SUB-SUBGIANTS IN THE OLD OPEN CLUSTER M67?

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ABSTRACT

We report the discovery of two spectroscopic binaries in the field of the old open cluster M67—S1063 and S1113—whose positions in the color-magnitude diagram place them ~1 mag below the subgiant branch. A ROSAT study of M67 independently discovered these stars to be X-ray sources. Both have proper-motion membership probabilities greater than 97%; precise center-of-mass velocities are consistent with the cluster mean radial velocity. S1063 is also projected within one core radius of the cluster center. It is a single-lined binary with a period of 18.396 days and an orbital eccentricity of 0.206. S1113 is a double-lined system with a circular orbit having a period of 2.823094 days. The primary stars of both binaries are subgiants. The secondary of S1113 is likely a 0.9 $M_\odot$ main-sequence star, which implies a 1.3 $M_\odot$ primary star. We have been unable to explain securely the low apparent luminosities of the primary stars. The colors of S1063 suggest 0.15 mag higher reddening than found for either M67 or through the entire Galaxy in the direction of M67. S1063 could be explained as an extincted M67 subgiant, although the origin of such enhanced extinction is unknown. The photometric properties of S1113 are well modeled by a cluster binary with a 0.9 $M_\odot$ main-sequence secondary star. However, the low composite luminosity requires a small (2.0 $R_\odot$) primary star that would be supersynchronously rotating, in contrast to the short synchronization timescales, the circular orbit, and the periodic photometric variability with the orbital period. Geometric arguments based on a tidally relaxed system suggest a larger (4.0 $R_\odot$) primary star in a background binary, but such a large star violates the observed flux ratio. Thus, we have not been able to find a compelling solution for the S1113 system. We speculate that S1063 and S1113 may be the products of close stellar encounters involving binaries in the cluster environment and may define alternative stellar evolutionary tracks associated with mass transfer episodes, mergers, and/or dynamical stellar exchanges.

Key words: binaries: spectroscopic — color-magnitude diagrams — open clusters and associations: individual (M67) — stars: evolution

1. INTRODUCTION

The open cluster M67 is one of the most comprehensively studied of all star clusters and has long been the prototype for old (4 Gyr) open clusters in the Galaxy. Indeed, one of the first photoelectric color-magnitude diagrams was derived for M67 by Johnson & Sandage (1955). Since that time, the precision of stellar photometry has steadily improved, and with it has the definition of the M67 giant branch (Janes & Smith 1984; Montgomery, Marshall, & Janes 1993). Indeed the remarkable narrowness of the M67 giant branch has served as a precise touchstone against which innumerable single-star evolution models have been tested (e.g., Dinescu et al. 1995).

However, even after application of strict proper-motion membership criteria, the color-magnitude diagram of M67 remains littered with stars that do not fall on a single-star isochrone (Fig. 1). Some of these seeming anomalies can be accounted for. For example, one luminous star to the blue of the giant branch is a spectroscopic binary whose composite light can be explained by a giant–main-sequence pairing; another is a giant–white dwarf pair with a complicated history (Mathieu, Latham, & Griffin 1990; Verbunt & Phinney 1995; Landsman et al. 1997). Many of the stars immediately above the turnoff and subgiant branch are spectroscopic binaries and, consequently, overluminous. In addition, the parallel sequence of stars to the red of the main sequence is assuredly made up of binaries in the cluster environment and may define alternative stellar evolutionary tracks associated with mass transfer episodes, mergers, and/or dynamical stellar exchanges.

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has defied explanation. A kinematic member in all three dimensions and lying in projection in the cluster core, its explanation as a nonmember remains possible but not satisfying (Mathieu & Latham 1986; Nissen, Twarog, & Crawford 1987). In this paper, we consider two more stars—S1063 and S1113—that by every indication are cluster members, yet whose locations in the M67 color-magnitude diagram are dramatically inconsistent with single-star evolutionary theory. Specifically, as shown in Figure 1, these stars lie below the subgiant branch.

Our attention has converged on these stars from two directions. We have underway a multidecade survey of the spectroscopic binary population in M67 (Mathieu et al. 1990; Latham, Mathieu, & Milone 1997). Both S1063 and S1113 were found to be spectroscopic binaries, with S1113 in particular being notable for the rapid rotation of its primary star. Belloni, Verbunt, & Mathieu (1998) have also undertaken a comprehensive study of stellar X-ray sources in M67 based on ROSAT observations. S1063 and S1113 were independently discovered to be X-ray sources, of
which there are only 25 known among cluster members. Both stars are also photometric variables (van den Berg et al. 2002), which are infrequent in a cluster of this age (Stassun et al. 2002).

In this paper, we present a comprehensive discussion of the orbital, spectroscopic, and photometric properties of S1063 and S1113. Regrettably, like the blue stragglers and S1072, their interpretation remains a puzzle.

