

A New Component of the Galaxy as the Origin of the LMC Microlensing Events

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Abstract. We suggest a new component of the Milky Way that can account for both the optical depth and the event durations implied by microlensing searches targeting the Large Magellanic Cloud. This component, which represents less than 4% of the total dark matter halo mass, consists of mainly old white dwarf stars in a distribution that extends beyond the thin and thick disks, but lies well within the dark matter halo. It is consistent with recent evidence for a significant population of faint white dwarfs detected in a proper motion study of the Hubble Deep Field that cannot be accounted for by stars in the disk or spheroid. Further, it evades all of the current observational constraints that restrict a halo population of white dwarfs.

1. Introduction

The past few years have yielded exciting new data from observational teams searching for evidence of MACHOs (dark compact objects) in the halo of our galaxy, data which have raised many new questions. The microlensing optical depth toward the Large Magellanic Cloud (LMC) obtained by the MACHO collaboration, $\tau_{\text{LMC}} = (1.2^{+0.4}_{-0.3}) \times 10^{-7}$ (Cook et al. 2000), is consistent with a significant fraction of the galactic halo ($\sim 20\%$) in the form of MACHOs. The duration of these events also indicates that, under the assumption of a spherical isothermal halo distribution for the MACHOs, the average MACHO mass is $\sim 0.5M_{\odot}$ (with large statistical uncertainties).

Such masses suggest several candidates for the lenses including faint halo stars, white dwarfs, and black holes. Direct searches for faint halo stars have placed severe limits on their contribution to halo, requiring it to be less than about 3% (Flynn, Gould, & Bahcall 1996; Graff & Freese 1996). Primordial black hole candidates require a fine tuning of the initial density perturbations, and details of QCD phase transition black hole formation remain to be worked out in order to assess their viability and mass function (Jedamzik & Niemeyer

1999). Thus in the standard halo model interpretation, white dwarfs appear to be the remaining strong candidate for the lenses.

However, other possible interpretations of the MACHO results have been proposed in order to avoid the difficulties associated with a large halo population of white dwarfs. The mass estimate for the lenses depends upon the assumed phase space distribution of MACHOs. There are large uncertainties in the halo model parameters, including the distribution and velocity structure of the dark matter, and attempts have been made to exploit these uncertainties in order to obtain mass estimates from the current data that are consistent with lenses in the substellar regime (e.g. brown dwarfs). Previous work by the authors and others have examined a wide range of halo models, including flattened halos, halos with a bulk rotational component to the velocity structure (Gyuk & Gates 1998) and halos with anisotropic velocity dispersions (Gyuk, Evans, & Gates 1998). These analyses have shown that for any reasonable (smoothly varying) phase space distribution of the lenses, the implied lens mass is still much larger than the hydrogen burning limit, and thus one cannot appeal to modeling uncertainties in order to invoke brown dwarfs as candidates for the MACHOs.

Other work has explored the possibility that the lenses are not in the halo of the Milky Way. LMC self-lensing was originally suggested by Sahu (1994), but recent work by Gyuk, Dalal & Griest (1999) has argued that this is unlikely to be able to account for the current data. More recently, an unvirialized component of the LMC has been proposed in order to produce sufficient LMC self-lensing (Graff 2000). Zaritsky & Lin (1997) and Zhao (1998) have suggested an intervening population of stars toward the LMC (tidal debris or a dwarf galaxy) could be responsible for the microlensing events. Again this suggestion has been subject to much debate, and a recent paper by Gould (1999) argues strongly against such a scenario. Galactic models in which dark extensions of known populations, such as a heavy spheroid or thick disk, could be the source of the lenses were explored by Gates, Gyuk, Holder & Turner (1998).

However, recent results from a proper motion study of the Hubble Deep Field (HDF) (Ibata et al. 1999), and from a comparison of the north and south HDF images (Mendez & Minniti 1999) have added a new piece to the puzzle. These studies provide further evidence that there may be a previously undetected population of old white dwarfs in the galaxy. Using new models for white dwarf cooling (Hansen 1999), the sources detected by Ibata et al. are consistent with 2-5 old ($> 12Gyr$), $0.5M_{\odot}$ white dwarfs with kinematics roughly consistent with that expected for halo objects. While earlier searches for the local counterparts did not find any such objects (Flynn et al. 2000), recent surveys have turned up several candidates (Hodgkin et al. 2000; Ibata et al. 2000). Overall, these data strengthen the interpretation of the MACHO lenses as white dwarfs in our own galaxy, and thus make alternative scenarios, such as LMC self-lensing, less appealing.

