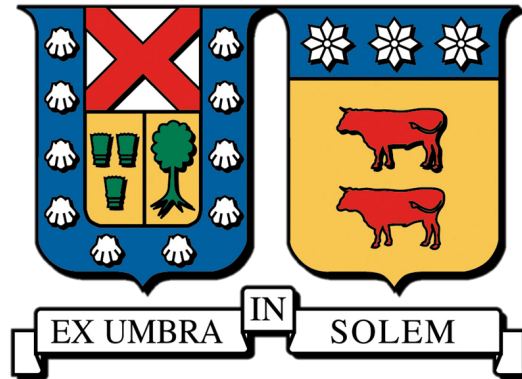


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DEPARTAMENTO DE FÍSICA



UNVEILING THE NATURE OF FIREBALLS IN
RAM PRESSURE STRIPPED JELLYFISH GALAXIES

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TESINA PARA OPTAR AL TÍTULO DE LICENCIADO EN ASTROFÍSICA

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Abstract

Galaxies residing in clusters environment undergo dramatic transformations due to their interaction with the IntraCluster Medium (ICM). Among the most dominant environmental processes is Ram Pressure Stripping (RPS), which drives the formation of jellyfish galaxies characterized by long, spectacular tails of ionized, stripped gas. Observations have consistently revealed pockets of active star formation within these tails, commonly referred to as fireballs or star-forming clumps. The standard theoretical model predicts that these newly formed structures should exhibit a clear stellar age gradient, with the youngest stars located furthest from the galactic disk.

In this work, we investigate the nature, internal dynamics, and long-term evolution of fireballs using a high-resolution hydrodynamical simulation. The simulation was done with the ENZO code in a wind-tunnel setup, modeling a gas-rich galaxy (analogous to observed objects like JO201) interacting with a high-speed variable wind representative of a massive cluster environment. Our methodology involved a Friends-of-Friends (FoF) algorithm combined with a novel frame-to-frame probabilistic tracking technique, which allowed us to identify, and follow the evolutionary history of 272 individual fireballs over a duration of ~ 600 *Myr*.

Our results demonstrate that the evolution of these structures is substantially more complex than the current models suggest. We find that a significant fraction of fireballs exhibits "mixed" or "inverted" age gradients, where older stellar populations lead the younger star-forming knots or where there is not a clear morphology for it. We provide evidence from the simulation that suggests that this age gradient inversion is a direct physical consequence of the deceleration of the dense gas clump due to the Ram Pressure drag force, while the recently formed stars—decoupled from the gas—continue their ballistic trajectory only affected by gravity. Furthermore, our statistical analysis indicates that high-velocity fireballs undergo short, intense starburst episodes in the outer regions of the tail. Crucially, the long-term orbital tracking reveals that a significant amount of the star-forming material does not escape the galaxy, but rather undergoes fallback, following damped oscillatory trajectories back towards the galactic disk.

This study contribute to the theoretical understanding of star formation in stripped tails and provides concrete, testable predictions. Our work establishes a new framework that can be used to interpret current and future integral field unit (IFU) observations, such as those from the GASP survey. Ultimately, identifying the predicted observational signature of this "flip" would allow for empirical constraints on the drag coefficient C_D of molecular clouds interacting with the ICM, a parameter useful to fully understand the evolution of jellyfish galaxies.

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Nomenclature

Symbol	meaning, units
a_{cloud}	Cloud/clump acceleration, km/s^2
C_D	Drag coefficient, adimensional
f_*	Star formation efficiency, adimensional
k_b	Boltzmann constant, erg/K
l	Linking length, kpc
M_{gal}	Mass of the galaxy, $M_\odot$
M_{jeans}	Jeans mass, $M_\odot$
P_{ram}	Ram pressure, dyn/cm^2
r_t	Truncation radius, kpc
t_{ff}	Free-fall time, Myr
v_{rel}	Relative velocity, km/s
Δ	Difference
∇	Gradient
ρ_{ICM}	IntraCluster Medium density, g/cm^3
ρ_{thresh}	Density threshold for star formation, g/cm^3
Σ_{gas}	Surface gas density, $M_\odot/pc^2$
Σ_{star}	Surface star density, $M_\odot/pc^2$
AMR	Adaptative Mesh Refinement
FoF	Friends of Friends
ICM	IntraCluster Medium
RPS	Ram Pressure Stripping
SFR	Star Formation Rate
LSS	Large Scale Structure

Chapter 1

Introduction

Galaxies do not evolve in isolation; their properties are strongly influenced by the environment in which they reside, a paradigm often referred to as 'nature versus nurture'. While galaxies in the field evolve largely due to internal secular processes, those residing in the densest nodes of the Large Scale Structure (LSS)—such as galaxy clusters—are subject to extreme environmental mechanisms.

The most defining feature of these cluster environments is the presence of a hot, diffuse Intracluster Medium (ICM). As predicted by the hierarchical model, massive halos undergo shock heating during their formation (Cole et al., 2000), resulting in virial temperatures of $10^7 - 10^8$ K that prevent the gas from cooling efficiently to form stars. Consequently, when gas-rich spiral galaxies fall into these hot and dense environments, they experience hydrodynamical interactions that can dramatically alter their star formation history.

In this chapter, we establish the theoretical background necessary to understand these interactions by reviewing first clusters of galaxies and their properties, then analyzing their environmental effects in individual galaxies and the possible connections with galaxy evolution. After this, we will talk about jellyfish galaxies and the region of star formation occurring in their tails, which we call fireballs, reviewing the possible mechanisms and conditions for star formation to understand how they are formed. Lastly the objective of this work will be presented.

1.1 Clusters of galaxies

Clusters of galaxies are the largest structures in the universe; therefore, they host the most extreme environments and contain a vast number of galaxies. Because of this, clusters are considered key laboratories for studying galaxy evolution across cosmic time. Our definition of clusters follows Abell (1958), who identified 1682 galaxy clusters—now known as Abell clusters. He classified clusters

as regular or irregular according to the spatial distribution of their member galaxies: symmetric and centrally concentrated systems are considered regular, while less ordered configurations are classified as irregular.

The fraction of elliptical and lenticular galaxies is about 80% in regular clusters and 50% in irregular clusters, when compared to the fraction observed in the field ($\sim 30\%$) strongly suggests that galaxies undergo morphological transformations in such dense environments (Mo et al., 2010). Topic that will be further explored in Section 1.2. More evidence for morphological evolution in clusters comes from the Butcher–Oemler effect (Butcher and Oemler, 1978), which shows that clusters at $0.3 \leq z \leq 0.5$ contain a significantly higher fraction of blue galaxies compared to present-day clusters ($z < 0.2$). In addition, spectroscopic data reveal that many galaxies in clusters at these redshifts exhibit strong Balmer absorption lines, indicating that their star formation activity was truncated within the last 1–2 *Gyr* (Dressler and Gunn, 1983). After this the following question arises, why do we see this properties?

1.1.1 X-ray observations in clusters

Because clusters are the most massive objects that we know in the LSS, they are also the hotter. This is reflected in multiple X-ray observations of clusters. We have detected X-ray luminosities of $L = 10^{43} - 10^{45} \text{ erg s}^{-1}$, which comes from thermal bremsstrahlung of the hot ICM with temperatures of $10^7 - 10^8 \text{ K}$ (Mo et al., 2010). These observations are relevant not only because they support the hierarchical model, but because we can infer the mass and the density distribution of the ICM gas through them.

In Chen et al. (2007) a model for the mass and the gravitational potential of a cluster was extracted, analyzing and fitting the X-ray surface brightness distribution of multiple clusters. Then a good approximation for the mass and the potential of clusters are defined as:

$$M(r) = \frac{3\beta k T_H r}{G\mu m_p} \frac{(r/r_c)^2}{1 + (r/r_c)^2}, \quad (1.1)$$

$$\Phi(i) = \frac{3}{2} \frac{\beta k T_H}{\mu m_p} \ln \left(1 + \left(\frac{r(i)}{r_c} \right)^2 \right), \quad (1.2)$$

Where β is a fit parameter that comes from the surface brightness (a single β model), r_c is the core radius and T_H the temperature of the halo. It's worth noting that the expression for the potential 1.2, is calculated in shells, because of the nature of continuous distributions of matter.

Given this observational picture, it becomes clear that galaxies in clusters are embedded in a

dense, hot, and dynamically complex environment. Could this environment explain the lack of blue spiral galaxies in clusters? In the following section, we are going to discuss some environmental effects affecting galaxies while falling into clusters, and its connections with galaxy evolution.

1.2 Environmental effects

When a galaxy falls into a dense environment like a group or a cluster of galaxies, there are three main interactions that will affect it due to the dynamics of the event. These effects are going to change the galaxy in multiple ways, and have been studied using numerical simulation and multiple observations. The following effects could all be happening at once, but they are mostly studied individually.

1.2.1 Tidal Stripping

Tidal Stripping (from now on TS) is a fundamental dynamical mechanism in galaxy evolution, one of the first studies of tidal forces in astronomy was done by [Hodge \(1966\)](#), who applied them to understand the dwarf galaxies in the local group. Following [Gnedin \(2003\)](#) analysis, the tidal effects depend on the relative sizes of the system and the perturber, such as the most well-known tidal interaction between the moon and earth. Earth is just ~ 4 times bigger than the moon, so the tidal effects are really noticeable. This can be extrapolated to clusters where galaxies are just 30 to 100 times smaller than clusters and therefore we should have this tidal effects present in these environments.

The TS is defined as the gradual removal of material (stars, gas, and dark matter) from a satellite galaxy, caused by the differential tidal force exerted by the overwhelming gravitational potential of the main cluster or a massive neighboring galaxy. TS is a direct consequence of the dynamical environment of clusters, where the gravity of the entire system outweighs the satellite's self-gravity in its outer regions.

1.2.2 Galaxy Harassment

The Galaxy Harassment was first introduced in [Moore et al. \(1996\)](#) and its defined as frequent high speed galaxy encounters. This process is not a direct effect of the dense ICM into the galaxy but instead a dynamical process caused by close high speed interactions between galaxies. Its a relevant process in dense environments due to the high speed that galaxies can reach while falling into the potential well of it, and because of the high amount of galaxies concentrated in clusters.

This galaxy interactions affect mostly to the stellar component of galaxies, which leads to big morphological change in them (e.g. [Moore et al. \(1999\)](#)), in the most extreme cases destroying dwarf galaxies and transforming spiral galaxies into SO type galaxies. It is worth noting that this process always comes with tidal effects because of their dynamical nature.

1.2.3 Ram pressure stripping

The ram pressure stripping (from now on RPS) was first introduced by [Gunn and Gott \(1972\)](#), and corresponds to the pressure that the ICM hot gas exerts over the gas of an infalling galaxy. This origin of the RPS makes it different from the last two processes, because it is a hydrodynamical process rather than a dynamical one. A simple but accurate equation dictates the behavior of the ram pressure. We say that ram pressure is going to strip gas from a galaxy if the following condition is satisfied:

$$\rho_{ICM}v^2 \geq 2\pi G \sum_{gas}(r) \sum_{star}(r), \quad (1.3)$$

where the left hand term corresponds to the ram pressure with ρ_{ICM} being the ICM density and v the relative velocity of the galaxy with respect to the medium. The right handed term is considered as the self-gravity per area, where $\sum_{gas}$ and $\sum_{star}$ are the surface density for the gas and stellar component of the galaxy respectively, which for spiral galaxies are considered only functions of the radius to the galactic center. From the ram pressure we can obtain the force of RPS and therefore the acceleration is defined as:

$$F_{RPS} = \rho_{ICM}v^2 A \quad (1.4)$$

$$a_{RPS} = \frac{\rho_{ICM}v^2}{\Sigma_{clump}} \quad (1.5)$$

where A is the surface area (or surface cross section) and Σ_{clump} the surface density of the gas clump being stripped.

RPS has been used to explain several observations of galaxies known as jellyfish galaxies (see section 1.3), and for galaxies exhibiting a truncated radius of star formation (e.g. [Abadi et al. \(1999\)](#)). When a galaxy falls into the cluster, it will reach a maximum velocity when passing through the center of it, this represents a limit for v , and so, for the ram pressure exerted in the galaxy. This leads to the "equal case" in Eq. 1.3

$$\rho_c v_{max}^2 = 2\pi G \sum_{gas} (r_t) \sum_{star} (r_t)$$

which defines a truncation radius r_t that satisfies the equation (Boselli et al., 2022). This is not the case for every galaxy, and we will have some galaxies with all of their gas stripped by the RPS (e.g. McCarthy et al. (2007)).

