Are coherent tidal streams consistent with dark matter substructure?

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Motivation

In recent years a number of tidal streams have been observed in the Milky Way. Iit has been suggested that the existence of coherent tidal streams is incompatible with the presence of dark matter subhalos predicted by lambda-CDM models.

We investigate whether current and upcoming observations may constrain the existence of dark matter substructure by examining the conditions under which coherent tidal streams can arise. To fully explore the range of possible scenarios, we simulate the disruption of a satellite on a variety of orbits in different host halo models.

Dark Matter Substructure

ΛCDM predicts an abundance of satellites in the halo of the Milky Way. Previous work: e.g., Johnston, Spergel, & Haydn (2002), Mayer et al. (2002), Ibata et al. (2002) suggests that dark matter substructure could tidally heat coherent streams making this a potentially powerful tool for testing the substructure picture.

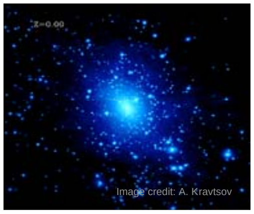


Image credit: A. Kravtsov

What factors result in coherent tidal streams?

In this study we consider the following questions:

- Which factors most influence the resulting debris?
  - Orbital path / halo shape
    - allowed orbital paths (depend on shape of potential)
    - phase space properties of orbit (resonant, regular or chaotic)
  - Substructure
    - perturbs smooth potential, may cause heating, destroy coherence
- What types of orbits lead to coherent streams? Are there 'special' orbits?
- Can we expect coherent streams to exist in any scenario with dark matter substructure?

Simulations

- Libraries of orbits are generated for different halo shapes to more fully explore possible scenarios
- Individual orbits are selected based on their phase-space properties
- Tidal disruption is simulated with and without dark matter substructure using N-body tree code GADGET-2 (Springel 2005)

Satellite:

- NFW dark-matter density profile with a subset of particles marked as "stars" in Hernquist distribution
- Initially 500k particles, 10^{10} M_{solar}
- Tidally stripped to produce 'remnant' in quasi-equilibrium with host potential, ~ 150k particles
- ~ 5 Gyr integration

Static Milky Way potential:

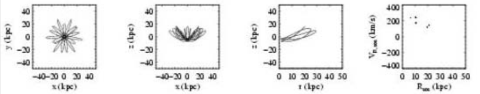
- NFW dark-matter halo, Miyamoto-Nagai disk, and Hernquist bulge
- Total mass ~ 10^{12} M_{solar}

'Live' dark matter substructure:

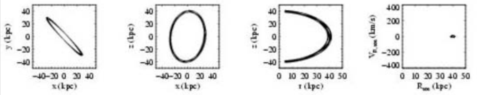
- Softened point masses drawn from a cosmological N-body simulation (Kravstov, Gnedin, & Klypin 2004)

A Few Selected Orbits

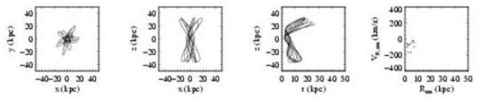
Orbit A: oblate halo



Orbit B: spherical halo

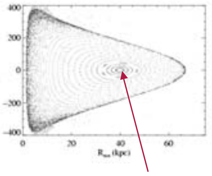


Orbit C: prolate halo



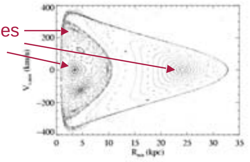
Phase Space Properties of Orbits

Spherical Halo



'Surface of section' plots can be used to map the phase space of the potential and to identify orbits as *regular*, *chaotic* or *resonant*

Prolate Halo



resonances

Resonant orbits conserve more than 3 integrals of motion and are confined to a lower dimension space than other orbits

