COLLISIONAL VERSUS COLLISIONLESS DARK MATTER

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ABSTRACT

We compare the structure and substructure of dark matter halos in model universes dominated by collisional, strongly self-interacting dark matter (SIDM) and collisionless, weakly interacting dark matter (CDM). While SIDM virialised halos are more nearly spherical than CDM halos, they can be rotationally flattened by as much as 20% in their inner regions. Substructure halos suffer ram-pressure truncation and drag which are more rapid and severe than their gravitational counterparts tidal stripping and dynamical friction. Lensing constraints on the size of galactic halos in clusters are a factor of two smaller than predicted by gravitational stripping, and the recent detection of tidal streams of stars escaping from the satellite galaxy Carina suggests that its tidal radius is close to its optical radius of a few hundred parsecs — an order of magnitude smaller than predicted by CDM models but consistent with SIDM. The orbits of SIDM satellites suffer significant velocity bias \(\sigma_{\text{SIDM}}/\sigma_{\text{CDM}} = 0.85\) and are more circular than CDM, \(\beta_{\text{SIDM}} \approx 0.5\), in agreement with the inferred orbits of the Galaxy’s satellites. In the limit of a short mean free path, SIDM halos have singular isothermal density profiles, thus in its simplest incarnation SIDM is inconsistent with galactic rotation curves.

Subject headings: dark matter — galaxies: halos — galaxies: formation — galaxies: kinematics and dynamics — galaxies: evolution — galaxies: clusters: general

1. INTRODUCTION

The nature of dark matter is still far from being resolved. Primordial nucleosynthesis and observational data suggest that the baryonic material accounts for just a fraction of the matter density in the universe. Fundamental particles remain the most likely candidate for the dark matter and much effort has been devoted to researching a class of weakly interacting, collisionless dark matter (CDM) (e.g., Davis \textit{et al.} 1985). However, the hierarchical gravitational collapse of cold collisionless particles leads to dense, singular dark matter halos – a result that is central to several fundamental problems with this model on small scales (e.g. Hogan & Dalcanton 2000 and references within).

It may be possible to solve the current problems with CDM by appealing to extreme astrophysical processes. Alternatively, we can explore other dark matter candidates that behave differently on non-linear scales. One possibility is strongly self interacting dark matter (hereafter SIDM). Originally proposed to suppress small scale power in the standard CDM model (Carlson \textit{et al.} 1992, Machaceck \textit{et al.} 1994, de Laix \textit{et al.} 1995), SIDM was recently revived by Spergel & Steinhardt (1999) to solve some of the outstanding problems with CDM. The behaviour of this component depends on the particles’ collisional cross-section. Large cross-sections imply short mean free paths, so that the dark matter can be described as a fluid that does not cool but can shock heat. Particles with a mean free path of order the scale length of a dark matter halo offers the possibility of conductive heat transfer to the halo cores (Spergel & Steinhardt 1999). In this Letter we contrast the dynamics and structure of “halos within halos” between collisional and collisionless dark matter and compare predictions with current observational constraints.

2. SIMULATING THE STRUCTURE OF SIDM HALOS

In this section we present the first numerical calculations of the structure of dark matter halos in which the particles have a large interaction cross-section. Self interacting dark matter behaves like a collisional gas and its evolution can be simulated using standard computational fluid dynamics techniques. We model the collisional dark matter fluid by approximating its behaviour as an ideal gas where the ratio of specific heats is 5/3. We use the smoothed-particle hydro dynamics (SPH) code Hydra (Couchman \textit{et al.} 1995) to follow the hierarchical growth of a massive dark matter halo. For added confidence in the robustness of key results, we perform independent collapse tests using an evolution of the Benz-Navarro SPH code (cf. Gelato & Sommer-Larsen 1999).

Our cosmological initial conditions were adapted from the “cluster comparison” simulation (Frenk \textit{et al.} 1999), in which a massive dark matter halo forms within a 64 Mpc box of a critical density universe. (We adopt \(H_0 = 50\) km s\(^{-1}\) Mpc\(^{-1}\) throughout.) We carry out two simulations: the first is a CDM plus 10% non-radiative gas and the second run is 100% non-radiative gas (≡ SIDM). The particle mass is approximately \(8.6 \times 10^9 M_\odot\) and the effective force resolution is 0.3% of the virial radius of the final cluster \(r_{\text{vir}} = 2.7\) Mpc (see Figure 1).

