COOL SUBDWARF INVESTIGATIONS. III. DYNAMICAL MASSES OF LOW-METALLICITY SUBDWARFS

Wei-Chun Jao (鈕惟君)¹,², Edmund P. Nelan³, Todd J. Henry⁴,⁵, Otto G. Franz⁴, and Lawrence H. Wasserman⁴
¹Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30302, USA; jao@astro.gsu.edu
²Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; nelan@stsci.edu
³RECONS Institute, Chambersburg, PA 17201, USA; thony@astro.gsu.edu
⁴Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001, USA; ogf@lowell.edu, lhw@lowell.edu

Received 2016 May 25; revised 2016 June 28; accepted 2016 July 4; published 2016 November 10

ABSTRACT

We report dynamical mass measurements for the components of the previously known double-lined spectroscopic subdwarfs G 006-026 B and C using the Fine Guidance Sensors on the Hubble Space Telescope. To build the empirical mass–luminosity relation for low-metallicity subdwarfs, we collect four other subdwarf systems with dynamical masses that we compare to theoretical models for various metallicities on the mass–luminosity relation. For most stars, they fall in the regions where the models predict them to be low metallicity. This effort highlights the scarcity of dynamical masses for subdwarfs, and that much work remains to be done to improve the mass errors and metallicity measurements of low-mass subdwarfs in our Galaxy.

Key words: astrometry – binaries: spectroscopic – solar neighborhood – stars: distances – stars: fundamental parameters

1. INTRODUCTION

Subdwarfs are Galactic fossils that presumably comprise the bulk of the halo, and are crucial touchstones of the star formation and metal enrichment histories of the Milky Way. The local paucity of subdwarfs and their intrinsic faintness make them difficult to characterize, unlike their disk counterparts. For example, there are currently only three confirmed subdwarf systems within 10 pc: µ Cas AB, CF UMa, and Kapteyn’s Star (Monteiro et al. 2006). Many subdwarfs are detected via high proper motion star surveys (e.g., Ryan & Norris 1991; Carney et al. 1994; Gizis 1997; Jao et al. 2005, 2008; Lépine et al. 2007, and Savcheva et al. 2014), yielding important information about their kinematics, chemical compositions, and space densities. However, their masses—the single most important parameter for a star—are still mostly unknown, but would be of great use in studies of the Galactic halo, globular clusters, and other old and/or low-metallicity systems.

There are currently only a half dozen subdwarf systems (here defined as stars having [m/H] or [Fe/H] ≤ −0.5) with dynamical mass measurements. McCarthy et al. (1993) used infrared speckle interferometry and Drummond et al. (1995) used adaptive optics to measure the masses of µ Cas AB, which has [Fe/H] = −0.71 (Karaali et al. 2003) and is one of the nearest subdwarf systems. Söderhjelm (1999) reported masses for GJ 704 AB (99 Her), which has [Fe/H] = −0.58 (see Table 5 below). Recently, Horch et al. (2015) reported total masses for two subdwarf binaries (HIP 85209AB and HIP 95575AB) using the Differential Speckle Survey Instrument (DSSI) to resolve these two doubled-lined spectroscopic binaries (Goldberg et al. 2002; Halbwachs et al. 2012). We use the mass-ratio from SB2 results and total masses from Horch et al. (2015) to get individual masses. All of these results are summarized in Table 1. We note that HIP 81023AB and HIP 103987AB both have metallicity less than −0.5, but have

³ Visiting Astronomer, Cerro Tololo Inter-American Observatory. CTIO is operated by AURA, Inc. under contract to the National Science Foundation.
testing of low-metallicity theoretical models remains to be done. In this paper, we present new dynamical masses of \(-0.47\) and 0.44 \(M_{\odot}\) for the low-metallicity subdwarfs, G 006-026 B and C, adding two subdwarf masses to establish the empirical MLR. We also recalculate the masses for GI 704 A and B by reassessing the resolved measurements to date.

