FAINT BLUE OBJECTS ON THE HUBBLE DEEP FIELD NORTH AND SOUTH AS POSSIBLE NEARBY OLD HALO WHITE DWARFS

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ABSTRACT

Using data derived from the deepest and finest angular resolution images of the universe yet acquired by astronomers at optical wavelengths, with the Hubble Space Telescope (HST) in two postage-stamp sections of the sky, plus simple geometrical and scaling arguments, we demonstrate that the faint blue population of point-source objects detected in those two fields could actually be ancient halo white dwarfs at distances closer than about 2 kpc from the Sun. This finding has profound implications, as the mass density of the detected objects would account for about one-half of the missing dark matter in the Milky Way, thus solving one of the most controversial issues of modern astrophysics. The existence of these faint blue objects points to a very large mass locked into ancient halo white dwarfs. Our estimate indicates that they could account for as much as one-half of the dark matter in our Galaxy, confirming the suggestions of the MACHO microlensing experiment. Because of the importance of this discovery, deep follow-up observations with HST within the next two years would be needed to determine more accurately the kinematics (tangential motions) of these faint blue old white dwarfs.

Subject headings: galaxies: halos — galaxies: stellar content — Galaxy: structure — stars: evolution — stars: Population II — white dwarfs

1. INTRODUCTION

The Hubble Deep Field data, in its northern (HDF-N) and southern (HDF-S) versions, have been heavily used to study the evolution of very distant galaxies (Livio, Fall, & Madau 1998), back to times when the universe was only a fraction of its present age. Indeed, the main motivation for the acquisition of these very deep images was the study of a small portion of the sky to an unprecedented depth (Williams et al. 1996, 1998). However, these data have also allowed astronomers to study and characterize the faint objects that compose our own Galaxy. In a series of papers (Elson, Santiago, & Gilmore 1996; Flynn, Gould, & Bahcall 1996; Méndez et al. 1996), the stellar sample derived from the HDF-N was used to set constraints on the faint end of the luminosity function for normal halo field stars, while the shallower but larger solid-angle data from the HDF-N flanking fields was used to better refine Galactic structural parameters (Méndez & Guzmán 1998).

In this paper we compare the stellar samples derived from the HDF-N and HDF-S pointings. Using a very simple, yet robust, model-independent argument, we demonstrate that the faint blue objects found on the HDF-N (Elson et al. 1996; Méndez et al. 1996) are indeed Galactic stars, not distant star-forming regions or compact galaxies as previously suggested (Elson et al. 1996). Our finding is corroborated by independent preliminary tangential motion measurements detected for these faint blue stars (Ibata & Lewis 1998; Ibata et al. 1999), which also prove that they are not distant Galaxies but, rather, nearby stars. Recent evolutionary tracks (Hansen 1998) indicate that, if these faint blue objects are Galactic, then they would be old halo white dwarfs, with ages in the range 10–12 Gyr located at distances of 1–2 kpc from the Sun.

2. POINT SOURCES IN THE HUBBLE DEEP FIELDS NORTH AND SOUTH

We have used the source catalogs produced by the Space Telescope Science Institute (STScI) from the combined (deepest), drizzled (spatial-resolution–enhanced) images from HDF-N and HDF-S, available through the World Wide Web. We note that the HDF-N catalog used here is based on a rereduction of the HDF-N images, providing some 10% increase in depth or, correspondingly, better signal-to-noise ratios for the brighter sources, than are available from the original images used to detect the faint blue objects. Both the HDF-N and HDF-S catalogs have been derived using exactly the same algorithms, procedures, and parameters, and thus they comprise a very homogeneous and self-consistent data set.

A critical step is the classification of point sources versus extended objects. This has been achieved by using a widely tested classifier trained with real images so as to provide the most robust separation of stars versus extended objects, using a neural-network scheme (Bertin 1995). Figure 1 shows the distribution of CLASS versus magnitude for HDF-N and HDF-S. CLASS is the probability that SExtractor assigns to an object as being pointlike, with CLASS = 0 being an extended source and CLASS = 1 being a pointlike object (CLASS is not a binary classifier but rather a continuous variable that can take any value from 0 to 1). This figure clearly indicates that there is reliable star-galaxy separation until about $V + I \sim 29$ and that both data sets are quite homogeneous and comparable in depth.

