The GalMer database: Galaxy Mergers in the Virtual Observatory*

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ABSTRACT

We present the GalMer database, a library of galaxy merger simulations, made available to users through tools compatible with the Virtual Observatory (VO) standards adapted specially for this theoretical database. To investigate the physics of galaxy formation through hierarchical merging, it is necessary to simulate galaxy interactions varying a large number of parameters: morphological types, mass ratios, orbital configurations, etc. On one side, these simulations have to be run in a cosmological context, able to provide a large number of galaxy pairs, with boundary conditions given by the large-scale simulations, on the other side the resolution has to be high enough at galaxy scales, to provide realistic physics. The GalMer database is a library of thousands simulations of galaxy mergers at moderate spatial resolution and it is a compromise between the diversity of initial conditions and the details of underlying physics. We provide all coordinates and data of simulated particles in FITS binary tables. The main advantages of the database are VO access interfaces and value-added services which allow users to compare the results of the simulations directly to observations: stellar population modelling, dust extinction, spectra, images, visualisation using dedicated VO tools. The GalMer value-added services can be used as virtual telescope producing broadband images, 1D spectra, 3D spectral datacubes, thus making our database oriented towards the usage by observers. We present several examples of the GalMer database scientific usage obtained from the analysis of simulations and modelling their stellar population properties, including: (1) studies of the star formation efficiency in interactions; (2) creation of old counter-rotating components; (3) reshaping metallicity profiles in elliptical galaxies; (4) orbital to internal angular momentum transfer; (5) reproducing observed colour bimodality of galaxies.

Key words. Methods: N-body simulations – Galaxies: interactions – Galaxies: kinematics and dynamics – Galaxies: stellar content – Astronomical data bases: miscellaneous – Methods: numerical

1. Introduction

In the framework of the present cosmological paradigm, mergers and interactions are among the most important mechanisms governing galaxy formation and evolution. Spitzer & Baade (1951) proposed that collisions of late-type disc galaxies should produce early-type ones. A natural consequence of this phenomenon is the morphology–density relation discovered three decades later (Dressler 1980): dense regions of the Universe, where galaxy collisions are supposed to be more frequent, contain larger fractions of early-type galaxies than sparsely populated areas.

Toomre & Toomre (1972) were the first to suggest that interactions ‘tend to bring deep into a galaxy a fairly sudden supply of fresh fuel in the form of interstellar material...’ The gas in the bar formed during the interaction loses its angular momentum due to the torques (Combes et al. 1990; Barnes & Hernquist 1996), falls onto the galaxy centre possibly inducing strong bursts of star formation (Mihos & Hernquist 1994a, 1996) and creating young compact central stellar components (Mihos & Hernquist 1994b) often observed in present-day early-type galaxies (Silchenko 2004; Kuntschner et al. 2006). Intense star formation episodes accompanied by supernova explosions, enrich the interstellar medium (ISM) with heavy elements, consumed into the stars hence increasing the observed metal abundances of the stellar population.

Large scale cosmological N-body simulations (e.g. Springel et al. 2006; Ocvirk et al. 2008) often lack the spatial resolution to trace in detail star formation and morphological transformation at galaxy scale. Therefore, usually they are complemented by semi-analytical prescriptions qualitatively accounting for phenomena strongly affecting galaxy evolution, such as star formation (e.g. Blaizot et al. 2004; Somerville et al. 2008). However, the parameters of the semi-analytical models have to be chosen based on more detailed simulations of galaxy interactions. High resolution galaxy simulations (e.g. Bournaud et al. 2008) cannot be performed in large statistical numbers. A compromise has then to be done between statistics and resolution. This becomes one of the main motivations for studying large numbers of galaxy interactions by means of dedicated intermediate-resolution numerical simulations.

Merger-induced star formation, as well as morphological transformation, strongly depends on the mass ratio of the interacting galaxies. Generally, the intensity of starburst decreases as the merger mass ratio increases (e.g. Cox et al. 2008). Equal mass mergers of disc galaxies (mass ratios below 4:1) usually result in early-type elliptical-like remnants (Toomre 1977; Naab & Burkert 2003) while minor mergers (ratios above 10:1) do not destroy the progenitor’s disc preserv-
ing its exponential mass distribution although making it thicker and dynamically hotter (Quinn et al. 1993, Walker et al. 1996, Velazquez & White 1995, Bournaud et al. 2005). A sequence of repeated minor mergers can form elliptical galaxies, with global morphological and kinematical properties similar to that observed in real ellipticals (Bournaud et al. 2007).

Orbital parameters of the interaction and orientation of galaxies also strongly affect the process of merger, e.g. star formation efficiency on retrograde orbits is generally higher than for direct encounters (Di Matteo et al. 2007).

One needs to explore a large multi-dimensional parameter space (different initial morphologies related to gas content, orbital configurations, mass ratios, etc.) by running thousands of simulations in order to fully understand the astrophysical consequences of galaxy interactions for the modern picture of galaxy evolution.

The GalMer project, developed in the framework of the French national HORIZON[1] collaboration, has the ambitious goal of providing access for the astronomical community to the results of massive intermediate-resolution numerical simulations of galaxy interactions in pairs, covering as much as possible the parameter space of the initial conditions and, thus allowing to study statistically the star formation enhancements, structural and dynamical properties of merger remnants. An important aspect is to integrate the data services into the framework of the International Virtual Observatory in order to take the full advantage of already developed technologies and data visualisation and processing tools.

This paper is a technical presentation of: (1) the GalMer TreeSPH simulations providing all essential details on initial conditions for galaxies of different masses and prescriptions used to model the processes of star formation including supernova feedback and metallicity evolution; (2) the GalMer database, the first VO resource containing results of TreeSPH simulations; (3) the GalMer value-added services aimed at facilitating the comparison between simulations and observations such as modelling the spectrophotometric galaxy properties using an evolutionary synthesis code.

The paper is organised as follows: in Section 2 we describe initial conditions of the numerical simulations and orbital parameters of galaxy interactions; Section 3 contains information on the numerical method, prescriptions for star formation and metallicity evolution; Section 4 provides the description of the GalMer database structure, its access interface, and mechanisms of data visualisation; Section 5 presents value-added services of the GalMer database; in Section 6 we define some astrophysical applications which can be tackled with our simulations; Section 7 contains a brief summary.

2. Initial conditions

2.1. Galaxy models: moving along the Hubble sequence

We model interactions among galaxies of different morphologies, from ellipticals to late-type spirals.

The adopted galaxy models consist of a spherical non-rotating dark-matter halo, which may or may not contain a stellar and a gaseous disc and, optionally, a central non-rotating bulge. For each galaxy type, the halo and the optional bulge are modelled as Plummer spheres, with characteristic masses \( M_h \) and \( M_{\text{BH}} \) and characteristic radii \( r_h \) and \( r_{\text{BH}} \). Our choice of adopting a core density distribution for the dark halo seems to be more in accordance with the rotation curves of local spirals and dwarf galaxies, than the cuspy profiles predicted by Cold Dark Matter simulations (see Di Matteo et al. 2008a, Sect. 2.4.3 for a discussion). The stellar and gaseous discs follow the Miyamoto & Nagai (1975) density profile, with masses \( M_s \) and \( M_g \) and vertical and radial scale lengths given, respectively, by \( h_r \) and \( a_s \), and \( h_g \) and \( a_g \). We refer the reader to Appendix A for the analytical expression of these profiles. For the initial models of the disc galaxies, we chose an initial Toomre parameter for the stellar disc \( Q_{\text{star}} = 1.2 \) and two different initial ones for the gas component, \( Q_{\text{gas}} = 0.3 \) and \( Q_{\text{gas}} = 1.2 \), in order to reproduce, at least partially, the variety of parameters found in real galaxies (Martin & Kennicutt 2001; Boissier et al. 2003, Hitschfeld et al. 2009).