G 006-026 BC is a double-lined spectroscopic binary with period of about 302 days (Goldberg et al. 2002). Carney et al. (1994) reported that the primary star in the system, the G-type star G 006-026 A, has a metallicity of [m/H] = \(-0.88\). Later, Casagrande et al. (2011) and Holmberg et al. (2009) use photometry to determine the primary’s [Fe/H] as \(-0.52\) and \(-0.60\), respectively. We assume that the B and C components have the same metallicity as the primary, and that they therefore meet our criterion for subdwarfs as stars having [Fe/H] \(< -0.5\). Of the seven orbital elements have been determined: period \((P)\), time of the periastron \((T)\), semimajor axis \((a)\), eccentricity \((e)\) and position of periastron \((\omega)\). The binary’s orbital inclination \((i)\) and longitude of the ascending node \((\Omega)\) remain unknown from spectroscopic data alone. Because of its relatively large \(a \sin i\) value among the 34 SB2 systems in Goldberg et al. (2002), we expected the Fine Guidance Sensor (FGS) on the Hubble Space Telescope \((HST)\) to be able to resolve the system at appropriate orbital phases. By accurately measuring the angular separation of the two components at only a few epochs, we can reliably determine all of the orbital elements and thus the individual masses of the B and C components.

2. OBSERVATIONS AND RESULTS

We utilized one of the \(HST\)’s three FGSs \((HST/FGS1r, hereafter simply FGS)\) in its TRANS mode to resolve G 006-026 BC. The FGS is a white light shearing interferometer. When operated in its high angular resolution TRANS mode, it scans a luminous source and produces interference fringes along two orthogonal axes \((X\) and \(Y)\). Resolved binary systems yield interference fringes, or S-curves, that have reduced amplitude and different morphology than those of point sources (unresolved stars). Model binary systems, built from point source templates, are used to determine the projected separation and relative brightness of the binary components along both the FGS \(X\) and \(Y\) axes. We carried out TRANS mode observations of G 006-026 BC during \(HST\) Cycles 15 and 19 to measure the separations and position angles for the C component relative to B at six epochs. Typically, we scheduled 30–32 scans on both \(X\) and \(Y\) axes during each visit, with scan lengths of 0.4–4.0\(^{\circ}\) on either side of the target. Observations were made through the F583W filter, which provides magnitude differences similar to the \(V_j\) band in the Johnson system (hereafter, simply \(V\)).

The spectroscopic data (Goldberg et al. 2002), available mass estimates, and the \(Hipparcos\) distance to G 006-026 A indicated that the maximum separation of the two stars would be \(\pm 25\) mas. However, because we did not know the position angle of the binary (due to lack of knowledge of the orbit’s inclination and longitude of ascending node), it was not possible to select with certainty an orientation of the \(HST\) that would guarantee that the binary would be resolved along both axes of the FGS, which has a per axis angular resolution close to 10 mas. For the first observation in 2006, we selected an observation date that corresponded to a time of maximum separation assuming an inclination of 45\(^{\circ}\), but still with no knowledge of the longitude of the ascending node. The binary was well resolved along the FGS \(X\) axis but unresolved along the \(Y\) axis. The observed separation along the \(X\) axis allowed for an estimate of the system’s inclination but left a position angle uncertainty of about \(+/- 27^{\circ}\) (because the actual \(X\) axis separation can be anywhere from \(+/- 10\) mas). Subsequent observations in 2011 through 2014 were planned using the spectroscopic orbital elements combined with the FGS data previously acquired. For our last epoch in 2014, we observed the binary in two consecutive \(HST\) orbits with a telescope roll change of 41\(^{\circ}\) between them in an attempt to resolve the system along both FGS axes, or to at least tightly constrain the binary position angle.

