PHYSICS OF GALACTIC COLLIDERS: HIGH-SPEED SATELLITES IN ACDM VERSUS MONDIAN COSMOLOGY

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ABSTRACT

The statistics of high-speed satellite galaxies, as reported in the recent literature, can be a powerful diagnosis of the depth of the potential well of the host halo, and hence discriminate between competing gravitational theories. Naively one expects that high-speed satellites are more common in modified Newtonian dynamics (MOND) than in cold dark matter (CDM) since an isolated MONDian system has an infinite potential well, while CDM halos have finite potential wells. In this Letter, we report on an initial test of this hypothesis in the context of the first generation of cosmological simulations utilizing a rigorous MONDian Poisson solver. We find that such high-speed encounters are approximately a factor of 4 more common in MOND than in the concordance ACDM model of cosmic structure formation.

Key words: cosmology: theory – dark matter – galaxies: formation – large-scale structure of universe – methods: N-body simulations

1. INTRODUCTION

The standard ACDM model (see Komatsu et al. 2009) explains the formation of cosmological structure in the non-linear regime in a hierarchical way, i.e., large structures are not formed monolithically but by the successive merging of smaller structures (e.g., Davis et al. 1985). Recent cosmological simulations also support the idea of hierarchical formation in modified Newtonian dynamics (MOND; Llinares et al. 2008, but see also the analytical models of Sanders 2008; Zhao et al. 2008). The hierarchical merging scenario naturally promotes the picture that we should observe collisions of galaxies. The question that immediately arises is: what is the nature of the distribution of the relative speed of such encounters? Observationally, there is evidence that some of these collisions actually occur with speeds that are not readily reproduced by simulations of ACDM structure formation (Hayashi & White 2006; Springel & Farrar 2007; Knebe et al. 2008). There is, for example, the famous “Bullet cluster,” an extremely high-velocity merger between two galaxy clusters whose relative speed is between 2500 and 4500 km s\(^{-1}\) depending on the interpretation of the shock speed and the method used to infer the collision speed (observations/models, analytical/numerical, N-body/hydro simulations; e.g., Nusser 2008; Springel & Farrar 2007; Markevitch 2006; Zhao 2007b). At first sight, the upper limit of this interval is too high and may be a problem for the standard ACDM model, but Hayashi & White (2006) showed using the Millennium cosmological simulation (Springel et al. 2005) that the probability of such an event, albeit low, is not zero.

There are a number of such high-speed encounters in the literature. One example of such a collision is the so-called “line-of-sight Bullet,” i.e., Abel 576, with a relative velocity of 3300 km s\(^{-1}\) (Dupke et al. 2007). Furthermore, the “Cosmic Train Wreck” Abel 520 is a collision with a velocity of approximately 1000 km s\(^{-1}\) (Mahdavi et al. 2007). The “Dark Matter Ring” cluster Cl0024+17 has a speculated impact velocity of 3000 km s\(^{-1}\) (Jee et al. 2007) and MACS J0025.4–1222 has two merging components whose relative velocity was measured to be 2000 km s\(^{-1}\) (Bradač et al. 2008). In comparison, the random dispersion of velocities in these clusters is only about 500–1000 km s\(^{-1}\).

A consequence of any high-speed collision of mass concentrations seems to be the decoupling or offsetting of the baryons from the dark component. Assuming this to be the case, additional examples of collisions are given in Jee et al. (2005a, 2005b) but see also Heymans et al. (2008). These kinds of objects, with offsets between baryon and DM components, have become what could be considered as yet another important standard test that any theory for gravity should pass before being seriously considered (e.g., Will 1993). Simply applying the MOND formula to a universe populated only with baryons seems to fail this test. Possible solutions could come from many ongoing efforts to embed the MOND idea in a relativistic framework by adding complementary (vector) fields besides the standard Einstein’s metric (Bekenstein 2004; Zlosnik et al. 2007; Zhao 2007a, 2008) or by the addition of neutrinos of various kinds (Angus & McGaugh 2008; Feix et al. 2008; Zhao 2008). However, we must have in mind that the same data on the Bullet cluster would have rejected general relativity in its original formulation without introducing one or more dark matter components plus a cosmological constant.