1.3 Jellyfish galaxies

Jellyfish galaxies are the most important visual examples of galaxies undergoing ram pressure stripping. These galaxies are generally gas-rich galaxies falling into clusters or groups that exhibit a long tail of gas that has been RPS by the ICM, and they are believed to be the intermediate stage in galaxy evolution for dwarfs irregular to dwarfs elliptical (Kenney et al., 2014). Thanks to the GASP project, we have now a large sample of jellyfish galaxies and their main features are listed:

1. Jellyfish are defined as galaxies that have a gas tail at least as long as the stellar disk diameter (Poggianti et al., 2025).
2. The majority of jellyfish galaxies have masses $\leq 4 \times 10^{10} M_\odot$ (Poggianti et al., 2025), but there are higher mass cases as well.
3. Jaffé et al. (2018) found that jellyfish galaxies are moving at higher speeds when they are near the cluster center, and that they are moving in radial orbits.
4. The stripped gas tails often display knots of vigorous star formation and young stellar clusters, indicating that the RPS process can induce a brief burst of star formation outside the main disk before the gas is fully dispersed (see subsection 1.3.1)

All these properties are based on observational data from the GASP sample (Poggianti et al. (2017b)), but they are all in great agreement with the theory of RPS exposed in 1.3, which helps as confirmation that jellyfish galaxies are in fact produced by extreme RPS. The resulting loss of cold gas strongly supports the hypothesis that RPS is the dominant mechanism responsible for the rapid quenching of star formation in infalling spiral and dwarf galaxies (Cortese et al., 2021).

1.3.1 Fireballs

It has been shown that the star formation in jellyfish galaxies is enhanced globally in short timescales (e.g. Cortese et al. (2021); Roberts and Parker (2020); Vulcani et al. (2018)). This star formation

can be seen in the main body of the galaxy, but also in the wakes of the gas tail that was removed from the disk, where turbulence can compress atomic hydrogen allowing its compression. Many observations of star formation in the tails of jellyfish galaxies have been done (e.g. [McPartland et al. \(2015\)](#); [Poggianti et al. \(2019\)](#)), but we want to focus on a particular observation made by [Kenney et al. \(2014\)](#) where he introduce what we now call fireballs.

Fireballs are regions of star formation in the tails of jellyfish galaxies that are being accelerated by ram pressure while forming stars. In Fig. 1.1 we can see the cartoon made in [Kenney et al. \(2014\)](#), which is a representation of what it is believed to be happening in fireballs.



Figure 1.1: Fireball model presented in [Kenney et al. \(2014\)](#), where the clump is accelerating outwards the galaxy due to ram pressure leaving a trail of stars on its way with a clear age gradient

It is theorize that fireballs exhibit the last age gradient due to observations of $H\alpha$ and NUV (Near Ultra Violet) emission in the tails, and it is explained because RPS only affects the gas component, so the stars that are being formed are decoupled from the gas, and in consequence they stop accelerating due to the ram pressure and start decelerating due to the gravitational pull of the main galaxy. Because the RPS tails are extreme environments for star formation to occur, we think that these smooth age gradients might not be the case for every clump on it, but instead that there should be a dependency of the age gradient with another variable of the fireball or the tail.

We believe that fireballs are a key component of jellyfish galaxies and their study is mandatory to understand the dynamical and hydrodynamical processes in the tails of jellyfish, and a puzzle

piece in the evolution of galaxies in extreme environments.

1.4 Star formation

Stars are the fundamental object in astrophysics because with them we can explain every phenomenon in the universe. In the context of our work we want to understand the origin and the conditions for star formation to associate it with the extreme environment of fireballs. For this purpose, We are going to summarize the review of [Ray \(2025\)](#)

1.4.1 Molecular clouds

Molecular clouds are the birthplaces of star formation. They typically have temperatures between 10 and 20 K and are primarily composed of molecular hydrogen, helium, and carbon monoxide, with densities $\rho \in [10^2 - 10^6] \text{ particles/cm}^3$. Their masses usually range from thousands to millions of solar masses, and their sizes from 10 to 100 parsecs.

These clouds exist because of a balance between gravitational, magnetic, and thermal forces. Many of them are close to virial equilibrium, where $2K + W + M = 0$, with K the kinetic energy, W the gravitational potential energy, and M the magnetic energy. if the magnetic potential is small, most clouds are in virial equilibrium $2K = |W|$ where the energies for a spherical cloud are

$$W = -\frac{3}{5} \frac{GM^2}{R}$$

$$K = \frac{3}{2} M \sigma^2$$

However, dense cores within molecular clouds often deviate from global virial equilibrium. In many cases, they satisfy the condition $|W| > 2K$ which corresponds to

$$\frac{5\sigma^2 R}{GM} < 1 \tag{1.6}$$

which is an early signal of collapse.

Jeans criterion: On the other hand, star formation in clouds starts when the gravity force is greater than the thermal internal pressure ([Carroll and Ostlie, 1996](#)). This analysis is analogous to the argument above, but here the kinetic energy is given by

$$K = \frac{3}{2} N k_b T$$

where N is the total number of particles approximated by

$$N = \frac{M_c}{\mu m_H}$$

where μ is the mean molecular weight. Now, the condition of collapse $|W| > 2K$ leads to the Jeans mass and Jeans scale criterion

$$M_J \approx \left(\frac{5k_b T}{G\mu m_H} \right)^{3/2} \rho^{-1/2} \quad (1.7)$$

$$\lambda_J = \left(\frac{\pi k_b T}{G\mu m_H \rho} \right)^{1/2} \quad (1.8)$$

These quantities set the characteristic mass and size of regions that become gravitationally unstable. For typical molecular cloud conditions, the corresponding length scale is on the order of ~ 0.1 pc, and defines the free fall timescale in which the collapse happens:

$$t_{ff} = \left(\frac{3\pi}{32G\rho} \right)^{1/2}. \quad (1.9)$$

Although the Jeans analysis provides useful first-order estimates, it neglects magnetic fields, turbulent motions, and non-uniform density structure, all of which significantly influence collapse in real clouds.

Bonnor–Ebert stability At early stages, dense cores evolve approximately isothermally because cooling processes compensate the heating from compression. As the core contracts and becomes optically thick, the collapse transitions toward adiabatic behavior. In this regime, stability is better described by the Bonnor–Ebert mass

$$M_{BE} \approx 1.18 \left(\frac{k_b T}{G\mu m_H} \right)^{3/2} \rho^{-1/2} \quad (1.10)$$

While similar to the Jeans mass, the Bonnor–Ebert model refines the stability criterion and has been shown to align well with observations of isolated pre-stellar cores. A classical example is Barnard 68, whose density profile is remarkably well fitted by a pressure-confined isothermal sphere (Alves et al., 2001). This makes B68 a benchmark case, demonstrating that thermal support + gravity can indeed describe the stability state of real molecular cloud cores.

1.4.2 Trigger mechanisms

We refer to trigger mechanisms as those that can produce the instability of the molecular clouds. In our context, we are going to review the ones that can be relevant for the tails of jellyfish galaxies.

Turbulent Compression: This mechanism (Federrath and Klessen (2012) and its references) consider that the intrinsic turbulence and magnetic fields of the cloud, creates local overdensities on it which lead to collapsing regions which with star formation. This could be relevant because of the nature of the environment of fireballs.

Cloud–Cloud Collisions: This mechanism (Habe and Ohta, 1992) is based on the idea that gravitational instabilities are formed due to collisions of two clouds, which leads to a burst of star formation after the collapse. We think that this process could create some fireballs because of the behavior of RPS.

External Pressure: Processes of external pressure are commonly associated to HII regions (Deharveng et al., 2010) and strong external ultraviolet radiation (Miao et al., 2006), which could be happening in fireballs.

1.5 Motivation and objectives

Despite significant progress, many open questions remain regarding galaxy evolution in dense environments and the mechanisms driving the Butcher-Oemler effect. Jellyfish galaxies represent a critical phase in this evolution, making them essential laboratories for studying environmental effects. In particular, the fireballs found in their tails are of great interest, as they offer a unique window into how Ram Pressure Stripping (RPS) affects gas dynamics and star formation outside the galactic disk.

In this work, we employ hydrodynamical simulations to investigate the formation conditions and physical properties of fireballs in jellyfish galaxies. While observations provide detailed snapshots, simulations allow us to trace the dynamical history and 3D geometry of these structures. Our main objective is to provide a theoretical framework to interpret recent state-of-the-art Hubble and MUSE IFU observations. Specifically, we aim to characterize the age gradient and internal properties of fireballs to understand their formation and evolution history, and link the fireballs to the global evolution of the jellyfish galaxy, allowing us to predict the ultimate fate of the stripped gas and stars formed outside the main disk.

Chapter 2

Methodology

2.1 The simulation

The simulation used in this work was made by [Akerman et al. \(2023\)](#) at the flatiron institute, and here the main features of it are summarized.

2.1.1 Setup

The simulation was done utilizing ENZO which is an adaptive mesh refinement (AMR) simulation code. To understand this, let's imagine a grid with dimensions $N \times N$, such that we have a particle in each cell of the grid. If we add another particle to the grid there would be a cell with 2 particles. The AMR will look at this cell and split it into two separated 1-particle cells, which allow us to have more resolution in that specific region without changing the whole grid. This tool allows us to have different resolutions at different regions of the simulation, saving a lot of computational work time without losing physics due to the resolution. In the simulation there are 5 levels of refinement where the smallest cell possible of 39 pc and the biggest 1.25 kpc.

2.1.2 Physical parameters of the simulation

Modeling the RPS: To model the RPS, instead of a galaxy falling into a cluster a wind-tunnel simulation was used. This means that the position of the galaxy was fixed in the center of the simulation box and then an "ICM wind" was added (see Fig. 2.1). If the intensity of the wind gets stronger, this type of simulation is a great approximation to the RPS in galaxies falling into the cluster accelerating due to gravity processes ([Akerman et al., 2023](#); [Tonnesen, 2019](#)).

To know how the galaxy is going to accelerate, the beta profile 1.2 was used matching the parameter β to observational X-ray data of the A85 cluster ([Akerman et al., 2023](#); [Campitiello](#)

et al., 2021) with a temperature of $7.1 \pm 0.2 \text{ keV} \equiv 8.24e7 \pm 0.2e7 \text{ K}$

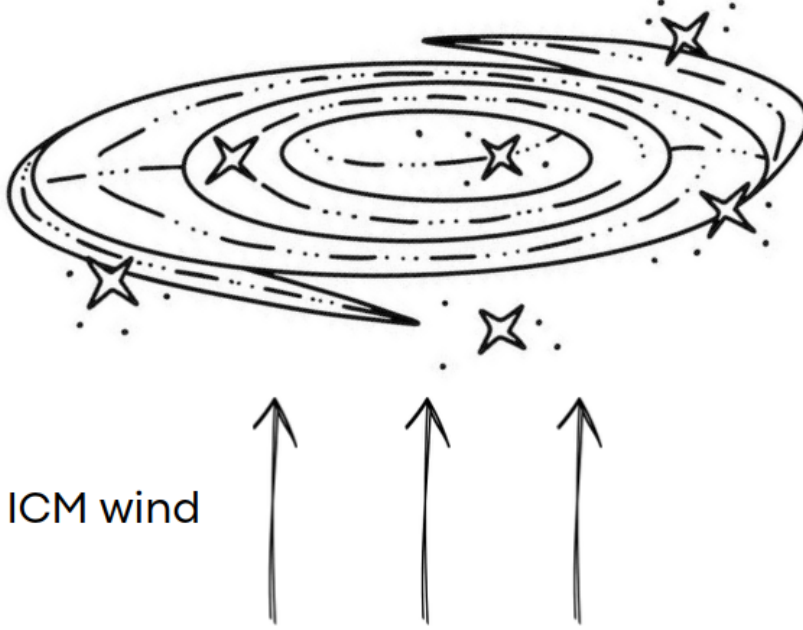


Figure 2.1: Visualization of the wind tunnel simulation, where the galaxy is fixed and ICM wind is coming from the z direction

Galaxy initial conditions: The initial conditions for the simulated initial galaxy are taken to be adjusted to observational data of the galaxy JO201 (Jellyfish Object 201 from the GASP team AGN sample (Poggianti et al., 2017a)). The kinematics of the galaxy are fitted from stellar rotation curves, and then fixing the mass of the stellar disk of the galaxy to $M_{star} = 10^{11} M_{\odot}$, the best parameters are obtained through fitting (Akerman et al., 2023): scale length $r_{star} = 5.94 \text{ kpc}$, scale height $z_{star} = 0.58 \text{ kpc}$ and for the DM halo $r_{DM} = 17.36 \text{ kpc}$. For the gas disk $M_{gas} = 10^{10} M_{\odot}$ and $r_{gas} = 1.7 \times r_{star} = 10.1 \text{ kpc}$

Star formation and feedback: In order to study the fireballs, we need to have knowledge about the star formation method used in Akerman et al. (2023). The model for star formation used is not a standard ENZO star formation parameter. Both star formation and stellar feedback follows from Goldbaum et al. (2016). This model assumes that the star formation is a function of the gas density in every cell, such that:

$$\frac{d\rho_*}{dt} = \begin{cases} f_* \frac{\rho}{t_{ff}} & , \quad \rho > \rho_{thresh} \\ 0 & , \quad \rho \leq \rho_{thresh} \end{cases} \quad (2.1)$$

Here f_* is the star formation efficiency, $t_{ff} = \sqrt{3\pi/32G\rho}$ the free-fall time associated to a pre-star molecular cloud and $\rho_{thresh} = \mu m_H n_{thresh}$ the threshold for the density. The parameter n_{thresh} is the most important one for the model, because it indicates that SF can happen in a cell if its mass exceeds the Jeans mass (Eq. 1.7). With this the following parameters are set: $n_{thresh} = 10 \text{ cm}^{-3}$, minimal mass for a star particle $M = 10^3 M_\odot$ and $f_* = 1\%$

The stellar feedback processes included are ionizing radiation from young stars, winds from massive stars and SN feedback, but our focus will be only in the star formation processes.

