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DISCOVERY OF HIGH PROPER-MOTION ANCIENT WHITE DWARFS: NEARBY MASSIVE COMPACT HALO OBJECTS?

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ABSTRACT

We present the discovery and spectroscopic identification of two very high proper-motion ancient white dwarf stars, found in a systematic proper-motion survey. Their kinematics and apparent magnitude clearly indicate that they are halo members, while their optical spectra are almost identical to the recently identified cool halo white dwarf WD 0346+246. Canonical stellar halo models predict a white dwarf volume density that is 2 orders of magnitude less than the $\rho \sim 7 \times 10^{-4}\ M_{\odot}\ \mathrm{pc}^{-3}$ inferred from this survey. With the caveat that the sample size is very small, it appears that a significant fraction, ~10%, of the local dark matter halo is in the form of very old, cool, white dwarfs.

Subject headings: dark matter — Galaxy: halo — solar neighborhood — white dwarfs

1. INTRODUCTION

Unless our present understanding of gravitation is incorrect, the Milky Way and most other galaxies possess halos of dark, or barely luminous, matter that extend well beyond the visible boundaries of their respective galaxies. Present cosmological constraints strongly favor nonbaryonic dark matter, although the problem is complicated by the possibility that there may be several types of dark matter; for instance, galactic dark matter may have little to do with dark matter in galaxy clusters or on larger scales (Bosma 1998). In our own Galaxy, this halo component appears to extend out to at least 50 kpc, as traced by the Magellanic Clouds (Lin, Jones, & Klemola 1995), and may well continue to beyond the orbit of Leo I at an ~200 kpc distance (Zaritsky 1999). Given the large uncertainty in the extent of these structures, their total mass is poorly constrained, but even within 50 kpc, it is clear that they must contain orders of magnitude more mass than the clearly visible baryons in the form of stars and gas.

One of the few direct constraints on the mass distribution of the constituent particles of galactic halos comes from the Magellanic Cloud microlensing experiments (Alcock et al. 1997; Afonso et al. 1999). The most recent report of the detection rate of microlensing events (Alcock et al. 2000) supports a simple model where approximately 20% of the Milky Way halo is made up of objects of ~0.5 $M_{\odot}$, consistent with the result of Afonso et al. (1999). Although the halo fraction and object mass are model dependent, the main uncertainty arises from the possibility that the LMC may possess a substantial (dynamically hot) stellar halo of its own. Given the absence of evidence for this latter possibility, the microlensing conclusions must be taken seriously. These MACHOs are most likely situated approximately halfway to the LMC, where the optical depth to microlensing is highest. However, unless the MACHOs were effectively decoupled from nucleosynthesis (as would presumably be the case for primordial black holes), it is unlikely that MACHOs fill galactic halos entirely since this would break nucleosynthesis constraints.

Apart from ancient white dwarfs (WDs), all stellar MACHO candidates can be safely ruled out. Ancient WDs, which have stellar masses in the range measured by the MACHO experiment (0.1–1.0 $M_{\odot}$), are not yet ruled out by direct star-count observations but are difficult to envisage as a MACHO population because of several indirect constraints (see, e.g., Fields, Freese, & Graff 1998 and Graff et al. 1999), including most importantly the chemical enrichment of the early Galaxy (Gibson & Mould 1997), although for a possible way around this problem, see Chabrier (1999). This renewed interest in ancient halo WDs is mainly due to a theoretical reappraisal of the WD cooling function. New models with a self-consistent treatment of radiation transfer and the inclusion of molecular hydrogen opacity (Hansen 1998; Saumon & Jacobson 1999) drastically change the predicted colors and magnitudes of the oldest, and hence coolest, WDs. In particular, hydrogen atmosphere (DA) WDs with ages $\gtrsim$10 Gyr have depressed red and near-infrared (NIR) fluxes; contrary to previous expectations, they become bluer, for instance, in $V-I$ with age.

Ibata et al. (1999) recently presented a proper-motion analysis using two epochs of *I*-band imaging data in the Hubble Deep Field (HDF). They identified a small sample of two to five faint and relatively blue compact sources that appear to move with respect to the numerous background galaxies. The colors, motions, and numbers of these sources are consistent with the hypothesis that they are members of a numerous halo population of ancient WDs, with a spectral energy distribution (SED) similar to that predicted by the Hansen models. The local mass density of this population appears similar to that of the "standard" halo model used by the MACHO and EROS collaborations (Alcock et al. 1997; Palanque-Delabrouille et al. 1998). Unfortunately, the measured proper motions are at the detection limit, and they are exceedingly faint ($V \sim 29$), so spectroscopic confirmation is currently impossible.

