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FORMATION AND EVOLUTION OF SELF-INTERACTING DARK MATTER HALOS

Kyungjin Ahn and Paul R. Shapiro

Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA

RESUMEN

Estudiamos la fomación y evolución de halos de materia oscura autointeractuante (SIDM). Encontramos soluciones analíticas de similaridad para su dinámica, que toman en cuenta la interacción de colisión entre las partículas de SIDM basada en una aproximación de fluido derivada de la ecuación de Boltzmann. Las soluciones son relevantes para la formación de halos de galaxias y cúmulos en el modelos de materia oscura fría. Se obtienen soluciones diferentes en función del párametro adimensional de colisionalidad, $Q \equiv \sigma\rho_b r_s$; donde σ es la sección recta de dispersión por unidad de masa para las partículas de SIDM, ρ_b es la densidad cosmica media, y r_s es el radio del choque. En todas las soluciones se encuentra un núcleo isotérmico, de densidad uniforme, que crece por la expansión cosmológica con una fracción constante de r_s. Por lo tanto, el colapso del núcleo se retrasa hasta que la caída de material se vuelve despreciable, contrariamente a lo que se encuentra en análisis de halos aislados, que predicen el colapso del núcleo en un tiempo de Hubble. Nuestras soluciones coinciden con simulaciones de N-cuerpos que reproducen curvas de rotación si $\sigma \sim [0.56 - 5.6]\, cm^2 g^{-1}$, lo que implica que $Q \sim [6.2 \times 10^{-7} - 3.6 \times 10^{-5}]$. Perfiles similares se encuentran cuando $Q \sim [1.37 \times 10^{-2} - 1.7 \times 10^{-1}]$, ó $\sigma \sim [1.2 \times 10^4 - 2.7 \times 10^4]\, cm^2 g^{-1}$, un regimen hasta ahora no simulado.

ABSTRACT

We study the formation and evolution of self-interacting dark matter (SIDM) halos. We find analytical, fully cosmological similarity solutions for their dynamics, which take proper account of the collisional interaction of SIDM particles, based on a fluid approximation derived from the Boltzmann equation. These similarity solutions are relevant to galactic and cluster halo formation in the cold dark matter (CDM) model. Different solutions arise for different values of the dimensionless collisionality parameter, $Q \equiv \sigma\rho_b r_s$, where σ is the SIDM particle scattering cross section per unit mass, ρ_b is the cosmic mean density, and r_s is the shock radius. For all solutions, a flat-density, isothermal core is present which grows in size as a fixed fraction of r_s, pumped by cosmological infall. Accordingly, core collapse must in general be delayed until infall becomes negligible, contrary to previous analyses based on isolated halos, which predict core collapse in a Hubble time. Our solutions agree with N-body simulations, which match observed galactic rotation curves if $\sigma \sim [0.56 - 5.6]\, cm^2 g^{-1}$, implying $Q \sim [6.2 \times 10^{-7} - 3.6 \times 10^{-5}]$. Similar profiles also arise for $Q \sim [1.37 \times 10^{-2} - 1.7 \times 10^{-1}]$, or $\sigma \sim [1.2 \times 10^4 - 2.7 \times 10^4]\, cm^2 g^{-1}$, a regime not previously simulated.

Key Words: **COSMOLOGY : DARK MATTER — GALAXIES: KINEMATICS AND DYNAMICS — LARGE-SCALE STRUCTURE OF UNIVERSE**

1. INTRODUCTION

The self-interacting dark matter (SIDM) model was proposed by Spergel & Steinhardt (2000) to resolve the discrepancy between the inner density profile of cold dark matter (CDM) halos found by N-body simulations and observations of galactic rotation curves. N-body simulations have a density cusp ($\rho \propto r^\beta$ where β ranges from -1 (Navarro, Frenk & White 1997; hereafter "NFW") to -1.5 (Moore et al. 1999; hereafter "Moore profile")), while observations of dark-matter dominated dwarf and LSB galaxies indicate flat-density (soft) cores. SIDM particles undergo nongravitational, microscopic interaction which is strong enough to produce a soft core by heat conduction. Cosmological N-body simulations which incorporate a finite scattering cross-section σ for the SIDM particles show that this scheme successfully produces soft cores in halos (e.g. Davé et al. 2001; Yoshida et al. 2000b).

