$$

and

$$f'(\varepsilon) = 1 + \Delta t_{cool} \frac{n_H^2}{\rho} \frac{\partial \Lambda(T, f_i)}{\partial T} \frac{T}{\varepsilon_n}, \quad (2.27)$$

where Δt_{cool} is the cooling timestep, n_H the number density of hydrogen atoms, ε_n the internal energy before cooling, ρ the density within a grid cell, T the temperature and f_i the ionisation fraction. Supernovae and in general the feedback of stars increase the temperature within a grid cell as well as the density, as material is released back to the grid. These high temperatures and densities can lead to an unphysical high cooling rate, resulting in the so-called overcooling problem. To avoid this problem, without completely shutting down the cooling in affected grid cells, the mass fraction of heated gas f_{SN} is traced and excluded from the general cooling process. Therefore, the specific internal energy after cooling becomes

$$\varepsilon_{n+1} = \varepsilon_n + (1 - f_{SN}) \Delta \varepsilon_{cool}, \quad (2.28)$$

where $\Delta \varepsilon_{cool} \leq 0$ is the energy loss due to radiative cooling. In addition to the dilution of f_{SN} as it is advected with the gas, it cools by a reduction of the mass fraction according to

$$f_{SN}^{n+1} = 1 - \frac{\Delta t}{\tau_{SN}} \times f_{SN}^n, \quad (2.29)$$

where Δt is the hydrodynamic timestep, $\tau_{SN} = 3$ Myr is the typical cooling time, f_{SN}^n and f_{SN}^{n+1} are the fractions of feedback heated gas before and after cooling, respectively. For details on the calculation of f_{SN} see Section 2.6.3.

2.6 Stars

Stars are an important impact factor of galaxy evolution and influence it in several different ways. The formation of stars reduces the galactic gas content and therefore reduce the available amount of gas for star formation. On the other hand, during the evolution of stars and particularly at the end of their life, stars return metal-enriched material back to the ISM. These so-called stellar feedback events can be highly energetic and therefore heat the ISM, this heating decreases the production rate of stars as they are formed out of

cold molecular gas. After a sufficient cooling time this enriched material will be available for further star formation.

Within the scope of the presented simulations, stars are treated as particles. Where one stellar particle represents a whole star cluster containing a single stellar population. The stellar population within one star cluster is described by the stellar initial mass function, which allows to derive the number of stars per mass interval. This treatment allows to determine how many stars in which mass interval end their life within one timestep and therefore provides information about the number and types of stellar feedback events. The star clusters are represented by three major parameters, the current mass, needed for the gravitational force calculation, the initial mass at the time of formation and the age of the cluster, which are both needed for the determination of the number of dying stars. The stellar particles routines developed by Ploekinger (2014) incorporate star formation and feedback, as described below. To advance the particles positions in time, within the potential of the TDG, a LeapFrog algorithm for adaptive timesteps is used. The additional effects of the external gravitational potential (i.e. tidal accelerations) are taken into account, see Section 2.7 for details on the calculation.

2.6.1 Star Formation

The used star formation recipe is fully self-regulated, in a way that feedback from stars influence and regulate the formation of new stars. Stellar particles are created according to the stellar birth function (SBF, ψ), which is only depending on the local gas density and temperature. This kind of recipe has the advantage that no threshold in density or temperature for star formation is needed, resulting in a smooth transition from regions with and without star formation. Following the prescription of Koeppen et al. (1995, hereafter KTH95) the SBF is given by

$$\psi(\rho, T) = C_n \rho^n f(T), \quad (2.30)$$

where ρ and T are the gas density and temperature, respectively, $n = 2$, $C_2 = 2.575 \times 10^8 \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-1}$ and $f(T)$ is an efficiency parameter depending only on the local gas temperature. In principle any function which tends to zero for $T \gtrsim 10^4 \text{ K}$ and to one for $T \lesssim 100 \text{ K}$ could be used for $f(T)$. This condition is attributed to the fact that stars form within cold molecular clouds. In the KTH95 description a simple exponential function

$$f(T) = e^{-T/T_s} \quad (2.31)$$

with a constant $T_s = 10^3 \text{ K}$, is used. This results in an efficiency of more than 90% for temperatures below 100 K and less than 5% above 3000 K.

In order to mimic the multiple phases of the ISM, within the single phase description of the used code, only the fraction of cold gas ($f_{\text{cold}} = 1 - f_{\text{SN}}$) is considered for star formation. Where f_{SN} is the mass fraction of gas, heated by the feedback of other stellar

particles, within a grid cell (calculated by the stellar feedback routines, see Section 2.6.3). Therefore, the actual used SBF is given by

$$\psi(\rho, T) = C_2 (1 - f_{SN}) \rho^2 e^{-T/T_s}, \quad (2.32)$$

with the parameters as defined above. As this kind of SF prescription also allows stars to form in regions with high temperatures and low densities, what would result in unphysically low cluster masses, a threshold on the SBF is introduced in the form of

$$\psi_{thres} = \theta_{sf} \times \frac{M_{cl,min}}{\tau_{sf} V_{GMC}}, \quad (2.33)$$

where $M_{cl,min}$ is the minimum cluster mass. τ_{sf} is the cluster formation time, i.e. the time span in which a stellar particle is allowed to accumulate material from the cells within the typical volume of a giant molecular cloud (V_{GMC}). θ_{sf} is a dimensionless factor, controlling the number of stellar particles with masses below $M_{cl,min}$. For $\theta_{sf} = 1$ and assuming a constant density and temperature during the formation time within V_{GMC} , the SBF-threshold translates into a minimal cut-off mass, i.e. after the formation time one stellar particle has to have at least a mass of $M_{cl,min}$. As the density and temperature are in general not constant over time, this threshold is acting as a filter on low initial particle masses, but does not necessarily prohibit particles with final masses below $M_{cl,min}$.

If the SBF within a cell is larger than ψ_{thres} and no other star forming particle lies within a radius of r_{GMC} as well as a convergent gas flow is present, then a new particle is created. Starting from the time of creation a stellar particle has τ_{sf} time to accumulate further material from its surrounding cells according to the SBF. After τ_{sf} or the maximum cluster mass $M_{cl,max}$ is reached the particle is closed for further star formation and the feedback processes start. Additionally to these general shut off parameters a condition based on the description of the initial mass function (IMF, Section 2.6.2) was introduced. As soon as massive stars are born they influence their environment by feedback processes and reduce the available amount of gas for star formation in their surroundings, therefore the accretion of material onto an existing stellar particle is stopped when the last IMF mass bin is populated by at least one star. If the star formation criteria are still fulfilled, then a new stellar particle is created within the distance of r_{GMC} from the fully populated particle. Table 2.1 summarises the used standard star formation parameters within this thesis, deviations from these values are listed in Table 3.2.

In order to conserve the momentum during the accretion phase, the new velocity of a stellar particle after accretion ($\mathbf{v}_{sp}^{n+1}$) is calculated by

$$\mathbf{v}_{sp}^{n+1} = \frac{M_{sp}^n \mathbf{v}_{sp}^n + \Delta m \mathbf{v}_{gas}}{M_{sp}^n + \Delta m}, \quad (2.34)$$

where M_{sp}^n is the mass of the stellar particles before the accretion of gas, Δm is the accreted gas mass, $\mathbf{v}_{sp}^n$ and $\mathbf{v}_{gas}$ are the velocities of the stellar particle before accretion and of the

Table 2.1: List of used standard star formation parameters.

Parameter	Value		used in Equation(s)
C_2	2.575×10^8	$\text{cm}^3 \text{ g}^{-1} \text{ s}^{-1}$	2.30, 2.32
T_s	1000	K	2.31, 2.32
θ_{sf}	1	—	2.33
τ_{sf}	1	Myr	2.33
r_{GMC}	160	pc	—
V_{GMC}	1.72×10^7	pc^3	2.33
$M_{cl,min}$	100	$M_\odot$	2.33
ψ_{thres}	5.83×10^{-6}	$M_\odot \text{ Myr}^{-1} \text{ pc}^{-3}$	2.33
$M_{cl,max}$	10^6	$M_\odot$	—

accreted gas, respectively. The initial metallicity of a stellar particle is mapped from the grids chemical composition to the particle. As it may vary over time, it is calculated after every accretion step as mass weighted average between the metallicity of the particle and the grid cell.

2.6.2 Initial Mass Function

In order to accurately calculate the feedback from the stellar particles, it is necessary to know the distribution of stellar masses within one star cluster particle. This can be calculated via the so-called initial mass function (IMF, $\xi(m)$), one of the most fundamental distribution functions in astrophysics. It is commonly described as a power-law function

$$\xi(m) = k m^{-\alpha}, \quad (2.35)$$

with k being a normalisation constant and the power-law index $\alpha = 2.35$ (Salpeter, 1955), or as a multi-part power-law (Kroupa, 2001) with α depending on the stellar mass range:

$$\alpha = \begin{cases} 1.3 & \dots & 0.1 \leq m/M_\odot < 0.5 \\ 2.3 & \dots & 0.5 \leq m/M_\odot \end{cases} \quad (2.36)$$

For the presented simulations two different IMF implementations were realised, within the standard settings a *filled IMF* is used, whereas comparison runs made use of the *integrated galactic initial mass function (IGIMF)*. In both cases the IMF is discretised into $nbin = 64$ equally spaced logarithmic mass bins in the mass range $0.1 \leq M_\star/M_\odot \leq 120$. Figure 2.3 shows the applied two part Kroupa (2001) IMF for 64 equally spaced logarithmic mass bins normalised to the total cluster mass.

Filled IMF

As the name suggests, for the filled IMF all mass bins are always populated, regardless if the stellar particle has enough mass to fill the IMF or not. Therefore, fractions of high

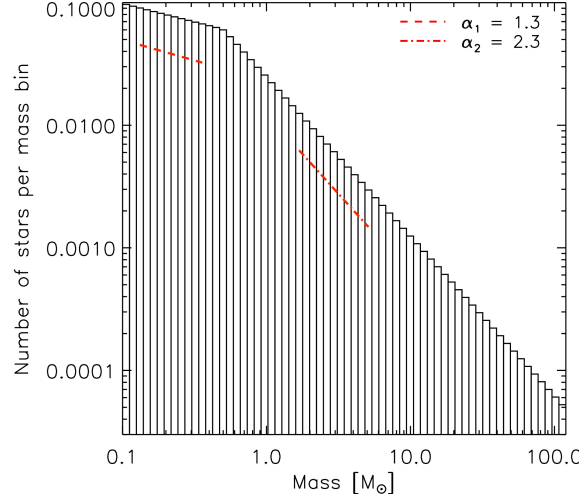


Figure 2.3: Number of stars per mass bin, for a Kroupa (2001) IMF, discretised with 64 logarithmic mass bins and normalised to the total cluster mass. The red lines indicate the slopes of the IMF according to Equation 2.36.

mass stars, which result in fractions of Type II supernovae, will occur. A star cluster has to have a mass of $M_{cl} \geq 19055 M_{\odot}$, in order to populate the highest mass bin, for $nbin = 64$ mass bins, with at least one star. The number of stars within a star cluster and the corresponding mass can be calculated by:

$$N(m) = \int_{m_{min}}^{m_{max}} \xi(m) dm, \quad (2.37)$$

$$M_{cl} = \int_{m_{min}}^{m_{max}} m \xi(m) dm, \quad (2.38)$$

where the limits of integration are the minimal and maximal stellar masses. The IMF is precalculated for a $1 M_{\odot}$ star cluster. This allows to calculate the number of stars for a certain mass bin and an arbitrary cluster mass by scaling the precalculated values with the cluster mass.

Integrated galactic initial mass function

By comparing observationally derived SFRs based on integrated H α - and FUV-luminosities, Lee et al. (2009) found large discrepancies between the different estimates for low mass galaxies with SFRs below $0.1 M_{\odot} \text{ yr}^{-1}$. Their conclusion requires a bottom heavy IMF, i.e. a relative overabundance of low mass stars, as the H α -FUV flux ratio is lower by up to one order of magnitude from expectations. Where SFRs derived from the H α flux trace massive O-stars ($M_{\star} \geq 17 M_{\odot}$) and the FUV-flux traces stars with $M_{\star} \geq 3 M_{\odot}$.

This discrepancy can be overcome by the IGIMF-theory (integrated galactic initial mass function, ξ_{IGIMF}), a galaxy wide IMF which is obtained by integrating over all star cluster IMFs (Kroupa and Weidner, 2003). Thereby it is assumed that all stars form in clusters

with a stellar mass distribution described by an universal IMF (e.g. Equation 2.35). The mass distribution of star clusters is generally assumed to follow a power law $\xi_{ecl} \propto M_{ecl}^{-\beta}$, with $\beta \approx 2$ (e.g. Lada and Lada, 2003). Therefore, clusters with low masses are more frequent and contribute the majority of stellar mass but do not contain massive stars, as their mass is too low to completely fill the IMF. This implies a steepening of the galaxy wide IMF at the high mass end. Additionally to the shape of the IMF and ξ_{ecl} the maximal mass of a star is constrained to $m_{max} \leq 150 M_{\odot}$ and is depending on the mass of the embedded cluster M_{ecl} (Weidner and Kroupa, 2004). Furthermore, M_{ecl} is depending on the global SFR of a galaxy, where higher SFRs lead to higher cluster masses or vice versa during phases of low star formation $M_{ecl,max}$ will be smaller and therefore the slope of the IGIMF will be steeper at the high mass end (Weidner and Kroupa, 2005). The IGIMF can be calculated by:

$$\xi_{IGIMF}(m) = \int_{M_{ecl,min}}^{M_{ecl,max}} \xi(m \leq m_{max}(M_{ecl})) \xi_{ecl}(M_{ecl}) dM_{ecl}, \quad (2.39)$$

where $\xi(m \leq m_{max}(M_{ecl}))$ is the stellar IMF of a star cluster, $\xi_{ecl}(M_{ecl}) \propto M_{ecl}^{-\beta}$ is the embedded cluster mass function with $\beta \approx 2$, $M_{ecl,min}$ and $M_{ecl,max}$ are the minimal and maximal embedded cluster masses, respectively.

In order to mimic the IGIMF-theory $\xi_{IGIMF}(m)$ is not calculated at every timestep but each stellar particles population is truncated above the uppermost mass bin which holds at least one star (truncated IMF). By this the IMF steepens automatically at the high mass end, as the total number of massive stars within a galaxy is reduced. In contrast to the IGIMF the truncated IMF only depends on the local SFR, rather than the global SFR. Furthermore, this truncation does not allow for fractions of high mass stars, which would cause fractional Type II supernovae. In the following the term IGIMF refers to the truncated IMF, for simplicity.

2.6.3 Feedback

Stellar feedback is one of the main internal drivers of galaxy evolution, especially in the context of chemical enrichment but also as regulating factor of star formation. As stars heat their environment, they reduce the amount of cold molecular gas, which is the reservoir of star formation, and therefore damp the formation of new stars. On the other hand, there are also several processes, during the evolution or at the end of the lifetime of a star, which return chemically enriched material back to the ISM. This material can, after a sufficient cooling time, be again used to form new stars. The mass and metallicity dependent lifetimes of stars, are taken from Portinari et al. (1998). This dependency is used to define the mass range of stars which will end their life during a timestep. Through the IMF description the number of stars in this mass range within a stellar particle is

calculated. If the average mass of an IMF mass bin lies in that mass range, all stars of that bin will end their life and return energy and chemically enriched material back to the ISM. The feedback of Type II supernovae (SN II), stellar radiation and winds are taken into account for stars with $M_\star \geq 8 M_\odot$. For stars in the mass range $1.4 \leq M_\star/M_\odot < 8$ Type Ia supernovae (SN Ia) are considered as well as the effects of mass loss during the asymptotic giant branch (AGB) phase.

Stellar Radiation

Massive stars with $M_\star \geq 8 M_\odot$ emit large amounts of Lyman continuum photons ($e_{phot} \geq 13.6$ eV) during their lifetime. This UV radiation ionises the surrounding ISM, producing an HII region. Its extent can be approximated by a Strömgren sphere, which requires that all recombining H-atoms are immediately ionised again. Although the temperature of an HII region is not constant with time, the applied sub-grid model assumes a constant temperature of $T_{HII} = 2 \times 10^4$ K. The Strömgren radius R_S is defined as the maximal distance at which ionisation and recombination are balanced. It is calculated by

$$R_S = \left(\frac{3S_\star}{4\pi n_H^2 \beta_2} \right)^{1/3}, \quad (2.40)$$

where β_2 is the recombination coefficient, calculated by

$$\beta_2 = 2.6 \times 10^{-13} \left(\frac{10^4 \text{ K}}{T} \right)^{0.85} \text{ cm}^3 \text{ s}^{-1}, \quad (2.41)$$

n_H the hydrogen number density and $S_\star$ the ionising photon flux. The ionising photon flux $S_\star$ of a massive star with mass m can be estimated by

$$S_\star = 3.6 \times 10^{42} \left(\frac{m}{M_\odot} \right)^4 \quad (2.42)$$

(Ploekinger et al., 2015). The mass of ionised hydrogen within a Strömgren sphere around a massive star is given by

$$M_{HII}(M_\star) = \frac{S_\star(M_\star) \mu^2 m_H^2}{\beta_2 \rho f_H^2}, \quad (2.43)$$

where ρ and μ are the density and mean molecular weight of the ambient gas, respectively, m_H the mass of a hydrogen atom, and f_H the hydrogen mass fraction in the ISM. The total mass of hydrogen ionised by a single star-cluster particle ($M_{HII,tot}$), can be calculated by summing over all IMF mass bins which contain stars with masses greater than $8 M_\odot$ (corresponding to b_{min}) until the last still populated mass bin (b_{max}):

$$M_{HII,tot} = \sum_{i=b_{min}}^{b_{max}} N_\star(i) M_{HII}(M_\star), \quad (2.44)$$

where $N_{\star}(i)$ is the number of stars in the i^{th} mass bin. The total mass of ionised gas is mapped back onto the grid variable $DHII$, it provides the fraction of ionised gas ($f_{ion} = DHII / DENS$). Which is needed to calculate the temperature of a grid cell as mass weighted average between the cells temperature and T_{HII} .

Stellar Wind

During their evolution, OB stars suffer a strong mass loss, which enriches and heats the ISM. The metallicity (Z) dependent mass-loss rate due to stellar winds is calculated by (Hensler, 1987; Theis et al., 1992)

$$\dot{m} = 10^{-15} \left(\frac{Z}{Z_{\odot}} \right)^{1/2} \left(\frac{L}{L_{\odot}} \right)^{1.6} M_{\odot} \text{ yr}^{-1}, \quad (2.45)$$

where L is the luminosity, derived from the mass-luminosity relation of Maeder (1996). The heating by an OB star is determined by the kinetic power of its wind,

$$\dot{E}_{kin} = \frac{1}{2} \dot{m} v_{\infty}^2, \quad (2.46)$$

with

$$v_{\infty} = 3 \times 10^3 \left(\frac{\bar{m}}{M_{\odot}} \right)^{0.15} \left(\frac{Z}{Z_{\odot}} \right)^{0.08} \text{ km s}^{-1}, \quad (2.47)$$

where v_{∞} is the winds final velocity and $\bar{m}$ is the average mass of a star in the considered IMF mass bin. The mass fraction of material released by the stellar wind, within one IMF mass bin, is calculated by

$$f_{wind}(bin) = \frac{\dot{m} \tau_{cl}}{\sum m_{EL}}, \quad (2.48)$$

where τ_{cl} is the age of a star cluster particle and $\sum m_{EL}$ is the sum of the produced elements, which will be returned to the grid. The energy released by the lost material is than given by

$$E_{wind,SP} = \epsilon_{wind} \dot{E}_{kin} \tau_{cl} \sum_{bin} f_{wind}(bin) N_{\star}(bin), \quad (2.49)$$

where ϵ_{wind} , set to 5%, is the wind efficiency and $N_{\star}(bin)$ the number of stars within an IMF mass bin.

Type II Supernova

Stars more massive than about $8 M_{\odot}$ end their life as core-collapse supernova, also called Type II supernova (SN II) (e.g. Maeder, 2009). If an IMF mass bin, represented by its average mass which has a mass greater than $8 M_{\odot}$, reaches the end of its lifetime, then all stars within that mass bin end their life. The energy released by a stellar particle due to

SN II is calculated by

$$E_{SNII,SP} = \epsilon_{SNII} E_{SNII} \sum_{bin} (1 - f_{m,wind}(bin)) N_{\star}(bin), \quad (2.50)$$

where the sum is carried out over all mass bins in which the stars reached the end of their lifetime at a certain timestep, $\epsilon_{SNII} = 5\%$ is the efficiency at which the energy is injected into the ISM, $E_{SNII} = 10^{51} \text{ erg}$ is the energy released by one supernova, $f_{m,wind}(bin)$ is the mass fraction of material which is released through stellar winds and $N_{\star}(bin)$ is the number of stars in a certain mass bin. The total SN II feedback energy is mapped back to the grid as thermal energy. The mass of the remaining neutron star or black hole is kept locked in the stellar particle and therefore is excluded from further star formation.

Asymptotic Giant Branch Stars

Stars of low to intermediate mass, below approximately $8 M_{\odot}$, pass through a phase of helium shell burning, the so-called asymptotic giant branch (AGB) phase. During this phase the energy input from stars to the ISM is negligible, but they do transfer material back to their surroundings, enriching it mainly by C and N. The effect of the AGB-phase feedback is only considered for stars in the mass range form $1.4 \leq M_{\star}/M_{\odot} < 8$ at the end of their lifetime. After the AGB-phase stars will evolve into white dwarfs of which a fraction will eventually end their life as Type Ia supernova.

Type Ia Supernova

Although the details of the explosion mechanism and the progenitor stars of SN Ia remain uncertain, it is commonly assumed that a carbon-oxygen white dwarf (CO-WD) in a binary system is involved. This CO-WD grows in mass by accretion from its companion until it approaches the Chandrasekhar mass limit of about $1.44 M_{\odot}$ (e.g. Iben and Tutukov, 1984; Hillebrandt and Niemeyer, 2000; Matteucci and Recchi, 2001). According to Renzini and Voli (1981) a star has to have a mass of at least $1.4 M_{\odot}$ on the main sequence in order to evolve into a CO-WD. Therefore, feedback by SNe Ia is only considered for stars in the main sequence mass range of $1.4 \leq M_{\star}/M_{\odot} < 8$. The rate of the occurrence of SNe Ia is dependent on the fraction of WDs in a binary system. Following the SN Ia rate equations from Matteucci and Recchi (2001) and Recchi et al. (2009) the probability for a star to be the secondary in a binary system can be calculate by

$$P(m_2) = 2^{1+\gamma} (1 + \gamma) A \sum_{i=i(m_2)}^{nimf} \frac{\xi(m_i, nimf)}{\xi(m_2, nimf)} \mu_i^{\gamma} \Delta\mu, \quad (2.51)$$

where $A = 0.09$ is a normalisation constant, μ_i is the mass ratio between m_2 , the mass of the secondary star, and the total mass of the binary system, $\xi(m_i, nimf)$ is the IMF. If a filled IMF is used $nimf$ is the last IMF mass bin, in cases where the IGIMF is used, it

refers to the mass bin at which the IMF is truncated. The parameter γ is related to the distribution function of mass ratios in binary systems, where $\gamma = 2$ favours systems with equal masses. The number of SNe Ia in one mass bin can then be calculated by

$$N_{SNIa}(bin) = P(m_2)N_{\star}(bin), \quad (2.52)$$

where $N_{\star}(bin)$ is the number of stars in one mass bin. The total energy released by a single stellar particle ($E_{SNIa,SP}$), assuming a SN Ia efficiency $\epsilon_{SNIa} = 5\%$ and an energy of $E_{SNIa} = 10^{51}$ erg is then given by

$$E_{SNIa,SP} = \epsilon_{SNIa} E_{SNIa} \sum_{bin} N_{SNIa}(bin), \quad (2.53)$$

where the sum is carried out over all mass bins in the mass range from 1.4 to 8 $M_{\odot}$ in which the stars reached the end of their lifetime. The released energy is purely injected as thermal energy onto the grid.

Material feedback & Chemical Enrichment

During the lifetime of a star, it processes the material which it is made of through nucleosynthesis, by this stars are producing heavy elements. This processed material is released into the interstellar space and thus enriches the ISM. Depending on the mass of a star, its evolution and therefore the produced amount of the various elements is very different. Stars with masses greater than 8 $M_{\odot}$ end their life as SN II and enrich the ISM mostly by α -elements. Stars with masses below 8 $M_{\odot}$ mostly enrich their environment with N and C, during the AGB phase of their evolution. Some of these stars will eventually end their life as SN Ia, which enriches the surroundings mostly by Fe. The produced amount of the traced elements H, He, C, N, O, Ne, Mg, Ca, Si, S, Fe and X, where X is the sum of all other elements, are mapped to the grid at the end of a stars lifetime. The mass fraction of material which is released by feedback processes f_{SN} , within a grid cell is tracked during the simulations and advected with the flow of the gas. It is used in Equation 2.32 to reduce the available amount of gas for star formation and to avoid the so-called overcooling problem (see Section 2.5). f_{SN}^{n+1} after the feedback processes is calculated by

$$f_{SN}^{n+1} = 1 + \frac{\rho_{old}}{\rho_{enriched}} \times (f_{SN}^n - 1), \quad (2.54)$$

where $\rho_{enriched}$ is the gas density within a grid cell after enrichment by the feedback processes, f_{SN}^n and ρ_{old} are the mass fraction of feedback heated gas and the gas density within a grid cell before the feedback occurred, respectively.

The stellar yields for Type II SNe, stellar winds and AGB stars are taken from Marigo et al. (1996) for $1 \leq M_{\star}/M_{\odot} \leq 4$ and from Portinari et al. (1998) for $M_{\star} \geq 6 M_{\odot}$, with linear interpolation between 4 – 6 $M_{\odot}$. For the enrichment by Type Ia SNe the yields are taken from the W7 model of Travaglio et al. (2004).

2.7 3D Orbit

In order to account for the tidal forces, caused by the gravitational potential of the interacting galaxies, acting on the TDG candidates, this module was introduced. It is based on the ORBIT module described by Ploekinger (2014) but allows a fully 3 dimensional treatment of the orbit. In the current implementation of the module ORBIT3D a central point mass, constant in time, is assumed. This can easily be adjusted to any other kind of central potential simply by changing the way how the gravitational acceleration is calculated. When TDGs move through the potential of the interacting galaxies they do not only experience the tidal field but also ram pressure induced by the hot halo gas. Therefore, the treatment of ram pressure is also included within this module. In order to control the activity of the different phenomena, related to the motion through the external potential, three runtime parameters were introduced, *useOrbit* which controls if the orbit module should be used or not, *useTidal* and *useRam* which control the activity of the tidal field and ram pressure, respectively. The module requires the position (X, Y, Z) , the distance R of the TDG, both with respect to the centre of the external potential, the orbital velocities (v_X, v_Y, v_Z) and the central mass M_{ext} as input parameters. In order to distinguish between the different coordinate systems capital letters (X, Y, Z) are used for the coordinates of the simulation box with respect to the mass centre of the interacting galaxies and lower case letters (x, y, z) for the coordinates of grid cells within the simulation box.

2.7.1 Tidal field

If the effects of the tidal field should be taken into account, the runtime parameter *useTidal* has to be set to *TRUE*. In this case the tidal accelerations are added to the accelerations within each cell as well as to the accelerations of the stellar particles. At every time t the position (X, Y, Z) and orbital velocities (v_X, v_Y, v_Z) of the TDG are known as it has been calculated at the previous time-step (or from the initial data). From this position the distance R is calculated by

$$R = \sqrt{X(t)^2 + Y(t)^2 + Z(t)^2}. \quad (2.55)$$

The external gravitational acceleration $\mathbf{g}_{ext} = (g_{ext,X}, g_{ext,Y}, g_{ext,Z})$ at a given distance R between the merging galaxies, with a combined total mass M_{ext} , and the TDG is given by:

$$\mathbf{g}_{ext} = -\frac{G M_{ext}}{R^2} \hat{\mathbf{R}}, \quad (2.56)$$

where G is the gravitational constant and $\hat{\mathbf{R}}$ the 3 dimensional unit vector pointing towards the centre of the simulation box.

The velocity and position the simulation box at the next time-step $(t + \Delta t)$ can then be

calculated by:

$$\begin{aligned} v_X(t + \Delta t) &= v_X(t) + \Delta t \, g_{ext,X}(t) \\ v_Y(t + \Delta t) &= v_Y(t) + \Delta t \, g_{ext,Y}(t) \\ v_Z(t + \Delta t) &= v_Z(t) + \Delta t \, g_{ext,Z}(t) \end{aligned} \quad (2.57)$$

$$\begin{aligned} X(t + \Delta t) &= X(t) + \Delta t \, v_X(t) \\ Y(t + \Delta t) &= Y(t) + \Delta t \, v_Y(t) \\ Z(t + \Delta t) &= Z(t) + \Delta t \, v_Z(t) \end{aligned} \quad (2.58)$$

To calculate the additional tidal acceleration and the resulting velocities within every grid cell the coordinates (x, y, z) of the cells have to be transformed to global coordinates (x', y', z') with respect to the external potential.

$$\begin{aligned} x' &= x + X(t) \\ y' &= y + Y(t) \\ z' &= z + Z(t) \end{aligned} \quad (2.59)$$

These global coordinates are used to calculate the distance r'_{cell} , according to Equation 2.55, from the centre of the external potential to a grid cell. The external gravitational acceleration acting within this grid cell $\mathbf{g}'_{cell}$ can then be calculated from Equation 2.56 replacing R with r'_{cell} and $\hat{\mathbf{R}}$ with $\hat{\mathbf{r}}'_{cell}$, the unit vector pointing towards a specific cell. The simulations are carried out in the rest frame of the simulation box and the external gravitational acceleration of the simulation box is therefore accounted by the translation of the box itself, thus it has to be subtracted from the acceleration within each grid cell. The resulting tidal acceleration $\mathbf{a}_{tidal}$ within a cell is then given by

$$\mathbf{a}_{tidal} = \mathbf{g}'_{cell} - \mathbf{g}_{ext}. \quad (2.60)$$

This acceleration is used to update the velocities within a grid cell analogous to Equation 2.57 using $\mathbf{a}_{tidal}$ instead of $\mathbf{g}_{ext}$. For stellar particles the effect of the tidal field is calculated the same way as for grid cells. Only the grid coordinates and accelerations are replaced by those of the stellar particles.

2.7.2 Ram pressure

When galaxies move through an ambient medium they feel a pressure force on their gaseous component. For example the intra-cluster medium when a galaxy falls into a cluster of galaxies or the hot halo gas of a galaxy that a satellite galaxy feels while it is orbiting around its central galaxy. This pressure force is called ram pressure P_{ram} and can be expressed by

$$P_{ram} = \rho_a v^2, \quad (2.61)$$

where ρ_a is the density of the ambient medium and v is the velocity at which the galaxy moves through this medium. A first approximation on the possibility for the loss of matter due to ram pressure can be obtained by comparing P_{ram} to the restoring gravitational force. If the ram pressure is acting perpendicular to the disk of a galaxy, material is stripped away from it if

$$P_{ram} \geq 2\pi G \Sigma_s \Sigma_g, \quad (2.62)$$

where Σ_s and Σ_g are the surface density of stars and gas, respectively (Gunn and Gott, 1972, for disk galaxies). Combining these two equations shows that the effect of RPS is stronger in high density environments and for large velocities.

Just as for the tidal field the ram pressure is controlled by the runtime parameter *useRam*, which has to be set to *TRUE*, if the effects of the relative motion between the TDG respectively the tidal arm and the ambient medium should be accounted for. As the simulations presented here are carried out in the rest frame of the simulation box, therefore the TDG candidates reside at the centre of the box, a wind tunnel like configuration is present. In such a configuration the object of interest stays at its initial position while the ambient medium is flowing around it. The initial velocity ($\mathbf{v}_{box}$) of the simulation box causes the ambient medium to travel with a velocity of $\mathbf{v}_{wind} = -\mathbf{v}_{box}$ through the box. As the velocity (absolute value and direction) of the simulation box along its orbit around the external potential changes, so does the velocity of the ambient medium. To account for this effect the wind velocity is updated at every time-step. The changing velocity of the simulation box only concerns the ambient medium, and does not affect the gas of the TDG and tidal arm or the stellar component directly. It is possible to differentiate between the tidal arm and the surrounding gas via the mass tracer *TDG_MSCALAR*. The ambient medium is initialized with *TDG_MSCALAR* = 0 and the tidal arm with *TDG_MSCALAR* = 1, this tracer is advected with the flow of the gas. If the two components are getting mixed, the mass scalar is calculated accordingly, this allows to trace the amount of mass within a cell which originates from the tidal arm. The velocity is only modified, to account for the motion of the box, if the value of *TDG_MSCALAR* is below 10^{-4} .

Chapter 3

Simulations

3.1 Initial data

The initial data for the presented simulations within this thesis are the result of a series of galaxy merger simulations from Prof. Hammer (Observatoire de Paris) and collaborators. These simulations made use of the smoothed-particle hydrodynamic (SPH) code `GADGET2` (Springel, 2005). In Hammer et al. (2010), they tried to explain many of the odd structural properties of the Andromeda Galaxy (M31), such as the ring structure, the northern loop or the giant stream, as a consequence of one single gas-rich merger. Their results indicate that M31 experienced a gas-rich merger, approximately 8 to 9 Gyr ago, with a gas fraction of $\sim 65\%$ gas, a mass ratio of approximately 3:1 and a polar orbit with $r_{\text{pericenter}} \approx 25$ kpc. During this simulations it turned out that the vast polar structure (VPOS), a disk of satellite galaxies almost perpendicular to the disk of the Milky Way (MW), might be a consequence of the Andromeda merger hypothesis. Both the geometry and angular momentum properties of the VPOS population can be reproduced by this model, as reported in Fouquet et al. (2012). After the discovery of a vast thin disk of satellites (VTDS) around M31 by Ibata et al. (2013), the merger scenario was further examined in Hammer et al. (2013) to verify if it is possible to explain this structure by the same merger. Finally the possibility of the MW dSph satellite galaxies being DM-free ancient TDGs was examined in Yang et al. (2014). All these results question the standard assumption that the local group has evolved quietly, without a significant major merger for most of its lifetime.

In the initial simulations from Hammer et al. (2010) a total number of particles ranging from 150.000 to 800.000 particles were used. This number was subsequently increased until 8 million particles (4 million DM and baryonic matter each) were reached for the Yang et al. (2014) simulations. The actual data were extracted from the 8 million particle simulation at a time of 1.5 Gyr after the first pericentre passage. Already at this early stage of the merger numerous tidal dwarf candidates can be identified embedded in the tidal arms of the progenitor galaxies.

Four of these TDG candidates, in three different simulation setups, have been further

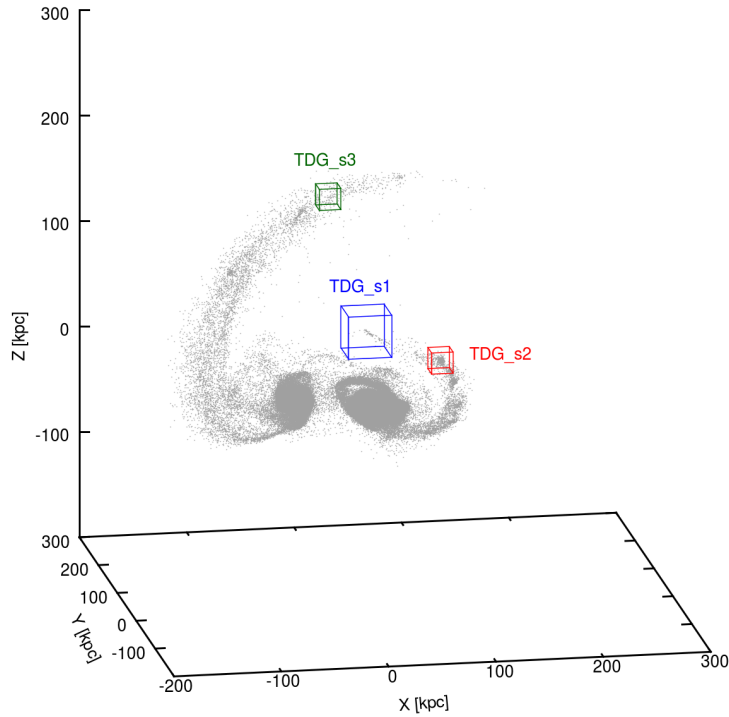


Figure 3.1: Initial distribution of stellar particles from Yang et al. (2014) (grey dots), 1.5 Gyr after the first pericentre passage. The colored boxes indicate the different simulation setups of the tested TDG candidates and are scaled to size.

investigated within this thesis. These candidates have been selected based on the following criteria: (1) The presents of an over-density in the initial distribution of the gaseous and stellar component. (2) A minimal gas mass within a radius of 2.5 kpc from the centre of the proto-TDGs of $M_{min} \gtrsim 10^8 M_{\odot}$. (3) No companion close to the edges of the later simulation box, as it would most likely influence the flow along the tidal arm, especially across the boundaries of the simulation box. (4) TDG candidates originating from both tidal arms should be included. Figure 3.1 shows the initial distribution of stellar SPH-particles from the Yang et al. simulation, with boxes highlighting the selected TDG candidates and their corresponding simulation domain.

