THE NATURE AND FATE OF THE SAGITTARIUS DWARF GALAXY

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The Sagittarius dwarf galaxy, located at a distance of $\sim$ 15 kpc behind the Galactic bulge, is in the process of being tidally disrupted and assimilated into the Milky Way. This unique event allows the physics of galactic merging to be probed in unprecedented detail, and may shed light on the hypothesized population of primordial galaxies that merged to form the Milky Way.

Numerical simulations, constrained by the latest kinematic and structural data, show that the luminous component of this dwarf galaxy must reside within a substantial dark matter halo for the dwarf to have survived the Galactic tides long enough to be seen at the present time. The minimum mass of the dark halo is then $\sim 5 \times 10^8 M_\odot$, which implies a global mass to light ratio of $\sim$ 100. It is found that the eventual fate of all the plausible models is to disrupt into a stream of particles that follows closely the original orbit of the dwarf through the Galactic halo, remaining stable for many Gyr. However, the timescale for the complete disruption of the Sagittarius dwarf is model-dependent and remains presently unknown.

1. Introduction

The Sagittarius dwarf spheroidal (Ibata, Gilmore & Irwin 1994, 1995), discovered during the course of a spectroscopic study of the bulge of the Milky Way (Ibata & Gilmore 1995a, 1995b), is the closest satellite companion galaxy to the Milky Way. This dwarf galaxy contains a mix of stellar populations ranging from relatively old stars – many RR Lyrae stars are observed (Mateo et al. 1995, Alard 1996) and at least one of its four globular clusters is as old as the oldest Galactic halo clusters (Richer et al. 1996; Chaboyer, Demarque and Sarajedini, 1996) – to intermediate age stars – several Carbon stars have been identified (Ibata et al. 1994, 1995). The dom-

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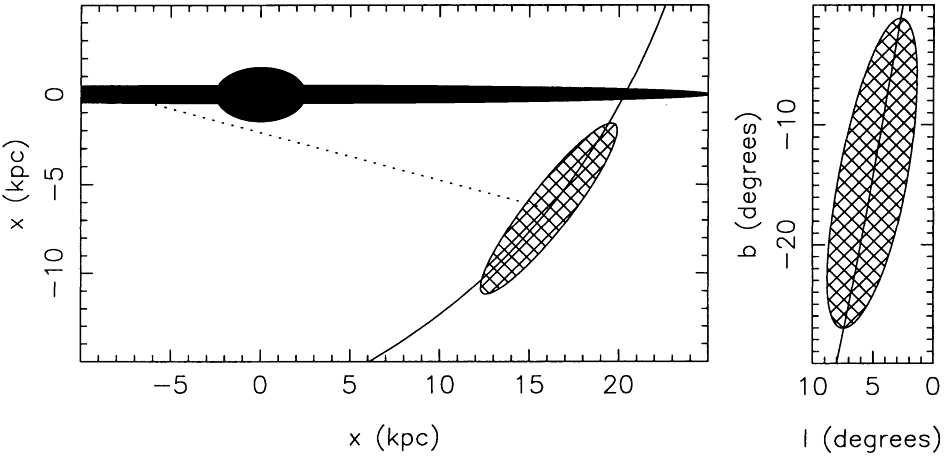

Figure 1. Schematic diagrams showing the position of the Sagittarius dwarf in relation to the Galaxy. In both diagrams, the orbital path of the dwarf is indicated with a solid line. The left hand panel is in the x–z plane of the Galaxy. The line of sight from the Sun to the center of the dwarf is marked with a dotted line. The right hand panel shows the projection of the Sagittarius dwarf on the sky.

inant population however, is 10 to 14 Gyr old (Fahlman et al. 1996) and has mean abundances between [Fe/H] $= -0.8$ and [Fe/H] $= -1.2$ (Whitelock, Catchpole & Irwin 1996). The full abundance range observed covers $\gtrsim$ 1dex around this mean.