2.2 Finding fireballs

Access was provided to information on all stars formed after ram pressure began to affect the galaxy. In this dataset, each star in the simulation is associated with an unique ID, and for each star we record its age, mass, metallicity, Cartesian positions (x, y, z) , cylindrical radius r (in kpc), and velocities (v_x, v_y, v_z, v_r) (in km/s). The simulation outputs are separated by 5 Myr, spanning from 45 Myr to 700 Myr, resulting in a total of 131 snapshots. For data visualization, we used the STIL Tool Set (hereafter STILTS), the command-line counterpart of TOPCAT.

2.2.1 Friends-of-Friends algorithm

To identify fireballs in the simulation, a Friends-of-Friends (FoF) algorithm was applied. FoF methods are powerful tools widely used to analyze astrophysical simulations (e.g. Miller et al., 2025; Chamberlain et al., 2024), especially when the aim is to identify groups or substructures within a given snapshot.

There are multiple FoF implementations. For example, the Amiga Halo Finder (AHF; Knollmann and Knebe, 2009) links objects using gravitational binding criteria. The code used in this work, provided by Dr. Rory Smith, instead groups objects based on a “linking length” parameter l . This class of algorithm was first introduced by Davis et al. (1985) and remains widely used to identify structures in simulations (e.g. García-Farieta et al., 2024; Chamberlain et al., 2024; Gutiérrez Adame, Adrián et al., 2024). The method operates by linking a particle to all others within a distance l (its “friends”), and then linking those particles to their own neighbors (friends-of-friends), ultimately forming extended networks of connected particles known as groups.

Typically, the linking length is chosen as $l = 0.2 l_{\text{mean}}$, where l_{mean} is the mean interparticle spacing. In our case, the linking length was not selected following this convention. Instead, it was calibrated through iterative testing, resulting in a final adopted value of $l = 1.5 \text{ kpc}$. This choice

allow us to reliably track fireballs that leave extended star-forming trails as they move outward from the disk, without incorrectly merging them with nearby unrelated clumps. After fixing the linking length, a second parameter must be defined: the minimum number of particles required for the FoF to register a group, N_{cut} . Because the number of stars formed in each clump is not known, this threshold was initially set to three and later increased to five. Once these parameters were established, the FoF algorithm was applied independently to each snapshot, producing a list of particle groups (i.e. candidate fireballs) for every output.

An example of this algorithm is shown in Fig. 2.2, where particles are grouped starting from particle 1 by drawing a circular region of radius l . In this simple illustration, particles 1 to 9 are linked into a single group (or fireball), while particle 10 lies outside the linking length and is therefore excluded. This procedure is repeated for every particle in the simulation when the FoF is executed.

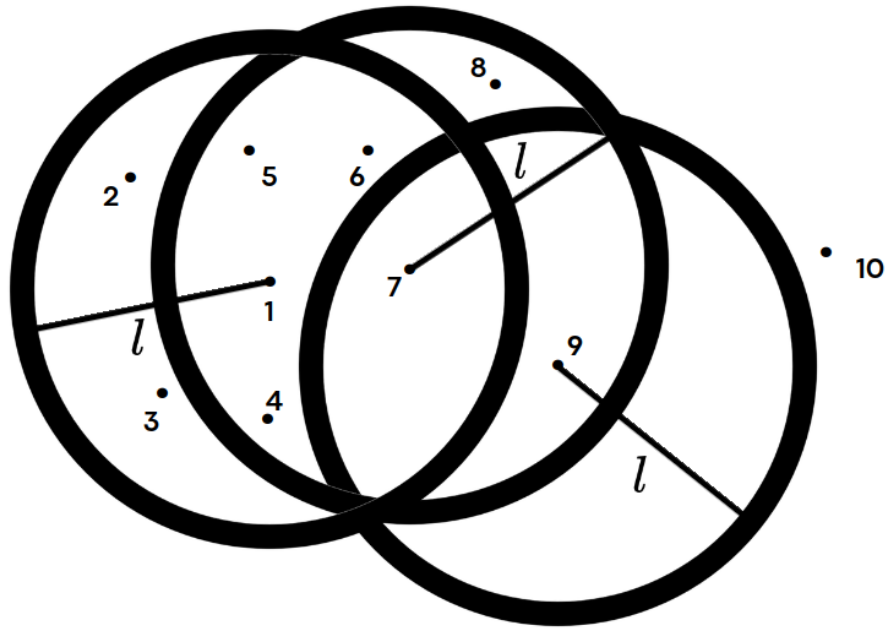


Figure 2.2: *Example of a FoF algorithm with linking length l . Particles 1 to 9 belong to the same group, while particle 10 does not.*

2.3 Tracking fireballs

After applying the FoF algorithm to every snapshot, the following step in our procedure is to connect the groups between consecutive outputs to follow the evolution and behavior of the fireballs. Since these objects are moving and continuously forming stars, the groups identified by FoF at different times may differ significantly. Therefore, to track the same object across snapshots, we connect groups using a probability-based approach (done with python), as illustrated in Fig. 2.3.

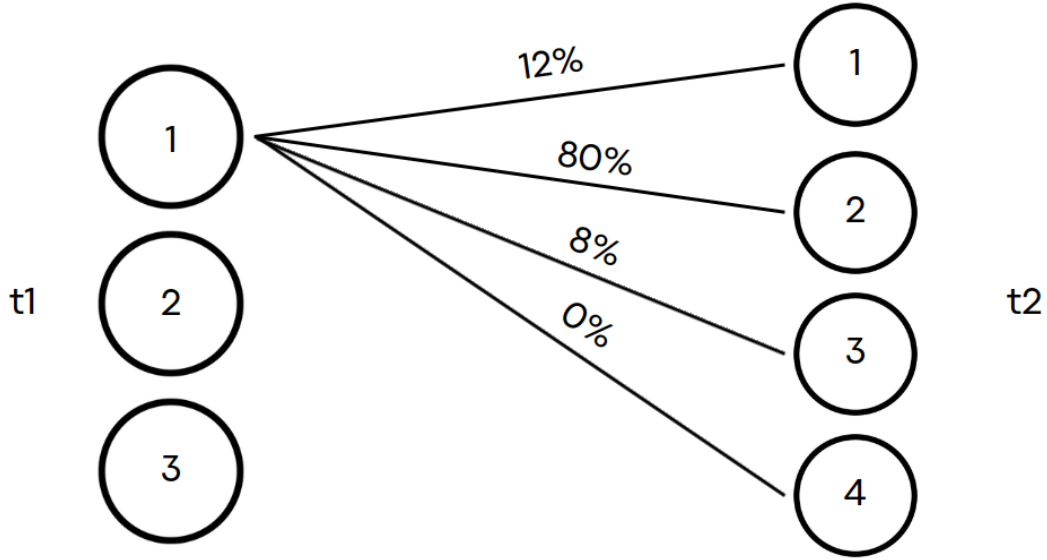


Figure 2.3: *Representation of the procedure used to connect groups between snapshots. All groups in snapshot t_1 are compared to all groups in t_2 in order to identify the most probable match. In this example, group 1 in t_1 is considered to be the same object as group 2 in t_2 .*

To compute the matching probability, we compare the stellar particle IDs in each group of t_1 with those in each group of t_2 . The group sharing the highest number of common IDs is considered the same object and is therefore linked across snapshots. However, relying solely on FoF is not sufficient. When a fireball falls back onto the central disk due to gravity, any nearby star in the disk could be artificially linked to the fireball by the FoF criterion alone. To avoid this, we introduce an additional condition based on the formation time of the stars. If the probability-based method assigns a new star to a fireball, we check its age to determine whether it was genuinely formed within the fireball. Since consecutive snapshots are separated by 5 Myr, any star such that $Age_* > 5 \text{ Myr}$ is not considered a part of the fireball. With these considerations we ended up with a sample of 272 individual fireballs with 5 or more stars.

2.4 Analyzing fireballs

Once we have our sample of fireballs in the simulation, our focus will be on fireballs that are formed 5 kpc away of the main disk, because it is a distance that we can distinguish those clumps observationally from the disk (based on observations of [Giunchi et al. \(2023\)](#); [Kenney et al. \(2014\)](#); [Vollmer et al. \(2024\)](#)). We are only going to consider fireballs with 9 or more stars in order to see a clear structure and to be able to calculate an age gradient. With this we ended up with a FIDUCIAL sample of 34 fireballs.

2.4.1 Age gradient

The study of the age gradient will be carried out in the z direction, following the direction of the ICM wind. We define the age gradient as

$$\nabla_z \text{age} = \frac{\Delta \text{age}}{\Delta z}, \quad (2.2)$$

where

$$\begin{aligned} \Delta \text{age} &= \text{age}_{\text{oldest}} - \text{age}_{\text{youngest}}, \\ \Delta z &= z_{\text{youngest}} - z_{\text{oldest}}. \end{aligned}$$

Both quantities are functions of time due to ongoing star formation and the kinematics of the clump. According to the theoretical expectations discussed in Section 1.4, if $\Delta z > 0$ (i.e. $z_{\text{youngest}} > z_{\text{oldest}}$), the youngest stars are located further away in the direction of the ICM wind, which corresponds to the expected behavior for ram-pressure-triggered star formation. In contrast, if $\Delta z < 0$ we say that the gradient is inverted.

Because the morphology of a fireball is not regular, the positions of the oldest and youngest stars are estimated using the mean position of the three youngest and the three oldest stars:

$$\begin{aligned} z_{\text{youngest}} &= \frac{1}{3} \sum_{i=1}^3 z_{i,\text{young}}, \\ z_{\text{oldest}} &= \frac{1}{3} \sum_{i=1}^3 z_{i,\text{old}}. \end{aligned}$$

Using three stars rather than a single one reduces variations arising from dispersion in the star formation and provides a more stable estimate of the spatial distribution of the age extremes.

To characterize the overall morphology of the fireball, we also compute the 3D age gradient, defined analogously to the z -gradient but using the full 3D separation between the oldest and youngest stars:

$$\nabla_d \text{age} = \frac{\Delta \text{age}}{\Delta d}. \quad (2.3)$$

Finally, to quantify the dispersion of the stars around the age gradient, we computed the distance of each star to the gradient line (defined by the youngest and oldest stars) as

$$d = \frac{\|\vec{AP} \times \vec{v}\|}{\|\vec{v}\|} \quad (2.4)$$

where $\vec{AP}$ connects the star to a point on the age gradient line, and $\vec{v}$ is the direction vector of that line. After computing all distances, the dispersion around the age gradient is expressed as the standard deviation

$$\sigma_{grad} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (d_i - \hat{d})^2}. \quad (2.5)$$

2.4.2 Statistical properties

To fully understand the behavior of the age gradient and the properties of fireballs, we will perform a statistical study of several characteristic quantities. These properties can be separated into two categories: kinematical properties and star formation properties. Our final goal is to construct a comprehensive correlation matrix¹ including all measured quantities for all fireballs. A schematic representation of these quantities is shown in Fig. 2.4.

For the kinematical properties, we record the relevant quantities at two key evolutionary moments for each fireball. The first is the snapshot in which the first star of the fireball forms (denoted by t_i ; if more than one star appears in this snapshot, we adopt the youngest). At this time we store its radial distance to the galaxy center (r_{ini}), its vertical position (z_{ini}), and its vertical velocity (v_{ini}).