3.1.1 Data extraction

It is of high importance to carefully select and extract the data for the simulations of TDGs, as the provided initial data cover a large volume of about $300 \times 550 \times 200 \text{ kpc}^3$, neglecting the low density halo gas and the distribution of DM. To simulate this whole volume on a grid with an adequate resolution would be computationally way to expensive, if one is only interested in the evolution of structures with a typical radius of only a few kpc. Therefore, only the SPH-particles within a box with a typical length scale of 22 respectively 44 kpc, depending on TDG candidate, are selected for the mapping process. This corresponds to 110% of the side of the later simulation box and is required for an

accurate determination of the gas properties at the edges of the simulation box. The centre of the TDG is found iteratively, starting from their approximated position. The mass centre of stellar and gas SPH-particles within a sphere of radius $r_{TDG} = 4$ kpc is calculated by

$$\mathbf{R}_M = \frac{1}{\sum_i m_i} \sum_i m_i \mathbf{r}_i, \quad (3.1)$$

where m_i and $\mathbf{r}_i$ are the mass and position of an SPH-particle, respectively. $\mathbf{R}_M$ is used in the next step as the centre of a new 4 kpc sphere and is recalculated, this process is repeated until convergence is reached.

The mass centre of the TDG candidate is used as initial position for the orbit module (see Section 2.7). The orbital velocity is calculated as mass-weighted mean velocity of all gas and stellar particles within r_{TDG} around the mass centre of the TDG. The position of the mass centre and its velocity are subtracted from the particles original position and velocity, in order to get the TDG candidate at rest in the centre of the simulation box. Note that the choice of the radius is crucial, as for larger radii the orbital velocity is likely to be contaminated by the flow velocity of the gas along the tidal arm. This can cause a significantly stronger drift of the TDG within the simulation box, than in the data presented here. For the central mass the mass of all DM, gas and star particles is summed up from the centre of the merger to the position of the TDG. These parameters fully describe the orbit of the TDG.

3.1.2 SPH-to-Grid mapping

As the provided initial data are the results from an SPH-simulation, special care is needed when the SPH-particle properties are mapped to the grid of FLASH. In order to map the particle masses to the grids density, the mass of one particle is folded with the so-called kernel function $W(r, h)$, as defined in Equation 3.3. It depends on the smoothing length h and the distance r between the particle and the cell centre. Therefore, the density within a grid cell is given by:

$$\rho_{cell} = \sum_{i=1}^N m_i W(r_i, h), \quad (3.2)$$

with m_i being the mass of the i^{th} particle and N the number of gas-particles of the SPH-simulation.

$$W(r, h) = \frac{8}{\pi h^3} \times \begin{cases} 1 - 6 \left(\frac{r}{h}\right)^2 + 6 \left(\frac{r}{h}\right)^3 & \text{if } 0 \leq \frac{r}{h} \leq 0.5 \\ 2 \left(1 - \frac{r}{h}\right)^3 & \text{if } 0.5 \leq \frac{r}{h} \leq 1 \\ 0 & \text{if } \frac{r}{h} > 1 \end{cases} \quad (3.3)$$

Equations 3.2 and 3.3 follow the standard recipe of GADGET2, except for the definition of the smoothing length. Throughout this work the smoothing length h is the distance to the 50th closest neighbour. Except in cases when more than 50 SPH-particles would

Table 3.1: Initial properties of the three different simulation setups. Column 1: Simulation setup as indicated in Figure 3.1; Columns 2-3: Number of stellar and gas SPH-particles within the simulation box; Columns 4-6: Initial orbital parameters (orbital velocity $|v|$, distance from the interacting galaxies R and the total mass of the interacting galaxies M_{ext} from their mass centre to R); Columns 7-11: Size of the simulation box along one coordinate direction, minimal and maximum level of refinement (l_{ref}), effective resolution Δx_{eff} at $l_{ref, max}$, the initial gas (M_g) and stellar mass ($M_\star$) within the simulation box after the mapping process.

Setup	# SPH-particles		Orbit			Simulation box				
	stars	gas	$ v $ [km s ⁻¹]	R [kpc]	M_{ext} [10 ¹¹ M _⊙]	size [kpc]	l_{ref}	Δx_{eff} [pc]	M_g [10 ⁸ M _⊙]	$M_\star$ [10 ⁶ M _⊙]
TDG_s1	76	48 789	127	184	4.9	40	3 - 6	78	10.8	2.1
TDG_s2	338	33 832	109	162	4.8	20	3 - 5	78	9.2	9.3
TDG_s3	117	22 091	187	313	5.4	20	3 - 5	78	2.6	2.2

fall within a grid cell, then h is adapted such that at least all particles within a cell are mapped into the cell. This additional requirement is needed as, on low refinement levels, it can happen that more than 50 SPH-particles lie within one grid cell. If, in this case, only the closest 50 particles would be considered, the density distribution on the grid might become too smooth, what could cause FLASH to stop the initial refinement process during the simulation setup, although it would be necessary. By the definition of h as being the distance to the n^{th} nearest neighbour, Equation 3.2 does not need to be evaluated for all particles within the original simulation. This is because, according to Equation 3.3, all particles that are further away do not contribute to the density of the considered cell. For the other gas properties (temperature and velocity) an inverse distance weighted average was used. By this method the closest particle to the cell centre got the largest influence on the cell's properties and is calculated by:

$$Q_{cell} = \frac{1}{\sum_{i=1}^n \frac{1}{r_i}} \sum_{i=1}^n Q_i \frac{1}{r_i}, \quad (3.4)$$

where r_i is again the distance from the cell centre to the i^{th} particle, n is the number of considered particles (as used for the definition of h), Q_{cell} and Q_i are the quantities of interest for a certain cell and the i^{th} SPH-particle respectively.

3.2 Simulation Setup

A series of numerical chemodynamical simulations of forming TDGs have been carried out, based on the 3 different simulation setups as indicated in Figure 3.1 and with some of their basic initial properties listed in Table 3.1.

3.2.1 Initial gas distribution

The initial gas distribution for the presented simulations are mapped from the SPH-data to the grid of the FLASH code according to the description of Section 3.1.2. In order to

prevent the simulation box from being fully refined at the beginning of the simulation run, the mapped density distribution is cut at the density ρ_{cut} . If the density in a cell lies below this threshold value, it is set to the constant density ρ_{IGM} , with temperature T_{IGM} , which define the state of the ambient medium. X-ray observations of the circum-galactic medium (CGM) of the Milky Way indicate $T_{CGM} \approx 10^6$ K and $n_{CGM} \approx 10^{-4}$ cm $^{-3}$ (e.g. Gupta et al., 2012). The IGM parameters are chosen in a way such that they are close to the above mentioned values and that the tidal arm is in an approximated pressure equilibrium, with a slightly higher internal than external pressure at the interface between the arm and the ambient medium. This setup design prevents strong external pressure forces onto the tidal arm, which could lead to an externally triggered collapse of the arm. Furthermore, the mass fraction *TDG_MSCALAR* is set to zero in cases where the density would lie below ρ_{cut} , otherwise it is set to one. Therefore, it also defines the initial region where the cell velocities are modified in order to account for the motion of the simulation box around the merging galaxies, i.e. to account for ram pressure. As the original simulations did not track the chemical evolution, the initial metallicity of the tidal tail was set to $Z = 0.3 Z_{\odot}$, with solar abundance ratios, in order to account for the preenrichment of the stripped gas within the merging galaxies. This metallicity is in agreement with observations of dwarf galaxies formed out of preenrichment material (e.g. Duc and Mirabel, 1998).

3.2.2 Initial stellar population

As in this simulations stellar particles are numerically treated as particles, the initial positions, velocities and masses of the SPH-star-particles of the Yang et al. (2014) simulation are used as initial values of the underlying old stellar population in the tidal arm. The age of these preexisting particles was set to 7 Gyr with a metallicity of $Z = 0.3 Z_{\odot}$ and solar abundance ratios.

3.2.3 Boundary conditions

For the presented simulations FLASHs standard outflow boundary conditions (BC) are used, i.e. zero gradient BC. For this BC all boundary cells get filled with the properties of the neighbouring cell within the computational domain. As the name suggest, outflow BC allow material to leave the simulation box, but they are not sensitive to the flow direction, therefore they also allow for inflow. A behaviour that may not be desirable for a large variety of hydrodynamic simulations. Contrary to that, in the context of young TDGs, which are still embedded in their host tidal arm, the inflow can be used to mimic a flow along the tidal arm which extends out of the simulation box.

3.2.4 Simulation runs

In order to distinguish between the simulation setups, which are defined by the initial data (see Figure 3.1) and the different simulation runs, upper respectively lower case notation is used. Where the upper case notation followed by the setup identifier (e.g. TDG_S1)

Table 3.2: Initial properties of the different simulation runs. Column 1: Simulation run identifier; Columns 2-4: Orbit control parameters, as defined in Section 2.7; Columns 5-7: Star formation parameters (IMF-description, star formation factor θ_{sf} and cluster formation time τ_{sf}); Columns 8-10: Density ρ_{IGM} and temperature T_{IGM} of the intergalactic medium and the cutoff density ρ_{cut} of the tidal arm.

Simulation run	Orbit			Star formation			Intergalactic medium		
	<i>useOrbit</i>	<i>useTidal</i>	<i>useRam</i>	IMF	θ_{sf}	τ_{sf} [Myr]	ρ_{IGM} [g cm ⁻³]	T_{IGM} [K]	ρ_{cut} [g cm ⁻³]
tdg1_orb	✓	✓	✓	filled	1	1	1×10^{-29}	10^6	2×10^{-27}
tdg1_iso	—	—	—	filled	1	1	1×10^{-29}	10^6	2×10^{-27}
tdg2_orb	✓	✓	✓	filled	1	1	1×10^{-29}	10^6	1×10^{-27}
tdg2_noRam	✓	✓	—	filled	1	1	1×10^{-29}	10^6	1×10^{-27}
tdg2_iso	—	—	—	filled	1	1	1×10^{-29}	10^6	1×10^{-27}
tdg2_noArm	✓	✓	✓	filled	1	1	5×10^{-28}	10^6	5×10^{-26}
tdg2_noArm_iso	—	—	—	filled	1	1	5×10^{-28}	10^6	5×10^{-26}
tdg2_igimf	✓	✓	✓	truncated	1	1	1×10^{-29}	10^6	1×10^{-27}
tdg2_sf1	✓	✓	✓	filled	0.1	10	1×10^{-29}	10^6	1×10^{-27}
tdg2_sf2	✓	✓	✓	filled	100	10	1×10^{-29}	10^6	1×10^{-27}
tdg3_orb	✓	✓	✓	filled	1	1	5×10^{-29}	10^6	1×10^{-26}
tdg3_noRam	✓	✓	—	filled	1	1	5×10^{-29}	10^6	1×10^{-26}
tdg3_iso	—	—	—	filled	1	1	5×10^{-29}	10^6	1×10^{-26}

refers to the simulation setup.

To examine the various environmental effects which influence the evolution of TDGs, several simulation runs for each simulation setup were carried out with varying settings for the orbit module. To tell apart these different simulation runs lower case notation plus a descriptive suffix is used. The suffix *_orb* corresponds to simulations using the full capabilities of the orbit module, *_noRam* does not include ram pressure, i.e. the IGM is initialised with zero velocity and its velocity is not modified according to the motion of the simulation box. *_iso* marks comparison runs without the influence of the external gravitational potential or ram pressure, but includes the tidal arms dynamics and density distribution. Simulations testing different values of the star formation parameters are labelled with *_sf* or *_igimf* to highlight simulation which use the IGIMF-theory instead of the filled IMF. The suffix *_noArm* is used for simulations which do not account for the dynamics and density distribution of the tidal arm, but include the influence of the tidal field as well as ram pressure. As the *_orb* and *_igimf* models make use of all the included environmental effect, these models resemble the real environment of TDGs best and should be used to compared against and make predictions for observations. The *noArm* simulations further allow for a direct comparison to earlier works from Ploeckinger et al. (2014, 2015), which do not include the tidal arm. A comprehensive view on the used settings for the orbit module, star formation and IGM for the different simulation runs is provided in Table 3.2.

If the results of different simulation runs for one setup are essentially indistinguishable, a lower case notation followed by an integer is used. In cases with multiple objects within the simulation box, each subcomponent is named with a character after the setup identifier (e.g. tdg1a_orb).

Figure 3.2 shows the initial ($t_{sim} = 0$) gas surface density, integrated along the z-axis, of the different simulation setups. The effect of varying the cutoff density can be seen in the differences of the plots on the right hand side. The top panel shows the standard values

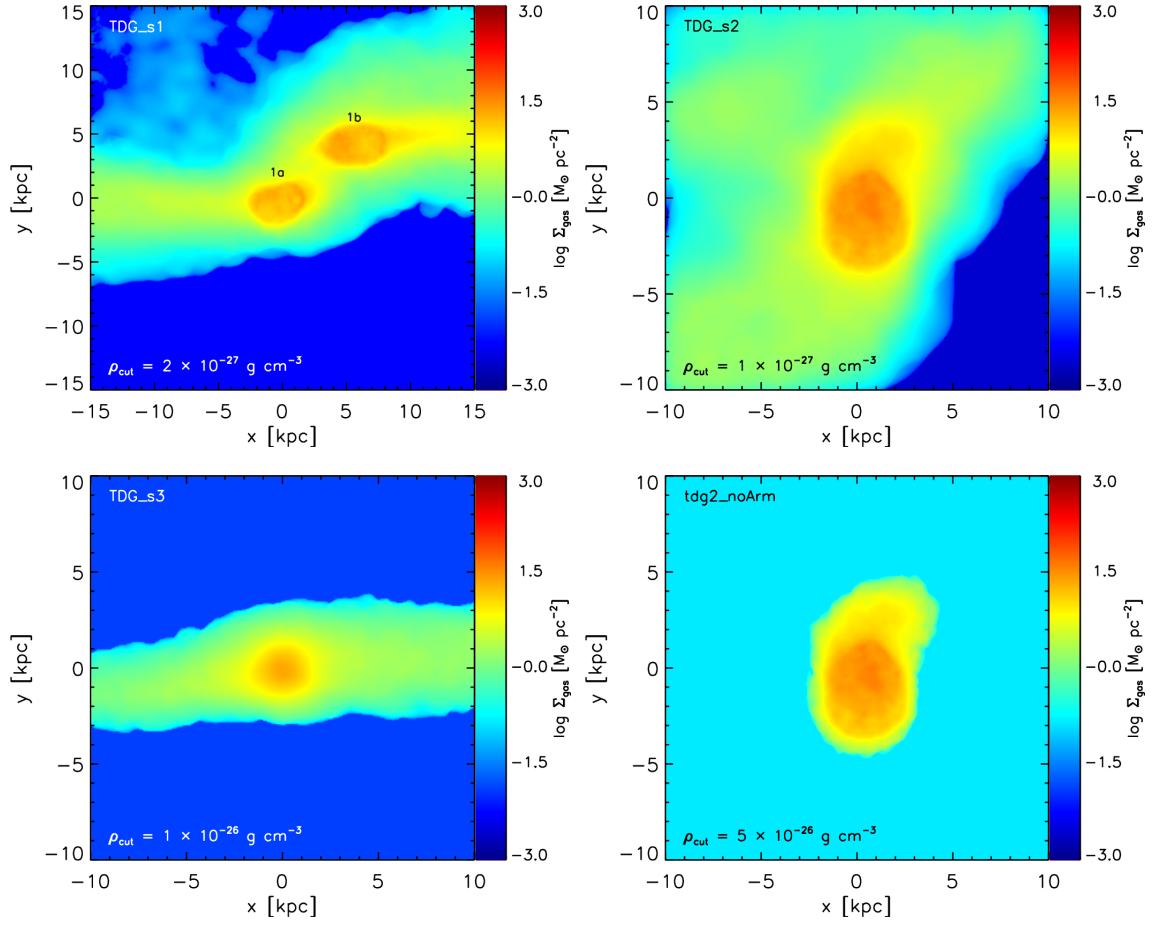


Figure 3.2: Initial ($t_{\text{sim}} = 0$ Myr) gas surface density, integrated along the z-axis, for the different simulation setups. Top left: TDG_s1, the labels correspond to the two subcomponents as used in the later data analysis, note the different length scale of this setup; Bottom left: TDG_s3; Top right: TDG_s2, with the standard IGM settings ($\rho_{\text{cut}} = 1 \times 10^{-27} \text{ g cm}^{-3}$ and $\rho_{\text{IGM}} = 1 \times 10^{-29} \text{ g cm}^{-3}$); Bottom right: tdg2_noArm, which is based on TDG_s2 with $\rho_{\text{cut}} = 5 \times 10^{-27} \text{ g cm}^{-3}$ and $\rho_{\text{IGM}} = 5 \times 10^{-28} \text{ g cm}^{-3}$.

for TDG_s2 and the bottom panel the simulation run tdg2_noArm, which has a higher cutoff and IGM density.

Chapter 4

Results

Within this chapter the results of the various simulation runs and some of the applied data analysis methods are presented. In Sections 4.1 to 4.3 the structural, chemical and dynamical properties and evolution are investigated. A comparison between the two different IMF descriptions, the filled IMF and IGIMF, is provided in Section 4.4 and the influence of the environmental effects is shown in Section 4.5. A comprehensive list of properties of the different models at their final simulation time can be found in Tables A.1 - A.5 of Appendix A.

4.1 Structural evolution of TDGs

4.1.1 Mass assembly

Starting from a cloudy distribution of almost purely gas embedded in the tidal arm, the different TDG candidates show a vibrant but similar assembly history. During the initial formation phase of a few tens of Myr, the cloudy structure remains but starts forming a high density core, resulting in a phase of low star formation. As the core accumulated enough material, it forces the surrounding matter to collapse. During this phase spiral arm-like structures are created which funnel the gas to the centre of the TDG within a free-falling time (Table 4.1). This leads to very high central densities, a high SFR and a very short gas consumption time. After the collapse-like mass assembly, with its duration

Table 4.1: Free-fall time τ_{ff} for several simulation runs at $t_{sim} = 0$ Myr for r_{50} . Column 1: TDG candidate; Column 2: Radius r_0 of the TDG; Column 3: Mass M_0 within r_0 ; Column 4: Free-fall time τ_{ff} .

simulation run / TDG candidate	r_0 [kpc]	M_0 $10^8 M_\odot$	τ_{ff} [Myr]
tdg1a	2.4	1.45	161.9
tdg1b	2.4	1.81	144.9
TDG_s2	2.7	2.80	138.8
TDG_s3	2.0	0.87	158.4

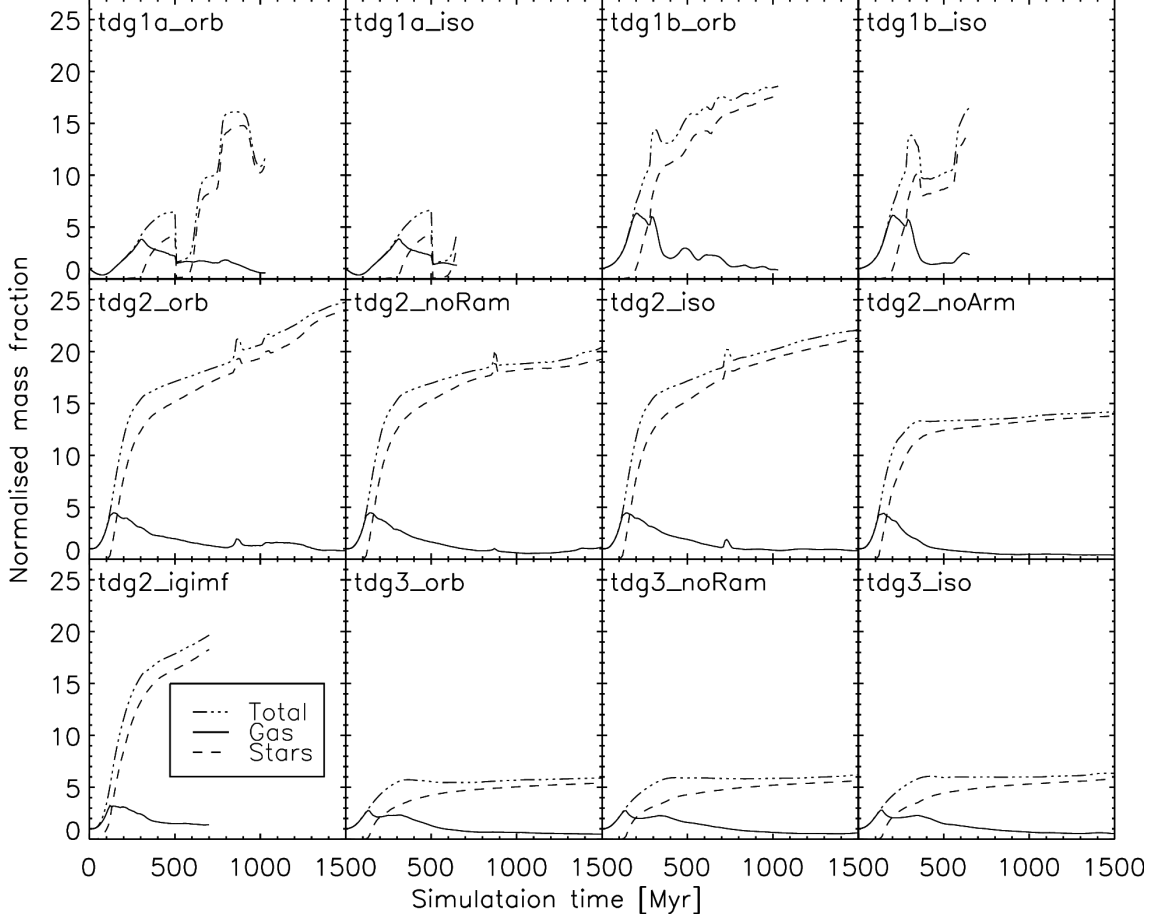


Figure 4.1: Relative mass fractions normalised to the total initial mass within 1.0 kpc around the mass centre of the different models, as indicated on each panel. The solid line is the gas fraction, the dashed line the stellar mass fraction and the dot-dashed line the total mass.

of a few 100 Myr, the majority of gas is converted into stars. Further mass accumulation during the rest of the simulation time is caused by accretion along the tidal arm. Figures 4.1 and 4.2 show the evolution of the relative mass fractions, normalised to the total initial mass, within spheres of 1.0 and 2.5 kpc radius around the TDG. During the collapse the total mass within 2.5 kpc increases to approximately 1.5 – 2.5 times the initial mass (dot-dashed line), depending on the model. The central regions ($r \leq 1.0$ kpc) are growing by factors of ~ 5 for TDG_s3 and ~ 15 for TDG_s2 in the initial collapse phase. Note that the jump in mass of tdg1a (first row, first and second panel of Figure 4.2) at $t_{sim} = 500$ Myr is caused by a close approach of two subcomponents (also see Figure 4.9). The transition from a gas to a stellar mass dominated system occurs at the intersection of the solid and dashed line. The influence of the tidal arm for the mass assembly can clearly be seen by comparing the models of tdg2_orb and tdg2_noArm (second row, first and last panel). Due to the lack of surrounding material tdg2_noArm only grows by a factor of 1.8, whereas tdg2_orb reaches 2.3 times of its initial mass within the 2.5 kpc sphere during the first 300 Myr of simulation time.

The mass growth rates in $M_{\odot} \text{ yr}^{-1}$, averaged over 10 Myrs, through spherical surfaces

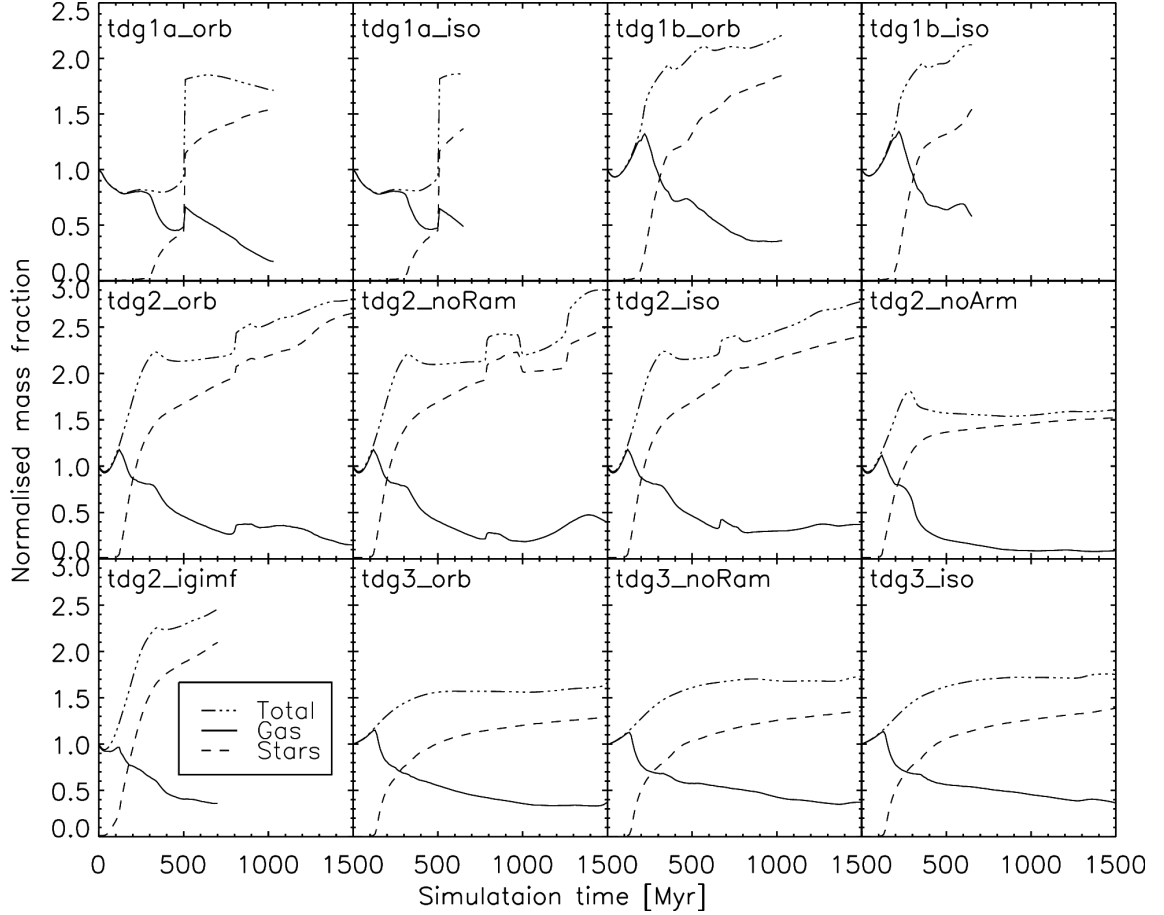


Figure 4.2: Same as Figure 4.1, for a radius of 2.5 kpc.

with radii of 1, 2.5 and 5 kpc around the TDGs are shown in Figure 4.3. The different panels correspond to the same models as in Figure 4.1. The growth rate through the 5 kpc sphere generally stays below $0.5 \text{ M}_{\odot} \text{ yr}^{-1}$ and is smaller than the growth rate through the other spheres. During the initial collapse the models of the setup TDG_s2 are reaching accretion rates of ~ 3 and $\sim 2 \text{ M}_{\odot} \text{ yr}^{-1}$ at distances of 1 and 2.5 kpc, respectively. Therefore, the majority of matter which build up the TDGs originates from its close surrounding, within a distance of 5 kpc. The thin spikes in the growth rate are the result of in-falling respectively ejected substructures, such as high density gas clumps and clusters of stellar particles. The only TDG which initially loses mass throughout all radii is tdg1a, but already after 30 Myr the outer sphere is accumulating matter again and the core starts to grow after 80 Myr.

In Figure 4.4 the gas dynamics during the collapse phase (upper panel, $t_{sim} = 150 \text{ Myr}$) and the inflow phase (lower panel, $t_{sim} = 300 \text{ Myr}$) is illustrated for the simulation run tdg3_noRam. The density-weighted velocity field of the tidal arm is over-plotted onto its surface density integrated along the z-axis. In the upper panel the signatures of the velocity field of a spherical collapse can be seen. During this phase the gas mass fraction, the accretion rate onto the core and the SFR are reaching their maximum values. Although the spherical collapse is still present in the lower panel, it can be seen that the gas of the

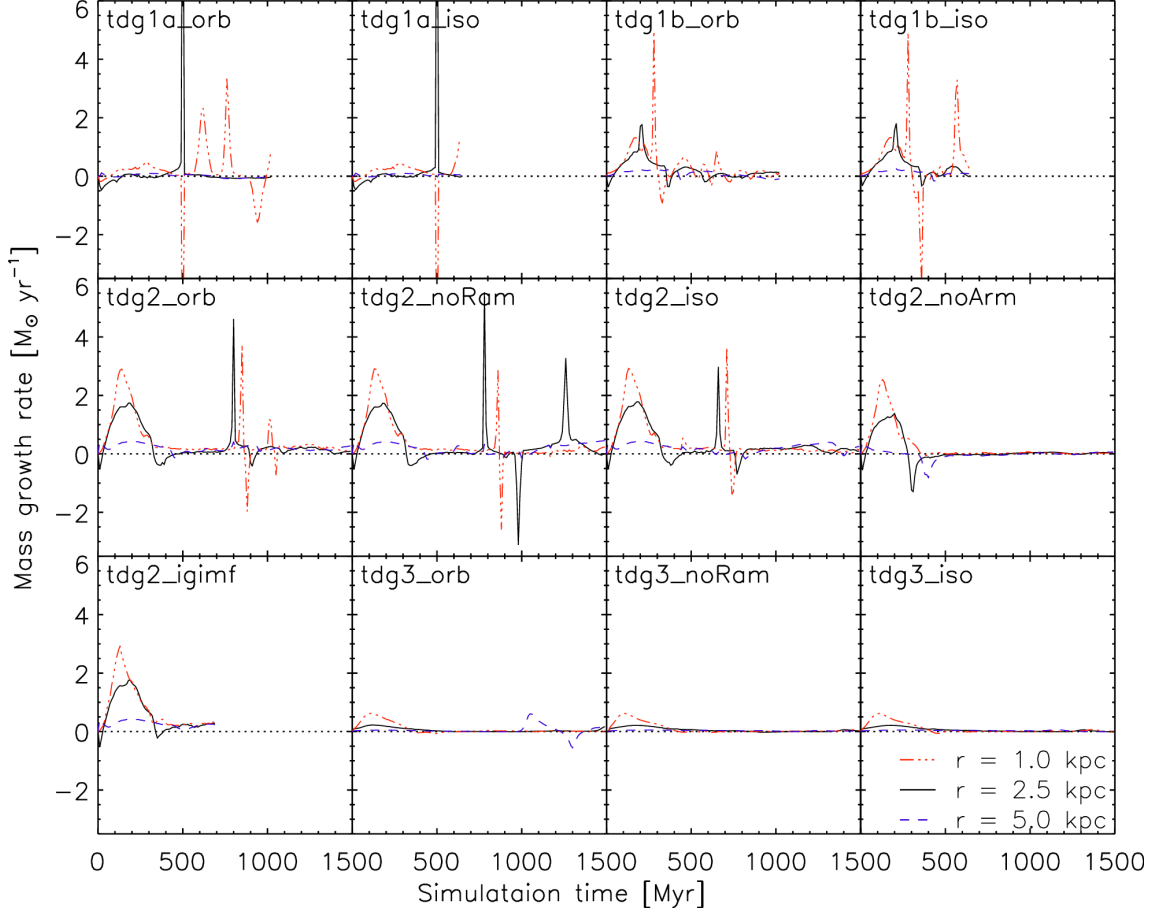


Figure 4.3: Mass growth rate through the surface of spheres with 1, 2.5 and 5 kpc radius, red dot-dashed, black solid and blue dashed line, respectively. The mass growth rate in $M_{\odot} \text{ yr}^{-1}$ is averaged over 10 Myrs of simulation time. The extreme spikes in two models of tdg1a reach accretion rates of $15 M_{\odot} \text{ yr}^{-1}$ and $-8 M_{\odot} \text{ yr}^{-1}$ for the 2.5 and 1.0 kpc spheres, respectively, and are caused by a close passage of two subcomponents.

tidal arm has been forming streams with higher surface densities, along which the gas is efficiently transported towards the centre of the TDG. At this phase the SFR is already declining again.

4.1.2 Star formation

Just as for the mass assembly, the star formation histories (SFH) show remarkable similarities between the different simulation setups and runs, regardless of the used settings of the orbit module (Section 2.7), star formation parameters (Section 2.6.1) or IGM settings. Figure 4.5 shows the SFR of the simulated TDGs. In the top panel the simulation runs of the setup TDG_s1 are compared. The second and third panel show the runs of TDG_s2, where the second one compares the different Orbit and IGM settings and the third panel the different SF settings. In the fourth panel the SFR of the three different runs of TDG_s3 are shown. The SFH of all TDG candidates can be described by three different stages, first an initial low star formation, followed by a strong starburst triggered by the collapse of the proto-TDG and a final inflow-regulated star formation episode. The different star

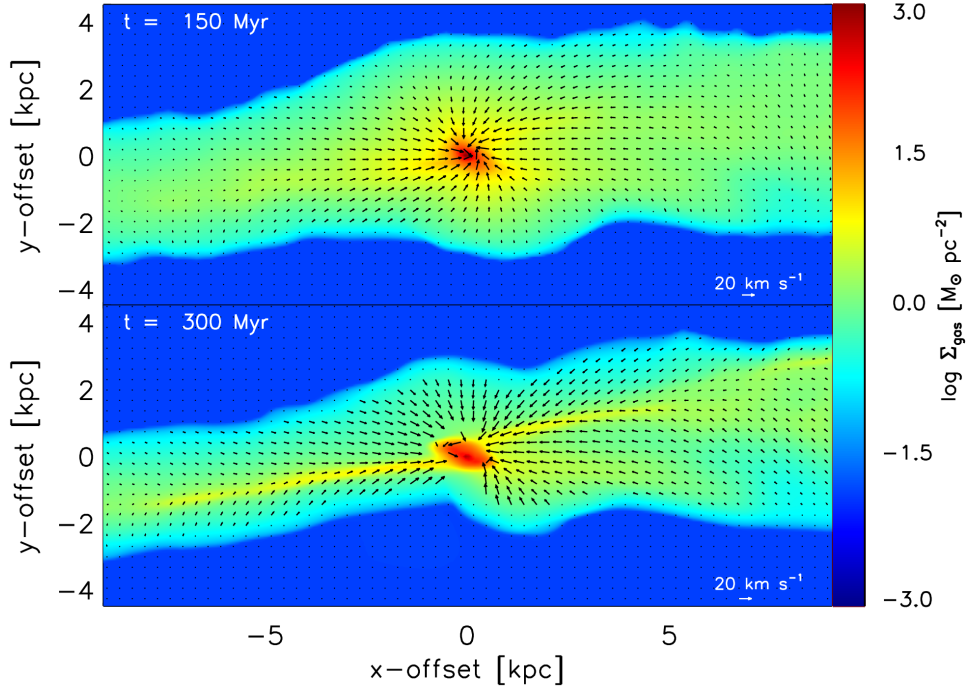


Figure 4.4: Density weighted gas velocity field of the simulation run `tdg3.noRam` along the tidal arm, over plotted onto its gas surface density. The snapshots are taken at $t_{sim} = 150$ and 300 Myr for the upper and lower panel, respectively. These snapshots are representative for the collapse and inflow phase, respectively. For demonstrational purposes, velocities greater than 20 km s^{-1} are not displayed, the white arrows at the lower right corners of each panel indicates a velocity of 20 km s^{-1} . Colour-coded is the logarithmic gas surface density in $M_{\odot} \text{pc}^{-2}$.

formation episodes correspond to the same evolutionary states as the mass assembly (Section 4.1.1). The low initial SFR is initiated by the early built up of the TDGs core. During this phase the SFR stays at low rates of a few times $10^{-2} M_{\odot} \text{yr}^{-1}$, except for the star formation test simulations of `TDG_s2` (third panel of Figure 4.5). This effect is attributed to the self-regulated star formation recipe. As the feedback of stars influences the local gas properties, in particular the temperature of the grid cells is increased, which is an important efficiency factor in the SBF (see Equation 2.30). For the simulation runs `tdg2_sf1` and `tdg2_sf2` the cluster formation time $\tau_{sf} = 10$ Myr. This longer formation time allows the stellar particles to accumulate more material leading to higher cluster masses. On the other hand, it also delays the onset of stellar feedback, what keeps the cell temperatures at a lower level. For these two simulation runs the initial SFR reaches values of about $5 \times 10^{-1} M_{\odot} \text{yr}^{-1}$. Also differences caused by the IMF description (`tdg2_igimf`) can only be seen in this star formation episode. Within the IGIMF implementation the IMF is truncated at the highest mass bin which is still populated by at least one star. By this truncation no fractions of massive stars and therefore no fractions of SN II can occur. As the number of high-mass stars is reduced, the intensity of the stellar feedback, especially from SN II is reduced and its onset is delayed as well. Again, through the reduced feedback the temperature of the grid cells stays lower and enables initial SFRs of $0.9 M_{\odot} \text{yr}^{-1}$.

