Sagittarius, a dwarf spheroidal galaxy without dark matter?

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Abstract. The existence of dwarf spheroidal galaxies with high internal velocity dispersions orbiting in the Milky Way raises questions about their dark matter content and lifetime. In this paper, we present an alternative solution to the dark matter dominated satellites proposed by Ibata & Lewis (1998) for the Sagittarius dwarf galaxy. We performed simulations of two kinds of N-body satellites: the first models (f-models) could correspond to satellites with high dark matter content and they represent initially isolated models. The second models (s-models) have either low or negligible dark matter content and they are constructed in a tidal field. In spite of being on the same orbits, the s-models are able to produce a better agreement with some observational constraints concerning Sagittarius. From our simulations, we can also infer that Sagittarius is in the process of being disrupted.

Key words: Galaxies: local group, interactions. Methods: numerical

1. Introduction

The current interest for dwarf spheroidal galaxies (hereafter DSphs) as satellites of the Milky Way is raised by two fundamental questions concerning their evolution: the real content of dark matter (DM) in these objects (see, for example, Mateo 1994, 1997, 1998; Piatek & Pryor 1995; Burkert 1997 and references therein) and their implication in the hierarchical formation of the galactic halo (e.g., Johnston et al. 1996).

The Sagittarius (Sgr) dwarf galaxy is the closest known satellite galaxy to the center of the Milky Way, $R_{GC} \sim 16$ kpc (Ibata et al. 1997, 1998). Due to its proximity we can expect from its study an additional contribution to our understanding of DSphs in general. Since the announcement of its discovery by Ibata et al. (1994) the structure and evolution of Sgr have been extensively discussed and simulated by various authors: Ibata et al. (1995), Johnston et al. (1995), Velázquez & White (1995), Whitelock et al. (1996), Mateo et al. (1996), Alard (1996), Ibata et al. (1997), Edelsohn & Elmegreen (1997), Layden & Saragedini (1997), Ibata & Lewis (1998), Mateo et al. (1998). Important problems concerning this system are: 1) its possible lifetime before dissolution, 2) the possible presence of DM in it. A critical point in the studies mentioned above is the question whether Sgr is in virial equilibrium or not.

Usually, the total inferred mass of the DSph is calculated by assuming it is in virial equilibrium. In this case, the central mass-to-light ratio depends on the velocity dispersion through the equation (Richstone & Tremaine 1986)

$$\frac{M}{L} = \eta \frac{9\sigma_o^2}{2\pi G \mu_o r_{hb}}$$

where $\eta$ is near unity for a wide variety of models, $\sigma_o$ the central velocity dispersion, $\mu_o$ the central surface brightness and $r_{hb}$ the half-brightness radius. The analysis of the validity of Eq. (1) for evolving DSphs has been studied in detail in the present context by Kroupa (1997, hereafter K97).

In Table 1 we have summarized the parameters of Sgr DSph measured by Ibata et al. (1997). For the values of $\sigma_o$,

| Parameter | Value |
|-----------|-------|
| $r_{hb}$  | 0.55 kpc |
| $\sigma_o$ | 11.4 km/s |
| $\mu_oV$  | 25.4 mag/arcsec$^2$ |
| $L_1$     | $\geq 10^7 L_\odot$ |
| $(M/L)_o$ | 50 M_\odot/L_\odot |
| $M_1$     | $> 10^9 M_\odot$ |
| $l, b$    | (5.6°, -14°) |
| $(U, V, W)^b$ | (232.0, 194) ± 60 km/s |
| $d_c$     | 25 kpc |
| $R_{GC}$  | 16 kpc |
| $v_r$     | 171 km s$^{-1}$ |
| $(dv/db)$ | -3 km s$^{-1}$/degree |

a Galactic coordinates
b Galactic velocities
c Heliocentric distance
d Galactocentric distance
e Radial velocity
f Gradient of the radial velocity

Table 1. Observational parameters of Sagittarius dwarf galaxy (Ibata et al. 1997)

In this paper, the inferred mass is always obtained by assuming a virial equilibrium for the satellite.
$r_{hh}$ and $\mu_{L,V}$ given in Table 1, these authors obtain a high central mass-to-luminosity ratio $(M/L)_o = 50 \, M_\odot/L_\odot$ by using the Eq. (1). Therefore, the total inferred mass assuming virial equilibrium, $M_t$, is DM dominated. The values of total luminosity, $L_t$, and the total inferred mass, $M_t$, are also listed in Table 1. However, the values of $(M/L)_o$ and $L_t$ suggested by Mateo et al. (1998) are different. These authors have discovered a tidal extension of Sgr, which implies that such a satellite galaxy is expected to be tidally disrupted and destroyed after several pericentric passages, unless a significant quantity of DM is present inside it, as inferred assuming virial equilibrium. The observations of the Sgr globular clusters give an age spread of its constituents $> 4$ Gyrs and the youngest globular cluster (Terzan 7) is 9-13 Gyrs old (Montegriffo et al. 1998). The fast disruption obtained by the numerical methods raise the question about the age and the dynamical history of Sgr. However, it must be emphasized that the initial time $t = 0$ of the simulations does not necessarily coincide with the time of formation of the oldest constituents of the satellite.

The partial formation of the galactic halo by hierarchical processes (accretion of small galaxies) has recently received an increase of interest, stimulated for instance by the investigation by Lynden-Bell & Lynden-Bell (1995) on the reality of streams (Lynden-Bell 1982) in the close environment of the Milky Way, among them the well known Magellanic Stream. DSphs seem to belong to one or another of these streams and their evolution clearly depends on their environment. This scenario of satellite formation involves a low DM content for the DSphs (Barnes & Hernquist 1992; Kroupa 1998). However, the only simulations of no-dark matter satellite galaxies able to survive in a tidal field are those of K97 and Klessen & Kroupa (1998, hereafter KK98). These authors have studied a region in the parameter space ($M_{sat}, r_{sat}$), where $M_{sat}$ and $r_{sat}$ are the mass and a typical radius of the satellite, and they have obtained a residual satellite from a more massive one. Nevertheless, their remnant satellite galaxies are fainter than a typical DSph, unless the true $(M/L)_\text{real} < 3$.