While these new data are still somewhat preliminary, they do raise the intriguing possibility that there is a previously undetected population of white dwarf stars that are not part of the disk or (known) spheroid. Along with the MACHO data and the inability of modeling to significantly change the mass estimates, these new results, seem to be relentlessly pointing to white dwarfs as the lenses. So, is the halo of our galaxy filled with white dwarfs? A standard

halo interpretation of these data would say yes – a significant fraction of the galactic halo must be in white dwarfs. However, such a scenario faces serious challenges from many directions.

2. White Dwarfs in the Halo?

When considering the possibility that a large fraction (or all) of the galactic halo might be in the form of white dwarfs, it is extremely important to recall the evidence for galactic dark matter, including estimates of the total mass of the Milky Way. A recent analysis of satellite radial and proper motions by Wilkinson and Evans (1999) found a total mass of the Galaxy $M_{TOT} \sim 2 \times 10^{12} M_{\odot}$, in good agreement with other recent estimates (Kochanek 1996; Zaritsky 1998). Wilkinson and Evans also find that the halo extends to at least 100kpc, and possibly much further to 150 or 200 kpc. Thus the total mass in a white dwarf population that comprises a significant fraction of the halo would be of order $10^{12} M_{\odot}$, a number which already severely strains the baryon budget of the Universe.

Models which propose such a population must also account for the mass in the progenitor population of stars and in the metal enriched gas produced during the formation of the white dwarfs. Combined with the above mass estimate for the galactic halo, such considerations provide serious challenges for these models. For example, consider a white dwarf halo which is comprised of at least 50% white dwarfs. The total mass in white dwarfs today is thus of order 10^{12} . The efficiency $\epsilon(m)$ for producing a white dwarf from a progenitor star of mass m is likely to be 0.25 or smaller, depending on the progenitor mass (with an upper limit of $\epsilon = 0.5$ for progenitor stars of $1 M_{\odot}$) (Adams & Laughlin 1996). Thus, for a white dwarf halo mass of M_{wd} , we expect a mass in the progenitor population $M_{Pstars} \geq 4M_{wd}$ and a mass in processed, metal rich gas $M_{zgas} \geq 3M_{wd}$. A halo of mass $M_{TOT} = 2 \times 10^{12}$, half of which is in white dwarfs, requires a progenitor mass of $M_{Pstars} \geq 4 \times 10^{12}$. This in turn requires an extremely efficient early burst of star formation, through which essentially all of the baryons in the Universe are processed.

From a cosmological point of view, we can consider the contribution of the white dwarfs and the progenitor population to the matter density of the Universe. The Milky Way has a mass to light ratio $M/L \sim 100$ or greater (Zaritsky 1998). If we assume that this is a typical value for all galaxies, then galaxies contribute $\Omega_g \gtrsim 100/1200h = 0.08h^{-1}$. Comparing this with $\Omega_b h^2 = 0.019 \pm 0.0024$ (95%cl, Burles et al. 1999), we find that a 50% white dwarf halo exceeds the baryon budget ($\frac{\Omega_{MACHOs}}{\Omega_b} \sim 2h$) even before considering the effects of processing most of the baryons through an early star phase. A 20% white dwarf halo is also difficult to reconcile with the above estimate of Ω_b , since the contributions of the progenitor stars will exceed Ω_b .

Many authors have explored the implications of a halo filled with white dwarfs. These analyses, combined with the estimates of the total mass in the halo, make the possibility of a white dwarf halo even less tenable.

First, the initial mass function (IMF) of the progenitor stars must be markedly different than the disk IMF. Limits on the IMF arise from both low and high mass stars. Low mass stars ($< 1 M_{\odot}$) would still be burning hydrogen

today and should be visible. High mass stars ($> 8M_{\odot}$) would have evolved into Type II supernovae, ejecting heavy metals back into the interstellar medium ¹. From limits on red dwarfs in the halo and the galactic metallicity, Adams & Laughlin (1996) and Chabrier et al (1996) find that the IMF must be sharply peaked about a progenitor star mass of $m \sim 2M_{\odot}$. Adams & Laughlin conclude that even with the above IMF, the white dwarf contribution to the halo is limited to less than 25% (with 50% being an extreme upper limit).

Next, the metal enriched gas produced when these stars become white dwarfs will pollute the remaining unprocessed gas, leading to high metallicities predicted for the Galactic disk and the interstellar medium (into which much of this gas must be blown out since the total mass in processed gas is much larger than the mass of the disk)(Fields, Matthews, & Schramm 1997). Gibson & Mould (1997) have estimated that the expected amount of C, N and O produced by the above IMFs, where the white dwarf mass is about $4 \times 10^{11}M_{\odot}$ (for a 20% MACHO halo), would be difficult to reconcile with that in pop II white dwarfs.