2. THE STARS

The stars S1063 and S1113 had attracted some attention prior to our radial velocity and X-ray studies. Both stars are included in the highly precise proper-motion study of Girard et al. (1989), in which S1063 is given a proper-motion membership probability of 97% and S1113 of 98%. Being a bit less than one core radius from the cluster center, S1063 has been included in most photometric studies of M67; S1113 is located at three core radii and thus only has been observed in the wider field photometric surveys. Racine (1971) noted that S1063 was photometrically unusual in that it lies roughly a magnitude in $V$ below the subgiant branch. S1113 has photometric properties very similar to those of S1063 but seems to have escaped notice until mentioned by Kaluzny & Radczynska (1991). In Figure 1, we show the color-magnitude diagram of M67 derived from the photometry of Montgomery et al. (1993); S1063 and S1113 are indicated with boxes.

Both stars have been found to be photometric variables. Racine (1971) noted a large range (0.18 mag) in photometric observations of S1063, and its variability was subsequently confirmed by other observers (Rajamohan et al. 1988; Kaluzny & Radczynska 1991). S1113 has a variable star designation—AG Cnc—and Kaluzny & Radczynska (1991) found S1113 to be photometrically variable at the 0.05 mag level. Based on the variability (but not light curves) of the stars and their location in the color-magnitude diagram, Kaluzny & Radczynska (1991) suggested that both stars are highly evolved W UMa binaries with extremely small mass ratios and consequently small photometric amplitudes.

Both S1063 and S1113 were included in a large survey for spectroscopic binaries among M67 proper-motion cluster members begun in the mid-1980s (last summarized in Latham et al. 1997). S1063 was found to be a single-lined spectroscopic binary, with no evident distinction otherwise. S1113 was immediately recognized as an unusual double-lined spectroscopic binary in that the primary star was a rapid rotator.

Independently, ROSAT Position Sensitive Proportional Counter observations of M67 identified these two stars as being among 25 cluster members detected to have X-ray emission (Belloni, Verbunt, & Schmitt 1993; Belloni et al. 1998). As members of this select group, S1063 and S1113 received optical spectroscopic attention by Pasquini & Belloni (1998) and van den Berg, Verbunt, & Mathieu (1999). Both stars show strong emission cores in the Ca ii H and K lines, indicative of chromospherically active stars. Both stars also show Hα emission. In S1063, the Hα line is asymmetric, showing emission that is blueshifted with respect to an absorption feature. The position of the absorption line agrees with the velocity of the primary, perhaps suggesting that the absorption can be attributed to the primary star and that the Hα emission originates elsewhere in the system. Alternatively, the Hα line profile is very similar to that seen from HK Lac by Catalano & Frasca (1994), who attribute the emission to a large flare lasting 6 days. In S1113, the Hα emission is broad and clearly centered on the velocity of the primary star, with an equivalent width of 15 Å.

3. OBSERVATIONS AND DATA ANALYSES

3.1. Speedometry and Orbital Solutions

Radial velocity observations of S1063 were begun in 1987, and 28 observations were obtained through 1989. Eighteen radial velocity observations were obtained for S1113 between 1989 and 1998. All observations were obtained with the Center for Astrophysics (CfA) Digital Speedometers (Latham 1992). Two nearly identical instruments were used on the Multiple Mirror Telescope and the 1.5 m Tillinghast Reflector atop Mount Hopkins, Arizona. Echelle spectrographs were used with intensified photon counting Reticon detectors to record about 45 Å of spectrum in a single order near 5187 Å with a resolution of 8.3 km s⁻¹ and signal-to-noise ratios ranging from 8 to 15 per resolution element.

The 28 radial velocities for S1063 were measured using the one-dimensional correlation package RVSAO (Kurtz & Mink 1998) running inside the IRAF2 environment. The template spectrum was drawn from a new grid of synthetic spectra (Morse & Kurucz 2003) calculated using Kurucz's code ATLAS9. We correlated our observed spectra against an array of solar-metallicity templates spanning effective temperature, surface gravity, and projected rotational velocity. The template giving the highest peak correlation (averaged over all observations) had log g = 3.5, $T_{eff} = 5000$ K, and $v \sin i = 6$ km s⁻¹. The radial velocities derived with this template are presented in Table 1. The average internal error of these observations is 0.86 km s⁻¹.

A single-lined orbital solution with period $P = 18.396$ days is easily derived from these data; the elements are given in Table 2, and the theoretical velocity curves are superposed on the data in Figure 2. The center-of-mass velocity of $\gamma = 34.3 \pm 0.2$ km s⁻¹ is consistent with the cluster mean radial velocity of $33.5 \pm 1$ km s⁻¹ and observed velocity dispersion of $0.5$ km s⁻¹ (Mathieu 1983), so the star is a kinematic cluster member in all three dimensions. Otherwise, the orbital elements are unremarkable.