These circumstances make questionable the maintenance of dynamical equilibrium and consequently the virial estimation of mass for these systems.

In this paper we present self-consistent N-body simulations of Sgr and a more accurate and plausible scenario of its evolution, which suggests that Sgr is likely to be able to survive for a long time (6 – 10 Gyr) by orbiting in the Galaxy without being dominated by DM.

In Sect. 2, we present the model of the Milky Way used in our simulations. In Sect. 3, we describe the different models of the satellite galaxy and corresponding scenarios of interaction with the Galaxy. In Sect. 4 some numerical considerations are given. In Sect. 5, we present the results of our simulations for the different chosen scenarios. These results are discussed in Sect. 6 in connection with recent conjectures by

![Fig. 1. Rotation curve of the initial Milky Way model (full line), with the contributions of each component](image-url)
3. Satellite models

The effects that a DSph suffers when it is accreted on a primary galaxy strongly depend on its structure and its orbit.

We have considered two kinds of satellite models. They correspond to two scenarios of interaction between the Galaxy and the satellite. In the first models (f-models), we represent the satellite as a standard King’s sphere (King 1966), which matches the observational constraints for the total virial mass, \( M_t \), the core radius, \( r_o \), and the central velocity dispersion, \( \sigma_o \), of the Sgr DSph. In this case, the effects on the DSph are maximal because the satellite, originally in an isolated situation, suddenly undergoes strong tidal perturbations.

Our alternative scenario (s-models) assumes that either the DSph is formed in the tidal tail of another major accretion event and therefore it is built in equilibrium with the environment, or the DSph falls slowly from a quasi-isolated situation to a tidal field region and it has enough time to readjust itself to the environmental forces. In both situations, we begin our simulations when the satellite has already reached the equilibrium with the dense environment and, therefore, the life time of the DSph orbiting in the galaxy is expected to be longer than in our first scenario. In the present case, the satellite is modelled by a modified King’s sphere (Gómez-Flechoso & Domínguez-Tenreiro 1998), which takes into account the tidal potential produced by the primary galaxy.

We have checked several orbits in order to compare the observational features of the Sagittarius dwarf and the numerical results in both fast and slow accreting scenarios. The orbits we have chosen reproduce the present position, \((l, b)\), and galactocentric velocity, \((U, V, W)\), of Sagittarius DSph in the observational range (Table 1), and, therefore, the simulated orbits are polar, as suggested by the void component of the proper motion parallel to the Galactic Plane. The orbits are either low eccentricity orbits in the central part of the Galaxy or high eccentricity orbits.

The central mass-to luminosity ratio of the models has been calculated by using the Eq. (1). The central velocity dispersion \( \sigma_o \) involved in this equation has been measured along the line-of-sight. We have removed the particles with the largest radial velocities (relative to the radial velocity of the center of mass of the satellite) to prevent contamination by outlying particles. We have only considered those particles with projected distance to the center of the satellite smaller than 0.5 kpc.

3.1. f-models

The distribution function of an isolated galaxy fulfills the collisionless Boltzmann equation. We can represent an isolated DSph as a solution of this equation. King’s spheres are an example of that.

If an initially isolated DSph reaches the inner regions of a galaxy within a short timescale, it has no time to modify its internal structure. In this case the satellite maintains its isolated King’s sphere distribution function at the beginning of the simulation. Once in the inner orbit, the satellite will evolve quickly, because tidal forces are strong in these regions. This scenario is unrealistic, because, in reality, a satellite which reaches the denser parts of the galaxy has suffered the influence of the galaxy potential for a long period of time. However, we have run simulations in such a case because they correspond to the common initial conditions assumed in the literature (Johnston et al. 1995, Oh et al. 1995, Velázquez & White 1995, Johnston et al. 1996, Edelsohn & Elmegreen 1997, K97, KK98, Ibata & Lewis 1998) and in order to compare the results with those of the more realistic s-model satellites.

The parameters of the King’s model we have selected for the satellite model in a fast accreting scenario are given in Table 2 and they have been chosen to reproduce the present characteristics of Sagittarius, as was done in other simulations (Velázquez & White 1995). The total mass of the satellite model corresponds to the virial mass inferred for Sgr. Therefore, if the observational constraints on the luminous mass are considered, the satellite model could represent a DM dominated DSph. For these models, we have assumed \((M/L)_{\text{real}}=10\,M_\odot/L_\odot\) for the calculations of surface brightness, which is the lower limit of the mass-to-luminosity ratio for DM dominated satellites. A higher \((M/L)_{\text{real}}\) would represent fainter satellite galaxies (for the same DM content) and an apparently faster dissolution process.

The initial apocenter and pericenter and the period of the low eccentricity orbit (f-A) and the high eccentricity orbits (f-B1 and f-B2) are listed in Table 3.

3.2. s-models

In the other possible scenario we assume that either the satellite has been formed inside the tidal tail of a major merger (e.g. numerical simulations by Barnes & Hernquist 1992, and the observational counterpart by Duc & Mirabel 1997) or it has been slowly accreted.

In the first case, if the dwarf galaxy is formed in equilibrium with the tidal force of the environment, it does not contain a significant amount of DM (Barnes & Hernquist 1992).