The database contains interacting galaxy pairs of different mass ratios (1:1, 1:2, 1:10), involving a giant galaxy (gE0 for a giant-like elliptical, gS0 for a giant-like lenticular, gSa for a giant-like Sa spiral, gSb for a giant-like Sbc spiral and gSd for a giant-like Sd spiral), interacting with:

- either another giant galaxy;
- or an intermediate-mass galaxy (hereafter iE0, iS0, iSa, iSb and iSd), having a total mass half that of the giant’s mass;
- or a dwarf galaxy (hereafter dE0, dS0, dSa, dSb and dSd) whose total mass is ten times smaller that that of the giant galaxy.

The complete Hubble sequence of the galaxy models is given in Fig.1 Moving along the Hubble sequence, from gE0 to gSd galaxies, the mass of the central spheroid varies from \( M_{\text{E0}} = 1.6 \times 10^{11} M_\odot \) for a gE0 to \( M_{\text{E0}} = 0 \) for a gSd, while the gas mass \( M_{\text{gas}} \) in the case of a gE0 and gS0, increases from \( 9.2 \times 10^9 M_\odot \) in a gSa to \( 1.7 \times 10^{10} M_\odot \) for a gSd (see Table 1 for a complete list of all the parameters of giant-like galaxies, and Tables 2 and 3 for the corresponding set of parameters of intermediate and dwarf systems). Our modelled Hubble sequence capture the main properties of local galaxies. We plan in the future to extend this library to higher redshift, considering larger gas fractions for the disc galaxies.

The initial rotation curves of the modelled disc galaxies are shown in Fig.2

Each galaxy is made up of a total number of particles \( N_{\text{TOT}} \) distributed among gas, stars and dark matter. Gas particles are actually “hybrid particles”, characterized by two mass values: one corresponds to the gravitational mass and stays unchanged during the whole simulation, and the other is the gas content of the particle, decreasing or increasing according to the local star formation rate and mass loss (see Sect. 3.1, Eq. 1). When the gas fraction is below a certain threshold, the particle is transformed into a star particle, and the remaining gas mass is distributed over neighbouring gas particles.

For giant-giant interactions, each galaxy is made up of a total number of particles \( N_{\text{TOT}}=120000 \), distributed among gas, stars and dark matter, depending on the morphology (Table 4). For giant-intermediate and giant-dwarf interactions, we increased by a factor 4 the total number of particles in the giant galaxy. This allowed us to improve the spatial resolution of the simulations and, in particular, to maintain a high enough numerical resolution for the smaller galaxy (\( N_{\text{TOT}}=240000 \) and \( N_{\text{TOT}}=480000 \) for the intermediate and dwarf galaxy, respectively; Tables 5 and 6).

To initialize particle velocities, we adopted the method described in Hernquist (1993).

In order to distinguish the role of interactions from secular evolution, for each galaxy model we provide in the database

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[1] http://www.projet-horizon.fr/
Fig. 1. Hubble sequence of the GalMer galaxy models. From left to right, and from the top to the bottom, projection on the x-z plane of giant, intermediate and dwarf galaxies. Different colors correspond to the different galaxy components: dark matter (grey), bulge (red), stellar disc (orange), and gaseous disc (blue). Each frame is 50 kpc × 50 kpc in size.

Fig. 2. Rotation curves for the different galaxy models. The initial rotation curve is shown (solid thick black curve), together with the contribution by the bulge component (thin solid red curve), the stellar disc (orange dashed curve), the gaseous disc (dot-dashed blue curve) and the dark matter halo (dotted grey curve). Lengths are in kpc and velocities in units of 100 km/s.

Table 1. Galaxy parameters for giant galaxies. The bulge and the halo are modelled as Plummer spheres, with characteristic masses $M_B$ and $M_H$ and characteristic radii $r_B$ and $r_H$. $M_\ast$ and $M_g$ represent the masses of the stellar and gaseous discs whose vertical and radial scale lengths are given, respectively, by $h_\ast$ and $a_\ast$, and $h_g$ and $a_g$.

| gE0 | gSO | gSa | gSb | gSd |
|-----|-----|-----|-----|-----|
| $M_B [2.3 \times 10^9 M_\odot]$ | 70 | 10 | 10 | 5 | 0 |
| $M_H [2.3 \times 10^9 M_\odot]$ | 30 | 50 | 50 | 75 | 75 |
| $M_\ast [2.3 \times 10^9 M_\odot]$ | 0 | 40 | 40 | 20 | 25 |
| $M_g/M_\ast$ | – | – | 0.1 | 0.2 | 0.3 |
| $r_B$ [kpc] | 4 | 2 | 2 | 1 | – |
| $r_H$ [kpc] | 7 | 10 | 10 | 12 | 15 |
| $a_\ast$ [kpc] | – | 4 | 4 | 5 | 6 |
| $h_\ast$ [kpc] | – | 0.5 | 0.5 | 0.5 | 0.5 |
| $a_g$ [kpc] | – | – | 5 | 6 | 7 |
| $h_g$ [kpc] | – | – | 0.2 | 0.2 | 0.2 |

2.2. Orbital parameters

For each pair of interacting galaxies, we performed several simulations, varying the galaxies’ orbital initial conditions (initial orbital energy $E$ and angular momentum $L$) and taking into account both direct and retrograde orbits (Tables 7, 8 and 9). For each interacting pair, we kept the disc (when present) of one of the two galaxies in the orbital plane ($i_1 = 0^\circ$), and varied the inclination $i_2$ of the companion disc, considering: $i_2 = 0^\circ$, $i_2 = 45^\circ$, $i_2 = 75^\circ$, and $i_2 = 90^\circ$. The clustering of the angles toward $i_2 = 90^\circ$, for an uneven sampling, is logical from a pure...
geometrical point of view, considering that the probability of the spin $i_2$ of the second galaxy to be oriented between 0 and $i_2$ is proportional to $1 - \cos(i_2)$: this means, for example, that an orientation $i_2$ between $45^\circ$ and $90^\circ$ has probability 2.3 times higher than an orientation $i_2$ between $0^\circ$ and $45^\circ$. However, the spins alignment may not be totally uncorrelated, as recently shown by Jimenez et al. (2010), but a distribution function, to our knowledge, is still lacking. For giant-giant interactions, we also consider a more generic case, with $i_1 = 33^\circ$, and $i_2 = 130^\circ$ (see Fig. 3 for a sketch of the initial orbital geometry and Table 10 for the orientation of the galaxy spins).

### 3. Numerical method

To model galaxy evolution, we employed a Tree-SPH code, in which gravitational forces are calculated using a hierarchical tree method (Barnes & Hut 1986) and gas evolution is followed by means of smoothed particle hydrodynamics (SPH, Lucy 1977, Gingold & Monaghan 1982). Gravitational forces are calculated using a tolerance parameter $\theta = 0.7$ and include terms up to the quadrupole order in the multipole expansion. A Plummer potential is used to soften gravitational forces, with same softening lengths for all particle types. We assume a softening length equal to $1/20$th of the particle diameter.

