# METAL-POOR FIELD BLUE STRAGGLERS: MORE EVIDENCE FOR MASS TRANSFER<sup>1</sup>

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<sup>&</sup>lt;sup>1</sup>Some of the results presented here used observations made with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona

Received \_\_\_\_\_; accepted \_\_\_\_\_

# ABSTRACT

We report radial velocity studies of five candidate metal-poor field blue stragglers, all known to be deficient in lithium. Four of the five stars are single-lined spectroscopic binaries, with periods ranging from 302 to 840 days, and low orbital eccentricities, in agreement with similar behavior found for other blue straggler candidates by Preston & Sneden (2000) and Carney et al. (2001). The limited data available for lithium abundances indicate that all blue straggler binaries have depleted lithium, but that constant velocity stars generally have normal lithium abundances. This suggests that the "lithium gap" for hot metal-poor main sequence stars may not exist or lies at higher temperatures than found in the Hyades. Our results and those of Preston & Sneden (2000) show higher values of  $v_{\rm rot} \sin i$  for the binary stars than those of comparable temperature constant velocity stars. The orbital periods are too long for tidal effects to be important, implying that spin-up during mass transfer when the orbital separations and periods were smaller is the cause of the enhanced rotation. The mass function distribution is steeper for the blue straggler binary stars than that of lower mass single-lined spectroscopic binaries, indicating a narrower range in secondary masses. We argue that if all secondaries are white dwarfs with the same mass, it is probably around 0.55 $M_{\odot}$ . The models of Rappaport et al. (1995), applied to white dwarf secondaries, suggest that the orbital elements of all metal-poor binary blue stragglers are consistent with stable mass transfer, with the possible exception of G202-65.

Subject headings: binaries: spectroscopic — blue stragglers — Galaxy: halo

# 1. INTRODUCTION

The "blue stragglers" were first identified by Sandage (1953) in the globular cluster M3. Since their discovery, blue stragglers have been found in many other globular clusters, and in open clusters as well. The frequency of blue stragglers is also correlated with position in clusters, being generally higher in the denser, more dynamically evolved portions, indicating that stellar interactions, perhaps stellar mergers or hardening of binaries leading to mass transfer, may be the cause or at least one of the causes of the phenomenon (Mateo et al. 1990). Hut et al. (1992), Stryker (1993), Livio (1993), Trimble (1993), Bailyn (1995), and Leonard (1996) have provided extensive reviews of blue stragglers in globular clusters.

Some globular clusters show declining frequencies (per unit luminosity) of blue stragglers in their lower density outer regions, but others (M3: Ferraro et al. 1993, 1997; M55: Zaggia et al. 1997; 47 Tuc: Ferraro et al. 2004 and Mapelli et al. 2004) show an enhanced frequency in the outermost, lowest density regions. This is explained qualitatively by invoking two different mechanisms for the creation of blue stragglers in clusters. In the central regions, dynamical effects involving collisions may enhance the probabilities for creating blue stragglers (Sills & Bailyn 1999). In the outer regions, normal stellar evolution may be responsible for their creation.

A variety of stellar evolution explanations have been proposed to explain such unusual systems, one of which (mass transfer: McCrea 1964) does not require any alterations to standard stellar evolution theory. But two explanations (pulsation-driven mass loss: Willson, Bowen, & Struck-Marcell 1987; internal mixing: Wheeler 1979a,b; Saio & Wheeler 1980) do require significant modifications and make the understanding of the blue straggler phenomenon of high importance. The mass transfer model is perhaps favored by the increasing blue straggler frequencies seen in the outer regions of the above clusters because that is where binary systems are most likely to survive. Mapelli et al. (2004), for example, were able to reproduce the blue straggler binary frequency distribution in 47 Tuc using a combination of collisional creation of blue stragglers and survival of mass transfer systems. The collisions, as expected, dominate the central regions, while the outer regions' blue stragglers arise both from collisions and mass transfer in binary systems.

Preston & Sneden (2000; hereafter PS2000) expanded on the earlier work of Preston, Beers, & Shectman (1994; hereafter PBS) and argued that *field* blue stragglers are created almost solely by the mass transfer process. Not only does this make good qualitative sense, but they supported the argument by noting that field blue stragglers are much more common per unit luminosity than are blue stragglers in the lower-density regions of globular clusters. As PS2000 noted, this is consistent with the idea that even in those low density regions of clusters, binary systems may have been destroyed, thereby lowering the numbers of blue stragglers.

In clusters, we must keep in mind that even the stars found in the low-density outer regions may be vulnerable to stellar encounters if their intra-cluster motions carry them into the central higher density regions. Field blue stragglers therefore provide the "cleanest" sample for the study of the mechanism that may create such stellar oddities via stellar evolution, independent of environment. The distributions of such observables as binary stars' periods and orbital eccentricities are therefore much less likely to have been among field stars than in clusters.

As we describe below, however, field star samples have introduced another puzzle, one at least as intriguing as the blue straggler phenomenon itself. We argued (Carney et al. 2001; hereafter CLLGM) and argue again here that binary star evolution and mass transfer is one path for the creation of blue stragglers, and apparently the most common among field stars. However, some metal-poor main sequence field stars that are hotter than globular cluster main sequence turn-offs are not binaries, but could be explained as the partial remnants of an accreted dwarf satellite galaxy whose star formation continued over a long period of time. Following PBS, we distinguish between stars with delayed evolution and those that are simply young stars. We regard the blue straggler phenomenon as the process(es) that delay(s) normal stellar evolution.

PBS identified a significant number of field metal-poor stars bluer than comparable metallicity globular cluster main sequence turn-off stars: candidate blue stragglers, in other words. Preston & Landolt (1998) found that the star CS 22966 - 043 is a very metal-poor  $([Fe/H] \approx -2.4)$  SX Phe pulsating variable, and is also a binary star with an orbital period of 431 days and a relatively low orbital eccentricity of 0.10. (SX Phe variables lie in the instability strip's extension to the main sequence domain, and thus represent the hotter blue stragglers in globular clusters: see Nemec, Nemec, & Lutz 1994 for a discussion and lists of such stars.) The orbital properties are a vital clue to its origin because the normal orbital eccentricity of main sequence binary stars is much higher, with  $\langle e \rangle$  close to 0.37 (Duquennov & Mayor 1991, Latham et al. 2002), independent of metallicity. An extensive study of blue metal-poor field stars by PS2000 found a surprisingly high fraction of binary stars, which led them to suggest that many of them were field blue stragglers. Many of these stars showed periods of hundreds of days with low orbital eccentricities, as in the case of CS 22966 - 043. CLLGM identified ten metal-poor field blue straggler candidate stars from the large survey of Carney et al. (1994), based on colors that were slightly to significantly bluer than globular cluster main sequence turn-offs (at similar metallicities). They found six of the stars to have periods in this same range, 167 to 844 days, and low orbital eccentricities ( $e \leq 0.26$ ;  $\langle e \rangle = 0.11$ ). They argued that these periods and eccentricities are consistent with mass transfer. They noted that mass transfer systems such as CH, subgiant CH, and dwarf carbon stars likewise have very high binary fractions and that those binary systems have similarly long orbital periods and low orbital eccentricities. Sneden, Preston, & Cowan (2003; hereafter SPC2003) have strengthened

the argument for mass transfer in their recent abundance analyses of six blue metal-poor stars from the PS2000 program, finding that the three constant velocity stars have normal element-to-iron abundance ratios for metal-poor stars, but that three binary stars show major enhancements of carbon and *s*-process elements, indicative of mass transfer from a highly-evolved AGB star. In summary, then, mass transfer appears to be the primary cause of the blue straggler phenomenon among field stars. Therefore, it may also be a major contributor to the formation of blue stragglers in clusters, although the situation there is more complicated by induced dynamical evolution of binary stars as well as outright capture and merger of stars.