The standard \texttt{stfits} routine in the IRAF/STSDAS package was used to convert the archived TRANS mode FITS files into GEIS files (generic edited information sets, the original file structure used for the legacy \(HST\) instrument calibration pipelines, but still in use for FGS). For each visit these GEIS data were processed through the FGS raw data processing routine \texttt{calfgsa}, resulting in sets of individual interference scans in the \(X\) and \(Y\) directions across the binary. The analysis package \texttt{ptrans} was then used to cross-correlate, and co-add the individual scans, and to smooth the final co-added \(X\) and \(Y\) axis scans for each visit. Additional details of the reduction procedure can be found in the \(HST/FGS\) Data Handbook (http://www.stsci.edu/hst/fgs/documents/datahandbook/).
The analysis of FGS TRANS mode observations of binary stars requires the availability of TRANS mode observations of single (point source) calibration stars of similar color. In 2009 January the FGS1r internal optics were re-aligned to re-optimize (change) the instrument’s interferometric response. Thus our early 2006 epoch observation uses SAO 185689 as the calibration star, which was observed in 2006, while all later epochs use LHS 73, which was observed in 2009 after the FGS re-optimization. The same data processing routines and packages discussed above were applied to these calibration stars. Routine monitoring of FGS TRANS mode performance by STScI indicates that its interference fringes have not changed since FGS’s realignment in 2009, so use of LHS 73 data from 2009 as the point source template for the later epochs is justified. We note that LHS 73 ($V-K_s = 3.44$) is a known low-metallicity K6 subdwarf (Jao et al. 2008) with a similar color to G 006-026 BC ($V-K_s = 4.14$). Two other often used FGS calibrators, Latcol-A and HD233877, do not yield better fits/residuals than LHS 73, so we use LHS 73 as our calibrator.

Finally, we used the standard binary_fit package discussed in the HST FGS Data Handbook to compare the interference fringes, or S-curves, of G 006-026 BC to the calibrators to calculate the best fitting component magnitude difference and separations in the $X$ and $Y$ directions. Figure 1 shows an example fitting result for both axes in 2013.09. The binary_fit program yields the best $\Delta m$ and separation by comparing with the calibrator. However, we notice that the fitting for this system is not sensitive to the $\Delta m$ for all scans as shown in Figure 2. For this reason, we fix the $\Delta m$ at 0.3 with an error of 0.3 mag and apply this fixed value for all other scans while we use the binary_fit routine.

We converted these separations along the FGS axes to separations $\rho$ and position angles $\theta$ on the sky using the HST keyword PA_APER in the GEIS header, which is the position angle of the FGS $Y$ axis at the time of the observation. Results for the six epochs of observation are given in Table 2. Measurement errors in the $\rho$ and $\theta$ are shown in parenthesis. For epochs 2006.55227 and 2011.83228 the binary was only resolved along one FGS axis, therefore the resultant uncertainty in position angle is large (assuming up to 10 mas uncertainty in separation along the unresolved axis). The data acquired in 2014 have the binary marginally resolved along the FGS $Y$ axis. For such small separations, solutions of opposite parity must be considered (i.e., a separation of $-12.4$ mas is nearly indistinguishable from a separation of $+12.4$ mas). However, a different parity of the $Y$-axis separation for either of the two visits produces incompatible position angles (205$^\circ$26 for the first visit, 299$^\circ$63 for the second visit). Thus by having changed the HST roll angle by 41$^\circ$ between the two visits, we are able to select the correct parity and tightly constrain the binary position angle at this epoch.

3. G 006-026 BC

We used the Multipurpose Interactive Image Processing System (Gudehus 2001) package to calculate all seven orbital elements as well as dynamical masses for the B and C components by using the FGS results from this work and radial velocities from Goldberg et al. (2002). The radial velocity dataset includes 43 epochs/observations taken with the Center for Astrophysics Digital Speedometers, which provide velocities with residuals on the order of 1 km s$^{-1}$. The radial velocity data are shown in Figure 3, with the fit to the data from our work. A total of five epochs of astrometric data from the FGS are used to complete the determination of the systems orbital elements. Figure 4 shows the plot of G 006-026 BC’s relative orbit. Table 3 shows our fit to the orbital elements along with those from Goldberg et al. (2002).

There are four ($P, e, \omega, T$) orbital elements and $\gamma$ (system velocity) from this work in common with measurements from Goldberg et al. (2002), and all are generally consistent. However, because this system is a challenge to resolve with FGS, the error in orbital inclination (4$^\circ$98) is relatively large and results in larger mass errors (11%) than anticipated. By combining the visual and spectroscopic orbits, we measure a
high-quality orbital parallax of 0.002634 ± 0.00002, placing the system at 37.9 pc. This is consistent with the trigonometric parallax measured by Hipparcos for the primary, G 006-026 A, 0.02561 ± 0.00134 (van Leeuwen 2007).