### Table 2. Galaxy parameters for intermediate galaxies. The bulge and the halo are modelled as Plummer spheres, with characteristic masses $M_B$ and $M_H$ and characteristic radii $r_B$ and $r_H$. $M_i$ and $M_S$ represent the masses of the stellar and gaseous discs whose vertical and radial scale lengths are given, respectively, by $h_v$ and $a_v$, and $h_R$ and $a_R$.

| iE0 | iS0 | iSa | iSb | iSd |
|-----|-----|-----|-----|-----|
| $M_B [2.3 \times 10^9 M_{\odot}]$ | 35 | 5 | 5 | 2.5 | 0 |
| $M_H [2.3 \times 10^8 M_{\odot}]$ | 15 | 25 | 25 | 37.5 | 37.5 |
| $M_i [2.3 \times 10^9 M_{\odot}]$ | 0 | 20 | 20 | 10 | 12.5 |
| $M_S [2.3 \times 10^9 M_{\odot}]$ | – | – | 0.1 | 0.2 | 0.3 |
| $r_B [kpc]$ | 2.8 | 1.4 | 1.4 | 0.7 | – |
| $r_H [kpc]$ | 5.0 | 7.0 | 7.0 | 8.5 | 10.6 |
| $a_v [kpc]$ | – | 2.8 | 2.8 | 3.5 | 4.2 |
| $h_v [kpc]$ | – | 0.35 | 0.35 | 0.35 | 0.35 |
| $a_R [kpc]$ | – | 3.5 | 4.2 | 5.0 |
| $h_R [kpc]$ | – | 0.14 | 0.14 | 0.14 |

### Table 3. Galaxy parameters for dwarf galaxies. The bulge and the halo are modelled as Plummer spheres, with characteristic masses $M_B$ and $M_H$ and characteristic radii $r_B$ and $r_H$. $M_i$ and $M_S$ represent the masses of the stellar and gaseous discs whose vertical and radial scale lengths are given, respectively, by $h_v$ and $a_v$, and $h_R$ and $a_R$.

| iE0 | iS0 | iSa | iSb | iSd |
|-----|-----|-----|-----|-----|
| $M_B [2.3 \times 10^9 M_{\odot}]$ | 7 | 1 | 1 | 0.5 | 0 |
| $M_H [2.3 \times 10^8 M_{\odot}]$ | 3 | 5 | 5 | 7.5 | 7.5 |
| $M_i [2.3 \times 10^9 M_{\odot}]$ | 0 | 4 | 4 | 2.5 |
| $M_S [2.3 \times 10^9 M_{\odot}]$ | – | – | 0.1 | 0.2 | 0.3 |
| $r_B [kpc]$ | 1.3 | 0.6 | 0.6 | 0.3 | – |
| $r_H [kpc]$ | 2.2 | 3.2 | 3.2 | 3.8 | 4.7 |
| $a_v [kpc]$ | – | 1.3 | 1.3 | 1.6 | 1.9 |
| $h_v [kpc]$ | – | 0.16 | 0.16 | 0.16 |
| $a_R [kpc]$ | – | 1.6 | 1.9 | 2.2 |
| $h_R [kpc]$ | – | 0.06 | 0.06 | 0.06 |

### Table 4. Particle numbers for giant-intermediate interactions (mass ratio 1:1)

| gE0 | gS0 | gSa | gSb | gSd |
|-----|-----|-----|-----|-----|
| $N_{\text{gas}}$ | 80000 | 80000 | 60000 | 40000 |
| $N_{\text{DM}}$ | 40000 | 40000 | 40000 | 40000 |

### Table 5. Particle numbers for giant-intermediate interactions (mass ratio 1:2)

| gE0 | gS0 | gSa | gSb | gSd |
|-----|-----|-----|-----|-----|
| $N_{\text{gas}}$ | 320000 | 320000 | 240000 | 160000 |
| $N_{\text{DM}}$ | 160000 | 160000 | 160000 | 160000 |

### Table 6. Particle numbers for giant-dwarf interactions (mass ratio 1:10)

| gE0 | gS0 | gSa | gSb | gSd |
|-----|-----|-----|-----|-----|
| $N_{\text{gas}}$ | 32000 | 32000 | 240000 | 160000 |
| $N_{\text{DM}}$ | 160000 | 160000 | 160000 | 160000 |

Fig. 3. Adopted orbital geometry for the simulations. We set up the collision in such a way that the orbital angular momentum is parallel to the z-axis and that the centers of the two galaxies initially are on the x-axis. The galaxy spins are represented by the blue and red arrows, respectively. They are specified in terms of the spherical coordinates $(i_1, \Phi_1)$ and $(i_2, \Phi_2)$. See Table 10 for their initial values.
presented by particles, which obey equations of motion similar to the gas.

The technique in which the gas is partitioned into fluid elements is rep-

Table 7. Orbital parameters for giant-giant interactions

| orb.id | $r_{ini}$ kpc | $v_{ini}$ km s$^{-1}$ | $L^x$ km$^2$s$^{-1}$ | $E^x$ km$^2$s$^{-2}$ | spin$^e$ |
|--------|--------------|-------------------|-----------------|-----------------|-------|
| 01dir  | 100.         | 2.                | 56.6            | 0.0             | up    |
| 01ret  | 100.         | 2.                | 56.6            | 0.0             | down  |
| 02dir  | 100.         | 3.                | 59.3            | 2.5             | up    |
| 02ret  | 100.         | 3.                | 59.3            | 2.5             | down  |
| 03dir  | 100.         | 3.7               | 62.0            | 5.0             | up    |
| 03ret  | 100.         | 3.7               | 62.0            | 5.0             | down  |
| 04dir  | 100.         | 5.8               | 71.5            | 15.0            | up    |
| 04ret  | 100.         | 5.8               | 71.5            | 15.0            | down  |
| 05dir  | 100.         | 2.                | 80.0            | 0.0             | up    |
| 05ret  | 100.         | 2.                | 80.0            | 0.0             | down  |
| 06dir  | 100.         | 3.                | 87.6            | 2.5             | up    |
| 06ret  | 100.         | 3.                | 87.6            | 2.5             | down  |
| 07dir  | 100.         | 3.7               | 94.6            | 5.0             | up    |
| 07ret  | 100.         | 3.7               | 94.6            | 5.0             | down  |
| 08dir  | 100.         | 5.8               | 118.6           | 15.0            | up    |
| 08ret  | 100.         | 5.8               | 118.6           | 15.0            | down  |
| 09dir  | 100.         | 2.0               | 97.9            | 0.0             | up    |
| 09ret  | 100.         | 2.0               | 97.9            | 0.0             | down  |
| 10dir  | 100.         | 3.0               | 111.7           | 2.5             | up    |
| 10ret  | 100.         | 3.0               | 111.7           | 2.5             | down  |
| 11dir  | 100.         | 3.7               | 123.9           | 5.0             | up    |
| 11ret  | 100.         | 3.7               | 123.9           | 5.0             | down  |
| 12dir  | 100.         | 5.8               | 163.9           | 15.0            | up    |
| 12ret  | 100.         | 5.8               | 163.9           | 15.0            | down  |

a Initial distance between the two galaxies.
b Absolute value of the initial relative velocity.

c $L = r_{ini} \times v_{ini}$.
d $E = v_{ini}^2/2 - G(m_1 + m_2)/r_{ini}$, with $m_1 = 2.3 \times 10^{11} M_\odot$ and $m_2 = 2.3 \times 10^{10} M_\odot$.
e Orbital spin, if the z-component is parallel (up) or anti-parallel (down) to the z-axis.