Table 2. Physical parameters of the isolated King’s model of Sgr (f-models): core radius, \( r_o \), central velocity dispersion, \( \sigma_o \), total mass, \( M_t \), dimensionless potential, \( W_o \) and tidal radius, \( r_t \)

| Model | \( r_o \) (kpc) | \( \sigma_o \) (km/s) | \( M_t \) (10\(^7\) M_\odot) | \( W_o \) | \( r_t \) (kpc) |
|-------|----------------|---------------------|-----------------------------|---------|----------------|
| f-A   | 0.527          | 15.0                | 12.0                        | 3.26    | 2.736          |
| f-B1  | 8              | 38                  | 0.45                        |         |                |
| f-B2  | 10             | 70                  | 0.95                        |         |                |

Table 3. Parameters of the orbits of the f-models

| Model | \( r_{\text{min}} \) (kpc) | \( r_{\text{max}} \) (kpc) | Period (Gyr) |
|-------|-----------------------------|-----------------------------|--------------|
| f-A   | 12                          | 18                          | 0.23         |
| f-B1  | 8                           | 38                          | 0.45         |
| f-B2  | 10                          | 70                          | 0.95         |
In the second case, according to cosmological models of hierarchical structure formation, satellite systems are produced around massive galaxies. These satellites could contain DM halos (e.g. Cole et al. 1994). Tidal forces could be negligible in the outer regions of the galaxy where the satellite is formed. However, if we assume that the satellite does not go through the denser and central regions of the main galaxy in the first perigalacticon, we could expect that an initially massive satellite falls slowly on the center of the galaxy by dynamical friction, loses part of its mass and reaches a central orbit. In this way, the satellite has time to modify its internal structure and to reach the equilibrium with the environment.

DSphs described in the two last scenarios have to be in equilibrium with the tidal forces of the environment. In the paper by Gómez-Flechoso & Domínguez-Tenreiro (1998), the structural parameters (total mass, $M_t$, velocity dispersion, $\sigma_o$, core radius, $r_o$, etc.) of a satellite in the tidal field of the primary galaxy have been estimated. Those authors have proved that, in general, a galaxy in a tidal field can be described by a two parameter distribution function. They have solved altogether the Poisson equation and the collisionless Boltzmann equation for a galaxy, taking into account the potential of the galaxy and the tidal potential of the environment. Only spherical terms of the tidal field were considered in this theory. However, the obtained equilibrium solutions are better representations of the system than isolated models.

This result suggests that in our problem we could represent a DSph in equilibrium with the tidal field of the primary galaxy as a modified King’s sphere (see Gómez-Flechoso & Domínguez-Tenreiro 1998) with two free parameters. We have chosen the central velocity dispersion, $\sigma_o$, and the core radius, $r_o$, as input parameters, because both can be determined from observations. In our simulations, the values for these two parameters are $r_o \sim 0.06 - 0.3$ kpc and $\sigma_o \sim 11 - 15$ km/s, which reproduce the characteristics of the Milky Way satellites. Thus, we will try to explain the Sagittarius satellite as a typical DSph which has evolved orbiting for a long time in the Galaxy potential. The other parameters of the model (total mass, tidal radius and dimensionless central potential) are automatically determined by the tidal potential at each position of the orbit.

The satellite parameters of the models which have been performed are listed in Table 3. The second column is the core radius, $r_o$, and the third column is the central velocity dispersion, $\sigma_o$, which are input parameters of the modified King’s spheres. The total mass, $M_t$, the dimensionless central potential, $W_o$, and the tidal radius, $r_t$, (columns 4, 5 and 6) are output parameters obtained by solving the collisionless Boltzmann equation with the tidal potential at the averaged distance of the orbit to the Galaxy center (parameter $r_{ave}$ in Table 5).

As it can be seen in Table 4, the dimensionless central potential and the mass of the satellite decrease for inner positions of the equilibrium satellite for models with the same $r_o$ and $\sigma_o$. Furthermore, the mass of the models is smaller than the mass inferred from observations using kinematic arguments (Ibata et al. 1997, Mateo 1994) and it is in agreement with the observed luminous mass, assuming $(M/L)_\text{real} \sim 2 - 5 \, M_\odot / L_\odot$. Therefore, we have assumed $(M/L)_\text{real} = 2 \, M_\odot / L_\odot$ for all the s-models, that is a typical value for the stellar population of a DSph. The low value of the mass-to-luminosity ratio is in agreement with satellites either formed in tidal tails of major accretion events or tidally modified by orbiting for a long time in a tidal potential.

The apocenter, $r_{max}$, the pericenter, $r_{min}$, and the period of the orbits are listed in Table 5. The s-A orbit is an orbit of low eccentricity in the inner region of the Galaxy and s-B1 and s-B2 orbits have higher eccentricity.

4. Numerical details

The models have been evolved using the treecode algorithm kindly provided by Barnes & Hut (1986) with a tolerance parameter $\theta = 0.7$ and a time-step $\Delta t = 1$ Myr. The number of particles of the luminous and dark halo components of the primary galaxy are 15671 and 29648, respectively, and the mass of the dark matter particles is 3 times larger than for the luminous particles. All the satellite models have 4000 equal-mass particles, except s-B2a and s-B2c which have 8000 particles.

We use a softening length varying proportionally to the cubic root of the particle mass of the component, in order to avoid well-known usual numerical effects in the simulations (e.g. Merritt 1996, Theis & Spurzem 1999). For the luminous particles of the Galaxy it is $\epsilon_L = 0.23$ kpc and for the dark matter halo $\epsilon_{DH} = 0.33$ kpc. The f-models have $\epsilon = 0.06$ kpc, but this value is changed to $\epsilon = 0.05$ kpc for the s-A, s-B1 and s-B2b satellites and $\epsilon = 0.04$ kpc for the s-B2a and s-B2c satellites.

