

## Constraining the Distribution of Dark Matter Lumps Around the Milky Way Using Tidal Debris

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**Abstract.** Dwarf galaxies that fall into the Milky Way's potential are tidally disrupted. Their tidal tails are one of the most powerful probes of the mass distribution in the Galaxy. If the distribution of dark matter in the Galaxy is lumpy, then these lumps will scatter stars in the stream and alter its shape. We describe our approach to using the tidal debris to constrain substructure in the Galaxy halo.

### 1. Introduction

Stars associated with the Sagittarius dwarf galaxy (Sgr) provide the best evidence for streams of debris from satellite destruction existing around the Milky Way. The main body of this galaxy is itself highly elongated in the direction of its proper motion (Ibata et al 1994, 1997). Moreover, there have been numerous reports of overdensities in star counts (Mateo, Olszewski & Morrison, 1998; Majewski et al 1999; Dohm-Palmer et al 2001; Martinez-Delgado et al 2001). and RR Lyrae variables (Mateo et al 1996; Alard 1996; Alcock et al 1997; Ivezić et al 2000; Vivas et al 2001) that plausibly align with its orbit up to 60 degrees away from its center. More recently, an overdensity has been revealed in the angular distribution of faint-high-latitude carbon stars along the Great Circle along Sgr's proper motion vector: 47 out of a sample of 100 lie within 10 degrees of this plane (Ibata et al 2001).

Simulations of satellite destruction show distortions of tidally stripped satellites and streams of associated debris aligned along their orbits remarkably reminiscent of Sgr's stellar retinue (Johnston, Spergel & Hernquist 1995; Johnston, Hernquist & Bolte 1996) — as illustrated in Figure 1. The dynamics of the debris is simple to describe in terms of test particle orbits around the parent galaxy. The streaming is caused by the small spread in orbital properties in the debris which leads to a corresponding spread in orbital times (Tremaine 1993; Johnston 1998; Helim & White 1999).

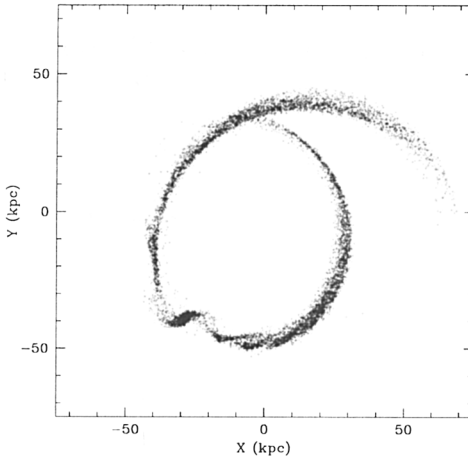


Figure 1. Final positions of particles from a simulation following 4.5 Gyears evolution of a  $10^8 M_{\odot}$  satellite in orbit, 30-55 kpc from the center of the Milky Way.

The combination of numerical models that show tidal debris as cold streams whose evolution is easy to understand and describe with observational samples that appear to mimic this behavior naturally leads us to ask to what extent these structures can be exploited to learn something about the parent galaxy around which they orbit. For example, as cosmological N-body simulations have reached higher and higher resolutions, it has become apparent that CDM cosmologies naturally produce far more dark matter satellites around galaxies than the number actually observed around the Milky Way (Moore et al 1999; Klypin et al 1999). What will happen to cold tidal streamers in a potential that includes many dark matter lumps on top of the global, smooth background? Simple intuition suggests that the lumps will scatter stars in the stream and distort it. Hence, the existence of (for example) the cold stream of Carbon stars associated with Sgr might be used to constrain the degree to which the Milky Way does in fact contain dark matter satellites. This idea is analogous to using the coldness of the Galactic disk to constrain the presence of possible substructures within it such as  $10^6 M_{\odot}$  black holes (Lacey & Ostriker 1985) or dark matter satellites (Font & Navarro 2001).