4. GJ 704 AB

GJ 704 AB is a visual binary with a ~56 year orbital period at 15.6 pc. The first visual measurement of the system dates back to 1859 (Mason et al. 2015, Heintz 1972, Söderhjelm 1999, and Kennedy et al. 2012) have all calculated orbits and individual masses for the components, while Malkov et al. (2012) reported a total mass for the system. The system is also a single-lined spectroscopic binary (SB1), with an orbit published by Abt & Willmarth (2006). Orbital results for all five studies are given in Table 4.

As of 2015, the Washington Double Star (WDS) catalog (Mason et al. 2015) lists 240 different epochs of observations for GJ 704 AB, with the most recent measurement being that of Kennedy et al. (2012). After removing epochs with uncertain measurements and large errors, we have adopted a dataset including 204 total measurements spanning 1859–2011 (i.e., the same coverage as Kennedy et al. 2012), and recalculate the relative orbit by combining both WDS resolved measurements and the radial velocity data from Abt & Willmarth (2006). For a given WDS epoch, we assign a weight for the astrometric position based on telescope aperture, system separation, and/or magnitude difference, following the prescription of Hartkopf et al. (2001). Table 4 lists our new set of orbital elements, which are consistent with previous efforts. Our resulting orbital fit is shown in Figure 5, where it is clear that there are few reliable measurements near periastron. We use the period and semimajor axis of this orbit and the weighted mean parallax of 64.3 mas from van Altena et al. (1995) and Söderhjelm (1999) to derive a total mass for the system of 1.40 ± 0.03 \( M_\odot \).

With the total system mass and orbital elements in hand, there are two ways to calculate the masses of the components. First, we use the mass function \( f(m) = 0.01273 \) of the SB1 reported by (Abt & Willmarth 2006) to determine individual masses of 0.91 \( M_\odot \) and 0.48 \( M_\odot \). Second, we use \( \Delta V = 3.3 \) mag and the photocentric semimajor axis of 0.0353 from Heintz (1972) to calculate the scale of the photocentric/relative orbit that yields the mass fraction, \( f = M_B/(M_A + M_B) = 0.379 \). Given the total mass, we then find masses of 0.86 \( M_\odot \) and 0.53 \( M_\odot \) for the components. For the final masses, we adopt the means of these two methods, and find masses of 0.89 \( M_\odot \) and 0.51 \( M_\odot \). The mean difference between these mean values, 0.03 \( M_\odot \), is adopted as their errors, as listed in Table 4.

According to SIMBAD, 55 publications have reported abundances for GJ 704 AB since 1960. Determining which [Fe/H] values are best is a monumental task beyond the scope of this paper. We select four measurements of [Fe/H] reported in refereed publications during the past 10 years and [Fe/H] measurements, including both spectroscopic and photometric methods. These measurements are given in Table 5, where we list a mean value of [Fe/H] = −0.58 (which indicates this to be a low-metallicity binary. We note only Holmberg et al. (2009) used photometry to measure [Fe/H].

5. \( M_V \) VALUES AS PROXIES FOR LUMINOSITIES

To develop an empirical MLR for subdwarfs we use \( M_V \) in the Johnson system as a proxy for luminosity. Two systems, \( \mu \) Cas AB and GJ 704 AB, have combined \( V \), \( \Delta V \), and parallax measurements, so it is straightforward to obtain individual \( V \) magnitudes for each component. However, the two subdwarf systems from Horch et al. (2015) have \( \Delta m_{692 \text{ nm}} \) and \( \Delta m_{880 \text{ nm}} \) rather than \( \Delta V \) measurements. To convert \( \Delta m_{692 \text{ nm}} \) from this special narrow band to the \( V \) filter, we may (1) use synthetic spectra for low-metallicity stars convolved with filter passbands to convert from \( \Delta m_{692 \text{ nm}} \) to \( \Delta V \), or (2) build an empirical relation from existing systems with both \( \Delta m_{692 \text{ nm}} \) and \( \Delta V \) measurements. The first method requires knowing the metallicity of each system and the spectral types or effective temperatures of each component so that we can select corresponding synthetic spectra with the same \( [m/H] \) and \( T_{\text{eff}} \). However, in order to make a direct comparison between empirical and model MLRs, here we try to limit the use of synthetic spectra to derive any stellar parameters, including \( V \), so we use the second method.

