A Sagittarius-Induced Origin for the Monoceros Ring

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\textbf{ABSTRACT}

The Monoceros ring is a collection of stars in nearly-circular orbits at roughly 18 kpc from the Galactic center. It may have originated (i) as the response of the disc to perturbations excited by satellite companions or (ii) from the tidal debris of a disrupted dwarf galaxy. The metallicity of Monoceros stars differs from that of disc stars at comparable Galactocentric distances, an observation that disfavors the first scenario. On the other hand, circular orbits are difficult to accommodate in the tidal-disruption scenario, since it requires a satellite which at the time of disruption was itself in a nearly circular orbit. Such satellite could not have formed at the location of the ring and, given its low mass, dynamical friction is unlikely to have played a major role in its orbital evolution. We search cosmological simulations for low-mass satellites in nearly-circular orbits and find that they result, almost invariably, from orbital changes induced by collisions with more massive satellites: the radius of the circular orbit thus traces the galactocentric distance of the collision. Interestingly, the Sagittarius dwarf, one of the most luminous satellites of the Milky Way, is in a polar orbit that crosses the Galactic plane at roughly the same Galactocentric distance as Monoceros. We use idealized simulations to demonstrate that an encounter with Sagittarius might well have led to the circularization and subsequent tidal demise of the progenitor of the Monoceros ring.

\textbf{Key words:} Galaxies: Stellar Content – Galaxy: Halo – Galaxy: Kinematics and Dynamics – Galaxy: Structure – Galaxies: Local Group – Galaxies: Individual: Name: Sagittarius

1 INTRODUCTION

In a hierarchical universe galaxies are expected to accrete a number of smaller systems through their lifetime. These frequent accretion events leave distinct imprints most easily identified in the outskirts of a galaxy, where crossing times are long and tidal features can survive for up to a Hubble time. Dramatic evidence in support of this scenario, in the form of tidal tails and recognizable recent and ancient streams, has been building up steadily in many nearby galaxies, and especially in the halo of the Milky Way and of the Andromeda galaxy (see, e.g., Ibata et al., 1994; Helmi & White, 1999; Ibata et al., 2003; Belokurov et al., 2006; Martinez-Delgado et al., 2009; McConnachie et al., 2009).

Among these features, one of the most intriguing is the Monoceros ring. It was discovered by Yanny et al. (2003) in the Galactic anti-center direction using Sloan Digital Sky Survey (SDSS) data. Numerous surveys, follow-up observations, and spectroscopic studies have now shown Monoceros to be a dynamically-coherent, kinematically-cold, low-metallicity, ring-like stellar structure spanning $\sim180^\circ$ in Galactic longitude (Ibata et al., 2003; Crane et al., 2003; Rocha-Pinto et al., 2003; Martin et al., 2005; Conn et al., 2005b; Martin et al., 2006; Conn et al., 2007, 2008; Juric et al., 2008; Ivezić et al., 2008; de Jong et al., 2010; Sollima et al., 2011).

The origin of the Monoceros ring (or “arc”, since it isn’t clear yet whether the structure persists around the whole Galaxy) is still controversial. A popular hypothesis ascribes it to debris from a tidally disrupted satellite galaxy (Helmi et al., 2003; Ibata et al., 2003; Conn et al., 2005a; Peñarrubia et al., 2005). However, it has also been argued that it could...
result from a perturbation to the disc, possibly linked to fly-by encounters with massive substructures or satellite companions (Kazantzidis et al., 2008; Younger et al., 2008).

The position, velocity, and metallicity of stars in the ring may be used to assess the viability of these scenarios. Ivezic et al. (2008), for example, report that Monoceros stars have metallicities distinct from either the halo or the disc at similar Galactocentric distance, a result that clearly favours the tidal debris hypothesis. Peñarrubia et al. (2005) are able to fit most available data assuming that the ring originates from the disruption of a satellite that was in a prograde, almost coplanar, and nearly circular orbit prior to disruption.

The main challenge for the latter scenario is to explain how a low-mass satellite found its way to a nearly circular orbit at a Galactocentric distance of only $\sim 18$ kpc: given its eventual disruption, the satellite clearly could not have formed there. Cosmological simulations show that most satellites are accreted in highly-eccentric orbits, which means that a mechanism that allows the satellite’s orbit to migrate and circularize must be postulated. The low mass of Monoceros’ suspected progenitor (estimated to be $\sim 6 \times 10^8 M_\odot$ by Peñarrubia et al. 2005) excludes the most obvious possibility: dynamical friction with the Galaxy’s dark halo.