White dwarfs in the halo would also produce heavy metals via Type Ia supernovae. Canal, Isern and Ruiz-Lapuente (1997) use this to limit the halo fraction in white dwarfs to less than 5 – 10% (or a total mass in white dwarfs of $5 - 10 \times 10^{10}M_{\odot}$). In addition, deep galaxy counts limit the fraction of the halo in white dwarfs to less than about 10%, since the brightly burning progenitor stars would be visible (Charlot & Silk 1995). Finally, it is worth mentioning that an all white dwarf halo would rule out the existence of other dark matter in the Universe (for example cold dark matter) (Gates & Turner 1994), opening the door to a host of problems with large scale structure formation.

3. A New Component of the Galaxy

Given the evidence for a previously undetected population of white dwarfs and the severe constraints on a halo population consistent with this evidence we propose a new component of the Galaxy. Such a component was first considered by the authors (Gyuk & Gates 1999) in the context of attempting to lower the mass estimates for the MACHO lenses, and in Gates et al. (1998) in considering dark extensions to known components.

This new component is essentially a very thick (scale height > 2 kpc) population of (mostly) old white dwarf stars. It is distinct from known galactic populations, both in distribution and age. This “extended protodisk” extends beyond the thin and thick disk populations, but lies well within the halo. While the details of the distribution cannot be determined without significantly more data, the general features of this proposed model can be illustrated with the following example:

Consider an exponential disk with a volume density given by

¹However, Venkatesan, Olinto & Truran 1999 have argued that the bounds on high mass stars are significantly relaxed for progenitor stars with very low ($10^{-4}Z_{\odot}$) or zero metallicity, which might relax this constraint somewhat.

$$\rho(r, z) = \frac{\Sigma_0}{2h_z} \exp((r_0 - r)/r_d) \operatorname{sech}^2(z/h_z) \quad (1)$$

where $r_d = 4.0\text{kpc}$ is the scale length and $h_z = 2.5\text{kpc}$ is the scale height. We assume standard values for the position and circular velocity of the Sun, $r_0 = 8.0\text{kpc}$ and $v_c = 220\text{km/s}$.

We also assume a velocity structure, which includes a rotational component $\tilde{v}_\phi \sim 130 - 170\text{km/s}$, of the form

$$f = \frac{\rho(r, \phi, z)}{m} \frac{1}{\sqrt{(2\pi)^3 \sigma_r \sigma_\phi \sigma_z}} e^{-\left[\frac{v_r^2}{2\sigma_r^2} + \frac{(v_\phi - \tilde{v}_\phi)^2}{2\sigma_\phi^2} + \frac{v_z^2}{2\sigma_z^2} \right]} \quad (2)$$

where the velocity ellipsoid varies as

$$\sigma_z^2 = 2\pi G \rho_0 h_z^2 = \pi G \Sigma_0 h_z. \quad (3)$$

$$\begin{aligned} \sigma_r^2 &\approx 2\sigma_z^2 \\ \sigma_\phi^2 &\approx \sigma_z^2. \end{aligned}$$

For details on varying these model parameters as well as different parameterizations of the generic extended protodisk model see Gyuk & Gates (1998, 1999).

We can also consider a spheroid-like distribution for this component. Dynamical estimates for the mass of the spheroid are considerably larger than the luminous mass, although recent studies of the mass function of the spheroid indicate that the known spheroid population is unlikely to be able to account for the microlensing events (Gould, Flynn, & Bahcall 1998). Thus a spheroidal distribution would again correspond to a previously undetected component. For such a distribution the total mass is constrained in order not to conflict with the inner rotation curve of the galaxy, which limits LMC optical depths $\tau \lesssim 1.2 \times 10^{-7}$.

The extended protodisk supports approximately half of the local rotation speed, with the remainder coming from the thin disk and dark (non-MACHO) halo (see e.g. Figure 1). The dark halo in these models has a large core radius ($> 7\text{kpc}$) and an asymptotic rotation speed of $\approx 180\text{kpc}$. The total mass in the Galaxy out to 50 kpc is $\approx 4.6 \times 10^{11} M_\odot$. For a total mass in the white dwarf extended protodisk of $M_{wd} = 7 \times 10^{10} M_\odot$, we find:

- The optical depth toward the LMC generated by this component is $\tau \sim 1 - 1.5 \times 10^{-7}$;
- The lens mass estimates for the current MACHO event durations is $m \sim 0.5 M_\odot$, consistent with white dwarf masses;
- We expect to see roughly twice as many white dwarfs in the HDF-South compared to HDF-North, similar to the halo models;
- Simulations of the proper motions for white dwarfs in this model are broadly consistent with the observations of Ibata et al. (1999).