Since the orbital characteristics are such an important component of the mass transfer model, more velocity data of known field blue stragglers and identification of additional candidates and their binary frequency and orbital characteristics are highly desirable. It is also important to employ consistent techniques for identifying candidate blue stragglers and for determining the orbital elements of the binary stars. In the latter case, we note that our criteria for identification of binaries and acceptance of final orbital solutions are more strict than those of some investigators (see Latham et al. 1988, Latham et al. 1992, and Latham et al. 2002). This has compelled us to re-evaluate the orbital solutions available in the literature, using the published velocity data, in order to re-analyze all the velocity data in a consistent manner. Thus, while PS2000 found 42 binaries among their 62 program stars, we could unambiguously identify only 29 stars as being binaries using their published velocities and our software and experience. The other 13 stars may indeed be binaries, but our criteria and experience lead us to believe that additional radial velocities are needed to confirm such identifications. We also note that for some stars, PS2000 did not have enough time coverage to obtain a unique orbital period and offered alternative solutions when necessary. We have retained for use in this paper only the ten stars from PS2000 whose orbital elements satisfy our criteria. In all these cases, our orbital solutions are

indistinguishable from those obtained by PS2000. SPC2003 have also addressed this point with additional radial velocity data for selected stars. We are confident that additional observations will resolve any remaining uncertainties. We add that G. Preston (priv. comm.) has obtained additional velocities for CS 29497 - 030 and CS 29509 - 027, and those results confirm the orbital solutions for those stars presented by SPC2003.

For this paper, we have chosen to concentrate our efforts on seeking additional stars, rather than refinements of existing orbital solutions presented by PS2000. The exciting results of SPC2003 provides another motivation: a larger sample, and of brighter stars, could enable further progress in the search for chemical signatures of mass transfer, and, perhaps, an understanding of different mass transfer mechanisms (e.g., red giant or AGB donor star?). Finally, we have not lost sight of perhaps the most intriguing discovery of PBS: they argued that many of their stars are merely masquerading as blue stragglers and that they may, in fact, be bona fide young, metal-poor stars, accreted perhaps from a small dwarf galaxy which had experienced a prolonged star formation history or perhaps a relatively recent burst of star formation. Candidate field blue straggler stars may therefore provide clues to both stellar evolution and the evolution of our Galaxy.

# 2. SELECTION OF FIELD BLUE STRAGGLERS & SOME INTERESTING PROBLEMS THEREIN

#### 2.1. Finding Candidate Blue Stragglers

We have two challenges in identifying metal-poor blue stragglers in the field population. The first is the rarity of such stars. Large samples of field stars must be studied to find those few that are bluer than the main sequence turn-off of comparable metallicity globular clusters, and we must also be assured that they are main sequence stars and not the more luminous blue horizontal branch stars. Thus accurate colors, reddenings, gravities, and metallicities are required for large numbers of stars. This is why the two major recent studies of metal-poor field blue stragglers have emerged from the "BMP" (Blue Metal Poor) studies like that of PBS and PS2000, and the "Carney-Latham-Laird-Aguilar" survey (Carney et al. 1994; CLLGM). Such methods pick up both true blue stragglers as well as any truly young metal-poor stars, which may have been acquired by the Galaxy during a minor merger event (PBS), as noted above.

In their study of 62 blue metal-poor stars, many of which qualify as blue straggler candidates using our color criterion, PS2000 found an abnormally high fraction of binary stars, roughly four times higher than those of the disk and halo populations (Duquennoy & Mayor 1991; Latham et al. 1988, 2002). On the other hand, the frequency of double-lined systems was unusually low, suggesting a population of underluminous secondary stars, possibly white dwarfs. Such evidence, plus a low fraction of binary systems with short orbital periods, and a very high fraction of binary systems with low orbital eccentricities, suggested to PS2000 that their large sample of blue metal-poor stars is a mixture of both relatively young stars, with, presumably, a normal frequency of binary stars and with orbital elements like those of Galactic disk and halo stars, plus a significant number of blue stragglers whose origin is most readily explained by mass transfer.

#### 2.2. The Role of Lithium

Lithium is a very "fragile" element, vulnerable to proton capture at the relatively low temperature of order  $2.5 \times 10^6$  K. Cool stars, with deep enough convection zones, may transport surface lithium to depths where lithium can be destroyed, thereby gradually depleting the lithium abundance in the photosphere. In metal-poor main sequence stars, lithium abundances are observed to decline with effective temperature for  $T_{\rm eff} < 5400$  K (see Thorburn 1994 and references therein), presumably due to the deeper convection zones for such stars. The same effect is seen in metal-poor subgiants (Pilachowski, Sneden, & Booth 1993). However, among the hotter main-sequence dwarfs and subgiants, lithium abundances in metal-poor stars show a near-constant value of log n(Li) = 2.2, which is often referred to as the "Spite Plateau", after its discovery by Spite & Spite (1982). There is now an extensive literature on lithium abundances in metal-poor stars (see Spite, Molaro, & Spite 1993 and Ryan et al. 2001 for additional observations and references).

Mass transfer (or mixing or pulsation-driven mass loss, for that matter) should lead to depletion of surface lithium abundances. Indeed, lithium is not found in many candidate blue stragglers studied to date (Hobbs & Mathieu 1991; Pritchet & Glaspey 1991; Glaspey, Pritchet, & Stetson 1994; CLLGM). On the other hand, normal lithium abundances have been found in some stars that are blue straggler candidates, suggesting that they are either blue stragglers created by an as-yet unidentified mechanism, or truly younger metal-poor stars (Ryan et al. 2001; CLLGM). We therefore include in Table 1 the lithium abundances for our program stars, insofar as they have been determined by others.

Alas, the lithium abundance may not be entirely capable of distinguishing a field metal-poor blue straggler star (low lithium) from a young metal-poor dwarf (normal lithium). In the Hyades cluster, Boesgaard & Trippico (1986) and Boesgaard & Budge (1988) found that lithium abundances are very depleted in main sequence stars with effective temperatures lying roughly in the range of 6400 K to 6800 K. This "lithium gap", if it arises during the evolution of normal metal-poor main sequence stars, could lead us to confuse a young but otherwise normal metal-poor dwarf with a metal-poor blue straggler. We discuss this further in Section 5.2.

#### 2.3. Other Elemental Abundances

SPC2003 discovered strong enhancements of elements probably created by *s*-process nucleosynthesis in three stars that satisfy the color conditions described below. These abundance anomalies speak strongly to mass transfer, and also the evolutionary state of the donor star, and hence we have searched the literature to determine what is known about the abundances of two elements which are often associated with *s*-process nucleosynthesis, strontium and barium. These abundances are also summarized in Table 1.

# 2.4. Our Five New Program Stars

We rely once more on a large sample of field stars to select our program stars. Stetson (1981) primarily used proper motion criteria to select possible high velocity stars from the SAO catalog, and obtained a list of high-velocity early-type stars (Stetson 1991). Based on high-resolution spectra, Glaspey, Pritchet, & Stetson (1994) found that these stars could be divided into three broad groups of stars, one of which is relevant to metal-poor field blue stragglers. Their Table 4 (part *iii*) includes six metal-poor stars that are also deficient in lithium. One of these stars, SAO 80390 (BD+25 1981) was studied by CLLGM, and found to be a possible radial velocity variable. The other five stars constitute our new sample.

In Table 1 we provide the basic photometric and chemical information for these five stars, plus the ten blue straggler candidates from CLLGM, and the ten metal-poor ([Fe/H] < -0.6) stars from PS2000 for which CLLGM could obtain satisfactory orbital solutions using their software and generally more conservative criteria. The de-reddened B - Vvalues, effective temperatures, and metallicities for the PS2000 stars were taken from that paper, while for BD+23 74, HD 8554, HD 109443, and HD 135449, the values were taken from or determined using data taken from Stetson (1991) and Glaspey et al. (1994). Values

for the remaining stars were determined following the same precepts discussed by Carney et al. (1994). In Figure 1 we show the color selection criterion for blue straggler candidates. As discussed by CLLGM, the solid line represents a second-order polynomial fit to the de-reddened B - V color indices of selected globular cluster main sequence turn-offs as a function of metallicity. Because the tail of the field star metallicity distribution extends to lower metallicities than that of the globular clusters, we have also employed the " $Y^{2}$ " isochrones (Kim et al. 2002). This use of the isochrones is far from rigorous since we ignore color shifts that may be required to bring the isochrones into agreement with observed cluster color-magnitude diagrams. Further, we have made the convenient, perhaps naive, assumption that all globular clusters have the same age. We simply chose the isochrones with enhanced abundances of the " $\alpha$ " elements,  $[\alpha/Fe] = +0.3$ , and then chose the cluster ages to all be 11 Gyrs, represented by the dashed line in Figure 1. This provides a reasonable match to the edge of the color distributions of the field stars over a wide range of metallicities, especially at the lowest metallicities, and a good match to the actual globular cluster turn-off distribution near the peak of the halo metallicity distribution ( $[m/H] \approx$ -1.6). Stars blueward of *both* of these lines are considered blue straggler candidates. Note that CS 22873 - 139 does not satisfy this criterion, and we exclude it from the following discussions.