5. Results

5.1. The main galaxy

The main galaxy develops a bar-like structure, described by Fux (1997) for an isolated model of our Galaxy.
The global effects of the satellite on the primary galaxy are weak, since the mass ratio of both objects is huge. Besides, the poor resolution of the Galaxy model prevents a detailed description of the local effects of the Sagittarius accretion on the Milky Way. Therefore, we only deal with dynamical effects felt by the satellite galaxy.

5.2. f-models

For our f-models, we begin the simulations when the satellite has already reached the inner regions of the primary galaxy. A DSph galaxy on a low eccentricity orbit in these inner dense regions of the Galaxy undergoes stronger disruptions than on more eccentric orbits, because the tidal forces are stronger at all positions on the trajectory.

5.2.1. f-A satellite

In Fig. 2a (b), we plot the angular distribution of the f-A satellite along (perpendicular to) the orbit (which has eccentricity \( e = 0.2 \)) as seen from 24 kpc away (it corresponds to the Solar neighbourhood viewpoint), for four snapshots. In this case, the lifetime of the dwarf galaxy, before significant disruption, is nearly 0.4 Gyr (Fig. 3a).

The material from the satellite galaxy is tidally stripped, forming a long stream and then, after 1.2 Gyr, an almost close great circle in an Aitoff projection, which survives for a long time (Fig. 4a). Moreover, as we can see in Fig. 2b, the mean width perpendicular to the orbit on the sky is \( 7^\circ \) (it was only \( 1.9^\circ \) at the initial time) and the projected surface brightness (Fig. 5a) is 5 mag fainter at the end of the simulation (after 2.1 Gyr).

5.2.2. f-B1 and f-B2 satellites

For both f-B1 and f-B2 orbits (\( e = 0.64 \) and 0.75, respectively), disruption mainly occurs at perigalacticon, because tidal forces are more efficient at small galactocentric radii. The lifetime of a satellite depends strongly on the orbit shape. The f-B1 satellite is destroyed after 0.5 Gyr (Fig. 3b) whereas the f-B2 satellite survives for 1 Gyr (Fig. 3c) due to the longer period of its orbit, at this time the f-B2 satellite undergoes a close interaction (\( r \sim 2 \) kpc) with the center of the primary galaxy and it is tidally destroyed.

The final destruction of dwarf galaxies is more efficient in our more eccentric orbits and they present fainter surface brightness at the end of the simulation than the satellite on a low eccentric orbit (Fig. 5). The satellite particles of f-B models are spread over all directions and no predominant streams are formed, as it can be seen in Fig. 3b for the f-B1 model. In Figs. 4a and 5b, we have represented the width (perpendicular to the orbit) of the stream. At the end of the simulations, the f-B2 models do not have any predominant peak in the mass distribution perpendicularly to the initial orbit.

As a general result, due to the tidal field on the satellite we observe: i) a modification of the internal structure of the satellite for both cases of orbits (eccentric and quasi-circular), with increase of the projected velocity dispersion, and ii) a continuous loss of satellite mass and luminosity. Anyone tempted to infer a \( (M/L)_\rho \) ratio from such experiments by assuming virial conditions would find values \( 100 - 200 \) times higher than the true ones at the disruption time (Fig. 6), confirming the results of K97.

5.3. s-models

In this subsection, we analyze the interaction effects on a DSph in equilibrium with the galaxy potential. Either it could have fallen down slowly from an intermediate region in the denser parts of the primary galaxy, loosing part of its mass and becoming a low DM satellite, or it could have been formed in a tidal tail of a major accretion event.

5.3.1. s-A model

DSphs which are theoretical equilibrium solutions to Sgr at a circular inner orbit are small and low mass galaxies. The tidal field is almost constant along this quasi-circular orbit and, therefore, interaction effects on the satellites in equilibrium are not important. For the s-A orbit, there is a continuous loss of
mass, but the satellite has still $\sim 20\%$ of the initial mass (Fig. 7c) after 2 Gyr and it is still detectable (Fig. 7a). The central surface brightness has only changed by 2.5 mag (Fig. 7a), evolving from 21.3 mag arcsec$^{-2}$ to 24.8 mag arcsec$^{-2}$. The line-of-sight velocity dispersion grows in the outer parts of the satellite in agreement with findings by K97, remaining almost constant in average in the inner parts ($< 0.2 - 0.3$ kpc) (Fig. 7b). We have calculated the mass inferred from the line-of-sight velocity dispersion, measured inside a radius of 0.5 kpc from the satellite center, using Eq. (1). Since the central velocity dispersion and the projected density (Fig. 7a) evolve slowly in the central region of the satellite at the beginning of the simulation, the inferred mass-to-luminosity ratio remains almost constant, contrary to the f-models. However, as we have explained above, the real mass of the satellite decreases and it is only $\sim 20\%$ of the initial value after 2 Gyrs. The structural evolution is slow (Fig. 7c) and it leads to a lower central surface brightness at the end of the simulation and a $(M/L)_o$ ratio calculated from the velocity dispersion (inside 0.5 kpc) which is 5 times higher than the real one (Fig. 7d). This effect could be dramatically increased if the velocity dispersion is measured inside a larger radius, because of the velocity dispersion increase in the outer region of the satellite, leading to a calculated $(M/L)_o$ ratio up to 10 times larger than the real one (Fig. 7d). Very faint tidal streams are formed, which are spread along $\sim 75 - 100\%$ of the orbit with a spatial width $\sim 6^\circ$ (Fig. 8).