The analyses of the S1113 spectra were done using the two-dimensional correlation technique TODCOR (Zucker & Mazeh 1994, as implemented at CfA). A two-dimensional array of templates in effective temperature and projected rotation velocity, again derived from Kurucz spectra, were correlated with all of the S1113 spectra. The effective temperatures and rotation velocities of the templates were selected so as to maximize the correlation peak heights, averaged over all 18 spectra and weighted according to signal-to-noise ratio. We find projected rotational velocities $v \sin i$ of 53 km s⁻¹ for the primary and 11 km s⁻¹ for the secondary, respectively, with a 1 $\sigma$ uncertainty of 2 km s⁻¹.

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1 Some of the observations reported here were obtained with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

2 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
on each. Van den Berg et al. (1999) previously measured $v \sin i$ for both stars, finding $45 \pm 6$ km s$^{-1}$ for the primary and $12 \pm 1$ km s$^{-1}$ for the secondary. Our derived effective temperatures are 4800 and 5500 K for the primary and secondary, respectively, with a 1$\sigma$ uncertainty of 150 K. Finally, we derive a luminosity ratio at 5187 Å of 0.32 or 1.23 mag.

The primary and secondary radial velocities derived with these template parameters are given in Table 3. We obtained a double-lined orbital solution using equal weighting for all radial velocity measurements. The dashed line shows the center-of-mass velocity of the binary. (e = 0) orbital solution in Table 4 and show the orbit curves superposed on the phased data in Figure 3. (In these elements, $T_0$ represents a time of maximum radial velocity.) Again, the center-of-mass velocity of $\gamma = 33.4 \pm 0.4$ km s$^{-1}$ is consistent with the cluster mean radial velocity. The mass ratio $M_2/M_1$ of the system is $q = 0.703 \pm 0.012.$

### Table 1
Radial Velocity Measurements for S1063

| HJD (+2,440,000) | $v_{\text{rad}}$ (km s$^{-1}$) |
|------------------|-------------------------------|
| 6,899.6818       | 21.94                         |
| 7,158.0132       | 26.21                         |
| 7,196.7906       | 44.67                         |
| 7,216.7438       | 42.04                         |
| 7,226.7088       | 17.03                         |
| 7,489.8904       | 29.52                         |
| 7,493.8522       | 46.04                         |
| 7,513.9289       | 52.67                         |
| 7,515.8531       | 53.39                         |
| 7,516.8802       | 50.36                         |
| 7,519.8331       | 21.04                         |
| 7,522.9810       | 14.87                         |
| 7,524.0511       | 17.48                         |
| 7,526.0601       | 26.21                         |
| 7,543.8490       | 23.10                         |
| 7,544.8949       | 27.58                         |
| 7,545.8256       | 33.04                         |
| 7,547.9579       | 43.67                         |
| 7,549.8533       | 52.55                         |
| 7,552.8487       | 52.40                         |
| 7,555.8172       | 31.66                         |
| 7,574.7462       | 27.03                         |
| 7,579.7805       | 19.95                         |
| 7,601.6697       | 35.60                         |
| 7,608.6951       | 52.30                         |
| 7,609.6639       | 46.29                         |
| 7,610.6930       | 36.26                         |
| 7,845.0409       | 51.18                         |

### Table 2
Orbital Elements for S1063

| Parameters          | Values          |
|---------------------|-----------------|
| $P$ (days)          | $18.396 \pm 0.005$ |
| $\gamma$ (km s$^{-1}$) | $34.30 \pm 0.20$ |
| $K$ (km s$^{-1}$)   | $20.0 \pm 0.3$   |
| $e$                 | $0.206 \pm 0.014$ |
| $\omega$ (deg)      | $95 \pm 5$       |
| $T_0$ (+2,440,000 days) | $7482.19 \pm 0.22$ |
| $a_1 \sin i$ (AU)   | $0.0330 \pm 0.0006$ |
| $f(m)$ ($M_2$)      | $0.0143 \pm 0.0007$ |
| Number of observations | 28              |
| $\sigma$ (km s$^{-1}$) | 0.99            |