We present in this Letter a mechanism capable of circularizing efficiently the highly-eccentric orbit of a low-mass satellite (Sec. 2). We then study how this mechanism applies to the formation of the Monoceros ring (Sec. 3). We end with a brief summary in Sec. 4.

### 2 ORBITAL CIRCULARIZATION THROUGH 3-BODY ENCOUNTERS

We have used the N-body/gasdynamical galaxy formation simulations reported by Steinmetz & Navarro (2002) and then analyzed in detail by Abadi et al. (2003a,b); Meza et al. (2005) and Abadi et al. (2006), to search for the presence of low-mass satellites (masses not exceeding $\sim 1\%$ of that of the main system) in nearly circular orbits. (Interested readers may wish to consult those papers for technical details.) These satellites are then traced back in time in order to recover their full trajectories.

Although the eight simulations we analyze are of relatively low resolution (about $10^5$ particles per galaxy), we are able to find a few examples of satellites whose orbital eccentricity does not exceed $e \equiv (r_{apo} - r_{per})/(r_{apo} + r_{per}) \sim 0.2$ at the time of their disruption or at $z = 0$. Most of these satellites were actually accreted into the halo of the main galaxy in highly-eccentric orbits, only to see their orbits abruptly become almost circular later on due to complex orbital changes that occur during first accretion or to collisions with more massive substructures. Collisions are more effective at modifying the orbit of satellites far from the center, given the reduced force exerted by the main Galaxy at such distances. This may have interesting implications for the puzzling low-eccentricity of the orbit of the Fornax dwarf spheroidal (Piatek et al., 2007). Although collisions seem to be the main mechanism for orbital circularization of low-mass satellites, we note that our simulation series is small, and that this conclusion should therefore be regarded as tentative until confirmed.

We show an example of the orbital evolution of such satellites in Figs. 1 and 2. These figures show the evolution of the galactocentric distance and the orbital tracks of two satellites accreted by the main galaxy, respectively. The less massive of the two is accreted early, crossing the virial radius of the main galaxy (shown with a dotted line in Fig. 1) for the first time at $t \sim 2.75$ Gyr.† It is in a highly eccentric orbit, reaching a first pericentric radius of $\sim 32$ kpc from a

*†* Although we quote times below in Gyr for ease of reference to the original simulation, we note that the simulation was not meant to reproduce the Milky Way and therefore these numbers should
turnaround radius exceeding 150 kpc. Because of the relatively large pericentric radius and the brief time the satellite spends near pericenter, it survives for several orbits, losing gradually its mass. Its apocenter and pericentric radii both shrink as the main galaxy grows in mass. At \( t \sim 6.3 \) Gyr, however, the satellite’s orbit changes abruptly as a result of a close encounter with another, more massive satellite (shown with a thick dashed line in Fig. 1). The more massive satellite disrupts quickly in the tidal field of the main halo, and does not survive its second pericentric passage. The less massive satellite, on the other hand, survives 4-5 full revolutions in a nearly circular orbit (\( r_{\text{apo}} \sim 30 \) kpc, \( r_{\text{peri}} \sim 22 \) kpc, \( e \sim 0.15 \)) before also disrupting fully.

Fig. 2 shows two different orthogonal projections of the orbital tracks of the two satellites. Note that the orbital planes of the two satellites are almost at right angles, and that the radius of the circular orbit into which the less massive satellite settles coincides with the galactocentric distance of the encounter between the two at \( t = 6.3 \) Gyr. Circularization requires both the angular momentum and energy of the orbit to be reduced by the encounter. This is most easily achieved if the closest approach between satellite and massive perturber happens when the perturber crosses the orbital plane of the satellite. This is the time when the perturbing force is greatest; the coplanar arrangement ensures that the direction of the perturbing torque is coincident with the satellite’s orbital angular momentum, maximizing the effect on the orbit. We have carefully reviewed the interaction shown in Fig. 2 to confirm that the orbital change of the less massive system is indeed almost exclusively due to the acceleration and torque exerted by the more massive satellite during the collision.