The second key moment corresponds to the snapshot in which the last star of the fireball forms (denoted by t_{form}). At this time we again record the same kinematical quantities (r_{form} , z_{form} , and v_{form}). This moment is particularly relevant because it allows us to derive several additional quantities not explicitly provided by the simulation, but which can help reveal the physical nature of the fireball. These include

¹For an accessible introduction to correlation matrices see: <https://www.youtube.com/watch?v=X-H0oFzTUDM>

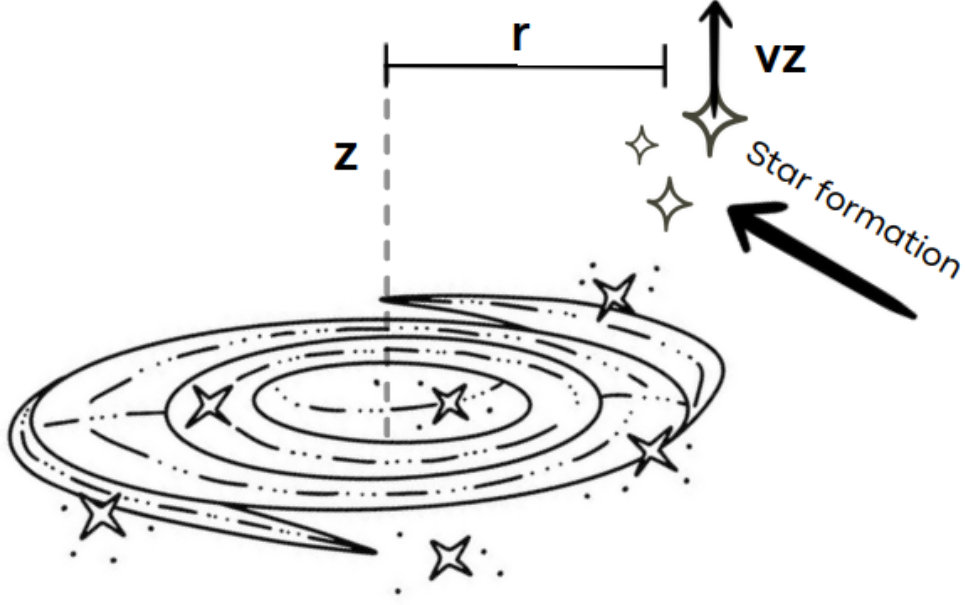


Figure 2.4: *Visualization of key properties of fireballs*

$$\Delta velocity = v_{form} - v_{ini}, \quad (2.6)$$

which measures the change in velocity between the first and last stars formed, and

$$acceleration = \frac{\Delta velocity}{t_{form} - t_i} \quad (2.7)$$

which provides an estimate of the average acceleration of the clump during its formation time. At t_{form} we also measure the dispersion of stellar positions relative to the mean position of the fireball, as well as the dispersion relative to the age–gradient line defined by Eqs. 2.3 and 2.4. Finally, as a sanity check for our measurements, we record the maximum height reached by the fireball (z_{max}) and the fallback time t_{fall} , defined as the snapshot at which the mean height of the fireball reaches the main body of the galaxy. If the fireball never falls back, the last available snapshot is taken as t_{fall} .

For the star formation properties, we record the following parameters: the total number of stars formed, the age difference between the first and last star (equal to the formation time of the fireball), the number of snapshots in which star formation occurs, the total stellar mass assembled, and the resulting star formation rate. These quantities are particularly relevant because they allow us to make observational predictions for the stellar components of jellyfish galaxy tails.

To summarize everything, a flowchart of the methodology used in this work is available in [A.1](#)

Chapter 3

Results and Discussion

In this chapter we present the results of the work. First we review some visual results from the simulation, afterwards the statistical results of our sample are exposed. Finally, A theoretical prediction regarding the fate of fireballs and jellyfish galaxies is stated.

3.1 Visual results

Here we present some interesting visual results from the simulation.

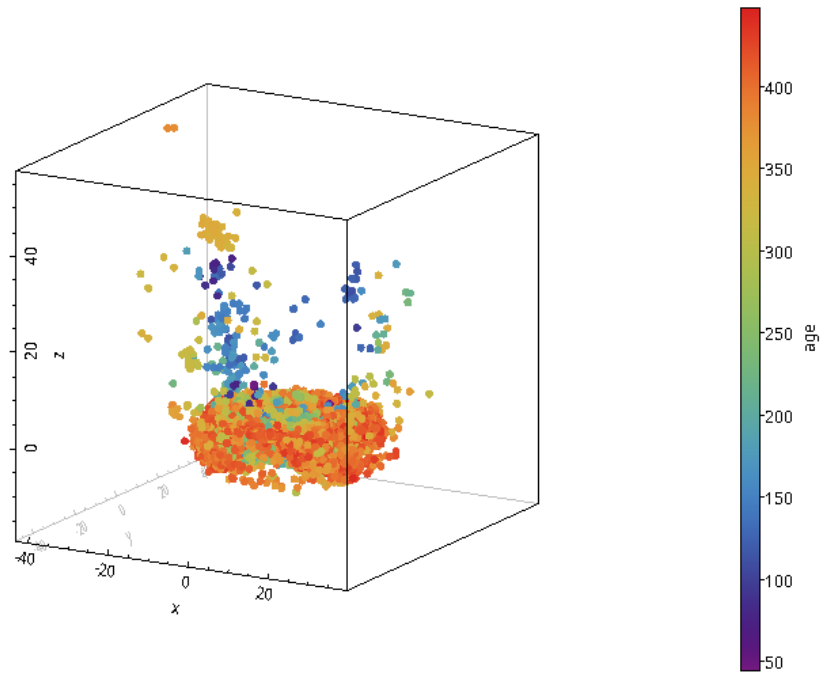


Figure 3.1: Output of the simulation colored by the age of the stars. We can see that in high altitudes, outside the plane of the disk we have the youngest stars and some older

In Fig. 3.1 we see the output of the snapshot $t = 490 \text{ Myr}$ ¹, where every star is colored by its age. We can clearly see that the older stars are located in the main disk while the younger ones are located in the RPS tail. This last result allows us to visualize the simulation as a whole, but we are interested in the behavior of individual fireballs.

We will focus now in the snap $t = 210 \text{ Myr}$ where there are some good examples of fireballs happening in the tail. First, let's see the full snapshot data in Fig. 3.2

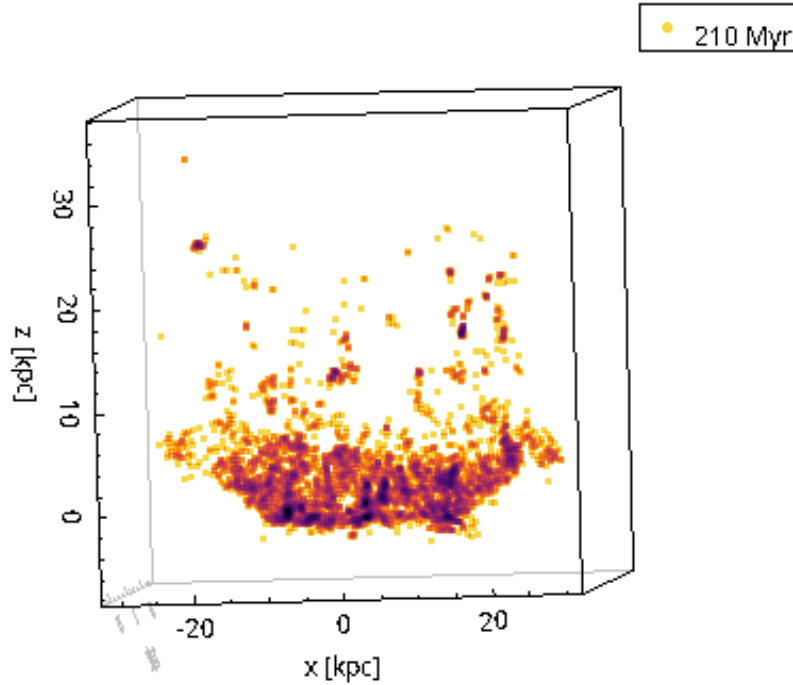


Figure 3.2: *Full output of the snapshot $t = 210 \text{ Myr}$, where the output is colored by the density of particles in the simulation. We can clearly see clumps of star formation outside the disk in heights up to 30 kpc.*

where, even though we have not applied the FoF algorithm yet, there are some visible structures formed in the tail. Now in 3.3 it is displayed what the FoF returns when applied for this snapshot. We can see that some stars are not considered by the friends of friends because they are not able to create groups of 5 or more stars, the stars that were considered into a groups are all colored by the "group color" to distinguish from one to another. We are going to analyze the fireballs a), b), c) and d) found in the snapshot.

¹A video with the full simulation colored is available in: https://www.youtube.com/watch?v=3Jr9S_ywEhk

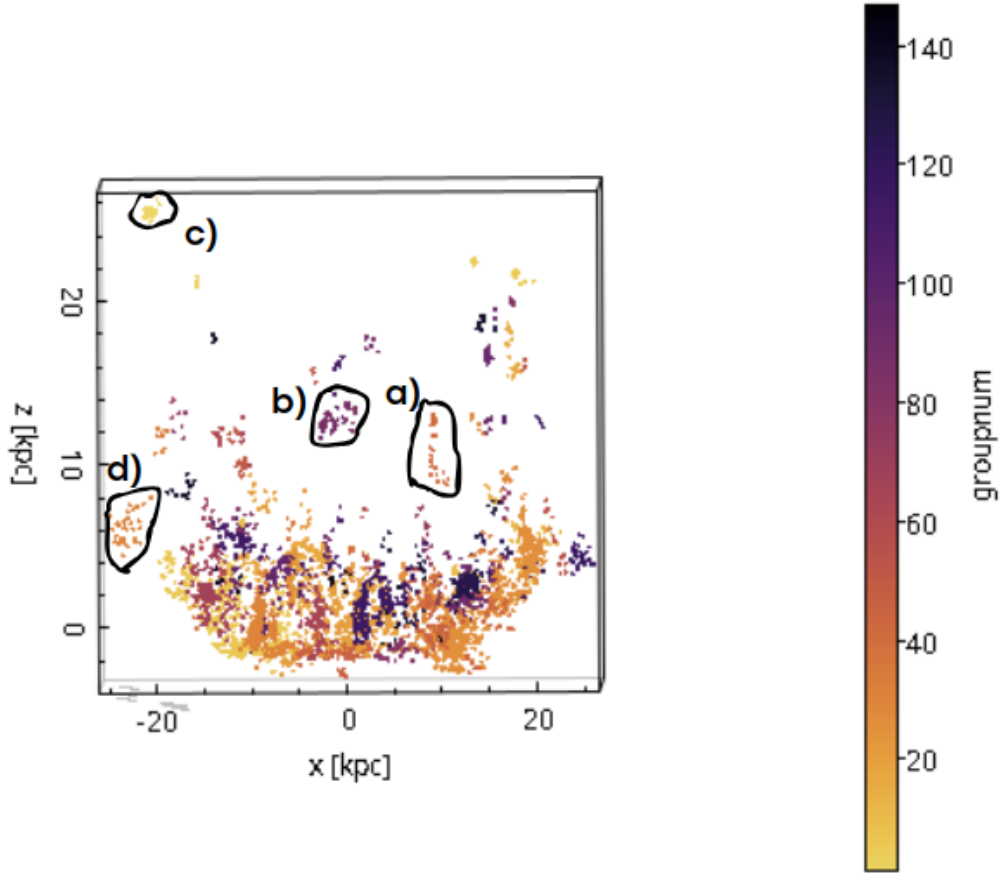


Figure 3.3: Output for the FoF algorithm applied to the snapshot $t = 210$ Myr colored by the groups, with 4 interesting fireballs marked. a) Fireball with a long strip of stars as predicted in section 1.3.1. b) Fireball with an interesting morphology near fireball a). c) The fireball at the most height. d) The fireball more radially away from the disk

With these four fireballs identified, we can zoom in to see how the age gradient is in them and if they match our expected theory.

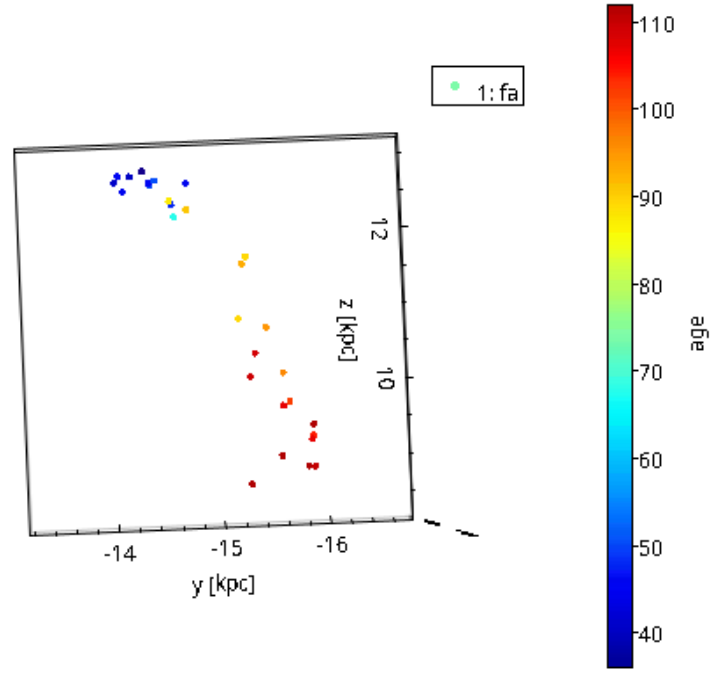


Figure 3.4: Zoom in of fireball a), where a clear age gradient in its distribution is visible

