

White Dwarfs and Dark Matter

Based on the identification of 38 white dwarfs with halo kinematics, in a survey covering 10% of the sky near the south galactic pole, Oppenheimer *et al.* (1) argued that at least 2% of the dark matter in the Milky Way galaxy has now been detected directly. Put into context, the Oppenheimer *et al.* result implies that the stellar remnant mass of the halo may be comparable to that of the entire disk of the galaxy. If true, that finding has crucial consequences for understanding the formation and evolution of the Milky Way. Careful examination of the results of Oppenheimer *et al.*, however, leads us to conclude that they have overestimated that the density of white dwarfs with halo kinematics.

Oppenheimer *et al.* (1) derived their local white dwarf density n via the $1/V_{\max}$ technique (2). The equation that applies for a survey covering 10% of the sky is

$$n = \sum_{i=1}^{38} V_{i,\max}^{-1} \approx 2.4 d_{i,\max}^{-3} \text{ pc}^{-3} \quad (1)$$

where V_{\max} represents the maximum volume in which the survey could have found each of the 38 white dwarfs listed in the study [table 1 in (1)] and d_{\max} is the distance in parsecs that determines V_{\max} . Oppenheimer *et al.* considered two relations for d_{\max} , one depending upon the limiting magnitude of the survey, $R59F_{\text{lim}}$, and the luminosities, $M_{i,R59F}$, of each of the 38 white dwarfs, and one depending upon the inferred distance d and observed proper motion μ .

Using equation 1 and the 38 white dwarfs in their sample, Oppenheimer *et al.* derived a white dwarf number density $n = 1.8 \times 10^{-4} \text{ pc}^{-3}$. We rederived n , employing equation 1, the data tabulated in table 1 of (1), and the identical $d_{i,\max}$ criteria used in their analysis, and found $n = 1.54 \times 10^{-4} \text{ pc}^{-3}$. Moreover, Oppenheimer *et al.* assumed a typical white dwarf mass of $0.6 M_{\odot}$, which, in combination with their derived number density, resulted in a local mass density of $1.1 \times 10^{-4} M_{\odot} \text{ pc}^{-3}$. By contrast, in metal-poor systems such as globular clusters—which would be expected to mimic to some degree the patterns in the galactic halo proper—the typical white dwarf mass is $0.51 \pm 0.03 M_{\odot}$ (3). That average mass, combined with our recalculated number density, results in a local white dwarf mass density of $0.79 \times 10^{-4} M_{\odot} \text{ pc}^{-3}$, 30% below that found by Oppenheimer *et al.* Even that revised density should be viewed with caution, because 32% of the density inferred from our reanalysis is being driven by only 8% of the sample—that is, three white dwarf candidates (LP651–74, WD0351–564, and WD0100–567) contribute 19%, 7%, and 6%,

respectively, to the total.

Oppenheimer *et al.* derived a mean V/V_{\max} of 0.46, assuming a limiting apparent magnitude of $R59F_{\text{lim}} = 19.80$, and suggested that a more appropriate $R59F_{\text{lim}}$ was 19.70, which yields a mean $V/V_{\max} = 0.50$ (the expected value for a uniform distribution). Using $R59F_{\text{lim}} = 19.70$ and an average halo white dwarf mass of $0.6 M_{\odot}$, they arrived at their quoted result of $1.3 \times 10^{-4} M_{\odot} \text{ pc}^{-3}$. Our analysis, by contrast, leads to a mean V/V_{\max} of 0.44. At face value, that result would imply that $R59F_{\text{lim}}$ should be adjusted to 19.55 to recover a mean $V/V_{\max} = 0.50$. Such an adjustment, however, has little effect, increasing the inferred local white dwarf mass density from $0.79 \times 10^{-4} M_{\odot} \text{ pc}^{-3}$ to $0.88 \times 10^{-4} M_{\odot} \text{ pc}^{-3}$.

Indeed, it should be stressed though that in both of the above cases, although the mean V/V_{\max} was below 0.50 for $R59F_{\text{lim}} = 19.80$, the median V/V_{\max} was exactly 0.50—that is, there is likely little reason to modify $R59F_{\text{lim}}$ from 19.80 to either 19.70 or 19.55. More important, perhaps, the increase in the mean $R59F_{\text{lim}}$ comes about by increasing the mean V/V_{\max} for several of the white dwarfs to values greater than one, a physical impossibility. The problem lies in the nonnormal distribution of V/V_{\max} for the sample, in which 13 of the 38 white dwarfs have $V/V_{\max} < 0.2$. Modifying $R59F_{\text{lim}}$ has little impact on those 13 white dwarfs, but increases V/V_{\max} for the white dwarfs whose ratios are larger. We conclude that modifying $R59F_{\text{lim}}$ from 19.80 to 19.55 or 19.70 is misleading and leads to unphysical values for V/V_{\max} , and thus we favor our result of $0.79 \times 10^{-4} M_{\odot} \text{ pc}^{-3}$ for the local white dwarf mass density, 40% below the $1.3 \times 10^{-4} M_{\odot} \text{ pc}^{-3}$ value found by Oppenheimer *et al.* (1).

