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DWARF SPHEROIDAL GALAXIES AND THE MASS OF THE NEUTRINO

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ABSTRACT

We argue that neutrinos cannot provide the missing mass in Draco and Ursa Minor, since for reasonable neutrino mass ($m_\nu \sim 30$ eV) phase-space limits would then require very large core radii (~ 10 kpc) and masses ($\sim 4 \times 10^{11}\ M_\odot$) for these dwarfs, which would make their dynamical friction decay times in the Galactic halo significantly shorter than a Hubble time. These limits are insensitive to assumptions about the anisotropy of the neutrino distribution.

Subject headings: dark matter — galaxies: local group

1. INTRODUCTION

Dwarf galaxies, because of their weak internal accelerations and shallow gravitational wells, are excellent laboratories for testing alternative theories of gravity and for constraining candidates for the Galactic dark matter. In this *Letter*, we argue that the presence of significant central densities of dark matter in Draco and Ursa Minor virtually rules out neutrinos as dark matter candidates for the halos of these dwarfs.

2. DARK MATTER IN DRACO AND URSA MINOR

Both Draco and Ursa Minor appear to contain large amounts of dark matter. In the absence of dark matter, the observed distribution of stars with core radius $r_c \sim 120$ pc would imply velocity dispersions of $\sigma \simeq 2$ km s^{-1} in Draco and $\sigma \simeq 1$ km s^{-1} in Ursa Minor. However, measurements of individual stellar velocities find $\sigma \simeq 10$ km s^{-1} in both cases (Aaronson 1983; Aaronson & Olszewski 1988). Aaronson & Olszewski (1988) argue that long-term monitoring of these dwarfs has reduced the possibility that contamination of the sample by binaries has spuriously raised these dispersions. The mass-to-light ratios seemingly implied for Draco and Ursa Minor by these data are $\xi \sim 20$–100, although the precise values depend on the assumed core radii of the dark material relative to those for the stars, and the possible anisotropy of the stellar orbits. (See Pryor 1991 for a review). For comparison, typical global mass-to-light ratios in globular clusters are 1.5–3 (Pryor et al. 1988).

If the spatial distribution of dark matter and luminous stars is similar, the central dark matter densities needed to explain the kinematic data are $\rho_D \sim 0.5$–$1\ M_\odot$ pc^3 (Kormendy 1987); much larger than in any bright galaxy with good rotation curve data. The effects of both a different spatial extent (core radius) for the dark (r_D) and luminous matter (r_C), and of an anisotropic velocity dispersion tensor for the stars were considered by Lake (1990) and Pryor & Kormendy (1990). These authors compared a set of two-component models to the published star count profiles and the observed velocity dispersions. A model-independent lower limit on the halo density can be obtained from the virial theorem (Merritt 1987); applying this result Pryor & Kormendy (1990) found lower limits of around $\rho_D \sim 0.07$–$0.15\ M_\odot$ pc^{-3} in Draco and Ursa Minor. These values will be somewhat reduced if the velocity distribution is strongly radial and the observed stars are mostly near the center.

It is easy to predict qualitatively the effect on the dark matter density introduced by a large halo core radius or by anisotropic stellar velocities. As long as the velocity distribution of the luminous matter is nearly isotropic, its observed core radius and velocity dispersion directly determine the central density via $(G\rho_0)^{-1/2} \sim 2r_c/(3^{1/2})\sigma_0$, or $\rho_0 \sim 1\ M_\odot$ pc^{-3}. Thus if the stars have the expected mass-to-light ratio of ~ 2, their contribution to the density is only $\simeq 3\%$, and the halo density must be high. There is no constraint on the halo core radius from the star count profile in this case, as one may invert an Abel equation to determine the energy distribution of the stars that produces the observed profile in an infinite constant density halo which dominates the potential. The constraints found by Pryor & Kormendy arise because of their specific choice of Michie-King models.

Anisotropy, however, can substantially modify the result. Consider an anisotropic distribution of test stars in a constant density halo core. If all stars were on *exactly* radial orbits, their space density profile would be singular. For a *nearly* radial orbit distribution the core radius of the test stars is set by the distribution of central impact parameters rather than by any scale referring to the potential itself. The velocity dispersion, of course, is still characteristic of the total mass distribution probed by the orbits. Thus in the anisotropic case, the core radius and velocity dispersion of the luminous matter do not immediately determine the central density, and one must resort to comparing dynamical models to the radial star count profile. Again, because of the enormous freedom of an arbitrary distribution function $f(E, L)$ for the stars, it is unlikely that any constraint on the halo core radius can be set, but Pryor & Kormendy (1990) in their extensive modeling found a lower limit to the halo densities in both Draco and Ursa Minor of $\simeq 0.05 - 0.1\ M_\odot$ pc^{-3}. This is consistent with the virial theorem result.