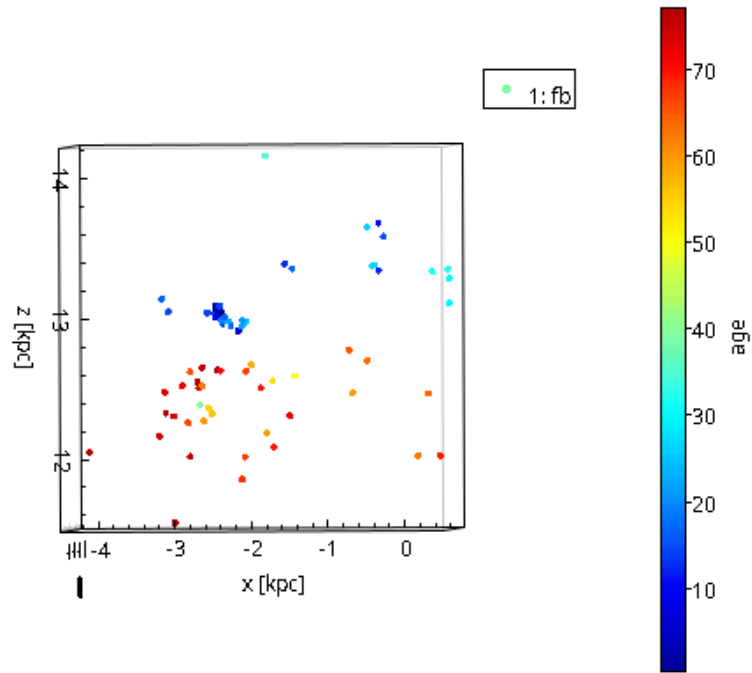


Figure 3.5: Zoom in of fireball b), where an age gradient is observed on it but the distribution of stars is also higher

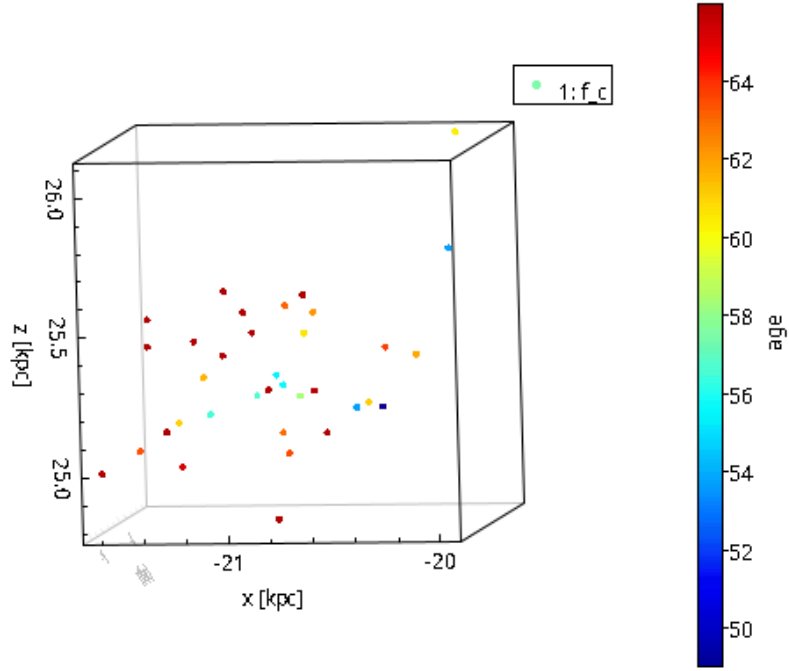


Figure 3.6: *Zoom in of fireball c), where the expected age gradient is not present on it. From only these examples we could attribute this behavior to the z position of the fireball (see section 3.2 for further analysis)*

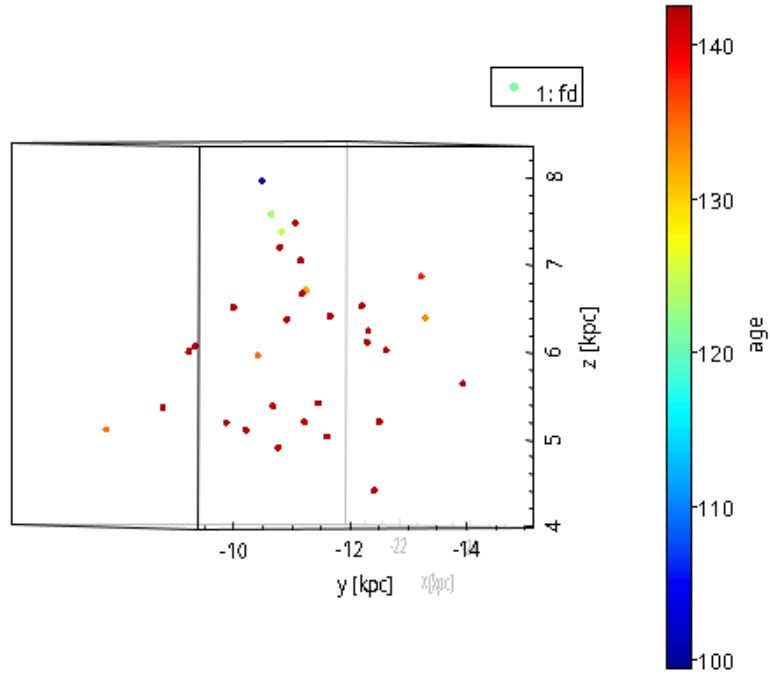


Figure 3.7: *Zoom in of fireball d), where the fireball even though it has an expected age gradient with the younger stars higher in z , the amount of old stars is higher than in the other examples, which in this case could be due to the radial distance to the center*

The identified fireballs give us great insight into what is happening with these objects in the galaxy. In Figs. 3.4 and 3.5 it is possible to see an expected age gradient as exposed in section 1.3.1, where the younger stars are higher than the older ones. Fig. 3.7 reveals that most of the stars on it are old with a little proportion of young stars, which could be related to its "low" position compared to the other fireballs. Finally in 3.6 we see a fireball with a totally unexpected fireball, with the older stars being higher than the younger ones. This could also be associated to the position of this fireball relative to the others but a different approach is studied in Section 3.2.1.

Some examples of the evolution of a single fireball in the three important snapshots explained in section 2.4.2, are found in Fig. 3.8² and 3.9³. We show this evolution with respect to the galaxy frame as a result of the tracking of the fireballs.

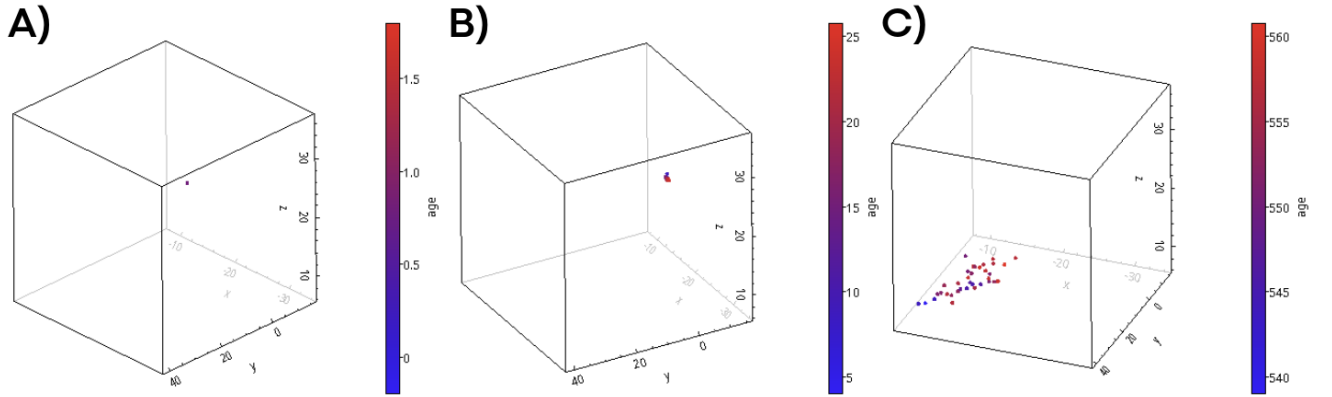


Figure 3.8: *Example of the tracking of the evolution of a fireball but in the frame of the galaxy in three snapshots. A) Snapshot of the first star formed in the fireball at $z \sim 15.8$ kpc above the main disk. B) Snapshot when all the stars are formed. C) Snapshot when the fireball is falling back to the galaxy. We can see that the fireball is moving following a similar rotation than the galaxy while is falling back.*

²see the complete evolution in <https://youtu.be/Fn66kRtD6ww>

³and here: <https://youtu.be/XZB7z9glaMA>

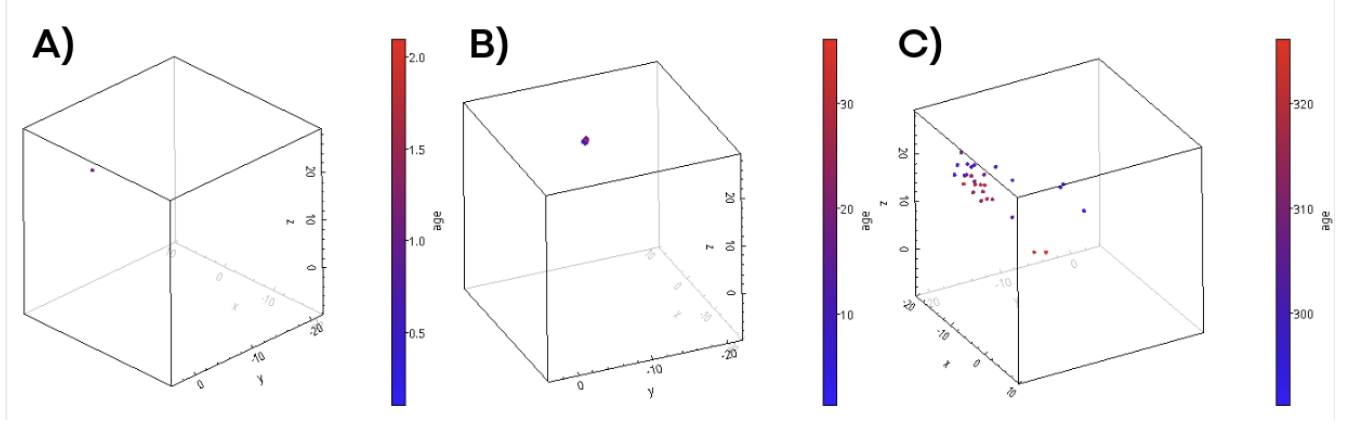


Figure 3.9: Example of the evolution of the fireball in the frame of the galaxy, The snapshots are analogous to Fig. 3.8. And we can also see that the fireball is moving following a similar rotation curve to the galaxy while is falling back.

In these last examples it is shown two interesting properties of the fireball. First, there is a big scatter in the distribution of stars along the fireball, which is why we need to use the mean of the three younger and older objects to measure age gradients. Second, we can see that the fireball is falling back to the main body of the galaxy in both cases because of its gravitational force which is in agreement with [Akerman et al. \(2025\)](#). Finally, in 3.8 there is a flip in the age gradient direction once the fireball is falling back to the galaxy, while in 3.9 the dispersion in the fireball is greater than in the previous example, having stars in $z \sim 20 \text{ kpc}$ and others in $z \sim 0$. For this reason we need to study the age gradient in a more analytic/consistent way.

To analyze the behavior of the age gradient using Eq. 2.2, we are comparing 4 plots side by side for each fireball of our sample: (1) $\Delta z \text{ vs. } t$, (2) $\nabla_z \text{age vs. } t$, (3) $\Delta \text{age vs. } t$ & (4) $\bar{z} \text{ vs. } t$. With these plots three cases were identified; "full normal" age gradient Fig. 3.10, "full inverted" age gradient Fig. 3.11 and "Mixed" age gradient Fig. 3.12 & 3.13.