Instead of a factor-of-ten excess relative to the mass density expected from a standard initial mass function (4), our revision puts the excess at a still significant factor of six. Oppenheimer *et al.* quoted a white dwarf halo mass fraction of 2% (rounded up from 1.6%), whereas our results imply a fraction of 1.0%. Both of these fractions, however, assume a local dynamical halo mass density of $8.0 \times 10^{-3} M_{\odot} \text{ pc}^{-3}$, based on the Oppenheimer *et al.* reading of the work of Gates *et al.* (5). Our reading of Gates *et al.*, by contrast, suggests that this local density should actually be $14 (\pm 5) \times 10^{-3} M_{\odot} \text{ pc}^{-3}$, a normalization that effectively reduces the local white dwarf halo mass fraction in our revised calculation from 1.0 to 0.6% (and that would change the Oppenheimer *et al.* result from 1.6 to 1.0%).

Finally, the local density of halo white

dwarfs claimed by Oppenheimer *et al.* does not seem consistent with the combined results of deep proper motions surveys taken to date (6). To find dark halo objects, these surveys use the so-called reduced proper motion, because this very clearly separates them from objects of the disk and stellar halo. The absolutely faintest white dwarf in the Oppenheimer *et al.* sample is at $M_{R59F} = 15.9$ (WD0351–564). If we conservatively allow 2% of the dark halo to be in the form of white dwarfs of this luminosity, then very significant numbers of them should have been found in existing surveys. In the Luyten Half Second survey (LHS), for example, with a limiting *R*-band magnitude of 18.5 and a proper motion window of $0.5 < \mu < 2.5 \text{ arcsec year}^{-1}$, this estimate would imply some 15 dark halo white dwarfs with reduced proper motions in the range 23.5 to 25.5; on the contrary, only a few such objects are known from that survey. The Oppenheimer *et al.* survey covered an almost identical volume for dark halo objects as the LHS (which was not as deep but covered about half of the sky). Thus, some 15 objects like WD0351–564 would also be expected in the Oppenheimer *et al.* survey in the same reduced proper motion range, whereas only three such objects were found (F351–50, WD0351–564, and LHS542). That finding strongly suggests that the local density of these objects has been overestimated. We estimate a 2σ upper limit of 0.5% for the contribution of objects of the luminosity of WD0351–564 to the local dark halo density, based on a conservative estimate that not more than five such objects are seen in the LHS and Oppenheimer *et al.* surveys combined. This independent assessment agrees with the 0.6 to 1.0% estimate derived above.

In sum, we argue that the objects found by Oppenheimer *et al.* have a local density that is a factor of two to four less than their claimed detection of 2% of the galactic dark matter. White dwarfs at present represent the most exciting (and least radical) of the candidates for a component of the galactic dark matter, even though the indirect problems associated with this identification remain daunting (7). The Oppenheimer *et al.* result shows that we may be close to experimental confirmation or rejection of this proposal. Deep proper motion surveys for fast-moving, faint objects could well resolve this issue within a few years.

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The recent survey by Oppenheimer *et al.* (1) found 34 high-velocity white dwarfs and concluded that those white dwarfs form a component of dark matter representing 2% of the local mass of the halo. The Oppenheimer *et al.* survey covered about two-thirds of the volume of the LHS survey (2), ignoring the proper-motion limits. (Oppenheimer *et al.* covered 10% of the sky; LHS covered two-thirds of the sky but went somewhat deeper.) The range of proper motion to which the analysis in (1) was sensitive was similar to that in LHS, though the range of velocities was not the same, because the Oppenheimer *et al.* survey would be expected to see objects to a larger distance and, hence, a larger velocity.

Given that the surveys were so similar, it is surprising that the results were so different. Closer examination, however, shows that the results were not different after all. A further analysis of the LHS survey including trigonometric parallax (3) showed that roughly half of the LHS white dwarfs had velocities greater than 94 km s^{-1} , as was true for those of the Oppenheimer *et al.* study. Whereas these objects were classified as disk or thick disk dwarfs in (3), they were classified as halo objects by Oppenheimer *et al.* (1). In both surveys, however, these stars represented the high-velocity Gaussian tail of the disk population. The density of halo main sequence stars is about 1/600 the density of disk stars. Although Oppenheimer *et al.* claimed that their cut at 94 km s^{-1} eliminated 95% of the disk population, this means that the remaining 5% of the disk dwarfs should still outnumber the halo dwarfs by 30 to 1.