To create a reliable conversion from \( \Delta m_{692 \text{ nm}} \) to \( \Delta V \), we first searched the WDS for systems with both measurements. Unfortunately, we found no such systems, but we did find 51 systems with both \( \Delta m_{692 \text{ nm}} \) and \( V_{\text{Tycho}} \) measurements. A linear relation between measurements through these two filters is shown in Figure 6.

Ideally, we would then convert \( \Delta V_{\text{Tycho}} \) to \( \Delta V \) using the polynomial conversion provided by (Mamajek et al. 2002).

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**Table 2**

| Epoch | X sep (mas) | Y sep (mas) | PA Aper (degree) | \( \rho \) (mas) | \( \theta \) (degree) |
|-------|------------|------------|-----------------|-----------------|------------------|
| 2006.5227 | +22.7 | -7.0 | 170.6 | 23.8(2) | 277.7(27) |
| 2011.3328 | +8.9 | 18.5 | 170.2 | 20.6(2) | 195.9(33) |
| 2013.09010 | -21.0 | 13.4 | 344.0 | 24.9(2) | 286.6(5) |
| 2013.12103 | -20.8 | 13.1 | 337.0 | 24.6(2) | 279.3(5) |
| 2014.03481* | -21.7 | 12.4 | 325.0 | 24.8 | 265.0 |
| 2014.03498* | -24.0 | -10.5 | 6.0 | 26.2 | 252.0 |

**Note.**

* We combine these two epochs of data to get a mean separation (25.5 ± 2 mas) and position (258.8 ± 7°) angle in 2014.0349 for our orbital fitting routine. The individual errors of \( \rho \) and \( \theta \) of these two epochs are not shown in this table.
However, this conversion requires the $B_T - V_T$ colors of each star, which are currently unavailable for either of the two systems. Nonetheless, we note that the error in our relation shown in Figure 4 is $\sim 0.46$ mag between $\Delta V_{\text{Tycho}}$ and $\Delta m_{692}$, which is much larger than the conversion error between Johnson $V$ and $V_{\text{Tycho}}$. Therefore, until direct $\Delta V$ measurements are available, we assume $\Delta V_{\text{Tycho}} \approx \Delta V$ for the two subdwarf systems in Horch et al. (2015) and adopt $\sim 0.46$ mag for our $V$ errors.

The G 006-026 BC system targeted with FGS also has no $\Delta V$ measurement, but we can use our $\Delta m_{583W}$ value from the FGS observations discussed in Section 2. Henry et al. (1999) have noted that the F583W filter in the HST’s FGSs nearly matches the Johnson $V$ passband, and provided a relation to convert $\Delta m_{583W}$ to $\Delta V$. Although their relation was derived for stars presumed to have solar metallicity, we assume that even if the magnitudes will be different for subdwarfs versus main sequence stars, the colors between two stars in a system will not be drastically different. So, we assume $\Delta m_{583W} \approx \Delta V$ for G 006-026 BC.

6. THE EMPIRICAL MLR AND DISCUSSION

We plot the 10 low-metallicity subdwarfs discussed here as solid points and empirical MLR shown in Figure 7. The masses come directly from Tables 1, 3 and 4 where, in addition to the subdwarfs, main sequence stars with masses from Delfosse et al. (2000), Torres et al. (2010), and Benedict et al. (2016) are plotted in Figure 7. These main sequence stars generally fall

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**Figure 3.** Radial velocity data for G 006-026 BC from Goldberg et al. (2002). Filled and open circles are for the primary and secondary velocities, respectively. Residuals are shown on the bottom of the figure for both primary and secondary. Because there is no error available for individual radial velocity measurements, the mean error of 0.7 km s$^{-1}$ is used for all measurements.

**Figure 4.** Relative orbital motion of G 006-026 BC is shown using the FGS results. Dashed lines connect observed and calculated positions.