The question that arises from all these data is how to match the low probability of high-speed encounters predicted by Hayashi & White (2006) for the ACDM model with the fact that this type of collision seems to be common in the observable universe. A clue comes from the MONDian point of view where the situation seems to be more favorable for high velocities. Previous authors have noted that the deep potential in MOND (Angus & McGaugh 2008; Zhao 2007b; Nusser 2008) is helpful in the context of the Bullet cluster. On a smaller scale, high-velocity stars have been studied in the context of the escape speed in the Milky Way (Perets et al. 2008). It was found that MOND can retain stars of higher velocity than CDM, and the MONDian escape velocity is more consistent with the RAVE data in the solar neighborhood (Famaey et al. 2007; Wu et al. 2007). Further, the revised (yet still discussed) speed of the
Magellanic Clouds also favors MOND (Wu et al. 2008). The question that previous authors cannot address is how to obtain a self-consistent strength of the external field in MOND since they lack a full cosmological simulation. And as MOND is a nonlinear theory, it violates the strong equivalence principle and hence it is mandatory to simulate galaxies within the cosmological framework and not in isolation.

The aim of this Letter is not to go further in an explanation of this kind of system using MONDian ideas, but to study the consequences of a MONDian cosmological toy model on the probability of such high-speed encounters. In order to do this, we study the velocity distribution of substructure extracted from cosmological simulations that have been run using standard and modified gravity. We show that high-speed collisions are more frequent in MOND than in the concordance ΛCDM model.

2. SIMULATIONS

The analysis presented in this Letter is based upon a set of two simulations published in Llinares et al. (2008), i.e., the ΛCDM and the OCBMond2 model, respectively. Both simulations were run in a box with a side length of 32h⁻¹ Mpc, using 128³ particles. They were both run with a modification of the N-body code MLAPM (Knebe et al. 2001). The ΛCDM model employs a background cosmology parameterized by Ω₀ = 0.3, Ωₐ = 0.7, and a normalization of the power spectrum of the density perturbation of σ₈ = 0.88. For the MONDian simulation, we chose an open universe with neither dark matter nor dark energy but characterized by Ω₀ = 0.04. In order to arrive at a comparable evolutionary stage to the ΛCDM model at redshift z = 0, we had to lower the normalization σ₈ to 0.4 due to the faster growth of structures in MOND (see Sanders 2001; Knebe & Gibson 2004; Llinares et al. 2008). Both simulations were started at redshift z = 50 and used a Hubble constant H₀ = 70 km s⁻¹ Mpc⁻¹.

We used the MPI version of the AHF halo finder⁶ AHF's-Halo-Finder (Knollmann & Knebe 2009) to identify objects; this is based on the AHF halo finder of Gill et al. (2004). For the identification of substructure, we employed the tool MergerTree that comes with the AHF software package. This algorithm was originally designed to follow halos through time by tracking the membership of individual particles, but it can also be used to locate the subhalos of a given host. Since particles that belong to subhalos will also belong to the corresponding host, constructing a merger tree of a halo catalog with itself will provide us with a “subhalo tree” (rather than a merger tree). It is important at this moment to make a remark about our terminology. We use the term subhalo to refer to the largest substructures embedded in host halos. The mass ratio between our host halos and the most massive subhalo has a median of 0.23 and 0.15 for the MONDian and Newtonian simulations, respectively. These numbers are in the range of typical mass ratios for collisions in mergers of host halos and are well above the typical ratio between hosts and real substructures (e.g., Madau et al. 2008). In order not to contaminate our result with unvialized objects, we further prune our halo catalog by removing objects with a high virial ratio, ending up with 64 and 58 objects in the Newtonian and MONDian simulations, respectively.

For more details regarding these simulations, we refer the reader to Llinares et al. (2008).

Figure 1. Correlations of velocity dispersion $(\sigma_{\text{host}} \text{ in km s}^{-1})$ vs. effective host mass $(M_{\text{host}} = 7.25M_{\text{baryon}}$ in solar masses) for virialized objects of various sizes in MONDian (circles) and Newtonian simulations (pluses). The lines are fits with arbitrary normalization for theoretically predicted scaling relations $\eta_{\text{host}} \propto M_{\text{host,baryon}}^{1/4}$ in MOND and $\eta_{\text{host}} \propto M_{\text{host,baryon}}^{1/3}$ in Newtonian simulations the best-fit slopes are very close to 1/4 and 1/3, respectively. Note that the value 7.25 scales the MOND baryonic mass to the Newtonian baryon plus halo mass.

3. ANALYSIS

While the primary focus of this Letter is the distribution of the relative velocity of two colliding systems, we still need to define a proper normalization for these velocities to correct for the fact that a more massive host system will lead to a larger acceleration toward its center. While others referred to the rotational velocity at the virial radius of the host for this purpose (e.g., Hayashi & White 2006), we rather use the mass-averaged velocity dispersion.