Results

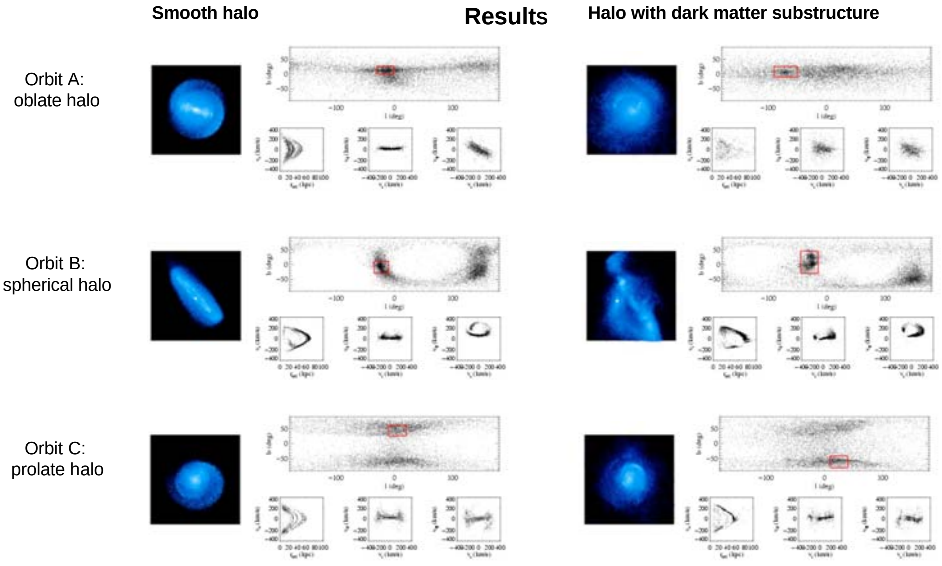


Figure 2. 'External' galaxy views, Galactic latitude and longitude of 'star' particles, and phase space structure of resulting debris for three selected orbits.

The image on the left of each set of plots shows the density of the dark matter particles viewing the x-y plane from outside the Galaxy. The color scale is logarithmic and is the same for all orbits shown.

At the beginning of the simulation, a subset of the dark matter particles were marked as stars according to a Hernquist profile. The final positions of these 'stars' are shown in the l-b plots. We also select stars from a region in the sky (outlined with a red box) and plot r-v_r, v_r-v_θ, and v_r-v_ϕ for these particles.

Orbit A shows significant structure in the phase space coordinates when simulated in the smooth halo, but that structure is largely absent when substructure is present. Similarly, for Orbit C, 4 clear bands in the r-v_r plot can be seen, but are not seen when simulated with substructure. Orbit B, on the other hand, shows a similar degree of coherence both with and without substructure.

We note that Orbits A and C are not typical, but are presented to highlight unique cases. Most of our orbits in non-spherical halo models show relatively little structure in any of these coordinates, regardless of the presence of dark matter substructure.

Conclusions

- In general, the presence or absence of dark matter substructure has a less important effect on the tidal debris than shape of the dark matter halo.
- The cumulative phase-space density distribution of the debris in a tidal stream gives a measure of its coherence (Figure 1). Curves that are further to the right are more coherent than curves on the left.
- This measure of coherence of the streams does not show a systematic behavior due to the presence of substructure (Figure 1).
- Although not all streams associated with phase space resonances are less susceptible to small-scale tidal heating by substructure, some may be more resilient, particularly in a spherical halo, as shown in Figure 1.
- Most orbits in a non-spherical halo appear to lose all coherence in both position and velocity regardless of the presence of dark matter substructure. However, some rare orbits (such as Orbits A and C) do retain a high degree of coherence in certain phase space parameters if dark matter substructure is absent, as shown in Figure 2.

Results

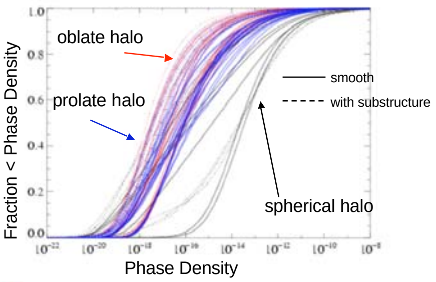


Figure 1

Figure 1. Cumulative phase density (ρ/σ_v^3) distribution of dark matter particles for all selected orbits.

Orbits simulated in oblate, prolate, and spherical halos are shown in red, blue, and black respectively. Simulations are shown with (dotted lines) and without dark matter substructure (solid lines).

While debris from some orbits retains a higher typical phase density, a substantial, systematic shift in the cumulative phase density distribution due to the presence of substructure is not seen. Furthermore, the range of phase densities spanned by different orbits (roughly 6 orders of magnitude) is far greater than the shift observed due to substructure for a given orbit. In the spherical halo, two of our selected orbits resulted in unusually high phase densities; these correspond to the closest associations to phase space resonances.

References

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