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ANGULAR MOMENTUM PROFILES OF WARM DARK MATTER HALOS

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ABSTRACT

We compare the specific angular momentum profiles of virialized dark halos in cold dark matter (CDM) and warm dark matter (WDM) models, using high-resolution dissipationless simulations. The simulations were initialized using the same set of modes, except on small scales, where the power was suppressed in WDM below the filtering length. Remarkably, WDM as well as CDM halos are well described by the two-parameter angular momentum profile of Bullock and coworkers, even though the halo masses are below the filtering scale of the WDM. Although the best-fit shape parameters change quantitatively for individual halos in the two simulations, we find no *systematic* variation in profile shapes as a function of the dark matter type. The scatter in shape parameters is significantly smaller for the WDM halos, suggesting that substructure and/or merging history plays a role in producing scatter about the mean angular momentum distribution, but that the average angular momentum profiles of halos originate from larger scale phenomena or a mechanism associated with the virialization process. The known mismatch between the angular momentum distributions of dark halos and disk galaxies is, therefore, present in WDM as well as CDM models. Our WDM halos tend to have a less coherent (more misaligned) angular momentum structure and smaller spin parameters than do their CDM counterparts, although we caution that this result is based on a small number of halos.

Subject headings: cosmology: theory — galaxies: formation

1. INTRODUCTION

Cold dark matter (CDM) models of structure formation have been very successful in describing the observed properties of galaxies at large scales. On subgalactic scales, however, there are some uncomfortable discrepancies. One problem concerns the sizes and angular momentum content of disk galaxies. Analytic investigations have been reasonably successful in reproducing the observed sizes of disks, but only under the simplistic assumption that disks arise from gas with the same average specific angular momentum as their host halos and that the gas experiences little angular momentum loss during the formation process (e.g., Fall & Efstathiou 1980; Blumenthal et al. 1986; Dalcanton et al. 1997; Firmani & Avila-Reese 2000). However, in more detailed numerical simulations, the gas appears to lose a large fraction of its initial angular momentum (e.g., Navarro & Steinmetz 2000). The resultant disks are considerably smaller than observed disks, unless gas cooling is delayed (Weil, Eke, & Efstathiou 1998) or the efficiency of stellar feedback is enhanced (Thacker & Couchman 2001).

It is not yet clear whether this discrepancy poses a serious problem for CDM or simply results from insufficient understanding or inadequate modeling. We can gain some insight by comparing the specific angular momentum (j) distribution of dark matter in galactic halos to that observed for galactic disks. In Bullock et al. (2001, hereafter B01), using a dissipationless CDM plus cosmological constant (ΛCDM) simulation, we found that angular momentum profiles of galactic CDM halos of mass M_v are well described by a two-parameter angular momentum profile of the form

$$M(<j) = M_v \frac{\mu j}{j_0 + j}, \quad \mu > 1. \tag{1}$$

Here, j is projected along the direction of the total angular momentum in the halo. The parameters μ and j_0 fully define the angular momentum content of the halo, where the global spin of the halo[2] $\lambda' \equiv J/\sqrt{2}M_v V_v R_v$, is related to μ and j_0 via $j_0\, b(\mu) = \sqrt{2} V_v R_v\, \lambda'$, where $b(\mu) = -\mu \ln(1-\mu^{-1}) - 1$; J is the absolute value of the total angular momentum of the halo; and V_v and R_v are, respectively, the virial velocity and virial radius of the halo.

This $M(<j)$ distribution is considerably different from that implied by the mass distributions in disk galaxies (B01; van den Bosch, Burkert, & Swaters 2001; van den Bosch 2001). For example, the dark matter has considerably more low j material than expected for an exponential disk, and certain models of feedback and bulge formation do not alleviate this problem. It appears, therefore, that in order for CDM to provide a successful theory of galaxy formation, the angular momentum in protogalactic gas must be rearranged relative to that of the dark matter.

The problem of angular momentum loss and other galactic-scale problems have led some to suggest various modifications to the standard paradigm. Among the most popular is the recommendation that warm dark matter (WDM) be substituted for CDM (e.g., Hogan & Dalcanton 2000). This acts to suppress power relative to CDM on scales below the filtering scale R_f, which is related to the WDM particle mass via $R_f = 0.2(\Omega_{\rm wdm}\, h^2)^{1/3}(m_w/{\rm keV})^{-4/3}$ Mpc, where $\Omega_{\rm wdm}$ is the warm dark

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[2] This spin parameter is a practical modification of the conventional spin parameter, defined as $\lambda = J|E|^{1/2}/GM_v^{5/2}$, where E is the halo internal energy.

matter density in units of critical density. The formation of halos with masses smaller than the corresponding filtering mass M_f is thus delayed or completely suppressed. The smaller number of small-mass halos at high redshifts can help to prevent angular momentum loss as subclumps fall into parent halos.