The derived geometrical picture is shown schematically in Fig. 1. The Sagittarius dwarf is a prolate body with axis ratios $\sim$ 3:1:1, oriented approximately perpendicular to the plane of the Galaxy from Galactic latitude $b = -4°$ to $b = -32°$, with its longest dimension aligned $\gtrsim$ 10 kpc along the coordinate line $\ell = 5°$. Its center is located $\sim$ 25 kpc from the Sun and 16 ± 2 kpc from the Galactic center, near its point of closest approach to the Galaxy. Such proximity to the Galactic center is expected to induce huge tidal stresses in the dwarf, which will lead to its eventual destruction, with its stars and globular clusters eventually becoming members of the Galactic halo. Thus, the Sagittarius dwarf is perhaps a prime, and it is certainly the closest, example of a small galactic building block, as envisaged in the currently popular picture of hierarchical structure formation. Depending on its orbit and mass, the Sagittarius dwarf may also significantly influence the Milky Way. The proximity allows us to study this interacting pair of galaxies in great detail; one may obtain very precise kinematics (including proper motions), accurate abundance measurements, and very deep photometry, all with a precision unobtainable in any other system; the observational constraints are reviewed in Ibata et al. (1997).

2. The orbit of the Sagittarius dwarf

Determining the orbit of the dwarf is the most important first task in understanding the interaction. Several numerical studies (Oh et al. 1995, Piatek & Prior 1995, Johnston et al. 1995, Velazquez & White 1995) have shown that dwarf satellite galaxies become elongated in the tidal field of their massive companion. The elongation, it transpires, always points parallel to the plane of the dwarf's orbit, and approximately along the direction of motion. Since the Sagittarius dwarf is almost directly behind the Galactic center, as viewed from Earth, the projected elongation must be aligned with the proper motion vector (and the projection of the orbit) to very good approximation. From these constraints, the pole of its orbit is deduced to be at ($\ell = 94°, b = 11°$) (Lynden-Bell & Lynden-Bell 1996). The component of the proper motion of the central regions of the Sagittarius dwarf along the direction of the deduced orbit has been measured, (Irwin et al. 1996, Ibata et al. 1997), indicating that it is moving northwards with a transverse velocity of $250 \pm 90\,\mathrm{km\,s^{-1}}$.

Unfortunately, this proper motion measurement has too large an uncertainty to provide a useful determination of the orbit. To get around this problem, one can simulate N-body models of the dwarf on a grid of orbits and compare the present-day structure of the models to the accurately determined radial velocity gradient (which has been obtained over a large portion of the major axis of the dwarf from $b = -10°$ to $b = -30°$). Such numerical experiments also allow the structural evolution of the Sagittarius dwarf to be studied. Since 'King models' (King 1962) fit the structure of present day dwarf spheroidal galaxies well (Irwin & Hatzidimitriou 1995), it is natural to use these models to represent the structure of the initial proto-dwarf galaxy. A grid of 21 structural models was set up, sampling the plausible parameter space of concentration, central velocity dispersion and central density. The evolution of the models was calculated using an N-body tree-code algorithm (Richardson 1993), which was altered to include the forces due to the assumed fixed Galaxy potential and due to dynamical friction, as approximated by the Chadrasekhar formula (Binney & Tremaine 1987). The models, comprising either 4000 or 8000 particles, were evolved for 12 Gyr, a time equal to the age of the dominant stellar population in the Sagittarius dwarf (Fahlman et al. 1996). This work is described in detail in Ibata & Lewis (1997).

Each of the 21 King models was simulated on one or more of the orbits shown in Fig. 2. The orbits are obtained by integrating the path of a massless tracer particle backwards in time under the influence of the fixed Galactic potential described in Johnston et al. (1995). Though the initial radial velocity of the tracer particle is identical in all four orbits, the proper

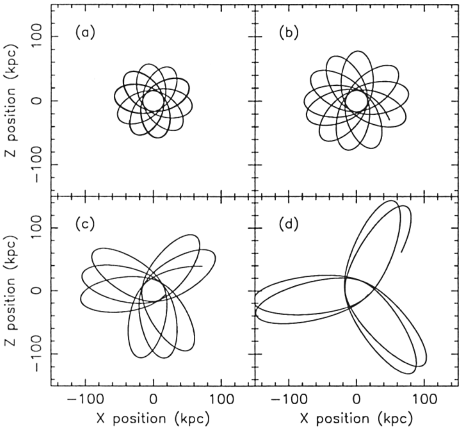

Figure 2. The four orbits on which the King models were launched. In the text, these orbits are referred to by the panel label in this plot.