## 2. Methods

We (Johnston, Spergel & Haydn 2001) have tackled the question of to what extent debris could be heated by dark matter satellites using N-body simulations of the evolution of test-particle streams as they orbit in a Galactic halo containing dark matter lumps. The halo is represented by  $10^7$  equal mass particles, whose mutual interactions are calculated using a basis-function-expansion technique (Hernquist & Ostriker 1992). The masses of the lumps are drawn from the

CDM circular-velocity distribution of dark matter satellites (Moore et al 1999) Each is represented by a fixed NFW potential (Navarro, Frenk & White, 1996, 1997) (which does not evolve during the simulation) with concentrations chosen to match the cosmology. Hence, the stream particles are scattered both by direct encounters with the lumps themselves and by the wake that they excite in the self-consistent halo (which is expected to produce an order-unity enhancement, Weinberg 1998) — resolving the latter effect adequately requires  $10^7$  particles.

### 3. Results

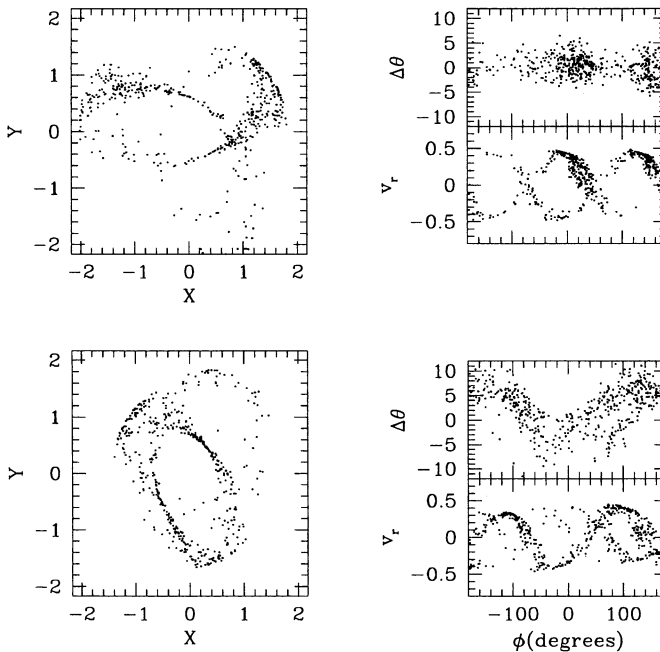


Figure 2. Final position of Sgr-like stream particles after 4 Gyears evolution in a smooth potential (upper panels) and one containing 256 lumps (lower panels). Left hand panels are coordinate-space projections and right-hand panels are observable space projections.

Figure 2 compares the results from the evolution of an Sgr-like stream distribution over 4 Gyears in a perfectly smooth halo potential (top panels), with one in which 256 lumps (chosen from the top end of the dark matter satellite mass spectrum) are also orbiting (bottom panels). The left hand panels show the final positions in coordinate space and the right hand panels show the final positions in “observables” relative to the Sun where  $v$  is the (Galactic standard of rest) line-of-sight velocity,  $\Psi$  is the angle along the original orbit of the satellite and  $\Delta\theta$  is the angle away from the original satellite orbit. Although there

are marked differences between these two simulations it is hard to visually assess the degree of scatter in the lower panels compared with the upper. Note that although the lower plot of  $\Delta\theta$  against  $\Psi$  does suggest that the plane of the orbit has precessed in the lumpy potential, this will not be generally observable as we only know the orbit of the satellite today.

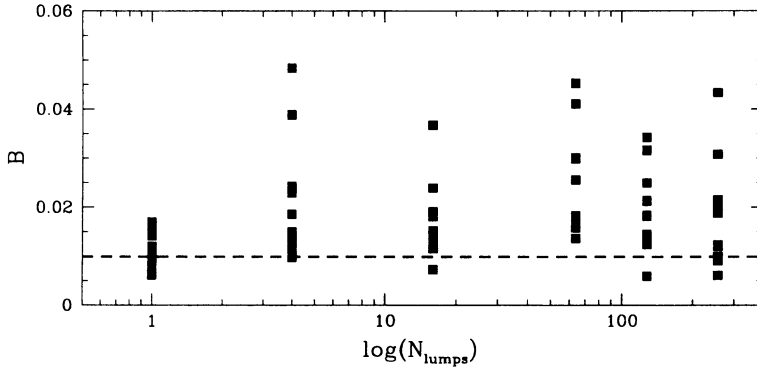


Figure 3. Scattering index,  $B$ , calculated for 500 stream particles as a function of number of lumps included in each simulation for all 36 simulations containing lumps (solid squares) and simulation in smooth potential (bold dashed line).