Striking confirmation that the new WD models are more appropriate has been given by Hodgkin et al. (2000). Their spectrum of WD 0346+246 shows a large suppression of the NIR flux relative to a blackbody model fit to the visible radiation, as predicted by Hansen (1998) for ancient DA WDs.

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Furthermore, the proper motion of WD 0346+246 and the measured parallax indicate that it is most likely a halo member.

Therefore, halo WDs do seem to exist, and the DA subset has bluer colors than originally expected (WD 0346+246 has $V-I = 1.52$). The next important question to address concerns the local mass density of this population. In particular, are they present in sufficient numbers to contribute significantly to the proposed halo of MACHOs?

2. SURVEY

To detect the nearby counterparts of the population of WD MACHOs tentatively detected by Ibata et al. (1999), we have undertaken complementary wide-field photographic plate surveys of very high proper-motion (VHPM = $>1''$ yr^{-1}) stars. With a survey limit ~10 mag brighter than the HDF limit, we need to cover a field that is 1 million times larger than the 1.4×10^{-3} deg^2 WFPC2 field in order to probe the same halo volume. The expected proper motions can be several arcseconds per year, and candidates will be predominantly at the faint limit of the plates, where existing catalogs (cf. the Luyten half-second [LHS] catalogue; Luyten 1979) are heavily incomplete. Faced with the difficulty of reliably identifying VHPM stars among thousands of potential candidates, we have investigated three independent techniques to cross-check the results. These analyses are based on different combinations of existing plate material and probe different aspects of the problem: survey 1 uses selected pairs of appropriate UK Schmidt Telescope (UKST) B_J plates with short-epoch differences for sensitivity to "blue" VHPM stars, survey 2 uses standard UKST B_J and R sky survey plate pairs and has the potential to probe all of the southern sky, and survey 3 includes an extra third-epoch ESO-SRC survey R plate to enable searching to deeper limits for $\delta < -17°$.

All of the southern sky has been observed by the UKST in both blue (B_J) and red (R) passbands, and the designated survey quality plates for more than half of this area have been processed by the Automatic Plate Measuring (APM) facility (Kibblewhite et al. 1984). This forms the basis for pilot studies using the three survey methods. The total error in measuring the relative proper motion is generally much less than $0''.1$ yr^{-1}, which is negligible in the context of the survey.

2.1. *Survey 1*

While the generic UKST B_J, R survey material is an excellent resource for locating objects of average color (g–k type) and modest proper motions ($\approx 0''.5$–$2''.0$ yr^{-1}), it may not be ideal for the detection of ancient halo WDs given the color uncertainty and the generally large epoch difference, 10–15 yr. Consequently, for survey 1, we have based proper-motion detection on only blue passband (B_J) UKST plates with a shorter epoch difference, $1 < T < 10$ yr, to enhance the sensitivity to the oldest WDs. As would be expected, the available UKST archival nonsurvey grade plates are a heterogeneous mixture of plate qualities and epochs. With the help of S. Tritton of the UKST Unit, we selected 21 deep "b"-grade B_J southern survey plates for scanning. This sample was chosen in fields with extant APM on-line UKST B_J and OR catalog data.

The search algorithm works as follows. First the overall plate-to-plate transformation is derived using all objects on the plates that match (iteratively) within $2''$. The extra "b"-grade B_J plate data are then matched to the existing survey B_J, R catalog. Objects matching within a radius of $2''$ for our purposes are taken to have negligible proper motions and are discarded. This leaves a catalog of what are mostly spurious detections (noise, diffraction spikes, extended object deblending problems, close object deblending problems, incompleteness problems, etc.), among which there is a tiny proportion of actual VHPM objects. To minimize contamination by spurious detections, unmatched objects were only considered as possible high proper-motion (HPM) objects if they were stellar in appearance and brighter than $B_J = 22$ on both blue plates. Remaining unmatched objects were then considered to be possible matches if they were within a search radius of $30''$.

In this way, we obtained a provisional list of 1426 candidates. After a visual examination of the APM object finding charts and the Digitized Sky Survey (DSS) images of the field (if available) and after a visual comparison with the R-band survey plates, we made a subselection of 101 candidate VHPM stars for follow-up observations. The majority of the 1325 rejected candidates were from situations in which there was a clear error, for example, a detection on the APM plate scan that did not appear on the DSS scan of the same plate or detections near large galaxies or bright stars. We note that some of the rejects at this stage were based on less secure criteria having, for example, suspiciously elongated profiles on the APM finding charts or apparently different magnitudes after allowing for the different plate depth between epochs. Unfortunately, the probity of rejection based on these last criteria is difficult to quantify, particularly near the plate limits. Two plates proved to be unusable, giving a total area of 19 fields in this survey.