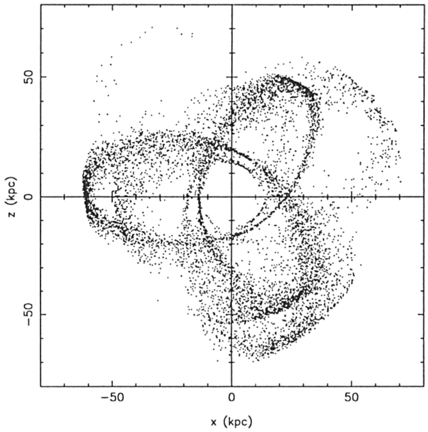

Figure 3. The end-point structure of the dwarf galaxy model whose initial structure was set up to match the present day observations of the Sagittarius dwarf.

motion increases from $250\,\mathrm{km\,s^{-1}}$ to $390\,\mathrm{km\,s^{-1}}$ from orbits 'a' to 'd'.

It transpires that all the models placed initially on the 'a' orbit give rise to a radial velocity gradient that is in good agreement with the observations, while those models on the longer period 'b', 'c' and 'd' orbits give progressively worse fits to the radial velocity data. This is illustrated in Fig. 4, which compares the observed radial velocity gradient along the major axis of the dwarf with the King models that managed to survive the interaction with the Milky Way. Thus the orbit of the Sagittarius dwarf is well approximated by the 'a' orbit, which has a short period $T \sim 0.7\,\mathrm{Gyr}$, and implies that there have been many collisions with the Galactic disk in the past.

3. Fate of the dwarf galaxy models

Models set up with an initial configuration to fit the observations of the present state of the Sagittarius dwarf turn out to be very fragile. In particular, setting the velocity dispersion to the observed value of $11.4\,\mathrm{km\,s^{-1}}$, the minor axis half-mass radius to the observed value of 0.55 kpc, and placing the model on the 'a' orbit, results in a model that becomes completely unbound after only 5.3 Gyr. This confirms, using constraints from a more complete data set, the findings of Velasquez & White (1995) and Johnston et al. (1995) that models of the Sagittarius dwarf, where light traces mass, are fragile. If so, one may deduce that the Sagittarius dwarf will be completely disrupted within $\sim 5\,\mathrm{Gyr}$, providing a source of new stars and

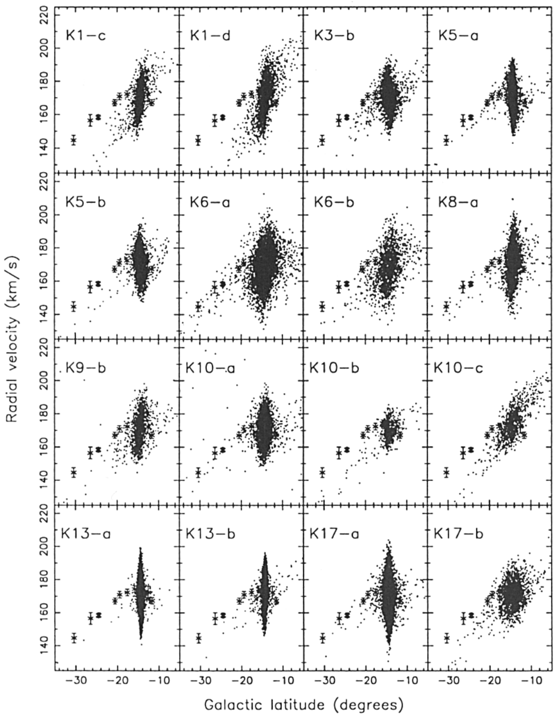

Figure 4. The radial velocity – Galactic latitude structure of the models that survive the tidal interaction with the Milky Way is compared to the observed radial velocity in fields along the major axis of the Sagittarius dwarf (points with error-bars). Each panel is marked with the model label from Ibata & Lewis (1997), where the letter following the hyphen identifies one of the four orbits of Fig. 2.

