HST Observations of M Subdwarfs

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ABSTRACT

We present the results of an HST snapshot program to search for very-low-mass stellar companions to nearby M subdwarfs. None of our nine targeted metal-poor primaries have companions more massive than the hydrogen burning limit, implying that the halo binary fraction is equal to or less than the Galactic disk binary fraction below \(0.3M_\odot\). In addition, the more distant tertiary VB12, an sdM3.0 companion to an F subdwarf double, is also unresolved. We show that the relation between WFPC2 F555W and F850LP photometry and ground V,I photometry is consistent with theoretical expectations. We also report that two recently observed Hyades M dwarfs appear single.

Subject headings: binaries: general — stars: low-mass, brown dwarfs – stars: Population II

1. Introduction

The old Population II stellar halo is a fossil relic of the formation of the Galaxy. Most observational studies to date have concentrated on F and G subdwarfs near the turnoff of the halo main sequence. The lowest-mass, metal-poor stars, M subdwarfs, are intrinsically less luminous, but have a higher local number density. Observations of these stars allow us to probe both the stellar mass function and the binary formation frequency favoured by star formation in the early Universe.

There is currently little information on the binary frequency for the lowest mass stars in the halo. The formation mechanism(s) of binaries remains uncertain, with no clear predictions as to

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whether conditions in the young Galaxy would favor the production of more or fewer very-low-mass binaries relative to the present-day Galactic disk. If the binary fraction is high, then the measurements of the field halo luminosity function (Gould, Flynn & Bahcall 1998; Gizis & Reid 1999) will be in error. Current transformations of Population II stellar luminosity functions into mass functions depend entirely upon theory, since there are no M subdwarfs with empirical mass measurements.

In order to search for M subdwarf binary systems, particularly systems suitable for mass determinations, we have obtained Hubble Space Telescope Planetary Camera (HST PC) images of spectroscopically classified metal-poor M subdwarfs (Gizis 1997) with well-determined trigonometric parallaxes. The targets were scheduled in Snapshot mode, which allowed only a fraction of the allocated targets to be observed. As it turned out, PC images were obtained of nine targets known to be within 50 parsecs of the Sun. An additional observation was obtained of VB12 (LHS 541), a more distant star of special interest since it is the lowest mass member of a metal-poor triple (Van Briesbroeck 1961; Gizis & Reid 1997b).

We report the results of our search in this paper. In Section 2, we discuss WFPC2 photometry for these stars. In Section 3, we discuss the results of our search for binaries. In Appendix A, we report on two Hyades systems observed by HST since the publication of Reid & Gizis (1997b).

### 2. Photometry

Our targets were observed using both the F555W and F850LP filters. Two F850LP images were obtained to allow cosmic ray removal. The standard HST pipeline processing was used. Photometry for the targets was measured on the HST flight system (Holtzman et al. 1995) including a correction for CTE effects:

\[
\text{mag} = -2.5 \log \left( \frac{\text{DN}}{t_{\text{exp}}} \right) + \text{ZP} + 2.5 \log(\text{GF}) - 2.5 \log \left( 1 + (0.04 \times Y/800) \right)
\]

where in our case GF = 1.987 for the PC chip, ZP = 21.725 for F555W, ZP = 19.140 for F850LP, and the counts are measured in a 0.5" aperture. The uncertainties due to Poisson statistics are less than 0.01 magnitude, but the uncertainties discussed by Holtzman et al. (1995) imply there may be effects that approach \(~0.02 - 0.03\) magnitude. The photometry is listed in Table 1, along with photometry and parallaxes compiled by Gizis (1997). Note that the original classification of LHS 407 as sdM5 was based upon a noisy Palomar 60-in spectrum. We have obtained a better spectrum using the Palomar 200-in. and found that the spectroscopic indices are TiO5 = 0.64, CaH1 = 0.60, CaH2 = 0.32, and CaH3 = 0.53, leading to a classification of sdM5.0 but placing it near the (arbitrary) esdM/sdM border.

In Figures 1 and 2, we compare the ground V and I_C photometry compiled by Gizis (1997) to our new HST photometry. Leggett (1992) estimated that a similar compilation of VI photometry had uncertainties of 0.05 magnitude. Also shown in each Figure are the polynomial fits based
on modelling determined by Holtzman et al. (1995). In the case of the F555W filter, Baraffe et al. (1997) have calculated both V and F555W magnitudes based on stellar models, and we also show those calculations in Figure 1. The figures suggest that the Holtzman et al. (1995) relation is reliable in transforming F850LP to $I_C$, while both Baraffe et al. (1997) and Holtzman et al. (1995) are consistent with the F555W-V data. The observed scatter is consistent with the probable uncertainties in the ground-based VI photometry. This result suggests that transformations used to study WFPC2 globular cluster color-magnitude diagrams are reasonable.