Fig. 5. Surface brightness $\mu_V$ of the f-models, assuming $(M/L)_{real,V} = 10 M_\odot/L_\odot$

5.3.2. s-B models

Perigalacticon and apogalacticon of high eccentric s-B1 and s-B2 orbits decrease with the time. The most dramatic example is the s-B1 orbit. The DSph passes 1 kpc from the galaxy center at its third passage at perigalacticon (Fig. 9a), because of the orbital energy loss. During this passage the satellite is
strongly tidally stripped and it loses most of its mass (Fig. 9d). The surface brightness of the satellite decreases with time (Fig. 9a) and the velocity dispersion and the mass-to-luminosity ratio increase in the outer parts (Figs. 9b and 9e). The satellite is finally completely destroyed after nearly 1 Gyr.

s-B2 is the most external and eccentric orbit which we have chosen. As the other models, it fulfills at certain times the position and velocity constraints for the Sagittarius DSpH orbit in the observational range (Ibata et al. 1997).

In order to investigate this case in more details, we have selected three different satellite models for orbiting on this trajectory (s-B2a, s-B2b and s-B2c). The concentration (defined as \( c = \log(r_t/r_o) \)) varies from 1.28 (s-B2a) to 0.83 (s-B2c). The concentration determines the fate of the satellite, as well as the evolution of the \((M/L)_o\) ratio. The more concentrated the satellite is, the less variation of the inferred \((M/L)_o\) ratio it suffers (Fig. 10).

The \((M/L)_o\) ratio in Fig. 10 has been calculated for the central region of the satellite \((< 0.5 \text{ kpc})\), where the tidal effects on the mass and the velocity dispersion are weaker. However, even in the most concentrated satellite (s-B2a), we obtain \((M/L)_o\) ratios which are \( \sim 10 \) \((M/L)_{\text{real}}\), these values rise up to several hundreds for the least concentrated model (s-B2c).

It is interesting to notice the strong variations of the inferred \((M/L)_o\) ratio with time. This behaviour is caused by the evolution of the surface mass density when the satellite suffers a close encounter with the core of the primary galaxy. It leads to a successive rearrangement of the internal structure of the satellite. Another important parameter in the \((M/L)_o\) calculations is the angle between the observer-satellite line and the main axis of the satellite. The strong anisotropies of the satellite (tails along the orbit, anisotropic velocity dispersion, etc) could produce various \((M/L)_o\) values (as already suggested by K97 and KK98).

The line-of-sight velocity dispersion evolves as shown in Fig. 11. The projected velocity dispersion decreases in the central part of the satellite \((r < 0.5 \text{ kpc})\) and it increases for \( r > 0.5 \text{ kpc}\). Thus, the \((M/L)_o\) ratio calculated from Eq. (1) varies, depending on the limit radius used for the measurement of the central velocity dispersion (this limit radius is related to the observational resolution).

s-B2a model:

The s-B2a model undergoes a long term evolution. It is the most concentrated model that we have chosen and it survives for at least 10 Gyrs. A mild loss of mass is produced, mainly at perigalacticon: the satellite looses the outer layers of mass, but a core enclosing 30% of the initial mass subsists (Fig. 12a). The limit radius is smaller than the initial one, but the half-brightness radius increases (the final satellite is less concentrated). The central surface brightness decreases (Fig. 13a),
changing from \( \sim 21.0 \text{ mag arcsec}^2 \) to \( \sim 22.0 \text{ mag arcsec}^2 \) (assuming \( (M/L)_{\text{real}} = 2 \text{ M}_\odot/\text{L}_\odot \)). The final s-B2a satellite is smaller \( (r_{bh} = 0.13 \text{ kpc}) \) than the observed Sgr DSph \( (r_{bh} = 0.55 \text{ kpc}) \) and the \( (M/L)_o \) ratio is not large enough to reproduce the inferred \( (M/L)_o = 50 \text{ M}_\odot/\text{L}_\odot \) by Ibata et al. (1997).

**s-B2b model:**

The mass loss of the s-B2b satellite (Fig. 12b) is stronger than that of the s-B2a satellite. The particles of the satellite outer region are stripped, mainly at perigalacticon. The tidal stripped material develops a stream forward and backward from the satellite along the orbit. In Fig. 13b, a low surface brightness tidal extension of the satellite can be seen at intermediate epochs. At the final snapshot \( (t = 10.5 \text{ Gyr}) \), the residual core of the satellite is still detectable, it has \( \sim 15\% \) of the initial mass (Fig. 12b) and a central projected surface brightness \( \mu_o \sim 23.8 \text{ mag arcsec}^{-2} \) assuming \( (M/L)_{\text{real}} = 2 \text{ M}_\odot/\text{L}_\odot \). The initial central surface brightness for the same \( (M/L)_{\text{real}} \) ratio was \( 21.3 \text{ mag arcsec}^{-2} \). The stream formed close to the satellite has a surface brightness which is 5.0-6.5 mag fainter than the center of the satellite. This stream is similar to those formed by extra-tidal stars observed close to some DSph satellites.

At some snapshots (i.e. 3.7 Gyr, 4.83 Gyr, 6.2 Gyr, 7.3 Gyr, 8.45 Gyr and 9.6 Gyr), when the tidal streams of the satellite are already formed, the radial velocity, \( v_r \), and the gradient of the radial velocity, \( |dv/db| \), of the s-B2b satellite and of the stream around the satellite reproduce the observations of Sgr DSph region. The observational values of \( v_r \) and \( |dv/db| \) of Sgr are given in Table 1. However, the values of both quantities in the models are strongly dependent on the position and orientation of the orbit. Therefore, small perturbations in the orbit of the models could lead to differences in \( v_r \) of several 10 km s\(^{-1}\). In general, the sign of the variation of the radial velocity depends on the position of the satellite along the orbit. For some particular positions, the radial velocity gradient is almost 0 km s\(^{-1}\)/degree. The s-B2b satellite at time 8.47 Gyr is an example of a model which has a good agreement in position with the observations of Sgr DSph (Fig. 14c). From the kinematical point of view, the particles in the stream show a velocity gradient \( |dv/db| \sim 4 \text{ km s}^{-1}/\text{degree} \) (Fig. 14a), which is slightly higher than the observed value \( (|dv/db| = 3 \text{ km s}^{-1}/\text{degree}) \), whereas the radial velocity is slightly lower. Moreover, this
satellite model presents a velocity dispersion ($\sigma \sim 6$ km/s, Fig. 14b) lower than the observed value ($\sigma \sim 11.4$ km/s). However, the projected velocity dispersion of the stream remains almost constant and equal to the velocity dispersion in the inner region of the system. Observational data show that regions close to the Sagittarius globular clusters (Terzan 8, Terzan 7, Arp 2) have a similar projected velocity dispersion (Ibata et al. 1997).

