1995

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Repository Citation
"Constraints on the Dwarf Star Content of Dark Matter" (with J. Uson), Phys. Rev. Letters 74, 216 (1995).

Constraints on the Dwarf Star Content of Dark Matter

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(Received 23 August 1994)

Infrared observations of the halo of the Milky Way show that less than 3% of the dynamically inferred dark matter is due to $0.1M_{\odot}$ stars ($M8$ dwarfs). Observations of the diffuse light in the rich cluster of galaxies Abell 2029 lead to even stronger limits. Indeed, less than about 1% of the cluster dark matter is due to $0.1M_{\odot}$ stars. Recent observations of microlensing candidates suggest that the dark matter in the halo of the Milky Way might consist of red/brown dwarf stars with masses in the range $0.01M_{\odot}$ to $1.0M_{\odot}$. If so, the mass function of these objects must be sharply peaked just below $0.1M_{\odot}$, the mass marking the onset of hydrogen burning.

PACS numbers: 95.35.+d, 95.85.Jq, 97.20.Vs, 98.35.Gi

The nature of the dark matter which is inferred from the dynamics of galaxies and clusters of galaxies remains one of the most important unsolved problems of cosmology. The dark matter is not composed of any of the usual astrophysical species, i.e., neutral and ionized gas, dust, or ordinary stars; otherwise, it would have been observed [1]. A variety of weakly interacting, massive particles have been discussed but none of these hypothetical particles has ever been detected [2]. Massive, collapsed objects, such as white dwarfs, neutron stars, and black holes, have also been suggested. However, unless these objects formed under extremely unusual circumstances, the gas expelled prior to their collapse should have increased the metallicity of the interstellar medium and this is not observed [1] (metallicity is an indicator of the relative abundance of elements heavier than lithium). Primordial black holes (i.e., formed in the early Universe) have also been considered. These are hard to rule out. Perhaps the most conservative model for the dark matter is a population of low-mass red dwarfs [$(0.1-0.2)M_{\odot}$, where $M_{\odot}$ is the mass of the Sun, $\sim 2 \times 10^{33}$ g] and still lower mass "brown dwarfs." The former are very faint stars that emit most of their light in the infrared (IR) while the latter are too small to support hydrogen fusion and are, therefore, even fainter. This hypothetical population has been the primary target of recent IR searches for dark matter.

Strong constraints on the red dwarf content of dark matter have come from observations of diffuse infrared light in four dense (Abell) clusters of galaxies [3]. These studies indicate that less than $5h^{-1}\%$ (h is Hubble's constant divided by 100 km s^{-1} Mpc^{-1}, currently believed to be in the range $0.4 \leq h \leq 1.0$, 1 Mpc $= 10^6$ pc $= 3.09 \times 10^{22}$ m) of the dark matter in these clusters can be in the form of $0.1M_{\odot}$ stars.

The limits are weaker for individual galaxies because there is less dark matter in them. Indeed, observations of diffuse IR light in the halos of galaxies have resulted in upper limits on the red dwarf content of the halo dark matter which are 1 order of magnitude larger than in clusters (i.e., 20%–40%) [4,5]. Measurements of diffuse emission from the halo of our own Milky Way are hampered by large uncertainties in the IR background and have not yielded useful limits. However, due to the proximity of our own halo, the effects of individual halo stars are large as we discuss below.

Gravitational lensing is another effect by which a red/brown dwarf population might be detected. Paczyński [6] proposed that any population of massive compact halo objects (MACHOs), which include dwarf stars, neutron stars, and black holes, could be detected by gravitational lensing of background stars, i.e., "microlensing." Several microlensing candidates have now been observed [7–11] and are consistent with a $(0.01-1.0)M_{\odot}$ MACHO population which comprises from 10% to 100% of the dark matter required by the standard halo model. On the other hand, Sahu has raised the possibility that these events could be due to lensing by the standard stellar population in the bar of the Large Magellanic Cloud [12]. Even if these candidates turn out to be halo microlensing events, more observations and an accurate dark matter halo model will be needed in order to determine the mass distribution. However, the lack of short duration lensing events implies that no more than 30% of the dark matter is in the form of MACHOs with masses in the range $(10^{-7}-10^{-2})M_{\odot}$ [10].