We study the formation and evolution of SIDM halos analytically with a proper treatment of cosmological infall (see also Ahn & Shapiro 2002). Previous analytical studies (Balberg, Shapiro & Inagaki 2002) and N-body simulations of *isolated* halos (Burkert 2000; Kochanek & White 2000) neglected

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cosmological infall which might delay the core collapse. We find that, for a realistic range of infall rates, the collapse of SIDM cores can be completely inhibited. Our results agree with N-body simulations for nonisolated halos, but also find that a range of higher scattering cross sections than previously simulated can also produce soft cores.

2. SELF-SIMILAR EVOLUTION OF SIDM HALOS

We use a fluid approximation derived from the Boltzmann equation to describe the dynamics of SIDM halos. A spherically symmetric, arbitrarily collisional system with isotropic random motions can be described by fluid equations for an ideal gas with $\gamma = 5/3$ (Bettwieser 1983).

For a collisionless system, collapse is "adiabatic" (i.e. no conduction), and if the initial overdensity has a scale-free power-law form,

$$\frac{\delta M}{M} \propto M^{-\varepsilon}, \tag{1}$$

where ε is a positive constant, the object which grows by adiabatic infall is self-similar (Fillmore & Goldreich 1984). Heat conduction generally breaks self-similarity by introducing an additional length (time) scale, but when $r_s \propto t^2$, or $\varepsilon = 1/6$, self-similarity is preserved even in the presence of heat conduction by SIDM particles with constant σ.

3. SELF-SIMILAR CDM HALOS ($\varepsilon = 1/6$; NO CONDUCTION)

The condition which is required to preserve self-similarity of the dynamics of SIDM halos deserves separate attention. We find that the adiabatic solution with $\varepsilon = 1/6$ is well fit, for example, by an NFW profile with concentration parameter $3 \leq c_{\rm NFW} \leq 4$. The inner density slope is -1.27, which is between -1 (NFW) and -1.5 (Moore profile) (see Fig. 1).

The theory of structure formation from density peaks in the Gaussian random noise distribution of initial density fluctuations gives an interesting clue to this correspondence. According to Hoffman & Shaham (1985), for a power-law power spectrum of initial fluctuations, $P(k) \propto k^n$, the initial density profile of density peaks can be approximated as $\frac{\delta\rho}{\rho} \propto r^{\kappa}$, where $\kappa = 3\varepsilon = n + 3$. The value $\varepsilon = 1/6$ corresponds to $\kappa = 1/2$, or $n = -2.5$: $n = -2.5$ roughly corresponds to galaxy-mass structures in ΛCDM.

4. SELF-SIMILAR SIDM HALOS ($\varepsilon = 1/6$; WITH CONDUCTION)

We find that different similarity solutions of SIDM halos arise for different values of the collisionality parameter, $Q \equiv \sigma\rho_b r_s$. High Q means high collision rate. We also find that there are two different regimes: the low-Q regime ($Q < Q_{th} = 7.35 \times 10^{-4}$) and the high-$Q$ regime ($Q > Q_{th}$).

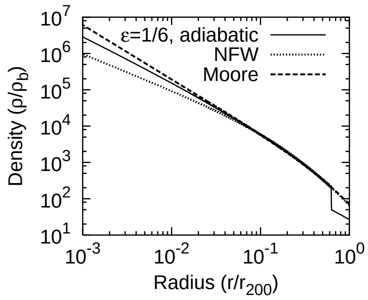

Fig. 1. Halo density profile for adiabatic solution with $\varepsilon = 1/6$ for standard CDM halos, compared to NFW and Moore profiles. The adiabatic solution, whose inner slope is -1.27, is a good fit to density profiles of CDM halos from N-body simulations.

In the low-Q regime, the collision mean free path in the core is larger than the size of the halo. In this regime, the flattening of the core density profile increases as Q increases (see Fig. 2).

In the high-Q regime, the mean free path in the core region is smaller than the size of the halo. The flattening of the core density profile decreases as Q increases, because the mean free path decreases (diffusion limit; see Fig. 2). The limiting case of $Q = \infty$ corresponds to the solution with no conduction, which agrees with N-body simulations with infinite cross-section (Yoshida et al. 2000a; Moore et al. 2000). In this case, the nonadiabatic solution approaches the adiabatic solution.