### Table 3
Radial Velocity Measurements for S1113

| HJD (+2,440,000) | $v_{\text{rad},p}$ (km s$^{-1}$) | $v_{\text{rad},s}$ (km s$^{-1}$) |
|------------------|---------------------------------|---------------------------------|
| 47,579.7541      | $-23.72$                        | 114.14                          |
| 47,610.8114      | $-24.26$                        | 117.76                          |
| 47,635.6961      | $-4.62$                         | 87.84                           |
| 47,903.0130      | 92.82                           | $-48.87$                        |
| 48,320.7433      | 93.49                           | $-48.93$                        |
| 48,338.7448      | $-18.47$                        | 103.52                          |
| 48,345.7097      | 74.53                           | $-22.31$                        |
| 48,644.8675      | 64.94                           | $-5.16$                         |
| 49,021.9789      | $-11.59$                        | 105.53                          |
| 49,057.7946      | 83.51                           | $-38.66$                        |
| 49,058.6665      | 9.15                            | 103.29                          |
| 49,348.0117      | 83.93                           | $-36.01$                        |
| 49,354.9585      | $-5.61$                         | 86.68                           |
| 49,465.7519      | 16.13                           | 103.53                          |
| 49,699.9173      | $-26.20$                        | 112.09                          |
| 50,799.0251      | 73.97                           | $-28.94$                        |
| 50,821.8463      | 92.94                           | $-53.73$                        |
| 50,821.8681      | 94.91                           | $-53.55$                        |

3.2. Photometry and Variability

Van den Berg et al. (2002) have photometrically monitored both stars, with 1 m telescopes at ESO (La Silla), Kitt Peak, and La Palma, in order to look for light variations that may provide insight into the nature of the systems. We here summarize their main results.

Van den Berg et al. (2002; Fig. 5) also find S1063 to be variable, but as yet no period has been identified in the photometric data. The variability is clearly of a long-term
TABLE 4

ORBITAL ELEMENTS FOR S1113

| Parameters                     | Values                           |
|--------------------------------|----------------------------------|
| $P$ (days)                     | 2.823094 ± 0.000014              |
| $\gamma$ (km s$^{-1}$)         | 33.4 ± 0.4                       |
| $K_1$ (km s$^{-1}$)            | 60.6 ± 0.9                       |
| $K_2$ (km s$^{-1}$)            | 86.2 ± 0.6                       |
| $e$                            | 0                               |
| $\omega$ (deg)                 | ...                             |
| $T_0$ (+2,440,000 days)        | 8,916.368 ± 0.004                |
| $a_1 \sin i$ (AU)              | 0.0157 ± 0.0003                  |
| $a_2 \sin i$ (AU)              | 0.0223 ± 0.0003                  |
| $M_1 \sin^2 i$ ($M_\odot$)     | 0.544 ± 0.012                    |
| $M_2 \sin^2 i$ ($M_\odot$)     | 0.382 ± 0.012                    |
| $q$                            | 0.703 ± 0.012                    |
| Number of observations         | 18                              |
| $\sigma_1$ (km s$^{-1}$)       | 3.15                            |
| $\sigma_2$ (km s$^{-1}$)       | 2.10                            |

Notes.—The primary is indicated with a “1,” the secondary with a “2.”

Fig. 4.—Light curve (top) and primary (solid) and secondary (dashed) orbit curves (bottom) for S1113 phased on the orbital period of 2.823094 days. The light curve shows $V$ data taken in 1998 January (open circles), 1998 February and March (filled triangles), and 2000 February (open triangles), taken from van den Berg et al. (2002). Note that maximum light brightness occurs when the primary star is moving toward us (in projection).

Fig. 3.—Theoretical velocity curves of S1113 shown with the phased radial velocity measurements for the primary (filled circle) and secondary (open circle) stars. The dashed line shows the center-of-mass velocity of the binary.

4. CLUSTER MEMBERSHIP

We use kinematic evidence to assess the membership of these binaries in the M67 cluster. As noted above, Girard et al. (1989) find the proper-motion membership probability of S1063 to be 97% and of S1113 to be 98%. The location of S1113 at three core radii in projection makes the argument for its membership somewhat less secure. However, even weighting by the cluster surface density distribution, Girard et al. (1989) give it a membership probability of 94%, reflecting the fact that S1113 lies within the half-mass radius of the cluster (Mathieu 1983). At the same time, both binaries have radial velocities within 1 km s$^{-1}$ of the cluster radial velocity.

The proper motions of Girard et al. (1989) are of very high precision, and thus their ability to distinguish cluster members and field stars is excellent (see their Fig. 5). Nonetheless, even the highest probability members have some chance of being field stars. Our radial velocity survey provides independent information that permits us to evaluate...
the percentage of field stars among the proper-motion high-probability members. Specifically, we consider the sample of stars with proper-motion membership probability greater than 95%. Within this sample, there are 140 stars with multiple radial velocity measurements obtained in the CfA survey and no indication of velocity variability. Of these 140 stars, only one has a velocity (25.6 km s$^{-1}$) indicating nonmembership. The remainder show a Gaussian velocity distribution with a mean velocity of 33.55 km s$^{-1}$ and a velocity dispersion of 1.06 km s$^{-1}$. This result remains true for the subset of 39 stars at projected radii greater than two core radii, which show a mean velocity of 33.45 km s$^{-1}$ and a velocity dispersion of 1.07 km s$^{-1}$. Based on the single field star interloper, we conclude that the field contamination among those high-probability proper-motion members is of order 1%.