2.2. *Survey 2*

This difficulty in probing near the plate limits led to our decision to undertake the second complementary survey to shallower depths, using only the already available APM on-line catalog B_J and R plate data. The results from the first search technique plus the properties of the halo white dwarf WD 0346+246 were used to fine-tune the selection criteria. In a similar manner to survey 1, brighter candidates that are stellar in appearance, with $12 < R < 19.5$ and $B_J < 21.5$ and with possible proper motions (PMs) $\geq 1''$ yr^{-1}, were selected from a random sample of 24 equatorial region fields. The bright limit was imposed because on deep UKST sky survey plates, images brighter than this are heavily saturated, show strong diffraction spikes, and are embedded in large reflection halos, making accurate photometry and astrometry difficult to achieve. Equatorial fields were chosen because, on average, they have much shorter epoch differences, ~5 yr, between the R and B_J survey plates compared with the so-called southern survey plates, $\delta \leq -20°$, where the average epoch difference is 14 yr.

Due to storage limitations at the time of catalog construction, the extant APM on-line catalog recorded data on the coordinate system of the reference R plate and only recorded separate coordinate information for the B_J plate data if there were no matches within $5''$, giving a lower limit to the proper motions that can be observed. Of the 24 selected equatorial fields, 11 had epoch differences of 3 yr or less and, although processed, were not used in the sample. The remaining 13 fields had epoch differences between 4 and 9 yr and produced a total of 87 candidates. After careful visual inspection of the on-line catalog data, 36 candidates were left. Finally, the remaining candidates were cross-checked with DSS images and visually inspected on first epoch (1950s) Palomar Sky Survey plates to check the reality of the candidate and the proper motion. This left a total of nine guaranteed VHPM candidates.

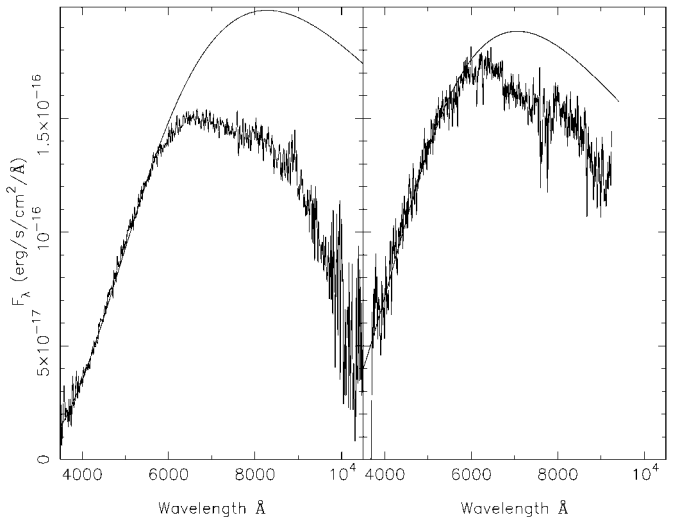

FIG. 1.—Flux-calibrated spectra of the two VHPM stars: F351-50 (*left*) and F821-07 (*right*). The blackbody SED models, fitted to $\lambda < 6500$ Å, have been overlaid. The blackbody temperatures are 3500 and 4100 K for F351-50 and F821-07, respectively.

2.3. *Survey 3*

The third strategy is based on a three-epoch plate analysis from the UKST APM on-line catalog and on ESO-*R* survey plates scanned by the MAMA (Guibert, Charvin, & Stoclet 1984)[6] and is more sensitive to bright red, extreme HPM objects. The survey covers 24 Schmidt plate fields at high Galactic latitude, selected according to the high-grade image quality of plates and with epoch differences between 3 and 15 yr. Of these, four fields are in common with survey 1, so the effective additional area surveyed is 20 fields.