Simulations by Sommer-Larsen & Dolgov (2001) indicate that disks formed in the WDM cosmology retain a considerably larger fraction of their angular momentum than their CDM counterparts, alleviating the angular momentum problem discussed above and adding to the motivation for the WDM model. It is interesting, therefore, to ask whether $M(<j)$ distributions in the WDM model are also closer to those of observed disks. Implications of the WDM scenario have recently been studied extensively using cosmological simulations (Colín, Avila-Reese, & Valenzuela 2000; Avila-Reese et al. 2001; Bode, Ostriker, & Turok 2001; Knebe et al. 2001; Eke, Navarro, & Steinmetz 2001). It was shown that WDM does help to alleviate problems of CDM with halo density profiles and, possibly, the spatial distribution of dwarf galaxies (Peebles 2001). In addition, Knebe et al. (2001) compared specific angular momentum distribution in CDM halos to that of the halos formed in WDM cosmology and found no systematic difference. However, they studied halos with masses much higher than the filtering mass of the simulation and neglected the thermal velocities of the WDM particles. Halos below the filtering mass are of much interest because the mismatch in angular momentum distributions is especially pronounced for dwarf galaxies (van den Bosch et al. 2001).

Additional motivation for this project comes from a desire to understand the nature of angular momentum acquisition and distribution in halos. This could provide valuable insight by highlighting specific reasons why (and how) the baryonic j distribution should differ from that of the dark matter. Traditionally, angular momentum in dark halos has been thought to derive from protohalo interactions with the large-scale tidal field (Peebles 1969; Doroskevich 1970; White 1984). Recently, however, a scenario in which mergers play a primary role in halo angular momentum acquisition has been investigated (Vitvitska et al. 2001; Maller, Dekel, & Somerville 2001). Of course, the real situation may be intermediate to these two pictures. Formation of halos in the WDM cosmology should involve very few mergers, and one might expect a different resulting distribution of the specific angular momentum if mergers are important in a halo's spin acquisition (A. Maller & A. Dekel 2001, in preparation).

In this Letter we use high-resolution dissipationless simulations of CDM and WDM cosmologies to study the effects of suppressed small-scale power and thermal velocities on the specific angular momentum distribution of dark halos. In particular, we focus on the halos with masses below the filtering mass of the WDM model. The Letter is organized as follows. In § 2 we briefly describe the numerical simulations used in our study, and we present our analysis and results in § 3. Discussion of the results and our conclusions are presented in § 4.

2. SIMULATIONS

Dark halos were modeled using three simulations, one of the ΛCDM cosmology and two of the ΛWDM cosmology. In each case we assume a total matter and baryon density in units of the critical density of $\Omega_m = 0.3$, $\Omega_b = 0.026$, with $\Omega_{\rm cdm} = \Omega_{\rm wdm} = \Omega_m - \Omega_b$, a Hubble constant of $h = 0.7$ in units of 100 km s^{-1} Mpc^{-1}, $\sigma_8 = 1.0$, and space made flat by a cosmological constant. The simulations are described in detail by Avila-Reese et al. (2001); here we will briefly summarize their main features. All simulations were run using the Adaptive Refinement Tree code (Kravtsov, Klypin, & Khokhlov 1997; Kravtsov 1999), which achieves high resolution by adaptively refining the initial uniform grid in the regions of interest. The simulations were done in a 60 h^{-1} Mpc box, and we focused our analysis on four halos. The four were first selected from a low-resolution 64^3 particle run. The particles within two virial radii of the halo centers were traced back to the initial epoch. The initial conditions in the Lagrangian volume marked by the particles were then reset with higher resolution using the multiple-mass technique described in Klypin et al. (2001). The final halos studied consist entirely of the highest resolution particles, of mass $m_p = 1.1 \times 10^9\ h^{-1}\ M_\odot$. We used the same power spectrum for both the ΛCDM and ΛWDM runs but in the ΛWDM simulations the modes below the filtering scale, R_f, were suppressed with an exponential cutoff (Bardeen et al. 1986):

$$P_{\rm WDM}(k) = P_{\Lambda{\rm CDM}}(k) \exp\{-0.5[kR_f + (kR_f)^2]\}, \qquad (2)$$

where $P_{\Lambda{\rm CDM}}$ is the power spectrum of the ΛCDM model. In this investigation we explore a model with $m_w = 125$ eV, corresponding to a filter mass of $M_f = 3.65 \times 10^{14}\Omega_{\rm wdm} \times R_f^3\ h^{-1}\ M_\odot \simeq 1.8 \times 10^{14}\ h^{-1}\ M_\odot$. The warm dark matter particles should also possess "thermal" velocities of an amplitude that is related to their mass. In this study we bracket the possible effects of the thermal velocities by comparing simulations without thermal velocities (ΛWDM) and simulations with thermal velocities 16 times the value expected for the assumed WDM particle mass (ΛWDM$_{\rm th}$). The same set of waves was used to set up the initial conditions of both the ΛCDM and WDM simulations. Therefore, the same halos form in all the simulations. This allows us to compare them individually and gauge the effects of the input cosmology more accurately.