A fraction of these field star contaminants may have radial velocities similar to that of the cluster. The field radial velocity dispersion is expected to be much larger than the observed cluster velocity dispersion of 0.5 km s$^{-1}$. As yet, the true field radial velocity distribution in the direction and magnitude range of the proper-motion study has not been measured. In its place, we model the field radial velocity distribution with a Gaussian having a typical galactic disk velocity dispersion of 20 km s$^{-1}$ (Sparke & Gallagher 2000) and conservatively center the field velocity distribution on the M67 radial velocity.$^3$ With these assumptions, we find that 4% of field stars have velocities within 1 km s$^{-1}$ of the cluster velocity, corresponding to 2 times the observed velocity dispersion of cluster members. Thus, we estimate that the percentage of field stars with both high proper-motion membership probability and radial velocities consistent with cluster membership is no more than 0.04%.

There are 246 stars in the proper-motion study with membership probabilities in excess of 95%. Using the binomial theorem and our estimated probability of 0.04%, there is a 0.4% chance that two of these stars are field stars with radial velocities consistent with cluster membership, and a 9% chance that one such star is a field star.

Given that the chances of one or even two field stars being three-dimensional kinematic members of M67 are not entirely negligible, the possibility that S1063 and S1113 are field stars rather than anomalous members must be explored. However, as we shall see in the next section, neither of these systems can be completely explained as field stars. Furthermore, S1063 and S1113 are not the only three-dimensional kinematic members of M67 without evident explanation; for example, S1072 already has been noted in § 1. The probability that all of these seemingly anomalous cluster members are simply field stars is indeed negligible. Finally, several of the authors would argue that S1063 and S1113 have been drawn from the much smaller sample of ROSAT-detected stars and therefore would conclude that the chances that they are field stars are yet smaller than presented here.

$^3$ As a plausibility check, we have examined the distribution of all radial velocity nonmembers in our survey. These stars have a mean radial velocity of 22 km s$^{-1}$ with an rms dispersion of 29 km s$^{-1}$. Since the survey selection was based on proper-motion membership, this distribution is not independent of the proper-motion distribution and thus may not be appropriate for use in this analysis. Nonetheless, these results give plausibility to the adopted radial velocity distribution.

5. PROPERTIES OF THE STARS

5.1. S1063

The most notable property of the orbit of S1063 may be its ordinairiness. If S1063 fell on the cluster main sequence or subgiant branch, its orbit would merit no further attention. For example, the eccentricity of $e = 0.206$ is quite typical for main-sequence and subgiant binaries in M67 with periods $\sim 20$ days (Mathieu et al. 1990).

If the primary star is more massive than the unseen secondary, then the orbit places an absolute lower limit on the primary and secondary masses of $0.06 M_\odot$, which is too low to be useful. Given the anomalous location of S1063 in the M67 color-magnitude diagram, we have no estimate of the primary mass based on stellar evolution theory. However, we will show below that the primary is an evolved star, with the surface gravity of a subgiant. Thus, we consider primary masses between 0.7 and $1.3 M_\odot$, delimited by the main-sequence lifetime equal to the age of the Galaxy and the upper mass limit on the formation of a subgiant branch. For this range in the primary mass, the orbit places a lower limit on the secondary mass between 0.23 and 0.34 $M_\odot$.

Evidently, the primary star dominates the light at 5187 Å. As noted above, the CfA spectra indicate an effective temperature of $T_{\text{eff}} = 5000$ K and a gravity of $\log g = 3.5$. New analyses of the higher signal-to-noise spectra of van den Berg et al. (1999) yield similar measures. Comparison of the $\text{V}$ $\lambda 6251.83$/$\text{Fe}$ $\lambda 6252.57$ line ratio with the spectral analyses of Gray (Gray 1989; Gray & Johanson 1991) yield a $T_{\text{eff}}$ of 5150 K for a dwarf and 4900 K for a giant. Alternatively, in Figure 5 we use the spectral diagnostic $I_s$ as defined by Maluuto & Schmidt-Kaler (1997) to derive a spectral type of G8–K0. Such a spectral classification indicates effective temperatures similar to the spectral line results (Schmidt-Kaler 1982; Bessell & Brett 1988; Bessell, Castelli, & Plez 1998).