Smoothed Particle Hydrodynamics (SPH) is a Lagrangian technique in which the gas is partitioned into fluid elements represented by particles, which obey equations of motion similar to the collisionless component, but with additional terms describing pressure gradients, viscous forces and radiative effects in gas. To capture shocks a conventional form of the artificial viscosity is used, with parameters $\alpha = 0.5$ and $\beta = 1.0$ (Hernquist & Katz 1998). To describe different spatial dynamical ranges, SPH particles have individual smoothing lengths $h_i$, calculated in such a way that a constant number of neighbours lies within $2h_i$. The giant-giant simulations were performed using a number of neighbours $N_i \sim 15$; for the giant-intermediate and giant-dwarf interactions $N_i \sim 50$. The gas is modelled as isothermal, with a temperature $T_{gas} = 10^4 K$. Because of the short cooling time of disc gas, fluctuations in the gas temperature are quickly radiated away, so that simulations employing an isothermal equation of state differ little from more realistic ones (Mihos & Hernquist 1996, Naab et al. 2006).

The equations of motion are integrated using a leapfrog algorithm with a fixed time step of $\Delta t = 5 \times 10^3$ yr.

### 3.1. Star Formation and continuous stellar mass loss

Numerous prescriptions and techniques exist (Katz 1992, Steinmetz & Mueller 1994, Springel & Hernquist 2003, Cox et al. 2006) for modelling star formation rate and feedback in numerical simulations. As in Mihos & Hernquist (1994b), we parametrized the star formation efficiency for a SPH particle as

$$\frac{M_{\text{gas}}}{\dot{M}_{\text{gas}}} = C \times \rho_{\text{gas}}^{1/2}$$

(1)
with the constant $C = 0.3 \, \text{pc}^3/\text{M}_\odot \, \text{yr}^{-1}$ such that the isolated giant disc galaxies form stars at an average rate of between 1 and 2.5 $\text{M}_\odot \, \text{yr}^{-1}$.

The choice of the parametrization in Eq. [1] is consistent with the observational evidence that on global scales the SFR in disc galaxies is well represented by a Schmidt law of the form $\Sigma_{\text{SFR}} = \Lambda \Sigma_{\text{gas}}^N$, $\Sigma_{\text{gas}}$ and $\Sigma_{\text{SFR}}$ being disc-averaged surface densities, with the best fitting slope $N$ about 1.4 (see Kennicutt 1998, but also Wong & Blitz 2002, Boissier et al. 2003, Gao & Solomon 2004). This relation seems to apply, with a similar slope, also to local scales, as shown in Kennicutt et al. (2003) for Messier 51.

As we checked, the prescriptions we adopted well reproduce the local scales, as shown in Kennicutt et al. (2003) for Messier 51.

Once the SFR recipe is defined, we apply it to SPH particles, using the hybrid method described in Mihos & Hernquist (1994b). In this method, each initial gas particle is in fact hybrid containing a gas fraction and a star fraction. Its gravitational mass $M_i$, changes over time according to Eq. [1]. Gravitational forces are always evaluated using the gravitational mass $M_i$, while hydrodynamical quantities, in turn, use the time-varying $M_{i, \text{gas}}$. If the gas fraction present in the hybrid particles drops below 5% of the initial gas content, the hybrid particle is totally converted into a star-like particle and the small amount of gas material still present is spread over the gas fraction of the neighbours.

The effects of star formation on the surrounding ISM were implemented using the technique described in Mihos & Hernquist (1994b). For each star-forming hybrid particle, we evaluate the number of stars formed with masses $>8 \, \text{M}_\odot$ a (Miller & Scalo 1979) stellar initial mass function (IMF) is adopted, and we assume that they instantaneously become supernovae, leaving behind remnants of 1.4 $\text{M}_\odot$ and releasing their mass to the surrounding ISM. The released mass also enriches the metallicity of the surrounding gas. This is done assuming a yield $y = M_{\text{rem}}/M_i=0.02$, where $M_{\text{rem}}$ is the total mass of all reprocessed metals and $M_i$ the total mass in stars. For each gas particle, mass and metals return is applied to the i-th neighbour gas particle, using a weight $w_i$ based on the smoothing kernel.

The energy injection in the ISM from SNe explosions is accounted assuming that only a fraction $e_{\text{kin}}$ of $E_{\text{SN}} = 10^{51} \, \text{erg}$ goes into kinetic energy, by applying a radial kick to velocities of neighbour gas particles; thus, for each SNe explosion, the i-th neighbour gas particle receives a velocity impulse directed radially away from the “donor”

$$\Delta v_i = \left( \frac{2 \, w_i \, e_{\text{kin}} \, E_{\text{SN}}}{M_i} \right)^{1/2},$$

where $w_i$ being the weighting based on the smoothing kernel and $M_i$ the mass of the receiver.

The value of $e_{\text{kin}}$ is chosen such that the total amount of kinetic energy received by a gas particle, due to the contribution from all its neighbours, is $\leq 1 \, \text{km} \, \text{s}^{-1}$ to prevent a rapid growth of the vertical thickness of the gaseous disc.

Together with star formation, we also take into account the competing process of stellar mass-loss: at each time step, an amount

$$M_{i, \text{st}}(t) = \frac{(M_i - M_{i, \text{gas}}(t)) \Delta c_0}{t - t_{\text{birth}} + T_0}$$

of the stellar mass formed in the hybrid particle is assumed lost by evolutionary effects, going to enrich the gas content $M_{i, \text{gas}}$ of the particle. In the formula above, $t_{\text{birth}}$ represents the birth time of the population, $T_0 = 4.97 \, \text{Myr}$ and $c_0 = 5.47 \times 10^{-2}$ (see Jungwiert et al. 2001 for details).

3.2. Metallicity evolution

The metallicity content of the modelled giant galaxies is initially distributed according to a radial profile

$$z_m(R) = z_0 \times 10^{-0.07 R}$$

where $R$ is the particle distance from the galaxy center and $z_0 = 3 \times z_0^*$ (Kennicutt et al. 2003, Magrini et al. 2007, Lemasle et al. 2008). For intermediate and dwarf galaxies, we generalised this formula, taken account a dependency on the galaxy mass and on its half-mass radius (Tremonti et al. 2004, Lee et al. 2006):

$$z_m(R) = \sqrt{M_{\text{gal}}/M_{\text{giant}} \, z_0} \times 10^{0.07 R - 4.85 R / R_0}$$

where $M_{\text{gal}}/M_{\text{giant}}$ is the mass of the intermediate (or dwarf galaxy), $R_0$ its half-mass radius, $M_{\text{giant}}$ the mass of the giant galaxy, and $R_0 = 4.85 \, \text{kpc}$ the average half-mass radius of giant galaxies in the sample.

The metallicity of the old stellar component is kept unchanged during the simulations, so that only remixing and dynamical effects can reshape the initial gradient of the old stellar population. In turn, the metallicity of the gas component and of the new stellar population (that formed during the simulation) changes with time, due to the release of metals from SNe explosions, as star formation proceeds. In more detail, hybrid particles are characterised by two metallicity values: $z_m$ and $z_{\text{new}}$. The first corresponds to the metallicity of the gas mass of the particle, while the second one provides the metallicity of the stellar mass contained in the hybrid particle. As for old stars, initially their metallicity $z_m$ is distributed into the galaxy disc according to Eq. [4] with the central regions more metal-rich than the outer disc. The metallicity $z_{\text{new}}$ of a new stellar component, is set equal to that of the gas in which it forms, while the reprocessed metals enrich the surrounding gas, according to the yield described before.