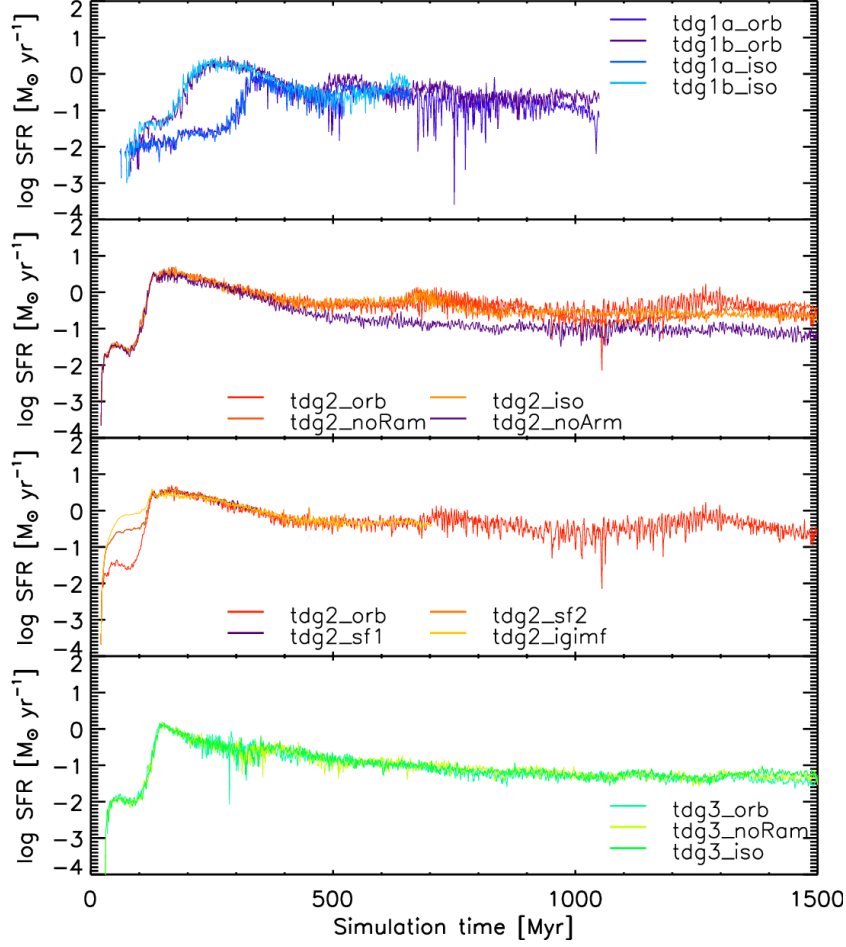


Figure 4.5: Star formation rates in 1 Myr-bins of the different simulation setups. The first panel compares the simulation runs of the setup TDG.s1. The second and third panel show the runs of TDG.s2, where the second one compares the different Orbit and IGM settings and the third panel the different SF settings. In the fourth panel the different runs of TDG.s3 are compared.

During the collapse of the TDGs, the SFR is pushed up, triggering a starburst with SFRs of a few solar masses per year, as the density is strongly increased. This starburst occurs within approximately one free-falling time, with larger deviations only for TDG.s1 as this setup contains two TDG candidates. In Figure 4.6 the SFR is plotted against the elapsed time since the first star formation event in units of the free falling time of the TDG candidates. The solid black line indicates τ_{ff} and the dotted lines $(1 \pm 0.3) \times \tau_{ff}$, the range where the SFR of the different TDGs peaks. The SFH are indistinguishable for the different star formation settings (see the third panel of Figure 4.5). At these high densities stellar particles reach masses higher than $19055 M_{\odot}$, i.e. the mass needed to fill the IMF, within only a few timesteps. As one stellar particle is closed for further star formation, if the IMF is fully populated, the feedback from these particles is equal, independent of the IMF description or star formation parameters.

After the collapse-triggered star formation, at a simulation time between 300 to 500 Myr, the starburst subsides and the SFR declines to values between 5×10^{-2} and $5 \times 10^{-1} M_{\odot} \text{ yr}^{-1}$ for all simulation runs. Although relatively constant, the SFR is declining

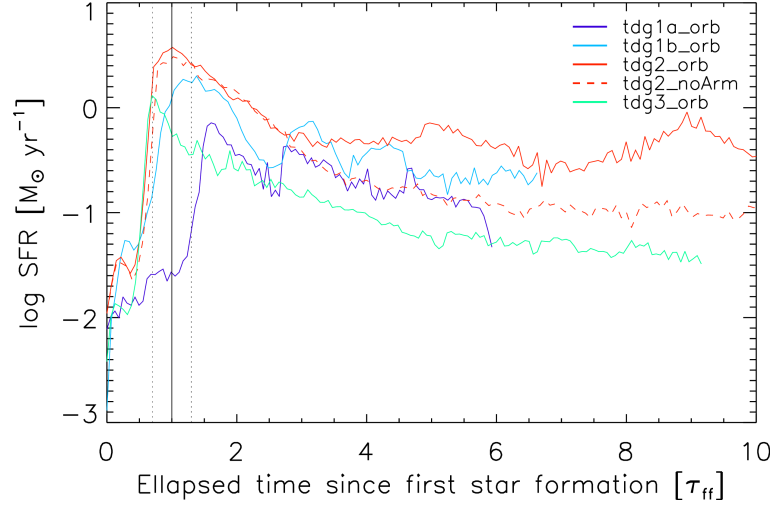


Figure 4.6: Comparison of the star formation rates, in 10 Myr-bins, of the simulation runs `tdg1_orb`, `tdg2_orb`, `tdg2_noArm` and `tdg3_orb`. Different simulation runs for the same setup are only considered when the cutoff density ρ_{cut} changes between these runs. The time-axis is normalised to the free-fall time τ_{ff} at the simulation time $t = 0$, see Table 4.1. The free-fall time is calculated within the half mass radius at $t = 0$. The solid black line marks the free-fall time of the corresponding spheres, the dotted lines represent $1 \pm 0.3 \times \tau_{ff}$.

during this phase as the fraction of gas is getting smaller over time. This relatively high SFRs are maintained by the high central density and the additional accretion of gas from the tidal arm. The influence of the density respectively the existence of a tidal arm can be seen in the second panel of Figure 4.5 and in Figure 4.6. The SFR of the simulation run `tdg2_noArm` stays below the values of `tdg2_orb` for one half to one order of magnitude.

4.1.3 Cluster mass function

The multi-phase behaviour of the SFR is also reflected in the embedded cluster mass function (CMF, ξ_{ecl}). It is commonly assumed to be a power-law function with a possible exponential drop or truncation at higher masses, i.e. a Schechter function in the form of

$$\xi_{ecl}(M_{ecl}) \propto M_{ecl}^{-\beta} e^{M_{ecl}/M_{\star}}, \quad (4.1)$$

where M_{ecl} is the mass of the stellar content of the cluster, β is the power-law slope at the low mass end and $M_{\star}$ the mass at which the drop off occurs (e.g. Gieles, 2009). Figure 4.7 shows the CMF, in the cluster mass range $10 \leq M_{ecl}/M_{\odot} \leq 10^6$, for four different simulation runs of the setup TDG_s2, namely `tdg2_orb`, `tdg2_noArm`, `tdg2_iso` and `tdg2_igimf`. The solid grey line is the CMF for all star clusters formed before $t_{sim} = 500$ Myr. For the red long-dashed lines only clusters formed in the simulation time interval 0–50 Myr are considered, corresponding to the low initial SFR. Star clusters formed during the starburst between $t_{sim} = 120$ and 170 Myr are represented by the blue short-dashed lines. The black dot-dashed lines correspond to star clusters formed at the transition from the collapse to inflow-triggered star formation at the time interval $450 \leq t_{sim}/\text{Myr} \leq 500$. The shape of the CMFs at cluster masses blow $\sim 500 M_{\odot}$ is affected by the star formation

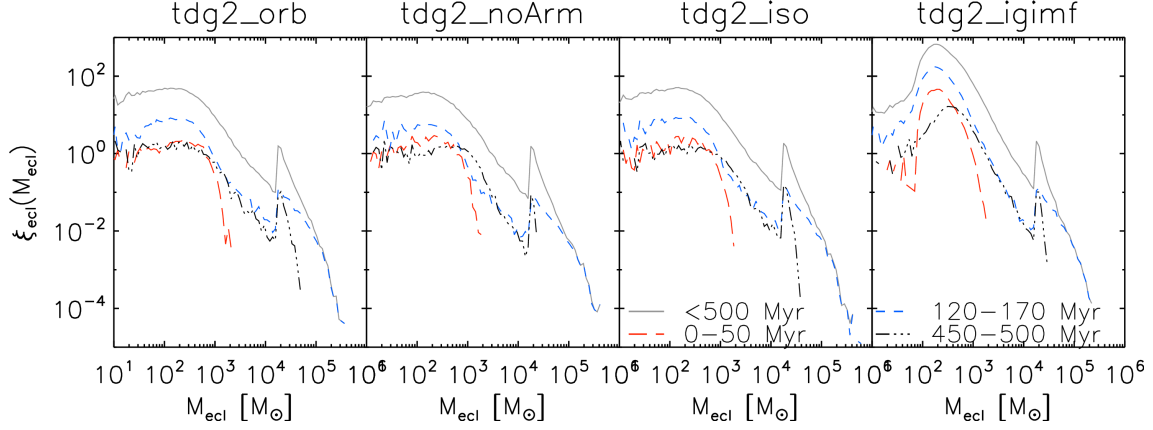


Figure 4.7: Embedded cluster mass function for various simulation runs of TDG.s2 (from left to right: tdg2_orb, tdg2_noArm, tdg2_iso, tdg2_igimf), discretised with 128 equally spaced logarithmic mass bins. The solid grey line is the CMF of all clusters formed before $t_{sim} = 500$ Myr. For the different dashed lines only the clusters formed in 50 Myr intervals are considered, where the time intervals correspond to the different star formation episodes. The peak around $2 \times 10^4 M_{\odot}$ and the slopes of the high as well as the low mass end ($M_{ecl} \lesssim 5 \times 10^2 M_{\odot}$) are affected by the star formation criteria.

criteria, i.e. the threshold on the SBF (Equation 2.33). As this criterion does not allow to form clusters with very low initial masses, which might be able to accumulate enough matter to fill the CMF at the lower mass end. Opposite to that, the peak at $M_{ecl} \approx 2 \times 10^4 M_{\odot}$ is caused by the 'closing' of stellar particles when their mass is high enough to fill the stellar IMF. This also leads to the steepening of the CMF, as stellar particles with masses greater than $19055 M_{\odot}$, the mass at which the IMF is filled, have to be formed essentially within a single timestep. As the high mass end of the CMF does not reflect the expected exponential turn-over, only a power-law ($\xi_{ecl} \propto M_{ecl}^{-\beta}$) is fitted to the data in order to derive the slope of the CMF.

During the initial star formation episode only the mass range $500 \leq M_{ecl}/M_{\odot} \leq 1100$ is considered, whereas for all others the mass range $500 \leq M_{ecl}/M_{\odot} \leq 18000$ is used. As it can be seen in Figure 4.7 the CMF for star clusters formed in the time interval 0 – 50 Myr is steeper than at the other time intervals and no high mass clusters are formed, this is also reflected by a large value of $\beta = 4.5 \pm 0.3$, averaged over all simulation setups. During the other time intervals the average values are $\beta = 1.9 \pm 0.5$ (120 – 170 Myr), 2 ± 0.3 (450 – 500 Myr) and 1.8 ± 0.2 for all clusters formed during the first 500 Myr of the simulations. The formation of high mass clusters only at times with high star formation agrees well with the observational established $M_{ecl,max} - SFR$ relation (e.g. Weidner et al., 2004). With the remark that it does not hold for the simulation run tdg2_igimf. For this run the global SFR at the first and third time interval, as used in Figure 4.7, are comparable, but no high mass clusters are formed during the initial star formation episode. A detail study of the dependency of $M_{ecl,max}$ on the SFR was not performed as both, the high and low mass end of CMF are affected by the star formation criteria.

Given that the CMF is not a condition on which the star formation prescription (Section 2.6) is based on, it is quite remarkable how well the resulting slope of $\beta \approx 2$ agrees to

various observational estimates. For example Zhang and Fall (1999) concluded that, for young clusters ($\lesssim 160$ Myr) in the mass range $10^4 \lesssim M_{\text{ecl}}/M_{\odot} \lesssim 10^6$ within the Antenna galaxy, the CMF can be represented by a power-law with $\beta = 2$. Hunter et al. (2003) report $\beta = 2 - 2.4$ for the Small and Larger Magellanic Clouds, whereas de Grijs and Anders (2006) found $\beta = 1.8 \pm 0.1$ and $\beta = 2 \pm 0.15$ for the LMC and SMC, respectively. Lada and Lada (2003) estimated $\beta \approx 2$ for star clusters in the mass range $20 \lesssim M_{\text{ecl}}/M_{\odot} \lesssim 1100$.

4.1.4 Stellar distribution

For the calculation of the luminosity of a stellar particle the luminosities of the underlying stellar population, according to the IMF description, are summed up. Therefore, all stars which have not yet reached the end of their lives get assigned a certain luminosity, according to a mass-dependent M/L -relation (Salaris and Cassisi, 2005) of:

$$\left(\frac{L_{\star}}{L_{\odot}}\right) \propto \begin{cases} (M_{\star}/M_{\odot})^{2.3}, & (M_{\star}/M_{\odot}) < 0.43 \\ (M_{\star}/M_{\odot})^4, & 0.43 \leq (M_{\star}/M_{\odot}) < 2 \\ (M_{\star}/M_{\odot})^{3.5}, & 2 \leq (M_{\star}/M_{\odot}) < 20 \\ (M_{\star}/M_{\odot}), & 20 \leq (M_{\star}/M_{\odot}). \end{cases} \quad (4.2)$$

The total luminosities of the stellar particles are summed up in circular annuli with $\Delta r = 50$ pc in the plane perpendicular to the direction of the angular momentum vector, resulting in the face-on view, of the TDGs. The resulting face-on surface brightness profiles are shown in Figure 4.8 for the simulation snapshots at $t_{\text{sim}} = 300, 600$ and $t_{\text{end}} = 1030$ (tdg1_orb), 650 (tdg1_iso), 700 (tdg2_igimf) else 1500 Myr. Figure 4.9 shows mock images with a resolution of $\Delta x = 50$ pc of the stellar surface brightness of various simulation runs at their final simulation time. The luminosity of a stellar particle is calculated according to Equation 4.2, and the top and bottom panels of each row show the face-on and edge-on view, respectively. Therefore, the coordinate system is rotated such that the angular momentum vector of a TDG is aligned with the positive z-axis. The top panel shows the two TDGs of the setup TDG_s1, sorted by the object. Both tidal dwarf galaxies within this setup, tdg1a and tdg1b, initial collapse in two massive star forming regions, these components can still be seen clearly at the final simulation times.

The different models of the simulation setup TDG_s2 show a large variety in their appearance, despite their similarities in the SFR (Figure 4.5) and cluster mass function (Figure 4.7). The simulation run tdg2_orb only shows a minor disc component, whereas both tdg2_noRam and tdg2_iso show a significant disk, especially visible in the edge-on view. The second clump visible in the images of tdg2_noRam is formed within the tidal arm in all runs of TDG_s2. While the simulation runs tdg2_orb and tdg2_iso are able to capture this component at its first encounter at a simulation time of $t_{\text{sim}} \approx 600 - 800$ Myr, tdg2_noRam is not. During this simulation run the second clump reaches distances greater than 2.5 kpc from the centre at a simulation time of roughly 1 Gyr. Shortly after the second approach

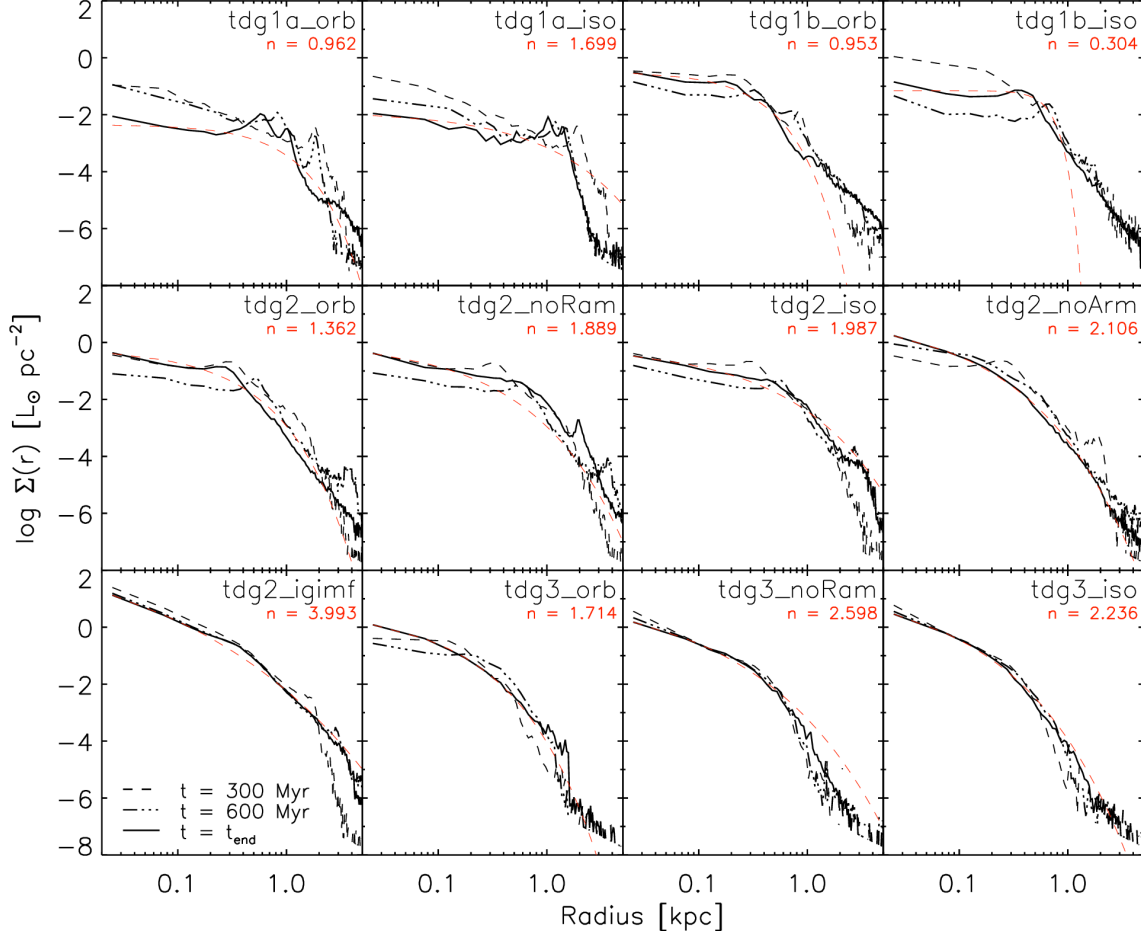


Figure 4.8: Face-on surface brightness profiles for simulated TDGs, at $t_{sim} = 300, 600$ Myr and t_{end} , where $t_{end} = 1030$ Myr (tdg1_orb), 650 Myr (tdg1_iso), 700 Myr (tdg2_igimf) else 1500 Myr. The thin red dashed line indicates the best fitting single component Sérsic profile at t_{end} , with its index given in each panel.

starts, it triggers the formation of a tidal arm and causes the spiral like structure. This behaviour is also visible in the peaks of the mass fraction and mass growth rate (see row 2, panels 1-3 of Figures 4.2 and 4.3). In contrast to TDG.s2, the simulation runs of TDG.s1 and TDG.s3 do not show a strong dependency of morphology on the presence of the external tidal field or ram pressure.

4.2 Chemical evolution of TDGs

The chemical evolution of a galaxy is closely related to the release of metals by stellar feedback processes. Where SN Ia enrich the ISM mostly with iron, SN II are the main source of α -elements such as oxygen or magnesium. On the other hand, inflow of metal-poor gas from the vicinity of a galaxy can reduce the metallicity and cause a rejuvenation of the galaxy, if the metallicity is used as proxy of age.

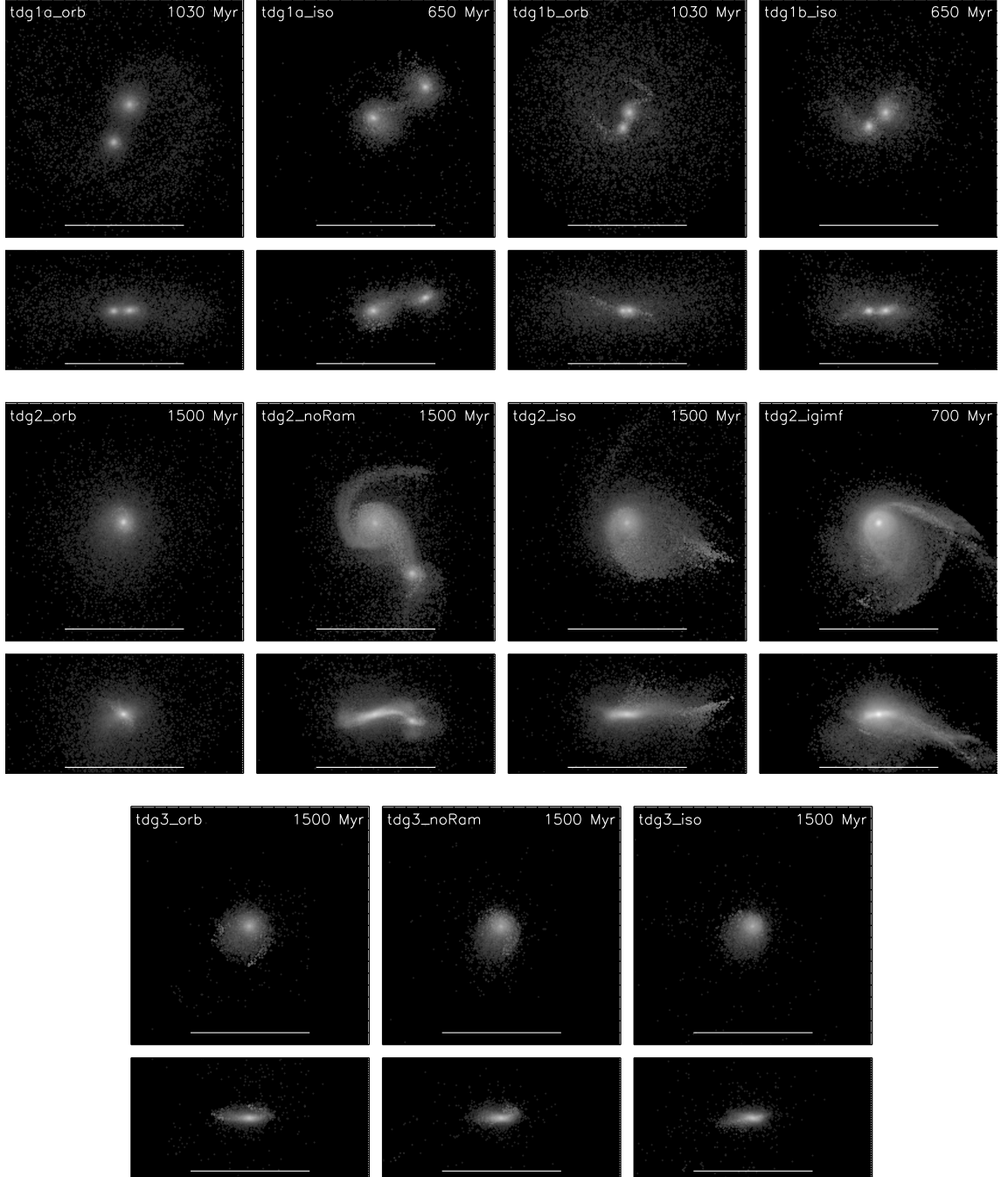


Figure 4.9: Stellar surface luminosity maps for various models, at their final simulation time, as indicated on each panel. The upper and lower image of each panel show the face and edge on view, respectively. The luminosity of a stellar particle is calculated according to Equation 4.2 and the resulting data are binned to a physical resolution of $50 \times 50 \text{ pc}^2$. The white bar in each plot indicates the length of 5 kpc.

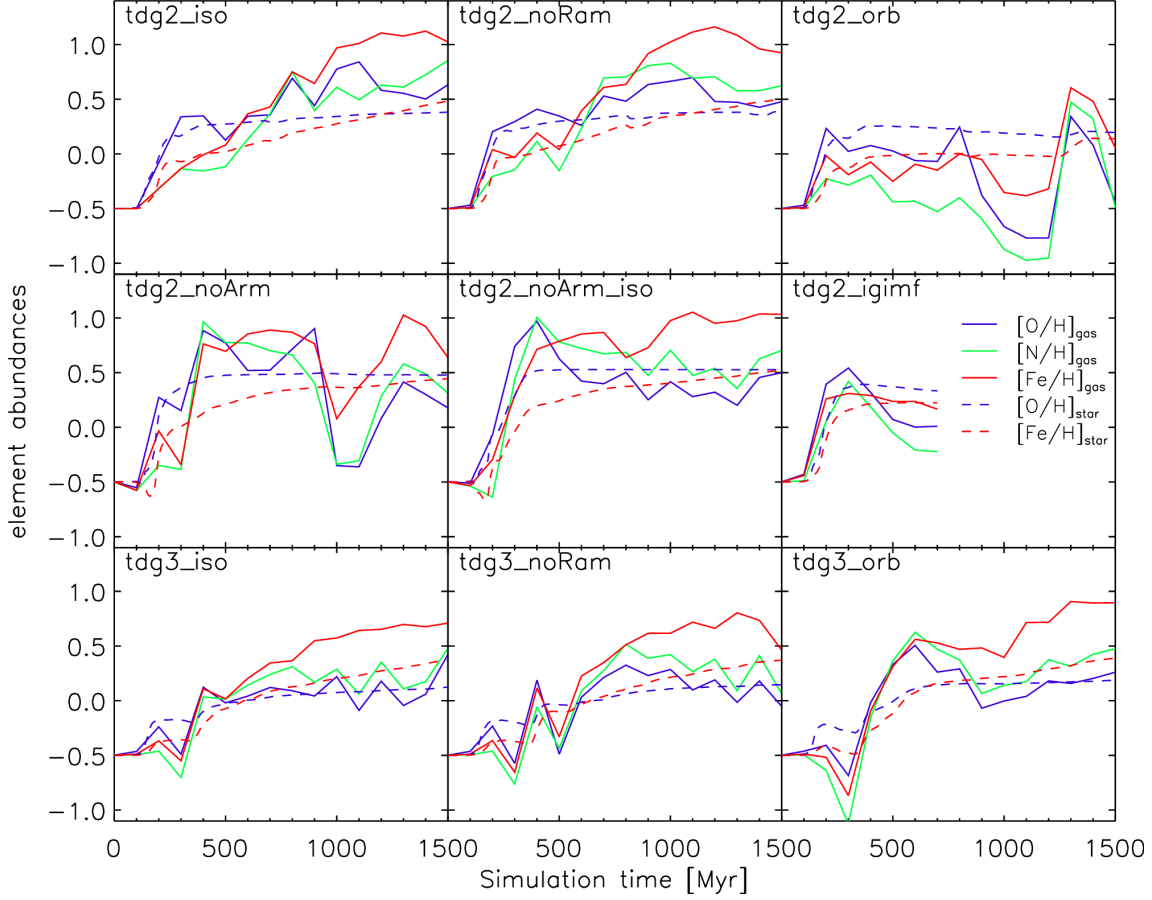


Figure 4.10: Element abundances evolution of different simulation runs. Shown are $[O/H]$, $[N/H]$ and $[Fe/H]$ for the gaseous component (solid lines) and for the stellar component (dashed lines) $[O/H]$ and $[Fe/H]$. Note that the initial metallicity was chosen to be $0.3 Z_{\odot}$, i.e. $[X/H] = -0.5$.

The abundance ratio between the elements X_i and X_j is defined as

$$\left[\frac{X_i}{X_j} \right] = \log_{10} \left(\frac{X_i}{X_j} \right) - \log_{10} \left(\frac{X_i}{X_j} \right)_{\odot}. \quad (4.3)$$

Figure 4.10 shows the evolution of the $[O/H]$, $[Fe/H]$ and $[N/H]$ abundance ratios for 9 different simulation runs. Where the gas phase abundance ratios are representative for a certain simulation time and the stellar metallicities correspond to the mean metallicities of all stellar populations of the TDG. During the early evolution the production of α -elements, represented by oxygen, by SN II is the dominant enrichment process. The enrichment with iron from SN Ia starts delayed, as lower mass stars have longer lifetimes. Therefore, after the massive stars, formed during the initial starburst, ended their life the ISM gets mostly enriched with iron from SN Ia. The oxygen abundance ratio reaches an approximated equilibrium level, depending on the details of the TDGs accretion history and SFH. For example, the strong peak in the abundance ratios of tdg2_orb at $t_{sim} = 1300$ Myr is caused by the slightly increased SFR around this simulation time. Figure 4.11 shows the stellar $[O/Fe]$ versus $[Fe/H]$ abundance ratio for nine different sim-

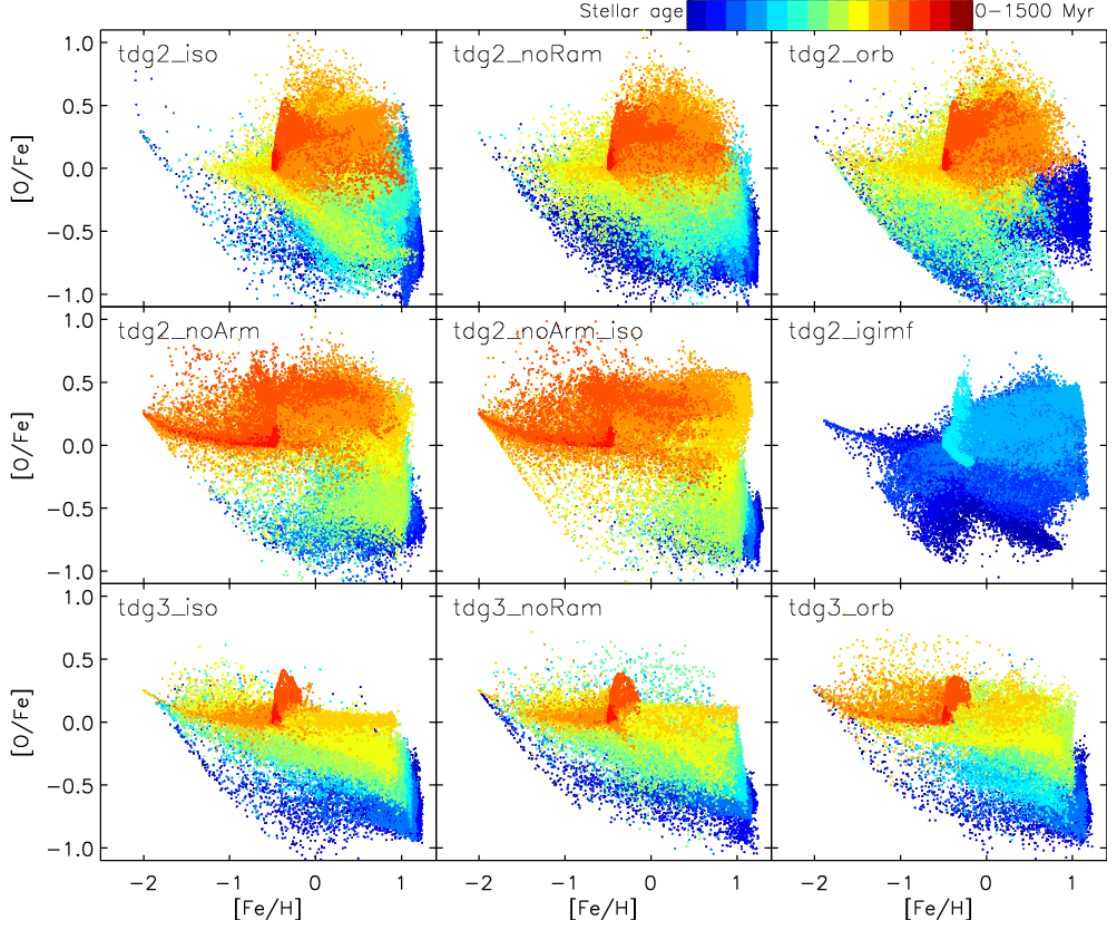


Figure 4.11: Stellar $[O/Fe]$ versus $[Fe/H]$ abundance ratio. The stellar age is colour coded in bins of 100 Myr, the first stars formed during the simulations are shown in dark red, except for tdg2_igimf where the oldest stars are shown in turquoise due to different simulation runtimes. The initial metallicity was chosen to be $0.3 Z_{\odot}$ with solar abundance ratios, i.e. $[Fe/H] = -0.5$ and $[O/Fe] = 0$. Initially SNe II are causing the strong increase of oxygen and thus $[O/Fe]$ (red points). The mixing of the tidal arm and the TDG with the IGM result in the stars with $[Fe/H] < -0.5$, an effect which is strongly dependent on the density distribution of the tidal arm. After most of the massive stars ended their life, the enrichment of iron by SN Ia becomes the dominant mode of enrichment, causing the increase of $[Fe/H]$ and the decrease of $[O/Fe]$. The three models in the right column are the most realistic models and allow for a comparison with observations. See text for details.

ulation runs. The three models in the right column are the most realistic models as they make use of the full capabilities of the orbit module (see Section 2.7). The initial gas abundance ratios of the tidal arm are 0.0 for $[O/Fe]$ and -0.5 for $[Fe/H]$, which proved the initial abundances for the first formed stars. These stars are shown as dark red points, except for tdg2_igimf where the oldest stars are shown in turquoise due to the different simulation runtimes. The stars formed during the collapse of the TDGs, and shortly after it, experience a strong enrichment of oxygen by SNe II and thus an increase of the $[O/Fe]$ abundance ratio. After the majority of the massive stars, which are formed during the collapse triggered SF episode, ended their life, the ISM becomes mostly enriched due to SN Ia feedback. Therefore, the ISM and the newly formed stars show an increase in the iron abundance (up to $[Fe/H] \approx 1.5$) and a decrease of the $[O/Fe]$ ratio.

Stars with $[\text{Fe}/\text{H}] < -0.5$ are formed out of rejuvenated material, i.e. a mixture of gas from the tidal arm and the IGM. The effect is particularly present in the two simulation runs `tdg2_noArm` and `tdg2_noArm_iso`, but at the earliest simulation times it is also stronger in `tdg3_orb` compared to `tdg2_orb`. This shows the strong dependency of the mixing process on the distribution of gas around the TDGs, as the `_noArm` models do not consider the gas distribution of the tidal arm and the section of the arm around `TDG_s3` is not as extended as around `TDG_s2` (see Figure 3.2 for the initial gas distribution). The mixing of the ISM with the IGM leads to the formation of stars with $-2.0 \leq [\text{Fe}/\text{H}] \leq -0.5$, already within the first 200-300 Myr, where the oxygen enrichment is caused by SN II.

The $[\text{O}/\text{Fe}]$ abundance ratio of `tdg2_igimf` stays generally lower in the first ~ 300 Myr of simulation time compared to the other models embedded in the tidal arm of `TDG_s2`. This is caused by the reduced number of high mass stars and consequently the lower number of SNe II.

Table A.3 provides a comprehensive list of the stellar and gas-phase abundance ratios at the final simulation time.

4.3 Dynamical evolution of TDGs

4.3.1 Stellar rotation curve

In order to study the stellar dynamics of the simulated TDGs, the luminosity-weighted rotational velocity around the centre of luminosity, in the plane perpendicular to the direction of the angular momentum, is calculated in radial bins of $\Delta r = 50$ pc. The luminosity-weighted rotation velocity $v_{\text{rot}}(r)$ is calculated by:

$$v_{\text{rot}}(r) = \frac{\sum_i \pm v_{\text{rot}}(i) L(i)}{\sum_i L(i)}, \quad (4.4)$$

where the sums are carried out over all stellar particles within a radial bin and the stellar luminosity $L(i)$ is calculated according to Equation 4.2. The rotational velocity $v_{\text{rot}}(i)$ of a stellar particle is assumed to be positive in case of a counter clock wise rotation, this corresponds to a prograde rotation with respect to the orbit of the TDG. Due to the double component structure and the resulting contamination of the rotation curves of the TDGs of the setup `TDG_s1` (see top panels of Figure 4.9), rotation curves for these four objects are not presented here.