Detailed analyses of the optical spectra obtained by van den Berg et al. (1999) indicate that the primary of S1063 is neither a giant nor a dwarf. We have taken two approaches to determining the surface gravity. First, we have compared the gravity-sensitive Mg $b$ lines with Kurucz spectra. In Figure 6, we show the spectrum of S1063 and Kurucz spectra at $T_{\text{eff}} = 5000$ K over a range of $\log g$. Based on the $b$ triplet line shapes, S1063 is neither a giant ($\log g = 2.5$–3.0) nor a dwarf ($\log g = 4.5$–5.0). Spectral fitting to the Mg $b$ lines (with $T_{\text{eff}}$ as a free parameter) results in $T_{\text{eff}} = 5000$ K, $\log g = 3.5$, and $v \sin i = 8 \text{ km s}^{-1}$, corroborating the results obtained from the lower signal-to-noise CfA spectra. However, the referee has correctly noted several disparities of relative line depths in other wavelength regions between the observed spectrum and the models, for example, comparing the Fe $\lambda 5187.9$ Å and Ti II/Ca I $\lambda 5188.8$ Å lines. More detailed spectroscopic analyses and modeling may prove fruitful.

Second, in Figure 5 we compare the values of $I_s$ and $I_2$ for S1063 with those of stars of all luminosity classes. Again, for stars of similar $I_s$, S1063 falls between the dwarfs and giants. Thus all of the spectroscopic evidence indicates that the primary of S1063 is a subgiant with an effective temperature of $T_{\text{eff}} \approx 5000$ K.

Montgomery et al. (1993) provide $UBV_I$ photometry (Table 5), which allows an analysis of the extinction toward S1063 under the assumption that the luminosity of the system derives solely from the primary star. We initially
consider the extinction of $E(B-V) = 0.032$ found for M67 by Nissen et al. (1987). Adopting the extinction curve of Cardelli, Clayton, & Mathis (1989), the dereddened colors of S1063 are given in Table 5. For comparison, we also give in Table 5 the colors of a solar-metallicity 4 Gyr 1.37 $M_\odot$ subgiant with the same value of $(B-V)_0$, using the Yale isochrones with the GDK color transformation (Yi et al. 2001). The intrinsic colors of S1063 are both 0.15 mag bluer in $U-B$ and 0.14 mag redder in $V-I$. Furthermore, the effective temperature implied by the $(B-V)_0 = 1.02$ mag is 4577 K, significantly cooler than the effective temperature of 5000 K derived from spectroscopy.

These color differences can be resolved if the extinction toward S1063 is taken as a free parameter. For example, we consider the colors of a 4989 K subgiant, specifically a 4 Gyr 1.35 $M_\odot$ subgiant as defined by the Yale models and presented in Table 5. Such a star implies a reddening of 0.18 mag, and the consequent intrinsic colors of S1063 are also given in Table 5. The dereddened $(U-B)_0$, $(B-V)_0$, and $(V-I)_0$ colors for S1063 agree very well with the 4989 K subgiant model.

We note that given the observed photometric variability of S1063 (§ 3.2), detailed modeling of colors as in Table 5 must be considered with care. S1063 shows little variation in $B-V$, and so combined with the spectroscopic derivation of the effective temperature the argument for enhanced extinction toward S1063 remains unchanged. The argument is also not sensitive to the surface gravity of the primary star, with which the colors vary only slightly. On the other hand, the observed $U-B$ and $V-I$ of S1063 show variations of up to 0.05 mag peak to peak, and so there is uncertainty in the use of the single-epoch Montgomerly et al. photometry to specify the nature of the system. (Perhaps surprisingly, the $U-B$ measurements of Montgomerly et al., Racine 1971, and Sanders 1989 agree to within 0.01 mag; the $B-V$ measurements agree to within 0.02 mag.)

The amount of inferred extinction also depends on the choice of stellar model. The Yale models have also been transformed to observables using the LCD transformations (Yi et al. 2001). In Table 5, we repeat the subgiant analysis with these colors. While the derived reddening of $E(B-V) = 0.14$ mag is somewhat smaller than with the GDK transformations, it nonetheless remains larger than the extinction toward M67 itself.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Spectral classification of S1063 according to the classification criteria of Malyuto & Schmidt-Kaler (1997). \textit{Left:} $I_S$, based on features between 4215 and 4360 Å and 5125 and 5290 Å, is an index for spectral type and places S1063 (solid line) between type G8 and K0. \textit{Right:} $I_2$, based on features between 4120 and 4280 Å is an index for luminosity class and places S1063 between dwarfs and giants.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{Comparison of S1063 spectrum with synthetic spectra of effective temperature $T_{\text{eff}} = 5000$ K, $v \sin i = 8$ km s$^{-1}$, and differing surface gravities (Kurucz 1979). The spectra are normalized to the continuum flux and shifted vertically in steps of 0.75 flux units. S1063 is best fit by the synthetic spectrum with $\log g = 3.5$.}
\end{figure}
Interestingly, correcting for a reddening of $E(B-V) = 0.18$ mag moves S1063 to a position 0.15 mag in $V$ below the base of the M67 giant branch. Given an observed variation in $V$ of 0.15 mag, S1063 remains a candidate for a normal cluster subgiant if an explanation for the higher extinction can be found. Adopting this reddening, the extinction curve of Cardelli et al. (1989), the bolometric correction of the Yale model, and a true distance modulus to M67 of 9.6, we can derive a radius of $2.4 R_\odot$, and a luminosity of $3.3 L_\odot$ for the primary star (Table 5). Given a log $g = 3.5$, this radius implies a mass of 0.7 $M_\odot$; however, we have not determined the gravity to better than a factor of 2–3. We stress that all of these values are only meaningful given cluster membership.