#### EDITOR: PLACE FIGURE 1 HERE.

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The normal stars, not known to be blue stragglers, are plotted as plus signs. However, compared to our earlier work (CLLGM), we have increased the number of normal stars for comparison. We have completed and are preparing for publication an additional sample of 470 metal-poor field stars selected from Ryan (1989) and Ryan & Norris (1991). Three of those stars, G121-54, BD-20 3682, and LTT 15049 (=HD 154578), plotted as plus signs but bluer than the two dividing lines, are now blue straggler candidates. We will report on their radial velocity behavior in a future paper.

We have also continued our observations of the four "constant velocity" stars in our earlier paper, BD+72 94, BD+40 1166, BD+25 1981, and HD 84937, and report the revised results as well.

# 3. OBSERVATIONS

The observations were made using the same procedures as described by CLLGM. We employed the Center for Astrophysics (CfA) Digital Speedometers (Latham 1985, 1992) on the Multiple Mirror Telescope and 1.5-m Tillinghast Reflector at the Whipple Observatory atop Mt. Hopkins, Arizona, and on the 1.5-m Wyeth Reflector located in Harvard, Massachusetts. The echelle spectrographs were used with intensified photon-counting Reticon detectors and recorded about 45 Å of spectrum in a single order centered near 5187 Å. The resultant resolution was about 8.5 km s<sup>-1</sup>. Typical signal-to-noise values ranged from from 7 to 50 per resolution element.

Radial velocities were measured from the observed spectra using the one-dimensional correlation package **rvsao** (Kurtz & Mink 1998) running inside the IRAF<sup>2</sup> environment. As before, we used a grid of synthetic spectra calculated using the model atmospheres

<sup>2</sup>IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation. computed using R. L. Kurucz's code ATLAS9. The details of the calculation of the models and the grid of synthetic spectra were presented by CLLGM.

For each of the five new blue straggler candidates we adopted a template from the grid of synthetic spectra with the effective temperature and metallicity nearest to the values for that star reported in Table 1. We used  $\log g = 4.0$  throughout. We computed correlations for all spectra of each star using all the available rotationally broadened synthetic spectra with the most appropriate temperature, gravity, and metallicity. To determine the radial velocity, we chose the rotationally-broadened template with the value of  $v_{\rm rot} \sin i$  that gave the highest average value for the peak of the correlation function. This established the optimum set of parameters for the synthetic spectrum template for each star. The parameters adopted for the final correlations are coded in the final column of Table 1: effective temperature,  $\log g$ , [Fe/H], and  $v_{\rm rot} \sin i$ .

Table 2 is an illustrative summary of the individual radial velocity measurements, including the heliocentric Julian Day of mid-exposure, and the velocity and internal error estimate returned by the IRAF task **rvsao**, both in  $\text{km s}^{-1}$ . The full table with all the velocity information is available electronically.

# EDITOR: PLACE TABLE 2 HERE.

# 4. **RESULTS**

#### 4.1. Radial Velocities

We summarize our radial velocity results in Table 3, including the total number of velocities measured for each star, the span of our velocity coverage (in days), the derived

rotational velocity,  $v_{\rm rot} \sin i$ , the mean radial velocity, and the uncertainty of the mean velocity. Note that for the binary stars, the mean radial velocity is not as appropriate as the systemic velocity that emerges from the orbital solution. For stars with orbital solutions, we therefore list here the systemic velocity and its uncertainty. We include in Table 3 the measured rms external error, E, and the mean internal error, I, of the velocity measurements (see Kurtz & Mink 1998), and the ratio, E/I. Large values of E/I ( $\approx 1.5$ and above) are suggestive of radial-velocity variability. We also employ the probability,  $P(\chi^2)$ , that the  $\chi^2$  value could be larger than observed due to Gaussian errors for a star that actually has constant velocity. We employ the internal error estimate,  $\sigma_{i,int}$ , obtained from **rvsao**, for each of n exposures when calculating  $\chi^2$ :

$$\chi^2 = \sum_{i=1}^n \left(\frac{x_i - \langle x \rangle}{\sigma_{i,\text{int}}}\right)^2.$$
 (1)

It is clear that at least four of our five new program stars display radial velocity variability.

# EDITOR: PLACE TABLE 3 HERE.

#### 4.2. Constant Velocity Stars

HD 142575 does not appear to be a radial velocity variable, and we show its velocity history in Figure 2. Table 3 shows that the probability that the measured value of  $\chi^2$ could arise by chance is large, which is a strong indicator of radial velocity stability. The four stars in our earlier work (CLLGM) that appeared to have constant radial velocities have rather small P( $\chi^2$ ) values, in particular for BD+25 1981. However, the ten new radial velocities have resulted in a higher P( $\chi^2$ ) value for this star than in our earlier paper, when it was only 0.000002. The rest of Figure 2 shows the velocity histories of these four stars. No obvious signs of orbital motion are seen, although BD+25 1981 remains an intriguing case.

#### EDITOR: PLACE FIGURE 2 HERE.

#### 4.3. Orbital Solutions

Orbital solutions for four of the five new program stars are given in Table 4, as well as calculated uncertainties. We include the orbital period P (in days), the systemic (mean) radial velocity,  $\gamma$ , the orbital semi-amplitude, K, the orbital eccentricity, e, the longitude of the ascending node,  $\omega$ , the time (in HJD) of the periastron passage, the projected semi-major axis of the primary star's orbit (in giga-meters), the mass function, f(M) (in units of a solar mass), the number of observations (and the span in days of the observations), and, finally, the probable error of the match of the observed velocities to the orbital solution. Please note that our radial velocity observations span several orbital cycles for all four stars. The orbital solutions and the phased velocity data are displayed in Figure 3.

#### EDITOR: PLACE FIGURE 3 HERE.

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#### 4.4. Rotational Velocities

We have attempted to derive internally consistent values for the stellar rotational velocities,  $v_{\rm rot} \sin i$ , using our synthetic spectra for all of our program stars. We have described above how we selected the optimum value of  $v_{\rm rot} \sin i$  for the synthetic spectrum to derive the radial velocities. To provide the best estimate for  $v_{\rm rot} \sin i$ , we interpolated between the average peak correlation values for all spectra using different values of  $v_{\rm rot} \sin i$  in the synthetic spectra. We used quadratic fits of the correlation values vs.  $v_{\rm rot} \sin i$  to select the final value. These are given in Table 3.

We have tested the accuracy of our derived rotational velocities by employing two sets of template spectra for each star. The first choice of templates are those given in Table 1. The second choice was made by the computer, with the template selected independently on the basis of the height of the peak of the correlation function for the fifteen stars with templates listed in the Table. In six cases this resulted in exactly the same adopted template. The other nine cases enable us to determine how a change in temperature or gravity alter our derived rotational velocity estimate. The greatest change was for HD 97916, where the computer's preferred template was 750 K cooler and 0.5 dex lower in gravity, and the  $v_{\rm rot} \sin i$  value changed by only 1.8 km s<sup>-1</sup>, down to 13.1  $\rm km\,s^{-1}$ . For BD+40 1166 and HD 84937, the computer chose templates 250 K cooler and hotter, respectively, than the values given in Table 1. Even here, where the derived rotation velocities are comparable to or smaller than our instrumental resolution, the changes were small, -1.1 and +0.7 km s<sup>-1</sup>, respectively. For more rapidly rotating stars, the sensitivity was even smaller. For BD+23 74, for example, a change of 1000 K changed the derived  $v_{\rm rot} \sin i$  value by only 0.4 km s<sup>-1</sup>. The power of synthetic spectra and the  $\chi^2$  fitting technique's sensitivity to many weak lines carrying the same information is demonstrated quite nicely by these tests.