The main feature of this model, however, is that it has a much lower total mass in white dwarfs than halo models. As outlined above, it is consistent with both the MACHO data and the HDF studies for a total mass in white dwarfs of $M_{wd} \lesssim 7 \times 10^{10} M_{\odot}$. This is approximately half of the mass that would be required for a halo distribution of MACHOs which would produce the same optical depth. Basically, this reduction can be understood because most microlensing is due to lenses within about 20 kpc of the Sun for either configuration. The extended protodisk has less mass beyond that distance than a halo.

The smaller mass in white dwarfs today also implies a smaller total mass in the progenitor population. For our above example the progenitor mass $M_{Pstars} \sim 3 \times 10^{11} M_{\odot}$, a crucial factor of 5 less than that for a 20% white dwarf halo, assuming the same IMF in both cases.

There are several predictions of this model that can eventually allow it to be distinguished from a standard halo white dwarf population. First, the LMC optical depth cannot be much greater than about 1.5×10^{-7} . Second, because the lenses are concentrated closer to the plane of the galaxy, the typical lens-observer distance will be smaller (of order 5 kpc). This in turn implies an increase in the expected number of parallax events (Gyuk & Gates 1999). Finally, the ratio of optical depths toward the Small and Large Magellanic Clouds is expected to be of order $\tau_{SMC}/\tau_{LMC} \sim 0.8$, in contrast with $\tau_{SMC}/\tau_{LMC} \sim 1.5$ (Sackett & Gould 1993) predicted for a standard halo.

The distribution of event durations and a detailed comparison of the distribution (in direction and magnitude) of the observed proper motions will also differ for a halo vs. extended protodisk white dwarf population, but these seem unlikely to be able to differentiate between models without significantly more data.

4. Model Implications

Because the total mass in the white dwarf population today is significantly lower in this model, some of the constraints on a halo white dwarf population can be evaded, including those which consider the progenitor population and the ejected metal enriched gas. The total mass in this new component represents less than about 4% of a total halo mass of 2×10^{12} . Since essentially all of the current constraints on white dwarf halos which limit the halo mass fraction in white dwarfs do so at only the 10% level, these constraints can be satisfied by our model. This includes the Type Ia supernovae constraints which are dependent on the mass in white dwarfs today, and cannot be evaded by scenarios which involve somehow hiding the metal enriched gas produced by the progenitor stars.

However, there remains much work to be done to more carefully consider the implications of this new component. First, we still require an IMF which differs significantly from the disk IMF. Assuming a log-normal distribution, Adams & Laughlin (1996) and Chabrier et al. (1996) used conservative constraints to limit the mass fraction of the high and low mass end of the progenitor IMF for a halo white dwarf population. While the lower total mass in our progenitor population will relax the constraints (which are based on the metallicity of the Galactic disk) somewhat at the high mass end, the mass fraction of low mass ($m < 1 M_{\odot}$) stars

is constrained by number counts of faint low mass stars locally. The extended protodisk has an increased local density relative to a halo distribution, but a lower total mass, resulting in a constraint similar to that for a halo. Thus we expect to require a fairly sharp low mass drop-off in the progenitor IMF. The implications of such an IMF, including the lower fraction of primordial baryons which is processed through this early population, need to be examined in greater depth.

This new component also provides some intriguing hints for cosmology. When did this component form and how is it related to galaxy formation scenarios? Can this early starburst population help us to trace the baryons in the Universe from their primordial state to the present, where we find most of the baryons in the intracluster medium?

5. Conclusions

We have argued that the microlensing data toward the LMC, combined with observations of white dwarf stars in a proper motion study of the HDF indicate the presence of a new component of the galaxy. This component can be generally described as an extended distribution that extends at least 2 kpc above the galactic plane, but resides well within the dark matter halo. It is consistent with all data and observations of the structure and kinematics of the galaxy, and significantly alleviates the considerable problems with a halo population of white dwarf stars that is consistent with microlensing data. Much work remains to carefully consider the implications of such a component, in particular the formation and evolution of the early population of progenitor stars (and resulting metal enriched gas) that produced this component. However, the significantly lower mass in the progenitor population as compared to that for a halo population of white dwarfs will allow a reasonable fraction of the baryonic mass of the Universe to remain in gas that has not been processed through these very early stars. Moreover, this component may be a more reasonable distribution for the remains of an early starburst population, in which one would expect a more condensed distribution than that of the halo.

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