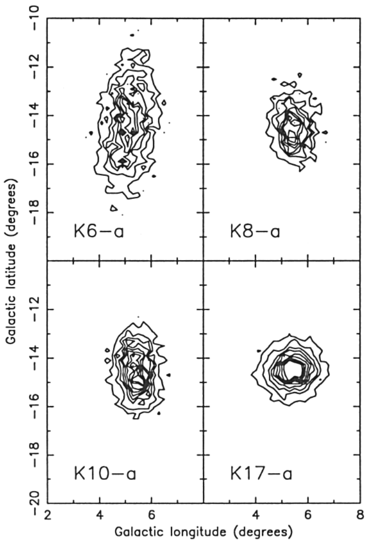

Figure 5. The final structure of the models that survived the Galactic tides and gave a good representation of the observed radial velocity gradient and radial velocity dispersion of the Sagittarius dwarf. However, all of the models have a *much* narrower half-mass radius than the observed half-brightness radius.

globular clusters to the Galactic halo. At the end of the integration, at 12 Gyr, the structure of the galaxy remnant is shown in Fig. 3. No bound concentration of particles remains; instead, streams of particles populate the orbital path of the former dwarf galaxy.

A search of parameter space with the extensive grid of models has revealed several configurations that do retain a bound core at the end of the simulation, and fit the radial velocity profile. Of these, the four models displayed in Fig. 5 also fit the observed radial velocity dispersion. However, no model manages to survive and be consistent with the observed minor axis width of the Sagittarius dwarf: we find that all models that have initially large half mass radii are rapidly destroyed by the Galactic tides. The half mass radius, it transpires, becomes smaller as disruption proceeds. So large initial half mass radii are required to match the observed half-brightness radius of $R_{\mathrm{HB}} = 550\,\mathrm{pc}$. Yet any model with such a large initial half-mass radius becomes completely unbound within a few orbital periods.

This problem was investigated by Ibata et al. (1997), who concluded that a self-consistent solution to the present existence of the dwarf can only be found if the requirement that light traces mass is relaxed. The tidal disruption of the Sagittarius dwarf can be impeded if the stellar component of the dwarf galaxy is enveloped in a halo of dark matter, which has a mass profile such that dark matter density is a factor of 2–3 larger than the mean Galactic density interior to its peri-galacticon distance. To be consistent with the observed low velocity dispersion of the stellar component embedded therein, the core radius of the dark halo would have to extend out to the photometric edge of the system. The deduced mass to light ratio would then be $M/L \sim 100$. With this model, the escape velocity from the center of the Sagittarius dwarf is substantial, $v_{\mathrm{e}} = 90\,\mathrm{km\,s^{-1}}$, which helps to explain the observed wide abundance range.

4. Survival of primordial galaxy fragments

All of the dwarf galaxy models give rise to streams of tidally disrupted material that follow the orbital path of the remnant quite closely. The disrupted fraction always exceeded 15%, so one may expect to find a sizeable fraction of the stellar component of the Sagittarius dwarf spheroidal, including perhaps one or more globular clusters, stretching along a ring around the sky. It will be very fruitful to detect such material, as its kinematics could provide a very sensitive test of the Galactic potential gradients.

One of the most significant consequences of the failure of the mass-traces-light models to reproduce the observations is that the merging fragments that made the Galaxy probably had a radially increasing mass to light ratio, so that the stars were more centrally concentrated and the dark matter more extended. Detailed numerical simulations are required to explore this question further, but one may expect such a structure to initially lose almost exclusively dark matter, with stars being lost only in the last stages of disruption. If dynamical friction causes significant orbital decay of the merging clumps, the luminous matter would be deposited more centrally than the dark matter in the global potential well, naturally giving rise to a radially increasing mass to light ratio in the halos of large galaxies.