The CDM run behaves as expected and as characterised by many previous authors (e.g., Barnes & Efstathiou 1987, Frenk \textit{et al.} 1999). One interesting point to highlight from this and similar simulations is that the gas ends up with a shallower density profile than the dark matter (cf. Figure 2). This is due to energy transfer between the two components and the fact that the entropy of the gas can increase through shocks that occur during the gravitational

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collapse. On large scales the SIDM run is similar to the CDM run although we note that the filaments appear narrower. On non-linear scales the two models behave very differently and we now discuss the salient features in more detail.

2.1. Density profiles

The final density profile of the most massive SIDM halo is shown next to its collisionless counterpart in Figure 2. This halo has more than $10^5$ particles within its virial radius. The profile is close to a singular isothermal sphere with slope $\rho(r) \propto r^{-2}$, even in the very central region. The hierarchical collapse imparts thermal energy into the particles which leads to a small amount of pressure support, however this is not sufficient to flatten their inner profiles.

To check these results we performed 3D spherical collapses of power-law spheres with zero initial kinetic energy and density profiles $\rho(r) \propto r^n$ with $n = -1, 0, +1$. We found consistent results with 100 and 5000 particles, indicating that the singular profile in the cosmological SIDM simulation is not purely an artifact of the high-redshift progenitor collapses being inadequately resolved. The collapse with $n = -1$ leads to a singular spherical isothermal structure. In this case the central particles are not strongly shocked and stay at a low entropy. The $n = 0$ and $n = +1$ collapses generate much higher entropies throughout the system. SIDM particles fall in from larger radii achieving higher velocities and significant thermal energy is generated during the collapse resulting in a pressure supported constant density core. A similar point has been made by Bertschinger (1985). Our cosmological Gaussian fluctuations resemble the former collapse which results in singular isothermal structures — what is needed is a mechanism that prevents low entropy material surviving, such as we find in more violent collapses.

2.2. Ram pressure truncation and viscous drag

Halos of SIDM suffer ram-pressure truncation and ram-pressure/viscous drag, however dynamical friction is largely suppressed in SIDM models since the bow shocks and the collisional nature of the fluid inhibit the formation of trailing density wakes. A good approximation is to adopt isothermal profiles for the substructure halo (subscript $s$) and parent halo (subscript $p$) such that $\rho(r) = v^2/(4\pi G\rho^2)$. The ram pressure, $\rho(r_p)v_p^2$, can be equated to the force required to retain a shell of material at radius $r_p$ from the centre of the substructure halo $F \approx m_s v_p^2/r_s$. Thus the stripping radius at position $r_p$ in the parent halo is $r_{\text{strip}} = kr_p(v_s/v_p)^2$ where $k$ is a constant of order $\pi$. This can be contrasted with the tidal radius of embedded isothermal halos, $r_{\text{tidal}} = r_p(v_s/v_p)$. Therefore, substructure halos of SIDM will be stripped to substantially smaller sizes than their CDM counterparts.

It is also interesting to compare the timescale for a substructure halo to sink to the centre of a larger system due to hydro-dynamical drag, $t_{\text{drag}} = \rho(r_p)v_p^2/4\pi \sigma^2$. For a circular orbit, $L = r_p v_p$, and the rate of specific angular momentum loss, $\dot{L}/dt = r_p F/m_s$, therefore $r_p^{-1} \dot{r}_p/dt = F/(m_s v_p)$. As the substructure is dragged deeper into the central potential, its radius decreases as calculated above and we can substitute for $v_s$. Thus we find $\dot{r}_p/dt = kv_p$ such that the drag timescale is simply...
of order of the crossing time $t_{\text{drag}} = kr_p/kp$. All SIDM substructure halos sink at a similar rate independent of their mass and on a timescale that is typically faster than that due to dynamical friction.