1 Based on observations collected with the Hubble Space Telescope, which is operated by AURA, Inc., under contract with the National Science Foundation.
CLASS > 0.90 to select our stars. In addition, the original source catalogs provided by STScI had to be trimmed to avoid the many spurious detections near the detector boundaries, where the lower signal-to-noise ratio leads to very high source confusion and poor photometry and shape classification. In the end, our sample consists of 78 point sources from HDF-N (solid angle of 4.334 arcmin$^2$) and 98 sources from HDF-S (solid angle of 4.062 arcmin$^2$). Photometry for these objects was calibrated using the precepts described by Ménédez & Guzmán (1998). Worst-case magnitude limits for the shallower HDF-S data (see legend to Fig. 1) have been computed from the STScI exposure-time calculator available through their World Wide Web pages. These limits are used here only as a guide, and they do not have a critical impact on the conclusions of this paper. Since the sample analyzed in this paper is several times brighter than the magnitude limit and the field is not crowded, we do not have to apply any completeness corrections, which should be negligible above 5 $\sigma$ the sky level, as shown by Paresce, de Marchi, & Romaniello (1996) on deep Hubble Space Telescope (HST) images of the globular cluster NGC 6397, acquired with the WFPC2. Actually, our discussion is restricted here to those sources above 15 $\sigma$ the sky level (see Fig. 3).

Figure 3 shows the calibrated color-magnitude diagrams (CMDs) derived from the catalogs. The faint blue stars are clearly seen in both figures, but they appear more numerous on the HDF-S sample. Indeed, this simple fact provides the central argument of this paper. HDF-N is located at Galactic coordinates ($l$, $b$) = (125.89, +54.83), while HDF-S is located at ($l$, $b$) = (328.25, -49.21). Therefore, HDF-N is looking toward the outer portion of the Milky Way, while HDF-S looks inward. It is well known that the stellar density decreases as a function of distance from the Galactic center, either in an exponential fashion for stars in the disk or as a power of the distance for halo stars (Majewski 1993).

Therefore, one would naturally expect to see more stars toward the HDF-S than toward the HDF-N. Is this actually the case? Figure 3 shows the loci for M dwarfs belonging to the Galactic disk at heliocentric distances of 1 kpc and M subdwarfs belonging to the Galactic halo at distances of 8 kpc, derived from the best available trigonometric parallaxes for these two types of stars (Monet et al. 1992). The characteristic distances adopted for these two types of stars correspond to the typical distances that one expects for them at these magnitudes and Galactic positions, as derived from a Galactic model that reproduces the observed HDF-N and flanking fields magnitude and color counts (Ménédez et al. 1996; Ménédez & Guzmán 1998).

From Figure 3 (see also Table 1), we see that on HDF-N there are 10 stars within the boundaries allowed by the M

| Objects                  | HDF-N | HDF-N (normalized$^a$) | HDF-S | Normalized HDF-S/HDF-N$^b$ |
|--------------------------|-------|-----------------------|-------|-----------------------------|
| Galactic stars .......... | 10    | 9.37                  | 22    | 2.35 ± 0.90                 |
| Faint blue sources ...... | 5     | 4.69                  | 10    | 2.13 ± 1.17                 |
| Extragalactic sources$^c$| 566   | 530.48                | 486   | 0.916 ± 0.057               |

$^a$ Normalized to same solid angle as HDF-S.
$^b$ Poisson noise from the original, unnormalized counts.
$^c$ Galaxies selected in same magnitude and color range as the faint blue sources.

Figure 1.—SEextractor CLASS parameter vs. HST $V$ + $I$ (uncalibrated) magnitude from the co-added (and deepest) F606W and F814W drizzled-combined frames produced by STScI for (upper panel) HDF-N and (lower panel) HDF-S. The total effective on-target integration times that went into the combined $V$ + $I$ frames are 64.63 and 50.44 hr for the northern and southern deep fields, respectively. It is apparent that we can reliably separate point sources (CLASS $\geq 1$) from extended objects (CLASS $\leq 0$) down to $V + I \sim 29$.