# 5. DISCUSSION

#### 5.1. Orbital Periods & Eccentricities

PS2000 drew attention to the relatively long periods and low orbital eccentricities of many of the binary stars they discovered. In combination with the high binary frequency and small fraction of double-lined systems, they argued that their results supported the identification of many of these binary systems as blue stragglers created by mass transfer, a model proposed originally by McCrea (1964).

CLLGM similarly drew attention to the unusual orbital properties of the six field blue stragglers they studied and the ten systems discovered by PS2000 with  $[Fe/H] \leq -0.6$  and for which our own software resulted in what we considered compelling orbital solutions. Neglecting the three PS2000 systems with periods of less than 20 days (and whose orbital elements may have been altered by tidal interactions, independent of mass transfer), we found that 10 of the 13 binaries had e < 0.15 and  $\langle e \rangle = 0.062 \pm 0.011$ . For all 13 systems, e < 0.29 and  $\langle e \rangle = 0.106 \pm 0.025$ . The periods ranged from 167 days up to roughly 1600 days. One should recall that the median orbital eccentricity for normal main sequence, single-lined spectroscopic binaries is about 0.37, independent of metallicity (Duquennoy & Mayor 1991; Latham et al. 2002).

Mass transfer appears to be the best explanation for these orbital characteristics, as discussed originally by Webbink (1986). Our earlier paper also discussed stellar systems where mass transfer is likely to have occurred, leaving an overabundance of elements synthesized during the AGB evolutionary stage deposited in the outer layers of the receptor. If we confine our attention to the more metal-poor stars, there are three classes of stars to consider. The CH stars are not luminous enough to be AGB stars themselves, yet show abundances expected of such stars, implying mass transfer has occurred and also that the companion star is likely to be a white dwarf. McClure & Woodsworth (1990) found that essentially all CH stars they studied are binaries, and those with orbital solutions showed periods of 328 to 2954 days, and low orbital eccentricities (e < 0.18;  $\langle e \rangle = 0.05$ ). The "subgiant CH" stars discovered by Bond (1974) may be descendents of some blue stragglers, as noted by Luck & Bond (1991). McClure (1997) found that 9 of the 10 such stars under long-term radial velocity monitoring are binary systems with long periods. He obtained orbital solutions for six of the sytems, finding orbital periods of 878 to 4140 days, and small orbital eccentricities (e < 0.13;  $\langle e \rangle = 0.11 \pm 0.02$ ,  $\sigma = 0.04$ ). Finally, the one well-studied dwarf carbon star, G77-61, has been found to have a nearly circular orbit and a moderately long period of 245 days (Dearborn et al. 1986).

One of the primary purposes of the observations reported in this paper was to test the idea that many blue stragglers are binary stars, and that their binary orbital properties confirm this kinship with the more obvious mass transfer systems described above. In Figure 4 we update Figure 4 from CLLGM, which showed the orbital eccentricity vs. log P for the 6 new binary systems reported therein, and the 10 systems fom PS2000 subjected to the same orbital solution analyses. For comparison, we included the 156 orbital solutions for cooler single-lined spectroscopic binaries from Latham et al. (2002). In this new Figure 4, we highlight the locations of the four new orbital solutions from Table 4 using filled circles. (Filled squares are our results from CLLGM; filled diamonds are stars from PS2000 with shorter periods.) As before, the longer orbital period binary stars have unusually low values of the orbital eccentricity.

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In Figure 5, we take a different perspective, and consider the distribution of orbital

eccentricities for stars in Figure 4 with periods longer than 20 days. Aside from the absence of high orbital eccentricities among the blue stragglers, we note that the orbital eccentricities cluster near zero but have a tail to higher values. This might indicate two different types of mass transfer and orbital evolution, despite the similarity of the orbital periods. Alternately, it may reflect the original distribution of orbital eccentricities since binary systems with very high eccentricities evolve more slowly, and so are more likely to preserve a higher-than-average orbital eccentricity.

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#### 5.2. Lithium

In Figure 6 we show the "lithium gap" seen among some members of the Hyades, using the results of Cayrel et al. (1984), Boesgaard & Trippico (1986), and Boesgaard & Budge (1988). Open circles are measurements and "v" symbols represent upper limits. The gap is easily seen between effective temperatures of about 6400 K and 6800 K. The normal lithium abundance for metal-poor dwarfs hotter than about 5400 K (the "Spite plateau"). is shown as a dashed line. That value is lower than the peak of the Hyades dwarfs and is in itself a long-standing puzzle, but beyond the point of this paper. We also show the stars from Table 1, with filled circles for stars that have measured lithium abundances, and which, it turns out, are all also stars with constant velocities. None of the binary stars in Table 1 have detectable lithium lines and hence the abundances are only upper limits. These stars are plotted as downward-pointing arrows. Note that for HD 142575, Glaspey et al. (1994) derived  $T_{\rm eff} = 6550$  K, and Fulbright (2000) adopted  $T_{\rm eff} = 6500$  K, but we have adopted the photometric temperature of 6700 K to maintain consistency with the derivation of the temperature for all of our program stars. We have adjusted the lithium abundance derived for the star by Fulbright (2000) as well to account for the change in temperature: log n(Li) rises from 1.45 to 1.58. (Note as well, however, that Glaspey et al. 1994 argued that log n(Li) < 0.7.)

# EDITOR: PLACE FIGURE 6 HERE.

The first interesting point is that three of the metal-poor single stars have normal lithium abundances, at least for metal-poor stars. Two of the stars, HD 84937 and CS 22873 – 139, are very close to our adopted color limits used to identify blue stragglers. Small changes in the measured B - V color index or in the reddening estimate could easily shift either star into or out of the blue straggler candidate domain. However, BD+72 94 is considerably bluer and hotter, and in the middle of the Hyades lithium gap, yet has a lithium abundance consistent with the Spite plateau. Conclusions from such a small sample may not be secure, but the results suggest the lithium gap may not exist for single metal-poor stars, or, perhaps, it is shifted to higher temperatures than the stars in our sample. A survey of the metal-poor single stars identified by PS2000 would answer this question.

Related to this point, HD 142575, which appears to be single and slightly hotter than the other three single stars, has a reduced lithium abundance according to Fulbright (2000). Is this star distinguishable in any way from the three constant velocity, normal-lithium stars? If our photometric temperature estimate is correct, the star is slightly hotter than the other single stars, and so might be in the metal-poor equivalent to the Hyades lithium gap. Table 3 may provide another clue: HD 142575 has a relatively large value for  $v_{\rm rot} \sin i$ . Is rotation a factor in either the formation of the lithium gap or the depletion of lithium more generally? We need more observations of lithium absorption line strengths in blue metal-poor stars, especially those studied by PS2000. We conclude that our use of low lithium abundances as a selection criterion is supported by the (admittedly limited) data available. We note also that the relation between blue stragglers and lithium depletion has been discussed extensively by Ryan et al. (2001).

#### 5.3. Rotation

Ryan et al. (2002) have noted the modest but significant levels of rotation in three of the blue stragglers discussed in our previous paper (CLLGM). For BD+51 1817, G66-30, and G202-65, they found  $v_{\rm rot} \sin i$  values of  $7.6 \pm 0.3$ ,  $5.5 \pm 0.6$ , and  $8.3 \pm 0.4$  km s<sup>-1</sup>, all of which are larger than values derived for cooler metal-poor dwarfs with normal lithium abundances. (Note that our method obtains somewhat higher values of 9.0, 8.1, and 11.6 km s<sup>-1</sup>, respectively.) Ryan et al. (2002) suggested that the likely origin of the rotation was the mass transfer process itself, and discussed the mechanisms by which such a process would lead to lithium depletion. These include mass transfer-induced deep mixing or transfer of lithium-depleted material from the donor star. Regarding the latter point, Pilachowski et al. (1993) found that surface lithium depletion in post-main sequence metal-poor stars begins before the stars reach the base of the red giant branch, so mass transfer from a more highly evolved red giant would deposit lithium-depleted material on the recipient main sequence star.