The problem is even worse, since this was a proper-motion-limited survey. Such a survey obviously selects for the highest velocity stars; thus, the typical velocity of a proper-motion-limited survey will be higher than that of the underlying population. A quick Monte Carlo simulation shows that the mean velocity in a proper-motion-limited survey is about twice that of the underlying population. The 94 km s^{-1} threshold chosen by Oppenheimer *et al.* (1), therefore, is actually a 1σ cutoff, and a fair fraction of detected disk stars would be expected to pass that threshold. This is borne out by an examination of figure 3 of (1): Most of the white dwarfs in

the sample are shown to be rotating around the galaxy in the same direction as disk stars (right half of the diagram). Oppenheimer *et al.* noticed this weighting in their sample, but claimed that this was due to a selection effect: that is, their analysis was not sensitive to the faster-moving halo stars. The upper limit to proper motions they studied was $3' \text{ year}^{-1}$. Only one star approached that limit, F351–50, at $2.5'' \text{ year}^{-1}$; the second-highest proper motion was $1.7'' \text{ year}^{-1}$ and the third highest was $1.1'' \text{ year}^{-1}$.

The Oppenheimer *et al.* study has not discovered a new dark matter population. It has only rediscovered the white dwarfs of the disk.

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Response: Gibson and Flynn cite several arguments to support their claim that our study (1) greatly overestimated the space density of halo white dwarfs. The first stems from a recomputation of our $1/V_{\text{max}}$ calculation. Their new value actually lies within the uncertainty in our estimate, however, so it is not clear to begin with that there is any discrepancy. Regardless of how the numbers were calculated, the uncertainties in the space densities are larger than the differences, and it is not meaningful to discuss them at the accuracies that Gibson and Flynn demand. Furthermore, Gibson and Flynn themselves do not uniformly apply their own criteria for what constitutes an “important” level of difference. They clearly view as significant the change wrought by their initial recalculation, which implies a 14% decrease in the calculated white dwarf density, and the change wrought by applying a white dwarf mass estimate drawn from globular clusters, which implies an additional 17% decrease in the density (paragraph 3 of their comment). Yet they disregard as having “little effect” a change of 11% in the opposite direction due to different assumptions for limiting apparent magnitude (paragraph 4 of their comment). Finally, the fact that we rounded our final number clearly indicates that we do not believe it is meaningful to distinguish between 1.6% and 2% based on current data. Deeper surveys are crucial for assessing the full extent of this population.

Gibson and Flynn also argue that our study used an average white dwarf mass, $0.6 M_{\odot}$ that was too high by 20%. We do not regard this argument as valid. Although the average white dwarf mass in globular clusters is indeed nearer to $0.5 M_{\odot}$ than to $0.6 M_{\odot}$, other research suggests that if our findings are correct and the population of stars represented by the white dwarfs in our study did emerge from a nonstandard initial mass function, the average white dwarf mass may actually be much higher. Chabrier (2), for example, found an average white dwarf mass of 0.7 to $0.8 M_{\odot}$.

Gibson and Flynn claim that our results are inconsistent with the LHS catalog, pointing out that no halo white dwarfs are seen in the northern portion of the LHS. Because of the similarities between our survey and the LHS, they maintain, there can be no halo white dwarfs in our survey. That assertion is incorrect, in part because there are several crucial differences between our survey and LHS and in part because there clearly are halo white dwarfs in the LHS. We discuss these issues in greater detail below, in our response to the Graff comment.

Finally, Gibson and Flynn conclude that only 0.5% of the dark matter is explained by white dwarfs. The argument through which they reach that number, however, is not logical. They take the dimmest star, WD0351–564, and place the entire space density of all of the white dwarfs found in our survey into the bin of the luminosity function corresponding to that faintest star—ignoring the fact that it only accounts for 7% of the space density. Then they argue that our survey did not find enough stars in this faintest luminosity bin. This circular argument is used to claim that we have overestimated the space density. Further, even if one chooses to accept that flawed argument, one must still contend with the fact that the 0.5% figure is only a lower limit. The complex detection limits (in proper motion and magnitude) and the incomplete sampling of the velocity parameter space suggest that a substantially larger population exists and that we have only found the tip of the iceberg.