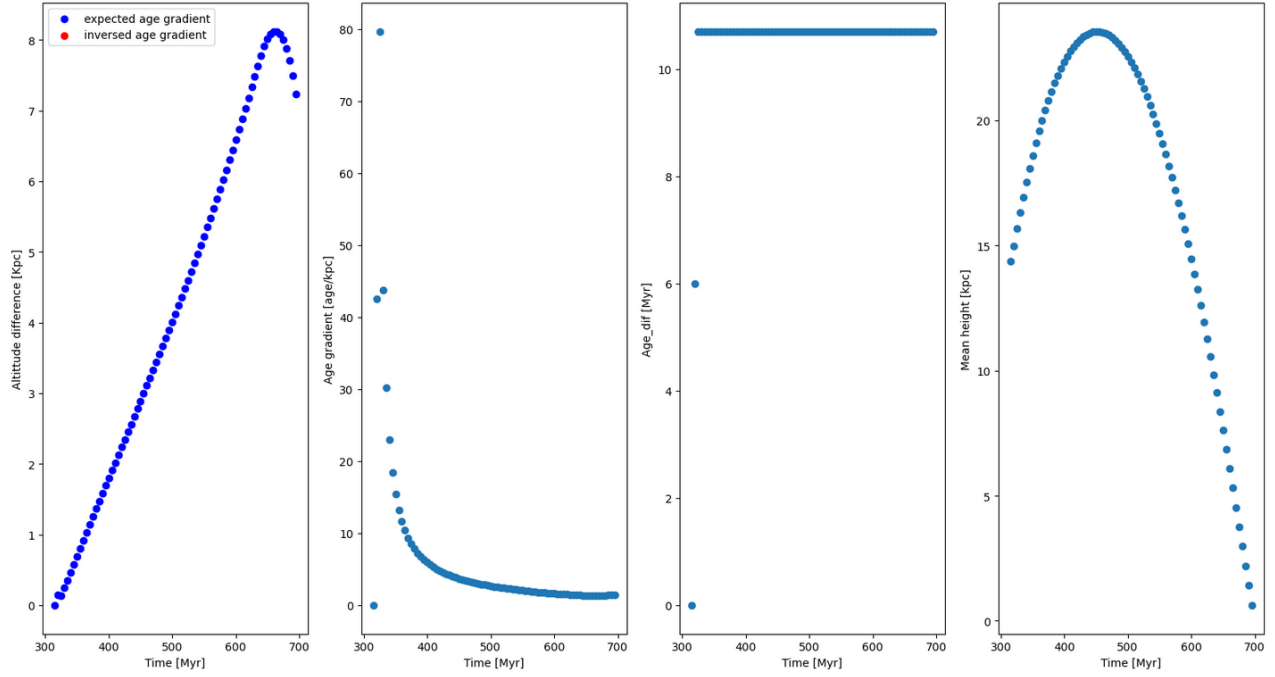


Figure 3.10: *Example of a fireball with an expected age gradient through all its life*

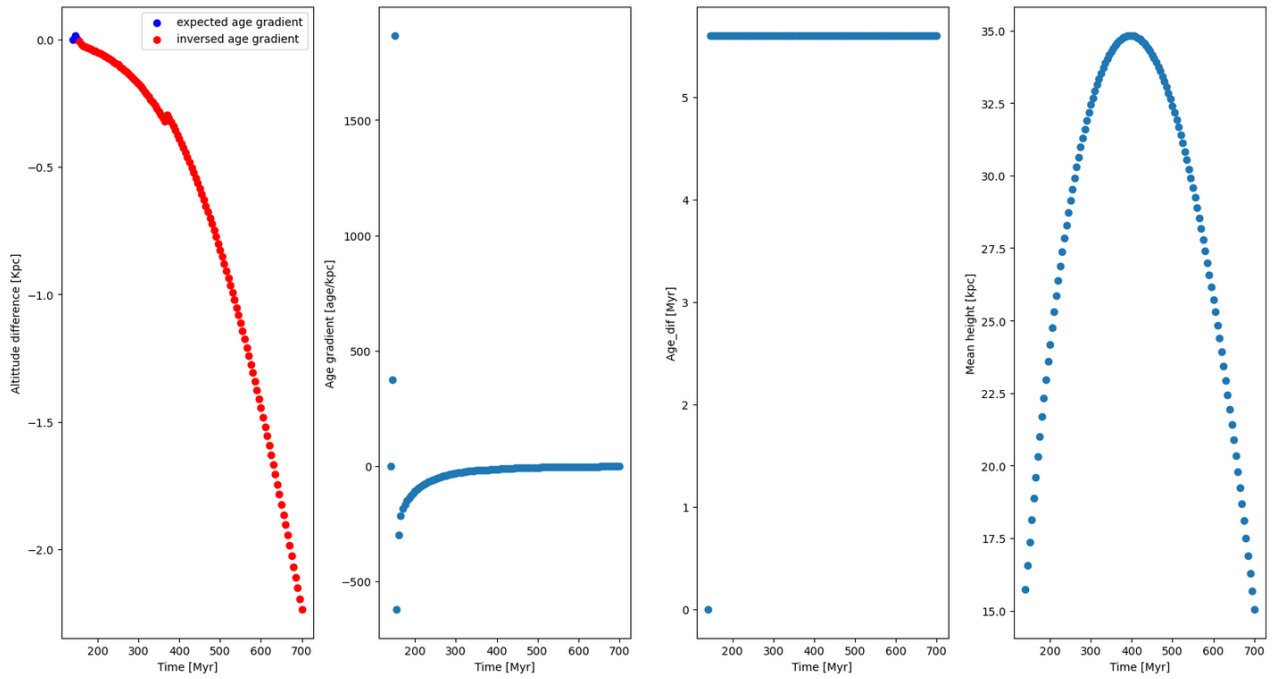


Figure 3.11: *Example of fireball with an inverted age gradient through all its life*

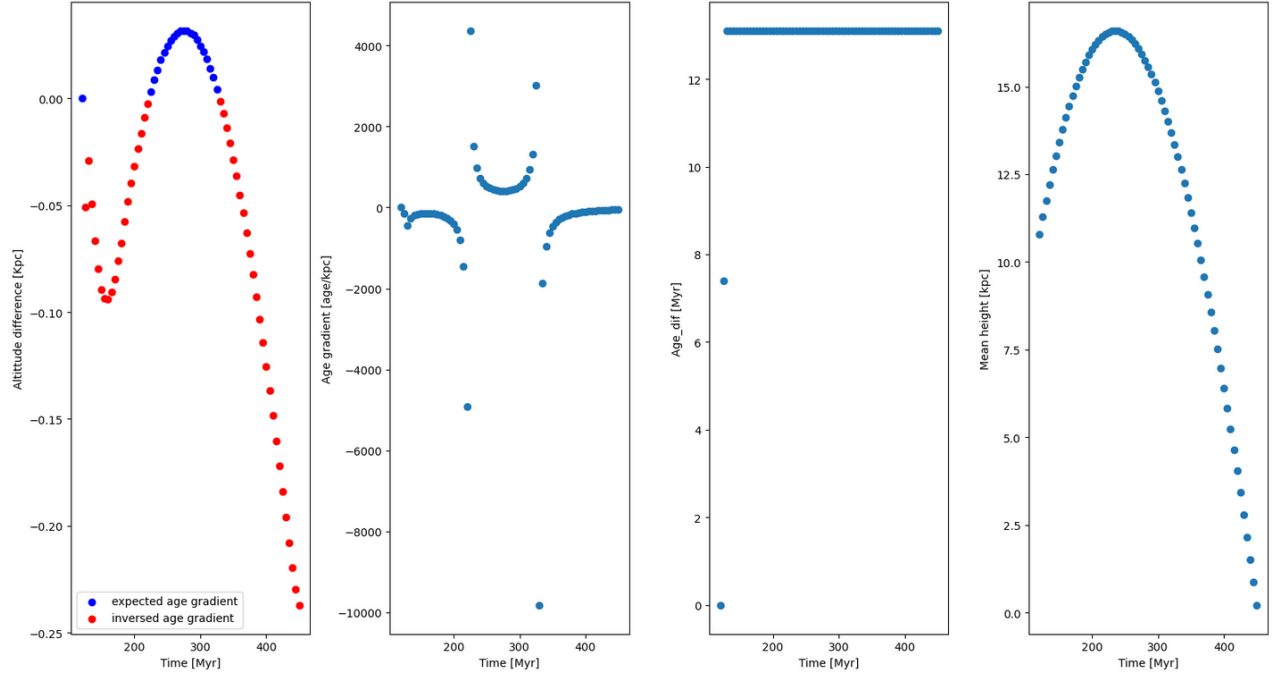


Figure 3.12: *Example of a fireball with a mixed age gradient. We can see two flips in the age gradient, represented with the change of color in the first panel, and because of the asymptotic behavior of the second panel. This is explained with the calculus of the age gradient with Eq. 2.2, when*

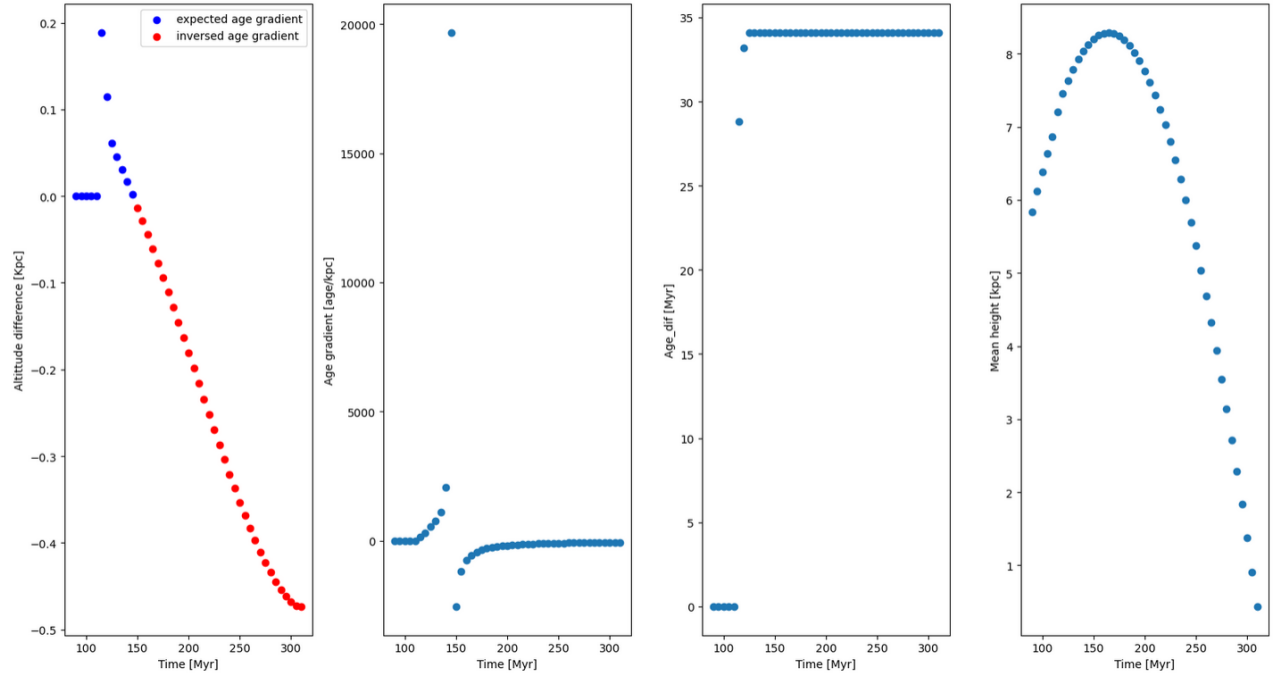


Figure 3.13: *Another example of an age gradient with a mixed behavior. In this case there is only one flip in the age gradient*

3.2 Correlations and fireball properties

	z ini	z fin SF	z max	v ini	v last star	# of stars	Formation time	Radial formation dist.	Radial initial dist.	Fallback time	z age gradient inversion	Total stellar mass	SFR	Grad velocity	Acceleration	Position dispersion	Fireball length at formation	Time pass since the beginning
z ini	1.00	0.94	0.88	0.63	0.66	-0.26	-0.29	0.42	0.44	0.69	-0.32	-0.22	0.39	0.22	0.02	-0.33	-0.21	0.14
z fin SF	0.94	1.00	0.87	0.73	0.73	-0.31	-0.20	0.60	0.57	0.73	-0.29	-0.29	0.28	0.16	0.02	-0.46	-0.24	-0.05
z max	0.88	0.87	1.00	0.85	0.86	-0.11	-0.24	0.60	0.64	0.94	-0.20	-0.06	0.61	0.21	-0.04	-0.45	-0.29	-0.12
v ini	0.63	0.73	0.85	1.00	0.92	-0.13	-0.01	0.69	0.73	0.91	-0.07	-0.13	0.48	0.01	-0.11	-0.53	-0.27	-0.43
v last star	0.66	0.73	0.86	0.92	1.00	-0.09	-0.28	0.58	0.68	0.88	-0.18	-0.06	0.56	0.39	0.13	-0.56	-0.41	-0.40
# of stars	-0.26	-0.31	-0.11	-0.13	-0.09	1.00	0.13	-0.12	0.05	-0.02	0.11	0.99	0.21	0.06	0.11	0.24	-0.12	0.10
Formation time	-0.29	-0.20	-0.24	-0.01	-0.28	0.13	1.00	0.19	0.06	-0.12	0.15	0.02	-0.50	-0.69	-0.02	0.27	0.19	0.10
Radial formation dist.	0.42	0.60	0.60	0.69	0.58	-0.12	0.19	1.00	0.93	0.73	0.13	-0.14	0.07	-0.14	-0.13	-0.41	-0.24	-0.59
Radial initial dist.	0.44	0.57	0.64	0.73	0.68	0.05	0.06	0.93	1.00	0.76	0.13	0.04	0.18	0.04	-0.08	-0.40	-0.36	-0.60
Fallback time	0.69	0.73	0.94	0.91	0.88	-0.02	-0.12	0.73	0.76	1.00	-0.05	0.01	0.64	0.12	-0.09	-0.46	-0.29	-0.34
z age gradient inversion	-0.32	-0.29	-0.20	-0.07	-0.18	0.11	0.15	0.13	0.13	-0.05	1.00	0.10	0.24	-0.30	-0.45	0.11	0.02	-0.24
Total stellar mass	-0.22	-0.29	-0.06	-0.13	-0.06	0.99	0.02	-0.14	0.04	0.01	0.10	1.00	0.31	0.14	0.12	0.25	-0.15	0.10
SFR	0.39	0.28	0.61	0.48	0.56	0.21	-0.50	0.07	0.18	0.64	0.24	0.31	1.00	0.35	-0.23	-0.35	-0.26	-0.07
Grad velocity	0.22	0.16	0.21	0.01	0.39	0.06	-0.69	-0.14	0.04	0.12	-0.30	0.14	0.35	1.00	0.61	-0.21	-0.42	0.00
Acceleration	0.02	0.02	-0.04	-0.11	0.13	0.11	-0.02	-0.13	-0.08	-0.09	-0.45	0.12	-0.23	0.61	1.00	0.09	-0.21	0.29
Position dispersion	-0.33	-0.46	-0.45	-0.53	-0.56	0.24	0.27	-0.41	-0.40	-0.46	0.11	0.25	-0.35	-0.21	0.09	1.00	0.59	0.43
Fireball length at formation	-0.21	-0.24	-0.29	-0.27	-0.41	-0.12	0.19	-0.24	-0.36	-0.29	0.02	-0.15	-0.26	-0.42	-0.21	0.59	1.00	0.25
Time pass since the beginning	0.14	-0.05	-0.12	-0.43	-0.40	0.10	0.10	-0.59	-0.60	-0.34	-0.24	0.10	-0.07	0.00	0.29	0.43	0.25	1.00

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First of all, the variables r_{ini} , r_{form} , v_{ini} , v_{form} , z_{ini} , z_{form} and z_{max} are all extremely positive correlated, which is telling us that faster fireballs tends to be created in the outskirts of the galaxy as we would expect according to Eq. 1.3, but its also interesting that faster fireballs often are created in higher altitudes, which could indicate that in the ram pressure model, the surface densities should be functions of r and z . Another variable highly positive correlated with these is the fallback time, which is a sanity check for the measurements, because is a fireball is faster in the z direction and its created in higher altitudes its fallback time should be higher. From now on because of these correlations, we will talk only of the velocities unless there is a change in the correlations for any of the variables exposed.