Figures 4.12 - 4.19 show the resulting stellar rotation curves for the different simulation runs. The black solid line is the luminosity-weighted rotation velocity with its standard deviation indicated by the grey error bars. The blue dashed and red dot-dashed lines show the contribution of the co- and counter-rotating components, respectively. The significance of the counter rotating component can be seen by the difference between the rotational velocity of the co-rotating component and the total rotational velocity,

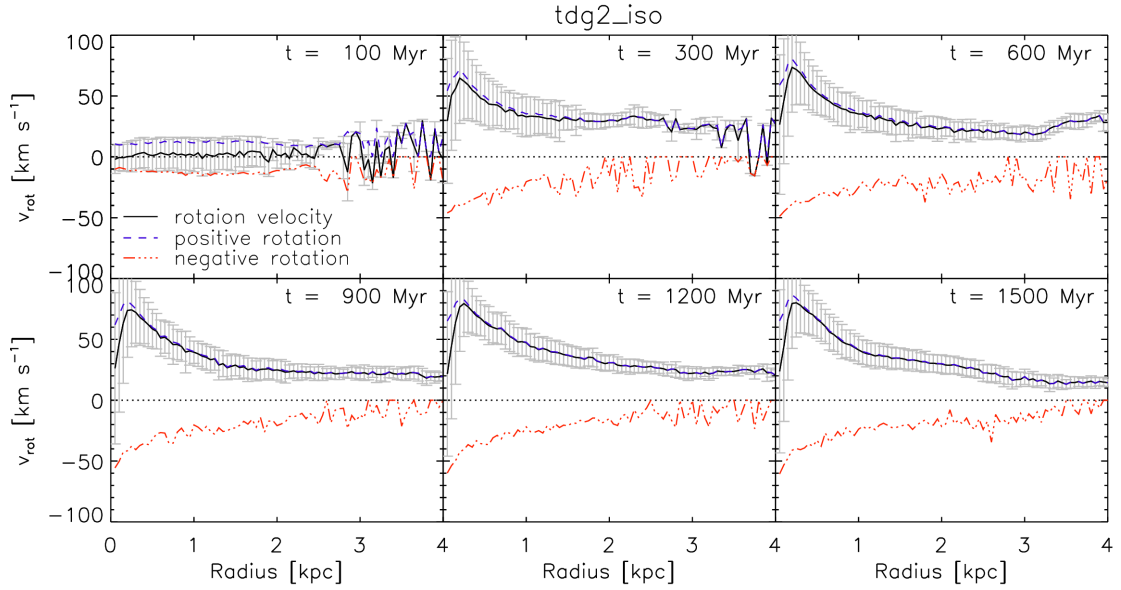


Figure 4.12: Rotation curve of `tdg2_iso` at $t_{sim} = 100, 300, 600, 900, 1200,$ and 1500 Myr. The black line shows the total luminosity-weighted rotational velocity with its standard deviation as grey error bars. The blue dashed and red dot-dashed lines indicate the contributions of the co- and counter-rotating components, respectively.

especially at the centre of various candidates. All models, except for `tdg2_igimf`, show a steeply increasing rotation curve with a strong peak followed by a Keplerian like decline. The models `tdg2_orb` and `tdg2_igimf` share identical initial conditions and use the same settings in the orbit module, only differing in the description of the underlying IMF. This variation results in a milder increase of the rotational velocity within the inner few hundred parsec, a smaller peak velocity ($\Delta v_{max} \approx 20 \text{ km s}^{-1}$) followed by a much weaker declining rotational velocity (compare Figures 4.14 and 4.16). Structural subcomponents such as companions and arm like features are also present in the rotation curves as secondary peaks or elevated rotation velocities in the outskirts. As example for `tdg2_noRam` an additional peak in the rotation curve is present at $r \approx 1.5 \text{ kpc}$ at $t_{sim} = 900 \text{ Myr}$ and a second rotating component at $r \approx 2.8 \text{ kpc}$ with a systemic velocity differing by $\sim 30 \text{ km s}^{-1}$ compared to the TDG at $t_{sim} = 1500 \text{ Myr}$ (Figure 4.13). The different shape of the rotation curve, including the lower peak value of v_{rot} , of the simulation run `tdg2_noRam` compared to `tdg2_orb` is a consequence of the different mass distribution and build up, as already mentioned in Section 4.1.1.

4.3.2 Stellar kinematic maps

Additionally to the derived rotation curves, 2D velocity respectively velocity dispersion maps were created, as kinematic substructures can be missed out by one dimensional analysis methods due to possible misalignment with respect to the rotation field of the main body (e.g. Toloba et al., 2014). These maps were created with a resolution of $50 \times 50 \text{ pc}$, corresponding to a resolution of approximately 0.7 arcsec at a distance of 16.5 Mpc , i.e.

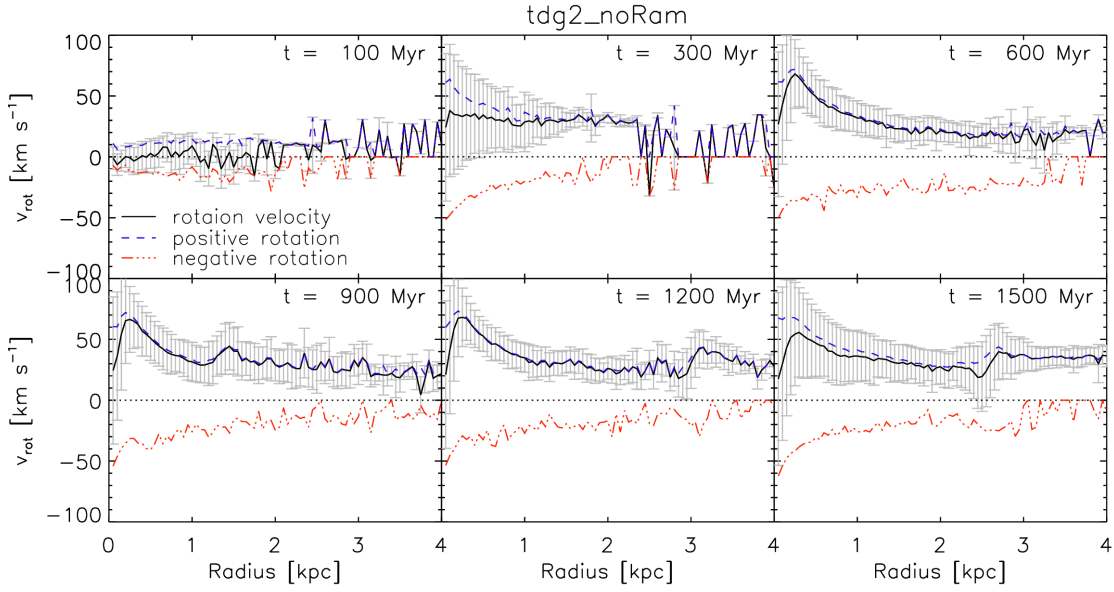


Figure 4.13: Same as Figure 4.12 for tdg2_noRam

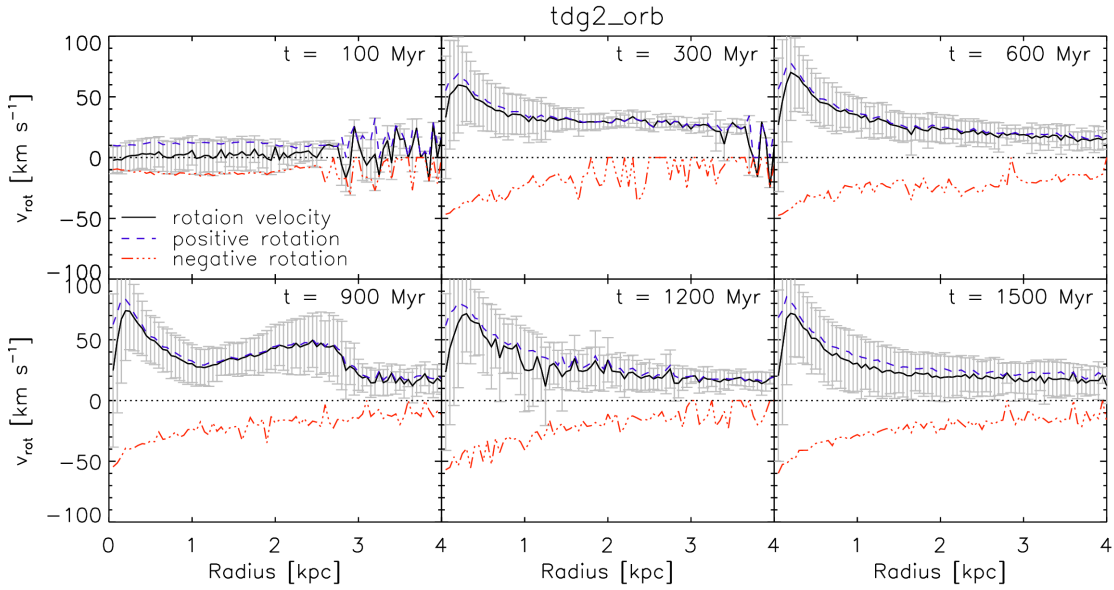


Figure 4.14: Same as Figure 4.12 for tdg2_orb

the distance of the Virgo-cluster (Mei et al., 2007). Velocity and velocity dispersion maps for each of the three coordinate directions of the simulation box were created. Considering the xy-plane, the line-of-sight velocity (v_{LOS}) is equal to the velocity component along the z-axis (v_z). As more massive stars are brighter than less massive stars, a weighting based on the mass respectively luminosity is needed in order to create kinematic maps which are comparable to observations. The luminosity of a stellar particle is calculated as described in Section 4.1.4. The luminosity-weighted line-of-sight velocity (v_{LOS}^*) within one spatial

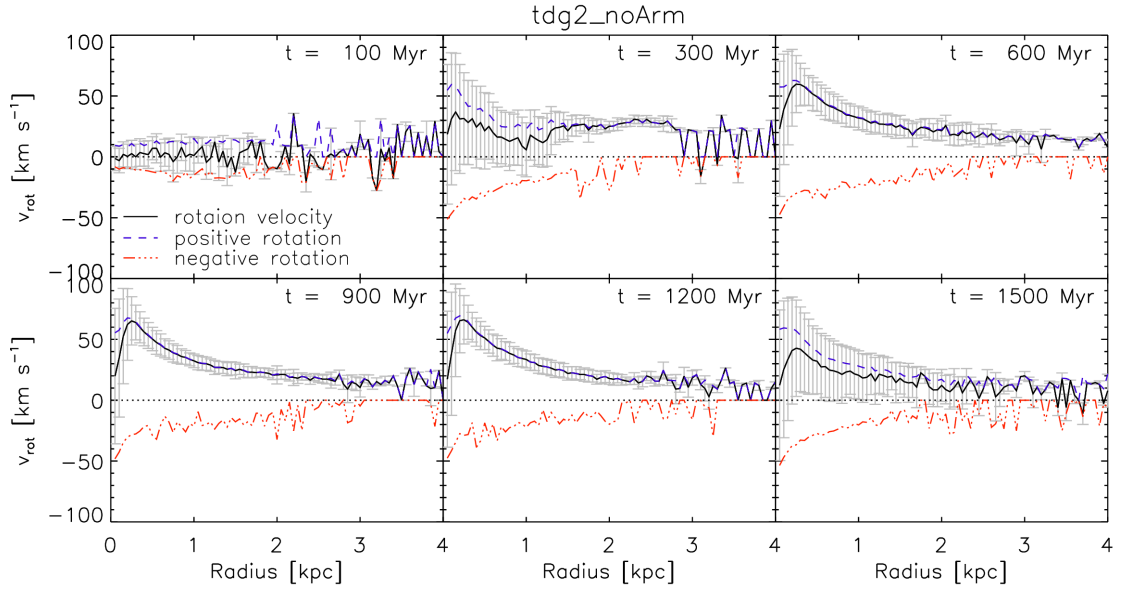


Figure 4.15: Same as Figure 4.12 for `tdg2_noArm`

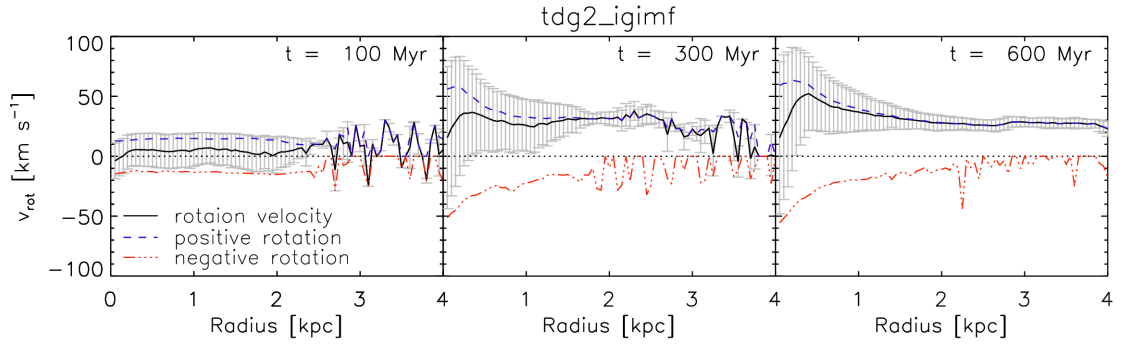


Figure 4.16: Same as Figure 4.12 for `tdg2_igimf` at $t_{sim} = 100, 300$ and 600 Myr

bin is then calculated by:

$$v_{LOS}^* = \frac{\sum_i v_{LOS}(i) L(i)}{\sum_i L(i)}, \quad (4.5)$$

where the sums are carried out over all stellar particles within a bin along the line-of-sight, $v_{LOS}(i)$ and $L(i)$ are the line-of-sight velocity and luminosity of the i^{th} star-cluster, respectively. Analogue to the v_{LOS}^* -maps, luminosity-weighted line-of-sight velocity dispersion (σ_{LOS}^*) maps are created, where σ_{LOS}^* within one spatial bin is calculated via:

$$\sigma_{LOS}^* = \left[\frac{\sum_i \left[L(i) (v_{LOS}(i) - v_{LOS}^*)^2 \right]}{\sum_i L(i)} \right]^{\frac{1}{2}}. \quad (4.6)$$

In the case of the setup `TDG_s1`, where two candidates lie within the simulation box, only stellar particles in an cube with a side length of 8 kpc, centred at the mass centre of the

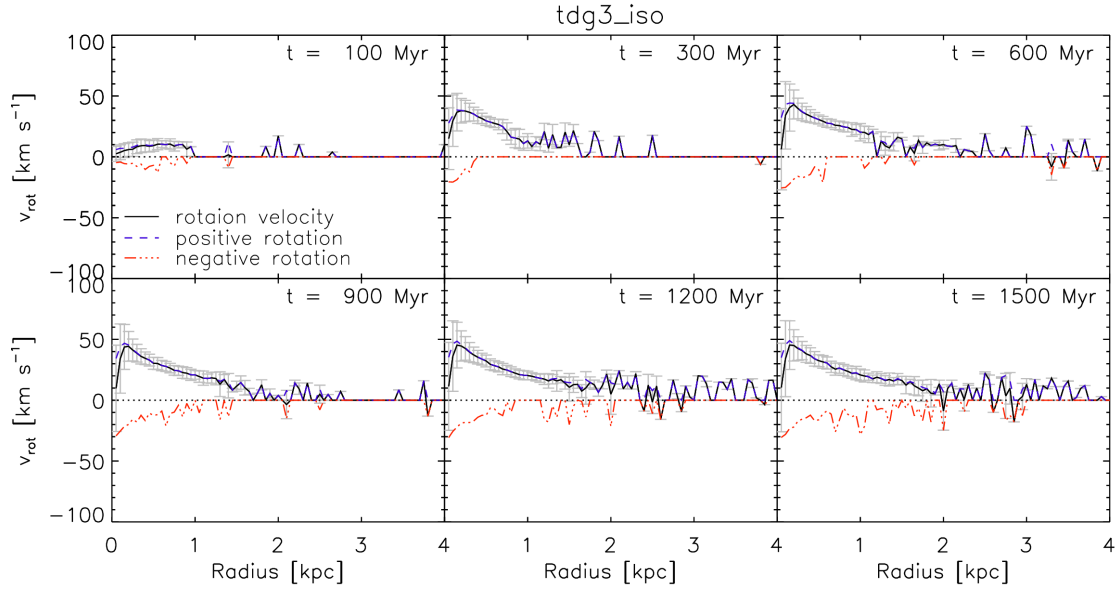


Figure 4.17: Same as Figure 4.12 for `tdg3_iso`

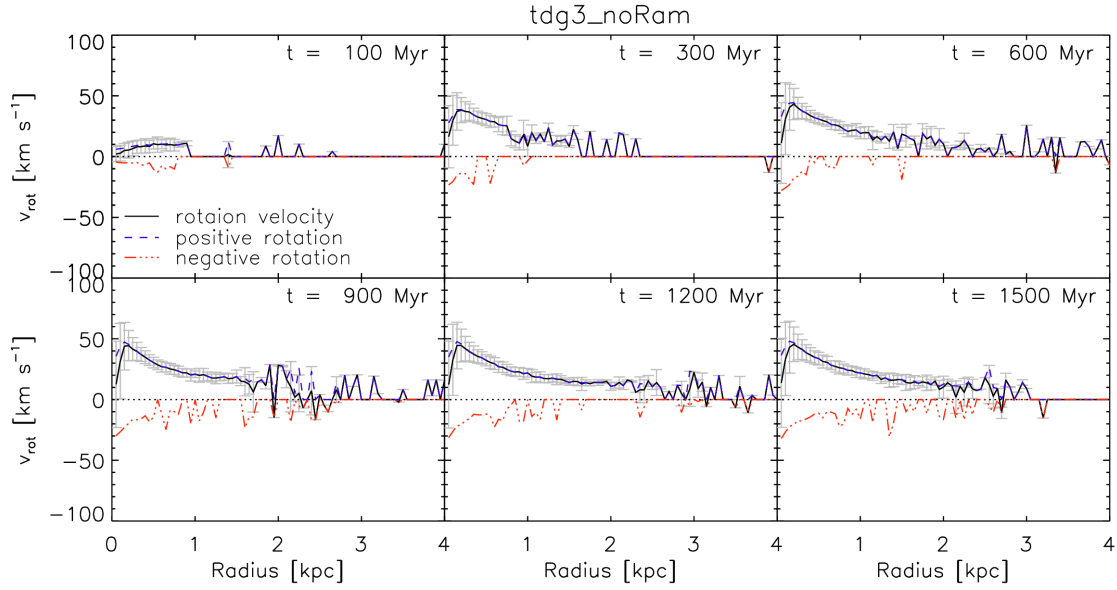


Figure 4.18: Same as Figure 4.12 for `tdg3_noRam`

candidates, are considered for the determination of the luminosity centre and the creation of the kinematic maps. The left panel of Figure 4.20 shows the exemplary luminosity-weighted stellar line-of-sight velocity map of `tdg3_iso` at $t_{sim} = 1500$ Myr. To further analyse the kinematic maps the `KINEMETRY`-package, as briefly described in Section 4.3.4, was used.

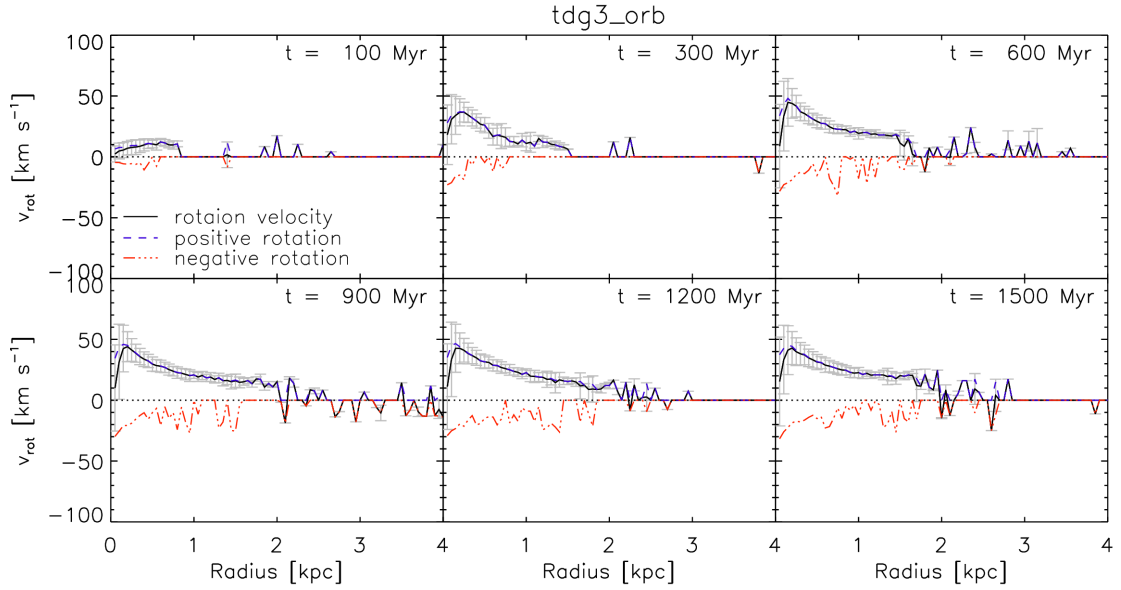


Figure 4.19: Same as Figure 4.12 for *tdg3_orb*

4.3.3 Gas dynamics

Similar to the luminosity-weighted velocity maps for stars, density-weighted line-of-sight velocity maps were created for the gaseous component of the TDGs, including the tidal arm. The line-of-sight velocities were calculated analogue to Equation 4.5, replacing $L(i)$ with the density ρ of the grid cells along the line-of-sight. The integration along the line-of-sights were performed throughout the whole simulation box along the three coordinate directions. As the simulations are performed in the frame of the TDGs, therefore the surrounding medium is travelling with the velocity v_{wind} relative to the TDGs, if ram pressure is included. To avoid contamination from the surrounding medium, only grid cells with more than 60% of their material originating from the tidal arm are considered for the integration, this can be traced with the mass scalar *TDG_MSCALAR* (see Section 2.7). In order to obtain smoother velocity maps the data were binned to twice the grid spacing resulting in a resolution of $156 \times 156 \text{ pc}^2$.

In order to demonstrate the principle differences between the stellar and gas line-of-sight velocity maps, the corresponding maps of *tdg3.iso* at $t_{sim} = 1500 \text{ Myr}$, integrated along the x-axis of the simulation box, are compared in Figure 4.20 (left: stars; right: gas). The spatial extent of the stellar velocity map ($2 \times 2 \text{ kpc}^2$) corresponds to black square in the velocity map of the gaseous component. The extent of the stellar component roughly corresponds to the highest gas-velocity regions in the centre of the TDG. The total rotating gas component of the TDG itself has a radius about 2-3 times larger than the stellar component. Depending on the model and line-of-sight, the velocity signature is contaminated by the streaming velocity along the tidal arm. At distances above 3-4 kpc the velocity signature purely traces the gas flow in the tidal arm. This contamination and the additional matter in form of the tidal arm might lead to wrong determination of the

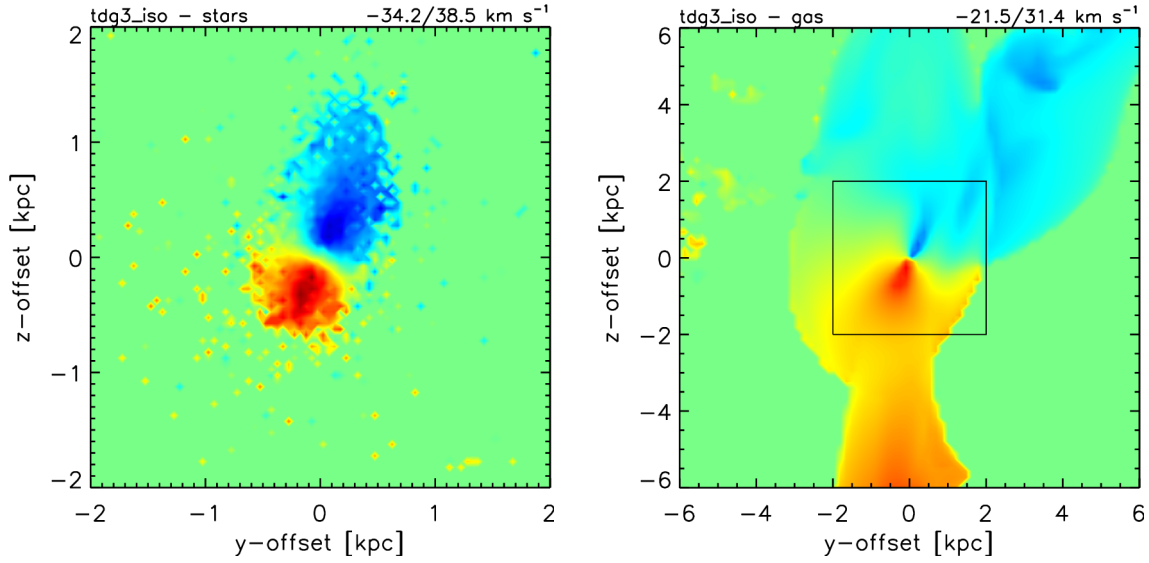


Figure 4.20: Line-of-sight velocity maps of the model `tdg3_iso` at $t_{sim} = 1500$ Myr, integrated along the x-axis of the simulation box ($v_{LOS} = v_x$). Left: Luminosity-weighted stellar line-of-sight velocity map, the data are binned to a resolution of 100×100 pc². Right: Density-weighted gas line-of-sight velocity map with a resolution of 156×156 pc². The black square indicates the extent of the stellar velocity map. The minimal and maximal line-of-sight velocities are given in the top right corner of each panel.

TDGs actual size and rotation velocity.

For example in the case of `tdg3_noRam` no clear decoupling from the tidal arm is visible in the k_1 -profile along the line-of-sight corresponding to the x-axis (see Figure 4.21, right hand side, third row). As for the stellar kinematic maps the KINEMETRY-package (Section 4.3.4) was applied for the analysis of the velocity maps and the results are outlined in Section 4.3.5.

4.3.4 Kinemetry

In order to derive the kinematic properties of the stellar and gaseous component of the TDGs the KINEMETRY-package developed by Krajnović et al. (2006) was adapted for simulation data. It is a generalization of surface photometry to the higher-order moments of the line-of-sight velocity distribution (LOSVD), where the first moment is the mean velocity and the second moment represents the velocity dispersion σ . In order to apply it, velocity respectively velocity dispersion maps from integral-field spectroscopic observations of galaxies are needed or in the case of simulations these maps have to be constructed (see Sections 4.3.2 and 4.3.3). The basic underlying assumption is that, for a thin-disk, the velocity profile along an ellipse can be described by a simple cosine-law in the form of

$$V(R, \psi) = V_0 + V_c(R) \sin(i) \cos(\psi), \quad (4.7)$$

where R is the radius of a circular ring in the plane of the galaxy (or the length of the semi-major axis of the ellipse on the sky), ψ the azimuthal angle measured from

the major axis, V_0 the system velocity, V_c the circular velocity along the ring and i the inclination. A velocity map $K(a, \psi)$ can be divided into a number of elliptical rings. Using Fourier analysis, the velocity profile of those rings can be represented by a finite number of harmonic terms:

$$K(a, \psi) = A_0(a) + \sum_{n=1}^N A_n(a) \sin(n\psi) + B_n(a) \cos(n\psi), \quad (4.8)$$

where ψ is the eccentric anomaly (corresponds to the azimuthal angle of Equation 4.7 in the case of a thin disk) and a is the length of the semi-major axis of the ellipse. Strictly speaking the representation of the LOSVD according to Equation 4.7 is only valid for a thin-disk approximation. In this case the B_1 -term in Equation 4.8 represents the circular velocity. Although triaxial systems such as early type galaxies do not behave like rotating disks, Krajnović et al. found that the velocity profiles of these systems are well described by a cosine-law. Despite this finding the interpretation of the different coefficients of the *sin*- and *cos*-terms is different to the thin-disk approximation. In order to describe the global properties of the kinematic maps of triaxial systems the coefficients of the same order are combined:

$$\begin{aligned} k_n &= \sqrt{A_n^2 + B_n^2}, \\ \phi_n &= \arctan\left(\frac{A_n}{B_n}\right). \end{aligned} \quad (4.9)$$

Using the combined coefficients, Equation 4.8 can be written in a more compact way

$$K(a, \psi) = A_0(a) + \sum_{n=1}^N k_n(a) \cos[n(\psi - \phi_n(a))]. \quad (4.10)$$

Within this notation k_1 represents the rotation velocity, and in the case of a purely rotating disk it reduces to B_1 as $A_1 \sin(\psi) = 0$ for all ψ (compare Equations 4.7 and 4.8). The coefficient k_5 is the first higher-order term not related to the best-fitting ellipse and describes the deviation from simple rotation. It is an indicator for complex structures on the velocity map. Furthermore, the position angle Γ and flattening $q = 1 - \varepsilon$, with ellipticity ε , for the best-fitting ellipse are extracted. Velocity maps with q close to 1 have large opening angles and appear round, while maps with small opening angles appear flat and have small values of q . Changes in these parameters give further insights to the kind of kinematic substructures, as a change in Γ of 180° would be indicative for a counter rotating core.

According to Krajnović et al., galaxies can be divided into four different kinematic groups, Disk-like rotation (DR), Multiple components (MC), Kinematic twists (KT) and Low-level rotation (LR). A short summary of the properties of this groups can be found in Table 4.2. DRs are mostly consistent with rotating disk galaxies, with a significant amplitude of the k_1 -term and only minor deviation from pure rotation, therefore the k_5 -term is almost zero. The position angle Γ and the flattening q remain constant throughout the whole

Table 4.2: Main features of the four different kinematic groups as described by Krajnović et al. (2006)

kinematic group		parameters			
		PA Γ [deg]	$q = 1 - \varepsilon$	k_1 [km/s ⁻¹]	k_5
Disk-like rotation	DR	const.	const.	substantial	≈ 0
Multiple components	MC	const.	change ^a	possible drop	peak ^a
Kinematic twist	KT	change ^a	change ^a	possible drop	> 0
Low-level rotation	LR	not definable ^b		low	high ($> k_1$)

Notes: ^a the change in Γ , q or the peak in k_5 occurs at the transition region between the subcomponents

^b as Γ and q cannot be determined, it is better to perform the analysis along circles

galaxy. MCs are similar to DRs but show signs of kinematically different components which are aligned at the same direction, having a constant Γ . This group can be traced by a change in q at the transition region between two subcomponents. Furthermore, the k_5 coefficient rises at this region, accompanied by a possible but not necessary drop of k_1 . A change in Γ , corresponding to a twist in the isovelocity contours, is a typical indication for KTs. Also the odd features from the MC group can be found, as KTs are essentially an extension of the MC-type with none constant Γ . The LR-class shows only minor to no signs of rotation, which is seen in low k_1 -values but substantially large k_5 -values which often exceeds the value of k_1 . As q and Γ cannot be determined for LRs, Krajnović et al. conclude that in this cases it is better to perform the analysis along circles.

4.3.5 The dynamics of TDGs

In this section the results of the KINEMETRY-analysis of the gaseous and stellar components of the different simulation runs are presented. Figure 4.21 shows the k_1 -profiles of the gaseous (solid lines) and stellar (dashed lines) component along three different line-of-sights of several simulation runs. The stellar k_1 -profiles of all models show some general similarities, like a strong peak at small radii followed by a rapid decline. Depending on the model and line-of-sight, additional features are present, such as flat intervals and secondary peaks. The k_1 -profiles of the gaseous component peaks at similar radii with comparable amplitudes, but strong differences are present at radii larger than the peak radius. These differences are in part attributed to the greater extend of the gas disk compared to the stellar disk but also to the presence of the tidal arm, and are strongly depending on the considered line-of-sight. For example tdg2_iso shows a strong second peak of the gas line-of-sight velocity at a distance of ~ 3.2 kpc along the y-axis of the simulation box. On the other hand, tdg3_noRam does not show a dynamical decoupling from the tidal arm along the x-axis, also seen in the right panel of Figure 4.20. On low resolution maps these features might lead to a significant miss interpretation of the dynamics, sizes and masses of TDGs, see Section 5.5.3 for a further discussion.

The dynamical properties at the final simulation time are listed in Table 4.3 and Tables A.4 and A.5 of Appendix A. Note that the TDGs of TDG_s1 are excluded from the analysis presented here, due to their structural properties. The following analysis and classification

Table 4.3: Stellar kinematic properties of the simulated TDGs at the final simulation time. Column 1: Simulation run; Column 2: Maximal rotation velocity v_{max} at the final simulation time (see Section 4.3.1); Column 3: Radius $r_{v_{max}}$ at which v_{max} is reached; Column 4: Maximum value of k_1 ; Column 5: Radius $r_{k_1, max}$ at which k_1, max is reached; Column 6: Average velocity dispersion $\bar{\sigma}$ within $r_{k_1, max}$; Column 7: Ellipticity ε at $r_{k_1, max}$; Column 8: Kinematic class.

model	v_{max} [km s ⁻¹]	$r_{v_{max}}$ [pc]	$k_{1, max}$ [km s ⁻¹]	$r_{k_1, max}$ [pc]	$\bar{\sigma}$ [km s ⁻¹]	ε	class
tdg2_iso	80.1	250	56.1	330	29.9	0.41	DR - MC
tdg2_noRam	55.7	300	47.0	273	41.8	0.50	?
tdg2_orb	71.8	200	62.1	273	43.1	0.30	MC (KT?)
tdg2_noArm	42.7	250	39.6	273	36.2	0.64	KT
tdg2_igimf	53.8	350	47.3	330	35.8	0.64	MC - KT
tdg3_iso	45.3	150	35.4	216	20.8	0.39	DR
tdg3_noRam	45.4	200	34.8	216	25.9	0.37	DR (MC?)
tdg3_orb	42.9	200	29.2	273	22.0	0.53	MC (DR?)

is solely based on the stellar dynamics of the simulated TDGs.

tdg2_iso shows some asymmetries and substructures in its stellar distribution, whereas the kinematic position angle Γ stays fairly constant with variations smaller than 10° and k_5/k_1 stays below 0.1 for more than 1.5 kpc. The k_1 profile is almost linearly declining beyond the peak radius of ~ 330 pc until $r \approx 1.5$ kpc, with only small variations at positions where the flattening q changes. Considering the Γ and k_5/k_1 profiles, tdg2_iso is classified as DR with an existing possibility of multiple kinematic components due to the changing q -values.

tdg2_noRam shows the strongest substructures in the stellar distribution, with a close companion on one side and a tidal arm like feature on the opposite side (Figure 4.9). The strongest signatures of the second component of tdg2_noRam are present in the KINEMETRY-analysis at radial distances beyond ~ 2.0 kpc, by unsteady values of Γ and the k_5/k_1 ratio. Furthermore, the method failed along two lines of sight, i.e. along the x- and y-axis, for the stellar velocity maps at large distances from the centre of the TDG ($r > 2.5$ kpc). Nevertheless, this method yields good results within the inner ~ 1.5 kpc of the TDG, with a k_5/k_1 ratio below 0.3 and only minor and smooth variations of Γ . The coefficient k_1 shows some secondary peaks at the positions of jumps in the flattening, indicating multiple rotational components. The classification of this object is uncertain as it shows signs of various kinematic groups, ranging from pure DR to KT. This TDG shows a variety of different morphological structures, which makes it unclear if the odd features in the kinematic parameters are caused by internal dynamics or by projection effects of the substructures along the line-of-sight.

tdg2_orb has the smoothest appearance in its stellar light distribution among the models of TDG.s2 (see Figure 4.9). Despite this rather clean shape, it shows signs of multiple kinematic components such as an increasing Γ with $\Delta\Gamma \approx 20^\circ$ and multiple humps in k_1 ,

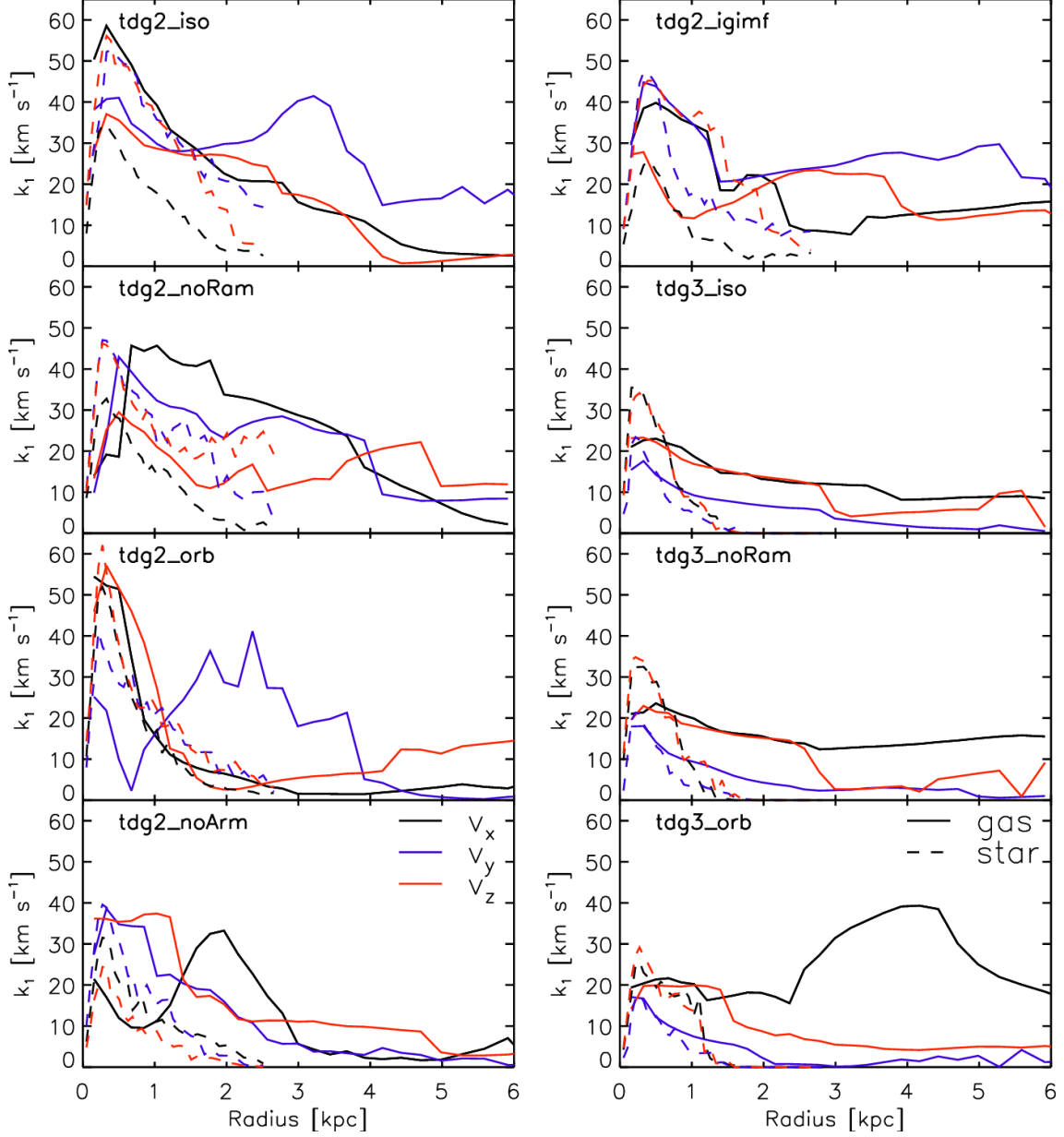


Figure 4.21: k_1 -profile of simulated TDGs for the gaseous (solid line) and stellar (dashed line) component along three different line-of-sights. For an explanation of k_1 see Section 4.3.4.

both with varying intensity depending on the line-of-sight. The flattening shows strong and sudden changes, especially at $r \approx 270$ pc, the radius of the maximal k_1 value but also at the locations of secondary peaks of k_1 . The ratio between k_5 and k_1 stays below 0.1 until $r = 700$ pc and below 0.5 until $r = 2.2$ kpc. Due to its multiple peaks in k_1 which correspond to jumps in q , it is classified as MC, with a possible kinematic twist as Γ is only smoothly varying.

tdg2_noArm is classified as KT, as Γ is changing by $10 - 50^\circ$ within $r < 1.2$ kpc and exhibits possible secondary low-amplitude humps in k_1 , both depending on the line-of-sight. Also the substructures in the k_1 profile are correlated to jumps in q . The ratio of

k_5/k_1 stays below 0.1 for $r < 600$ pc and 0.3 until $r = 1.2$ kpc.

tdg2_igimf harbours a small central stellar disk encompassed by a spherical stellar envelope, most prominent in the edge-on view of Figure 4.9 and an arm like feature. The kinematic position angle of **tdg2_igimf** remains roughly constant until $r \approx 1.3$ kpc and has a k_1 profile similar to what is expected for Keplerian rotation. Also the k_5/k_1 ratio remains below 0.2 until that radius. Only for the line-of-sight along the x-axis a higher deviation from a constant Γ with $\Delta\Gamma \leq 20^\circ$ can be found. Along this direction the k_1 profile shows higher rotational velocities and a weaker decline, both effects are most likely attributed to the arm feature of **tdg2_igimf**. Considering the k_1 profile along the x-line-of-sight and morphological features, **tdg2_igimf** is classified as MC with a high possibility of also being a member of the KT class.

tdg3_iso is the apparently most disk like galaxy among all model TDGs, in both the stellar distribution and the kinematic parameters. The kinematic position angle stays constant, with an increase by less than 10° . Also the deviations from disk like rotation are only marginal, i.e. the ratio k_5/k_1 is consistent with zero until $r \approx 600$ pc and < 0.15 within the inner 1 kpc. The asymmetries in the stellar distribution, and therefore in the velocity maps, are reflected in discontinuities in the flattening and k_1 between $r = 0.5$ and 0.7 kpc, depending on the line-of-sight. As the odd kinematic features are attributed to the morphology of the TDG, it is still classified as disk-like rotator (DR).

tdg3_noRam shows the same principle morphological appearance as **tdg3_iso** but has some minor substructures as well. Furthermore, the kinematic parameters of these simulation runs are very similar until $r \lesssim 600$ pc. Beyond this radius the flattening becomes unsteady, the k_5 -to- k_1 ratio increases to values between 0.1 and 0.5, depending on the line-of-sight. The k_1 profiles show some indications of multiple kinematic components, as additional peaks and flat spots appear in the interval $\sim 0.5 \lesssim r/\text{kpc} \lesssim 1.3$, which corresponds to jumps in q . As it does not only show disk like features, but deviations are on a low level, it is classified as DR with possible multiple components.

tdg3_orb generally has a similar morphology and kinematics to **tdg3_iso** and **tdg3_noRam**. Among the three simulation runs of TDG.s3 it is the one with the strongest signatures of multiple components, such as additional peaks in k_1 at the positions of discontinuities in q . At radii greater than ~ 500 pc the deviations from disk like rotation are still small but the k_5 -to- k_1 ratio reaches values of 0.2 until $r = 1.0$ kpc. Below 500 pc the ratio is close to zero. Due to the secondary peaks in k_1 it is classified as MC but the possibility of being constituted by a single rotating component is not excluded.