4. The GalMer Database

All the results of the GalMer simulations are accessible online using Virtual Observatory technologies. The three essential blocks for providing online access to the data are: (1) storing the data; (2) storing and querying the data description, i.e. metadata; (3) mechanisms for accessing and visualising the data. Besides, we provide services to perform online data analysis, which are described in detail in the next section.

4.1. Data format and storage

Aimed at interoperability and performance, we chose the FITS Binary Table format (Cotton et al. 1995, Hanisch et al. 2001) to store the simulation results. The FITS format is handled by a variety of tools widely used by the astronomical community. A FITS binary table can be easily incorporated into the VOTable format (Ochsenbein et al. 2004) used by new generation astronomical software tools introduced by the Virtual Observatory.

Every galaxy interaction (“GalMer experiment” hereafter) includes 50 to 70 snapshots with a 50 Myr time interval containing data for individual particles traced by the simulations,
thus following the evolution of an interacting galaxy pair for 2.5–3.5 Gyr. We store each snapshot as an individual file. The following properties are provided for every particle: Cartesian coordinates (X, Y, Z), three-dimensional velocity vector (v_X, v_Y, v_Z), total mass (M), particle type (hybrid, star or dark matter), identification of a galaxy which a given particle belonged to in the initial step of the simulation. Besides, we provide metallicities and birth, i.e. the average birth time of the stellar material in a given particle; for stellar particles, they are kept fixed through the simulations, since these particles do not evolve. For hybrid particles we provide mean birth and metallicities instead, as well as gas masses, metallicities of stars formed during the previous timestep (i.e. current gas metallicity).

All the information related to the input parameters of a given GalMer experiment: morphological types of galaxies, orbital configuration, units of masses, coordinates, and velocities, as well as the epoch of a current snapshot are provided in FITS headers of snapshot files, making them self-consistent and available for further stand-alone analysis without need to connect to the GalMer database.

A typical snapshot containing 240000 particles has a size of 12 MBytes, resulting in 0.6–0.9 GBytes per GalMer experiment. The present data release contains simulations of about a thousand giant–giant interactions having a total volume of ~0.9 TBytes. New simulations will be ingested into the database and put online as soon as they have been completed.

4.2. Simulation metadata

The metadata are computed for every individual snapshot at the time of the database update. Since the data are archived and do not change in time, neither the metadata do, the access to the database is read-only, unless new simulation results are ingested into it.

The metadata of GalMer simulations conform to the current version of the SimDB data model (Lemson et al. in prep.) being presently developed by the International Virtual Observatory Alliance (IVOA). SimDB is supposed to provide a complete self-sufficient description of N-body simulations results using object-oriented approach and is designed using Unified Modeling Language (UML). For practical usage, e.g. for constructing a database containing the numerical simulation metadata, a UML data model has to be serialized. We partly serialize the SimDB data model into a relational database schema keeping another part (modified Characterisation class of SimDB) serialized into native XML.

We use the open-source object-relational database management system (DBMS) PostgreSQL\textsuperscript{2} to implement the advanced metadata querying mechanisms described in detail in Zolotukhin et al. (2007). We modified the original SimDB data model by replacing its Characterisation object with the full IVOA Characterisation Data Model (CharDM) metadata {Louys et al. 2008}. CharDM is a way to say where, how extended and in which way the observational or simulated dataset can be described in a multidimensional parameter space. Our metadata querying approach allows us to use additional WHERE clauses in standard SQL queries expressed as XPath statements to constrain particular CharDM elements without need to serialize rather complex CharDM structure into a relational database schema and, therefore, prevents additional complications of SQL queries.

The relational DBMS stores metadata including links to FITS files containing all coordinates and data of individual simulation particles. Therefore, to execute operations involving particles, such as cutouts or statistics, it is necessary to fetch the actual datasets. However, all global properties of simulations, such as total masses of gas and stars are available inside the DBMS making possible to extract a global star formation history of a given GalMer experiment at the database level. This function is implemented as a stored procedure inside the SQL database and is accessible from the web-interface.

All actual metadata queries are executed by the server-side of the database web-interface using the parameters visualised in web-pages, therefore user does not need to type in SQL queries inside web-based forms.

4.3. Data access and visualisation

The interactive access to the data is provided through the WWW interface at http://galmer.ohp.mr.fr. It is based on a de facto standard asynchronous JavaScript and XML (AJAX) technology and, thus, supports most widely-used modern Internet-browsers: Mozilla Firefox ver.>1.5, Microsoft Internet Explorer ver.>5, Apple Safari ver.>3. Individual snapshots for every simulation can be directly accessed in a batch mode as well.

The web-site provides a database query interface for accessing simulations for given galaxy morphological types and orbital parameters of interactions. Being a part of SimDB metadata, this information is stored in the database, and is retrieved dynamically and displayed in a pop-up window, once user has selected particular elements in the query form. In order to use all available features of the GalMer database web-interface, the following software components have to be installed/enabled on the user’s computer: (1) JavaScript support in a web browser; (2) SUN Java\textsuperscript{3} including the Java Applet browser plug-in and support for the Java WebStart functionality which are normally configured automatically during the installation of SUN Java.

The interactive data access includes several steps (see Fig.\textsuperscript{4}). At first, galaxy morphological types and orbital configurations of an interaction are chosen using the “DB Query” tab. Then, the user is asked to select one GalMer experiment in the “Query Results” tab from a list of those matching the selection criteria provided at the first step. Once an experiment has been selected, the user can download or visualise its integrated star formation history and/or download individual snapshots provided in the “Experiment” tab. Then, it is possible to preview the contents of a given snapshot and get access to the value-added data analysis tools for it using the “Snapshot” tab.

In the “Snapshot” tab we provide a powerful AJAX\textsuperscript{4}–based preview mechanism for interactive data manipulation directly from the web-browser (see bottom right panel in Fig.\textsuperscript{4}). The main purpose of the snapshot visualisation and manipulation is an interactive choice of the projection and scaling parameters for the generation of projected maps and synthetic images and/or spectra as described in the next section.

Although the interactive data visualisation capabilities available inside the web-browser remain limited, this limitation can be overpassed by using dedicated software tools if the data are sent to them directly from the database web-interface.

We implemented the interaction between the GalMer database web-interface and existing Virtual Observatory tools dedicated for dealing with tables (topcat\textsuperscript{3} Taylor 2005), im-

\textsuperscript{1} http://www.postgresql.org/
\textsuperscript{2} 3 http://www.java.com/
\textsuperscript{3} 4 http://www.star.bris.ac.uk/~mbt/topcat/
Fig. 4. Interactive data access using the GalMer web-interface: (1) selecting galaxy morphologies and orbital types; (2) choosing one GalMer experiment from the list of those matching the selection criteria; (3) selecting a snapshot; (4) previewing the snapshot and accessing data analysis tools for it.

5. Data Analysis Services

We developed an application programming interface (API) library to access and analyse the results of GalMer simulations. The mergerapi library is implemented in ANSI C and needs a minimal set of prerequisites to compile: the cfitsio FITS API library to access the simulation data and the GD library to generate gif and png output images directly viewable inside a web-browser. The mergerapi library is installed on the server side and is used by several on-the-fly data analysis services described hereafter.