This provides a prime example of the way in which a low-mass satellite can have its orbit circularized before disruption, even when dynamical friction effects are negligible. Although clearly there is an element of chance here (i.e., not all close encounters between satellites lead to circularization) the fact that we have found a few examples of this mechanism at work in the eight simulations we have analyzed leads us to conclude that one should not dismiss the possibility that this process may apply to Monoceros’ progenitor. To strengthen the case, we need (i) to identify the culprit, and (ii) to verify that the collision could have taken place at the same Galactocentric distance of Monoceros. We explore these issues below.

3 APPLICATION TO MONOCEROS

Fig. 3 shows the (past) orbital track of the Sagittarius dwarf (solid line), shown projected on a plane perpendicular to the Galactic disc that contains the Sun. The track follows the most recent 2 Gyr of the orbit, assuming a non-evolving, rigid potential for the Milky Way that consists of a spherical dark matter halo and a stellar disc. The halo follows a Hernquist profile (Hernquist, 1990) of mass \( M_H = 1.4 \times 10^{12} \) \( M_\odot \) and characteristic radius \( r_H = 20 \) kpc. The disc potential is modeled by a Miyamoto-Nagai disc of mass \( M_{MN} = 6 \times 10^{10} \) \( M_\odot \) and scale-lengths \( a_{MN} = 4 \) kpc and \( b_{MN} = 1 \) kpc.

The footprint of the Galactic disc is shown in Fig. 3 to guide the eye; the position of the Sun is shown with a dotted circle. Fig. 3 also shows, in color, the residuals from a smooth Milky Way model obtained by Jurić et al. (2008) from SDSS data and projected azimuthally onto the same plane. These residuals show the location of several notable stellar streams/overdensities within the SDSS volume: the one just above and to the left of the Sun is the Monoceros ring, seen “edge-on” in this projection.

Inspection of Fig. 3 shows that the nearly polar orbit of Sagittarius crossed the disc three times at the same Galactocentric distance of Monoceros; \( \sim 0.6, \sim 1.1, \) and \( \sim 1.7 \) Gyr ago. This implies that Sagittarius satisfies the first condition laid out in the previous section in order to link Sagittarius to Monoceros. The case for such identification is strengthened by the fact that Sagittarius is one of the most luminous (and likely most massive) satellites of the Milky Way, and therefore could have perturbed the orbit of a lesser satellite without itself experiencing much tidal damage or orbital evolution.

Is it possible that a collision with Sagittarius might have modified the orbit of a small satellite and placed it onto a circular orbit at 18 kpc from the Galactic center? What was the orbit of Monoceros’ progenitor like before the collision? We explore these issues by integrating the orbits of test particles in the potential of the Galaxy. We place the test par-
articles in coplanar, nearly circular orbits at $R = 18$ kpc, and integrate them backwards in time, scanning the results for particles whose orbits change drastically after collisions with Sagittarius. Reckoned forward in time, these indicate candidate orbits for possible Monoceros progenitors. We seek in particular orbits with large initial apocenters (i.e., highly eccentric) since those are most easily reconciled with cosmological accretion. In addition, satellites on such orbits would spend little time in regions of large tidal forces, which would enable the satellite to survive disruption for several orbital periods (Peñarrubia et al., 2008).

Orbital changes induced by Sagittarius depend mainly on the depth of its gravitational potential, which scales directly with mass and inversely with size: the more massive and centrally concentrated Sagittarius is, the easier it can perturb the orbits of low-mass satellites. The simulations were run with Gadget-2 (Springel, 2005) and model Sagittarius as a rigid spline sphere (Monaghan & Lattanzio, 1985) of fixed mass and size. Given the uncertainties in these parameters, we explore a range of them in order to identify parameter choices that enable the efficient circularization of low-mass satellites. We have experimented with 4 choices for Sagittarius’ mass and size (defined as the radius where the density of the spline drops to zero): $M_{\text{Sag}} = 2 \times 10^{10}$, $1 \times 10^{10}$, $2 \times 10^{10}$ and $5 \times 10^{10} M_\odot$, as well as $r_{\text{Sag}} = 2.8$, 5.6, 11.2, and 22.4 kpc.

Since we are mainly interested in a proof of principle, we show in Fig. 4 the orbit of one test particle for each choice of the mass and size of Sagittarius (chosen from among those that have experienced large orbital changes). Each panel in this figure corresponds to different Sagittarius masses; the various line types correspond to different choices for the size, as specified in the caption. Thin solid lines outline the orbit assumed for Sagittarius; the grey band indicates the Galactocentric distance of Monoceros.