**Table 3**

| Parameters                | Goldberg      | This Work     |
|---------------------------|---------------|---------------|
| Period (P year)           | 0.826 ± 0.001 | 0.826 ± 0.0003|
| Semimajor axis ($a''$)    | ...           | 0.0108 ± 0.0004|
| Eccentricity (e)          | 0.582 ± 0.017 | 0.577 ± 0.004 |
| Inclination ($i$)         | ...           | 128.31 ± 4.98 |
| Ascending Node ($\Omega$) | 252.8 ± 1.9   | 253.24 ± 0.46 |
| Longitude of Periastron ($\omega$) | 1991.4385 ± 0.004 | 1991.4394 ± 0.0008 |
| Epoch of Periastron (T year) | 1.76 ± 0.12  | 1.76 ± 0.03   |
| System Velocity (γ km s$^{-1}$) | 14.25 ± 0.42 | 14.16 ± 1.44  |
| Primary Amplitude ($K_1$ km s$^{-1}$) | 15.48 ± 0.44 | 15.39 ± 1.57  |
| Primary Amplitude ($K_2$ km s$^{-1}$) | 15.48 ± 0.44 | 15.39 ± 1.57  |
| Parallax ($\pi''$)        | ...           | 0.02634 ± 0.0002 |
| Total Mass ($M_e$)        | ...           | 0.911 ± 0.110 |
| $M_{A,e}$                 | 0.474 ± 0.053 |
| $M_{B,e}$                 | 0.436 ± 0.049 |
The ages of low-metallicity stars are primarily measured using nearby GCs. Recently, Bono et al. (2010) and Correnti et al. (2016) acquired deep optical and near-IR photometry from the ground and HST to extend the detected GC populations down to early M dwarfs. Many of these clusters/cool dwarfs have ages estimated to be around \( \sim 11 \) Gyr. In addition, Monteiro et al. (2006) measured the first ages for two cool field K subdwarfs via their white dwarf companions’ cooling curves, and found that these likely thick disk subdwarfs have ages of \( 6–9 \) Gyr.

However, until we can link the origins of these field subdwarfs to nearby GCs, we conservatively adopt \( 6 \) Gyr as the age for the all nearby subdwarfs. We sketch \( 6 \) Gyr isochrones for stars with \( [\text{metallicity}] = -0.5, -1.0, \) and \(-2.0\) from BT-Settl isochrones (Baraffe et al. 2015) in Figure 7 to permit comparisons to the empirical points for the subdwarfs.

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**Table 4**

| Parameters                  | Heintz (1972) | Söderhjelm (1999) | Malkov et al. (2012) | Kennedy et al. (2012) | Abt et al. (2006) | This Work  |
|-----------------------------|--------------|-------------------|----------------------|-----------------------|-----------------|------------|
| Period (\( P \) year)       | 55.8         | 56.4              | 56.04                | 56.3                  | 56.4 (fixed)    | 55.91 ± 0.12|
| Semimajor axis (\( a \))    | 1.00         | 1.00              | 1.123                | 1.06                  | ...            | 1.05 ± 0.02 |
| Eccentricity (\( e \))      | 0.74         | 0.75              | 0.798                | 0.766                 | 0.75 (fixed)   | 0.761 ± 0.007|
| Inclination (\( i \))       | 32.0         | 34.0              | ...                  | 39                    | ...            | 36.18 ± 1.72 |
| Ascending Node (\( \Omega \)) | 218.7       | 216.0             | ...                  | 41                    | ...            | 223.62 ± 3.21 |
| Longitude of Periastron (\( \omega \)) | 300.6 | 301.0             | ...                  | 116                   | 120.4          | 295.38 ± 2.84 |
| Epoch of Periastron (\( T \)) | 1941.8      | 1998.0            | ...                  | 1997.62               | 1999.52        | 1997.8 ± 0.09  |
| Parallax (\( \pi \))        | 0.064        | 0.0639            | 0.06393              | 0.06393               | ...            | 0.0643 ± 0.00068 |
| Total Mass (\( M_\ast \))   | 1.49         | 1.25              | 1.73                 | 1.4                   | ...            | 1.40 ± 0.03  |
| Astrometric Coverage (year)  | 1859–1968    | 1859?–1997?       | unknown              | 1859–2011             | 1988–1996 \((V_{\text{rad}})\) | 1859–2011  |
| \( M_{A,0} \)               | 0.90         | (0.75)            | ...                  | 0.94                  | ...            | 0.89       |
| \( M_{B,0} \)               | 0.59         | (0.50)            | ...                  | 0.46                  | ...            | 0.51       |