2. NEUTRINO MASS CONSTRAINTS

Can the dense halos in Draco and Ursa Minor be made of massive neutrinos? The present neutrino phase-space density is constrained by the collisionless Boltzmann equation to be less than or equal to the neutrino phase-space density at the time of neutrino decoupling (Tremaine & Gunn 1979). This places a lower limit to the mass of the neutrinos that can make up an isothermal spherical halo. When this argument was applied to the dwarf spheroidals by Faber & Lin (1983), the difficulty proved to be the unknown halo core radius. Formally, a halo with infinite core radius has zero phase-space density.

With the lower limit to the density now known to be 0.05–0.10 $M_\odot$ pc^{-3}, we are now in a better position to use the phase space argument for constraining the contribution of neutrinos to the observed dark matter in Draco and Ursa Minor. Using King's formula we can convert the conventional neutrino mass constraint for an isothermal sphere model to

$$m_\nu \gtrsim 170 \text{ eV}\left(\frac{1 \text{ kpc}}{r_D}\right)^{3/4}\left(\frac{0.1\ M_\odot \text{ pc}^{-3}}{\rho_D}\right)^{1/8} g_\nu^{-1/4}, \qquad (1)$$

where g_ν is the product of the number of neutrino spin states and number of neutrino species of this mass, and r_D and ρ_D are the core radius and core density of the dark matter halo, assumed in this case to consist of neutrinos. Notice that in this form the constraint is not very sensitive to the halo density. Requiring a cosmologically reasonable mass for the dominant neutrino, $m_\nu = 30$ eV, and using equation (1) and the inferred densities, we obtain halo core radii for Draco and Ursa Minor of $r_D = 10$ kpc, or *core* masses of $4 \times 10^{11}\ M_\odot$. The missing mass in Draco and Ursa Minor can be composed of neutrinos only if the neutrino halo core radius is 100 times larger than the stellar core radius and if the global mass-to-light ratios exceeds 2×10^6. Objects of such enormous masses would have spiraled into and merged with the Milky Way long ago. If the neutrinos in the halo are on radial orbits, then, as noted earlier, King's formula can overestimate the core mass for given r_D and velocities (Richstone & Tremaine 1984), or here: overestimate the phase-space density at fixed space density. This has only a small effect on the neutrino mass limit; see the discussion below.

We can turn the argument around and ask what limits can be set on m_ν by demanding that Draco and Ursa Minor have not undergone significant dynamical friction against the Galactic halo during the past Hubble time. Even if the Milky Way's halo goes out only to somewhat less than their galactocentric distance, we still expect significant friction due to resonance coupling; see Weinberg (1986). One objection to this argument might be that the two dwarfs could have just spiraled to their present distances from further out in the last 10^{10} yr. But to avoid assuming special initial conditions, one would have to assume that our galaxy once contained several other such massive satellites, which started at smaller radii and have spiraled into the inner Galaxy, where they would have heated the disk. Based on the small velocity dispersions of old disk stars, Toth & Ostriker (1992) find that the Galaxy can at most have accreted a few percent of its mass during the age of the disk—the accretion of just one 10^{10} solar mass object violates their limit.

The friction time for an object of mass M on a circular orbit in an isothermal halo with $v_c = 220$ km s^{-1} is

$$t_{\text{fric}} = \frac{1.0 \times 10^{10} \text{ yr}}{\ln \Lambda}\left(\frac{r}{60 \text{ kpc}}\right)^2\left(\frac{v_c}{220 \text{ km s}^{-1}}\right)\left(\frac{2 \times 10^{10}\ M_\odot}{M}\right). \qquad (2)$$