Alternatively, the colors of S1063 can be modeled with a background giant star having an effective temperature somewhat in excess of 4900 K. For specificity, we show in background giant star having an effective temperature the gravity to better than a factor of 2–3. We stress that 0.18 mag moves S1063 to a position 0.15 mag in $V$ agrees well with the intrinsic colors of S1063 given $E(B-V)$ compared with the log $g$ for the primary also has the modest difficulty of a lower sur-

| TABLE 5 |
| Photometric Analyses of S1063 |
|---|---|---|---|---|---|---|---|
| $V$ | $U-B$ | $B-V$ | $V-I$ | $J-H$ | $H-K$ | $L$ ($L_\odot$) | $T_{\text{eff}}$ (K) | $R$ ($R_\odot$) |
|---|---|---|---|---|---|---|---|---|
| Observed................................. | 13.79 | 0.72 | 1.05 | 1.20 | 0.60 | 0.10 | ... | 5000 | ...
| Intrinsic$^a$ [$E(B-V) = 0.032$]........... | ... | 0.69 | 1.02 | 1.15 | ... | ... | ... | ... |
| Model (1.37 $M_\odot$, 4 Gyr)$^b$......... | ... | 0.84 | 1.02 | 1.01 | ... | ... | ... | 4577 | ...
| Intrinsic$^c$ [$E(B-V) = 0.18$]........... | ... | 0.55 | 0.87 | 0.90 | ... | ... | 3.34 | 5000 | 2.4
| Model (1.35 $M_\odot$, 4 Gyr)$^b$......... | ... | 0.56 | 0.87 | 0.90 | ... | ... | ... | 4989 | ...
| Intrinsic$^c$ [$E(B-V) = 0.14$]........... | ... | 0.60 | 0.91 | 0.97 | 0.55 | 0.07 | 3.28 | 5000 | 2.4
| Model (1.35 $M_\odot$, 4 Gyr)$^b$......... | ... | 0.65 | 0.92 | 0.97 | 0.52 | 0.09 | ... | 4921 | ...
| Model (2.3 $M_\odot$, 0.8 Gyr)$^c$......... | ... | 0.62 | 0.91 | 0.94 | 0.50 | 0.01 | 35.1 | 4990 | 7.9

$^a$ Using extinction curve of Cardelli et al. 1989; luminosity and radius are derived assuming cluster membership.

$^b$ Derived from Yale isochrones (solar metallicity, LCD transformation).

$^c$ Derived from Yale isochrones (solar metallicity, LCD transformation).

the enhanced reddening. A conjecture is that the reddening might be due to circumstellar or circumbinary material local to the system. Indeed, the slow but substantial $V$ brightness variation observed in this system might be attributed to variations in local extinction; however, such an explanation is confounded by the lack of associated variation in $B-V$. We also note that the system shows no evidence of a near-infrared excess. Infrared colors have been obtained from the 2MASS survey and are given in Table 5. Theoretical colors are also available from the Yale models with the LCD transformation, also given in Table 5 for the 1.35 $M_\odot$ model at 4 Gyr. The dereddened observed colors and theoretical colors agree to within the 4% measurement errors on the colors. Reducing these errors and extending measurements to longer wavelengths would be worthwhile.

Of course, these color analyses presume that the colors of the primary star are not abnormal for a 5000 K star, and that the composite light of the system derives only from the primary photosphere. We encourage more careful spectroscopic analyses of S1063, among other things to precisely compare abundances with cluster members, to better determine the surface gravity, and to search for evidence of extincting matter. We also recommend photometric observations over a broader wavelength range to search for other contributors to the composite light.