On the other hand, the velocity shows moderate negative correlations with the position dispersion and the length of the fireball (being the length of the fireball the distance of the age gradient Δd), while these last two variables are positively correlated. This implies that if a fireball is faster, the dispersion of the stars will be lower and therefore the length of the fireball tends to be lower. This is counterintuitive, and we think that this result suggest that this correlation is strictly related to the RPS, because when the clump has higher velocities, it means that the ram pressure was stronger for that clump. This powerful dynamic pressure would have acted to compress the fireball, resulting in a more compact structure (lower dispersion and smaller length), which could explain the observed inverse relationship.

Another interesting parameter correlated to the velocities is the time that has elapsed since the RPS started affecting the galaxy, because we see negative correlations with the velocities and the radial distance (as expected from the theory of RPS) but no correlation with the z parameters, which could be explained if the radial distribution of matter is more important than the z distribution, which is true for spiral galaxies, but not necessarily for dwarf galaxies as some studies have shown (e.g. [Hunter and Elmegreen \(2006\)](#); [van der Kruit and Searle \(1981\)](#)).

Other interesting correlation are the ones that the SFR parameter reveals. First of all it has a positive correlation with the velocity, implying that fireballs with higher velocities will have higher SFR. This according to what was exposed in section 1.4.2 could be interpreted as a Cloud-Cloud Collision happening in the tail, producing a burst of star formation in the fireball when there is high velocity collision of two clumps. This is reinforced when we realize that the SFR doesn't have a correlation with the radial distance of the fireball (further study of fireballs with higher velocities can be found in Section 3.2.1). Alongside this result and in relation with what was discussed above, there is a negative correlation between the SFR and the dispersion of the fireball, which we believe it's explained due to higher pressure in the clump. There is a final interesting correlation between the Δv (Eq. 2.6) and the SFR. We found that if the difference in velocities is higher the SFR is also higher, and the formation time of the fireball is lower, which again implies that there are

possible regions of starburst in the tails.

Age gradient correlations: Now let's explore which variables are correlated to the inv % defined in the previous section. Surprisingly there are only a few properties that have a relevant or even slightly relevant correlation with our parameter. We have positive correlations with total stellar mass of the fireball and the SFR, meaning that fireballs with more stellar mass have a more inverted or mixed behavior in the age gradient, while we have negative correlations with Δv and the acceleration 2.7, meaning that when a fireball undergoes a big acceleration we won't have a flip in the age gradient, while decelerating fireballs will have mixed or completely inverted behaviors. These last correlations are easy to understand, because if the velocity of the last star formed is lower than the velocity of the first, the older will end up higher than the younger and so the flipped will be produced. The correlation between the inv % and the star formation parameters is related to the kinematical ones, in 3.15 it is displayed a representation of this phenomena, where we have two clouds of masses M_1 and M_2 , such that $M_1 > M_2$. Because the ram pressure is the same for both clumps this implies that they will have two different accelerations a_1 and a_2 , such that $a_2 > a_1$ because of the relationship with the masses

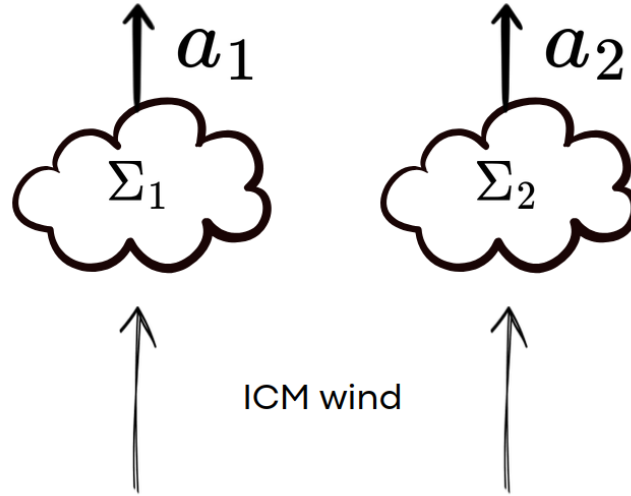


Figure 3.15: Representative picture for 2 clouds affected by the ICM wind. The idea is that if one cloud is more dense than the other (in this case $\Sigma_1 > \Sigma_2$) the resulting acceleration due to the ICM will be different for both clouds as we should expect from Eq. 1.5.

In summary, the age gradient inversion is driven by the inertia of massive fireballs undergoing lower accelerations, providing the dynamical basis for the following section.

3.2.1 Physics of the flip

In the previous section, we observed that the flip in the age gradient occurs due to the velocity difference between older and younger stars, driven by the deceleration of the clump during the star formation process. In this section, we derive a simple analytic expression to determine the environmental conditions required for this phenomenon.

Let us imagine a clump traveling through the ICM with an initial velocity v_i creating the first star of the fireball at an altitude z_i . Let t_i be the time of decoupling of the first star, t_f the time of formation of the last star, and t_c time when the flip is going to happen. With these definitions, the positions of these two stars will be given by:

$$z_{old}(t_c) = z_i + v_i(t_c - t_i) - \frac{1}{2} \frac{GM_{gal}}{z^2} (t_c - t_i)^2. \quad (3.1)$$

$$z_{young}(t_c) = z_i + v_i(t_c - t_i) + \frac{1}{2} a_{cloud}(t_f - t_i)^2 - \frac{1}{2} \frac{GM_{gal}}{z^2} (t_c - t_f)^2. \quad (3.2)$$

Where the older star decoupled from the cloud will only be affected by gravity, while the clump is subject to a hydrodynamical force and gravity. Therefore the acceleration of the cloud will be:

$$a_{cloud} = \pm C_D \frac{\rho_{ICM} v_{rel}^2}{\Sigma_{cloud}} - G \frac{M_{gal}}{z^2} \quad (3.3)$$

Where C_D is the drag coefficient that depends on the medium and on the clump characteristics. The $\pm$ will depend on the relative velocity (v_{rel}) between the cloud and the medium in which its moving. If the flip occurs, the older star and the youngest star must be in the same height. Thus we require:

$$z_{old}(t_c) = z_{young}(t_c)$$

Canceling similar terms, this leads to the condition between accelerations

$$-\frac{GM_{gal}}{z^2} (t_c - t_i)^2 = \left(\pm C_D \frac{\rho_{ICM} v_{rel}^2}{\Sigma_{cloud}} - G \frac{M_{gal}}{z^2} \right) (t_f - t_i)^2 - \frac{GM_{gal}}{z^2} (t_c - t_f)^2 \quad (3.4)$$

If we do some algebraic work for Eq. 3.4, we will end up with the following relation:

$$\frac{2GM_{gal}}{z^2} (t_f^2 - t_f(t_c + t_i) + t_c t_i) = \pm C_D \frac{\rho_{ICM} v_{rel}^2}{\Sigma_{cloud}} (t_f - t_i)^2 \quad (3.5)$$

From Eq. 3.5 we can assume that if the cloud is faster than the medium (i.e. the drag acceleration will have the minus), we will always satisfy the condition imposed. But if the cloud is

slower than the medium (i.e. keeps getting accelerated by the ram pressure stripping), implies that for an age gradient flip to be possible the gravity must be stronger than the ram pressure that will depend in a wide set of parameters.

Depending on what we want to do and the data available we can work with Eq. 3.5 to estimate t_c or to estimate C_D knowing t_c . For this let's derive expression for both variables with just algebraic work we can get:

$$C_D = \mp \frac{2GM_{gal}\Sigma_{cloud}(t_f^2 - t_f(t_c - t_i) + t_c t_i)}{z^2 \rho_{ICM} v^2 (t_f - t_i)^2} \quad (3.6)$$

$$t_c = t_f \mp \frac{C_D \rho_{ICM} v^2 z^2}{2GM_{gal}\Sigma_{cloud}} (t_f - t_i) \quad (3.7)$$

From Eqs. 3.5 and 3.6 if we start with a "positive" drag acceleration, our result for C_D is not physical because it has to be a positive value. So, the only possible case for deceleration due to a drag force would be if the clump is moving faster than the ICM in a certain region of the tail, will be given by the following conditions:

$$a_{cloud} = -C_D \frac{\rho_{ICM} v_{rel}^2}{\Sigma_{cloud}} - G \frac{M_{gal}}{z^2} \quad (3.8)$$

$$C_D = \frac{2GM_{gal}\Sigma_{cloud}(t_f^2 - t_f(t_c - t_i) + t_c t_i)}{z^2 \rho_{ICM} v^2 (t_f - t_i)^2} \quad (3.9)$$

$$t_c = t_f + \frac{C_D \rho_{ICM} v^2 z^2}{2GM_{gal}\Sigma_{cloud}} (t_f - t_i) \quad (3.10)$$

By this way, we can do some estimations for the behavior of the fireball if we know the properties of the molecular cloud and the ICM, but it escapes the data available for this work.

3.2.2 Fast fireballs

In the previous section, we observed significant correlations between velocity and many other variables. This led us to hypothesize that studying a subsample of fast fireballs could unveil even more about their nature.

For this new subsample, we selected fireballs with a speed of $v_Z > 50 \text{ km/s}$ and consisting of at least 9 stars, without imposing any restrictions on their initial position. This resulted in a sample of 35 individual fireballs. The correlation matrix for this specific sample is presented in Fig. 3.16.

The first noticeable difference between the matrices is the correlation of the variables v_{ini} , v_{form} , z_{ini} , z_{form} , and z_{max} with r_{ini} and r_{form} , where in this fast subsample, the latter two variables

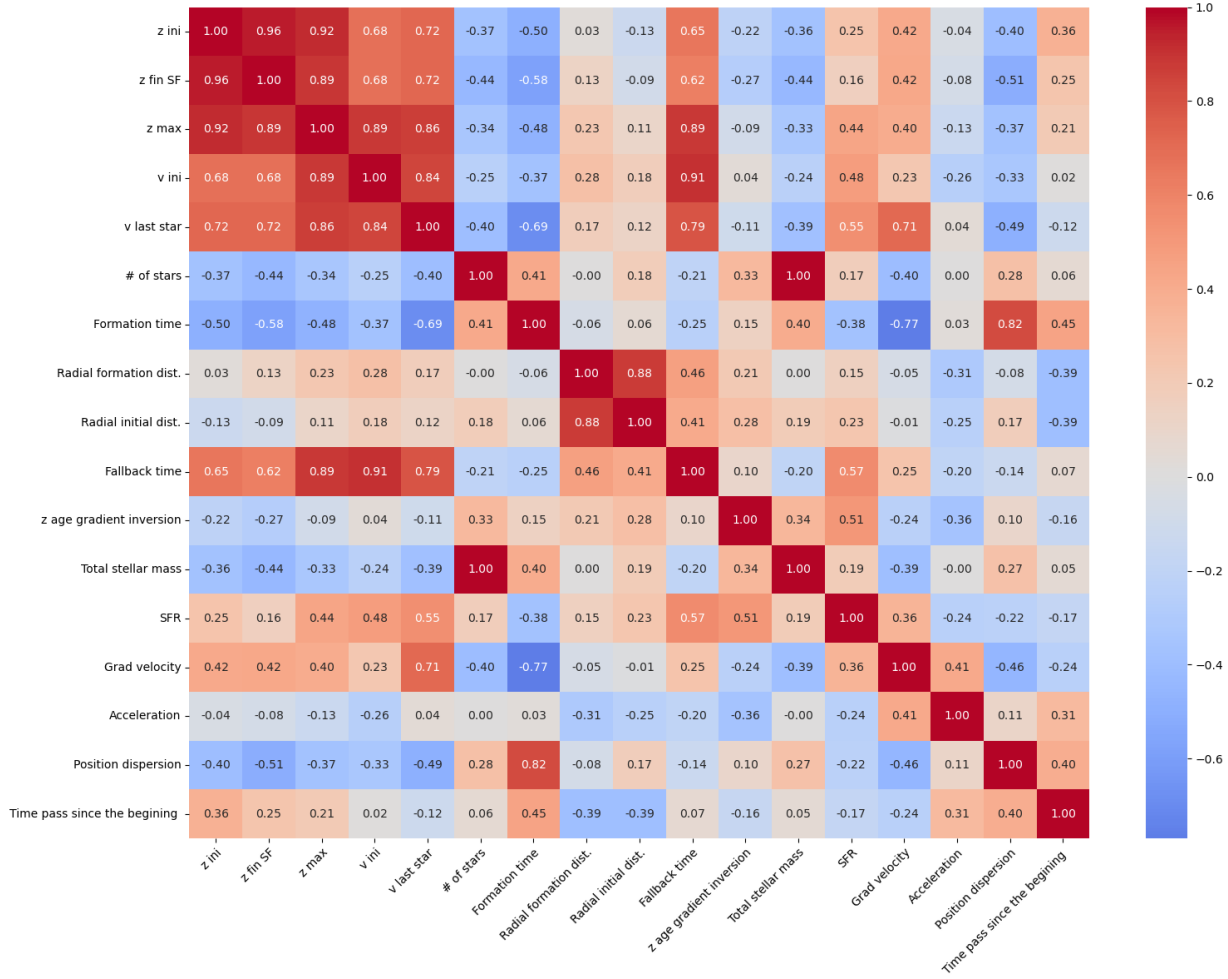


Figure 3.16: Correlation matrix for the fast subsample of fireballs

are much less correlated than in our previous sample. This could be explained by considering the nature of the RPS equation 1.3. Although the equation depends on r , the threshold for ram pressure to occur remains constant. Consequently, for fireballs with a high speed the radial distance becomes a less determinant parameter.