3. Binarity

Our observing technique and analysis is essentially identical to our previous surveys of Hyades (Gizis & Reid 1995; Reid & Gizis 1997b) and field (Reid & Gizis 1997a) M dwarfs. Companions with $\delta m_{850}$ of 0, 1, 3 and 5 magnitudes respectively can be resolved at 0.09, 0.14, 0.23, and 0.32 arcseconds respectively. However, we do not detect any companions to our target stars.

We estimate that our observations are sensitive to stars at the bottom of the halo main sequence for separations of $>10$ A.U.. The Baraffe et al. (1997) models predict that end of the metal-poor main sequence lies at $M_I \approx 14$. The last 1.7 magnitudes correspond to masses between 0.083 and 0.090 $M_\odot$, and are predicted to have very red colors but lie in a regime where the models are very uncertain. These subdwarfs are presumably rare, and they have not yet been detected. Using the Holtzman et al. (1995) transformations, we predict that these dwarfs have $M_{850} \approx 12.5$, as illustrated in Figure 3, but at present there is no empirical verification of the validity of the color transformations for subdwarfs of such extreme colors. For Figure 3, we have not allowed the $I_C$ to F850LP correction to exceed 1.5 magnitudes. We compare these values to coolest sdM (LHS 377, observed $M_{850} = 11.43$) and esdM (LHS 1742, tranformed $M_{850} = 11.1$) with parallaxes. Gizis & Reid (1997a) and Schweitzer et al. (1999) have found extreme M subdwarfs that are slightly cooler than LHS 1742a, but no parallaxes are yet available. A multi-epoch HST study of NGC 6397 found no detected cluster members by $M_I \approx 12.2 - 12.7$ (King et al. 1998), which would correspond to $M_{850} \approx 11.5 - 12.0$. While the hydrogen burning limit may be at or fainter than this point, it seems clear that the probability of detecting a subdwarf in this very small mass range is very low. Most of our targets are classified sdM, and therefore are more metal-rich than NGC 6397, which may result in a slightly redder, fainter hydrogen burning limit. We are sensitive to $M_{850} = 12$ companions as close as 4-10 A.U. for all of the primary targets except LHS 174 (for which the limit is 15 A.U.), and at distances of $\gtrsim 12$ A.U. we are typically sensitive to companions as faint as $M_{850} = 14 - 16$.

Since we detect no companions but have only nine nearby targets, the significance of our result is limited. In both the nearby Hyades cluster (Gizis & Reid 1995; Reid & Gizis 1997b) and field (Reid & Gizis 1997a), we found that 20% of our HST targets (which have similar mass but near-solar metallicity) were resolved into doubles, corresponding to an overall companion rate of 35%. Thus we expect to observe 1.8 M subdwarf companions rather than the none actually seen. Most of our targets are actually closer than the typical objects in our previous programs, and we reach
the hydrogen burning limit, so if anything the fraction of observable companions should be slightly higher.\(^2\) Our failure to detect any companions suggests that the binary fraction of M subdwarfs is less than or equal to that of Galactic disk M dwarfs. We note also the contrast between our result and the success found by Koerner et al. (1999), who found that three of ten L brown dwarf targets were resolved into near-equal-luminosity systems with separations of 5-10 A.U. – we would have detected equal-luminosity systems in that range of separations.

The possibility that the high-velocity, metal-poor stars have a low binary fraction dates back to Oort (1926), who found that high velocity stars were deficient in visual binaries. More recently, Abt & Wilmarth (1987) argued that both visual and spectroscopic binary fraction of Population II stars is only 40\% that of Population I stars. If so, this is a signature of the formation of the Galactic halo — Stryker et al. (1985) have shown that disruption of halo binaries is insignificant. Stryker et al. (1985) and others, however, have argued that the halo binary fraction is in fact comparable to that of the disk. Carney et al. (1994) have found that at least 15\% of their sample of halo FG subdwarfs are spectroscopic binaries with periods less than 3000 days. This is identical to the 14\% spectroscopic binary fraction of local disk G dwarfs (Duquennoy & Mayor 1991; Mazeh et al. 1992) in the same period range. Given our small number statistics, our data are consistent with either scenario. Our data and the G dwarf data taken together strongly suggest that the binary fraction is not greater than that in the disk. On the basis of imaging of wide binaries in IC 348, Duchêne, Bouvier & Simon (1999) argue that loose associations exhibit an excess of binaries with respect to both denser open clusters (IC 348, Trapezium, the Pleiades) and the solar neighborhood. They suggest that the disk binary frequency depends on stellar density within the cluster (or perhaps some other parameter which also controls the density). If this scenario is correct, and if it applies to the halo, it suggests that most halo stars form in clusters of densities comparable to or greater than the typical disk star formation region.