5. Interaction with the Milky Way

The models of the Sagittarius dwarf galaxy that are designed to reduce tidal disruption have sufficient mass to affect the structure of the Milky Way. Indeed, in this case, the tidal forces on the Milky Way due to the Sagittarius dwarf will be substantially larger than those due to the Large Magellanic

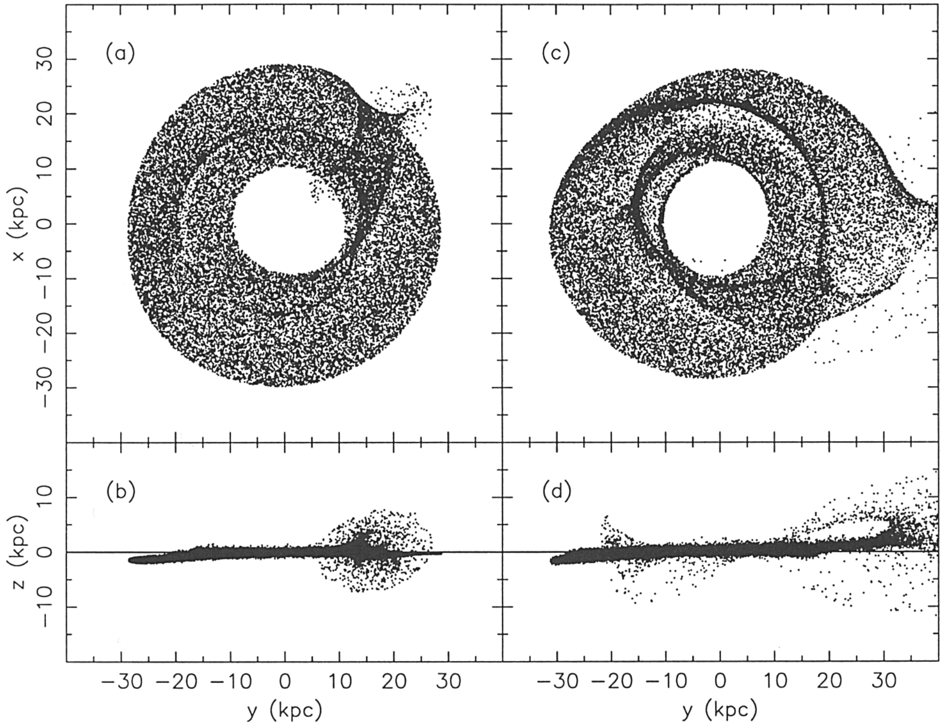

Figure 6. The structure of the Galactic H I disk is shown at 150 Myr and 0.7 Gyr after the impact in, respectively, the left- and right-hand panels. The mass of the dwarf in this simulation is $M = 10^9\ M_\odot$. The coordinate system is inertial, chosen such that the Galactic center lies at the origin and the *present* position of the Sun is at (-8,0,0). The Galactic plane is viewed from above, so the sense of Galactic rotation is clockwise in the upper panels.

cloud, which has previously been invoked as a possible perturber of the H I disk (Weinberg 1995). To investigate this possibility, hydrodynamical calculations were undertaken to simulate the collisional interaction between the Sagittarius dwarf and the Galactic outer H I disk (Ibata & Razoumov 1997). It is found that a significant distortion of the Galactic H I disk will be induced by the collision if the mass of the dwarf exceeds $\sim 10^9\ M_\odot$. Though the precise details of the interaction are compromised in these simulations by the lack of a live Galactic halo, it is found that for model masses $\gtrsim 5 \times 10^9\ M_\odot$, prominent spiral arms and a substantial lopsidedness in the outer disk are produced. Furthermore, a noticeable warp-like structure is induced in the disk (see Fig. 6). Thus the Sagittarius dwarf may have significantly affected the star formation history and structure of the outer Galaxy.

6. Conclusions

The Galaxy and its dwarf companion in Sagittarius provide an ideal laboratory in which we may probe the complex processes that take place during the merging of galaxies. Due to the accuracy of the data now being obtained, it is possible to model this interaction in great detail. Analysis of the kinematic data provide severe constraints on, and in fact almost completely exclude, standard numerical models of the tidal disruption of dwarf satellites near large galaxies, since according to these models Sgr should have been destroyed long ago. The implications of this conclusion for topical models of the growth of large galaxies by repeated mergers is considerable.

This review has discussed mainly the dynamical constraints. However, much interesting work remains to be done in understanding the chemical evolution of the dwarf (and the outer regions of the Galaxy) and how this is affected by the interaction. From this, one may gain insights into the chemical evolution of galaxies during a merger event, and in turn about dominant evolutionary processes occurring during hierarchical formation of 'normal'-sized galaxy units.

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