The density contour map of the s-B2b model at 8.47 Gyr (Fig. 14c) resembles the observational map for the region around the center of the satellite (see for example Fig. 1 in Ibata et al. 1997), in spite of the low resolution (few mass points) of the simulation. However, the center of our satellite has a steeper density profile, the half-brightness radius of the model is $r_{hb} = 0.12$ kpc and that of Sagittarius DSp 0.55 kpc. Even at the end of the simulation ($t = 10.5$ Gyr) the satellite remains too concentrated ($r_{hb} = 0.17$ kpc). This discrepancy could mean that either the real Sagittarius DSp has undergone a stronger tidal field, which has caused an effective destruction of the satellite core, or it has suffered tidal disruption for a longer time, or the initial density profile of the Sagittarius satellite was more extended than that of our model. In order to test the latter hypothesis, we have built the s-B2c model, which is less concentrated than s-B2b but more massive. s-B2c follows the same orbit as s-B2b.

s-B2c model:

The s-B2c satellite survives 5.5 Gyr before disruption. The effects at perigalacticon (Fig. 12c) are stronger than those of the other s-B2 models, because of the lower concentration. Low surface brightness trailing and leading streams are formed. At 5.88 Gyr, the residual satellite looks like a long tidal extension with a maximum projected surface brightness $\mu \sim 27.0$ mag arcsec$^{-2}$, assuming $(M/L)_{\text{real}} = 2 M_\odot/L_\odot$ (Fig. 13c).
Radii which enclose 70%, 60%, 50%, 40%, 30%, 20% and 10% of the initial mass of the satellite, for s-B2 models.

Surface brightness $\mu_V$ of the s-B2 satellites, assuming $(M/L)_\text{real, } V = 2 \frac{M_\odot}{L_\odot}$.

Fig. 12. Radii which enclose 70%, 60%, 50%, 40%, 30%, 20% and 10% of the initial mass of the satellite, for s-B2 models.

Fig. 13. Surface brightness $\mu_V$ of the s-B2 satellites, assuming $(M/L)_\text{real, } V = 2 \frac{M_\odot}{L_\odot}$.

arcsec$^{-2}$, which are slightly lower than observational values, but they evolve to larger half-brightness radius and lower surface brightness as the satellite approaches the Galactic disc and gets more disrupted. For example, at $t = 5.565$ Gyr we obtain the best accord between the simulations and the observations for $r_{hb}$ and $\mu_o$ (the values of the model are 0.5 kpc and 25.4 mag arcsec$^{-2}$, respectively), but the position and the velocity do not reproduce the observations ($b \sim 20^\circ$ and $(U, V, W) \sim (103, 0, 86)$ km/s).

The radial velocity gradient along the orbit of s-B2c satellite depends on the orientation of the trajectory, as in the s-B2b model. At 5.38 Gyr we obtain $|dv/db| \sim 1.5$ km s$^{-1}$/degree for the trailing stream, which is lower than the observed value. However, the radial velocity $v_r$ is in agreement with the observations ($v_r = 171$ km s$^{-1}$). The satellite velocity dispersion measured inside 0.5 kpc has decreased ($\sigma \sim 7$ km/s), but it is still large enough to give $(M/L)_o \sim 10(M/L)_\text{real}$.

It is interesting to analyze not only the region around the center of mass of the satellite but also the tidal tails which are formed along the orbit. We have done it for several tidal tails close to the satellite. In Fig. 14 we plot the surface brightness of the trailing tail of the s-B2c model at various timesteps, assuming $(M/L)_\text{real} = 2 \frac{M_\odot}{L_\odot}$ (a larger value of $(M/L)_\text{real}$ moves the lines down in the figure and vice versa). The simulations are compared with the trailing tail observed by Mateo et al. (1998) recently. As we can see, except for the region closest to the satellite center ($< 12^\circ$), the simulations reproduce the observations, giving a better result when the satellite is more disrupted. This supports the hypothesis that Sgr DSph is close to its destruction. In our simulations, we also obtain a leading tail similar to the trailing one. Unfortunately,
Fig. 15. s-B2c satellite, at 5.38 Gyr: a Radial velocity, $v_r$, along the orbit (constant galactic latitude), b velocity dispersion, $\sigma$, along the orbit and c contour density map (the star represents the mass center of the satellite, located at $b = -10.7^\circ$), the solid contours correspond to $\mu = 24.3, 25.0, 25.5, 26.7, 27.5$ mag arcsec$^{-2}$ from the center and the dashed contour corresponds to $\mu = 30$ mag arcsec$^{-2}$

the proximity of the Galactic disc to Sgr center makes difficult to test this result of symmetric tails due to still poor observational data. To give another example of the complexity of the satellite structure, we plot in Fig. 17 the contour density levels and the kinematic behaviour of a tidal tail, at 5.25 Gyrs from the beginning of the simulation. It looks like the Sgr DSph from the kinematical point of view, having radial velocity (Fig. 17a) and velocity dispersion (Fig. 17b) similar to Sagittarius observed values ($v_r = 171$ km s$^{-1}$ and $\sigma = 11.4$ km s$^{-1}$). The shape of the tail (Fig. 17c) also looks like a tidally disrupted satellite, however, the central surface brightness is $\mu_o \sim 29.5$ mag arcsec$^{-2}$ (fainter than a typical DSph) and the computed $(M/L)_o$ ratio is $200(M/L)_{\text{real}}$ (higher than the estimation for DSph galaxies). Nevertheless, this example illustrates, on one hand, the difficulty of distinguishing between a tidal tails and a DSph galaxy when the latter is close to the disruption and, on the other hand, the possibility of identifying objects (globular clusters, etc) which have been tidally disrupted from a satellite galaxy by measuring their kinematic characteristics.