5.1. Projected Maps

For a given snapshot we provide a set of services for the on-the-fly server-side computation of projected maps of various quan-

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5 http://aladin.u-strasbg.fr/
6 http://esavo.esa.int/vospec/

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7 http://heasarc.gsfc.nasa.gov/docs/software/fitsio/fitsio.html
8 http://www.libgd.org/
Database web-interface

Middleware

Virtual Observatory tools

Fig. 5. The middleware connecting the GalMer database web-interface with the VO tools dedicated for advanced data manipulation at top, is illustrated a projection with mergerapi, and at below, a VOSPEC spectrum, and a map in Aladin.

In order to generate maps on-the-fly, we developed an efficient computational algorithm. All the maps are computed for a parallel projection onto a plane (i.e. assuming an observer at the infinite distance) at the same time allowing to specify a spatial scale (i.e. to give an effective distance from an observer to the barycentre). Therefore, the viewport is uniquely defined by the two quantities: azimuthal ($\phi$) and polar ($\theta$) angles. To simplify the comparison of computed maps with observations and mosaicing of maps with different spatial sampling (e.g. zoom-in on a given regions of a merger remnant with the overall image) we use the FITS WCS convention (Greisen & Calabretta 2002) assuming a tangential projection and assigning right ascension and declination of zero to the projected barycentre position. In this case, the coordinates of a particle on the projected plane are computed as:

\[
x_{\text{proj}} = -X \sin \phi + Y \cos \phi \\
\eta = 206265 \frac{x_{\text{proj}}}{r} \\
y_{\text{proj}} = -X \cos \phi \sin \theta - Y \sin \phi \sin \theta + Z \cos \theta \\
\xi = 206265 \frac{y_{\text{proj}}}{r}
\]  

(6)

Here $\eta$ and $\xi$ define the tangential coordinates on the sky in arcsec which are used to compute synthetic images comparable directly to observations as demonstrated in Section 6.2. The radial velocity and the position on the line of sight are given by:

\[
v_r = v_X \cos \phi \cos \theta + v_Y \sin \phi \cos \theta + v_Z \sin \theta \\
z = X \cos \phi \cos \theta + Y \sin \phi \cos \theta + Z \sin \theta
\]  

(7)

(8)

Then,

- A grid corresponding to the desired map size and sampling is created.
- In a single loop over all particles, we compute, which bin each particle will contribute to, and take into account this contribution.
- In a second loop over the bins (pixels) we compute (if necessary) the actual values of a physical parameter.

The algorithm is sufficiently fast to perform the map computation in real time, e.g. the generation of a $400 \times 400$ pixels map takes a fraction of a second. In Fig. 6 we show an example of projected maps for one of the interactions.

5.2. Spectrophotometric Properties

We developed a technique using PEGASE.HR (Le Borgne et al. 2003) and PEGASE.2 (Fioc & Rocca-Volmerange 1997) to model spectrophotometric properties of interacting galaxies from the results of GalMer simulations. By taking into account kinematics, star formation (SFH) and chemical enrichment history (CEH) we model spectra and broadband photometric colours. We will present all the details regarding the spectrophotometric modelling in a separate paper (Chilingarian et al. in prep.), but here we will briefly introduce the algorithms and results which can be obtained.

There were several successful attempts (Chakrabarti & Whitney 2009; Jonsson et al. 2011) of modelling the spectrophotometric properties of the results of N-body simulations. However, in all the known cases the stellar population information is taken into account in an approximate way, by characterising N-body particles by their mean ages and metallicities. At the same time, the behaviour of spectral features is a strongly non-linear function of age and metallicity and it also differs significantly along the wavelength domain, in particular, due to the dust attenuation. Hence, SEDs computed using mass-weighted average ages and metallicities may not reflect real spectral energy distribution in galaxies. With the GalMer simulations, thanks to the usage of hybrid particles we are (1) able to trace SFH and CEH in detail through the entire duration of the simulation for every particle of this type; and (2) make use of this information. Therefore, we are able to make qualitatively better modelling of the spectrophotometric properties of interacting galaxies (and results of other N-body
TreeSPH simulations as well) and make direct comparison with observations. The SFH and CEH are computed using a whole sequence of snapshots in a given GalMer experiment as differences of gas masses in each *hybrid* particle in each of the 10 metallicity bins from [Fe/H] = −2.5 to +1.0 dex.

The most time-consuming part of the modelling is running the PEGASE.HR code. Due to the complexity of the evolutionary synthesis even with the present state of the art computer hardware it takes several seconds per spectrum (i.e. per *star* particle), resulting in several hours per snapshot including up to 160000 *hybrid* and *star* particles. Computation of spectra for individual particles is absolutely crucial to properly model effects of dust extinction and intrinsic broadening of spectral lines caused by motions of particles along a line of sight (i.e. internal kinematics of galaxies). However, we can avoid the actual execution of the evolutionary synthesis code.

The algorithms of evolutionary synthesis such as PEGASE.HR include:

1. computation of isochrones for different ages and metallicities based on a given set of stellar evolutionary tracks and stellar IMF;
2. picking up stellar spectra from a stellar library (either empirical or theoretical) for the atmosphere parameters corresponding to a given point on the isochrone;
3. co-adding contributions of different types of stars according to the weights on the isochrone, making up simple stellar population (SSP) spectrum including stars of a single age and metallicity;
4. co-adding different SSPs to reproduce complex SFH and CEH.

For a case when the IMF is fixed and SFH and CEH are traced on a pre-defined grid of ages and metallicities, it becomes possible to execute only the 4th step from the list above. This means that if we pre-compute only once a grid of SSPs corresponding to a given IMF (Miller & Scalo [1979] in our case) and the grid of ages and metallicities, we can reuse it for all the particles, improving the efficiency of the computations by several orders of magnitude. Once for every GalMer experiment we also pre-compute the SFH and CEH and store them as a two-dimensional histogram for every particle.

For every spatial bin (see definition in the previous section) we first sort the particles along a line of sight to be able to account for dust extinction. Then, either a high-resolution spectrum or a broad-band spectral energy distribution (depending on the mode of the computation) is computed for every particle starting from the most distant one from the observer.

This is done by co-adding the pre-computed SSPs from the grid mentioned above with the weights corresponding to a mass contribution of stars of each age and metallicity contained in the SFH and CEH.

The dust extinction is then applied to the total spectrum or multi-colour spectral energy distribution (SED) as it was computed at the previous step (i.e. excluding the current particle). For a known gas column density and a solar metallicity, we assume a standard dust-to-gas mass ratio to compute extinction as $A_V = N_H/1.871 \times 10^{21}$ (Bohlin et al [1978]), where $N_H$ is a number of hydrogen atoms per cm$^2$, assuming $R_V \equiv A_V/(B-V) = 3.1$. We compute $N_H$ along the line of sight and scale this formula linearly with metallicity. Then, we account for the wavelength dependence of extinction according to Fitzpatrick [1993], and apply it to the total stellar population SED generated at this step.

After having applied the dust extinction, the total spectrum of a current particle is blue- or redshifted according to its radial velocity, which is done as a simple shift operation with linear interpolation, since our SSP grid is rebinned with a logarithmic step in the wavelength corresponding to a fixed pixel size in km s$^{-1}$.

At the end, the total spectrum (or SED) of a current particle is co-added to the result.

This algorithm makes it possible to compute in a few seconds for a given snapshot a total intermediate-resolution ($R = 3000$, $3900 < \lambda < 6800$ Å) spectrum, based on the ELODIE 3.1 empirical stellar library. The total number of co-added SSP in this extreme case reaches $10^6$. The broad-band FUV to NIR SED based on the low-resolution theoretical BaSeL [Lejeune et al [1997]] stellar library is computed much faster, because the number of SED points in it is only about a dozen compared to several thousands, allowing us to compute a $400 \times 400$ pixels multi-colour databace in a few seconds.