Multiband photometry of the rich cluster of galaxies A2029 (this is number 2029 in Abell's catalog of rich clusters of galaxies [13]) reveals a component of diffuse intergalactic light which is an extension of the central, elliptical cD galaxy [14–15]. We observed the diffuse light in the B (440 nm), V (550 nm), R (660 nm), and H (1650 nm) photometric bands. The surface brightness is well fit by a deVaucouleurs profile out to a distance

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of $0.5h^{-1}$ Mpc [16]. If even a small fraction of the dynamically inferred dark matter in A2029 were in the form of red dwarf stars, then the color of the diffuse light would be redder than that of an ordinary stellar population. Furthermore, the diffuse light would exhibit a radial color gradient since the mass-to-light ratio increases with distance from the cluster center. The diffuse light has no such color gradient as shown in Fig. 1. Also shown in Fig. 1 are the color profiles expected if $1h^{-1}\%$ of the dark matter were in the form of $M8$ dwarfs. The dark matter distribution was computed for an isothermal King profile with a core radius of $0.2h^{-1}$ Mpc and a line-of-sight velocity dispersion of 1430 km s^{-1} [17]. Although estimates of the total cluster mass made in this way are sensitive to the detailed distribution of the matter, we have shown that projected mass densities from 0.5 to 3 core radii are far less dependent on the distribution of dark matter, in particular, on the core radius [3]. It is clear that the data are inconsistent with even a small component of the dark matter being in the form of red dwarf stars.

The V, R, and H magnitudes of a $0.1M_\odot$ dwarf were taken to be those of the star W359 [18] which is an $M8$ dwarf with roughly solar metallicity. However, one might expect that a dwarf component of the dark matter might be a very old population and, therefore, have a low metallicity. It has been pointed out by Burrows *et al.* [19] that low and zero metallicity dwarfs are hotter (bluer) and brighter than previously thought. In the H band, these two effects (temperature and luminosity) roughly

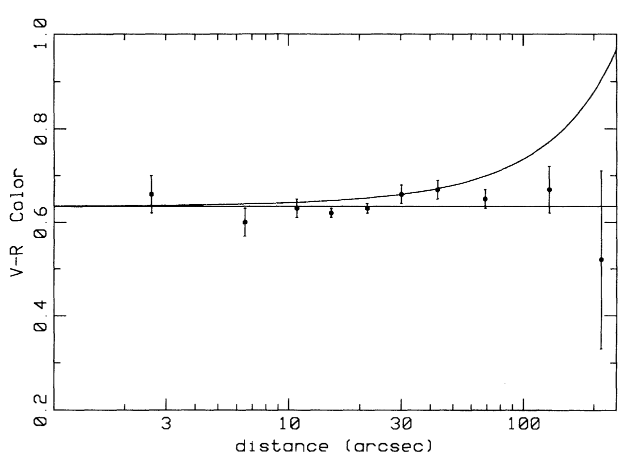

FIG. 1. (a) V-R color profile of the diffuse light in Abell 2029. $V\text{-}R \equiv 2.5 \log_{10}(I_R/I_V)$ (plus a constant arbitrarily defined such that the color of an A0 star is zero), where I is the surface brightness in the respective photometric band. The curve is the expected color profile if $1h^{-1}\%$ of the dark matter consists of $M8$ red dwarfs (see text). The data are better fit by the horizontal line which corresponds to a constant color. (b) R-H color profile of Abell 2029. Again, $R\text{-}H \equiv 2.5 \log_{10}(I_H/I_R)$ (again plus a constant such that $R\text{-}H = 0$ for an A0 star). The curve is expected if $1h^{-1}\%$ of the dark matter consists of $M8$ dwarfs.

cancel. On the other hand, in the R band, both effects tend to increase the R band luminosity of a zero metallicity, $0.1M_\odot$ star. An accurate estimate of this effect requires a detailed stellar atmospheric model. We obtained a rough approximation by using the total luminosity values computed by Burrows *et al.* [19] and taking the colors to be that of a (hotter) $M0$ dwarf. We conclude that the H band luminosity of a low metallicity star is similar to that of a solar metallicity dwarf while its R band luminosity is about 1 order of magnitude larger. Therefore, the constraints on the low metallicity red dwarf content of the dark matter are even stronger than those presented above.