3.1. Velocity Dispersion–Mass Relation for MOND and CDM

In the Newtonian case, the velocity dispersion scales with the mass $M$ as follows: $\sigma \propto V_{\text{cir}} = \sqrt{GM/R} \propto R \propto M^{1/3} \propto M_{\text{baryon}}$, where we used $M \propto \bar{\rho} R^3$ where $\bar{\rho}$ is the background density which depends only on redshift. A similar scaling relation between velocity dispersion $\sigma$ and mass $M$ can be easily obtained for deep MOND: $\sigma \propto V_{\text{cir}} \propto (GM_{\text{baryon}}a_0)^{1/4} \propto M_{\text{baryon}}^{1/4}$ for a spherical isolated body. Although not rigorous, we find that this scaling holds fairly well as a mass-averaged total dispersion of the system even in the intermediate MOND regime.

Figure 1 shows the $\sigma$–$M$ relation for the host systems selected in both our simulations. The lines indicate power-law fits whose index agrees closely with the theoretical values 1/4 and 1/3 for MONDian and Newtonian theory, respectively. The fitted normalization is higher than the theoretical one owing to the fact that the simulated halos break the hypothesis of constant density used in the theoretical approach.

3.2. Normalizing the Relative Velocities

Special care must be taken when comparing Newtonian dark matter simulations to collisionless MONDian simulations, especially when it comes to “halos.” While we set out to use

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⁶ AHF is freely available from http://www.aip.de/People/aknebe.
Further, our results appear to be robust against slight changes in redshift, i.e., we neither observe a change in the fact that MONDian velocities are bigger nor are our results contaminated by the fact that we may capture collisions at a particular time of accidentally high velocity. The latter is confirmed by analyzing the simulations at \( z = 0.036 \), leading to an indistinguishable plot. The same conclusion is reached when we experiment with other plausible normalizations or compute the distributions of unnormalized relative speed.

As a final test, we compare our results against a Newtonian model that does not contain a cosmological constant \( \Lambda \), i.e., the open OCBM model of Knebe & Gibson (2004) characterized by \( \Omega_0 = 0.04 \) and \( \Omega_\Lambda = 0.0 \). We acknowledge (though not explicitly shown here) that the relative velocity distribution of the OCBM model is akin to the \( \Lambda \)CDM model presented in Figure 2; we therefore ascribe the differences found in that plot to the effects of MOND rather than the (missing) cosmological constant.

5. CONCLUSIONS

Inspired by the observational evidence for high-speed encounters of galaxy clusters, we studied the velocity distribution of collisions present in two cosmological simulations: a standard \( \Lambda \)CDM model as well as MOND. While there may be a problem for \( \Lambda \)CDM to accommodate such extraordinary events (e.g., Hayashi & White 2006), we set out to quantify the probability for them in MOND. Within the limitations of our simulations, we find that there are substantial differences in the collision velocity of objects in the standard model of cosmology and its (possible) MONDian counterpart. We observe a much greater likelihood for high-speed collisions in MOND and therefore argue that this statistic can be used as a discriminator for the two competing theories.

We further verify numerically the velocity dispersion–mass relation for deep MOND gravity; its slope is different to the Newtonian case (\( \sigma \propto M^{1/3} \) for MOND instead of \( \sigma \propto M^{1/3} \) for Newtonian physics). There is a mild scatter about these relations.

We close with a cautionary note: the box size of our simulation (32h\(^{-1}\) Mpc) is too small to find objects directly comparable to systems like the Bullet cluster. The collisional velocity expected for the Bullet cluster (\( V_{\text{rel}}/\sigma \approx 2.04 \)) is close to the limit of what we resolve in Figure 2. While the current result is interesting, and the rescaled \( V_{\text{rel}}/\sigma \) is likely insensitive to details of the simulation setup, more simulations (e.g., with a possible neutrino component and a cosmological constant in MOND) are required to understand how our prediction depends on the cosmological model employed.

Nevertheless, our results here may have far-reaching implications as well. Historically, Dark Matter and MOND are competing theories. Recent studies argue that MOND is a prescription for interactions of a coupled Dark Energy–Dark Matter field. Effectively, MOND is made by a nonuniform Dark Energy field. The places where this field condenses are identified as dark halos. Our results here could argue that we might differentiate between theories with interacting Dark Matter–Dark Energy versus classical \( \Lambda \)CDM using data of high-speed encounters. It is encouraging that some subtle differences on how the Dark Sector self-interacts could leave signatures on “large astronomical colliders” (LAC).

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Figure 2. Accumulated probability of the relative velocity \( V_{\text{rel}} \) between our host halos and their most massive subhalo normalized with the effective dispersion \( \sigma_{\text{host}} = 0.01 (7.25 \, M_{\text{host,baryon}})^{1/3} \) km s\(^{-1}\) (see the text for explanation).
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