Unlike the APM candidate selection that used the *x*-*y* pixel coordinates of the scanned plates, the ESO-*R* plate MAMA data matching used celestial coordinates based on Tycho catalogue astrometric solutions (Robichon et al. 1995). VHPM candidates were selected by requiring a consistent alignment of celestial coordinates at the three epochs. The candidates were selected to have similar *R* magnitudes on UKST-*R* and ESO-*R* plates. Two regimes were considered: for $R < 18$, PMs of $\mu < 10''$ yr^{-1} were sought, while for $R > 18$, a PM upper limit of $\mu < 1\farcs5$ yr^{-1} was imposed. The 417 candidates thus detected were inspected visually on DSS-I and -II images (when available) and also on ESO-*R* plates, from which 20 objects were selected for observation, corresponding to the bluest detections ($B_J - R < 2$) with the highest PMs.

3. OBSERVATIONS

All of the 101 candidate VHPM stars detected in survey 1 were imaged with EFOSC2 on the ESO 3.6 m telescope on the night of 1999 October 1. Short *g*-band exposures (to match the B_J passband) were obtained, centered on the discovery positions. Of the 101 candidates, 72 detections were found to be due to incompleteness of the photographic plates, and 20 objects were confirmed to be genuine VHPM stars, while a further nine candidates were consistent with objects that had moved out of the 5′ field of view of the instrument (i.e., possibly amazingly high PM objects, but most likely just due to noise).

Of the 20 candidates from survey 3, direct CCD exposures

[6] See also http://dsmama.obspm.fr.

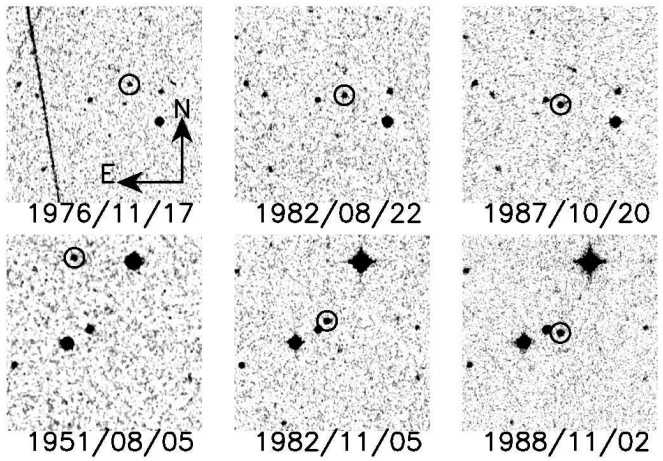

FIG. 2.—From left to right, the direct plate images (2.′5 × 2.′5) of F351-50 (*top panels*) are from ESO *B*, UKST B_J, and UKST *R* plates, and those of F821-07 (*bottom panels*) are from Palomar O, UKST B_J, UKST *R* plates, showing proper motion.

revealed that 18 were real moving stars with $\mu < 1''$ yr^{-1}, while the two most extreme PM candidates were rejected, being in fact due to spurious alignments of three different stars, each one appearing alone on each plate, an expected occurrence close to the detection limit of plates.

On the nights of 1999 October 2 and 3, four of the 20 confirmed candidates from survey 1 were observed with the spectroscopic mode of EFOSC2. Very high winds limited our choice of targets, while the poor seeing conditions made us set the slit width to 2″, reducing the spectral resolution. All objects were first observed with grating 1 (3185–10940 Å) to obtain an identification spectrum, followed up with the higher resolution gratings 9 (4700–6770 Å) and 12 (6015–10320 Å). Finally, the spectrum of the most extreme high PM star of survey 2, in UKST field f821, was kindly observed for us by L. Storrie-Lombardi & C. Peroux at the Cerro Tololo Inter-American Observatory (CTIO) 4 m on the night of 1999 October 13 using the Ritchey-Chrétien spectrograph with the Loral 3k CCD and the KPGL-2 grating covering the wavelength range of 3350–9400 Å, sampled at 2 Å pixel^{-1}.

4. RESULTS

The full results of these surveys will be presented in a forthcoming paper. Here we focus on two VHPM stars discovered in surveys 1 and 2.

In the left panel of Figure 1, we display the flux-calibrated low-resolution spectrum of the highest PM star in survey 1, F351-50, a featureless WD with $B_J = 19.76$, $B_J - R = 1.65$, $R - I = 0.31$ (*I*-band photometry from DENIS), and $\mu = 2\farcs33$ yr^{-1} at a position angle (P.A.) of 130.°1, located at $\alpha_{J2000} = 0^h45^m17\fs78$, $\delta_{J2000} = -33°29'10\farcs0$ (epoch 1987.88). The top panels of Figure 2 act as finders and also demonstrate the high PM of the object. The absence of distinct absorption lines and the color of F351-50 are consistent with it being a cool DA WD. (Unfortunately, this absence of spectral lines makes it impossible to measure a radial velocity for this object, even from the higher spectral resolution data.) Also superposed on Figure 1 is a 3500 K blackbody model, which provides a good fit to the visual region of the spectrum with $\lambda < 6500$ Å. It is readily apparent that there is a substantial depression of the flux redward of 6500 Å in this object, precisely as was originally seen

in the now confirmed ancient halo WD star WD 0346+246 (Hambly, Smartt, & Hodgkin 1997, their Fig. 3).