Our similarity solutions naturally explain how cosmological infall affects SIDM halos dynamically. New matter which falls into the halo from outside gets shock-heated (i.e. virialized) to such an extent that the temperature is always greater in the halo than in the core. Accordingly, in our similarity solutions, core collapse is completely prohibited. Therefore, core collapse will be inhibited in general until the infall rate becomes negligible at late times in the evolution of individual halos, as reported for N-body simulations by Wechsler et al. (2002).

5. THE ALLOWED RANGE OF SCATTERING CROSS-SECTION FOR AN SIDM UNIVERSE

We find that a relatively narrow range of Q values,

$$Q \simeq [0.62 - 3.6] \times 10^{-5} \left(\frac{h}{0.70}\right) \left(\frac{\sigma}{5.6 cm^2 g^{-1}}\right), \tag{2}$$

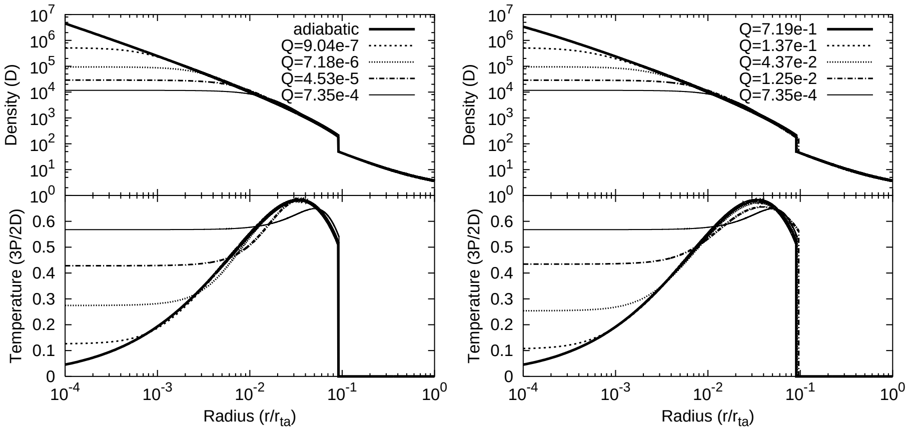

Fig. 2. Similarity solution dimensionless profiles for low-Q (left panels) and high-Q (right panels) regimes. Even though values of Q are very different, profiles of high-Q solutions are indistinguishable from those of low-Q solutions.

characterizes the entire range of halo masses from $10^6 h^{-1} M_\odot$ to $10^{13} h^{-1} M_\odot$, in the currently-favored ΛCDM universe (see Fig. 3).

The range $\sigma = [0.56 - 5.6]\, cm^2 g^{-1}$ is the preferred range of the scattering cross section found by cosmological N-body simulations for the ΛCDM universe to match observed galactic rotation curves (e.g. Davé et al. 2001). Equation (2) with $h = 0.7$ then yields $Q = [6.2 \times 10^{-7} - 3.6 \times 10^{-5}]$, which is in the low-$Q$ regime.

As shown in § 4, there also exist high-Q solutions which yield profiles which are quite similar to the low-Q solutions which produce observationally acceptable soft cores. We find that $Q = [1.37 \times 10^{-2} - 1.7 \times 10^{-1}]$ in the high-Q regime produces profiles similar to those in the low-Q regime for $Q = [6.2 \times 10^{-7} - 3.6 \times 10^{-5}]$. From the relationship between σ and Q (equation 2), we predict that $\sigma = [1.2 \times 10^4 - 2.7 \times 10^4]\, cm^2 g^{-1}$ can also produce acceptable soft cores, therefore. Cosmological N-body simulations which incorporate SIDM particles with $\sigma \simeq [5 \times 10^3 - 5 \times 10^4]\, cm^2 g^{-1}$ would, therefore, be of interest.

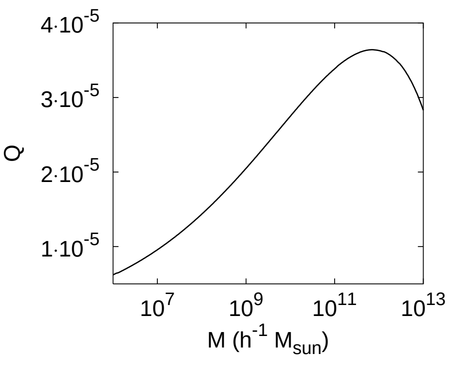

Fig. 3. The collisionality parameter Q vs. mass of halos at their typical formation epoch for $\sigma = 5.6 cm^2 g^{-1}$ and $h = 0.7$ in ΛCDM universe.

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