We explore here the available rotational velocity information for the stars of Table 3. As described above, we are able to estimate  $v_{\rm rot} \sin i$  using our grid of synthetic spectra. Because different approaches appear to derive different values of  $v_{\rm rot} \sin i$ , we proceed differentially by comparing  $v_{\rm rot} \sin i$  values of constant velocity and binary stars only within a particular methodology. Thus we make comparisons only between stars we have studied, or among the stars studied by PS2000, but we do not intermingle those results. For the stars for which we have estimated  $v_{\rm rot} \sin i$ , we must first explore the results for a "control sample". In Figure 7 we show the histograms of the derived  $v_{\rm rot} \sin i$  values using data taken from Latham et al. (2002). We include only single stars judged to be main sequence dwarfs, and single-lined spectroscopic binary stars with periods exceeding 25 days. Tidal circularization effects are clearly present for metal-poor dwarfs with orbital periods of 20 days or less, but should not be significant for the longer period systems we consider here. None of these three different groups were found to have different distributions of  $v_{\rm rot} \sin i$ . However, metallicity does seem to have a small influence on the  $v_{\rm rot} \sin i$  values we derive, as may be seen in Figure 7. We do not claim that Figure 7 represents the true distribution of rotational velocities of metal-poor dwarfs because our instrumental resolution ( $\approx 8.5$  $\mathrm{km\,s^{-1}}$ ) prevents accurate determinations for values much smaller than that. On the other hand, we are confident of our results for rotational velocities at or above that of our instrumental resolution. The fraction of stars with  $v_{\rm rot} \sin i \ge 8.0 \ {\rm km \, s^{-1}}$  in the combined sample is only 4.0% (7.7% for the more metal-poor stars and 0.3% for the more metal-rich stars). Note that we do not believe these results imply that metal-poor dwarfs rotate somewhat faster than metal-rich dwarfs. The differences may be artificial in the sense that the synthetic spectrum templates may introduce metallicity-dependent differences in the derived rotational velocities.

#### EDITOR: PLACE FIGURE 7 HERE.

In Figure 8 we show the rotational velocities we have derived (open and filled circles) for the stars of Table 3, plus  $v_{\rm rot} \sin i$  values from PS2000 (open and filled squares). While the observations of PS2000 were obtained using a system with velocity resolution comparable to ours, they derived  $v_{\rm rot} \sin i$  values using a different method than have we, which is why we distinguish the two sets of results graphically. The key question is whether mass transfer is a major cause of the blue straggler phenomenon and whether evidence for it exists in higher rotational velocities for the binary systems. Because tidal interactions

will spin up short-period binary systems, independent of mass transfer, we have excluded binary systems with orbital periods of less than 20 days from the Figure or from further consideration here.

# EDITOR: PLACE FIGURE 8 HERE.

We consider the results from PS2000 first. There are 14 stars in their study that appear to have constant velocity and have  $[Fe/H] \leq -0.5$ . Recall that they have interpreted (correctly, we believe) these stars to be bona fide young metal-poor main sequence stars. Note that all of them have  $v_{\rm rot} \sin i \le 12 \text{ km s}^{-1}$ , and  $\langle v_{\rm rot} \sin i \rangle = 10.1 \text{ km s}^{-1}$  ( $\sigma = 1.7$  $\mathrm{km}\,\mathrm{s}^{-1}$ ). CS 22873 - 139, which is a binary system but which we do not consider to be a blue straggler candidate, has  $v_{\rm rot} \sin i = 10 \ {\rm km \, s^{-1}}$ . [We have assigned CS 22960 - 058 a temperature of 6925 K rather than 6900 K so it would not be overplotted on another star.] If we restrict the sample to those stars from PS2000 for which we could obtain an independent orbital solution that agrees with their results (CLLGM, Table 4), we find that none of the seven binary stars with orbital periods longer than 20 days have  $v_{\rm rot} \sin i$  values as small as the largest value found for the single stars, and that  $\langle v_{\rm rot} \sin i \rangle = 17.3 \ {\rm km \, s^{-1}}$  $(\sigma = 3.5 \text{ km s}^{-1})$ . [Here we have altered the temperature for CS 29518 – 039 from 7050 K to 7000 K to inhibit it being overplotted on another star.] If we further consider the 11 more binary stars for which PS2000 presented only one orbital solution, but which are not plotted in Figure 8, only two have  $v_{\rm rot} \sin i$  values of 12 km s<sup>-1</sup> or less, while the remaining nine stars have values reaching as high as  $160 \text{ km s}^{-1}$ .

Our own results, from our previous work (CLLGM) and this paper, confirm this picture. We consider BD+25 1981 an uncertain case and have plotted it in Figure 8 as an open triangle. The other four constant velocity stars (BD+72 94, BD+40 1166, HD 84937, HD 142575) have  $\langle v_{\rm rot} \sin i \rangle = 7.8 \text{ km s}^{-1} (\sigma = 3.8 \text{ km s}^{-1})$ , while the ten binary stars in

Table 3 have  $\langle v_{\rm rot} \sin i \rangle = 18.7 \, {\rm km \, s^{-1}} (\sigma = 10.0 \, {\rm km \, s^{-1}}).$ 

In summary, our own studies and the results of PS2000 show that blue straggler candidates which are binaries show significantly enhanced surface rotation compared to constant velocity stars. Because the orbital periods imply separations far too great for tidal interactions to *currently* have any significant effects on the stars' rotational periods, we believe the enhanced rotation indicates mass transfer has occurred and is the cause of the spin-up. The mass transfer model predicts that the originally more massive star transfers mass to the lower mass secondary, diminishing the orbital period and separation, until the original secondary star becomes the more massive component. At that point, the stars begin the separate, but mass transfer has transformed orbital angular momentum into rotational angular momentum, and tidal interactions or some mechanism has reduced the orbital eccentricities.

# 5.4. AGB Signatures: Carbon and s-process Elements

As noted above, Luck & Bond (1991) suggested that some blue stragglers may be progenitors of the subgiant CH stars. Until recently, there has been little information regarding abundances of carbon and s-process abundances in blue stragglers that would indicate mass transfer from an AGB star, but such data are now beginning to appear, and so we have summarized in Table 1 the abundances of the s-process elements strontium and barium. The available data for most candidate blue straggler stars are consistent with the normal abundances of these elements in metal-poor main sequence and red giant branch stars (see McWilliam 1997). Recently, SPC2003 have found strong enhancements of these elements in three of the blue metal-poor stars discussed previously by PS2000. Thus for these stars the evidence favors mass transfer from an evolving AGB star, supporting the hypothesis of Luck & Bond (1991). If mass transfer from a highly-evolved AGB star is responsible for the *s*-process enhancements, whereas the stars without such enhancements experienced mass transfer from a normal red giant, we might expect to see some differences in the orbital properties of the two samples. Mass transfer from an AGB star could imply, for example, that mass transfer did not occur during the preceding red giant evolutionary phase, and, therefore, the original orbital periods of binary systems destined to experience mass transfer from an AGB star should be longer than those which undergo mass transfer from a first ascent red giant. One might expect, then, that blue stragglers showing signs of AGB mass transfer (*s*-process enhancements) should have longer minimum orbital periods than those that (presumably) arose from mass transfer from a red giant (no such enhancements).

Qualitatively, Table 1 confirms this view. Excluding CS 22956 - 028, the eight stars with normal strontium and barium abundances have orbital periods as low as 167 days, and none exceed 500 days. The six subgiant CH stars with orbital solutions obtained by McClure (1997) have periods only as short as 878 days, and extend up to 4140 days. The eight (giant) CH stars studied by McClure & Woodsworth (1990) have orbital periods ranging from 328 and 2954 days, roughly consistent with this simple picture. CS 22956 – 028 is consistent with this trend, with an orbital period of 1307 days (SPC2003). Its orbital eccentricity is also on the high side (0.21) for the ensemble of field halo blue stragglers, as Figure 4 shows.

However, the other two stars with s-process enhancements, CS 29497 – 030 and CS 29509 – 027, show rather short periods, according to SPC2003, with 342 days (and  $e \approx 0$ ) and 194 days (and  $e \approx 0.15$ ), respectively. We have not included these stars in Table 1 because our orbital solutions using the data available to SPC2003 indicated that alternative periods and eccentricities were possible, although less likely. Preston (private communication) has continued to observe these stars and these orbital periods are increasingly robust. In particular, we have been able to confirm to our own satisfaction the orbital period for CS  $29497 - 030^3$ . Additional velocity data are needed, however, for CS 29509 - 027.

We are therefore confronted with the results that mass transfer from red giant and AGB stars yield similar ranges in orbital periods and eccentricities. We can only speculate that diversity in the masses of the original primary stars and their original orbital periods contribute to this splendid if confusing variety.

