dSph Satellite Galaxies without Dark Matter: a Study of Parameter Space

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A parameter study is underway in Heidelberg that aims to find and constrain possible solutions to the dSph satellite problem under the assumption that some of these systems may not be dark matter dominated. The present state of the parameter survey of tidally disrupting spheroidal dwarf galaxies is described, and examples of preliminary results are presented.

1. Introduction

At least about ten dwarf spheroidal (dSph) galaxies are known to orbit the Milky Way at distances ranging from a few tens to a few hundred kpc. On the sky they are barely discernible stellar density enhancements. Their velocity dispersions are similar to those seen in globular clusters and they have approximately the same stellar mass. However, they are about two orders of magnitude more extended. For spherical systems in virial equilibrium with an isotropic velocity dispersion, the overall mass of the system can be determined from the observed velocity dispersion. Comparing this ‘gravitational’ mass to the luminosity of the system determines the mass-to-light ratio, $M/L$ (in the following always given in solar units $M_\odot/L_\odot$). Values for $M/L$ of about 10 or larger are usually taken to imply the presence of dark matter in a stellar system.

For the dSph satellites, $M/L$ values as large as a few hundred are inferred, implying that these systems may be completely dark matter dominated (for reviews see Mateo 1997, 1998).

An alternative possibility relying on Newtonian physics, is that some of the observed dSph satellites may not be in virial equilibrium and may not be spherical but with non-isotropic velocity dispersions, in which case the observed $(M/L)_{\text{obs}}$ ratios may not be physical. That such systems may exist is shown by the simulations of the long-term evolution of initially spherical satellite galaxies with masses of $10^7 M_\odot$, initial Plummer radii of 300 pc on eccentric orbits in an extended Galactic dark halo with a circular velocity of 200 km/s (Kroupa 1997, hereinafter K97). The finding is that about 99 per cent of the mass is lost from the satellites through repetitive tidal modification, remnants with $(M/L)_{\text{obs}} > 10$ remain that survive for a few orbital periods. This study is extended by Klessen & Kroupa (1998, hereinafter KK98) covering more orbits and Galactic halo masses using two different numerical codes.

A shortcoming common to these remnants is that they have a central surface brightness too faint by about one order of magnitude, if $(M/L)_{\text{true}} = 3$ is the mass-to-light ratio of the stellar population. One possible solution to this problem is to postulate that $(M/L)_{\text{true}} \approx 0.3$ (K97). However, this implies an unusual initial mass function. Another possibility is to scale the satellite up in mass and size so that each particle carries a larger mass (for simulations with the same number of particles) and thus light, while keeping the binding energy of the satellite roughly unaffected (KK98). This, however, leads to remnants that have too large half-light radii.

It is thus clear that the simulations mentioned above, as well as other observational evidence summarised in K97 and KK98, give a strong hint that some of the Galactic dSph satellites may not be dark matter dominated but that they may be significantly affected by tides. However,
much work remains to be done to establish if models can be produced that fit all the observational properties of at least some of the known dSph satellites.

It is the purpose of this contribution to give a preliminary account of the extensive parameter survey under way in Heidelberg that aims at constraining the possible region in (initial satellite binding-energy, mass and extend of the Galactic dark matter halo, and orbit) parameter space in which viable “dSph solutions” exist in the tidal scenario. If none such region can be found then the conclusion that all of the dSph satellites are dark matter dominated is strengthened.

2. Simulations

The study of parameter space is performed with SUPERBOX, which is a particle mesh code with nested sub-grids. It is described by Madejski & Bien (1993) with a brief description of the modern version given by K97. A more thorough account will be available in Fellhauer et al. (1998). The reason for using SUPERBOX lies in its tremendous efficiency: the self-consistent interaction of two galaxies consisting in total of $1 - 2 \times 10^6$ particles can be computed on small workstations and personal computers with Pentium processors within a few days.

The problem under investigation here is reduced to the interaction of a low-mass satellite galaxy with a massive Galactic dark halo. The details of setting up the satellite and Galactic halo models can be found in K97. The dark halo is assumed to be an isothermal mass distribution with a circular velocity of 200 km/s and a cutoff radius of $R_c$. The satellite is defined by its initial mass, $M_{\text{sat}}$, and its initial Plummer radius, $R_{\text{Pl}}$. The satellite is placed into the Galactic dark halo at apo-galactic distance $R_{\text{apo}}$ and with a tangential velocity $v_t$. The resulting orbit has an eccentricity $e = (R_{\text{apo}} - R_{\text{peri}})/(R_{\text{apo}} + R_{\text{peri}})$, where $R_{\text{peri}}$ is the peri-galactic distance.

The satellite is observed as an observer from Earth sees a dSph satellite. It’s projected brightness profile is measured. The central surface brightness and half-light radius are computed through profile fitting, and the line-of-sight velocity dispersion is determined. The hypothetical observer thus estimates $(M/L)_{\text{obs}}$ as a function of time.

3. Some Results

The parameter study proceeds by varying $M_{\text{sat}}$, $R_{\text{Pl}}$, $R_c$, $R_{\text{apo}}$ and $v_t$. Most of the simulations done so far concentrate on a satellite with $M_{\text{sat}} = 10^7 M_\odot$ and $R_{\text{Pl}} = 300$ pc in a Galactic dark halo with $R_c = 250$ kpc or 40 kpc.

Typically, $(M/L)_{\text{obs}}$ remains constant at its initial low value until disruption time, when the satellite looses most of its remaining mass during passage through peri-galacticon. Thereafter, a remnant with roughly 1 per cent of the initial satellite mass remains. It has properties rather similar to typical dSph satellites, with large $(M/L)_{\text{obs}}$. Evolution curves for $(M/L)_{\text{obs}}(t)$ and other satellite parameters are presented in K97 and KK98.