4.3.6 Counter rotating stars

Although no dominant KDC is formed during the simulations, a counter rotating stellar component is always present, regardless if the TDG candidates are treated in isolation or within the external gravitational potential of the merging galaxies. As it can be seen from the stellar rotation curves (Figures 4.12 - 4.19), the influence of the counter rotating stars on the rotational velocity is strongest at the centre of the TDGs.

In the top panels of Figures 4.22 and 4.23 the radial distribution of the different rotating stellar components is investigated for the three models `tdg2_orb`, `tdg2_iso` and `tdg2_igimf`. The upper left panel shows the radial distribution of stars normalised to the total number of stars within a radius of $r = 2.5$ kpc at $t_{sim} = 100$ Myr and the upper right panel at $t_{sim} = 1500$ Myr ($t_{sim} = 600$ Myr for `tdg2_igimf`). The black line indicates the radial distribution of all stars within a distance of 2.5 kpc, whereas the blue and red lines show the distribution of the mathematically positive and negative rotating components, respectively. During the early star formation phase ($t_{sim} = 100$ Myr) an almost equal partition of rotation directions is present, where the negative rotating component shows a greater radial extent than at later times, i.e. at $t_{sim} = 1500$ Myr, respectively 600 Myr for `tdg2_igimf`. This is particularly visible at radii greater than 400 pc, where the fraction of negative rotating stars almost reaches zero, compared to $1.5 - 2\%$ at $t_{sim} = 100$ Myr.

In the lower left panel the age distribution of star clusters is shown, again split into the different rotating components and normalised to the total number of stars. Although the counter rotating component is predominately formed at early simulation times, resulting in an older stellar component, it can be seen that negative rotating stars are also formed throughout the whole simulation. An age segregation as observed by Toloba et al. (2014) with a much younger KDC than the main body, differing by several Gyr in stellar ages, is not present. Therefore, the old stars, expelled from the disks of the interacting galaxies, would have to show a preferred rotation direction. These stars are collected in the oldest age-bin ranging from 1490-1500 Myr (610-620 Myr for `tdg2_igimf`) and contribute equally to the positive and negative rotational direction. This equal distribution might be an effect caused by the low number of preexisting stars, as listed in Table 3.1.

The lower right panel shows the distribution of the angles α between the stellar orbital planes with respect to the angular momentum direction of the TDG at $t_{sim} = 100$ and 1500 Myr (100 and 600 Myr for `tdg2_igimf`). Stellar orbits with an angle $\alpha \geq 90^\circ$ are considered as counter rotating. At the early evolutionary stages stellar orbits close to polar are preferred, which is also reflected in the rotation pattern, as at $t_{sim} = 100$ Myr only a minor rotation, if any, can be seen. During the further evolution co-rotating orbits with $\alpha \lesssim 30^\circ$ become dominant but still with a significant fraction of about $10 - 20\%$ of stars showing orbital angles larger than 90° at the final simulation time.

The general similarities of the distribution of co- and counter-rotating stars, of the different simulation runs indicated that the formation of a KDC or a counter rotating stellar component might not be a consequence of the tidal field but is rather related to initial gas

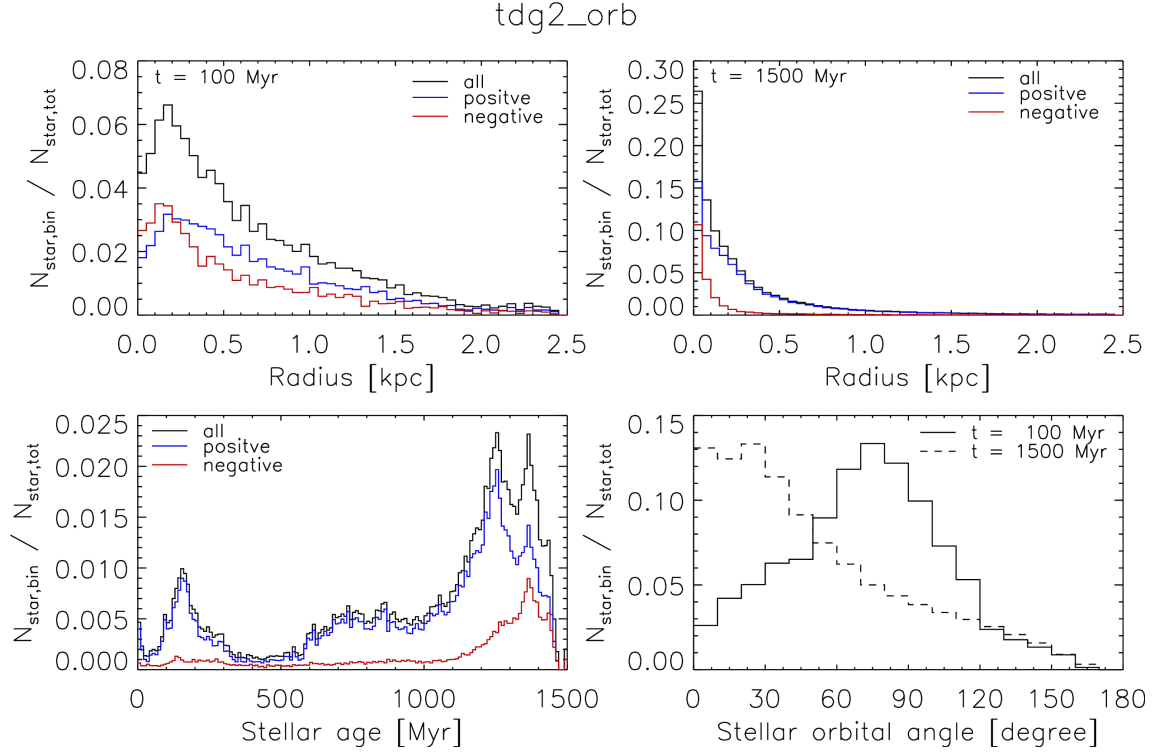


Figure 4.22: Stellar distribution statistics within a radius $r = 2.5$ kpc around the centre of luminosity of the model `tdg2_orb`. Top row: Radial distribution of stars at $t_{sim} = 100$ & 1500 Myr for the left and right panel, respectively. The number of stars per radial bin ($\Delta r = 50$ pc) is normalised to the total number of stars at the considered timestep. The black line indicates the relative number of stars per radial bin, whereas the blue and red lines correspond to the positive and negative rotating component, respectively. The definition of the rotation directions is as in Section 4.3.1. Bottom left: Distribution of stellar ages in stellar age bins of 10 Myr, the pre-existing stellar population is collected in the last bin ($1490 - 1500$ Myr). The colour code is the same as in the top panels, the number of stars per bin is normalised to the total number of stars formed until $t_{sim} = 1500$ Myr. Bottom right: Distribution of angles between the direction of the TDGs angular momentum and the orbit of a stellar particle at $t_{sim} = 100$ & 1500 Myr, indicated by the solid and dashed line, respectively. Stellar particles with orbital angles $\alpha \geq 90^\circ$ are considered as counter rotating (labelled as *negative*) and show a retrograde rotation with respect to the orbit of the TDG.

density and velocity distribution.

Within this thesis non-idealised initial conditions are used as they are resulting from a merger simulation, therefore the initial gas distribution does not show symmetries or a clear rotation pattern. In comparison Ploekinger et al. (2015) used a spherical symmetric gas distribution with an initial rotation velocity defined by:

$$v(r) = \sqrt{\frac{G M(r)}{r}}. \quad (4.11)$$

These irregularities of the initial conditions are reflected in the spatially extended distribution of star forming regions within the early phases of the simulations. As the initial gas cloud and the first formed stars collapse to form the TDG, it is possible for a stellar particle to pass on either side of the centre of the TDG, and therefore get captured on orbits with arbitrary angular momentum directions. Figure 4.24 shows the surface brightness map of

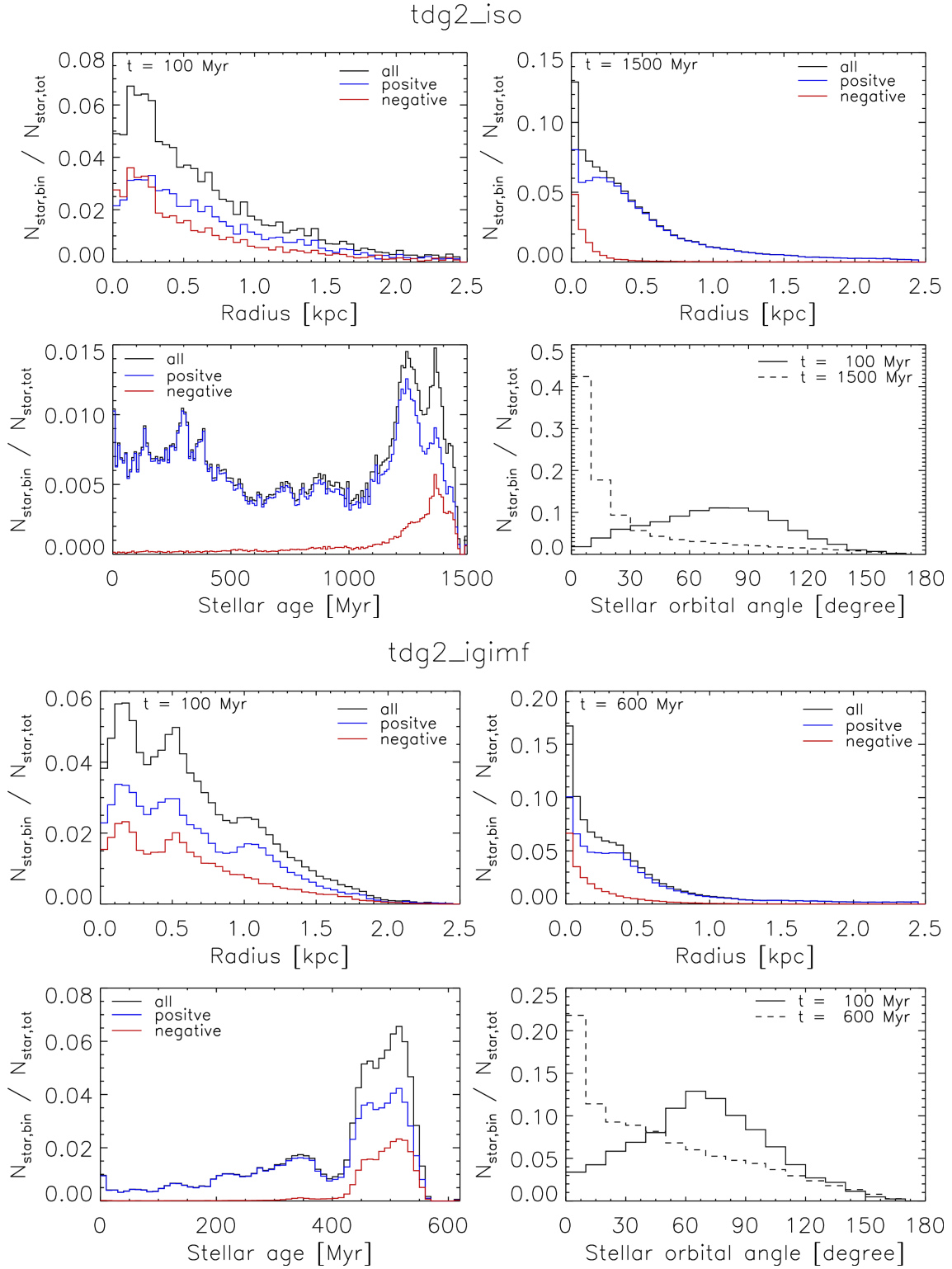


Figure 4.23: Same as Figure 4.22 for `tdg2_iso` (top set) and `tdg2_igimf` (bottom set). Note the different output times for `tdg2_igimf` ($t_{\text{sim}} = 100$ & 600 Myr) and the collection of pre-existing stars in the age bin 610 – 620 Myr.

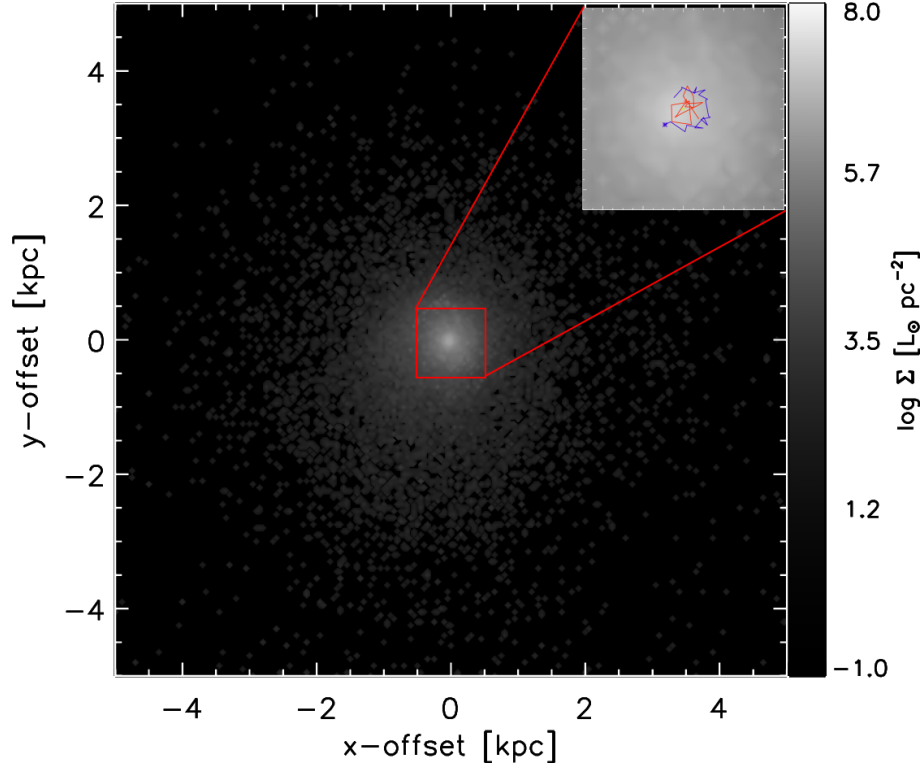


Figure 4.24: Stellar surface brightness map of the model `tdg2_orb` at $t_{sim} = 1500$ Myr. The insert enlarges the inner $1 \times 1 \text{ kpc}^2$ and shows two exemplary orbits of stellar particles formed during the initial star formation episode, the blue and red line represent the co- and counter rotating orbit, respectively. For clarity the orbits are only shown for the simulation time interval $t_{sim} = 700 - 900$ Myr, with the position at $t_{sim} = 700$ Myr marked by a symbol.

`tdg2_orb` at $t_{sim} = 1500$ Myr, with the central $1 \times 1 \text{ kpc}^2$ enlarged in the insert. The blue and red lines represent the orbits of one co- and one counter-rotating stellar particle in the simulation time interval $700 \leq t_{sim}/\text{Myr} \leq 900$, respectively. Both particles are formed during the first episode of low star formation, between $t_{sim} = 30$ and 40 Myr.

4.4 The influence of the IMF description

The two simulation runs `tdg2_orb` and `tdg2_igimf` share identical initial conditions and both use the full capabilities of the orbit module, i.e. include the effects of the tidal field and ram pressure. The only difference lies in the IMF description, where `tdg2_orb` uses the standard filled IMF and `tdg2_igimf` uses the IGIMF description instead. Therefore, these two simulation runs can be directly compared and the influence of the IMF description on the evolution of TDGs can be investigated. Within the filled IMF description the IMF is, as the name suggests, always filled to the uppermost mass bin, even with fractions of high-mass stars. These fractions of high mass stars result in an early onset of feedback processes related to these stars, such as stellar winds and SN II. Whereas, the IGIMF description does not allow for fractions of stars and thus fractional feedback, resulting in a delayed or suppressed feedback from high-mass stars, depending on the mass of the star

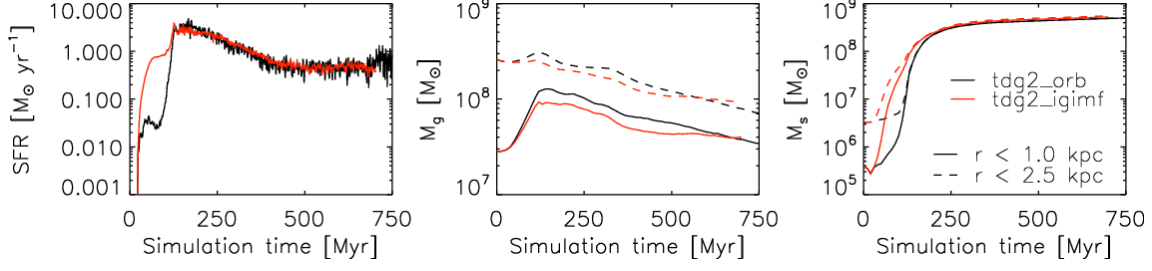


Figure 4.25: Comparison of the SFR, gas mass M_g and stellar mass M_s of the simulation runs `tdg2_orb` (black) and `tdg2_igimf` (red). The solid and dashed lines correspond to the mass within spheres of $r = 1.0$ and 2.5 kpc, respectively.

cluster. This difference in the onset of stellar feedback consequently results in a higher initial SFR and a faster built up of stellar mass with a directly related lower gas mass (see Figure 4.25).

In Figure 4.26 density slices through the inner 10×10 kpc of the simulation box centred at the mass centres of the two simulation runs are presented for the simulation times $t_{sim} = 50, 200$ and 400 Myr. These simulation times correspond roughly to the three different star formation phases as described in Section 4.1.2. During the first star formation period the filamentary structure of the proto-cloud is slightly less confined in the case of the filled IMF (i.e. `tdg2_orb`, top row). This is due to the mentioned early onset of fractional feedback events from high mass stars and the resulting preheating of the ISM. As the cloud collapse proceeds the SFR gets high enough to completely fill the IMF of the individual stellar particles and therefore SN II and stellar winds also occur in the IGIMF run (`tdg2_igimf`, bottom row). The apparently largest difference between these two simulation run is the formation of the galactic wind in the IGIMF run. The wind starts to build up around the simulation time $t_{sim} \approx 170$ Myr and forms a chimney like cavity in the tidal arm which remains present for several hundreds of Myr until it gets destroyed due to ram pressure. Whereas, only minor feedback driven bubbles emerge from the galactic disk in the case of the filled IMF. The influence of the galactic wind on the lower gas mass of `tdg2_igimf` is negligible, as it is almost exclusively attributed to the faster conversion of gas into stars.

4.4.1 Star formation and stellar feedback

Not only the SFR is altered by the IMF description but also the distribution of star forming regions, especially at early simulation times. In Figure 4.27 the star formation rate surface density $\Sigma_{SFR} [M_\odot \text{ Myr}^{-1} \text{ pc}^{-2}]$ is shown for the two simulation runs using either the filled IMF (top) or the IGIMF (bottom), at the same timesteps as the density slices of Figure 4.26. Note that the scaling of these two images is different. The local SFR is only depending on the density and temperature of the grid cells, according to the SBF (Equation 2.30). As the feedback from fractions of high-mass stars, in the filled IMF run, increase the temperature of the surrounding gas, the efficiency at which gas gets converted into stars is reduced. This results in locally weaker and less confined star forming regions,

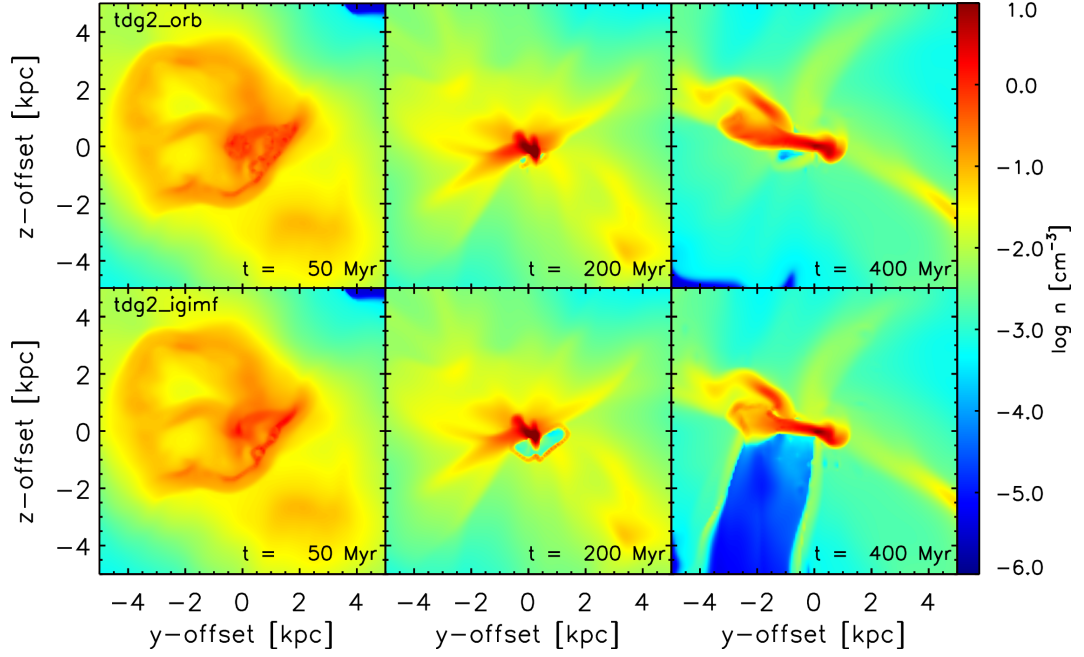


Figure 4.26: Density slices (in atoms cm^{-3}) of the simulation runs `tdg2_orb` (top) and `tdg2_igimf` (bottom) at $t_{\text{sim}} = 50, 200$ and 400 Myr.

compared to the IGIMF run (lower panels). Due to the locally weaker feedback at this early simulation time more star clusters, with lower masses, can be formed when the IGIMF is used. As the simulations advance, the extended gas cloud collapses, what leads to high local gas densities and enables a rapid cooling of gas, providing conditions for high SFRs. With a similar behaviour for both simulation runs, differing only in the outer parts of the TDGs, where the local SFRs are higher in the IGIMF run (middle & right panels). In the IGIMF run a higher number of star clusters with preferential lower masses are formed (see also Figure 4.7), within these star clusters the IMF is not completely filled to the uppermost mass bin, providing more intermediate mass stars which eventually end their life as SN Ia.

Figure 4.28 compares the stellar feedback energy, number of feedback providing IMF mass bins, i.e. the sum of mass bins which ended their life during the last Myr per star cluster summed over all clusters and the actual number of feedback events. The larger number of star clusters in the IGIMF run automatically provides a larger number of low to intermediate mass IMF mass bins. Therefore, one would also assume that the number of actual SN Ia has to be larger in this case, but except for the simulation time interval $80 < t_{\text{sim}}/\text{Myr} < 200$ the energy released by SN Ia and also their number is equal in both cases. Within the filled IMF the probability of an intermediate mass star to end its life as SN Ia is independent of the cluster mass. Whereas, the number of possible stars that one star can pair with to form a binary system, which eventually ends as SN Ia, is lower in the IGIMF case. Especially if the star cluster is truncated at a mass bin below $8 M_{\odot}$, the applied upper mass limit for a star to be considered as possible SN Ia progenitor (see Section 2.6.3). Therefore, the probability of a star to become a type Ia SN is smaller.

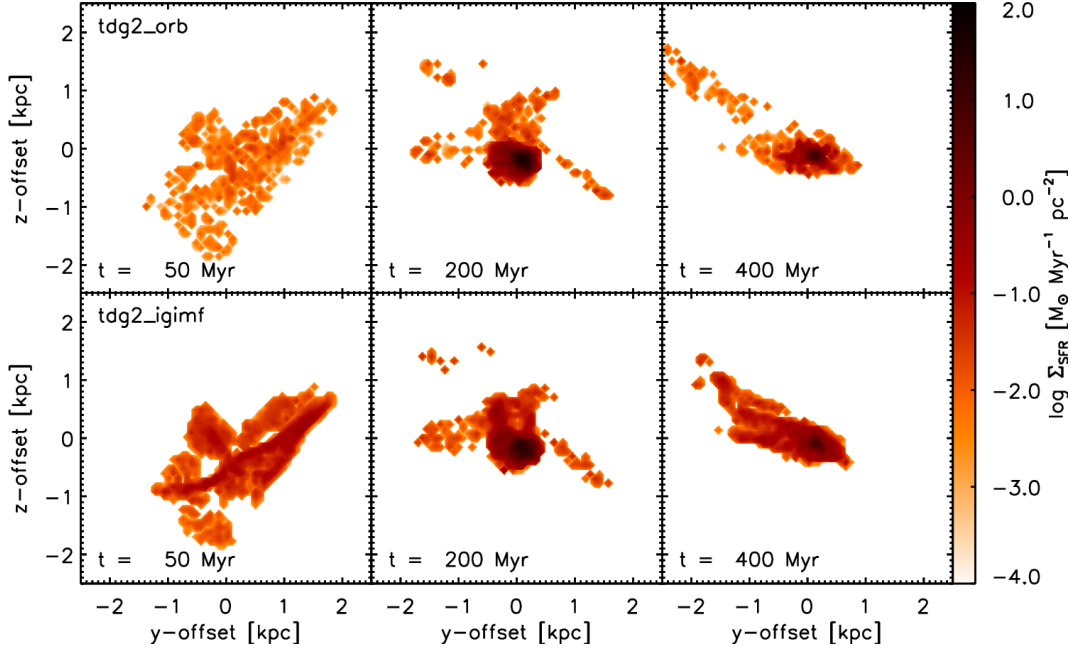


Figure 4.27: Star formation rate surface density Σ_{SFR} in $M_{\odot} \text{ Myr}^{-1} \text{ pc}^{-2}$, at three different simulation times $t_{sim} = 50, 200$, and 400 Myr (from left to right) for the models `tdg2_orb` (top) and `tdg2_igimf` (bottom).

Within the presented simulations the higher number of star clusters with lower SN Ia probability (IGIMF) cancel out against the lower number of star clusters with constant SN Ia probability (filled IMF), for most of the simulation time.

The black and overlaying blue lines (middle and right panel) show the number of high mass bins ($M_{\star} > 8 M_{\odot}$) which ended their life in the previous Myr. The number of SN II and stellar wind providing mass bins is initially lower in the IGIMF simulation, this is due to the truncation of the IMF at the last mass bin that still holds at least one star. As the SFR increases more and more star clusters are able to fill their IMF and the number of SN II providing mass bins equals out between the two simulation runs. Interestingly, the actual number of SN II behave quite different (see right panel), for the first 70 Myr of simulation time the behaviour is as expected with a lower number of SN II in the IGIMF simulation. As the mass of the star clusters exceeds $19050 M_{\odot}$ the IMF gets completely filled in both simulations and the influence of fractional SN becomes smaller, in the case of the filled IMF. The number of SN II and stellar wind events of the IGIMF run exceeds the number of the filled IMF simulation in the time interval $70 < t_{sim}/\text{Myr} < 140$, before it becomes essentially indistinguishable. A similar behaviour is observed for the integrated feedback energy of SN II (left panel).

The difference between the two IMF descriptions becomes clearly visible if the distribution of released feedback energy (Figure 4.29) and the feedback events, especially of SN Ia (Figure 4.30), is considered. As long as the elapsed simulation time since the first star formation event is too short for SN Ia to occur ($\lesssim 40 - 50$ Myr), the released feedback energy is only provided by stellar winds and SN II. In the IGIMF run the local SFR is too

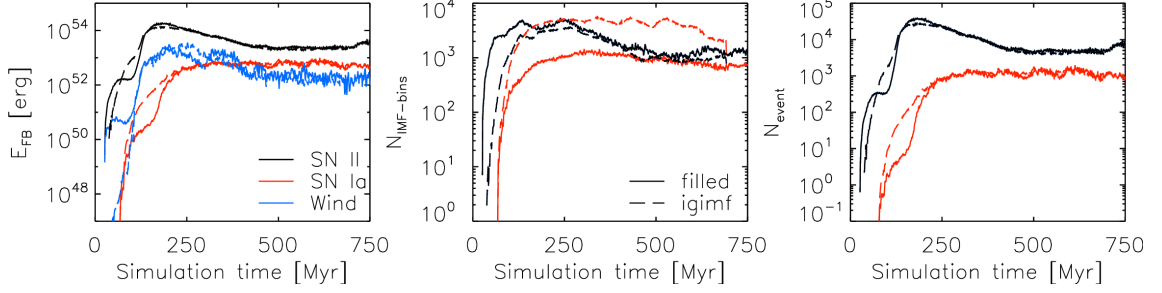


Figure 4.28: Comparison of feedback energies and number of events of the simulation runs `tdg2_orb` (solid) and `tdg2_igimf` (dashed). Note that the term *Wind* refers to stellar winds driven by mass loss and does not include ionising radiation. The number of SN II and stellar wind events are equal, therefore the black and blue lines overlap in the middle and right panel.

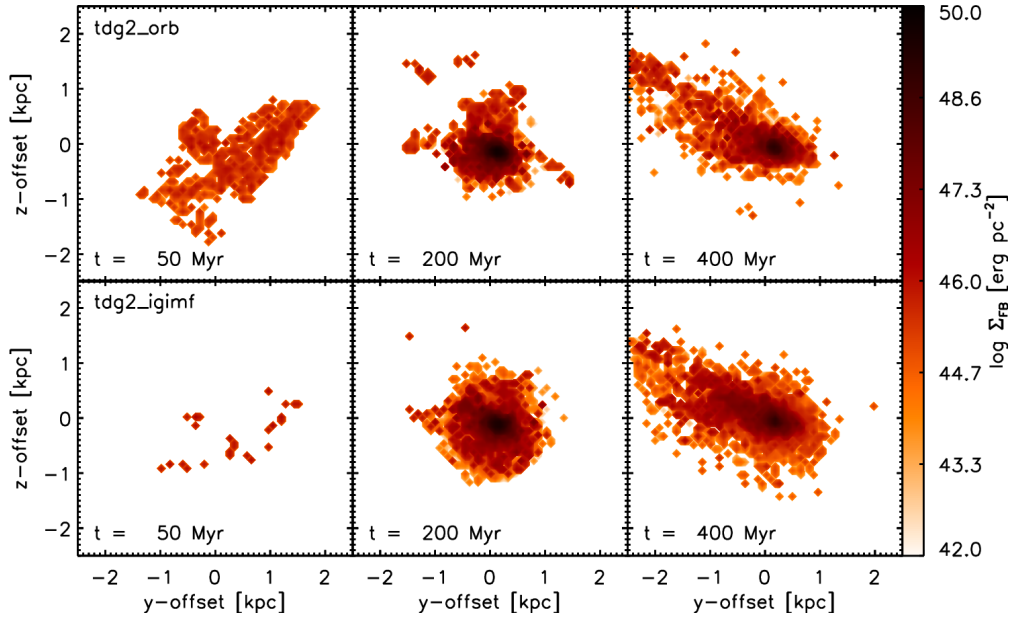


Figure 4.29: Cumulative released feedback energy surface density Σ_{FB} [erg pc^{-2}], at three different simulation times $t_{sim} = 50, 200$, and 400 Myr (from left to right) for the models `tdg2_orb` (top) and `tdg2_igimf` (bottom). The feedback events within a timespan of 1 Myr are considered and spatially binned to the effective grid resolution ($\Delta x = 78$ pc).

small to fill the IMF of individual star clusters to produce stellar masses greater than $8 M_{\odot}$, therefore the feedback is very localised around the most massive star clusters, whereas the fractions of high-mass feedback in the filled IMF run nicely follow the extended distribution of star forming regions (compare the left panels of Figure 4.29). As the simulations proceed the local SFRs become high enough in order to fill the IMF of star clusters in the IGIMF case, therefore the distribution of regions with high feedback energy release is matching well in both runs. The most energy injected into the ISM is released by high-mass stars, which trace the distribution of star forming regions, whereas the distribution of SN Ia from intermediate mass stars is causing the apparent difference in the distribution of released feedback energy. This is illustrated in Figure 4.30 for the number density of SN Ia at $t_{sim} = 200$ Myr, where, in the simulation using the filled IMF (left panel), SN Ia are almost exclusively confined to distances below ~ 0.5 kpc from the centre. In the case of

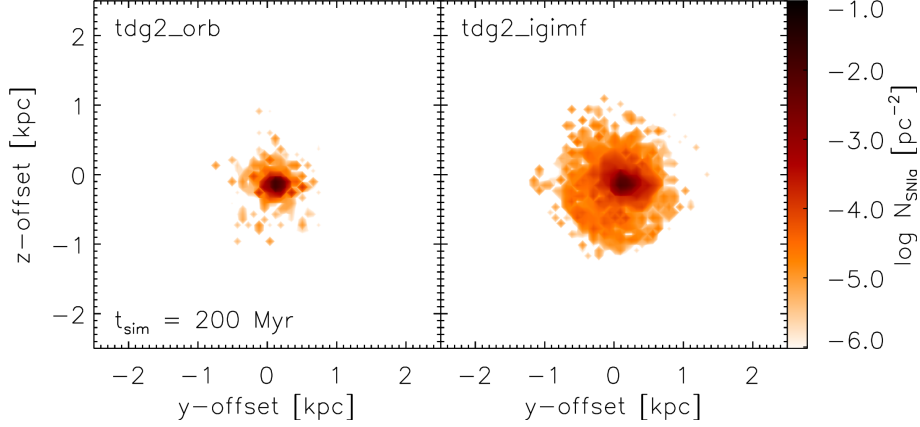


Figure 4.30: Distribution of type Ia supernovae of the simulation runs `tdg2_orb` (left) and `tdg2_igimf` (right) at the simulation time $t_{sim} = 200$ Myr.

the IGIMF (right panel) their distribution is reaching larger distances up to 1 kpc and beyond, as a consequence of the higher number of star clusters and their spatially extended distribution.

4.5 Environmental influences

In this section the influence of the different effects of the environment, i.e. ram pressure, the tidal field and the tidal arm, on the evolution of TDGs is examined. To illustrate the environmental effects on the evolution of TDGs, comprehensive time sequences of close up ($10 \times 10 \text{ kpc}^2$), particle number density slices through the simulation boxes centred at the mass centre of the TDGs, are provided in the Figures 4.35 to 4.37, based on the models of the setup TDG_s3. Within these models the tidal arm is roughly aligned with the x-axis, therefore the presented slices cut almost perpendicular through the tidal arm.