6. Discussion

Summing up the results obtained in our simulations and comparing them with other published works, we agree with other authors (Velázquez & White [1995]; Ibata & Lewis [1998]) that Sgr DSph has a short period orbit ($T \leq 1$ Gyr). This constraint comes from measurement of the position and the radial velocity of Sgr DSph in a realistic model of the Galaxy. However, we disagree about the DM content. These previous works claim that Sgr DSph is a DM dominated satellite, because, contrary to us, they could not obtain a low mass satellite which survives...
by orbiting in the potential of the Galaxy. Therefore, they cannot explain the complex evolutionary pattern inferred for the Sagittarius Dsph, which has suffered a chemical enrichment and evolution and the age interval of its globular clusters which suggests a long life orbiting in the Galaxy.

Ibata & Lewis (1998) have tested low massive models in order to reproduce the Sgr Dsph characteristics, reaching an unsuccessful result on the matter and concluding that Sgr Dsph must have a large DM content. There are two differences between their study and ours. Firstly, they use a rigid potential to model the Galaxy, so no energy interchange is allowed between the satellite and the Galaxy. This restriction could eventually prevent a readjusting of the internal energy of the satellite in order to reach an equilibrium with the environment. Even if the energy transfer from the satellite to the halo is not important in all cases, we emphasize that our treatment is a priori adaptable to satellites of various masses. Secondly (and mainly), Ibata & Lewis (1998) do not take into account the tidal potential of the Galaxy as they build their satellite model. We have confirmed that the fate of such satellites is different from that of the satellites in equilibrium with the tidal potential as considered here. Consequently, a more accurate model of the initial satellite, that reflects the true dynamical situation of the Dsph, is required in order to avoid spurious effects in the simulations. These differences in the models are responsible for the opposite conclusions reached by Ibata & Lewis, compared with ours concerning DM. Furthermore, the recent observations of Sgr by Mateo et al. (1998) prove the existence of a long trailing tail, which supports the hypothesis that Sgr Dsph has suffered strong tidal forces, it is close to disruption and, therefore, it is not in virial equilibrium. The existence of this tail also reduces the inferred (M/L)o ratio.

Our low DM satellites (modified King’s models) establish important restrictions on the satellite formation theory. Thus, the satellite galaxies grow either in a quasi-isolated region (falling slowly on the center of the primary galaxy and having time for readjusting their internal structure to the tidal forces), or inside the main galaxy, in the tidal tails of a major accretion event, which automatically implies equilibrium with the tidal forces at the satellite formation epoch. Furthermore, the survival time of the equilibrium satellites in the potential of the Galaxy depend on the initial concentration of the Dsph (the larger concentration, the longer the life-time). We have obtain models (i.e., s-B2a) which survive more than 10 Gyr. The evolution of these satellites gives rise to tidal streams and modifications in the outer velocity dispersion of the satellite and it leads to high observed mass-to-light ratios if dynamical equilibrium is assumed. We have obtained a rather good qualitative agreement with the observational constraints for the model s-B2c in a time interval (from 5.38 to 5.7 Gyr), although this agreement is not achieved simultaneously on all the constraints. We remind that the simulation time does not necessarily correspond with the age of the oldest globular cluster of Sgr and, therefore, the s-B2c model is not necessarily in disagreement with the observations. In this case, two possibilities could be invoked to explain the age of the oldest Sgr globular clusters: (i) either the satellite has been orbiting for a long time in a more external region (where tidal forces are smaller), it suffers dynamical friction or/a deflection with a dense structure of the MW and it reaches the present orbit where, eventually, it is disrupted, or (ii) it has formed in a tidal tail which contained an old stellar population (Kroupa 1998d).

The tidal tail models illustrate that a Dsph without DM orbiting through central regions of the Galactic potential could preserve its structural parameters for a long time. Later on, the Dsph could show high inferred (M/L)o values as it becomes disrupted. The only restriction of the model is that the satellite must reach the central regions of the Galaxy in equilibrium with the tidal forces. That could be possible whether the satellite has been formed in a tidal tail of an accretion event or it has been slowly accreted from the external parts of the Galaxy. The latter possibility could increased the estimated life-time of the satellite before destruction.

Recently, K98 has discussed the parameter space of the DSphs which could survive in a tidal field. In spite of the different initial distribution functions, our s-models seem to be located in the available region of the (Msat, rsat) space for surviving satellites. However, the main difference between the approaches to the problem is that we build the model of the satellite initially in equilibrium with the tidal forces by solving the Boltzmann equation (Gómez-Flechoso & Domínguez-Tenreiro 1998) and that assures a priori the survival of the satellite for a long time.

7. Summary
We have performed simulations of Sagittarius-like satellites to follow the evolution of these systems. The satellite and the primary galaxy are modelled as N-body systems, that prevents possible purely numerical effects which could appear in a non-selfgraviting scheme (i.e. if one of the interacting system is represented by a rigid potential). Two satellite models have been tested:

1. First of all, we have used isolated King’s models (three free parameter models) for the satellite, but they are tidally stripped and destroyed in a short interval of time, undergoing a fast evolution.