What Galactic population does this object belong to? Lacking a parallax, we may still estimate its distance from other constraints. First, the universe is not old enough for even 0.5 $M_\odot$ DA WDs to have cooled fainter than $M_V = 18$ (Hansen 1998), so F351-50 must be located at a distance $d > 15$ pc. At this distance, its total space velocity with respect to the Sun is $v > 170$ km s^{-1}, which clearly indicates that it is not a thin or thick disk member. The only remaining alternative is that it is a halo object. Assuming an upper limit to the space motion of 300 km s^{-1}, its distance is constrained to be closer than 26.5 pc (this neglects the radial velocity component). Finally, assuming, for now, a similar absolute magnitude to WD 0346+246 places it at a distance of ~25 pc. At that distance, the expected reflex solar motion for a stationary halo object is $\mu = 1\farcs95$ yr^{-1} at P.A. = 145°.2, in good agreement with the observed motion.

Given the success of this initial B_J plate survey and the similar color to WD 0346+246, we subsequently checked whether the result was reproduced in survey 2, which used the extant APM catalog scans. The spectrum of F821-07, the most extreme HPM star found in survey 2 ($B_J = 18.91$, $B_J - R = 1.16$, $\mu = 1\farcs72$ yr^{-1} at P.A. = 201°.2, and $\alpha_{J2000} = 23^h19^m09\fs96$, $\delta_{J2000} = -6°12'32\farcs5$ [epoch 1988.92]), is shown in the right-hand panel of Figure 1, together with finding charts and demonstrable HPM in the bottom panels of Figure 2. F821-07 also has a similar spectral shape to WD 0346+246 (Hodgkin et al. 2000), showing it to be another featureless WD star, and the very large proper motion, $\mu = 1\farcs72$ yr^{-1}, implies halo membership for the same reasons as stated previously for F351-50.

Interestingly, after careful inspection of the LHS catalogue, it was clear that F821-07 had the same proper motion within measurement errors and was within 1′ of the position of the previously known HPM object LHS 542. F351-50 has no plausible counterpart in the LHS catalogue and remains a new discovery. As we will show in a forthcoming paper, the population of known nearby white dwarfs contains a previously unnoticed ancient halo population, and LHS 542, in particular, is an excellent candidate for a cool halo WD. Furthermore, the known parallax of LHS 542 implies a distance of 31 ± 3 pc (Leggett, Ruiz, & Bergeron 1998) and hence a high space motion typical of halo objects.

5. CONCLUSIONS

No ancient WDs were found in survey 3. This is partly due to the added incompleteness from the requirement that a star be detected, and be classified as stellar, on three rather than two plates. At each epoch, for $R \sim 19$, the probability of detection and correct classification is ~85%. For rapidly moving sources, there is also an ~5% chance that they will be randomly situated close (within 3″) to the detection isophote of a stationary source and so not be detected as a point source. We estimate that the completeness of surveys 1 and 2 is, respectively, ~65% and ~80%, while survey 3 is ~50% complete. Survey 3 is also not sensitive to faint $R > 18$, high PM $\mu > 1\farcs5$ yr^{-1} stars: one of the two detected HPM stars is outside of the selection limit of this survey. This implies that the efficiency of the detection is close to half the efficiency of the first two strategies, reducing the completeness of survey 3 to ~25%.

Discounting the overlapping regions between adjacent plates, and the area occupied by bright stars and unusable regions of the plates, surveys 1, 2, and 3 have areas of 551, 377, and 506 deg^2, respectively, giving a total effective area of $\Omega \sim 790$ deg^2 explored. We have only followed up obvious detections up to $R = 19$. Model predictions (B. Hansen 1999, private communication) for $T > 3500$ K DA WDs are that $M_R < 16.4$, so we are sensitive to a distance modulus of $m - M_0 = 2.7$, i.e., a distance of $d = 33$ pc.