4.5.1 Orbit

Environmental effects on the evolution of TDGs are strongly related to their orbits around the host galaxy, as the ram pressure is caused by the relative motion of the TDG through the IGM and the strength of the tidal field is dependent on the distance from the host. The top panel of Figure 4.31 shows the orbits of the different simulation setups in the coordinate frame of the merging galaxies projected to the xy-plane. The thin black lines follow the predicted orbits for 5 Gyrs, whereas the thick coloured lines represent the actual distance covered during the simulations. The lower panels show the distance from the TDGs to the merger remnant normalised to its initial distance at a simulation time of $t_{sim} = 0$ Myr (left), as listed in Table 3.1 and the absolute three dimensional orbital velocity (right). Assuming a time constant central point mass as representation of the merger remnant, as it has been used for the orbit module (see Section 2.7), the absolute escape velocities $|v_{esc}| = 151, 160$ and 122 km s^{-1} for the simulation setups TDG_s1, s2 and s3, respectively. By comparing the initial velocities (see Table 3.1) with the escape velocities it turned out

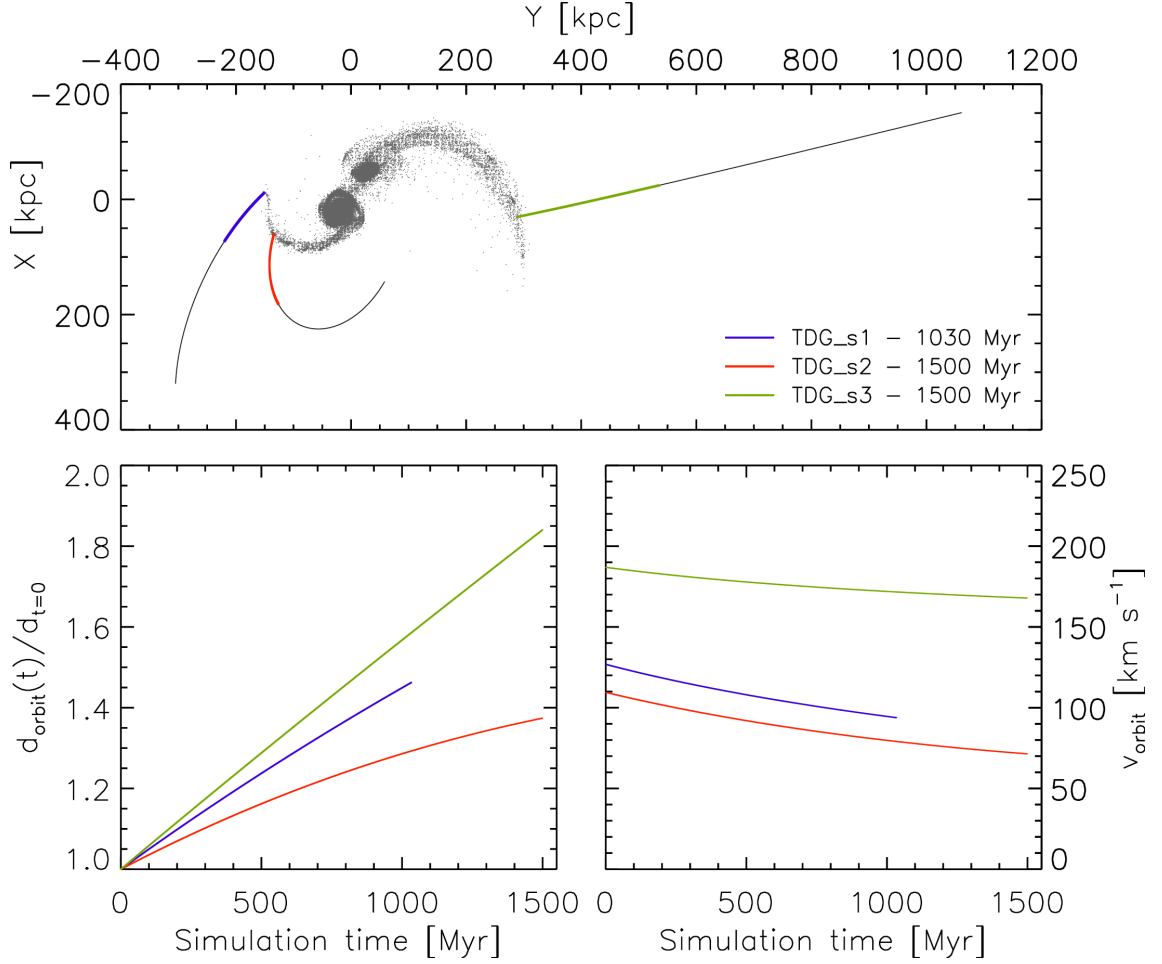


Figure 4.31: Orbits of the TDGs around the merging galaxies, projected to the xy-plane in the coordinate frame of the merger. Top: The thick coloured line correspond to the distance made by the simulation boxes until the final simulation time, whereas the thin black lines trace the predicted orbits for 5 Gyrs. The colour code and final simulation times are indicated in this panel. Note that the coordinate axis are switched, therefore the horizontal axis represents the Y-axis. The stellar distribution of the initial merger simulation 1.5 Gyr after the first pericentre passage is shown for illustrative purposes. Bottom left: Distance of the TDG to the centre of mass of the merger remnant, normalised to their distance at $t_{\text{sim}} = 0$. Bottom right: Absolute orbital velocity.

that TDG_s3 is on an unbound orbit being ejected into the intergalactic space. The orbits of the other two setups remain bound to the merger remnant with orbital periods of 10.6 and 8.9 Gyr for TDG_s1 and s2, respectively. Starting from the initial position along the orbits, these setups are increasing their distance from the merger remnant with declining velocities (see bottom panels of Figure 4.31), as they are on their way towards their orbits apocentres.

4.5.2 Tidal field

In order to investigate the influence of the tidal field on the evolution of TDGs, the simulation runs `tdg2_noRam` - `tdg2_iso` and `tdg3_noRam` - `tdg3_iso` are compared. The `_iso` models do not feel any tidal accelerations or ram pressure whereas the `_noRam` models are

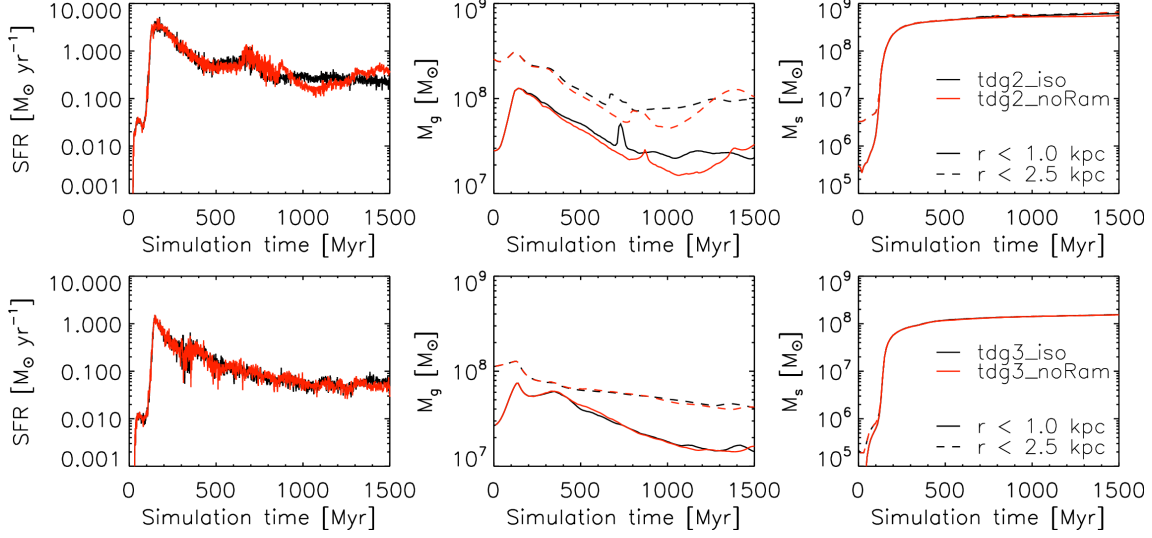


Figure 4.32: Comparison of simulation runs without (`_iso`, black) and with (`_noRam`, red) the influence of the tidal field of the setups TDG_s2 (top) and TDG_s3 (bottom). Left: Star formation rate; Middle: Total gas mass; Right: Total stellar mass. The line styles are equal in all panels and a legend is provided in the right panel. The solid and dashed lines in the middle and right panels correspond to the mass within spheres of 1.0 and 2.5 kpc around the mass centre, respectively.

exposed only to the tidal field, therefore the pure effect of the tidal field can be studied. The compressive effect of a tidal field decreases with increasing distance from the host galaxy (e.g. Ploekinger, 2015). As the distances from the merger remnant are large with $D > 160$ kpc and increasing with time, the influence of the tidal field on the TDG is expected to be small within the presented simulations. Figure 4.32 compares, from left to right, the SFR, gas mass M_g and stellar mass M_s of the two models mentioned above of TDG_s2 (top) and TDG_s3 (bottom). For both setups no difference can be seen in the evolution of the SFR, M_g or M_s which could be attributed to the tidal field. The deviations in the models of TDG_s2, starting at $t_{sim} \approx 600$ Myr, result from different accretion histories of substructures formed in the outskirts of the TDG respectively the tidal arm at distance greater 2.5 kpc (see also Figures 4.2 and 4.3). Also within the density slices of the models `tdg3_iso` and `tdg3_noRam` (compare Figure 4.35 and 4.36) no significant differences can be seen, with the only deviations in regions with particle densities below ~ 0.01 atoms cm^{-3} .

4.5.3 Ram pressure

The effect of ram pressure on the evolution of TDGs can be investigated by comparing models which are either embedded in a static IGM or placed in a wind tunnel like configuration. In both cases the TDGs are exposed to the tidal field. In Figure 4.33 the models `_orb` (black) and `_noRam` (red) of the setups TDG_s2 (top) and TDG_s3 (bottom) are compared. As for the influence of the tidal field, the difference in SFR and gas mass of the setup TDG_s2 are attributed to substructures formed in the close vicinity of the TDG and cannot be directly linked to an environmental effect on the TDG itself.

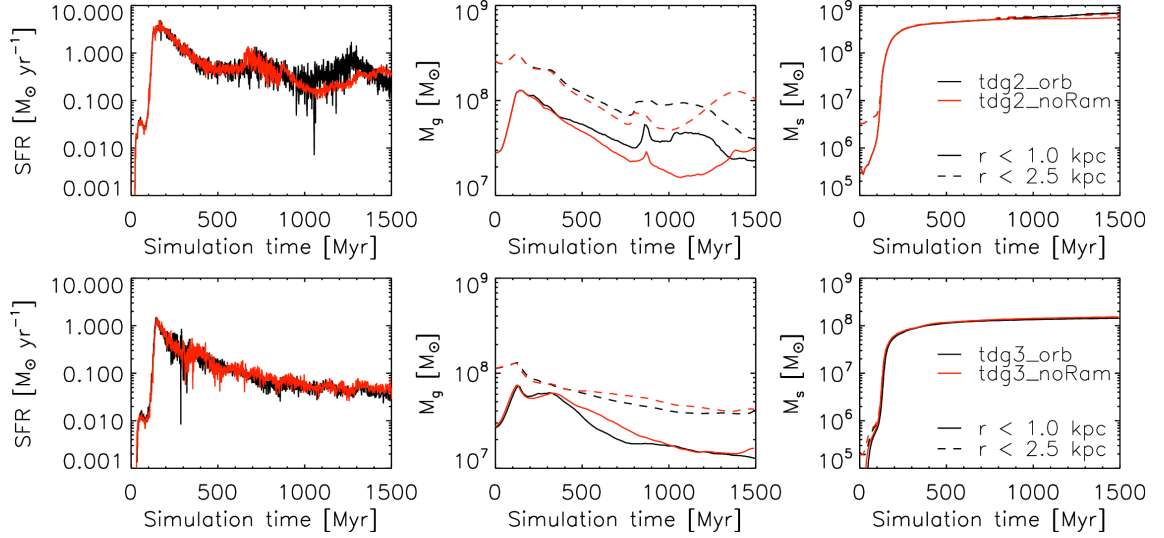


Figure 4.33: Same as Figure 4.32 for the simulation runs exposed to the tidal field with (`_orb`, black) and without (`_noRam`, red) ram pressure, of the setups TDG_s2 (top) and TDG_s3 (bottom).

Both models of TDG_s3 show identical SFR and stellar masses throughout the whole simulation time, differing only in the gas mass starting at $t_{sim} \approx 500$ Myr. At this time, the low density gas from the tidal tail gets pushed away further than 2.5 kpc from the centre and the higher density disk starts feeling the ram pressure, visible in the drop of gas mass within the inner kpc. As the tidal arm itself is also exposed to the ram pressure it gets compressed as well, leading to slightly increased accretion rates, therefore the ram pressure model regains an equal gas mass within 1 kpc of radius until $t_{sim} = 1000$ Myr. The effect of ram pressure on the low density gas surrounding TDG_s3 can be seen in Figure 4.37. The wind caused by the motion of the TDG through the intergalactic medium, pushes the gas from the upwind side around the TDG and strips it away on the lee side ($t_{sim} = 150$ and 300 Myr panels). During this early phase the higher density ($n > 0.1 \text{ atoms cm}^{-3}$) regions of the TDG are not effected by the ram pressure until $t_{sim} \approx 450$ Myr. At this time, the lowest density gas has already been removed and the ram pressure starts acting onto to disk of the TDG, resulting in a stronger confined and shorter gas disk compared to the case without ram pressure (compare to Figure 4.36). Note that the density peak at $z \approx 4$ kpc in the $t_{sim} > 1050$ Myr panels is caused by the compression of the tidal arm and does not belong to the TDG it self. The lopsided appearance of the different models of TDG_s3, as seen in Figure 4.9, is rather an effect of internal dynamics than of ram pressure or the tidal field, as it is present in all three models.

Smith et al. (2013) performed a parametric study of the influence of ram pressure on DM-free TDGs, with wind velocities in the range of $100 < v_{wind}/\text{km s}^{-1} < 800$ and an intergalactic gas density $n_{IGM} = 10^{-4} \text{ H cm}^{-3}$. Reasonably, they found a strong dependency of gas stripping on the wind velocity, where a velocity of 100 km s^{-1} causes $\sim 10\%$ of the gas to be lost and for $v_{wind} = 200 \text{ km s}^{-1}$ typically $10 - 30\%$ at most 50% , for models with low central surface densities, of the gas is striped. Above $\sim 600 \text{ km s}^{-1}$ the gas is almost

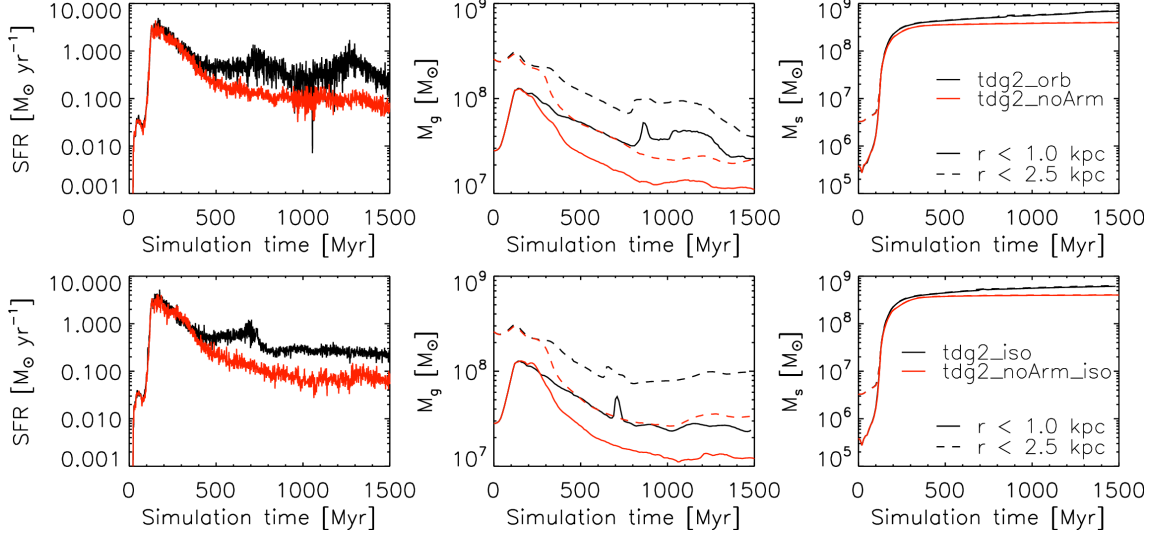


Figure 4.34: Same as Figure 4.32 for simulation runs embedded in the tidal arm (black) and without the density distribution of the arm (red), which are either exposed to the tidal field and ram pressure (top) or none of them (bottom).

instantaneously removed. At $v_{wind} \geq 200 \text{ km s}^{-1}$ they also found a strong effect on the stellar component which forms a stream in the opposite direction of the striped gas. Considering that young TDGs are actually embedded in a tidal arm, which shields the TDGs against the IGM and that the orbital velocities are below 200 km s^{-1} (see bottom right panel of Figure 4.31), it is not surprising that the effect of ram pressure on the evolution of TDGs within the presented simulations is rather small. Another effect which might help to protect the TDGs is the fact that the ram pressure is not acting perpendicular to the disk of the TDGs. Furthermore, an influence of ram pressure on the stellar components is not observed in the presented simulations.

4.5.4 Tidal arm

The strongest environmental impact factor within the presented simulations is the presence respectively absence of the tidal arm, which has not been taken into account in previous numerical studies of TDGs, like those by Smith et al. (2013); Yang et al. (2014); Ploekinger et al. (2014, 2015). Figure 4.34 compares the SFR, gas mass M_g and stellar mass M_s of the models `tdg2_orb` with `tdg2_noArm` and `tdg2_iso` with `tdg2_noArm_iso` in the top respectively bottom row. Initially the models start with the same gas distribution within more than 2.5 kpc from the centre of the TDG and retain equal gas masses for the first $\sim 250 \text{ Myr}$ of the simulations. After the collapse of the proto-cloud, around $t_{sim} \approx 300 \text{ Myr}$, the gas mass of the models without tidal arm declines significantly stronger compared to the models embedded in the tidal arm. This behaviour is caused by the lack of surrounding material which could be accreted by the TDGs. At the final simulation time ($t_{sim} = 1500 \text{ Myr}$) the models with tidal arm retained twice as much gas than those without, within the inner kpc. Going to larger distances the deviations can be

as large as a factor of 3 or 5 for 2.5 and 5 kpc, respectively.

The star formation histories of these models nicely follow the available amount of gas, therefore showing a strong starburst during the cloud collapse followed by a decrease in the SFR as the available gas reservoir gets reduced. The SFR of the models without the tidal arm declines stronger after $t_{sim} \approx 300$ Myr, compared to the embedded models, as their reservoir does not get refilled. This results in a three times higher SFR at the end of the simulations if the tidal arm is included, where the models without arm have final SFRs of about $6 \times 10^{-2} \text{ M}_{\odot} \text{ yr}^{-1}$ and $2 \times 10^{-1} \text{ M}_{\odot} \text{ yr}^{-1}$ if the tidal arm is included. The two models embedded in the tidal arm increase their stellar mass after a simulation time of $t_{sim} \approx 300$ Myr by a factor of roughly 2 until the end of the simulations. Starting from this time the stellar masses of the models without tidal arm are approaching an equilibrium level with only a marginal increase of the stellar mass until the final simulation time.

These characteristics show the importance of the tidal arm during the evolution of TDGs, as the tidal arm provides a rich reservoir of gas available for accretion and subsequent conversion into stars. The accumulation of additional material allows the simulated TDGs to increase their total mass within a radius of 2.5 kpc substantially. The model `tdg2_noRam` grows its mass by a factor of ~ 2.9 , as the maximum value among the simulation runs of `TDG_s2`, whereas `tdg2_noArm`, a model without tidal arm, increases its mass only by 60%. The models of `TDG_s3` grow by a factor of ~ 1.7 (also see Figure 4.2).

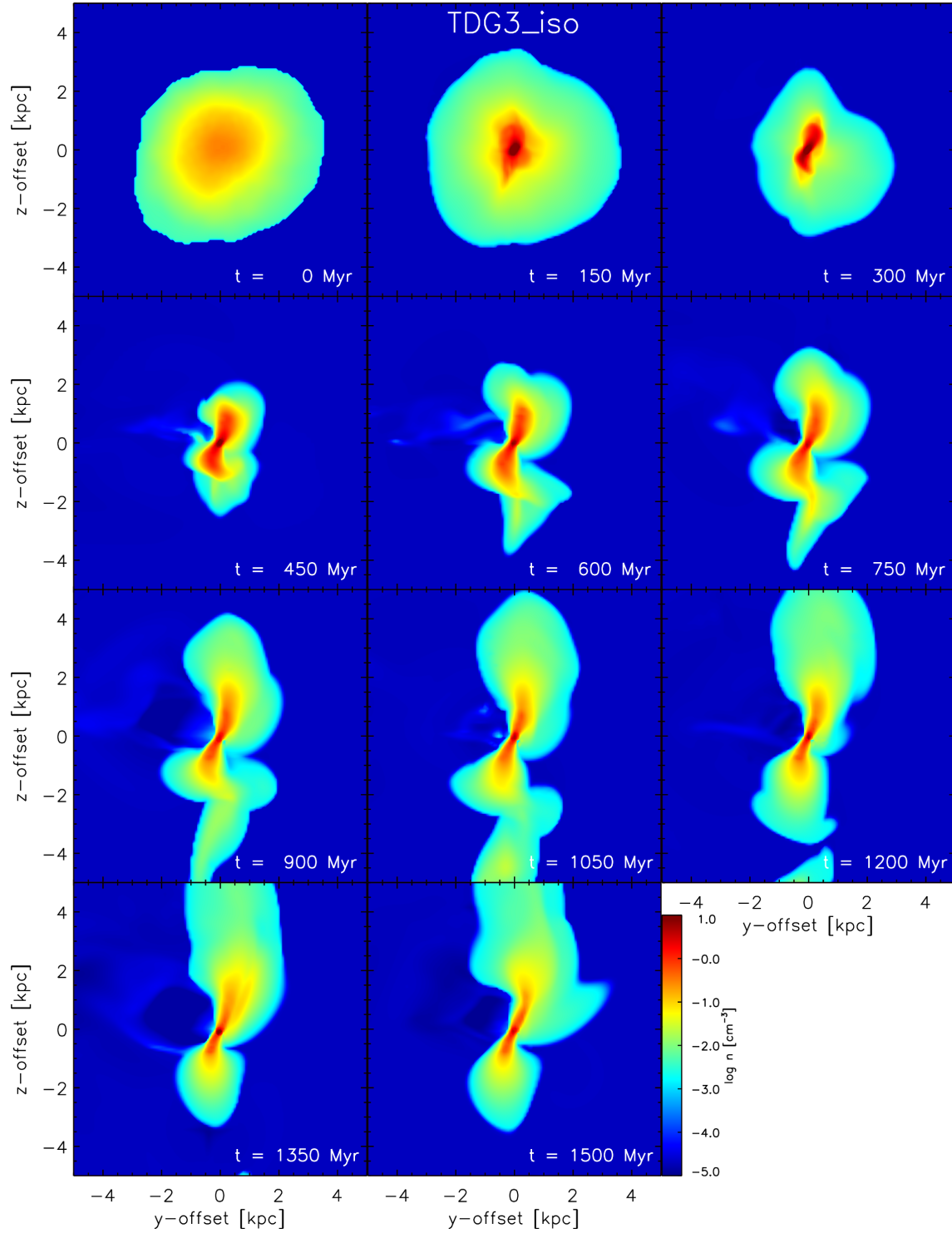


Figure 4.35: Slice through the centre of mass of the simulation run tdg3_iso at different simulation times as indicated on each panel. Colour coded is the particle number density [atoms cm⁻³].

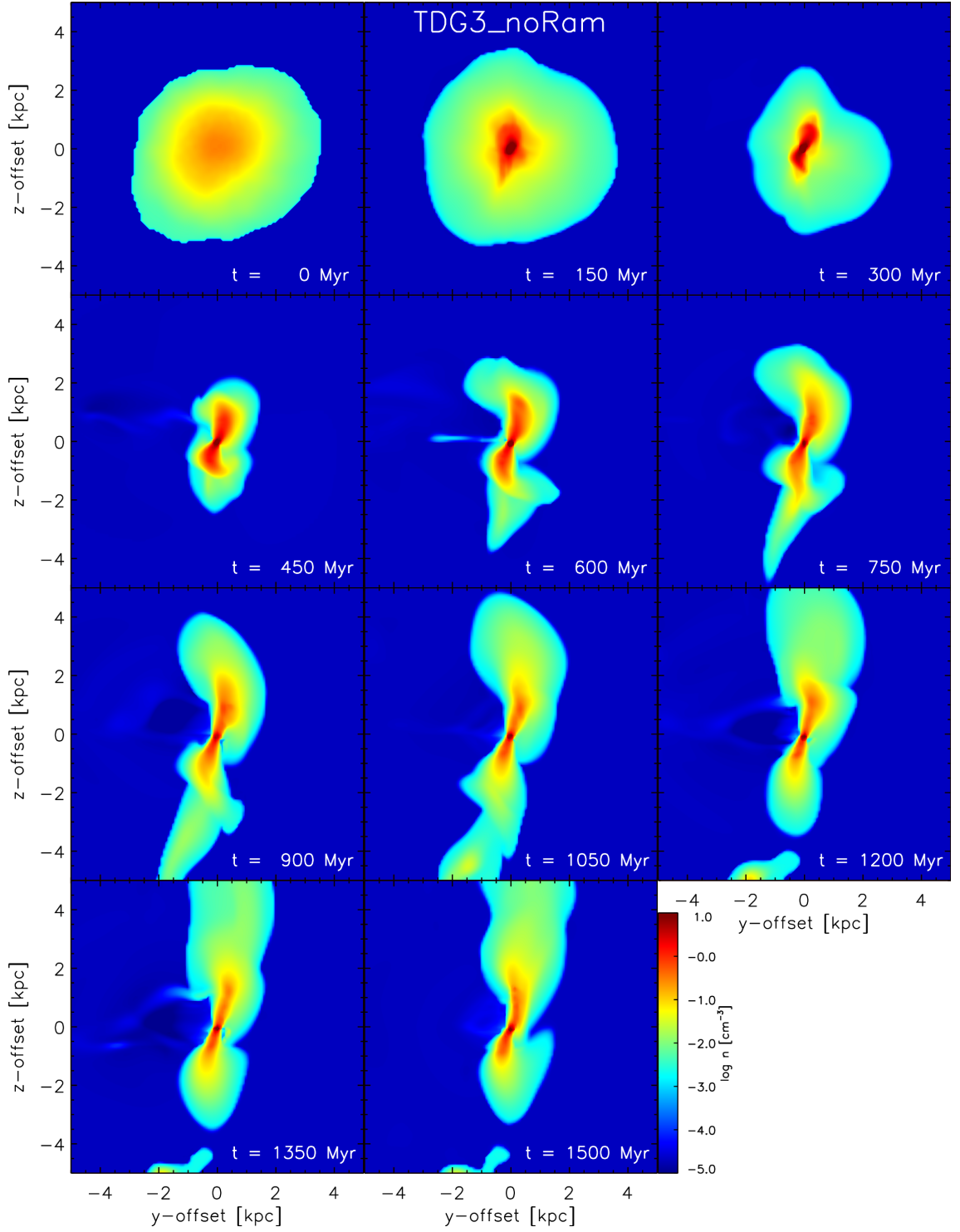


Figure 4.36: Same as Figure 4.35 for the model `tdg3_noRam`.

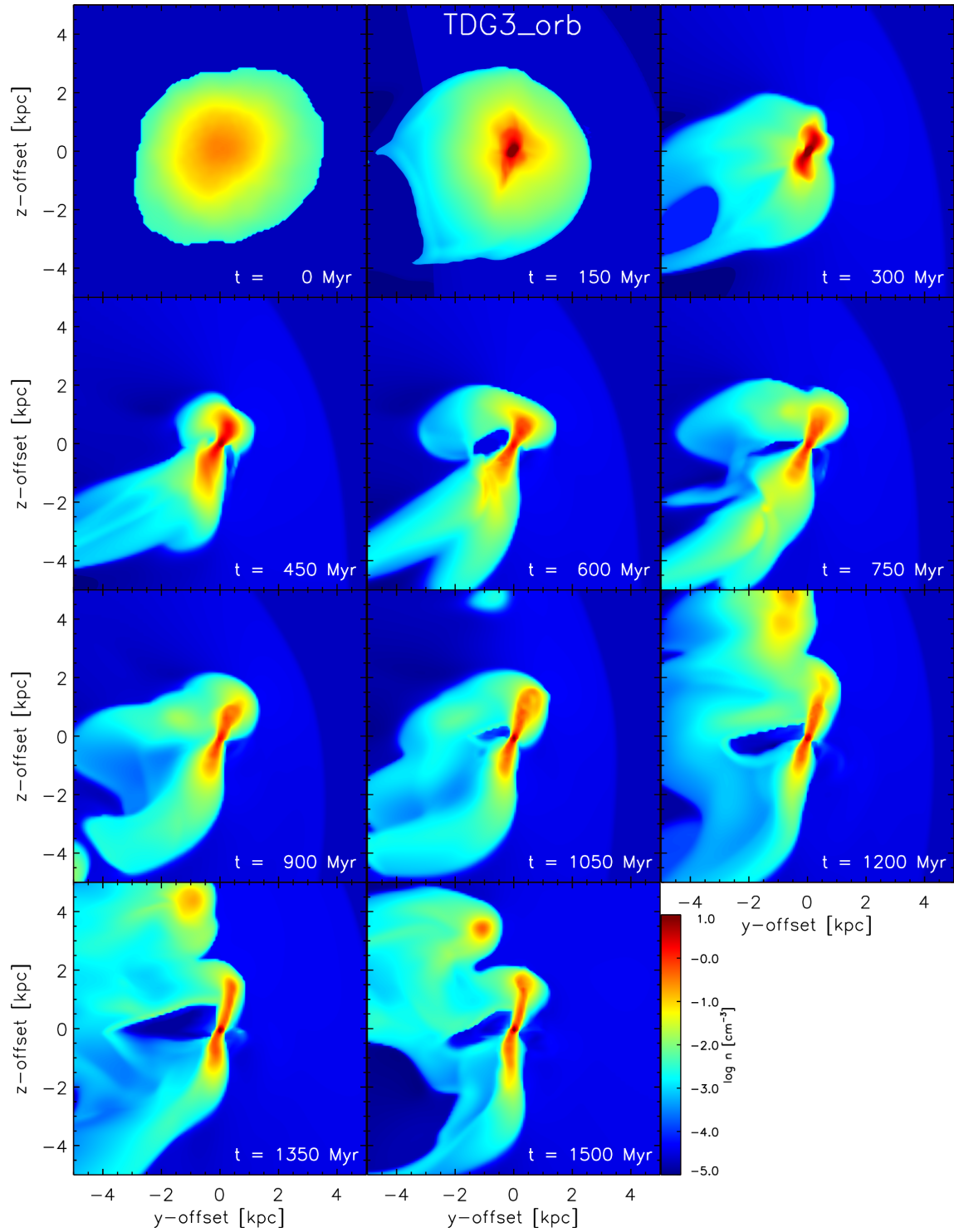


Figure 4.37: Same as Figure 4.35 for the model `tdg3_orb`.

Chapter 5

Discussion

Within this thesis chemodynamical simulations of tidal dwarf galaxies exposed to different combinations of environmental effects are presented. Furthermore, the effect of the tidal arm, in which the TDGs are embedded, is explored, a component previously ignored in detailed numerical studies of TDGs. Studying the impact of these effects on the evolution of TDGs provides new hints to observationally distinguish dwarf galaxies embedded in DM halos and those without. Additionally these simulations help to put further constraints on the survivability of TDGs against a strong initial starburst, the disrupting effects of the tidal field and the removal of gas through ram pressure.

5.1 Star Formation

At first sight the peak SFRs of the simulated TDGs might seem unusually high for low-mass galaxies in general and in particular for TDGs. Which show observationally derived SFRs orders of magnitudes lower than those of the presented simulations, especially within the first ~ 500 Myr of simulation time. For example Duc and Mirabel (1998) derived SFRs, for TDGs around NGC 5291, in the range of 10^{-3} to $\sim 6 \times 10^{-2} \text{ M}_{\odot} \text{ yr}^{-1}$, based on the $\text{H}\alpha$ luminosity, whereas the SFR of the simulated TDGs peak around $\sim 2 \text{ M}_{\odot} \text{ yr}^{-1}$ and decline to values in the range 10^{-2} to $5 \times 10^{-1} \text{ M}_{\odot} \text{ yr}^{-1}$ until the end of the simulations. On the other hand, the star formation histories and distribution of stellar ages appear rather normal for TDGs, considering the formation scenario described by Elmegreen et al. (1993). Within this scenario most of the stars of a TDG are formed during a starburst at the time when itself is formed, followed by a low SFR. Only a minor fraction, no more than 50%, of the stars originate from the parent galaxies.

Considering the short duration of the starburst of the simulated TDGs, it is not surprising that observed TDGs are in general not caught in this phase of massive star formation. The validity of a linear relation between $\text{H}\alpha$ luminosity and SFR, as found by e.g. Kennicutt (1998), is uncertain for galaxies with SFRs below $0.1 \text{ M}_{\odot} \text{ yr}^{-1}$, as the $\text{H}\alpha$ luminosity is expected to flatten for such low SFRs (e.g. Pflamm-Altenburg et al., 2007). Taking this break of the $L_{\text{H}\alpha}$ -SFR relation into account, would indicate that observationally derived

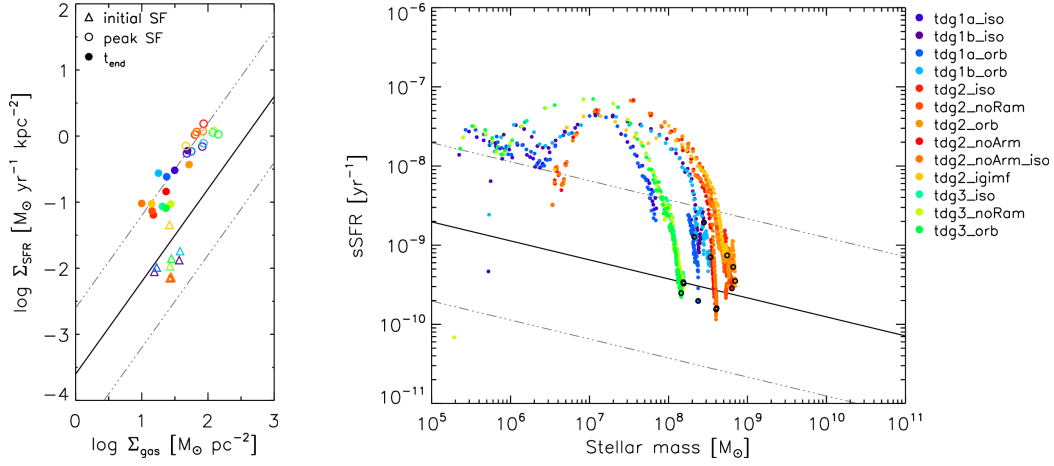


Figure 5.1: Left: Location of TDGs along the Kennicutt-Schmidt law at 3 different simulation times, corresponding to the different SF episodes (initial SF - triangles, peak SF - circles, final SF at t_{end} - filled circles). Right: Location of TDGs along the main sequence of star forming galaxies. The coloured points show the temporal evolution of the different simulation runs along the main sequence and the black circles indicate their locations at the final simulation time. The dot dashed lines in both plots represent a deviation of 1 dex from the relations.

SFR are at most only lower limits on the true SFR of TDGs.

To further investigate how well behaved the SFRs of the simulated TDGs are, the simulations are compared to well known SF related scaling relations. The Kennicutt-Schmidt (KS) law links the SFR per unit surface area to the gas surface density:

$$\Sigma_{\text{SFR}} = A \Sigma_{\text{gas}}^N, \quad (5.1)$$

with $A = 2.5 \times 10^{-4}$ and $N = 1.4$ (Kennicutt, 1998). In the left panel of Figure 5.1 the location of the simulated TDGs along the Kennicutt-Schmidt law for the three different SF episodes is shown. During the initial SF episode all TDGs, except for tdg2_igimf, lie below the KS relation. As the collapse of the proto-TDGs proceeds the gas surface density grows, also Σ_{SFR} increases, shifting the data points to the top right, towards the region of the $\Sigma_{\text{SFR}} - \Sigma_{\text{gas}}$ -diagram which is typically inhabited by starbursting DGs. At the final simulation time t_{end} the gas surface density declined to roughly its initial value but the SFR stays about a factor 10 higher, compared to the initial SFR. For all the considered times the TDGs remain close, within approximately one order of magnitude, to the KS relation.