Graff’s arguments likewise do not withstand close scrutiny. He begins with the premise, also proposed by Gibson and Flynn, that our survey and the LHS catalog are very similar. As we have already noted, that premise is incorrect; our survey and the LHS are not directly comparable. Our survey reached more than a magnitude deeper and found many objects to which the LHS was not sensitive. A clear indication that we have not simply repeated the LHS work is contained in our reduced proper motion diagram [figure 1 in (1)]: The LHS catalog, as Gibson and Flynn mention, has relatively few objects with reduced proper motion $H_R > 22$; much of our sample, by contrast, is drawn from the

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stars with $H_r > 22$. The Liebert *et al.* (3) sample of LHS white dwarfs, on which Graff particularly focuses, likewise included stars with a smaller range of proper motions than we allowed in our survey. It is more logical to interpret these differences as indicating that our survey is deeper and more complete than to assume that the previous studies of white dwarfs in the LHS are complete and we have made a mistake.

In addition, one of the coolest white dwarfs known before our survey, LHS 3250, was first cataloged in the LHS and is notably absent from the previous studies of the white dwarf content of LHS. This star, and other cool white dwarfs that were previously cataloged, had never been studied spectroscopically before our study. Rather, the assumption was that their colors suggested that they were main sequence stars, not blue, cool white dwarfs with collision-induced absorption (4). Indeed, to this day, there remain many objects in the LHS that have not been measured spectroscopically.

These issues render comparison of our survey with the LHS, or the Liebert *et al.* sample of that survey, much more complicated than simple, back-of-the-envelope calculations based on the tables in Liebert *et al.*, as proposed by Graff. In reality, a complete Monte Carlo simulation of the populations and the survey is necessary to assess the sensitivity of our survey in detail. Let us assume for the moment, however, that the Liebert *et al.* survey and our survey are indeed directly comparable, as Graff suggests. He claims that the stars we classify as halo stars would simply have been dubbed thick disk stars by Liebert *et al.* We point out, though, that the Liebert *et al.* sample contained stars that unambiguously are members of the galactic halo, along with others that may indeed be members of the halo. For example, the star LHS 542, which is in their survey, was clearly shown to be a halo member by Ibata *et al.* (5). The Liebert *et al.* (3) study is also missing stars: LHS 3250, which may or may not be a halo member, is conspicuously absent from the Liebert *et al.* study, partly because it was shown to be a white dwarf only recently (4), and Liebert *et al.* took known white dwarfs from LHS without a complete search through the LHS catalog for white dwarfs that had not been observed in detail. The halo star WD 0346+246 (6, 7) is missing from both Liebert *et al.* (3)

and the LHS, even though it was within the photometric and proper motion detection limits of the LHS—which suggests that LHS is not complete at the $R = 18.5$ level for white dwarfs. The latter two stars both have peculiar spectral energy distributions.

In short, the LHS survey certainly does contain dark halo white dwarfs that have not previously been identified as such. Indeed, 11 of the 38 stars that we listed [table 1 in (1)] were in the LHS or LP catalog. However, the LHS catalog contains only a small number of halo white dwarfs, and it is certainly not complete at the detection levels necessary to reveal a convincing fraction of the halo white dwarf population.

Graff continues by claiming that because the local density of halo main sequence stars is 600 times smaller than the density of disk main sequence stars (8), the same should be true for the white dwarfs. That claim has no basis in our current understanding of these two different populations of stars. First of all, if the halo is composed of substantially older stars that formed roughly coevally, as is generally believed, one would expect substantially different ratios of white dwarfs and main sequence stars in the halo and disk. The disk is believed to be a population of stars that have been continuously forming since the disk formed. The comparison is thus moot, and the assertion that 1 in 30 of the stars in our sample may be halo white dwarfs is rendered incorrect. The first examples of halo white dwarfs were discovered convincingly only in the past few years, and the construction of relative numbers of these stars is impossible if one disregards the results that we published in (1).

According to Graff, because our survey is proper-motion limited, we necessarily have included more of the disk stars than we thought. Effectively, he claims, our 2σ exclusion is relegated to a 1σ exclusion of the disk stars. That statement clearly does not hold in all cases and, most important, in this case. Halo and even thick-disk stars should have average proper motions higher than those of the disk; their kinematics are necessarily different from those of the Sun. Furthermore, the 94 km s^{-1} number—which is actually centered at the point $(V,U) = (-35,0)$, not $(V,U) = (0,0)$, as Graff seems to have assumed—comes from the survey by Chiba and Beers (9), which examined the velocity distributions of stars

that were not kinematically selected. Therefore, there is no question that 94 km s^{-1} is a 2σ value.

To respond to Graff's final point, we have not yet assessed the sensitivity of the survey in (1) as a function of proper motion with any accuracy. [We did point out in (1) that there was a less than 10% chance that we would find any stars with 3 arcseconds of motion per year or greater.] To assess that sensitivity—and, more important, the sensitivity of our survey in the VU parameter space that we plotted [figure 3 in (1)]—will require detailed modeling of the survey and the various galactic populations.

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