**Note.** The span of astrometric coverage is for visual relative positions, \( \rho \) and \( \theta \), except in the case of Abt & Willmarth (2006), where the duration of the radial velocity measurements is given. The astrometric coverage for Söderhjelm (1999) is estimated to be up to 1997, which is the latest astrometric reference in that paper. We use \( f = 0.4 \) and the total mass from Söderhjelm (1999) to estimate individual masses for that effort. Malkov et al. (2012) do not clearly state the timespan of observations used for their analysis. We note that the total masses are different between Heintz (1972) and Söderhjelm (1999), even though their orbital elements are essentially identical. The values in this table are directly from their papers. Based on Kepler’s third law, the total masses should be 1.49 and 1.25, respectively for Heintz (1972) and Söderhjelm (1999).

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**Figure 5.** Relative orbital motion of GJ 704 AB is shown using data from the WDS. Dashed lines connect observed and calculated positions.

**Figure 6.** Relation \( \Delta V_{\text{Tycho}} \) vs. \( \Delta m_{\text{HJD2}} \) from 51 binaries in the WDS catalog. The solid straight line is a fit \( (\Delta V_{\text{Tycho}} = -0.35 + 0.95 \times \Delta m_{\text{HJD2}}) \) for these points.

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**Table 5**

| Metallicity Values for GJ 704 AB |
|----------------------------------|
| **Publications**                | \([\text{Fe/H]}\) |
| Takeda & Takada-Hidai (2013)     | -0.58          |
| Maldonado et al. (2012)          | -0.6           |
| Korotin et al. (2011)            | -0.6           |
| Holmberg et al. (2009)           | -0.55          |
| **Mean**                         | -0.58          |

along the 1 Gyr theoretical isochrone from Baraffe et al. (2015), shown with a solid line.

Note. The span of astrometric coverage is for visual relative positions, \( \rho \) and \( \theta \), except in the case of Abt & Willmarth (2006), where the duration of the radial velocity measurements is given. The astrometric coverage for Söderhjelm (1999) is estimated to be up to 1997, which is the latest astrometric reference in that paper. We use \( f = 0.4 \) and the total mass from Söderhjelm (1999) to estimate individual masses for that effort. Malkov et al. (2012) do not clearly state the timespan of observations used for their analysis. We note that the total masses are different between Heintz (1972) and Söderhjelm (1999), even though their orbital elements are essentially identical. The values in this table are directly from their papers. Based on Kepler’s third law, the total masses should be 1.49 and 1.25, respectively for Heintz (1972) and Söderhjelm (1999).
According to the models, low-metallicity subdwarfs appear brighter in $M_V$ than dwarfs at a given mass, or alternatively, are less massive for a given $M_V$.

Systems like $\mu$ Cas AB and GJ 704 AB are clearly seen above the MLR of main sequence stars. The locations of $\mu$ Cas A and B, which have $[\text{m/H}] = -0.71$, are well matched to the model predictions for stars with $[\text{m/H}] = -1.0$ at an age of 6 Gyr. The metallicity of GJ 704 AB appears much lower ($[\text{m/H}] < -1.0$) than what has been measured $[\text{Fe/H}] = -0.58$, but the two subdwarfs certainly appear to be of lower metallicity than main sequence stars. We note that Kennedy et al. (2012) used Herschel’s Photodetector and Array Camera and Spectrometer at 100 and 160 $\mu$m to reveal a rare and convincing circumbinary polar-ring debris disk around GJ 704 AB. This makes this system very unusual because this disk has somehow been maintained or created around a presumably old subdwarf binary. $M_V$ values used in Figure 7 for GJ 704 A and B do not include any adjustment for obscuration by the disk, which is likely to be minimal. If such an adjustment is required, the points would move to brighter $M_V$, and the locations of the points would be toward even lower metallicity.