# 5.5. The Mass Transfer Process and Its Outcome

A point stressed by McClure & Woodsworth (1990) and McClure (1997) was that the mass functions of the CH and subgiant CH stars, respectively, were small and indicative of a uniform secondary mass, roughly that of a white dwarf with  $0.6M_{\odot}$ . We undertook a similar analysis in our previous paper, which we revisit here.

# 5.5.1. The Mass Functions

We begin by comparing the distribution of the mass functions of the blue stragglers and the somewhat lower masses of the primary stars in the single-lined spectroscopic binaries of Latham et al. (2002) for stars with orbital periods longer than 20 days. The mass function for a spectroscopic binary is defined to be

$$f(M) = \sin^3 i \frac{M_2^3}{(M_1 + M_2)^2},\tag{2}$$

where the numerical value of f(M) is derived from the parameters of the orbital solution.

<sup>&</sup>lt;sup>3</sup>The confirmation of the short orbital period for CS 29497 - 030 has cost the first author payment of a wager with Dr. Preston that longer periods would be preferred.

Figure 9 shows that the two mass function distributions are quite different, with the steeper one for the blue stragglers indicative of a narrower range of secondary masses, as in the cases of the CH and subgiant CH stars.

# EDITOR: PLACE FIGURE 9 HERE.

#### 5.5.2. Estimating the Secondary Masses

So what is that secondary mass? We must begin with an estimate of the masses of the primary stars, then exploit the mass functions to get some idea of the secondary masses of the ensemble. As we have noted, the lack of a detectable secondary spectrum in any of the blue straggler binary systems is suggestive of underluminous secondaries, and we explore here the idea that all the secondaries are stellar remnants with similar masses.

In CLLGM, we estimated the mass of each primary star using the derived effective temperatures and chemical compositions, plus the isochrones of Girardi et al. (2000). The isochrone ages were relatively young, generally 1.7 to 2.0 Gyrs, to accomodate the high temperatures and apparent high masses of the primaries. The isochrones were computed using elemental abundances consistent with solar values and, to allow for enhanced abundances of the " $\alpha$ " elements ([ $\alpha$ /Fe] = +0.3), we employed the scaling relation of Salaris, Chieffi, & Straniero (1993) to calculate  $Z_{\text{eff}}$  for each primary. Here we exploit the "Yonsei-Yale" (Y<sup>2</sup>) isochrones of Yi, Kim, & Demarque (2003), which were computed using  $\alpha$ -enhanced abundances and somewhat more appropriate (and variable) helium mass fractions. We used isochrones with an age of 2.0 Gyrs in all cases. Table 5 shows the results. We have also compared these new primary mass estimates with those computed using the Girardi et al. (2000) isochrones. The maximum difference in derived primary mass was 0.04  $M_{\odot}$ , and the mean difference, in the sense of Y<sup>2</sup> minus Girardi et al. (2000), was  $0.005 \pm 0.005 M_{\odot}$ , with  $\sigma = 0.018 M_{\odot}$ .

#### EDITOR: PLACE TABLE 5 HERE.

From the estimated value of  $M_1$ , we can estimate the <u>minimum</u> mass of the undetected companion; i.e. for  $\sin i = 1$ , using a revised version of Equation 2:

$$M_2 \sin i = f^{1/3}(M) \times (M_1 + M_2)^{2/3}.$$
(3)

These are also provided in Table 5. All of the minimum masses lie below the expected mass of a metal-poor white dwarf,  $\approx 0.55 M_{\odot}$ . They also lie far below those expected for a metal-poor main sequence turn-off star ( $\approx 0.8 M_{\odot}$ ) or that of a neutron star ( $\approx 1.4 M_{\odot}$ ). The mean difference in secondary masses derived using the two sets of isochrones is only  $0.002 \pm 0.004 M_{\odot}$ , with  $\sigma = 0.016 M_{\odot}$ .

If all the secondaries have roughly the same mass, is it closer to that of a white dwarf or a neutron star? If we assume that all the secondaries have the same mass of  $0.55M_{\odot}$ , and calculate the orbital inclinations that this would imply, we obtain the sin *i* values listed in Table 5. The average sin *i* for the 17 stars in Table 5 is  $0.69 \pm 0.05$  ( $\sigma = 0.19$ ), which is not far from the value of  $\pi/4 = 0.785$  expected for randomly oriented orbits. (Use of the isochrones of Girardi et al. 2000 leads to an identical result.) Increasing the assumed secondary mass to  $0.65 M_{\odot}$ , results in  $< \sin i >= 0.61 \pm 0.04$  ( $\sigma = 0.17$ ), which is inconsistent with the expectation by a significant amount, although we must recognize that our results suffer some observational bias in that very low values of sin *i* result in smaller observed radial velocity variations and such systems are more likely to elude detection. If we further assume the secondaries are all neutron stars, with  $M = 1.4M_{\odot}$ , we find  $<\sin i>= 0.37 \pm 0.03$  ( $\sigma = 0.11$ ), and we rule out that class of secondaries, at least in the general case.

We conclude that our orbital solutions are consistent with all the unseen companions in our low-eccentricity long-period orbits being white dwarfs viewed at random orbital orientations, which supports the mass-transfer model for the formation of field blue stragglers. If all the secondaries are white dwarfs with the same mass, then that mass can not be much smaller than  $0.50M_{\odot}$ , because the three largest minimum masses are  $0.55 \pm 0.06M_{\odot}$  (CS 22956 - 028),  $0.52 \pm 0.06M_{\odot}$  (CS 29518 - 039), and  $0.50 \pm 0.01M_{\odot}$ (G202-65), where the quoted errors include only the contribution from the mass functions and not from possible systematic errors in our estimates of the primary masses. On the other hand, the secondary masses can not be larger than about  $0.65M_{\odot}$ , because then the average value for the orbital inclinations would become seriously inconsistent with random orientations of the orbits.

# 5.5.3. Stable or Unstable Mass Transfer?

Ryan et al. (2002) have discussed the mechanism for the mass transfer that might have increased the rotational velocities of the stars we see now as blue stragglers. One of the questions they raised was whether the mass transfer mechanism could have involved stable Roche lobe overflow or whether the mass transfer process was unstable. Sudden mass loss via a supernova, for example, would be such an unstable process, although we have essentially ruled out neutron star companions among this sample of field blue stragglers.

Rappaport et al. (1995) modelled the results of Roche lobe overflow. They considered the evolution of binaries undergoing stable mass transfer, but for the case where the recipient is a neutron star. The same physics should also apply to systems where the recipient is a main-sequence star. The essence of the model is that short-period systems are so close that mass transfer begins early, when the expanding red giant core has not yet grown to a "mature" size. Therefore, the resultant white dwarf will appear with a small, "premature" mass. In Figure 10, we plot the minimum white dwarf mass as a function of the orbital period and eccentricity,  $\log [P(1-e)^{\frac{3}{2}}]$ . We also show the model predictions of Rappaport et al. (1995) using their coefficient  $R_0$  to be 3300  $R_{\odot}$ , consistent with the Population II case that they discussed. If all the secondary stars were white dwarfs and had evolved via stable mass transfer, their minimum masses, plotted in Figure 10, should all lie to the left of the theoretical curve, and we find that the data do so, more or less, except for G202-65. Thus almost all of the blue stragglers in Table 5, with orbital periods longer than 20 days, have orbital periods and eccentricities consistent with stable mass transfer. This includes CS 22956 - 028, the star that shows signs of *s*-process enhancements and an implied AGB donor star. We show in Figure 10 the locations of the other two such stars from SP2003, CS 29497 - 030 and CS 29509 - 027. All three stars lie well within the regime of stable mass transfer.