The finding of $n = 2$ stars closer than $d = 33$ pc over the $\Omega \sim 790$ deg^2 area of the survey implies a local density of

$$\rho \sim n \frac{3}{\Omega d^3} M_\star, \tag{1}$$

where $M_\star$ are the individual object masses. Lacking any information on individual masses, we assume a reasonable value of $M_\star \sim 1\ M_\odot$ (Chabrier 1999). Thus, the local mass density of this population is

$$\rho \sim 0.0007\ M_\odot\ \mathrm{pc}^{-3}. \tag{2}$$

The expected mass density of white dwarfs in the stellar spheroid, given the subdwarf star counts and assuming a standard initial mass function (IMF), is $1.3 \times 10^{-5}\ M_\odot$ pc^{-3} (Gould, Flynn, & Bahcall 1998), i.e., approximately 2 orders of magnitude lower than this estimate. This suggests that the IMF is not universal and was substantially steeper in the progenitor population of these WDs.

The density derived above is ~10% of the local density ($0.0079\ M_\odot$ pc^{-3}) of the "standard" dark matter halo model used by the MACHO collaboration (Alcock et al. 1997). However, the halo mass fraction in WDs could be even larger, since surveys 2 and 3 are probably not sensitive to the older (and bluer) DA WDs, while similarly aged helium atmosphere (DB) WDs would be too faint to be detected by any of these methods (see Hansen 1998). We note that our density estimate is consistent with the updated results from the MACHO collaboration (Alcock et al. 2000), which appeared after the submission of this Letter.

Thus, it appears that a significant fraction of galactic dark matter may be baryonic and may be in the form of cool and hence very old WDs, which are the remnants of the first stellar populations. We caution that this analysis is based on very low number statistics and therefore requires confirmation. An all-sky survey to $R \sim 19$ at Galactic latitudes $b > |30|$ (as is feasible to undertake with extant photographic plates) and with completeness similar to the present work should find ~14 such stars, providing a sample with which the halo may be age-dated in a way that is independent of isochrone fits (Richer et al. 1997). Also, very deep *Hubble Space Telescope* proper-motion data toward the Galactic center and anticenter directions will constrain the radial density gradient of this population, thereby checking whether this is a local, perhaps transient, feature or a massive Galactic structure.

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REFERENCES

Afonso, C., et al. 1999, A&A, 344, L63
Alcock, C., et al. 2000, ApJ, submitted (astro-ph/0001272)
———. 1997, ApJ, 486, 697
Bosma, A. 1998, Celest. Mech. Dyn. Astron., 72, 69
Chabrier, G. 1999, ApJ, 513, L103
Fields, B., Freese, K., & Graff, D. 1998, NewA, 3, 347
Gibson, B., & Mould, J. 1997, ApJ, 482, 98
Gould, A., Flynn, C., & Bahcall, J. 1998, ApJ, 503, 798
Graff, D., Freese, K., Walker, T., & Pinsonneault, M. 1999, ApJ, 523, L77
Guibert, J., Charvin, P., & Stoclet, P. 1984, in IAU Colloq. 78, Astronomy with Schmidt-Type Telescopes, ed. M. Capaccioli (Dordrecht: Reidel), 165
Hambly, N., Smartt, S., & Hodgkin, S. 1997, ApJ, 489, L157
Hansen, B. 1998, Nature, 394, 860
Hodgkin, S., Oppenheimer, B., Hambly, N., Jameson, R., Smartt, S., & Steele, I. 2000, Nature, 403, 57
Ibata, R., Richer, H., Gilliland, R., & Scott, D. 1999, ApJ, 524, L95
Kibblewhite, E., Bridgeland, M., Bunclark, P., & Irwin, M. 1984, in Proc. Astrononical Microdensitometry Conference, ed. D. A. Klinglesmith (NASA CP-2317; Washington, DC: NASA), 277
Leggett, S. K., Ruiz, M. R., & Bergeron, P. 1998, ApJ, 497, 294
Lin, D., Jones, B., & Klemola, A. 1995, ApJ, 439, 652
Luyten, W. 1979, LHS Catalogue (2d ed.; Minneapolis: Univ. Minnesota Press)
Palanque-Delabrouille, N., et al. 1998, A&A, 332, 1
Richer, H. B., et al. 1997, ApJ, 484, 741
Robichon, N., et al. 1995, A&A, 304, 132
Saumon, D., & Jacobson, S. 1999, ApJ, 511, L107
Zaritsky, D. 1999, in ASP Conf. Ser. 165, The Third Stromlo Symposium: The Galactic Halo, ed. B. K. Gibson, T. S. Axelrod, & M. E. Putman (San Francisco: ASP), 34