3. RESULTS

We study four halos in each simulation; each is identified by position and numbered 1–4. The studied sample of four halos is too small to draw statistical conclusions. However, the identical setup of the initial conditions in CDM and WDM simulations has allowed us to study *systematic* differences between *the same* individual halos formed in two different cosmologies.

Halo angular momentum profiles were constructed using the methods discussed in B01. Briefly, halos were identified using a spherical overdensity method, with the virial radius, R_v, set using the standard virial overdensity criterion. Once the halo is defined, we use the total angular momentum in each halo to assign the z-direction. We then subdivide the spherical halo volume into many spatial cells, as outlined here, using spherical coordinates about the halo center (r, θ, ϕ). Radial shells from $r = 0$ to R_v are defined such that each contains approximately the same number of particles. The number of shells is always fewer than 30. Each radial shell is then subdivided into three azimuthal cells of equal volume between $\sin\theta = 0$ and 1, each spanning the full 2π range in ϕ. As in B01, each of the three azimuthal cells consists of two separated volume elements, one above and one below the equatorial plane at fixed $\sin\theta$. Each cell contains between 500 and 1000 particles. The value of j in the z-direction is measured for each cell, and $M(<j)$ profiles are constructed by counting the cumulative mass in cells with angular momentum less than j.

Since j is a projected component, it is possible for a cell to have a negative j value. Although this is rare (for cells containing ~1% of the total halo particles, as do ours), it does occur on occasion in CDM halos (B01) and, as discussed below, seems to be more common for WDM halos. When a cell's projected angular momentum is negative, we remove the cell completely from the constructed $M(<j)$ profile. We record the fraction of mass in *cells* with negative j and designate it as f_m. Quoted λ'-values do include the particles contained in the negative j cells, but neglecting them results in changes of less than 5% in λ' in all halos except ΛWDM$_{\rm th}$ halo 3.

Table 1 lists the angular momentum properties of all four halos as well as their masses in each of the three simulations. We find that the $M(<j)$ profiles are well fitted by the universal curve given by equation (1). As illustrated in Figure 1, the WDM halos show no systematic difference in their j distributions compared to the CDM halos, although there is a dramatic decrease in scatter about the average profile.

Note that the masses of the halos systematically decrease as the cosmology shifts from ΛCDM to ΛWDM and again to ΛWDM$_{\rm th}$. The pattern holds for all halos except halo 2, which, by chance, has just experienced a major merger in the ΛWDM$_{\rm th}$ simulation. The same halo is undergoing a merger in ΛWDM, but the merger has not yet occurred in ΛCDM. A similar trend is apparent in the values of λ', which decrease systematically from ΛCDM to ΛWDM to ΛWDM$_{\rm th}$. The lone exception is halo 2 in the ΛCDM simulation, which, because of its lack of a recent merger, may not provide a fair comparison. Similarly, the ΛWDM$_{\rm th}$ halos are significantly more misaligned than the ΛCDM halos. The thermal velocities in this model are quite high, $v_{\rm th} \approx 16 \times 0.16(1+z)(m_w/100\ {\rm keV})^{-1} \simeq 21\ {\rm km\ s^{-1}}$ at $z = 0$. This is comparable to the spin rotation speed in halos in our mass range. For example, an $M_{\rm vir} = 5 \times 10^{13}\ h^{-1}\ M_\odot$ halo with $V_{\rm vir} \simeq 800$ km s^{-1} will have a bulk rotation velocity of $\langle V_{\rm rot}\rangle \simeq \sqrt{2}\lambda' V_{\rm vir} \simeq 50\ {\rm km\ s^{-1}}$ for $\lambda' = 0.05$. Because the thermal velocities are similar in magnitude to the bulk rotation, the spin signal tends to be washed out. This leads to significant misalignment in the measured angular momentum.