While a direct measurement of the diffuse emission from the halo of the Milky Way is extremely difficult, observations of individual halo stars as well as of the spatial fluctuations due to these stars are much easier. Both the deep B, V, I (780 nm), and K (2200 nm) survey of Cowie *et al.* [20] and the K band primeval galaxy search of Boughn, Saulson, and Uson [21] can be used to set strong limits on the red dwarf content of the dark matter in the Milky Way.

Consider the distribution of dark matter in a canonical halo model:

$$\rho(r) = \rho_0 \frac{(r_0^2 + r_c^2)}{(r^2 + r_c^2)}, \tag{1}$$

where $\rho(r)$ is the mass density, $\rho_0 = 1.0 \times 10^{-2} M_\odot$ pc^{-3}, $r_0 = 8.5$ kpc (the distance to the galactic center), and $r_c = 4$ kpc (the dark matter core radius). This model corresponds to a dark matter gravitational field with an asymptotic rotational velocity of 220 km s^{-1}. If a fraction f of the dark matter is in the form of $0.1M_\odot$ red dwarfs, then the number density of these stars is simply

$$n(r) = f\rho(r)/0.1M_\odot . \tag{2}$$

Again we take as a canonical $M8$ dwarf the star W359 which has an absolute K band magnitude of $M_K = 9.1$ [18]. It is straightforward to compute the expected surface density of such objects as a function of limiting magnitude in any direction.

In their survey, Cowie *et al.* [20] found six stars brighter than apparent magnitude $m_K = 21.4$ in a 1.6 arcmin^2 field. The I-K colors of these stars correspond to those of one K dwarf, one early-M dwarf, three mid-M dwarfs, and one late-M dwarf, possibly an $M8$. These are consistent with the known stellar halo population, i.e., there is no evidence that they are members of a new, dark matter population. An upper limit to the red dwarf content of the dark matter can be derived by computing the probability [from Eq. (2)] that six or more stars would be observed at an apparent magnitude of $m_K = 21.4$ or brighter. Our Monte Carlo simulations of a galactic halo with a number density given by Eq. (2) indicate that at the 90% confidence level no more than 3% of the canonical halo can be in the form of $0.1M_\odot$ red dwarfs.

Since this limit depends on the parameters of the halo model, we have performed Monte Carlo simulations using several other models. The models of van der Kruit [22] and Gilmore *et al.* [23] assume a flat rotational velocity of 220 to 230 $\mathrm{km\,s^{-1}}$ out to 15 kpc and a somewhat smaller asymptotic rotational velocity of 200 $\mathrm{km\,s^{-1}}$. They differ in the mass they attribute to the disk and bulge of the Milky Way. The red dwarf limits derived from these two distributions are only slightly larger than our canonical model (about 3.5%).

A more conservative limit can be derived by considering the "maximum disk" model of Sellwood and Sanders [24]. They attempted to account for as much of the Galactic gravitational field as possible (inside the Sun's orbit) with the galactic bulge and disk, i.e., they minimized the dark matter in the halo. This model pushes all the constraints to the limit. In particular, the local bulge density is more than twice the observational constraint [25]. If one assumes that the rotational velocity at 12 kpc is 220 $\mathrm{km\,s^{-1}}$ and the same value for the asymptotic rotational velocity, then the model implies $\rho_0 = 0.0055 M_\odot\ \mathrm{pc}^{-3}$ and $r_c = 10$ kpc. In this case, Monte Carlo simulations give a 90% confidence level upper limit of 6% on the $0.1 M_\odot$ dwarf content of the halo dark matter. If the asymptotic rotational velocity is lowered to 200 $\mathrm{km\,s^{-1}}$, the core radius must be decreased to 8 kpc and the limit is unchanged.

An independent, although less stringent, constraint on the red dwarf content of the dark matter in the Milky Way comes from the limit on spatial fluctuations in the IR background. In the primeval galaxy search of Boughn, Saulson, and Uson [21], eighty-eight 11 in. diameter regions and sixty-nine 65 in. diameter regions were observed in the K band. No spatial fluctuations were detected in excess of the system noise, which was equivalent to $m_K = 20.2$ ($2.2 \times 10^{-29}\ \mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$) for the smaller regions and $m_K = 16.5$ ($8.3 \times 10^{-28}\ \mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$) for the larger regions. In order to reduce systematic noise, adjacent regions were subtracted, which resulted in 56 independent measurements of spatial fluctuations. The reduced χ^2_{56} ($=0.90$) is entirely consistent with 56 deg of freedom, i.e., there is no evidence for spatial fluctuations.