The remaining subdwarf systems generally fall along the low-metallicity curves. Because of the large mass errors of HIP 85209 AB and HIP 95575 AB measured by Horch et al. (2015), it is difficult to make a direct comparison between observations and models. Latham et al. (1992) reported a metallicity for HIP 85209 AB (HD 157948 AB) of $[\text{m/H}] = -0.75$, whereas Goldberg et al. (2002) reported $[\text{m/H}] = -0.5$. Horch et al. (2006) measured the dynamical masses of these subdwarfs using FGS, and determined via comparisons to the theoretical Yale-Yonsei models that the system should have metallicity close to $-0.5$. We note that the mass errors for HIP 85209 A and B are relatively large, so these two stars do not place strict constraints on the models.

Finally, both components in the new system described in this paper, G 006-26 B and C, merge with points for main sequence stars with solar metallicity in the MLR. This presents a conflict with the low-metallicity measurements discussed in Section 1—the points should lie near the $[\text{m/H}] = -0.5$ or $-1.0$ lines in Figure 7. For example, Carney et al. (1994) used a high signal-to-noise ratio echelle spectrograph to determine the metallicity of the primary in the system G6-26A, which is also a SB2 binary with a period of 8.7 days (Goldberg et al. 2002). They discussed the challenges of measuring the metallicities of SB2 binaries in detail, but there is no flag of the system regarding quality of their result of $[\text{m/H}] = -0.88$. Casagrande et al. (2011) and Holmberg et al. (2009) used photometry of the unresolved primary to determine $[\text{Fe/H}] = -0.52$ and $-0.60$, respectively, thereby providing results that match Carney’s, again indicating that the system is metal-deficient.

In order to move the masses of B and C components to the low-metallicity region, the B component’s mass would need to be reduced to $\sim 0.3 M_\odot$ (62.7% of $0.478 M_\odot$) to fall on the $-0.5$ metallicity curve on Figure 7. From Kepler’s third law, such a mass decrease requires that the semimajor axis of this system regarding quality of their result of $[\text{m/H}] = -0.88$. Casagrande et al. (2011) and Holmberg et al. (2009) used photometry of the unresolved primary to determine $[\text{Fe/H}] = -0.52$ and $-0.60$, respectively, thereby providing results that match Carney’s, again indicating that the system is metal-deficient.

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Given the overall trend that subdwarf systems are elevated in the MLR and match with the model, there are several confounding factors that challenge observational programs focusing on mapping the MLR for subdwarfs, including: (1) metallicity errors may be large because all available subdwarf binaries have separations less than 1″, so the acquired spectra used to determine metallicities are for two objects, not one, with consequent complications when measuring linewidths (G 006-026 AB is the only system to have an early-type primary, which can be used to determine metallicity independently); (2) mass errors are large because subdwarfs are rare and further away than comparable main sequence systems in the solar neighborhood, so parallax errors are larger; (3) accurate ΔV measurements are not available for a few systems and conversions from other filters are imperfect (although overall, this is not likely to be a major problem); (4) not all of the systems are of the same age, so comparison to a single isochrone for 6 Gyr old systems may not be appropriate.

This work shows that building an empirical MLR for subdwarf systems has just begun. Only two subdwarf systems, μCas AB and GJ 704 AB, are clearly off the metallicity curves for main sequence stars and have low mass errors, so there remains significant work to do in understanding the astrophysics that drives the locations of low-metallicity stars on the MLR. We can make progress in our understanding of these Galactic fossils, as well as the star formation history and mass distribution of stars in the Milky Way, by discovering more subdwarf binaries for which high-quality metallicities, luminosities, and masses can be measured.

We thank D. Latham and A. Bieryla for providing us with their unpublished metallicity of GJ 704 AB. We thank G. Kennedy for the discussions of GJ 704 AB. We also thank the anonymous referee for very valuable comments that improved this manuscript. The HST-FGS observations were supported for program number 10927 and 12561 by NASA through grants from the Space Telescope Science Institute, which is operated by the Association for Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This work also has used data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center at California Institute of Technology funded by NASA and NSF. This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory.

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