4. DISCUSSION AND CONCLUSIONS

We found no evidence for a systematic difference in the shapes of the specific angular momentum distributions of WDM and CDM halos. This is interesting because there are reasons to expect that $M(<j)$ is sensitive to a halo's merging history (Vitvitska et al. 2001; Maller et al. 2001). The CDM and WDM halos examined had significantly different merging histories because their masses were below the WDM filtering scale, so our results indicate that mergers (rather than from diffuse, unclustered mass accretion) cannot play a crucial role in shaping the angular momentum distribution. This poses a challenge for models striving to explain the angular momentum distribution as a result of a series of mergers. Larger scale

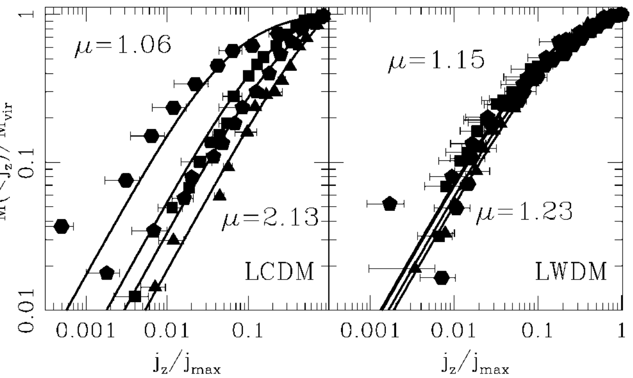

FIG. 1.—Cumulative specific angular momentum distributions for the ΛCDM and ΛWDM halos. Filled points show the profiles as measured in from the simulated halos, and solid lines show the best-fit profiles given by eq. (1). Individual halos (identified by matching positions in the two simulations) retain the same point types in both the ΛCDM and ΛWDM panels. Although no systematic differences are observed, the ΛWDM halos demonstrate significantly less scatter about the mean profile.

phenomena or processes associated with halo virialization may be the major contributors.

We found evidence that WDM halos possess systematically smaller spins than their counterparts in ΛCDM. This result is in agreement with findings of Knebe et al. (2001) who reported systematically lower spins for halos in the WDM models with higher filtering mass. We showed that the addition of initial thermal velocities resulted in even lower spins in the WDM halos as well as a significantly larger misaligned (negative j) mass fraction. This is a potentially significant result because the angular momentum in CDM halos is barely sufficient to produce disks with realistic sizes (e.g., de Jong & Lacey 2000). Although it is not clear why $M < M_f$ WDM halos should have smaller spins than their CDM counterparts, in the context of merger-driven spin evolution it might be expected because WDM halos accrete most of their mass quiescently. A decrease in spin during periods of quiescent accretion is also observed in cosmological simulations (Vitvitska et al. 2001).

Recently, Sommer-Larsen & Dolgov (2001) used gas-dynamic simulations to argue that WDM helps to resolve the angular momentum problem. However, this was true only for disk galaxies in halos with mass greater than M_f. For halos with $M \lesssim M_f$ they found no increase in j compared to CDM. If, as they argued, the gas in the WDM model retains more of its initial angular momentum because of the lower abundance of small-mass halos, this should also be true for the halos with $M < M_f$. The relatively small specific angular momentum for the $M < M_f$ should then be due to the lower overall spin of the gas and DM, which is consistent with our results. Unless there is a mechanism that allows baryons to acquire more angular momentum than the dark matter, this result may be problematic

TABLE 1
HALO ANGULAR MOMENTUM AND MASS IN THREE SIMULATIONS

	ΛCDM				ΛWDM				ΛWDM$_{\rm th}$			
HALO	M_v	μ	λ'	f_m	M_v	μ	λ'	f_m	M_v	μ	λ'	f_m
1 ……	9.53	2.13 ± 0.55	0.057	0.02	7.38	1.19 ± 0.09	0.043	0.02	6.61	1.10 ± 0.05	0.035	0.04
2 ……	6.37	1.22 ± 0.10	0.028	0.00	5.73	1.16 ± 0.07	0.041	0.01	14.7	1.18 ± 0.09	0.017	0.14
3 ……	4.44	1.41 ± 0.20	0.023	0.04	3.83	1.15 ± 0.05	0.010	0.27	3.19	1.10 ± 0.04	0.004	0.48
4 ……	5.61	1.06 ± 0.02	0.043	0.16	3.76	1.23 ± 0.10	0.029	0.06	2.65	1.07 ± 0.03	0.023	0.10

for WDM models. If one tunes the filtering mass to alleviate the j problem in massive galaxies ($M_f \sim 10^{11}\ M_\odot$), dwarf galaxies will then be associated with $M \ll M_f$ halos. The WDM dwarf disks should, therefore, possess smaller spins than those in CDM models, which are already uncomfortably low compared to observations (van den Bosch et al. 2001).

In conclusion, changing from cold to warm dark matter does not produce dark matter halos with higher angular momenta or with more desirable angular momentum distributions. For WDM disks forming in halos with masses smaller than the filtering mass, the angular momentum problem might actually be worse. Our results fail to provide an additional motivation for the WDM scenario and highlight a possible problem at dwarf galaxy scales.

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