These results can be used to set an upper limit on the red dwarf content of the dark matter in the manner described above. Monte Carlo simulations of the canonical halo model plus instrumental noise were effected, and the resulting χ^2 was compared to that observed. 90% confidence levels were derived by requiring that in only 10% of the Monte Carlo trials did χ^2 exceed that observed. We conclude that the data exclude, at the 90% confidence level, models in which 8% or more of the dark matter is in the form of $0.1 M_\odot$ stars. This limit is nearly 3 times larger than the limit we obtained from the Cowie *et al.* observations; however, as the area surveyed was 66 sq arcmin, this limit is more robust if the hypothetical $M8$ dwarf population is clustered.

It is clear from the above limits that if the dark matter in the halo of the Milky Way is composed primarily of a population of red/brown dwarfs, then the mass (distribution) function of these objects must cut off sharply above $0.1 M_\odot$. On the other hand, if the microlensing events have been correctly interpreted the masses of individual lensing objects can be estimated from the amplitude and duration of the lensing events provided that the motion of the lensing and lensed objects are known [6]. Thus, mass determination is at best a statistical computation and, even then, a good model of the halo is required. Nevertheless, if one assumes the standard halo model, then the most probable masses of the six observed lensing candidates fall in the range of $(0.02-0.3) M_\odot$. If the dark matter halo has significant rotation, then these values could be decreased by as much as a factor of 2.

The interpretation of the microlensing candidates as a red/brown dwarf population comprising the bulk of the halo dark matter is presently consistent with the constraints on objects with masses greater than $0.1 M_\odot$. Figure 2 shows a hypothetical dark matter mass function which might describe a red/brown dwarf halo population and which satisfies the constraints described above. It has relatively sharp cutoffs outside the range $0.01-0.1 M_\odot$, i.e., 3% of the mass falls above $0.1 M_\odot$ and 3% of the mass falls below $0.01 M_\odot$. For simplicity we chose a Gaussian form for $dM/d[\ln(m)]$ which represents the mass per octave and a normalization so that the area under the curve, i.e., the total mass, is unity. For comparison, the mass function of stars in the solar neighborhood is

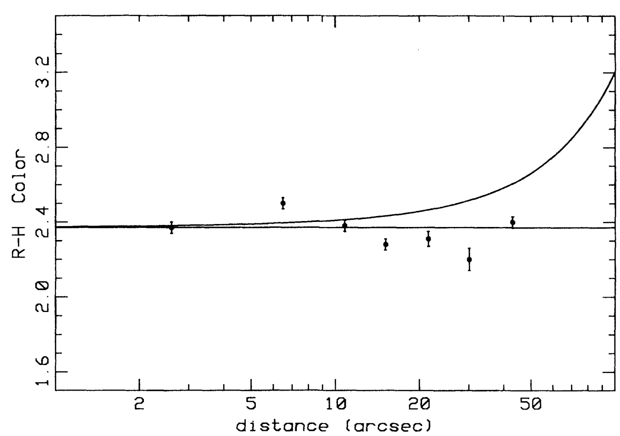

FIG. 2. Mass functions: The thick curve is a hypothetical mass function for MACHOs expressed as mass per octave, i.e., $dM/d[\ln(m)]$, where $M(m)$ is the mass contained in objects with mass less than m. The normalization is chosen so that the total mass is unity. The thin curve is the mass function of stars in the solar neighborhood with the same normalization.

included in Fig. 2. This is the Salpeter mass function [26] above $0.5M_{\odot}$ and the distribution found by Tinney [27] below $0.5M_{\odot}$. Below $0.1M_{\odot}$, the distribution is unknown; however, limitations on the mass of the galactic disk imply that most of the mass is in stars with masses above $0.1M_{\odot}$.

As microlensing observations continue to accumulate, the inferred mass function should show the same cutoff above $0.1M_{\odot}$. This constraint would not hold if the microlensing events were due in part to collapsed objects; however, the lack of enrichment of the interstellar medium from the formation of such objects makes this alternative unlikely.

We thank Garrett Schneider for his collaboration with the H band observations of Abell 2029. We also thank Adam Burrows, Jeff Kuhn, and Bohdan Paczyński for stimulating discussions. We also thank Ed Groth and Dave Wilkinson for their hospitality and support at the Gravity Group of the Physics Department of Princeton University where part of this work was done. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

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