To quantify the degree of scatter we defined the quantity  $B$  to be sensitive to the small-scale structure in the observables:

$$\begin{aligned}
 B_m^\Psi &= [\Sigma\Delta\theta_i \cos(m\Psi_i)]^2 + [\Sigma\Delta\theta_i \sin(m\Psi_i)]^2 \\
 B_m^v &= [\Sigma\Delta\theta_i \cos(mv_i/v_{\max})]^2 + [\Sigma\Delta\theta_i \sin(mv_i/v_{\max})]^2 \\
 B_m &= \sqrt{B_m^\Psi + B_m^v/N} \\
 B &= \sqrt{\Sigma_{m=5,10} B_m^2}
 \end{aligned} \tag{1}$$

where the sum is over all  $N$  particles in the stream and  $v_{\max}$  is the maximum line-of-sight velocity. Note that we define  $\Psi$  and  $\Delta\theta$  by first finding the best-fit Great Circle to the stream stars using the method of Great Circle Cell Counts (Johnston, Hernquist & Bolte 1996). Figure 3 illustrates the results of calculating  $B$  using all 500 particles in our stream from all 36 of our simulations — 6 sets of 6 simulations, containing the top 1,4,16,64,128 or 256 most massive lumps. The 6 simulations within each set had the same mass lumps, but different random orbits for each lump. The bold dashed line in the figure shows the results for a stream evolved in a smooth potential. The figure demonstrates that although  $B$  serves as a good general discriminant between smooth and lumpy potentials, the results are very sensitive to the exact orbits of the lumps. It also suggests that the top few most massive lumps have the most influence on the scattering.

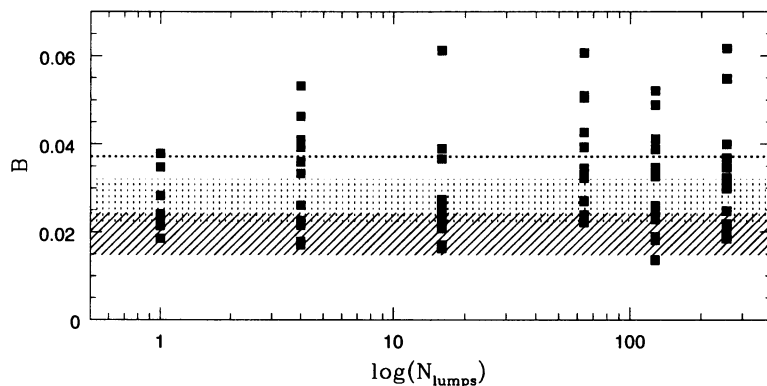


Figure 4. Scattering index for Sgr carbon star stream (bold dotted line), compared to 47 particles from simulations with lumps (squares), smooth potential simulation (lower shaded region) and simulation with LMC-like lump (upper shaded region).

#### 4. Application to the Sagittarius Carbon Star Stream

We now apply our results to the Carbon star stream associated with Sgr. We calculate  $B$  for the 47 Carbon stars lying within 10 degrees of Sgr's orbital path. We then repeat our analysis of our simulations, this time drawing just 47 particles, restricted to lie at Galactic latitudes  $|b| > 30$  degrees and within 10 degrees of the best-fit Great Circle to the stream. Figure 4 compares the results of the real data (bold dotted line) with the simulations in lumpy potentials (solid squares). The results for a set of ten different samples drawn from the simulations in the smooth potential are indicated by the lower shaded region. Clearly the signal from Sgr's stream lies above that of the stream evolved in the smooth potential. Nevertheless, we are hesitant to see this as evidence that the halo is filled with dark matter lumps since we have not assessed the degree of contaminants in the Sgr data set. Moreover, we do know of one very massive, visible lump in our own halo: the Large Magellanic Cloud. The upper shaded region indicates the degree of structure induced when a simulation is performed containing an LMC-like lump in an appropriate orbit relative to our Sgr stream.

We conclude that, although the current data set for Sgr does not provide a strong constraint on the degree of dark matter substructure around the Milky Way, the future prospects are brighter. As large scale halo surveys such as the Sloan Digital Sky Survey (Ivezic et al 2000; Yanny et al 2000) and other giant-star surveys (Majewski et al 2000; Morrison et al 2000) are completed we can hope to both refine the Sgr debris data set and find debris associated with other satellites. These streams could be used in combination to search for signatures of dark matter lumps.

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