#### EDITOR: PLACE FIGURE 10 HERE.

# 6. SUMMARY & FUTURE WORK

Our new search for radial velocity variability of five metal-poor and lithium-deficient field stars has shown that four of them are single-lined spectroscopic binaries with orbital periods of a few hundred days and small orbital eccentricities. Combining these results with those of PS2000 and CLLGM, we have found that field metal-poor dwarfs hotter than comparable metallicity globular cluster turn-offs may represent stars with two very different origins. Many of the binary stars studied by PS2000 and most, if not all, of the binary stars studied by CLLGM and in this paper are distinguished from normal binary stars by their unusually low lithium abundances and unusually low binary orbital eccentricites. We have shown that the secondaries appear to have a unusually narrow range of masses, and are consistent with white dwarfs of 0.55  $M_{\odot}$ . Despite the long periods of these binary systems, we find that their  $v_{\rm rot} \sin i$  values are, on average, higher than those of single stars with comparable temperatures, suggesting spin-up as part of a mass transfer event. Using the models of Rappaport et al. (1995), we argue that in all cases but one (G202-65), the orbital periods and eccentricities are consistent with stable mass transfer. In some cases, SPC2003 found enhanced values of *s*-process abundances, signifying mass transfer from an evolved AGB star, but not all blue stragglers show such enhancements. We have not discovered any correlation between the presence or lack of such enhancements and the binary system orbital properties.

Another interesting result is that among the constant velocity stars, lithium abundances are normal, including one star, BD+72 94, that appears to be in the "lithium gap". HD 142575, on the other hand, may lie in the metal-poor equivalent lithium gap, which may occur at somewhat higher temperatures than is seen in the Hyades. More lithium abundance determinations for constant velocity stars in this temperature regime would be very interesting, both to strengthen the use of lithium as a distinguishing feature of blue stragglers created by mass transfer, and as a tool for exploring the cause of the lithium gap as well. These constant velocity stars may have originated within a dwarf satellite galaxy that underwent star formation over a long period of time and which only recently merged with the Milky Way, as suggested by PBS.

Additional radial velocities should be obtained of the constant velocity and binary stars in our samples (CLLGM and this paper) as well as those stars studied by PBS, PS2000, and SPC2003 to refine the spectroscopic orbital solutions and more securely identify the true constant velocity stars.

Finally, additional detailed abundance work should be undertaken of these stars as well, following up on the fascinating results of PS2000 and, especially, SPC2003.

It is a pleasure to thank the National Science Foundation for financial support to the University of North Carolina and to Bowling Green State University during the many years that we have been puzzling over the blue straggler phenomenon. As always, we are indebted to the many people who made observations for this project, especially Joe Caruso, Perry Berlind, Bob Davis, Robert Stefanik, Jim Peters, Mike Calkins, Ed Horine, Joe Zajack, Skip Schwartz, Willie Torres, Ale Milone, and Dick McCroskey.

Table 1. Stellar Data

Star	B - V	$[\mathrm{Fe}/\mathrm{H}]$	${\rm T}_{\rm eff}$	Р	Gap?	Li <sup>a</sup>	Ref	$[\mathrm{X/Fe}]^{\mathrm{b}}$	Ref	Template
$BD+23~74^{c}$	0.19	-0.91	7500	837	No	< 1.32	1			8000/4.0/ - 1.0/30
$HD 8554^{d}$	0.29	-1.46	6780	302	Yes	< 1.11	1			7250/4.0/ - 1.5/12
HD 109443 <sup>e</sup>	0.36	-0.55	6650	724	Yes	< 0.67	1			6500/4.0/-0.5/30
HD 135449 <sup>f</sup>	0.32	-0.92	6740	327	Yes	< 1.1	1,14			6250/4.0/ - 1.0/30
HD 142575 <sup>g</sup>	0.33	-0.97	6550		Yes	1.45	1,3	$\cdots$ ;+0.05	3	6250/4.0/ - 1.5/14
$BD+72$ $94^{h}$	0.32	-1.62	6620		Yes	2.42	2			6250/4.0/ - 1.5/4
BD+40 1166 <sup>i</sup>	0.42	-0.76	6200		No					6250/4.0/ - 1.0/8
BD+25 1981	0.29	-1.26	6860		No	< 0.72	1			6750/4.0/ - 1.5/10
BD-12 2669	0.28	-1.49	6710	381	Yes					7000/4.0/ - 1.5/30
HD 84937	0.37	-2.18	6300		No	2.23	10,11	+0.57/-0.03	$3,\!8,\!10$	6250/4.0/ - 2.0/4
HD 97916	0.415	-1.31	6250	663	No	< 1.2	2	$\cdots$ ;+0.05	3	6250/4.0/ - 1.5/12
HD 106516	0.45	-0.87	6120	844	No	< 1.3	$7,\!12,\!13$	$\cdots$ ;-0.83	4	6000/4.0/ - 1.0/10
BD+51 1817 <sup>j</sup>	0.38	-1.10	6330	517	No	< 1.64	2			6250/4.0/ - 1.0/8
G66-30	0.37	-1.75	6280	688	No	< 1.61	2	-0.09;+0.16	15	6250/4.0/ - 1.5/6
G202-65	0.36	-1.50	6560	167	Yes	< 1.67	2			6500/4.0/ - 1.5/10
22166 - 041	0.16	-1.30	6560	486	Yes			-0.21;+0.46	5	
22170 - 028	0.17	-0.68	8050	1.0	No					
22873 - 139	0.34	-2.85	6420	19	Yes	2.15	2			
22876 - 008	0.28	-1.88	6630	303	Yes			+0.27;-0.05	5	
22890 - 069	0.20	-2.00	7700	2.0	No					
22892 - 027	0.30	-1.03	6720	485	Yes			+0.26;+0.15	5	
22948 - 068	0.31	-1.37	6590	300	Yes			+0.15;+0.16	5	
22956 - 028	0.34	-2.08	6900	1307	No			+1.38;+0.37	6	
22966 - 054	0.28	-1.17	6785	306	Yes			+0.15;+0.19	5	
29518 - 039	0.30	-2.49	6510	1576	Yes					

<sup>a</sup>Li abundances are given as log n(Li), where log n(H) = 12.00

 $^{\rm b} \rm Values$  given are [Sr/Fe] and [Ba/Fe], respectively.

 $^{c}BD+23$  74 is cited as SAO 74088 by Glaspey et al. (1994).

 $^{\rm d}{\rm HD}$  8554 is cited as SAO 109871 by Glaspey et al. (1994).

 $^{\rm e}{\rm HD}$  109443 is cited as SAO 180920 by Glaspey et al. (1994).

 $^{\rm f}{\rm HD}$  135449 is cited as SAO 206470 by Glaspey et al. (1994).

 $^{\rm g}{\rm HD}$  142575 is cited as SAO 121258 by Glaspey et al. (1994).

 $^{\rm h}{\rm BD}{+72}$  94 is often cited as G245-32.

Table 2. Radial Velocities

Tel	HJD	$v_{\rm rad}$	$\sigma$	
BD -	+23 74 00:32:4	3.3 + 24	:13:21	
W	2450630.7792	33.98	2.89	
W	2450655.7600	23.57	2.44	
W	2450670.8359	31.28	1.85	
W	2450691.8055	31.59	1.93	
W	2450713.8439	28.01	1.61	
W	2450728.7021	28.16	2.42	
W	2450745.5618	37.96	2.48	
W	2450771.5908	32.73	3.33	
W	2450791.6284	26.96	3.94	
W	2450811.5603	25.90	3.57	

Star	$\alpha$ (J2000) $\delta$	$N_{\rm obs}$	Span	$v_{\rm rot} \sin i$	$v_{\rm rad}$	σ	Е	Ι	E/I	$\mathbf{P}(\chi^2)$
			New	Program Sta	urs					
BD+23 74	00:32:43.3 +24:13:21	55	2558	29.6	32.52	0.60	4.47	2.27	1.97	0.00000
HD 8554	01:24:42.3 + 07:00:05	32	1544	11.0	11.13	0.64	3.60	1.05	3.44	0.00000
HD 109443	12:34:46.7 - 23:28:32	43	2342	29.1	43.36	0.48	3.14	1.25	2.50	0.00000
HD 135449	15:16:10.3 - 32:53:33	33	2575	29.5	-42.00	0.69	3.94	1.37	2.88	0.00000
HD 142575	15:55:02.8 + 05:04:12	16	4758	13.0	-64.98	0.17	0.54	0.68	0.80	0.78493
		Bina	ry Stars f	from Carney o	et al. (2001)	)				
BD-12 2669	08:46:39.6 -13:21:25	135	2097	33.3	41.60	0.26	6.72	1.59	4.23	0.00000
HD 97916	11:15:54.2 + 02:05:12	32	5083	14.9	61.04	0.16	4.12	0.72	5.74	0.00000
HD 106516	12:15:10.5 - 10:18:44	39	5181	11.5	4.41	0.09	4.84	0.50	9.79	0.00000
BD+51 1817	13:08:39.1 + 51:03:59	28	2194	9.0	-58.64	0.21	5.94	0.73	8.17	0.00000
G66-30	14:50:07.8 + 00:50:27	27	4366	8.1	-115.10	0.14	4.50	0.81	5.55	0.00000
G202-65	16:35:58.5 + 45:51:59	49	3871	11.6	-245.60	0.26	11.35	0.89	12.80	0.00000
	С	onstant '	Velocity S	stars from Ca	rney et al.	(2001)				
BD+72 94	01:47:12.3 + 73:28:27	40	7441	5.5	-268.67	0.12	0.79	0.67	1.17	0.06069
BD+40 1166	05:05:28.7 + 40:15:26	38	7997	8.6	105.31	0.12	0.75	0.66	1.13	0.06740
BD+25 1981	08:44:24.6 + 24:47:47	81	6909	10.0	57.54	0.08	0.75	0.57	1.33	0.00013
HD 84937	09:48:56.0 + 13:44:39	82	7355	4.8	-15 38	0.10	0.91	0.73	1.24	0 00568