2. In order to correctly model the observed situation we had to introduce the modified King’s models (two free parameters models), which allow us to build up the distribution function of the satellite, taking into account the tidal force of the environment. These s-models correspond to no DM dominated satellites. In this framework, the initial concentration of the satellite and the trajectory determine its life-time. Central circular orbits lead to more effective tidal destruction events than highly eccentric orbits. For a given kind of orbit, the most concentrated satellites live longer. The model which better reproduces the observations is the s-B2c model after orbiting 5.38-5.6 Gyr in the potential of the Milky Way. For the same orbits, the s-models survive a longer time orbiting in the Galactic potential than
the f-models, despite the s-models having smaller masses (smaller binding energies).

According to the results presented here, our main conclusions about the evolution of Sgr are:

1. Sagittarius may not be a dominated DM satellite.
2. It follows an eccentric orbit (perigalacticon and apogalacticon are approximately 15 and 70 kpc).
3. It was more concentrated in the past than at the present epoch.
4. It could have been orbiting in the Galactic halo for a long time (minimum 5 Gyr).

As general conclusions about the DSph satellites, we can remark that:

1. High values of $(M/L)_o$ found in the literature (Ibata et al. 1995; Irwin & Hatzidimitriou 1995; Mateo 1998 for a review of the Galactic satellites) could be due to an erroneous use of the virial theorem and not to the presence of DM (as already suggested by K97; KK98).
2. The progenitor of these satellite could be either lumps formed in a major accretion event or other dwarf galaxies (maybe dwarf irregulars or dwarf spirals) which fall in the potential well of the Galaxy, lose their gas content and evolve to the equilibrium configuration in the tidal field of the Milky Way, giving rise to the population of DSphs. The finding of intermediate states of this evolution could be a support to the proposed scenario.
3. According to some of the present results, some DSphs are able to survive for long times orbiting in the Galactic halo. That should be taken into account for the calculations of the dissolution rate of dwarf galaxies in the halo of the primary galaxy.

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References
Alard, C., 1996, ApJ 458, L17
Barnes J.E., Hernquist L., 1992, Nature 360, 715
Barnes J.E., Hut P., 1986, Nature 324, 446
Becklin E.E., Neugebauer G., 1968, ApJ 151, 145
Burkert A., 1997, ApJ 474, L99
Cole S., Aragón-Salamanca A., Frenk C.S., Navarro J.F., Zepf S.E., 1994, MNRAS 271, 781
Due P.A., Mirabel I.F., 1997. In: Sanders D.B. (ed.), IAU Symposium 186: Galaxy Interactions at Low and High Redshift, preprint astro-ph/9711253
Edelsohn D.J., Elmegreen B.G., 1997, MNRAS 290, 7
Fux R., 1997, A&A 327, 983
Gómez-Flechoso M.A., Domínguez-Tenreiro R., 1998, MNRAS, submitted

Ibata R.A., Lewis G.F., 1998, ApJ 500, 57
Ibata R.A., Gilmore G., Irwin M.J., 1994, Nature 370, 194
Ibata R.A., Gilmore G., Irwin M.J., 1995, MNRAS 277, 781
Ibata R.A., Wyse F.G., Gilmore G., Irwin M.J., Suntzeff M.B., 1997, AJ 113, 634
Irwin M., Hatzidimitriou D., 1995, MNRAS 277, 1354
Johnston K.V., Spergel D.N., Hernquist L., 1995, ApJ 451, 598
Johnston K.V., Hernquist L., Bolte M., 1996, ApJ 465, 278
King I., 1966, AJ 71, 64
Klessen R.S., Kroupa P., 1998, ApJ 498, 143
Kroupa P., 1997, New Astronomy 2, 139
Kroupa P., 1998. In: Duschl W., Einsel C. (eds.) Dynamics of Galaxies and Galactic Nuclei, preprint astro-ph/9801047
Kroupa P., 1998b. In: Richtler T., Braun J.M. (eds.) The Magellanic Clouds and Other Dwarf Galaxies, preprint astro-ph/9804255
Kroupa P., 1998c, MNRAS 300, 200
Layden A.C., Sarajedini A., 1997, ApJ 486, L107
Lynden-Bell D., 1982, The Observatory 102, 202
Lynden-Bell D., Lynden-Bell R.M., 1995, MNRAS 275, 429
Mateo M., 1994. In: Meylan G., Prugniel P. (eds.) ESO/OHP Workshop on Dwarf Galaxies. ESO, Garching, p. 309
Mateo M., 1997. In: Arnaboldi M., Da Costa G.S., Saha P. (eds.) The Nature of Elliptical Galaxies, in press
Mateo M., Mirabal N., Udalski A., Szymański M., Kalużyń J., Kubiak M., Krzeminski W., Stanek K. Z., 1996, ApJ 458, L13
Mateo M., 1998, ARA&A 36, 435
Mateo M., Olszewski E.W., Morrison H.L., 1998, preprint astro-ph/9810015
Matsumoto T., Hayakawa S., Koizumi H. et al., 1982. In: Riegler G., Blandford R. (eds.) The Galactic Center. American Institute of Physics, New York, p. 48
Merritt, D., 1996, AJ 111, 2462
Montegriffo P., Bellazzini M., Ferraro F.R., Martins D., Sarajedini A., Fusi Pecci F., 1998, MNRAS 294, 315
Oh K.S., Lin D.N.C., Aarseth S.J., 1995, ApJ 442, 142
Piatek S., Pryor C., 1995, AJ 109, 1071
Preston G.W., Shectman S.A., Beers T.C., 1991, ApJ 375, 121
Richstone D.O., Tremaine S., 1986, AJ 92, 72
Theis, Ch., Spurzem, R., 1999 A&A 341, 361
Velázquez H., White S.D.M., 1995, MNRAS 275, L23
Whitelock P.A., Irwin M., Catchpole R. M., 1996, New Astronomy 1, 57
Zinn R., 1985, ApJ 293, 424