Due to the limited spatial resolution of GalMer simulations, we are unable to reach the spatial scales sufficient to take into account properly the gas clumpiness, therefore we adopt a scale of 250 pc for the computation of extinction, which roughly corresponds to the resolution of the simulations, and which results in the values of total extinction in simulated GalMer isolated galaxies well resembling observations. Our limited resolution also causes overestimation of extinction effects in central regions with high gas densities, where large amount of gas falls...
Fig. 7. Examples of synthetic spectra generated by the specklephotometric modelling algorithm applied to the results of GalMer simulations. Two curves correspond to two different positions along the projected major axis of a merger remnant: centre approaching (blue), and receding (red). The spectra are normalised to unity at $\lambda = 5000$ Å for clarity.

At present, we do not attempt to model nebular emission lines, because our simulations do not trace at sufficient level of detail the physical conditions in the ISM. Only qualitative modelling can in principle be performed, assuming fixed ISM temperature and density depending only on the gas metallicity which is available for hybrid particles. This modelling will be addressed in detail in a separate paper (Melchior et al. in prep.)

6. Astrophysical applications

6.1. Galaxy properties from modelling

At present, we explored the GalMer database to study a variety of physical processes related to galaxy interactions, such as induced star formation enhancements, evolution of metallicity gradients, angular momentum redistribution, and its impact on the final kinematical properties of the merger remnant.

In Di Matteo et al. (2007) and Di Matteo et al. (2008a) we investigated the enhancement of star formation efficiency in galaxy interactions and mergers. We showed in Di Matteo et al. (2007) that, in the final merging phase, retrograde encounters have greater star formation efficiency than direct encounters, that the amount of gas available in the galaxy is not the main parameter governing the star formation efficiency in the burst phase, and that there is a negative correlation between the amplitude of the star forming burst at the merging phase and the tidal forces exerted at pericentral passage. The general result presented in Di Matteo et al. (2008a) shows that, at low redshift, galaxy interactions and mergers, in general, trigger only moderate star formation enhancements. Strong starbursts where the star formation rate is increased by a factor greater than 5 are rare and found only in about 15% of major galaxy interactions and mergers. Merger-driven starbursts are also rather short-lived, with a typical duration of activity of a few $10^8$ yr. These conclusions are found to be robust, independent of the numerical techniques and star formation models. At higher redshifts, where galaxies are gas-rich, gas inflow induced starbursts are neither stronger nor longer than their local counterparts. These results are in good agreement with a number of observational works (Bergvall et al. 2003; Li et al. 2008; Jogee et al. 2009; Knapen & James 2009), demonstrating that interactions and mergers do not trigger strong bursts of star formation.

More recently, Di Matteo et al. (2009b), we investigated how the metallicity gradients in dry merger remnants depend on the structure and metallicity gradients of the galaxies involved in the merger. Our aim was to understand if dry mergers could lead to metallicity gradients as observed in elliptical galaxies in the local Universe, and if they always lead to a flattening of the initial (i.e., pre-merger) gradient. The analysis of the whole set of dry merger simulations in the GalMer database allowed us to show that the ratio of the remnant and the initial galaxy slopes spans a wide range of values, up to $> 1$ (with values greater than one resulting only when companions have gradients twice that of the progenitor). For a merger between two ellipticals having identical initial metallicity slopes (i.e., equal companion and galaxy slopes), the metallicity profile of the remnant flattens, with a final gradient about 0.6 times the initial one. This flattening depends neither on the characteristics of the orbit of the progenitors or on their initial concentration. If the companion slope is sufficiently steep, ellipticals can maintain their original pre-merger metallicity gradient. These results, compared to the observed variety of metallicity gradients in dwarf elliptical and lenticular galaxies (Chilingarian 2009), may suggest the mergers to be an important channel of dE/dS0 evolution.

Given the diversity in outcomes of the mergers, we concluded that dry mergers do not violate any observational constraints on the systematic characteristics of metallicity gradients in local ellipticals (Ogando et al. 2005).

The redistribution of the orbital angular momentum into internal rotation, and its impact on the kinematical properties of the merger remnant, became a subject of two studies Di Matteo et al. (2008b, 2009a).

In Di Matteo et al. (2008b), we presented a new scenario to form counter-rotating central components in early-type galaxies, by dissipative and dissipationless “mixed” mergers, consisting of elliptical-spiral systems in retrograde orbits. We demonstrated that the counter-rotation can appear both in dissipative and dissipationless retrograde mergers, and it is mostly associated to the presence of a disc component, which preserves part of its initial spin. In turn, the external regions of the two interacting galaxies acquire part of the orbital angular momentum, due to the action of tidal forces exerted on each galaxy by the companion. In the case of dissipative mergers, the central decoupled core could be composed of two distinct populations: the old stellar population, which has preserved part of its initial spin, and a new stellar population, born in situ from the kinematically decoupled gas component.

Even the merger of two initially non-rotating, pressure supported progenitor galaxies can lead to remnant galaxies having peculiar kinematical properties. In Di Matteo et al. (2009a), we have indeed shown that it is possible to generate elliptical-like galaxies, with $v/r > 1$ outside one effective radius, as a result of the conversion of orbital into internal angular momentum. This conversion occurs “outside-in”: the external regions acquire part of the angular momentum first, and it affects both the baryonic and the dark matter components of the remnant galaxy (i.e. both acquire part of the angular momentum, the relative fractions depend on the initial concentration of the merging). If the
initial baryonic component is sufficiently dense and/or the encounter takes place on a orbit with high angular momentum, the remnant galaxy exhibits hybrid properties, i.e. an elliptical-like morphology, but rotational support in the outer stellar halo \((v/\sigma > 1)\). Systems with these properties have been recently observed through a combination of stellar absorption lines and planetary nebulae for kinematic studies of early-type galaxies (Coccato et al. 2009). Our results are in qualitative agreement with such observations and demonstrate that even mergers composed of non-rotating, pressure-supported progenitor galaxies can produce early-type galaxies with significant rotation at large radii.

6.2. Synthetic observations: virtual telescope

Some of the value-added data analysis services we provide for the GalMer database can be used as a "virtual telescope" to create simulated images and spectra of interacting galaxies. Thanks to the high-quality stellar population modelling provided by the PEGASE.2/PEGASE.HR code, we are able to compare the simulated data to real observations.

In Fig. 8 we present an RGB false-colour composite image of an interacting galaxy pair created from the results of spectrophotometric modelling described above applied to GalMer simulations. The simulation result is superimposed over the background showing the Sloan Digital Sky Survey Data Release 7 (Abazajian et al. 2009) image of the galaxy cluster Abell 85. We used SDSS g, r, and i bands in both observational and simulated data, and the RGB visualisation code implementing the algorithm by Lupton et al. (2004) to generate a false-colour image. Since the results of our spectrophotometric modelling are expressed in physical units, they can be transformed into observables \((\text{mag arcsec}^{-2})\) and projected on-to the sky (see eq[6]) providing a direct way of comparing them to observational data. By co-adding model broadband fluxes and those coming from SDSS direct imaging, we can create realistically looking false-colour images such as the one shown in Fig. 8.

Simulated images can then be analysed using classical observational techniques, e.g. surface photometry. A successful example of such analysis is demonstrated in Chilingarian et al. (2009b), where we found a match between a rather complex three-component observed density profile of the lenticular galaxy NGC 6340 and a merger remnant from the GalMer simulations, supporting the major merger to be an important event in the evolution of this particular object.