Regarding the SFR parameters, the tendency observed in the previous subsample remains present, though the effects are now stronger. We observe a negative correlation between the velocities and the number of stars in the fireball, the formation time, and the total stellar mass. We interpret this stronger anti-correlation as faster fireballs are likely to exhibit a short burst in star formation, which is reflected in their short formation times. Despite the anti-correlation with the final stellar mass, this behavior leads to a positive correlation between the velocity and the overall SFR.

Finally, for this subsample, we can see that the parameter describing the flip of the age gradient exhibits more significant correlations than before. We find new negative correlations between this

parameter and the fireball’s z altitude, and a new positive correlation with the total stellar mass created. Conversely, its correlations with Δv and the acceleration remain approximately unchanged. Our interpretation is that, for faster fireballs the flip is more likely to occur when they are formed in the inner regions of the tail, which we think could be related to the regions where the acceleration of the clump is dictated by Eq. 3.8, or regions where the gravity force exerted by the galaxy is enough to produce the flip. However, further studies are necessary to confirm this theory regarding the nature of the age gradient flip.

3.3 Observational predictions and the fate of fireballs

From our results we are able to make a few observational predictions of fireballs. First of all, we have seen that fast fireballs will pass through a burst of star formation, and through the correlations found we predict to localize them mostly far away of the galaxy. These could be found with future spectrograph with high enough resolution.

We believe that the localization of fireballs that will present an inverted age gradients is also possible observationally. Following the procedure made in [Kenney et al. \(2014\)](#), we can make observations in NUV and $H\alpha$ to identify fireballs with an inverted age gradient, or with probability to be inverted. Because of the correlation, if we can measure the SFR of a clump the identification of these regions could allow us to study the properties of the medium as well.

3.3.1 After the fallback

So far we have only been discussing what happens with the fireball before they fallback, but in our simulations we can find out what happens with the fireball after it fallback. Going back to our FIDUCIAL sample, but now tracking the fireballs until the end of the simulation (700 Myr after RPS starts) using the same plots described in section 3.1, we see that the following behavior is usual

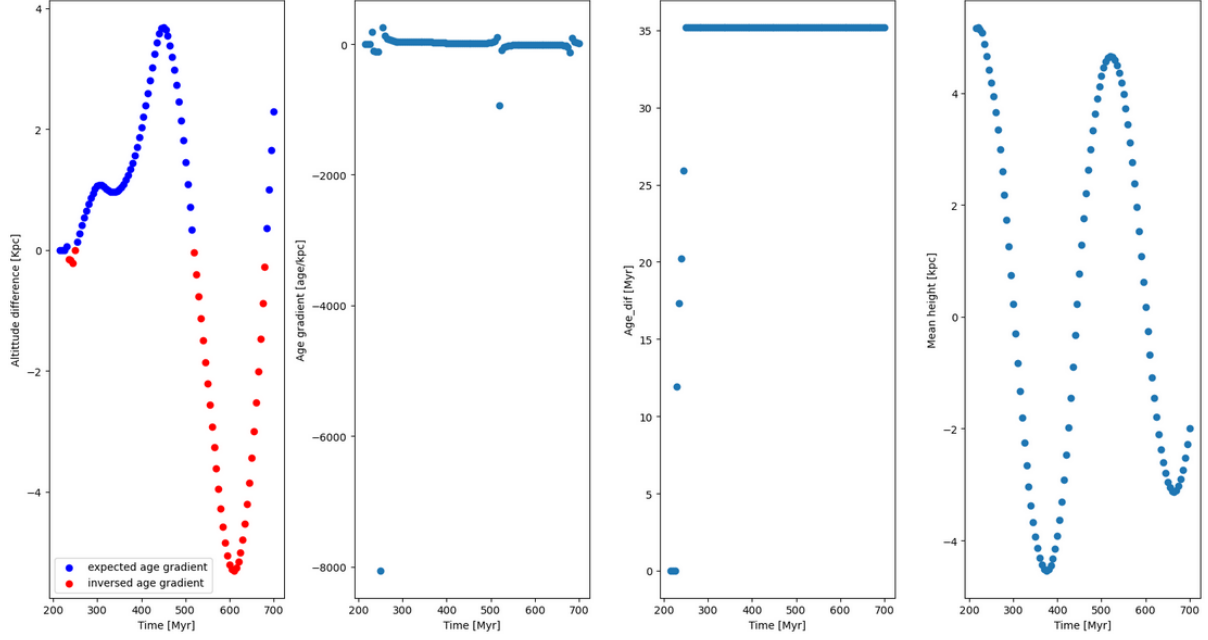


Figure 3.17: *Example of a fireball evolving even further than the first fallback. From left to right: (1) Δz vs. t , (2) $\nabla_z \text{age}$ vs. t , (3) Δage vs. t & (4) $\bar{z}$ vs. t . In the plot at the right, we can see a damped oscillatory behavior in the trajectory of the fireball, meaning that it will end up in the main body of the galaxy doing small oscillations*

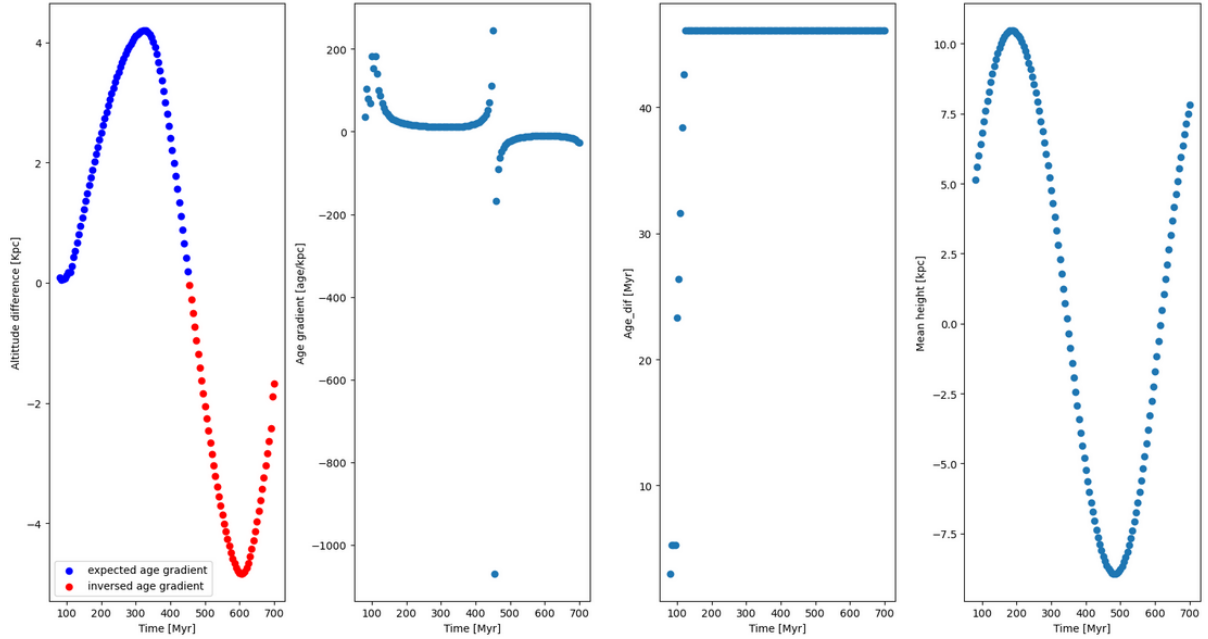


Figure 3.18: *Another example of a fireball evolving even further than the first fallback. From left to right: (1) Δz vs. t , (2) $\nabla_z \text{age}$ vs. t , (3) Δage vs. t & (4) $\bar{z}$ vs. t . In this case the trajectory of the fireball is well represented by a simple harmonic oscillator. The reason of the different behavior compared to 3.17 is unknown*

where almost all fireballs (30/34) present a mixed behavior in the age gradient. This could be explained by how the age gradient is calculated. In Eq. 2.2 we are considering Δz without taking into account the sign of z . If all the stars of the fireball get through the galactic center the calculus of Δz is

$$\Delta z_- = -|z_{young}| + |z_{old}| \quad (3.11)$$

Following our definitions of section 3.2, this last equation implies that if the older stars are more far away from the disk the age gradient will be normal and it will be inverted otherwise. We think that in this new regime, the study of the age gradient requires a different analysis and that it stops to have a significant role or sense because strictly speaking the fireball is a clump with active or recent star formation. From Fig. 3.17 and 3.18 we believe that it should be possible to localize groups of stars oscillating around the main disk⁴, but the resolution of a telescope for this to be possible needs to be better than it is now.

⁴example of this in the simulation can be found in: https://youtu.be/3D_ptc4kBxs

Chapter 4

Conclusion

4.1 Summary and conclusion

The main results of our work are presented:

(i) We have successfully identified and tracked 272 fireballs in a wind-tunnel simulation of a jellyfish galaxy. Contrary to the simple 'fireball model' where youngest stars are always at the head, a key finding of this work is that we found that inverted age gradients are common for these objects.

(ii) Through a simplified analytical derivation, we showed that this flip in the age gradient could be driven by the deceleration of the gas clump due to a Ram Pressure dragging force. Massive clumps with lower acceleration tend to exhibit inverted gradients, while faster, highly accelerated clumps maintain the expected gradient.

(iii) Our statistical analysis revealed that high-velocity fireballs tend to undergo short, intense bursts of star formation (high SFR, short formation time). These objects are likely created in the outskirts of the galaxy where the gravitational restoring force is weaker

(iv) Finally, tracking the fireballs in our simulation revealed that most of them do not escape the galaxy immediately but fall back onto the disk, following approximately damped oscillatory trajectories. This suggests that RPS contributes to the redistribution of stellar mass within the galaxy, but the processes behind the damp trajectory remains unclear.

From our results we also propose the following future works regarding this area:

(i) We would like to analyze the properties of the gas component before and after the formation of the fireball in the simulation, to have a broader view of this phenomena and the possibles star formation mechanisms happening in the tails.

(ii) We propose to test our theoretical predictions of the inverted age gradients by mapping the spatial offset between $H\alpha$ emission and NUV continuum, in real jellyfish galaxies so we can

reconstruct the star formation history along the tails. Specifically, we would aim to identify decelerating fireballs where the peak of the NUV emission appears upstream from the $H\alpha$ peak or really near it, confirming the deceleration scenario derived in our analytical model, or to find another possible explanation for the flip of the age gradient.

(iii) A more detailed theoretical analysis of the equations derived in Section 3.2.1 is required to fully characterize the mechanics of the age gradient inversion. We propose using observational data, such as that from the GASP survey, to constrain the drag coefficient (C_D) of real clumps interacting with the ICM. This study is crucial to fully comprehend the nature of these objects and their impact on both the host galaxy and the ICM.

Ultimately, decoding the complex dynamics of fireballs reveals that the extreme environment of galaxy clusters is not merely a graveyard for spiral galaxies, but an active laboratory where new stellar systems are born, evolving through a delicate interplay between hydrodynamics and gravity. If we fully understand their nature, we are going to be a bit closer to fully comprehend the metamorphic journey of jellyfish galaxies in the cosmic web.

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Appendix A

Methodology flowchart