 Table 3.
 Mean Velocities and Errors

 Table 4.
 Orbital Parameters

Star	P (days)	$\gamma$ $(\mathrm{kms^{-1}})$	$\frac{K}{(\mathrm{kms^{-1}})}$	e	ω (°)	$T_0$	$a_1 \sin i$ Gm	f(M) $(M_{\odot})$	NSpan	$\sigma$ (o-c) (km s <sup>-1</sup> )
	,	. ,	. ,					,	_	. ,
BD+23 74	840.4	+32.71	5.21	0.168	35	51974.6	59.4	0.0118	55	2.5
	$\pm 14.8$	$\pm 0.36$	$\pm 0.50$	$\pm 0.099$	$\pm 32$	$\pm 72.5$	$\pm 30.0$	$\pm 0.0171$	2558	
HD 8554	302.5	+11.86	5.11	0.026	222	51111.1	21.2	0.0042	32	0.9
	$\pm 1.6$	$\pm 0.17$	$\pm 0.25$	$\pm 0.047$	$\pm 103$	$\pm 85.9$	$\pm 1.8$	$\pm 0.0011$	1544	
HD 109443	684.5	+42.48	4.36	0.109	99	51743.3	40.8	0.0058	42	1.3
	$\pm 7.8$	$\pm 0.26$	$\pm 0.34$	$\pm 0.079$	$\pm 39$	$\pm 73.1$	$\pm 4.0$	$\pm 0.0035$	2342	
HD 135449	326.1	-42.50	5.49	0.053	283	51630.1	24.6	0.0056	33	1.3
	$\pm 1.9$	$\pm 0.30$	$\pm 0.34$	$\pm 0.062$	$\pm 70$	$\pm 61.9$	$\pm 4.0$	$\pm 0.0027$	2575	

Star	$\log P$	e	[Fe/H]	$(B-V)_0$	$T_{\rm eff}$	$M_1$	$M_2 \ (\min)$	$\sin i$
	Ι	Previous	results fr	om Carney e	t al. (20	001)		
BD -12 2669	2.586	0.071	-1.49	0.28	6710	0.91	0.38	0.742
HD 97916	2.822	0.042	-1.00	0.41	6235	0.93	0.39	0.771
HD 106516	2.926	0.041	-0.87	0.45	6100	0.91	0.42	0.818
BD +51 1817	2.713	0.043	-1.10	0.38	6340	0.94	0.35	0.702
G66-30	2.838	0.293	-1.75	0.38	6310	0.85	0.26	0.551
G202-65	2.224	0.145	-1.50	0.36	6340	0.87	0.50	0.935
CS 22166-041	2.687	0.024	-1.32	0.32	6560	0.96	0.48	0.901
CS 22876-008	2.481	0.075	-1.37	0.28	6630	0.97	0.34	0.685
CS 22892-027	2.686	0.259	-1.03	0.30	6720	1.05	0.21	0.508
CS 22948-068	2.477	0.044	-1.88	0.31	6590	0.89	0.24	0.503
CS 22956-028	3.116	0.207	-2.08	0.34	6335	0.83	0.52	0.955
CS 22966-054	2.486	0.059	-1.17	0.28	6785	1.04	0.40	0.776
CS 29518-039	3.198	0.075	-2.49	0.30	6510	0.86	0.55	1.000
			Ne	w results				
BD+23 74	2.923	0.18	-0.91	0.19	7500	1.28	0.31	0.619
HD 8554	2.481	0.017	-1.46	0.29	6780	0.98	0.18	0.390
HD 109443	2.860	0.27	-0.55	0.36	6650	1.18	0.22	0.471
HD 135449	2.514	0.043	-0.92	0.32	6740	1.08	0.21	0.447

Table 5. Mass and  $\sin i$  Estimates

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This manuscript was prepared with the AAS  ${\rm L\!AT}_{\rm E\!X}$  macros v4.0.



Fig. 1.— De-reddened B-V color indices are plotted vs. metallicity for metal-poor field main sequence stars (plus signs), and for the five new blue straggler candidates discussed in this paper (red filled circles). Also shown are the six blue straggler binaries with orbital solutions from Carney et al. (2001; blue filled circles) and the seven blue straggler binaries with orbital solutions and periods longer than 20 days from PS2000 (filled squares). BD+25 1981, which may be a binary star, is plotted as an open blue circle. The solid line represents a fit to observed globular cluster main sequence turn-off colors, and the dashed line is the theoretical equivalent for clusters with identical ages, as discused in the text.



Fig. 2.— The time histories of the measured radial velocities for (a) HD 142575; (b) BD+72.94; (c) BD+40.1166; (d) BD+25.1981; and (e) HD 84937.



Fig. 3.— The orbital solutions and observed velocities for: (a) BD + 2374; (b) HD 8554; (c) HD 109443; and (d) HD 135449.



Fig. 4.— The orbital eccentricity vs. log period for 156 single-lined spectroscopic binaries from Latham et al. (2002) are plotted as open circles. The orbital solutions for the blue stragglers shown in Figure 1 are also shown. Filled circles are the new orbital solutions from Table 4, filled squares are our orbital solutions from CLLGM, filled diamonds are stars from PS2000 with periods longer than 20 days, and open squares are stars from PS2000 with shorter periods.



Fig. 5.— The distributions of the orbital eccentricities of the stars shown in Figure 4.



Fig. 6.— The derived abundances of lithium in Hyades dwarfs are shown as open circles, taken from Cayrel et al. (1984), Boesgaard & Trippico (1986), and Boesgaard & Budge (1988). Stars with only upper limits are plotted as "v". The lithium abundances of the four stars discussed in this paper are shown as filled circles, and upper limits are signified by arrows, as summarized in Table 1. The dashed line represents the "Spite plateau" of lithium abundances for metal-poor main sequence stars with  $6200 > T_{eff} > 5400$  K.



Fig. 7.— The distribution of  $v_{\rm rot} \sin i$  values for metal-poor main sequence stars, taken from Latham et al. (2002). Recall that our instrumental resolution is 8.5 km s<sup>-1</sup>, so values much smaller than that should not be considered reliable. Very few metal-poor dwarfs show signs of rotation at or above the level of our instrumental resolution.



Fig. 8.— The derived  $v_{\rm rot} \sin i$  values for single stars hotter than comparable metallicity main sequence turn-off stars taken from PS2000 (open squares), as well as binary blue stragglers from PS2000 (filled squares) plus constant velocity stars (open circles) from Carney et al. (2001) and this paper and binaries (filled circles). The possible velocity variable BD+25 1981 is plotted as a triangle.



Fig. 9.— The cumulative fractional distribution of the mass functions of the single-lined spectroscopic binaries from Latham et al. (2001) and the blue stragglers in Table 5.



Fig. 10.— The observed orbital periods of blue straggler binary stars from this paper (red filled circles), PS2000 (filled blue squares), and Carney et al. (2001; blue filled circles) are compared with theoretical predictions for stable mass transfer via Roche lobe overflow from Rappaport et al. (1995). We have also included the two other *s*-process enhanced stars CS 29497 – 030 and CS 29509 – 27 from SPC2003 as red open circles.