3. THE FAINT BLUE OBJECTS AS WHITE DWARFS

Figure 2 shows the frequency of CLASS as a function of this parameter. The large peak at low CLASS values indicates that the sample is indeed dominated by galaxies, while the smaller yet conspicuous peak at larger values of CLASS reveals truly pointlike objects. Visual inspection reveals that all objects with CLASS < 0.85 are clearly extended, and thus we have used the very conservative cut at CLASS = 0.90 to select our stars. In addition, the original source catalogs provided by STScI had to be trimmed to avoid the many spurious detections near the detector boundaries, where the lower signal-to-noise ratio leads to very high source confusion and poor photometry and shape classification. In the end, our sample consists of 78 point sources from HDF-N (solid angle of 4.334 arcmin$^2$) and 98 sources from HDF-S (solid angle of 4.062 arcmin$^2$). Photometry for these objects was calibrated using the precepts described by Ménédez & Guzmán (1998). Worst-case magnitude limits for the shallower HDF-S data (see legend to Fig. 1) have been computed from the STScI exposure-time calculator available through their World Wide Web pages. These limits are used here only as a guide, and they do not have a critical impact on the conclusions of this paper. Since the sample analyzed in this paper is several times brighter than the magnitude limit and the field is not crowded, we do not have to apply any completeness corrections, which should be negligible above 5 $\sigma$ the sky level, as shown by Paresce, de Marchi, & Romaniello (1996) on deep Hubble Space Telescope (HST) images of the globular cluster NGC 6397, acquired with the WFPC2. Actually, our discussion is restricted here to those sources above 15 $\sigma$ the sky level (see Fig. 3).

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dwarf and subdwarf sequences, while the number of similar objects on HDF-S is 22. Their ratio is roughly a factor of 2. Whether the absolute numbers observed in each field within those boundaries are what one would expect from a standard Galactic model is actually irrelevant to this discussion (however, it has been already shown that the Galactic model predictions and the observed counts do agree on HDF-N and its flanking fields; Méndez et al. 1996; Méndez & Guzmán 1998; see also the extensive study on classification of point sources on HDF-N and a comparison of different studies by Conti et al. 1999). If the faint blue objects are actually extragalactic in nature, as has been suggested (Elson et al. 1996), then one should not see a variation in their numbers when going from HDF-N to HDF-S, since the universe is isotropic on large scales (see Table 1). We should remind the reader that, if these objects are assumed to be extragalactic, they would be located at redshifts of $z \geq 1$ (Elson et al. 1996), and at these scales the angular correlation function (which measures the number of galaxy pairs at a given angular separation, in excess of a random distribution) has been found to be zero to within $5 \times 10^{-4}$ for angular separations larger than 6′ (the HDF-N and HDF-S are 165° apart in the sky; Maddox et al. 1990). However, what we find from Figure 3 is that the number of faint blue objects is five on HDF-N and 10 on HDF-S, a ratio of 1.2, almost exactly as for normal stars. This argument suggests that the faint blue objects are not extragalactic and that, furthermore, their space distribution follows that of normal Galactic stars. Assuming a Poisson distribution, the probability of seeing 10 sources on HDF-S when five are expected is only 1.3% (account has to be made for the different solid angles covered by the two samples). Therefore, even though the samples are small, the observed difference in the number of expected objects if they had an isotropic north-south distribution is highly significant. Additional indication that the faint blue objects are actually nearby is provided by Ibata & Lewis (1998; Ibata et al. 1999), who have obtained preliminary tangential motions for the point sources on HDF-N using a 2 yr baseline on HST. They find that four of the five faint blue objects do have detectable tangential motions at a 3σ level or more, thus ruling out the hypothesis that they are extragalactic objects (their motions are actually consistent with halo kinematics at 1–2 kpc, see below). A more robust proper-motion determination would require additional observations with HST within the next two years to increase the time baseline for the tangential motion measurement.

4. CONCLUSIONS AND IMPLICATIONS FOR THE NATURE OF DARK MATTER IN THE GALAXY

The MACHO microlensing experiment has found that a significant fraction of dark matter is baryonic and made of objects with $0.5 \ M_\odot$ (Alcock et al. 1997). They have suggested white dwarfs (WDs) as possible candidates because they have the right mass and, though very numerous, old ones would be faint enough to have remained undetected thus far. Figure 3 shows the locus of old WDs as recently computed by Hansen (1998) using the latest atmospheric models and opacity tables, and confirmed observationally on the cool and low-luminosity WD LHS 3250 (Harris et al. 1999). It is clear from this figure that the faint blue objects do fall into the region predicted by these models, as originally pointed out by Hansen himself for HDF-N. This fact, plus the discussion in the preceding paragraph, indicates that we have detected a population of old faint and blue white dwarfs belonging to the Galactic halo and located at heliocentric distances of up to 2 kpc. This finding has profound implications for the nature of dark matter in our own galaxy. If the objects that we have detected are actually old WDs from the halo, then their expected number in HDF-N versus that in HDF-S should follow that of the general halo population. Is this actually the case? For a density law similar to that exhibited by halo field tracers (e.g., RR
Lyraes or blue horizontal branch stars [Sluis & Arnold 1998], i.e., $\rho \sim R^{-3}$ with an axial ratio of 0.8, where $R$ is the distance from the Galactic center, we find that the expected ratio of the number of halo stars in HDF-N to that in HDF-S is about 1.71. Therefore, the factor of 2 increase when going from HDF-N to HDF-S is consistent with their being associated with the halo field (given the uncertainties in the halo density law).