We are also able to simulate the whole data cubes corresponding to the data produced by modern integral-field unit (IFU) spectrographs, such as SAURON at 4.2 m William Herschel Telescope, VIMOS at ESO Very Large Telescope, and GMOS at Gemini. Our spectral resolution and coverage allows us to model high-resolution blue setting of VIMOS (HR-Blue, \(R = 2500\)) and B600 grating of GMOS \((R = 2200)\) usually chosen to study stellar kinematics of nearby galaxies.

The spatial resolution of our simulations \((0.20–0.28 \text{ kpc})\) is comparable to that of the SAURON (de Zeeuw et al. 2002) survey targeting nearby galaxies at distances between 10 and 40 Mpc, thus, having spatial resolution of 0.05 to 0.2 kpc given the average atmosphere seeing quality of 1 arcsec. At the same time, we can degrade the spatial resolution of our simulation in order to match observations made with VIMOS, e.g. post-starburst galaxies presented in Chilingarian et al. (2009a).

As the stellar population models improve, we will be able to upgrade the spectrophotometric modelling engine in the GalMer database in order to simulate data coming from next generation IFU facilities such as the second-generation VLT instrument MUSE.

6.3. Colour-magnitude relations

The spectrophotometric modelling facilities allow us to compute total magnitudes and colour of interacting galaxies and to directly compare them to observational data.

The colour–magnitude and colour–colour plots comparing results of GalMer simulations to a large observational dataset are presented in Fig. 9. A well-known galaxy colour bimodality (see e.g. Strateva et al. 2001) is clearly seen in the contour plot pre-
senting the distribution of some 80000 nearby galaxies ($z < 0.3$) from the SDSS survey. The photometric data were corrected for the Galactic extinction according to Schlegel et al. (1998) and converted into rest-frame, i.e. $k$-corrected using the analytical approximations presented in Chilingarian et al. (submitted). The “red sequence” and the “blue cloud” separated by the “green valley”, a locus of post-starburst galaxies (e.g. Goto et al. 2003) can be identified.

The total magnitudes of GalMer mergers in SDSS bands are computed using the spectrophotometric modelling described above. We show the positions of GalMer galaxy models (isolated galaxies) of different masses and morphological types. Elliptical and lenticular galaxies (red and yellow symbols) are sitting on the red sequence, while spiral galaxies are bluer, directed down toward the blue cloud. GalMer Sa and Sb spiral galaxies (green and blue symbols) at an evolutionary stage shown in Fig. 9 reside in the green valley.

We also follow the evolution of an interacting pair from the time when galaxies merged (red diamonds connected with lines) till the end of the simulation showing intermediate snapshots every 50 Myr. Right after the gas-rich merger, remnants sit in the “blue cloud”, despite very strong internal extinction of regions of massive star formation. Then, as the star formation decreases, luminosity-weighted ages of stellar populations increase causing global colours to become redder and, thus, moving merger remnants in the top-right direction across the “blue cloud” through the “green valley” toward the “red sequence”. Finally, 400–600 Myr after the merger time, all remnants settle on-to the “red sequence”, although some residual star formation is still observed.

One can see that merger remnants cross the “green valley” very fast giving possible explanation why there is at present a deficit of galaxies in this region of the colour–magnitude diagram, given that all mergers in this mass range have not yet been included in the database.

7. Summary
We present the GalMer database providing online access to the results of TreeSPH simulations. The structure of the database conforms to recent International Virtual Observatory standards. We describe the interactive data access web-interface, advanced mechanisms for data visualisation and manipulation using connection to the Virtual Observatory tools dedicated for dealing with tabular, imaging and spectral data.

After having stored the snapshots in FITS binary table format, giving access to all coordinates and data on individual simulation particles, we provide a set of value-added tools using the results of TreeSPH simulations. These include: (1) generator of projected maps of various physical quantities traced by the simulations; (2) engine to perform the modelling of spectrophotometric properties of interacting and merging galaxies based on the PEGASE.2/PEGASE.HR evolutionary synthesis code. The latter tool can be used as a virtual telescope and synthetic images, spectra, and datacubes generated using it are directly comparable to observational data.

We provide examples of several use-cases for the GalMer database using our value-added tools.

The database will be updated by including new simulations as they have been completed.

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Appendix A: Galaxy models: density profiles

In Sect. 2.1 we presented the galaxy models adopted for the simulations. In particular, we saw that the dark halo and the optional bulge are modelled as a Plummer sphere (Binney & Tremaine 1987, pag. 42), with characteristic masses $M_B$ and $M_H$ and characteristic radii $r_B$ and $r_H$. Their densities are given, respectively, by the following analytical formula:

$$ \rho_B(r) = \frac{3M_B}{4\pi r_B^3} \left( 1 + \frac{r^2}{r_B^2} \right)^{-5/2} \quad (A.1) $$

and

$$ \rho_H(r) = \frac{3M_H}{4\pi r_H^3} \left( 1 + \frac{r^2}{r_H^2} \right)^{-5/2} \quad (A.2) $$

The stellar and gaseous discs follow a Miyamoto-Nagai density profile (Binney & Tremaine 1987, pag. 44):

$$ \rho_s(R, z) = \left. \frac{h^2 M_s}{4\pi} \right| \frac{a_s R^2 + (a_s + 3 \sqrt{a_s^2 + h^2}) \left. (a_s + \sqrt{a_s^2 + h^2})^2 \right| a_s^2 + \left. (a_s + \sqrt{a_s^2 + h^2})^2 \right| (a_s^2 + z^2)^{5/2} \left. \left( z^2 + h^2 \right)^{3/2} \right| (A.3) $$

$$ \rho_g(R, z) = \left. \frac{h^2 M_g}{4\pi} \right| \frac{a_g R^2 + (a_g + 3 \sqrt{a_g^2 + h^2}) \left. (a_g + \sqrt{a_g^2 + h^2})^2 \right| a_g^2 + \left. (a_g + \sqrt{a_g^2 + h^2})^2 \right| (a_g^2 + z^2)^{5/2} \left. \left( z^2 + h^2 \right)^{3/2} \right| (A.4) $$

with masses $M_s$ and $M_g$ and vertical and radial scale lengths given, respectively, by $h_s$ and $a_s$, and $h_g$ and $a_g$.

Appendix B: Galaxy models evolved in isolation

Since the aim of this work is to study the effects that interactions and mergers have in driving galaxy evolution, it is important to study, for comparison, also the evolution of the galaxies in isolation, in order to distinguish properly secular processes from those related to the interaction. In Figs. B.1 and B.2, we show the evolution of the gaseous and stellar components of the giant gasa, sgb and sgd galaxies, respectively, evolved in isolation for 3 Gyr. As it can be seen, all the models evolve rapidly in the first 0.5-1 Gyr: a stellar bar and spiral arms form, and at the same time gas compresses into density waves and clumps and partially falls into the central regions, where a star formation enhancement takes place (for the star formation rate of these galaxies, we refer the reader to Di Matteo et al. 2007).
Fig. B.1. Gas maps of the gSa, gSb, and gSd models with $Q_{\text{gas}} = 0.3$ evolved in isolation. Snapshots are equally spaced in time from $t=0$ to $t=3$ Gyr. Each map is 60 kpc x 60 kpc in size.

Fig. B.2. Star maps of the gSa, gSb, and gSd models evolved in isolation. Snapshots are equally spaced in time from $t=0$ to $t=3$ Gyr. Each map is 60 kpc x 60 kpc in size.