The right panel of Figure 5.1 shows the main sequence of star forming galaxies, it relates the SFR per unit stellar mass ($\text{sSFR} = \text{SFR}/M_{\star}$) to the stellar mass of a galaxy. Based on a large sample of star forming galaxies, Peng et al. (2010) derived the functional form of the main sequence as:

$$\text{sSFR} = 2.5 \times 10^{-9} \left(\frac{M_{\star}}{10^{10} \text{ M}_{\odot}} \right)^{\beta} \left(\frac{t}{3.5 \text{ Gyr}} \right)^{-2.2} \text{ yr}^{-1}, \quad (5.2)$$

where M_* is the mass of the stellar content of a galaxy, $\beta = -0.24$ (Renzini and Peng, 2015) and t is the considered age of the universe (solid black line, $t = 13.7$ Gyr). The grey dashed lines indicate a scatter of one order of magnitude from the relation, roughly the width of the observationally derived distribution from Peng et al. (2010). The coloured dots show the temporal evolution of the TDGs along the main sequence. During the early evolutionary phases, while the stellar mass is low and the mass of the TDGs is dominated by their gas content, strong deviations can be seen. After most of the stellar mass has been built up the TDGs approach towards the main sequence. Especially the models of TDG_s3, which have formed most of their stellar mass around 500 Myr of simulation time and experience only a minor growth in stellar mass since then, lie particularly close to the observed relation. The models of TDG_s2 show a larger scatter around the sequence, due to their varying accretion history. The models embedded in the tidal arm, which allows them to accrete gas for an extended period of time, are located above it. Opposite to that, the models without the tidal arm lie slightly below the main sequence. This indicates that the main sequence of star forming galaxies is a natural consequence of self regulated star formation, even in the extreme case of young DM-free TDGs. The observed scatter is then related to different evolutionary stages and different accretion histories of individual galaxies.

5.2 IMF description

The comparison of `tdg2_orb` and `tdg2_igimf` highlights the difference and the need for a proper treatment of the IMF, as it influences the evolution of galaxies in several ways. As long as the IMF of single star clusters cannot be filled, and therefore the feedback from high-mass stars (SN II and stellar winds) is suppressed for the IGIMF, its SFR is higher. This higher SFR is caused by the missing preheating from fractional feedback events. This has direct influence on the conversion of gas into stars, especially at the lower density outskirts, where the ISM and the local SF properties are stronger effected by the heating from feedback events. So not only the rate at which gas is converted into stars but also the distribution of SF regions is altered (see Figure 4.27). As soon as the local SFR is high enough to fill the IMF of star clusters, the number of SN II and thus the energy released equals for both descriptions and follows roughly the same spatial distribution. But this is not true for SN Ia, which show a much wider distribution in the IGIMF run (see Figure 4.30), which is caused by the higher SFR in the low density ISM. The galactic outflow of `tdg2_igimf` is therefore not only attributed to the differences of SNe II but also to the distribution of SNe Ia. Despite these differences also the IGIMF run (`tdg2_igimf`) nicely follows the SF related scaling relations, with differences only in the CMF, as more low mass clusters are formed.

Furthermore, the IGIMF description shows indications to also influence the stellar dynamics. Where `tdg2_igimf` shows a lower peak rotation velocity, at a larger distance from the centre. Also the decline of the rotation curve is weaker, with higher rotation velocities at

larger radii compared to `tdg2_orb` (see Figures 4.14 and 4.16).

5.3 Self-regulated star formation recipe

The self-regulated star formation recipe according to KTH95 has proven to be a good approximation for star formation in single-phase ISM simulations. It well reproduces scaling relations of galaxies with stellar context, such as the Kennicutt-Schmidt law and the main sequence of star forming galaxies (left and right panel of Figure 5.1). Furthermore, the slope of the cluster mass function ($\beta \approx 2$) can be derived over a wide range of cluster masses, with some limitations due to additional star formation criteria at the low- and high-mass end (see Figure 4.7). The ability of the recipe to reconstruct these relations is even more remarkable, considering that it is not built upon any relation like those but only depends on the local properties of the ISM. The limiting factor of the CMF at the low-mass end is the threshold on the SBF (Equation 2.33) which might act too aggressive in preventing low mass star clusters in the mass range $100 \lesssim M_{cl}/M_{\odot} \lesssim 500$, as the flattening of the CMF indicates. On the other side of the mass spectrum, the unrealistic peak in the CMF above $\sim 1.9 \times 10^4 M_{\odot}$ is caused by the closing of a star cluster for star formation after it completely filled all IMF mass bins with at least one star. Therefore, more massive star cluster have to build their mass essentially within one or two timesteps, what is much shorter than the allowed cluster formation time $\tau_{cl} = 1$ Myr. This criterion was introduced by Ploekinger et al. (2014) to ensure an early onset of stellar feedback, in order to test the survivability of TDGs against stellar feedback.

5.4 Environmental influences

TDGs are not isolated systems and therefore the influence of their surroundings has to be taken into account. For example Ploekinger et al. (2015) found a strong increase of the SFR of TDGs after the apocentre passage and an additional but weaker peak close to the pericentre. Both enhancements cannot be seen in the presented simulations, as during the covered simulation time spans neither the apo- nor the pericentre of the different setups is passed. A clear influence of the tidal field and ram pressure on the simulated TDGs is not present. This is mostly attributed to the location of the TDGs along their orbits, approaching their apocentres, but still remaining far from it, with declining velocities. As the velocities get smaller the ram pressure, which is proportional to the square of the velocity, decreases. By comparing the gas mass of `tdg2_noRam` and `tdg2_orb` (1.04 and $0.94 \times 10^8 M_{\odot}$, respectively) one might conclude that $\sim 10\%$ of gas from `tdg2_orb` is striped away by ram pressure, but this difference is caused by the detailed mass assembly history of these TDGs rather than by ram pressure. Also the tidal field weakens with increasing distance from the host galaxy of the TDGs.

The apparently largest environmental impact factor on the evolution of TDGs is the presence of the huge gas reservoir provided in the form of the tidal arm. This is, for the

first time, included in the detailed numerical study of TDGs presented within this thesis. During the initial collapse the tidal arm does not show a direct influence on the initial mass build up or the starburst. But as time proceeds and the starburst subsides, the presence of the tidal arm becomes significant, as it provides an additional reservoir of gas from which the TDGs are fed. Therefore, the embedded models are able to build up roughly twice the stellar mass and at the same time they are able to retain a higher gas mass. Furthermore, their SFRs are about three to four times higher at the final simulation time compared to the models without tidal arm. The shielding of TDGs against RPS provides another possible way how the tidal arm can influence the evolution of TDGs. This shielding might help the TDGs to retain higher gas masses, as the ram pressure needs to remove the arm first before it can act on the TDG itself. Therefore, the TDGs have more time to accumulate and bind mass to them, what in turn deepens their gravitational potential and helps them to withstand the tidal field of their host galaxy. Further investigations are needed in order to quantify the relevance and strength of the different effects.

5.5 Distinguishing primordial DGs from TDGs

TDGs are by nature DM-free and are therefore supposed to have a shallower gravitational potential well. The absence of DM should in principle be reflected in some of their structural and dynamical properties. Also the metallicities of TDGs, at least of those formed from significantly pre-enriched material, is subject of deviations from the standard MZ-relation of dwarf galaxies.

5.5.1 Structural differences

According to Dabringhausen and Kroupa (2013) TDGs are indistinguishable from primordial DGs based on their location along the MR-relation. Whereas, Duc et al. (2014) found effective radii of 1.8 and 2.3 kpc for the oldest confirmed TDGs around the ETG NGC 5557. These values are roughly one order of magnitude larger than the derived half-light radii of the simulated TDGs studied within this thesis. Figure 5.2 compares the locations of the simulated TDGs along the MR-relation to the observationally derived relations for Es and dEs. Giant Es lie along a common MR-relation with globular clusters (GC) and ultra-compact dwarfs (UCD), dEs constitute a separated relation (both indicated by dashed lines). The simulated TDGs presented within this thesis follow the relation of Es and UCD, with half-light radii between 80 and 500 pc. For comparison the half-light radii of UCDs are typically below 100 pc (e.g. Mieske et al., 2012), thus the most compact objects presented (the models of TDG_s3) fall in the regime of the largest UCDs. But they still contain about 20% gas, assuming a slow removal of gas the half-light radii would further increase. According to Kroupa (2008) this expansion can be estimated by

$$r_f = r_i \times \frac{M_i}{M_f}, \quad (5.3)$$

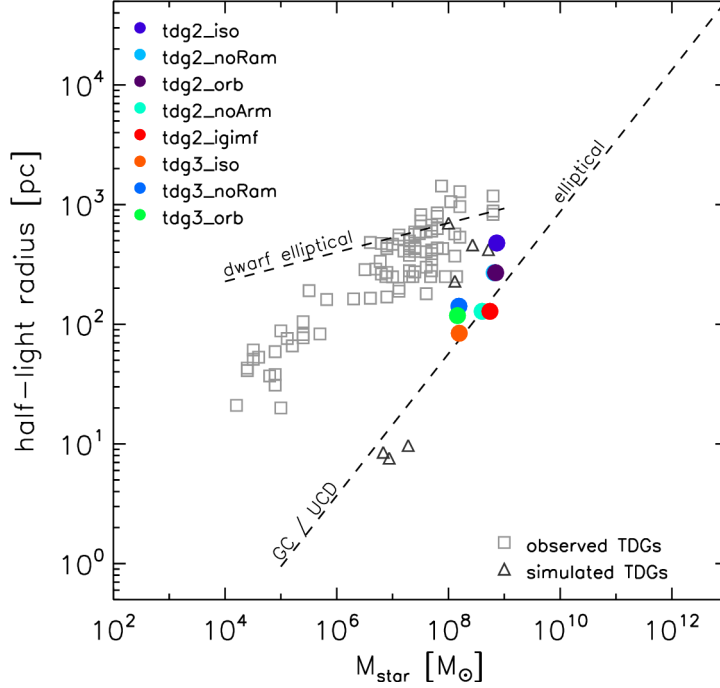


Figure 5.2: Mass-radius relation of simulated TDGs (coloured points). The dashed lines indicate the mass-radius relations for dEs and giant Es, which share the same relation as globular clusters (GC) and ultra compact dwarf galaxies (UCD). The grey squares indicate the locations of observed TDGs and the black triangles previous simulations of TDGs. Both data sets were compiled by Dabringhausen and Kroupa (2013).

where r_f and r_i are the half-light radii after and before the removal of gas and M_i and M_f are the corresponding masses. Assuming r_i is the half-light radius, M_i is the total mass and $M_f = M_*$, all at the final simulation time, then for $f_g \approx 20\%$ the final radius is approximately 25% larger than r_i . This increase of the half-light radius would result in a small shift from the MR-relation of Es towards the relation of dEs, but still remain smaller than the Duc et al. (2014) values for NGC 5557-E1 and E2.

5.5.2 Metallicity

The gas phase metallicity is assumed to be the most reliable way to distinguish between primordial DGs and TDGs. TDGs show an offset along the MZ-relation, as a result of the formation out of already pre-processed material, which was already enriched with metals prior to the TDG forming interaction. This is true for young TDGs where the host galaxies had sufficient time to enrich their ISM. Old TDGs, i.e. those formed in the early universe, form out of less enriched material and therefore the self-enrichment during their evolution becomes more important. These TDGs are expected to lie along the MZ-relation of DGs (e.g. Recchi et al., 2015). Figure 5.3 shows the gas phase MZ-relation of primordial DGs (squares), TDGs in general and particularly the simulated TDGs show a significant offset from this relation. Simplified chemodynamical evolution model of TDGs (Recchi et al., 2015) predict $8.2 \lesssim 12 + \log(\text{O}/\text{H}) \lesssim 8.8$ for $7 < \log(M_*/M_\odot) < 9$ and initial metallicities of $Z = 0.1 - 0.5 Z_\odot$ after three billion years of evolution. Compared to the observed

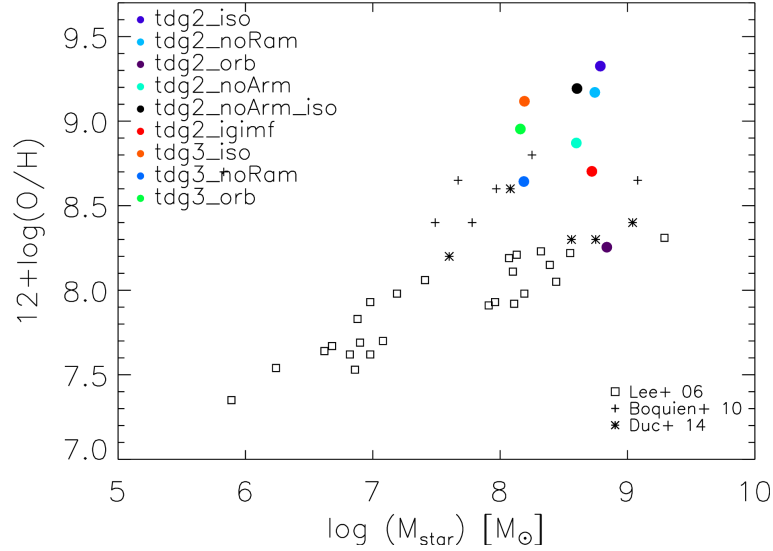


Figure 5.3: Mass-metallicity relation of simulated TDGs (coloured points). For comparison local DGs are shown as black squares (Lee et al., 2006) and observed TDGs from Boquien et al. (2010) as plus and Duc et al. (2014) as asterisk.

TDGs and the simplified model, the simulations presented within this thesis show a much stronger offset from the relation, with $12 + \log(\text{O}/\text{H})$ reaching values up to ~ 9.3 . This deviation might be explained by the used filled IMF description as standard model. Within this description the IMF of a single stellar particles is always completely filled, even with fractions of stars (see Section 2.6.2), therefore also fractions of SN II occur, which provide an additional source of oxygen compared to the IGIMF description. Also the gas phase metallicity of `tdg2.igimf` ($12 + \log(\text{O}/\text{H}) = 8.7$) lies in the expected range, this further indicates that the discrepancy between the observations and simulations is in part related to the IMF description.

Peeples et al. (2008) reported about 41 outliers from the MZ-relation in the mass range $7.4 < \log(M/M_\odot) < 10.0$, i.e. in the mass range of DGs, which are fairly isolated. These galaxies, with $8.6 < 12 + \log(\text{O}/\text{H}) < 9.3$, have similar abundances as the simulated TDGs presented within this thesis, making them potential TDG candidates which have dissolved from their parent galaxies.

5.5.3 Dynamics

Three TDGs in NGC 5291 have been widely studied in the literature with varying results concerning their mass content and dynamical state. For example Bournaud et al. (2007) found raising rotation curves, similar to those of primordial DGs, and concluded that these TDGs are virialized. To explain the rotation velocities and shapes of the rotation curves, they proposed that these TDGs contain an additional but unseen baryonic mass component. The amount of this baryonic DM would be twice as much as the visible matter of the TDGs and is most likely composed out of cold molecular gas. Whereas, Gentile et al. (2007) showed that their dynamics can be described without the need of any dark

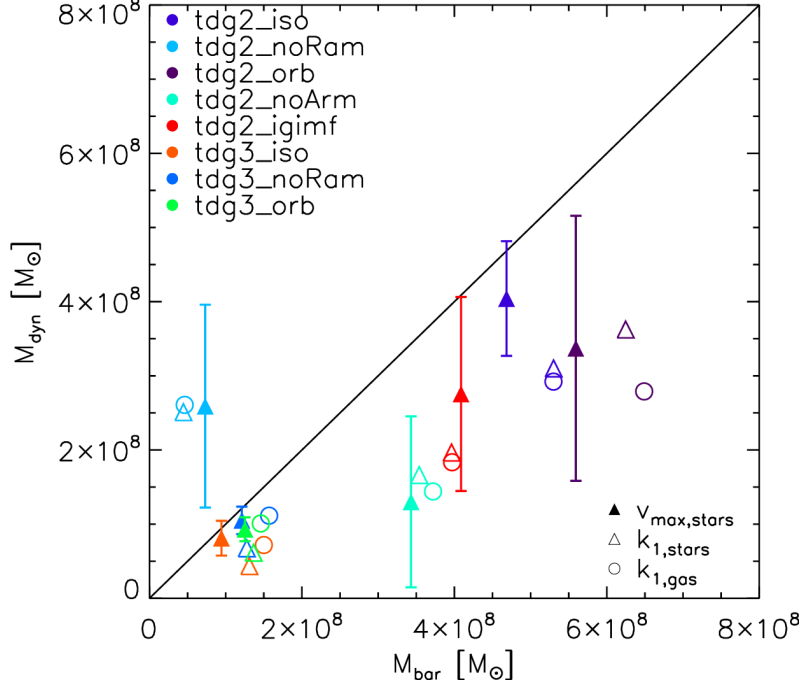


Figure 5.4: Baryonic and dynamic masses of simulated TDGs within the radius where the rotational velocity peaks. The different symbols correspond to different methods to derive the rotational velocity or galaxy components. Open symbols correspond to $k_{1,max}$, according to Section 4.3.4, where triangles and circles represent the stellar and gaseous component, respectively. The filled triangles correspond to the maximal rotational velocity of stars v_{max} (Section 4.3.1). The error bars are based on the standard deviation of the rotational velocity and the black line indicates the equality of the baryonic and dynamical mass.

component by applying modified Newtonian dynamics (MOND). Recent observations from Flores et al. (2016) argue against the need of unseen baryonic matter or MOND. Their high resolution 3D spectroscopic data indicate lower rotation velocities than the previous data. Also Flores et al. argue that these TDGs cannot be considered as virialized rotating disks as they significantly deviate from the baryonic Tully-Fischer relation.

Figure 5.4 compares the baryonic to the dynamical mass of the simulated TDGs. The dynamical mass for a spherical mass distribution and circular orbits can be estimated by

$$M_{dyn} = \frac{r(v^2 + \sigma^2)}{G}, \quad (5.4)$$

where G is the gravitation constant, r is the radius where the velocity v reaches its maximum and σ is the velocity dispersion (e.g. Bournaud et al., 2007). For comparison M_{dyn} is once calculated for the maximal rotation velocity of stars v_{max} with the velocity dispersion perpendicular to the galactic plane σ_z and twice using the dynamical results from the KINEMETRY-analysis k_1 and $\bar{\sigma}$ from the line-of-sight velocity maps, once for the gaseous and once for the stellar component. The error bars on the dynamical mass related to v_{max} are based on the standard deviation of the rotational velocity. Although the large-scale mass distribution of the simulated TDGs is not spherical the estimate according to Equation 5.4 is used without corrections for the shape, as within the small peak radii the

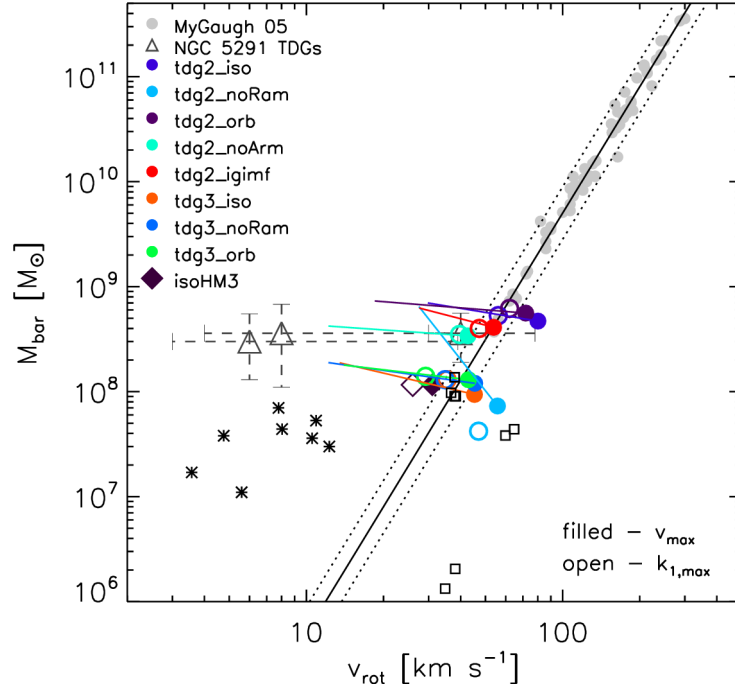


Figure 5.5: The black lines indicate the baryonic Tully-Fischer relation of local galaxies (solid line) and its 1σ deviation (dotted line) as derived from McGaugh et al. (2000) with the data points from McGaugh (2005) as grey dots. The dark grey triangles mark the position of 3 TDGs in the NGC 5291 system with their associated measurement errors (Flores et al., 2016). The coloured points show the locations of the simulated TDGs at their final simulation time. Filled symbols correspond to the maximal rotation velocity and the open symbols to the maximal value of k_1 . The black asterisks and squares show the locations at $t_{sim} = 100$ and 300 Myr, respectively. For comparison the results of a simulation of an isolated dwarf galaxy from Steyrleithner (2015, isoHM3 model) are shown as purple diamonds. The coloured lines indicate the locations of the TDGs in case the maximal velocity cannot be resolved, for illustration the values of v_{rot} and M_{bar} at $r = 2.0$ kpc are used.

difference is considered to be only marginal. The corresponding values for the velocity, velocity dispersion, peak radii and masses can be found in Tables A.4 and A.5. Almost all TDGs lie below the equal-mass line, with the models of TDG.s3 being particularly close to it. These TDGs have a rather quiet evolution, with gas accretion only within the first 500 Myr of the simulations, and are therefore the most relaxed systems. The other extreme tdg2_noRam, which is interacting with a close companion that has not yet been accreted, shows a strong mismatch between the dynamical and the systems baryonic mass.

The central peak velocity of the gaseous component might not be resolved on kinematic maps with lower resolution, this possibly leads to a misinterpretation of its extent and subsequently a wrong estimate of M_{dyn} . For example tdg3_orb has $M_{dyn} \approx 10^8 M_\odot$ based on the central peak velocity, but for $k_{1,max}$ along the x-line-of-sight at $r = 4.4$ kpc (see Figure 4.21) the dynamical mass becomes ~ 16 times higher. This would imply that tdg3_orb is suggested to be highly DM dominated. In general the M_{dyn} estimates for the central peak velocities and the worst combination of $k_{1,max}$ and r vary by factors of 3 to 6. This wrong dynamical mass estimate would place all the simulated TDGs, which are intrinsically free from DM, in the regime of DM dominated dwarf galaxies.

The Tully-Fischer (TF) relation links a galaxies luminosity to its rotational velocity and as such the luminous to the total mass ($M_{gas} + M_{\star} + M_{DM}$). It is commonly used as distance indicator for disk galaxies based on their apparent luminosity and rotation velocity (Tully and Fisher, 1977). For low mass galaxies the classical TF relation breaks, but the simple relation can be restored by considering the total baryonic mass instead of the luminous mass, i.e. the sum of the stellar and gas mass instead of just the stellar mass. The resulting relation is called baryonic Tully-Fischer (bTF) relation. Its existence and small scatter require a considerable strong fine tuning of the amount of DM and its distribution within all disk galaxies (e.g. McGaugh et al., 2000). Figure 5.5 shows the location of the simulated TDGs (filled coloured circles for $t_{sim} = t_{end}$) along the bTF relation of local galaxies. The grey triangles show the three TDGs in the NGC 5291 system, based on which Flores et al. (2016) concluded that TDGs cannot be used to probe DM in galaxies. The filled and open circles correspond to the different analysis methods, i.e. the maximal rotational velocity v_{max} according to Section 4.3.1 and the maximum of k_1 , described in Section 4.3.4, respectively. For comparison the results of a simulated isolated dwarf galaxy, embedded in a DM halo, from Steyrleithner (2015, isoHM3 model) are shown as dark purple diamonds. At early simulation times, when the TDGs evolution is dominated by the collapse of the gas cloud, only little, if any, signs of rotation can be seen in their rotation curves (see Figures 4.12 - 4.19). At this evolutionary stage the TDGs significantly deviate from the bTF relation towards lower velocities, indicated by black asterisks for $t_{sim} = 100$ Myr. Depending on the details of their further evolution, i.e. gas accretion or disturbance by super star cluster, the TDGs can either rapidly transform into virialized systems or continue to lie off the relation (black squares, $t_{sim} = 300$ Myr). The simulation runs of TDG_s3 are quickly reaching an equilibrium and follow the bTF relation already after 300 Myr. Opposite to that the models of TDG_s2, which show a more violent evolution, remain off the relation. Despite their lack of DM all the simulated TDGs lie close (within 3σ) to the bTF relation at their final simulation time, except for the disturbed TDG - tdg2_noRam.

The interaction of tdg2_noRam with its companion causes a redistribution of mass from the central region to form the tidal arm like feature, whereas the stellar velocities are only weakly altered. Therefore, the dynamical mass is over estimated and tdg2_noRam is shifted above the equality line in the $M_{bar} - M_{dyn}$ plot. This relocation of mass, due to the interaction, also explains the location along the bTF relation, where this TDG seems to fall off the relation. Neither very young TDGs, which are in an evolutionary state that is dominated by the collapse of the proto-cloud, nor young TDGs with ages of 300 Myr, roughly the age of the TDGs around NGC 5291 (360 Myr, Bournaud et al., 2007) can unambiguously be used to probe DM or modified gravitational laws.

The location close to the bTF relation at the end of the simulations generally questions the need or importance of DM on the dynamics of disk galaxies. Especially if the strong restrictions on the amount and distribution of DM are taken into consideration, as they are required by the bTF relation.

5.6 Counter rotating stars and KDCs in TDGs

In contrast to earlier studies, like those of Ploekinger et al. (2014, 2015), the presented simulations do not start from idealised initial conditions. Therefore, the distributions of the hydrodynamic quantities, such as density or temperature, are not forced to follow a predefined mathematical distribution, also a rotation law is not enforced. This results in a collapse of the proto-TDGs at early simulation times, with high SFRs. During the collapse phase the formed star clusters can be captured on arbitrary orbits around the mass centre, as the gas distribution was not forced to rotate in a predefined manner. As a result star clusters are captured with angular momentum directions differing by more than 90° from the total angular momentum direction of the TDGs, these star clusters are taken into account as counter rotating. Considering the number of star clusters within 2.5 kpc a significant fraction of 10 – 20% are on counter rotating orbits. If only the star clusters within $r_{v_{max}}$, the radius at which the rotation curve peaks, is considered, the fraction of counter rotating stars is rising to 25 – 45%. In the exceptional case of `tdg2_iso` the contribution of the different rotating populations is almost equal, with 50.4% of the star clusters having angular momentum directions inclined by more than 90° with respect to the total angular momentum. But still the positive rotation direction appears to be the more luminous one, as in the luminosity weighted rotation curve (Figure 4.12) a CRC can not be seen.

A KDC similar to those observed by Toloba et al. (2014) in the dEs VCC 1183 and VCC 1453, where the KDC is several Gyrs younger and more metal-rich than the main body of the galaxy, cannot be seen in the simulations. For this kind of KDC a much larger number of initial star clusters, formed in the merging galaxies, before the interaction started, is required. Also these old clusters have to be numerous enough to be able to outshine the newly formed clusters, which contain bright O and B stars, in the outskirts of the TDGs. Within the presented simulations the preexisting clusters are equally contributing to both rotation directions, an issue that might also be attributed to their low number.

Although no dominant KDC was formed in the presented simulations, the theory at test cannot be ruled out, as only three of the nearly infinite possible initial conditions have been examined. Furthermore, an additional possibility arises from the performed simulations, where KDCs might result from inhomogeneous gas distributions in collapsing entities. A larger set of simulations, with a wider range of initial conditions, preferably from different merger geometries, would be required to put further constraints on the theory and to answer the question:

*Are Tidal Dwarf Galaxies the birth sites of
kinematically decoupled cores in Dwarf Galaxies?*

Chapter 6

Outlook

One of the selection criteria for the TDG models was motivated by the definition of TDGs proposed by Duc et al. (2004), i.e. an object formed within a tidal arm has to have a minimal mass of $10^8 M_{\odot}$, in order to be classified as TDG. Therefore, the models presented within the thesis have initial gas masses between 9×10^7 and $3 \times 10^8 M_{\odot}$. Due to the strong accretion of material along the tidal arm, these models increase their total mass by a factor of roughly two to three during their evolution.

But both observations and simulations of interacting galaxies and their extended arms show that also objects less massive are commonly formed within the tidal arms, such as super star clusters with typical masses above $10^6 M_{\odot}$.

In order to extend the variety of the models and the range of validity of the results, the restriction on the lower mass limit should be loosened for future studies on embedded TDGs. Assuming an increase of mass during the evolution of TDGs of up to an order of magnitude, then the lower mass limit should not be higher than $10^7 M_{\odot}$. This strong increase of mass appears realistic for TDG candidates located close to the base of the tidal arm, where the width of the arm is larger and the densities are higher.

Appendix A

Summery of model properties

Tables A.1 - A.5 summarises the model properties presented in Chapter 4 and discussed in Chapter 5 at their final simulation time t_{end} . A list of the initial properties and run time parameters of the different models can be found in Tables 3.1 and 3.2.

Table A.1: Mass budget - Column 1: Simulation run identifier; Column 2: Final simulation time; Columns 3-4: Gas and stellar mass (M_{gas} & $M_{\star}$) within $r = 2.5$ kpc around the centre of the TDG; Column 5: Gas fraction $f_{gas} = M_{gas}/(M_{gas} + M_{\star})$; Columns 6-7: Star formation rate at the final simulation time ($SFR(t_{end})$) and its maximum value (SFR_{peak}); Column 8: Slope of the CMF β_{CMF} .

Simulation run	t_{end} [Myr]	M_{gas} [$10^8 M_{\odot}$]	$M_{\star}$ [$10^8 M_{\odot}$]	f_{gas}	$SFR(t_{end})$ [$M_{\odot} \text{ yr}^{-1}$]	SFR_{peak} [$M_{\odot} \text{ yr}^{-1}$]	β_{CMF}
tdg1a_iso	650	0.76	2.11	0.26	0.269	1.32	1.79 ± 0.07
tdg1b_iso	650	1.10	2.81	0.28	0.544	2.09	2.14 ± 0.07
tdg1a_orb	1030	0.27	2.38	0.10	0.047	1.13	2.20 ± 0.12
tdg1b_orb	1030	0.66	3.41	0.16	0.240	2.00	1.66 ± 0.13
tdg2_iso	1500	0.98	7.32	0.12	0.180	3.46	1.93 ± 0.09
tdg2_noRam	1500	1.04	6.60	0.14	0.350	3.55	1.91 ± 0.08
tdg2_orb	1500	0.39	7.00	0.05	0.212	3.57	1.75 ± 0.08
tdg2_noArm	1500	0.23	4.01	0.05	0.062	2.96	1.86 ± 0.08
tdg2_noArm_iso	1500	0.34	4.07	0.08	0.065	2.95	1.88 ± 0.10
tdg2_igimf	700	0.95	5.53	0.15	0.411	3.25	2.26 ± 0.03
tdg2_sf1	500	—	—	—	0.435	4.33	—
tdg2_sf2	500	—	—	—	0.431	4.58	—
tdg3_iso	1500	0.41	1.56	0.21	0.051	1.22	1.91 ± 0.14
tdg3_noRam	1500	0.42	1.54	0.21	0.052	1.23	2.04 ± 0.11
tdg3_orb	1500	0.42	1.45	0.22	0.036	1.27	1.98 ± 0.25

Table A.2: Stellar luminosity - Column 1: Simulation run identifier; Column 2: Effective radius r_e ; Column 3: Central surface luminosity Σ_0 ; Column 4: Total luminosity L_{tot} ; Column 5: Sérsic index n ; Column 6: Ellipticity ε . All values are derived at the final simulation time as listed in Table A.1

Simulation run	r_e [pc]	Σ_0 [$L_\odot \text{ pc}^{-2}$]	L_{tot} [$10^4 L_\odot$]	Sérsic index	ε
tdg1a_iso	1080.0	0.011	2.15	1.70	—
tdg1b_iso	388.3	0.142	5.69	0.30	—
tdg1a_orb	649.0	0.009	1.57	0.96	—
tdg1b_orb	235.3	0.306	4.87	0.95	—
tdg2_iso	477.5	0.341	9.13	1.99	0.41
tdg2_noRam	269.5	0.423	10.96	1.89	0.50
tdg2_orb	269.5	0.433	6.68	1.36	0.30
tdg2_noArm	128.2	1.731	6.10	2.11	0.64
tdg2_igimf	128.2	13.320	46.06	3.99	0.64
tdg3_iso	84.1	2.877	6.49	2.24	0.39
tdg3_noRam	141.5	1.510	5.38	2.60	0.37
tdg3_orb	118.1	1.215	4.25	1.71	0.53

Table A.3: Metallicity - Column 1: Simulation run identifier; Column 2-4: Stellar [O/H], [Fe/H] and [O/Fe] abundance ratio; Column 5-8: Gas phase abundance ratios ([N/H], [O/H], [Fe/H]) and $12+\log(\text{O/H})$. All values are derived at the final simulation time as listed in Table A.1.

Simulation run	Stars			Gas			
	[O/H]	[Fe/H]	[O/Fe]	[N/H]	[O/H]	[Fe/H]	$12+\log(\text{O/H})$
tdg2_iso	0.382	0.481	-0.099	0.854	0.632	3.698	9.326
tdg2_noRam	0.388	0.501	-0.112	0.624	0.477	3.754	9.170
tdg2_orb	0.195	0.138	0.058	-0.489	-0.439	3.800	8.255
tdg2_noArm	0.477	0.443	0.034	0.313	0.177	3.767	8.871
tdg2_noArm_iso	0.527	0.518	0.009	0.703	0.500	3.840	9.193
tdg2_igimf	0.333	0.225	0.108	-0.223	0.010	3.463	8.703
tdg3_iso	0.125	0.370	-0.245	0.479	0.424	3.593	9.118
tdg3_noRam	0.145	0.369	-0.224	0.067	-0.051	3.821	8.643
tdg3_orb	0.186	0.390	-0.204	0.475	0.260	3.942	8.954

Table A.4: Stellar dynamical properties - Column 1: Simulation run identifier; Column 2: Maximal rotation velocity v_{max} ; Column 3: Velocity dispersion σ_z perpendicular to the plane of rotation at $r_{v_{max}}$; Column 4: Radius where v_{max} is reached; Column 5: Baryonic mass within $r_{v_{max}}$; Column 6: Dynamical mass within $r_{v_{max}}$; Column 7: Maximum value of $k_{1,max}$; Column 8: Average line-of-sight velocity dispersion $\bar{\sigma}$ within $r_{k_{1,max}}$; Column 9: Radius where $k_{1,max}$ is reached; Column 10: Baryonic mass within $r_{k_{1,max}}$; Column 11: Dynamical mass within $r_{k_{1,max}}$; All values are derived at the final simulation time as listed in Table A.1

Simulation run	v_{max} [km s $^{-1}$]	σ_z [km s $^{-1}$]	$r_{v_{max}}$ [pc]	$M_{bar,v_{max}}$ [$10^8 M_\odot$]	$M_{dyn,v_{max}}$ [$10^8 M_\odot$]	$k_{1,max}$ [km s $^{-1}$]	$\bar{\sigma}$ [km s $^{-1}$]	$r_{k_{1,max}}$ [pc]	M_{bar,k_1} [$10^8 M_\odot$]	M_{dyn,k_1} [$10^8 M_\odot$]
tdg2_iso	71.8	45.8	200	5.59	3.37	62.1	43.1	273	6.25	3.63
tdg2_noRam	55.7	24.8	300	0.73	2.59	47.0	41.8	273	0.44	2.51
tdg2_orb	80.1	23.3	250	4.68	4.04	56.1	29.9	330	5.30	3.10
tdg2_noArm	42.7	20.4	250	3.43	1.30	39.6	36.2	273	3.54	1.66
tdg2_igimf	53.8	22.2	350	4.09	2.76	47.3	35.8	330	3.96	1.97
tdg3_iso	42.9	12.8	200	1.23	0.93	29.2	22.0	273	1.37	0.61
tdg3_noRam	45.4	14.1	200	1.21	1.05	34.8	25.9	216	1.28	0.67
tdg3_orb	45.3	16.5	150	0.94	0.81	35.4	20.8	216	1.31	0.43

APPENDIX A. SUMMERY OF MODEL PROPERTIES

Table A.5: Gas dynamical properties - Column 1: Simulation run identifier; Column 2: Maximal rotation velocity $k_{1,max}$; Column 3: Radius where $k_{1,max}$ is reached; Column 4: Baryonic mass within $r_{k_{1,max}}$; Column 5: Dynamical mass within $r_{k_{1,max}}$. All values are derived at the final simulation time as listed in Table A.1

Simulation run	$k_{1,max}$ [km s ⁻¹]	$r_{k_{1,max}}$ [pc]	M_{bar,k_1} [10 ⁸ M _⊙]	M_{dyn,k_1} [10 ⁸ M _⊙]
tdg2_iso	58.6	328	5.30	2.92
tdg2_noRam	42.9	501	0.46	2.61
tdg2_orb	57.1	328	6.49	2.79
tdg2_noArm	38.6	328	3.72	1.44
tdg2_igimf	44.8	328	3.97	1.83
tdg3_iso	23.3	328	1.50	0.72
tdg3_noRam	23.6	501	1.57	1.11
tdg3_orb	21.6	501	1.46	1.01

Abstract English

The term kinematically decoupled cores (KDC) refers to dynamical substructures at the centres of galaxies, which can be present in various different forms like counter rotating cores or kinematic twists. The most commonly discussed formation scenarios involve gravitational interaction between galaxies, like repeated close encounters or the merging of two galaxies. These scenarios have been found to describe the properties of luminous early type galaxies with KDCs reasonably well. It is far from obvious that the same processes cause the formation of KDCs in dwarf elliptical galaxies (dEs), especially in galaxy clusters, where the majority of dEs can be found. As due to the high velocity dispersion within galaxy clusters, the time span for gravitational interactions is too short in order to transfer a sufficient amount of angular momentum and significantly change their dynamics. It would be possible that KDCs in dEs are formed in groups of galaxies where the relative velocities are smaller and thus the gravitational interaction got more time to act on the dwarf galaxies. These KDC hosting dwarfs, as well as the whole galaxy group, could subsequently fall into the gravitational potential of a cluster.