![Figure 2](image)

**Fig. 2.** The radial density profiles of CDM versus SIDM halos. The spherical collapse halos are plotted using an arbitrary scale at the upper right. In this case, the solid curve is the CDM density profile, the dotted and dashed curves are the the spherical SIDM collapses with $n = 0$ and $n = -1$ respectively. The density profiles of the hierarchical collapses are shown for SIDM (dotted curve) and for CDM (solid curve) with 10% non-radiative gas (dashed curve).

2.3. Orbital and velocity bias

These results have fascinating implications for biasing and the survival of substructure within dense environments. In dynamically old objects, such as galaxy halos, there may have been time for most of their substructure to sink to the centre. Any surviving substructure that passes close to the Galactic disk will be stripped to a negligible mass, therefore disk heating is not a problem in SIDM models. Hydro-dynamical destruction may be happening to the Sagittarius dwarf right now: its current SIDM halo radius would be approximately 100 pc. We may also expect that galaxies orbiting through the central regions of rich clusters will have lost most of their dark matter halos. Younger systems, such as galaxy clusters have only had sufficient time to concentrate and bias their “satellites” towards the central regions. SIDM satellites suffer significant velocity bias due to drag: an analysis of the 20 most massive satellites within the largest dark matter halo yields $\sigma_{\text{SIDM}}/\sigma_{\text{CDM}} = 0.85$.

The orbits of the Milky Way’s satellites with known proper motions are surprisingly circular (e.g., Grebel et al. 1998, van den Bosch et al. 1999), whereas circular orbits are rare in CDM models (Ghigna et al. 1998). We find that the anisotropy parameter for SIDM satellites, $\beta_{\text{SIDM}} = 0.5$, compared with $\beta_{\text{CDM}} = 0.32$ (where $\beta = v_r^2/(v^2 + v_z^2)$), which results from the efficient angular momentum loss of satellites at pericentre. SIDM may also account for the “Holmberg–Zaritsky” effect (Holmberg 1969, Zaritsky et al. 1997). The angular momentum of SIDM halos is distributed differently than in the CDM halos leading to a rotationally flattened central core. The baryons are most likely to dissipate into this plane that aligns with the large scale filamentary structure. It is material that flows from these cold filaments into the larger halos that spins up the dark matter: satellites infalling along this “special” plane will rapidly sink once they make contact with the SIDM galaxy halos. Furthermore, those satellites sinking in the retrograde direction to the parent halo’s angular momentum will be preferentially destroyed due to the enhanced drag which is $\propto v^2$ (cf. Figure 1b).

2.4. Halo shapes

The shapes of dark matter halos provide another clear discriminant between SIDM and CDM. The typical ratio of short to long axis for CDM halos is 0.5 with a log-normal distribution (Barnes & Efstathiou 1987). Figure 3 shows the ratio of short to long axis, $c/a$, and intermediate to long axis, $b/a$, as a function of radius for a well resolved halo in the simulation. The virialised part of the halo is rotationally flattened into an oblate shape such that $\epsilon_{\text{max}} \approx 0.2$. This is typical of the other SIDM halos which are generally flattened in the range $0.0 \leq \epsilon \leq 0.2$. For comparison we also show the shape of the same halo in the collisionless CDM simulation which has a prolate configuration with $c/a \approx b/a = 0.6$ within $r_{\text{vir}}$.

![Figure 3](image)

**Fig. 3.** The axial ratios of a CDM and an SIDM halo are plotted as a function of radius from the centre. Within the virial radius, this CDM halo is prolate, whereas the SIDM halo is slightly flattened by rotation into an oblate configuration.

Analyses of polar ring galaxies and X-ray isophotes tend to give flattened dark matter potentials, whereas techniques that use disk flaring and the precession of warps yield spherical mass distributions (Olling & Merrifield 1998). Ultimately, gravitational lensing will resolve this issue, but for now we note that a lensing study of CL0024+1645 constrains the asymmetry of the projected mass distribution to be less than 3% (Tyson et al. 1998). With the notion that collisional halos should be spherical, Miralda-Escude (2000) argued that the cluster MS2137-23 rules out SIDM since analysis of its gravitational arcs demonstrates that its mass distribution must be flattened such that $\epsilon \geq 0.1$ in the central region. At the moment, SIDM and CDM are both consistent with these data.