A particularly noteworthy result obtained by KK98 is that a remnant has a line-of-sight velocity dispersion $\sigma > 6$ km/s if $e > 0.5$. This suggests a useful observational criterion, for if $e < 0.5$ for $\sigma > 6$ km/s then the respective system is probably dark matter dominated. Here, preliminary additional results are presented for this satellite, with some discussion of other models as well.

The time when $(M/L)_{\text{obs}} \geq 50$ occurs is denoted by $\tau_{50}$; it increases for increasing $e$, as is evident from Fig. 1. From the figure it is apparent that $\tau_{50}$ is primarily a function of $e$ and $R_{\text{apo}}$.

Two observational constraints are plotted: The dSph satellite Ursa Minor contains only old stars with ages $\tau \approx 15$ Gyr (van den Bergh 1994). It’s preliminary proper motion (without an uncertainty) is reported by Olszewski (1998), from which the orbital eccentricity is estimated. The dSph satellite Sculptor has stars with ages in the range $\tau \approx 5 - 15$ Gyr (van den Bergh 1994), and the proper motion has been estimated by Schweitzer et al. (1995). Both satellites are at a distance of 60-70 kpc. It is interesting to note that UMi has $(M/L)_{\text{obs}} = 95 \pm 43$, while Scl has $(M/L)_{\text{obs}} = 10.9 \pm 7.5$ (Irwin & Hatzidimitriou 1995).
dSph satellites without dark matter

Figure 1: The time $t = \tau_{50}$, when $(M/L)_{\text{obs}}(t) \geq 50$, is plotted against orbital eccentricity for a number of simulations with $M_{\text{sat}} = 10^7 M_\odot$ and $R_{Pl} = 300$ pc, as defined in the key.

The application of Fig. 1 is as follows: If the entire satellite was assembled a few Gyr ago then this would imply some recent merger event strong enough to lead to the formation of tidal tail dwarfs (e.g. Kroupa 1998). It is not clear if there is any other evidence for such an event. The present masses of the stellar components (assuming $(M/L)_{\text{true}} = 3$) of UMi and Scl are, respectively, about $6 \times 10^5 M_\odot$ and $4 \times 10^6 M_\odot$ (Irwin & Hatzidimitriou 1995), which may be too low to accrete gas from a hypothetical gas cloud on a similar orbit (e.g. Magellanic or similar stream), or let alone retain gas over time-spans of many Gyr. Any stars with nuclear ages of a few Gyr were probably born from some gas-accretion event during a more massive past. Perhaps one may identify the nuclear age, $\tau$, of the youngest stars as being the time when the satellite was massive enough for the last time to accrete some gas. The precursor satellite galaxies will have been two orders of magnitudes more massive than the dSph satellites, if the tidal scenario is applicable. Thus, $\tau_{50} < \tau$ if the respective dSph satellite is in the remnant phase with artificially inflated $(M/L)_{\text{obs}}$.

Unfortunately the observational constraints are too weak to allow any definitive conclusions. But it is clear that if a dSph with $(M/L)_{\text{obs}} > 10$ containing relatively young stars (a few Gyr old, e.g. Scl) can be shown with high confidence to be on a low eccentricity ($e < 0.3$) orbit, then the case for dark matter in this system would be rather strong.

Ultimately, the parameter study will allow constraining that region in $(M_{\text{sat}}, R_{Pl})$ space that may lead, within a Hubble time, to a remnant phase that agrees with the observational properties of at least some of the dSph satellites. Fig. 3 demonstrates this schematically. In this figure, the thick ($D = 100$ kpc) and thin ($D = 50$ kpc) short-dashed lines are the tidal radii, $\log_{10} r_t = -3.51 + (1/3)\log_{10} M_{\text{sat}} + (2/3)\log_{10} D$ in kpc, where $M_{\text{sat}}$ is in $M_\odot$ and $D$ is the distance from the Galactic centre in kpc. Satellites that lie initially to the right of these ($R_{Pl} > r_t$) are more or less immediately destroyed on injection into the dark halo. The long-dashed line, $\log_{10} M_{\text{sat}} = 8.3 + (1/2)\log_{10} R_{Pl}$ (units as above), is the binding energy, $E_b = (GM_{\text{sat}}^2)/R_{Pl}$, of the satellite. Satellites that initially lie above this line do not enter the remnant phase within a Hubble time. The filled dot is the satellite mentioned above, and the open circle represents a series of simulations that barely lead to any solutions, irrespective of $e$.

Once the solution region is delineated in this diagram, inferences can be drawn about the physical properties of the progenitors of those dSph satellites that are not dark matter dominated.
This in turn may allow conclusions about the physical conditions that lead to the birth of such systems.

4. Conclusions

The simulations towards the parameter study briefly reported here have been running for a couple of years, having consumed about 1 CPU yr, and a total of more than 13 GB of data have accumulated. The present results do not unambiguously demonstrate that dSph-like systems without dark matter exist. Nevertheless, some of the models bear surprising similarities with the dSph satellites, and some inferences can already be drawn from this survey.

There exists in \((M_{\text{sat}}, R_{Pl})\) space a region that leads within a Hubble time to remnants of satellites that appear tantalisingly similar to the dSph satellites (K97). Predictions of correlations between observable parameters can be arrived at (KK98, Fig. 1). Also, information as to the possible initial state of the progenitors of those dSph satellites that may not be dark matter dominated is emerging (Fig. 2).

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