In this thesis a novel theory for the formation of KDCs in the framework of tidal dwarf galaxies (TDGs) is investigated. Within this hypothesis the main body of the KDC harbouring TDG is constituted of old stars expelled of the parent galaxies. Whereas, the in situ formed stars, which receive their dynamics from the collapsing gas, form the counter rotating core.

For the first time numerical zoom-in simulations of TDGs, including the density and velocity distribution of the tidally disrupted arms of their parent galaxies, are carried out. Furthermore, the influence of different combinations of environmental effects, such as the tidal field and ram pressure, on the evolution of TDGs are investigated. It turned out that, within the presented simulations, these effects are only marginal. It has been shown that young TDGs, which are just forming, can survive star formation rates of more than $1 \text{ M}_{\odot} \text{ yr}^{-1}$, without being disrupted by stellar feedback processes. Although no dominant KDC was formed a significant fraction of 10 – 20% of the in situ formed stars show an inverted rotation direction. Moreover, the results of the numerical simulations are compared to observed dwarf galaxies and TDGs.

Abstract Deutsch

Der Ausdruck kinematisch entkoppelte Kerne (Eng.: kinematically decoupled cores, KDCs) bezieht sich auf dynamische Substrukturen in den Zentralbereichen von Galaxien und kann in den verschiedensten Formen präsent sein. Dazu zählen unter anderen Kerne mit invertierter Rotationsrichtung oder eine sich im radialen Verlauf ändernde Rotationsachse. Die am meisten diskutierten Formationsszenarien basieren auf gravitativen Wechselwirkungen zwischen Galaxien, wie Beinahe-Kollisionen und Verschmelzungen. Mit Hilfe dieser Ereignisse ist es möglich die Eigenschaften von leuchtstarken elliptischen Galaxien mit KDCs gut zu beschreiben. Es ist jedoch nicht geklärt ob diese Prozesse auch für die Entstehung von KDCs in elliptischen Zwerggalaxien (Eng.: dwarf ellipticals, dEs) verantwortlich sind. Speziell in Galaxienhaufen, wo sich die meisten dEs befinden sind die Relativgeschwindigkeiten zu hoch und die Zeitspanne ist für gravitative Wechselwirkungen zu kurz um ausreichend Drehimpuls zu übertragen und ihre Dynamik zu ändern. Es wäre denkbar, dass sich die KDCs in dEs in Galaxiengruppen gebildet haben, da in diesen, aufgrund der geringeren Relativgeschwindigkeiten, die Zeitskalen für gravitative Wechselwirkungen länger sind. Die so entstandenen dEs mit KDC könnten anschließend in das Gravitationspotential eines Galaxienhaufens eingefallen sein.

In dieser Masterarbeit wird eine neue Theorie zur Entstehung von KDCs in dEs, im Rahmen von Gezeitenzwerggalaxien (Eng.: tidal dwarf galaxies, TDGs), untersucht. Bei dieser Hypothese wird der äußere Bereich der TDGs von den alten Sternen der verschmelzenden Galaxien gebildet. Wohingegen die vorort entstehenden Sterne, welche ihre Bewegung durch die Eigenbewegung des interstellaren Mediums vorgegeben bekommen, den Kern bilden. Um dies zu untersuchen wurden, zum ersten Mal, numerische Simulationen, von jungen und noch in den Gezeitenarm eingebettete TDGs durchgeführt.

Des Weiteren wurde der Einfluss verschiedener Umgebungseffekte, wie des Gezeitenfeldes der verschmelzenden Galaxien oder Staudruck, auf die Evolution von TDGs untersucht. Es zeigte sich, dass diese Effekte, in den präsentierten Simulationen, nur eine untergeordnete Rolle spielen. Es konnte gezeigt werden, dass junge, sich gerade bildende TDGs Sternentstehungsraten von mehr als $1 \text{ M}_{\odot} \text{ yr}^{-1}$ überleben können, ohne von stellaren Feedbackprozessen zerstört zu werden. Obwohl kein dominanter KDC gebildet wurde weist ein signifikanter Anteil von 10 – 20% der in den TDGs geborenen Sterne eine invertierte Rotationsrichtung auf. Außerdem wurden die numerischen Ergebnisse mit Beobachtungen von Zwerggalaxien und TDGs verglichen.

Bibliography

- Arnaud, M. and Raymond, J. (1992). Iron ionization and recombination rates and ionization equilibrium. *ApJ*, 398:394–406.
- Arnaud, M. and Rothenflug, R. (1985). An updated evaluation of recombination and ionization rates. *A&A*, 60:425–457.
- Arp, H. (1966). Atlas of Peculiar Galaxies. *ApJ*, 14:1.
- Balcells, M. and González, A. C. (1998). Formation of Kinematic Subsystems in Stellar Spiral-Spiral Mergers. *ApJ*, 505:L109–L112.
- Balcells, M. and Quinn, P. J. (1990). The formation of counterrotating cores in elliptical galaxies. *ApJ*, 361:381–393.
- Barnes, J. and Efstathiou, G. (1987). Angular momentum from tidal torques. *ApJ*, 319:575–600.
- Barnes, J. E. and Hernquist, L. (1992). Formation of dwarf galaxies in tidal tails. *Nature*, 360:715–717.
- Bendo, G. J. and Barnes, J. E. (2000). The line-of-sight velocity distributions of simulated merger remnants. *MNRAS*, 316:315–325.
- Boehringer, H. and Hensler, G. (1989). Metallicity-dependence of radiative cooling in optically thin, hot plasmas. *A&A*, 215:147–149.
- Bois, M., Emsellem, E., Bournaud, F., Alatalo, K., Blitz, L., Bureau, M., Cappellari, M., Davies, R. L., Davis, T. A., de Zeeuw, P. T., Duc, P.-A., Khochfar, S., Krajnović, D., Kuntschner, H., Lablanche, P.-Y., McDermid, R. M., Morganti, R., Naab, T., Oosterloo, T., Sarzi, M., Scott, N., Serra, P., Weijmans, A.-M., and Young, L. M. (2011). The ATLAS^{3D} project - VI. Simulations of binary galaxy mergers and the link with fast rotators, slow rotators and kinematically distinct cores. *MNRAS*, 416:1654–1679.
- Boquien, M., Duc, P.-A., Galliano, F., Braine, J., Lisenfeld, U., Charmandaris, V., and Appleton, P. N. (2010). Star Formation in Collision Debris: Insights from the Modeling of Their Spectral Energy Distribution. *AJ*, 140:2124–2144.

-
- Boselli, A., Boissier, S., Cortese, L., and Gavazzi, G. (2008). The Origin of Dwarf Ellipticals in the Virgo Cluster. *ApJ*, 674:742–767.
- Bournaud, F. (2010). Tidal Dwarf Galaxies and Missing Baryons. *Advances in Astronomy*, 2010.
- Bournaud, F., Duc, P.-A., Brinks, E., Boquien, M., Amram, P., Lisenfeld, U., Koribalski, B. S., Walter, F., and Charmandaris, V. (2007). Missing Mass in Collisional Debris from Galaxies. *Science*, 316:1166–1669.
- Braine, J., Duc, P.-A., Lisenfeld, U., Charmandaris, V., Vallejo, O., Leon, S., and Brinks, E. (2001). Abundant molecular gas in tidal dwarf galaxies: On-going galaxy formation. *A&A*, 378:51–69.
- Braine, J., Lisenfeld, U., Duc, P.-A., Brinks, E., Charmandaris, V., and Leon, S. (2004). Colliding molecular clouds in head-on galaxy collisions. *A&A*, 418:419–428.
- Braine, J., Lisenfeld, U., Due, P.-A., and Leon, S. (2000). Formation of molecular gas in the tidal debris of violent galaxy-galaxy interactions. *Nature*, 403:867–869.
- Cappellari, M., Emsellem, E., Krajnović, D., McDermid, R. M., Scott, N., Verdoes Kleijn, G. A., Young, L. M., Alatalo, K., Bacon, R., Blitz, L., Bois, M., Bournaud, F., Bureau, M., Davies, R. L., Davis, T. A., de Zeeuw, P. T., Duc, P.-A., Khochfar, S., Kuntschner, H., Lablanche, P.-Y., Morganti, R., Naab, T., Oosterloo, T., Sarzi, M., Serra, P., and Weijmans, A.-M. (2011). The ATLAS^{3D} project - I. A volume-limited sample of 260 nearby early-type galaxies: science goals and selection criteria. *MNRAS*, 413:813–836.
- Croxall, K. V., van Zee, L., Lee, H., Skillman, E. D., Lee, J. C., Côté, S., Kennicutt, Jr., R. C., and Miller, B. W. (2009). Chemical Abundances of Seven Irregular and Three Tidal Dwarf Galaxies in the M81 Group. *ApJ*, 705:723–738.
- Dabringhausen, J. and Kroupa, P. (2013). Dwarf elliptical galaxies as ancient tidal dwarf galaxies. *MNRAS*, 429:1858–1871.
- Dalgarno, A. and McCray, R. A. (1972). Heating and Ionization of HI Regions. *ARA&A*, 10:375–426.
- de Grijs, R. and Anders, P. (2006). How well do we know the age and mass distributions of the star cluster system in the Large Magellanic Cloud? *MNRAS*, 366:295–307.
- de Rijcke, S., Dejonghe, H., Zeilinger, W. W., and Hau, G. K. T. (2004). Dwarf elliptical galaxies with kinematically decoupled cores. *A&A*, 426:53–63.
- Duc, P.-A. (2012). Birth, Life and Survival of Tidal Dwarf Galaxies. *Astrophysics and Space Science Proceedings*, 28:305.
- Duc, P.-A., Bournaud, F., and Masset, F. (2004). A top-down scenario for the formation of massive Tidal Dwarf Galaxies. *A&A*, 427:803–814.

-
- Duc, P.-A. and Mirabel, I. F. (1994). Recycled galaxies in the colliding system ARP 105. *A&A*, 289:83–93.
- Duc, P.-A. and Mirabel, I. F. (1998). Young tidal dwarf galaxies around the gas-rich disturbed lenticular NGC 5291. *A&A*, 333:813–826.
- Duc, P.-A., Paudel, S., McDermid, R. M., Cuillandre, J.-C., Serra, P., Bournaud, F., Cappellari, M., and Emsellem, E. (2014). Identification of old tidal dwarfs near early-type galaxies from deep imaging and H I observations. *MNRAS*, 440:1458–1469.
- Efstathiou, G., Ellis, R. S., and Carter, D. (1982). Further observations of the elliptical galaxy NGC 5813. *MNRAS*, 201:975–990.
- Elmegreen, B. G., Kaufman, M., and Thomasson, M. (1993). An interaction model for the formation of dwarf galaxies and 10 exp 8 solar mass clouds in spiral disks. *ApJ*, 412:90–98.
- Emsellem, E., Cappellari, M., Krajnović, D., van de Ven, G., Bacon, R., Bureau, M., Davies, R. L., de Zeeuw, P. T., Falcón-Barroso, J., Kuntschner, H., McDermid, R., Peletier, R. F., and Sarzi, M. (2007). The SAURON project - IX. A kinematic classification for early-type galaxies. *MNRAS*, 379:401–417.
- Flores, H., Hammer, F., Fouquet, S., Puech, M., Kroupa, P., Yang, Y., and Pawlowski, M. (2016). Young tidal dwarf galaxies cannot be used to probe dark matter in galaxies. *MNRAS*, 457:L14–L18.
- Fouquet, S., Hammer, F., Yang, Y., Puech, M., and Flores, H. (2012). Does the dwarf galaxy system of the Milky Way originate from Andromeda? *MNRAS*, 427:1769–1783.
- Franx, M. and Illingworth, G. D. (1988). A counterrotating core in IC 1459. *ApJ*, 327:L55–L59.
- Fryxell, B., Olson, K., Ricker, P., Timmes, F. X., Zingale, M., Lamb, D. Q., MacNeice, P., Rosner, R., Truran, J. W., and Tufo, H. (2000). FLASH: An Adaptive Mesh Hydrodynamics Code for Modeling Astrophysical Thermonuclear Flashes. *ApJ*, 131:273–334.
- Geha, M., Guhathakurta, P., and van der Marel, R. P. (2005). NGC 770: A Counterrotating Core in a Low-Luminosity Elliptical Galaxy. *AJ*, 129:2617–2627.
- Gentile, G., Famaey, B., Combes, F., Kroupa, P., Zhao, H. S., and Tirit, O. (2007). Tidal dwarf galaxies as a test of fundamental physics. *A&A*, 472:L25–L28.
- Gieles, M. (2009). The early evolution of the star cluster mass function. *MNRAS*, 394:2113–2126.
- González-García, A. C., Aguerri, J. A. L., and Balcells, M. (2005). Harassment origin for kinematic substructures in dwarf elliptical galaxies? *A&A*, 444:803–812.

-
- Gunn, J. E. and Gott, III, J. R. (1972). On the Infall of Matter Into Clusters of Galaxies and Some Effects on Their Evolution. *ApJ*, 176:1–19.
- Gupta, A., Mathur, S., Krongold, Y., Nicastro, F., and Galeazzi, M. (2012). A Huge Reservoir of Ionized Gas around the Milky Way: Accounting for the Missing Mass? *APJ*, 756:L8–L13.
- Hammer, F., Yang, Y., Fouquet, S., Pawlowski, M. S., Kroupa, P., Puech, M., Flores, H., and Wang, J. (2013). The vast thin plane of M31 corotating dwarfs: an additional fossil signature of the M31 merger and of its considerable impact in the whole Local Group. *MNRAS*, 431:3543–3549.
- Hammer, F., Yang, Y. B., Wang, J. L., Puech, M., Flores, H., and Fouquet, S. (2010). Does M31 Result from an Ancient Major Merger? *ApJ*, 725:542–555.
- Harsoula, M. and Voglis, N. (1998). Counterrotating galaxies formed by cosmological collapses. *A&A*, 335:431–442.
- Hau, G. K. T., Carter, D., and Balcells, M. (1999). The shell elliptical galaxy NGC 2865: evolutionary population synthesis of a kinematically distinct core. *MNRAS*, 306:437–460.
- Hau, G. K. T. and Thomson, R. C. (1994). A New Model for the Formation of Kinematically Decoupled Cores in Elliptical Galaxies. *MNRAS*, 270:L23.
- Hensler, G. (1987). Galactic Evolution - Some Aspects towards a Consistent Understanding. *Mitteilungen der Astronomischen Gesellschaft Hamburg*, 70:141–190.
- Hernquist, L. (1990). An analytical model for spherical galaxies and bulges. *ApJ*, 356:359–364.
- Hernquist, L. and Barnes, J. E. (1991). Origin of kinematic subsystems in elliptical galaxies. *Nature*, 354:210–212.
- Hillebrandt, W. and Niemeyer, J. C. (2000). Type IA Supernova Explosion Models. *ARA&A*, 38:191–230.
- Huang, J. and Greengard, L. (2000). A fast direct solver for elliptic partial differential equations on adaptively refined meshes. *SIAM J. Sci. Stat. Comput.*, 21:1551–1566.
- Hunter, D. A., Elmegreen, B. G., Dupuy, T. J., and Mortonson, M. (2003). Cluster Mass Functions in the Large and Small Magellanic Clouds: Fading and Size-of-Sample Effects. *AJ*, 126:1836–1848.
- Hunter, D. A., Hunsberger, S. D., and Royce, E. W. (2000). Identifying Old Tidal Dwarf Irregulars. *ApJ*, 542:137–142.

-
- Ibata, R. A., Lewis, G. F., Conn, A. R., Irwin, M. J., McConnachie, A. W., Chapman, S. C., Collins, M. L., Fardal, M., Ferguson, A. M. N., Ibata, N. G., Mackey, A. D., Martin, N. F., Navarro, J., Rich, R. M., Valls-Gabaud, D., and Widrow, L. M. (2013). A vast, thin plane of corotating dwarf galaxies orbiting the Andromeda galaxy. *Nature*, 493:62–65.
- Iben, Jr., I. and Tutukov, A. V. (1984). Supernovae of type I as end products of the evolution of binaries with components of moderate initial mass (M not greater than about 9 solar masses). *ApJ*, 54:335–372.
- Illingworth, G. (1977). Rotation in 13 elliptical galaxies. *ApJ*, 218:L43–L47.
- Jedrzejewski, R. and Schechter, P. L. (1988). Evidence for dynamical subsystems in elliptical galaxies. *ApJ*, 330:L87–L91.
- Kaviraj, S., Darg, D., Lintott, C., Schawinski, K., and Silk, J. (2012). Tidal dwarf galaxies in the nearby Universe. *MNRAS*, 419:70–79.
- Kennicutt, Jr., R. C. (1998). The Global Schmidt Law in Star-forming Galaxies. *ApJ*, 498:541–552.
- Kleineberg, K., Sánchez-Blázquez, P., and Vazdekis, A. (2011). Evidence of a Distinct Stellar Population in the Counterrotating Core of NGC 1700. *ApJ*, 732:L33.
- Koeppen, J., Theis, C., and Hensler, G. (1995). Self-regulated star-formation in chemodynamical models of galaxies. *A&A*, 296:99–109.
- Kormendy, J. (1984). Recognizing merger remnants among normal elliptical galaxies NGC 5813. *ApJ*, 287:577–585.
- Krajnović, D., Cappellari, M., de Zeeuw, P. T., and Copin, Y. (2006). Kinemetry: a generalization of photometry to the higher moments of the line-of-sight velocity distribution. *MNRAS*, 366:787–802.
- Krajnović, D., Emsellem, E., Cappellari, M., Alatalo, K., Blitz, L., Bois, M., Bournaud, F., Bureau, M., Davies, R. L., Davis, T. A., de Zeeuw, P. T., Khochfar, S., Kuntschner, H., Lablanche, P.-Y., McDermid, R. M., Morganti, R., Naab, T., Oosterloo, T., Sarzi, M., Scott, N., Serra, P., Weijmans, A.-M., and Young, L. M. (2011). The ATLAS^{3D} project - II. Morphologies, kinematic features and alignment between photometric and kinematic axes of early-type galaxies. *MNRAS*, 414:2923–2949.
- Kroupa, P. (2001). On the variation of the initial mass function. *MNRAS*, 322:231–246.
- Kroupa, P. (2008). Initial Conditions for Star Clusters. In Aarseth, S. J., Tout, C. A., and Mardling, R. A., editors, *The Cambridge N-Body Lectures*, volume 760 of *Lecture Notes in Physics*, Berlin Springer Verlag, page 181.

-
- Kroupa, P. and Weidner, C. (2003). Galactic-Field Initial Mass Functions of Massive Stars. *ApJ*, 598:1076–1078.
- Lada, C. J. and Lada, E. A. (2003). Embedded Clusters in Molecular Clouds. *ARA&A*, 41:57–115.
- Leach, R. (1981). On the triaxiality of elliptical galaxies. *ApJ*, 248:485–498.
- Lee, H., Skillman, E. D., Cannon, J. M., Jackson, D. C., Gehrz, R. D., Polonski, E. F., and Woodward, C. E. (2006). On Extending the Mass-Metallicity Relation of Galaxies by 2.5 Decades in Stellar Mass. *ApJ*, 647:970–983.
- Lee, J. C., Gil de Paz, A., Tremonti, C., Kennicutt, Jr., R. C., Salim, S., Bothwell, M., Calzetti, D., Dalcanton, J., Dale, D., Engelbracht, C., Funes, S. J. J. G., Johnson, B., Sakai, S., Skillman, E., van Zee, L., Walter, F., and Weisz, D. (2009). Comparison of H α and UV Star Formation Rates in the Local Volume: Systematic Discrepancies for Dwarf Galaxies. *ApJ*, 706:599–613.
- Lee-Waddell, K., Spekkens, K., Cuillandre, J.-C., Cannon, J., Haynes, M. P., Sick, J., Chandra, P., Patra, N., Stierwalt, S., and Giovanelli, R. (2014). An extremely optically dim tidal feature in the gas-rich interacting galaxy group NGC 871/NGC 876/NGC 877. *MNRAS*, 443:3601–3611.
- Lelli, F., Duc, P.-A., Brinks, E., Bournaud, F., McGaugh, S. S., Lisenfeld, U., Weilbacher, P. M., Boquien, M., Revaz, Y., Braine, J., Koribalski, B. S., and Belles, P.-E. (2015). Gas dynamics in tidal dwarf galaxies: Disc formation at $z = 0$. *A&A*, 584:113.
- Lin, D. N. C. and Faber, S. M. (1983). Some implications of nonluminous matter in dwarf spheroidal galaxies. *ApJ*, 266:L21–L25.
- Lisenfeld, U., Braine, J., Duc, P. A., Boquien, M., Brinks, E., Bournaud, F., Lelli, F., and Charmandaris, V. (2016). Molecular gas and star formation in the tidal dwarf galaxy VCC 2062. *A&A*, 590:92.
- Löhner, R. (1987). An adaptive finite element scheme for transient problems in CFD. *Computer Methods in Applied Mechanics and Engineering*, 61:323–338.
- MacNeice, P., Olson, K. M., Mobarrry, C., de Fainchtein, R., and Packer, C. (2000). PARAMESH: A parallel adaptive mesh refinement community toolkit. *CPC*, 126:330–354.
- Maeder (1996). From stars to galaxies: the impact of stellar physics on galaxy evolution. In Leitherer, C., Fritze-von-Alvensleben, U., and Huchra, J., editors, *Astronomical Society of the Pacific Conference Series Vol. 98*.
- Maeder, A. (2009). *Physics, Formation and Evolution of Rotating Stars*. Berlin: Springer.

-
- Malin, D. F. and Carter, D. (1980). Giant shells around normal elliptical galaxies. *Nature*, 285:643–645.
- Marigo, P., Bressan, A., and Chiosi, C. (1996). The TP-AGB phase: a new model. *A&A*, 313:545–564.
- Matteucci, F. and Recchi, S. (2001). On the Typical Timescale for the Chemical Enrichment from Type Ia Supernovae in Galaxies. *ApJ*, 558:351–358.
- McDermid, R. M., Emsellem, E., Shapiro, K. L., Bacon, R., Bureau, M., Cappellari, M., Davies, R. L., de Zeeuw, T., Falcón-Barroso, J., Krajnović, D., Kuntschner, H., Peletier, R. F., and Sarzi, M. (2006). The SAURON project - VIII. OASIS/CFHT integral-field spectroscopy of elliptical and lenticular galaxy centres. *MNRAS*, 373:906–958.
- McGaugh, S. S. (2005). Balance of Dark and Luminous Mass in Rotating Galaxies. *Physical Review Letters*, 95:171302.
- McGaugh, S. S., Schombert, J. M., Bothun, G. D., and de Blok, W. J. G. (2000). The Baryonic Tully-Fisher Relation. *ApJ*, 533:L99–L102.
- Mei, S., Blakeslee, J. P., Côté, P., Tonry, J. L., West, M. J., Ferrarese, L., Jordán, A., Peng, E. W., Anthony, A., and Merritt, D. (2007). The ACS Virgo Cluster Survey. XIII. SBF Distance Catalog and the Three-dimensional Structure of the Virgo Cluster. *ApJ*, 655:144–162.
- Mestschersky, J. (1902). Über die Integration der Bewegungsgleichungen im Probleme zweier Körper von veränderlicher Masse. *AN*, 159:229.
- Mieske, S., Hilker, M., and Misgeld, I. (2012). The specific frequencies of ultra-compact dwarf galaxies. *A&A*, 537:A3.
- Mirabel, I. F., Dottori, H., and Lutz, D. (1992). Genesis of a dwarf galaxy from the debris of the Antennae. *A&A*, 256:L19–L22.
- Mirabel, I. F., Lutz, D., and Maza, J. (1991). The Superantennae. *A&A*, 243:367–372.
- Mo, H., van den Bosch, F., and White, S. (2010). *Galaxy Formation and Evolution*. Cambridge University Press.
- Moore, B., Katz, N., Lake, G., Dressler, A., and Oemler, A. (1996). Galaxy harassment and the evolution of clusters of galaxies. *Nature*, 379:613–616.
- Okazaki, T. and Taniguchi, Y. (2000). Dwarf Galaxy Formation Induced by Galaxy Interactions. *ApJ*, 543:149–152.
- Oosterloo, T., Balcells, M., and Carter, D. (1994). NGC5982 - a Smooth Triaxial Elliptical. *MNRAS*, 266:L10.

-
- Peeples, M. S., Pogge, R. W., and Stanek, K. Z. (2008). Outliers from the Mass-Metallicity Relation. I. A Sample of Metal-Rich Dwarf Galaxies from SDSS. *ApJ*, 685:904–914.
- Peng, Y.-j., Lilly, S. J., Kovač, K., Bolzonella, M., Pozzetti, L., Renzini, A., Zamorani, G., Ilbert, O., Knobel, C., Iovino, A., Maier, C., Cucciati, O., Tasca, L., Carollo, C. M., Silverman, J., Kampczyk, P., de Ravel, L., Sanders, D., Scoville, N., Contini, T., Mainieri, V., Scodeggio, M., Kneib, J.-P., Le Fèvre, O., Bardelli, S., Bongiorno, A., Caputi, K., Coppa, G., de la Torre, S., Franzetti, P., Garilli, B., Lamareille, F., Le Borgne, J.-F., Le Brun, V., Mignoli, M., Perez Montero, E., Pello, R., Ricciardelli, E., Tanaka, M., Tresse, L., Vergani, D., Welikala, N., Zucca, E., Oesch, P., Abbas, U., Barnes, L., Bordoloi, R., Bottini, D., Cappi, A., Cassata, P., Cimatti, A., Fumana, M., Hasinger, G., Koekemoer, A., Leauthaud, A., Maccagni, D., Marinoni, C., McCracken, H., Memeo, P., Meneux, B., Nair, P., Porciani, C., Presotto, V., and Scaramella, R. (2010). Mass and Environment as Drivers of Galaxy Evolution in SDSS and zCOSMOS and the Origin of the Schechter Function. *ApJ*, 721:193–221.
- Pflamm-Altenburg, J., Weidner, C., and Kroupa, P. (2007). Converting $H\alpha$ Luminosities into Star Formation Rates. *ApJ*, 671:1550–1558.
- Ploekinger, S. (2014). *On the Formation and Evolution of Tidal Dwarf Galaxies*. PhD thesis, University of Vienna, Department of Astrophysics.
- Ploekinger, S. (2015). Tides or dark matter sub-haloes: Which ones are more attractive? *MNRAS*, 452:3742–3751.
- Ploekinger, S., Hensler, G., Recchi, S., Mitchell, N., and Kroupa, P. (2014). Chemo-dynamical evolution of tidal dwarf galaxies. I. Method and IMF dependence. *MNRAS*, 437:3980–3993.
- Ploekinger, S., Recchi, S., Hensler, G., and Kroupa, P. (2015). Chemodynamical evolution of tidal dwarf galaxies - II. The long-term evolution and influence of a tidal field. *MNRAS*, 447:2512–2525.
- Portinari, L., Chiosi, C., and Bressan, A. (1998). Galactic chemical enrichment with new metallicity dependent stellar yields. *A&A*, 334:505–539.
- Recchi, S., Calura, F., and Kroupa, P. (2009). The chemical evolution of galaxies within the IGIMF theory: the $[\alpha/\text{Fe}]$ ratios and downsizing. *A&A*, 499:711–722.
- Recchi, S., Kroupa, P., and Ploekinger, S. (2015). The mass-metallicity relation of tidal dwarf galaxies. *MNRAS*, 450:2367–2372.
- Recchi, S., Theis, C., Kroupa, P., and Hensler, G. (2007). The early evolution of tidal dwarf galaxies. *A&A*, 470:L5–L8.
- Renzini, A. and Peng, Y.-j. (2015). An Objective Definition for the Main Sequence of Star-forming Galaxies. *ApJ*, 801:L29–L35.

-
- Renzini, A. and Voli, M. (1981). Advanced evolutionary stages of intermediate-mass stars. I - Evolution of surface compositions. *A&A*, 94:175–193.
- Rich, R. M., Collins, M. L. M., Black, C. M., Longstaff, F. A., Koch, A., Benson, A., and Reitzel, D. B. (2012). A tidally distorted dwarf galaxy near NGC 4449. *Nature*, 482:192–194.
- Ricker, P. M. (2008). A Direct Multigrid Poisson Solver for Oct-Tree Adaptive Meshes. *ApJ*, 176:293–300.
- Rubin, V. C., Graham, J. A., and Kenney, J. D. P. (1992). Cospatial counterrotating stellar disks in the Virgo E7/S0 galaxy NGC 4550. *ApJ*, 394:L9–L12.
- Salaris, M. and Cassisi, S. (2005). *Evolution of Stars and Stellar Populations*. Chichester: Wiley.
- Salpeter, E. E. (1955). The Luminosity Function and Stellar Evolution. *ApJ*, 121:161.
- Schure, K. M., Kosenko, D., Kaastra, J. S., Keppens, R., and Vink, J. (2009). A new radiative cooling curve based on an up-to-date plasma emission code. *A&A*, 508:751–757.
- Smith, R., Duc, P. A., Candlish, G. N., Fellhauer, M., Sheen, Y.-K., and Gibson, B. K. (2013). The influence of ram pressure on the evolution of tidal dwarf galaxies. *MNRAS*, 436:839–853.
- Springel, V. (2005). The cosmological simulation code GADGET-2. *MNRAS*, 364:1105–1134.
- Statler, T. S. (1991). Is the kinematically distinct core in NGC 5982 necessarily the remnant of an accreted companion? *ApJ*, 382:L11–L14.
- Steyrleithner, P. (2015). *Evolution of Dwarf Galaxies during the Infall into Galaxy Clusters*. Master’s thesis, University of Vienna, Department of Astrophysics.
- Sweet, S. M., Drinkwater, M. J., Meurer, G., Bekki, K., Dopita, M. A., Kilborn, V., and Nicholls, D. C. (2014). Choirs H I Galaxy Groups: The Metallicity of Dwarf Galaxies. *ApJ*, 782:35.
- Thakar, A. R. and Ryden, B. S. (1998). Smoothed Particle Hydrodynamics Simulations of Counterrotating Disk Formation in Spiral Galaxies. *ApJ*, 506:93–115.
- Theis, C., Burkert, A., and Hensler, G. (1992). Chemo-dynamical evolution of massive spherical galaxies. *A&A*, 265:465–477.
- Thomas, D., Brimiouille, F., Bender, R., Hopp, U., Greggio, L., Maraston, C., and Saglia, R. P. (2006). A counter-rotating core in the dwarf elliptical galaxy VCC 510. *A&A*, 445:L19–L22.

-
- Toloba, E., Guhathakurta, P., van de Ven, G., Boissier, S., Boselli, A., den Brok, M., Falc3n-Barroso, J., Hensler, G., Janz, J., Laurikainen, E., Lisker, T., Paudel, S., Peletier, R. F., Ry3, A., and Salo, H. (2014). Stellar Kinematics and Structural Properties of Virgo Cluster Dwarf Early-type Galaxies from the SMAKCED Project. I. Kinematically Decoupled Cores and Implications for Infallen Groups in Clusters. *ApJ*, 783:120–131.
- Toomre, A. and Toomre, J. (1972). Galactic Bridges and Tails. *ApJ*, 178:623–666.
- Toro, E. F. (2009). *Riemann Solvers and Numerical Methods for Fluid Dynamics*. New York: Springer, third edition.
- Travaglio, C., Hillebrandt, W., Reinecke, M., and Thielemann, F.-K. (2004). Nucleosynthesis in multi-dimensional SN Ia explosions. *A&A*, 425:1029–1040.
- Truelove, J. K., Klein, R. I., McKee, C. F., Holliman, II, J. H., Howell, L. H., Greenough, J. A., and Woods, D. T. (1998). Self-gravitational Hydrodynamics with Three-dimensional Adaptive Mesh Refinement: Methodology and Applications to Molecular Cloud Collapse and Fragmentation. *ApJ*, 495:821–852.
- Tsatsi, A., Macci3, A. V., van de Ven, G., and Moster, B. P. (2015). A New Channel for the Formation of Kinematically Decoupled Cores in Early-type Galaxies. *ApJ*, 802:L3.
- Tully, R. B. and Fisher, J. R. (1977). A new method of determining distances to galaxies. *A&A*, 54:661–673.
- van den Bosch, R. C. E., van de Ven, G., Verolme, E. K., Cappellari, M., and de Zeeuw, P. T. (2008). Triaxial orbit based galaxy models with an application to the (apparent) decoupled core galaxy NGC 4365. *MNRAS*, 385:647–666.
- Weidner, C. and Kroupa, P. (2004). Evidence for a fundamental stellar upper mass limit from clustered star formation. *MNRAS*, 348:187–191.
- Weidner, C. and Kroupa, P. (2005). The Variation of Integrated Star Initial Mass Functions among Galaxies. *ApJ*, 625:754–762.
- Weidner, C., Kroupa, P., and Larsen, S. S. (2004). Implications for the formation of star clusters from extragalactic star formation rates. *MNRAS*, 350:1503–1510.
- Weilbacher, P. M., Duc, P.-A., and Fritze-v. Alvensleben, U. (2003). Tidal dwarf candidates in a sample of interacting galaxies. II. Properties and kinematics of the ionized gas. *A&A*, 397:545–555.
- Wen, Z.-Z., Zheng, X.-Z., Zhao, Y.-H., and Gao, Y. (2012). Tidal dwarf galaxies at intermediate redshifts. *Ap&SS*, 337:729–737.
- Wetzstein, M., Naab, T., and Burkert, A. (2007). Do dwarf galaxies form in tidal tails? *MNRAS*, 375:805–820.

-
- Yang, Y., Hammer, F., Fouquet, S., Flores, H., Puech, M., Pawlowski, M. S., and Kroupa, P. (2014). Reproducing properties of MW dSphs as descendants of DM-free TDGs. *MNRAS*, 442:2419–2433.
- Zhang, Q. and Fall, S. M. (1999). The Mass Function of Young Star Clusters in the “Antennae” Galaxies. *ApJ*, 527:L81–L84.
- Zwicky, F. (1956). Multiple Galaxies. *Ergebnisse der exakten Naturwissenschaften*, 29:344–385.

List of Figures

1.1	Observed rotation curves of KDC hosting ETGs (NGC 3608, NGC 4494, VCC 1183)	2
1.2	Composite images of TDGs in the vicinity of their host galaxies	7
1.3	Formation of KDC in TDGs	10
2.1	Exemplary AMR decomposition in two dimensions	13
2.2	Radiative cooling rate coefficient $\Lambda(T)$	21
2.3	Kroupa (2001) IMF, normalised to the total cluster mass	26
3.1	Initial distribution of stellar SPH-particles	36
3.2	Initial surface density of the different simulation setups	41
4.1	Normalised mass fractions	44
4.2	Normalised mass fractions	45
4.3	Mass growth rate	46
4.4	Velocity field of the simulation run <code>tdg3_noRam</code> at $t_{sim} = 150$ and 300 Myr	47
4.5	Star formation history in 1 Myr-bins	48
4.6	Comparison of star formation histories (time in units of τ_{ff})	49
4.7	Embedded cluster mass function	50
4.8	Face-on surface brightness profiles	52
4.9	Stellar surface luminosity maps	53
4.10	Evolution of element abundances	54
4.11	Stellar [O/Fe] versus [Fe/H] abundance ratio	55
4.12	Rotation curve - <code>tdg2_iso</code>	57
4.13	Rotation curve - <code>tdg2_noRam</code>	58
4.14	Rotation curve - <code>tdg2_orb</code>	58
4.15	Rotation curve - <code>tdg2_noArm</code>	59
4.16	Rotation curve - <code>tdg2_igimf</code>	59
4.17	Rotation curve - <code>tdg3_iso</code>	60
4.18	Rotation curve - <code>tdg3_noRam</code>	60
4.19	Rotation curve - <code>tdg3_orb</code>	61
4.20	Stellar and gas line-of-sight velocity maps of <code>tdg3_iso</code>	62
4.21	k_1 -profile of simulated TDGs	66

4.22	Stellar statistics of tdg2_orb	69
4.23	Stellar statistics of tdg2_iso and tdg2_igimf	70
4.24	Example orbits of co- and counter rotating stars	71
4.25	SFR, gas mass M_g and M_s for a filled IMF and the IGIMF description of TDG_s2	72
4.26	Density slices of tdg2_orb and tdg2_igimf	73
4.27	Star formation surface density density of tdg2_orb and tdg2_igimf	74
4.28	Feedback energies and number of events of tdg2_orb and tdg2_igimf	75
4.29	Feedback energy surface density of tdg2_orb and tdg2_igimf	75
4.30	Distribution of SN Ia of tdg2_orb and tdg2_igimf at $t_{sim} = 200$ Myr	76
4.31	Orbits of TDG candidates around the merging galaxies	77
4.32	Influence of the tidal field	78
4.33	Influence of ram pressure	79
4.34	Influence of the tidal arm	80
4.35	Density slice - tdg3_iso	82
4.36	Density slice - tdg3_noRam	83
4.37	Density slice - tdg3_orb	84
5.1	Kennicutt-Schmidt law and main sequence of SF galaxies	86
5.2	Mass-radius relation	90
5.3	Mass-metallicity relation	91
5.4	Baryonic and dynamic masses of simulated TDGs	92
5.5	Baryonic Tully-Fischer relation	93

List of Tables

2.1	List of used standard star formation parameters.	25
3.1	Initial properties of the different simulation setups	38
3.2	Initial properties of the different simulation runs	40
4.1	Free-fall times	43
4.2	Main features of the four different kinematic groups as described by Kra- jnović et al. (2006)	64
4.3	Stellar kinematic properties	65
A.1	Summary of model properties - mass budget	99
A.2	Summary of model properties - stellar luminosity	100
A.3	Summary of model properties - metallicity	100
A.4	Summary of model properties - dynamical properties - stars	100
A.5	Summary of model properties - dynamical properties - gas	101