Our results suggest that further study of the binary fraction of halo stars of all masses will be profitable. A few more M subdwarfs are available for study within 50 parsecs; significant improvement in the sample size requires extending the sample out to 100 parsecs – increasing numbers of such subdwarfs are being identified. In addition to imaging, a radial velocity monitoring campaign is needed to search for closer objects. Comparison of such data to higher mass halo stars (Carney et al. 1994) and data for disk stars in a variety of environments may provide an important constraint on the formation and subsequent evolution of the Galactic halo. The importance of density on the star formation process and the subsequent evolution of halo binary systems also needs to be investigated.

\(^2\)We do not expect that the sample is biased against binaries, which would be overluminous in HR diagrams and therefore closer to the disk sequence, because the sample of high velocity parallax stars observed by Gizis (1997) include many spectroscopic non-subdwarfs near the disk main sequence. It is unclear whether overluminous binaries would be preferentially included or excluded by parallax and spectroscopic studies based on proper motion surveys.
4. Summary

We have found that color transformations of WFPC2 F555W and F850LP to ground V,I photometry are consistent with predictions. This supports analysis of WFPC2 color-magnitude diagrams of globular clusters. We find no companions to a sample of nine isolated nearby M subdwarfs and one tertiary M subdwarf. A binary fraction as high as that for similar mass disk M dwarf cannot be ruled out on the basis of such a small sample, but the lack of observed binaries suggests that the binary fraction is not high enough to seriously bias the luminosity function. Unfortunately, we have not yet found a system suitable for mass determinations.

This research was supported by NASA HST Grant GO-07385.01-96A.

A. Hyades Stars

Since our last analysis of our Hyades HST observations (Reid & Gizis 1997b), two more snapshots have been obtained. RHy 164 and RHy 326 have no detected companions. There are now nine resolved binaries out of 55, or 16%; including the three marginally resolved systems pushes the fraction up to 22%. The effect on our analysis is insignificant.

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Fig. 1.— Observed F555W and V magnitudes. Open squares are sdM, the solid triangle is our only esdM (LHS 364), and the crosses are late K subdwarfs. The solid line represents the synthetic Holtzman et al. (1995) prediction, while the small points represent metal poor models of Baraffe et al. (1997). The models appear to describe the data well, but some of the photometry appears suspect.
Fig. 2.— Observed F850LP and I_C magnitudes. The Holtzman et al. (1995) synthetic relation shown as a solid line matches the observations well. Symbols are as in Figure 1
Fig. 3.— Our target stars compared to model calculations. Symbols for the targets are as in Figure 1. The solid lines represent Baraffe et al. (1997) models with \([M/H]\) = −2.0, −1.5, −1.3, and −1.0 from left to right. Since companions with \(\delta m_{850} = 5.0\) and 3.0 would be detected at 0.32 and 0.23 arcsecond respectively. The very red tail beyond \(m_{555} - m_{850} = 4\) corresponds to masses less than 0.01\(M_\odot\) above the hydrogen burning limit where the models and colors are very uncertain.
Table 1. Targets

| LHS | $m_{555}$ | $m_{850}$ | V   | $I_C$ | d (pc) | Sp.  |
|-----|-----------|-----------|-----|------|-------|------|
| 169 | 14.179    | 12.146    | 14.13 | 12.41 | 32.4  | esdK7 |
| 174 | 12.776    | 10.567    | 12.75 | 10.92 | 49.0  | sdM0.5|
| 216 | 14.676    | 12.125    | 14.66 | 12.58 | 32.7  | sdM2.0|
| 320 | 14.088    | 11.456    | 14.00 | 11.86 | 38.5  | sdM2.0|
| 364 | 14.531    | 12.208    | 14.61 | 12.66 | 26.7  | esdM1.5|
| 377 | 18.441    | 14.161    | 18.39 | 14.91 | 35.2  | sdM7.0|
| 407 | 16.666    | 13.646    | 16.57 | 14.18 | 31.7  | esdM5.0|
| 522 | 14.213    | 12.261    | 14.15 | 12.53 | 37.3  | esdK7 |
| 536 | 14.687    | 12.450    | 14.65 | 99.99 | 44.1  | sdM0.5|
| 541 | 16.574    | 13.882    | 16.46 | 14.37 | 80.6  | sdM3.0|
| 3409| 15.187    | 11.893    | 15.16 | 12.34 | 20.0  | sdM4.5|