If, as the preceding discussion suggests, we have detected a population of faint blue old halo WDs in the vicinity of the Sun, then what is their contribution to the local Galactic mass budget? Their mass contribution ($M_{\text{Halo WD}}$) is given by

$$M_{\text{Halo WD}} = N_{\text{Halo WD}} \times \mu_{\text{WD}}$$

where $N_{\text{Halo WD}}$ is the number of halo WDs with typical mass $\mu_{\text{WD}}$ observed on HDF, $\Omega$ is the solid angle (in arcmin$^2$) subtended by the HDF, $\rho_{\odot}$ is the mass density of this component in the solar neighborhood (in $M_{\odot} \text{pc}^{-3}$),

$$= 8.46 \times 10^{-8} \Omega \rho_{\odot} R_{\odot}^3 \int_0^{\text{lim}} \frac{r^2}{R^3} dr,$$

FIG. 3.—Color-magnitude diagrams in calibrated Johnson-Cousins $I$ vs. $V - I$ for point sources from (upper panel) HDF-N and (lower panel) HDF-S. The red dotted line is the locus for disk M dwarfs at 1 kpc from the Sun, while the green dotted line is the locus for subdwarfs at a heliocentric distance of 8 kpc. The solid black lines indicate the 15 magnitude limits imposed by the exposure time in the combined HDF I frame (horizontal line) and the $V$ combined frame (diagonal line). Only objects above the intersection of these two solid lines are firm detections, with good star-galaxy separation. The red stars are bona fide Galactic stars as predicted, in number and location on the CMD, from standard Galactic models. The faint blue stars are shown by the blue symbol. The true nature of these objects is revealed as old, cold halo WDs (see text). The blue dotted line indicates the theoretical predicted locus for halo WDs of 0.6 $M_{\odot}$ at 1 kpc, while the solid line indicates the locus for the same stars at 2 kpc. WDs in the mass range 0.5–0.9 $M_{\odot}$, encompassing the full range of models computed by Hansen, exhibit a similar color-magnitude distribution. The blueing of the WD tracks occurs at an age of about 10 Gyr and $T_{\text{eff}} \sim 3500$ K. Uncertainties in the physics of the models and the transformation of its predictions to the observational plane can account for up to 0.5 mag in the predicted WD colors (B. M. S. Hansen 1999, private communication).
We should also consider that errors intrinsic to the calculation of WD tracks are actually not large, 0.1 mag or less, and mostly come from uncertainties in the temperature and pressure behavior in the atmosphere (cool white dwarfs are convective to the photosphere), although the results seem to be fairly insensitive to mixing length prescriptions (B. M. S. Hansen 1999, private communication). Another uncertainty is from opacities not as yet included in the models, in particular the higher H$_2$ level transitions. Even though lower transitions are dominant, these higher transitions might take notches out of the flux between the broad absorption bands, and this would likely make WDs appear bluer. Given that the lower bands are the dominant opacity contributor, the general trend should be robust, but the detailed colors could vary somewhat, perhaps by as much as 0.5 mag. Finally, a bigger uncertainty, which can reach several tenths of a magnitude, comes from the fact that cool WD atmospheres are distinctly nonblackbody and have many spectral signatures, making them quite susceptible to the adopted bandpasses. Calculations for both $HST$ and Johnson–Kron-Cousins colors can differ by up to about 0.5 mag. Hansen has adopted, for the models used here, the synthetic magnitudes described in § 5.2 of Holtzman et al. (1995). This was done because transformations such as those described in the earlier sections of the Holtzman paper are based on standard stars and will not hold well for stars whose spectra do not resemble the standard stars. Furthermore, the procedure in § 5.2 also matches those used in other WD atmosphere calculations well, making comparisons easier. After calculating the WFPC2 magnitudes, magnitudes and colors on the $VRI$ system were computed using the transformations defined on Table 10 of the Holtzman et al. paper, following thus the same procedure employed to convert our observed $HST$ magnitudes to the Johnson-Cousins system. Given all these uncertainties, it is reassuring that the more recent independent model calculations by Saumon & Jacobson (1999), which overcome some of the simplifying assumptions of the earlier models, do agree with Hansen’s original calculations. In particular, Saumon & Jacobson conclude that very cool ($T_{\text{eff}} < 3500$ K) halo ($t_{\text{age}} > 10$ Gyr) WDs would have $V - I < 1.4$.

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