2.5. The extent of halos within halos

The dwarf satellites of the Milky Way have internal velocities of order 10–30 km s$^{-1}$, that in isolation would extend to 10–30 kpc but are tidally limited according to
their orbits within the Milky Way’s potential. Numerical simulations confirm this simple expectation (Ghihna et al. 1998). For example, the dark matter halo surrounding the Carina satellite would be truncated to $r_{\text{tidal}} \approx (r_{\text{peri}}/50 \text{kpc})(v_{\text{esc, Carina}}/v_{\text{AW}}) = 2.7 \text{kpc}$ at its current position. In an SIDM universe, the halo of Carina would be reduced to a size $r_{\text{strip}} \approx 400 \text{pc}$.

Observations of stars escaping from satellites constrain the extent of their dark matter halos (Moore 1996, Burkert 1997). Tidal streams have recently been spectroscopically confirmed for Carina (Majewski et al. 1999) and are also claimed for Draco and Ursa Minor (Irwin & Hatzidimitriou 1993). These observations imply that the dark matter extends only as far as the optical radii, about 300 parsecs for all of these satellites and much smaller than their expected sizes if they had halos of CDM.

Similarly, the dark matter halos of cluster galaxies are truncated by the global cluster potential and their sizes can be constrained by quantifying their effects on strongly and weakly lensed images of background galaxies. Natarajan et al. (1999) have analysed several of the clusters imaged by the Hubble Space Telescope and claim that the dark matter halos of bright cluster galaxies are severely truncated to between 15–30 kpc. These galaxies have typical internal velocity dispersions of $150 \text{ km s}^{-1}$ and sample the projected central 500 kpc region of the clusters (else they wouldn’t lie in the HST frames). Thus we expect $r_{\text{tidal}} \approx 30–60 \text{kpc}$ from gravitational stripping, but $r_{\text{strip}} \approx 10–30 \text{kpc}$ from maximal collisional stripping.

3. DISCUSSION

The properties of dark matter halos of strongly interacting particles are markedly different from their collisionless counterparts. SIDM halos are close to spherical with a modest degree of rotational flattening. Observations of halo shapes cannot currently distinguish between the models examined here; however, future lensing observations will determine if SIDM is a viable dark matter candidate. Halos within halos suffer ram-pressure truncation that decreases their sizes to less than the tidal radius. Current observational data on galactic halos in clusters and satellite galaxies in the Galactic halo are naturally reproduced in SIDM models: the extent of Carina’s halo is an order of magnitude smaller than predicted by CDM. Ram-pressure drag creates significant velocity and orbital bias in the substructure halos which sink on a short timescale—of order the crossing time—indeed of their mass. Another positive feature of SIDM is the ability to produce satellite systems on near circular orbits which are very rare in CDM models.

Both CDM and SIDM with a large cross-section fail to reproduce observed rotation curves of dwarf and LSB galaxies. We have seen that the final density profiles are sensitive to the shape of the initial fluctuations: more violent collapses end up with constant density cores. Alternatively, SIDM with a mean free path between kiloparsec and megaparsec scales may solve this problem (Spergel & Steinhardt 1999). In this case, particles could transfer heat to the cold central regions that occur in standard CDM collapses, creating an initial expanding phase with lower central density. It is not obvious that a cold core would be generated and maintained in a hierarchical scenario since the dense mini-halos collapsing at high redshift may form singular isothermal structures. The dense substructure halos would rapidly sink to the centres of the parent halos by hydro-dynamical drag, depositing high density low entropy material and conserving isothermal profiles.

Simulating intermediate mean free paths is relatively straightforward. One technique would be to use the neighbour lists to choose random particles to collide (Burkert 2000). Simulations in progress will demonstrate whether SIDM can reproduce the observed rotation curves of dwarf galaxies. A solution to this problem will naturally resolve the abundance of dark matter substructure in the Galactic halo since substructure with shallow potentials would be easily disrupted.

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