(Binney & Tremaine 1987); t_{fric} is essentially unchanged if the object moves on noncircular orbits or if the Galactic halo is slowly rotating. Using distances for Draco and Ursa Minor of $r = 75$ kpc and $r = 60$ kpc, respectively, and a value of $\ln \Lambda = 3$, the requirement that $t_{\text{fric}} \lesssim 10^{10}$ yr then leads to mass constraints of $M_{\text{Draco}} \lesssim 1 \times 10^{10}\ M_\odot$ and $M_{\text{UMi}} \lesssim 8 \times 10^9\ M_\odot$, and thus to neutrino mass constraints of $m_\nu \gtrsim 77$ eV and $m_\nu \gtrsim 81$ eV for a dark matter density of $\rho_D = 0.1\ M_\odot$ pc^3. The total masses obtained for the two dwarfs in this way are still very large; yet the neutrino mass limits derived from them are uncomfortable in view of both current measurements for the electron neutrino mass, and—given that we know the total number of neutrinos in the universe—the limits set by the age of the universe on the mass of any type of neutrino.

Ralston & Smith (1991) have argued that if the neutrinos move on extremely radial orbits, then the Tremaine & Gunn formula can significantly overestimate the present maximum phase-space density and therefore the neutrino mass limit. We can estimate the effect as follows. Suppose that the neutrino halo has a radial anisotropy profile $\beta(r) \equiv 1 - \sigma_\theta^2/\sigma_r^2$ defined in the standard way, and an apparent core radius, r_D, set by the anisotropic distribution of orbits as discussed above. The general solution of the spherical Jeans equation is

$$\rho\sigma_r^2(r) = e^{-p(r)}\int_r^{r_t} dr\, \rho \frac{d\Phi}{dr} e^{p(r)}, \qquad (3)$$

where r_t is the tidal radius and the function $p(r)$ in the integrating factor is $p(r) = \int dr\, 2\beta(r)/r$. If the halo density profile is $\rho_D \propto r^{-2}$ for $r > r_D$, we find from equation (3) that the radial velocity dispersion σ_r in the core of the maximally anisotropic model [with $\beta(r) = 1$ for $r > r_D$] exceeds the corresponding velocity dispersion in the isotropic ($\beta = 0$) model by a factor of $[2 \log (r_t/r_D)]^{1/2}$. Due to this higher velocity dispersion, the phase space density, $f \approx \rho/\langle v^2\rangle^{3/2}$ can be lowered by up to a factor $[2 \log (r_t/r_D)]^{-3/2}$, and thus

$$m_\nu \gtrsim 170 \text{ eV}\left(\frac{1 \text{ kpc}}{r_D}\right)^{3/4}\left(\frac{0.1\ M_\odot \text{ pc}^{-3}}{\rho_D}\right)^{1/8}\left(2 \log \frac{r_t}{r_D}\right)^{-3/8} g_\nu^{-1/4}. \qquad (4)$$

It is clear that for high-energy radial orbits to have a significant effect we need $r_t \gg r_d$. In this case the mass of the halo is essentially $M_h = 4\pi\rho_0 r_D^2 r_t$. Thus, in order to reduce the central phase-space density by a factor of 16 and the neutrino mass limit by a factor of 2 at fixed ρ_0 and r_D, we must make $r_t \geq 20r_d$ and add of order 20 times more mass at those radii than already present in the core region, with all of that mass moving on essentially radial orbits. Evidently this extra mass in the outer halo would significantly shorten the dynamical friction time scale of equation (2). To reconcile the central density inferred from observations with a 30 eV neutrino, equation (4) even predicts that a maximally anisotropic halo with $r_D = 1$ kpc should extend to further than the center of the Milky Way! Note that assuming a more steeply falling density profile than $\rho \propto r^{-2}$ reduces the effect of anisotropy on the velocity dispersion in the core, while a much shallower density profile is inconsistent with very radial orbits and so would bring us back to equation (1).

Thus radial anisotropy of the neutrino halo does not circumvent the combined constraints of equations (1) and (2), and to the extent that the velocity dispersion measurements in these two dwarf spheroidals are reliable, neutrinos are therefore unlikely to be the constituents of the halos of Draco & Ursa Minor.

3. CONCLUSION

We conclude that fermionic light particles face severe difficulties in accounting for the observed kinematic properties of the dwarf spheroidal galaxies around the Milky Way. The velocity dispersions observed in Draco and Ursa Minor would require neutrino halos of 4×10^{11} $M_{\odot}$ to be compatible with phase-space limits. Baryonic or cold dark matter may better explain the halos of Draco and Ursa Minor. Yet even then galaxy formation theories still have the challenge of explaining the origin of the large dark to luminous matter ratio in these dwarf galaxies (see Lake 1990 and Pryor 1991 for further discussion).

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