Fig. 4 makes clear that, provided that Sagittarius has a total mass of at least $10^{10} M_\odot$, it is able to modify substantially the orbit of potential Monoceros progenitors. As expected, increasing $M_{\text{Sag}}$ or reducing $r_{\text{Sag}}$ induce more drastic changes in the orbits, allowing more eccentric initial orbits to circularize after colliding with Sagittarius. For example, for $M_{\text{Sag}} = 2 \times 10^{10} M_\odot$ and $r_{\text{Sag}} = 5.6$ kpc, we find that an orbit with an initial apocenter of 60 kpc and pericenter of 15 kpc can be transformed into a nearly circular orbit after colliding with Sagittarius.

Interestingly, some of the largest changes are seen to occur after a couple collisions with Sagittarius, which results from the fact, alluded to above, that Sagittarius crosses several times the Galactic plane at about the same Galactocentric distance in the past 2 Gyr. In some cases even “unbound” orbits may be captured; see, for example, the dotted curves in the two top panels of Fig. 4. Although these are unrealistic for Monoceros, they are useful as demonstration curves in the two top panels of Fig. 4. Although these are unrealistic for Monoceros, they are useful as demonstration curves in the two top panels of Fig. 4. Although these are unrealistic for Monoceros, they are useful as demonstration curves in the two top panels of Fig. 4. Although these are unrealistic for Monoceros, they are useful as demonstration curves in the two top panels of Fig. 4.

4 SUMMARY AND DISCUSSION

We have used numerical simulations to explore a possible origin of the Monoceros ring. As in earlier work (see, e.g., Peñarrubia et al., 2005), this scenario envisions Monoceros as the result of the tidal disruption of a low-mass satellite, but suggests a compelling explanation for the nearly circular orbit required for the satellite at the time of disruption. This is important, for the progenitor clearly could not have formed at its disruption radius. Furthermore, since circular orbits are extremely rare in cosmological simulations it is necessary to find a mechanism able to place a low-mass satellite in a nearly circular orbit prior to disruption.

We find, using a set of cosmological simulations of galaxy formation, that the majority of low-mass satellites in such orbits are the consequence of chance encounters between satellites. We show an example that illustrates two requirements of this scenario: the collision must involve a more massive partner, and it must occur at the same galactocentric distance as the circularized orbit radius.

These results make the Sagittarius dwarf a potential culprit: it is one of the most massive satellites of the Milky Way (except for the Magellanic Clouds) and it has, in the past 2 Gyr, crossed three times the Galactic plane at about the same distance as Monoceros. A series of idealized simulations show that, in order for Sagittarius to effect substantial changes on satellites that may cross its path at $\sim 18$ kpc from the Galactic center (the location of Monoceros), Sagittarius must have been fairly massive at the time when the collision took place, at least $\sim 10^{10} M_\odot$. Although this seems high, it can not be easily ruled out, as recently argued by Niederste-Ostholt et al. (2010).

Further modeling should help define and refine observational tests of the scenario we propose here. The properties of the ring at Galactic longitudes well away from the anti-Galactic center direction where it was discovered should be particularly telling, and likely to yield diagnostics of the origin of Monoceros. Further observational work should aim to secure not only better constraints on the total mass of Sagittarius (Peñarrubia et al., 2011), but also on the kinematics of Monoceros stars. Indeed, much of the work presented here is predicated on indications that Monoceros stars follow nearly circular orbits around the Galaxy. However, the samples of stars with measured kinematics are small, and contamination by disk stars may in principle confuse the interpretation. A dedicated observational campaign design to survey Monoceros around the Galaxy and to map its kinematics seems essential in order to ascertain the true origin of this puzzling structure.

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Figure 4. Test-particle orbits in simulations that include the effects of Sagittarius in a standard Milky-Way potential. Each panel corresponds to different assumptions for the mass of Sagittarius (as labeled), which is modeled as a rigid spline sphere. Different curves correspond to various choices for Sagittarius’ size: $r_{\text{Sag}} = 22.4$ kpc (green dot-dashed curve); 5.6 kpc (blue dashed line); and 2.8 kpc (red dotted curve). The particles shown are chosen amongst those that suffer large orbital changes as a result of collisions with Sagittarius at a Galactocentric distance of $\sim 18$ kpc. The grey band indicated the Galactocentric distance of the Monoceros ring.

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