Finally, we briefly discuss the rotation of the primary star in the context of an M67, 1.3 $M_\odot$ subgiant with a system $E(B-V) = 0.18$ mag. The nondetection of the secondary in our spectra requires that the secondary star have $V > 16$, roughly 2 mag fainter than the primary (here taken as equivalent to the composite light). If the secondary is a main-sequence star in the cluster, then based on this magnitude limit and extinction the Yale isochrones give an upper limit on the mass of the secondary of 0.9 $M_\odot$ and an associated lower limit on the inclination angle of $28^\circ$ from the orbital solution. For aligned rotational and orbital axes and a measured $v \sin i$ of 6 km s$^{-1}$, the true equatorial rotation velocity could be as large as 13 km s$^{-1}$. For a primary radius of $2.4 R_\odot$, the rotational period could be as short as 9.5 days. Such a short rotation period would be consistent with the observed X-ray emission, chromospheric activity, and possible flares. Perhaps most plausibly the pseudosynchronous rotation period of 14.64 days (cf. Claret & Giménez 1993), requiring an inclination angle of $i = 46^\circ$, is permitted by the
primary mass range and the upper limit on the secondary mass. However, we remind the reader that the photometric data show no evidence of periodicity at this rotation period, nor is there strong Hα emission from the primary (van den Berg et al. 1999).

5.2. S1113

The spectroscopic detection of the secondary permits substantially more information to be derived for this binary. Here we analyze the system first from a distance-independent geometric perspective, and then we take a distance-dependent photometric approach.

For the geometric argument, we presume that the stellar rotational periods are synchronized with the orbital period, and that the rotational and orbital axes are aligned. Both are expected for a circularized orbit, since alignment and synchronization happen on shorter timescales than circularization (Hut 1981), and synchronization is further supported by the observed photometric variation on a period very similar to the orbital period.

Given these two assumptions, the mean density of either star can be written as

$$\rho \propto \frac{(M \sin^3 i)}{(P \sin i)^3}$$

The mean density is thus independent of the unknown inclination angle and completely determined by the observables $M \sin^3 i$, $P$, and $v \sin i$. Using the values for these observables and $T_{\text{eff}}$ given in § 3.1, both stars can be placed on the density–effective temperature diagram, as shown in Figure 7. Also shown in Figure 7 are solar-metallicity Yale isochrones for a set of ages. The 4 Gyr isochrone, comparable to the age of M67, is shown as a dashed line.

The mean density of the secondary indicates a main-sequence star with an age of between 1 and 10 Gyr. While the uncertainties are too large to precisely determine the secondary age, the inferred secondary mass varies little as a function of age. For a 4 Gyr isochrone, the mass of the secondary star is $0.93 M_\odot$, and the range on mass implied by the uncertainties extends from 0.89 to 0.97 $M_\odot$. For a mass of 0.93 $M_\odot$, the dynamical mass ratio implies a mass for the primary star of 1.33 $M_\odot$, with a range of 1.27–1.38 $M_\odot$. The inclination of the system becomes 48°, and the semimajor axis is $11.0 R_\odot$. The primary and secondary radii, presuming synchronous rotation for both stars, are 4.0 and 0.90 $R_\odot$, respectively.

TABLE 6
PHOTOMETRIC ANALYSES OF S1113

| $V$ | $U-B$ | $B-V$ | $L$ ($L_\odot$) | $T_{\text{eff}}$ (K) | $R$ ($R_\odot$) |
|-----|-------|-------|-----------------|----------------------|---------------|
| Observed Composite | 13.77 | 0.52 | 1.01 | ... | ... |
| Primary | 14.07 | 0.55 | 1.07 | 2.0 | 4800 | 2.1 |
| Secondary | 15.30 | 0.45 | 0.85 | ... | 5500 |
| $1.37 M_\odot$ | ... | 0.88 | 1.04 | ... | 4534 |
| $0.90 M_\odot$ | 5.673 | 0.43 | 0.82 | 0.50 | 5311 | 0.83 |

- Derived from observed composite colors and model secondary colors.
- Derived from $0.90 M_\odot$ model reddened by $E(B-V) = 0.032$.
- Intrinsic absolute magnitude $M_V$ and colors from Yale isochrone (solar metallicity, GDK transformation).
Yale models (GDK transformation). The derived secondary 
$V$ magnitude, a reddening of $E(B-V) = 0.032$ mag, and an 
apparent distance modulus of 9.6 mag (Montgomery et al. 
1993) gives a secondary absolute magnitude $M_v = 5.6$, 
indicating a 4 Gyr 0.90 $M_\odot$ main-sequence model for the 
secondary star (Table 6). Notably, this mass is similar to the 
secondary mass of 0.93 $M_\odot$ derived from independent geo-
metric arguments. It is also encouraging that the effective 
temperature of the 0.90 $M_\odot$ cluster member is 5311 K, 
within the measurement uncertainties of the spectroscopi-
cally determined effective temperature of 5500 K (§ 3.1).

If we adopt the model colors for a 0.90 $M_\odot$, 5 Gyr, main-
sequence star, then we can determine colors for the primary 
star as presented in Table 6. These results for the primary 
and secondary are also plotted as open boxes in Figure 1. 
The primary lies somewhat further below the subgiant 
branch and further to the red than indicated by the 
composite light.

This color deconvolution leaves an interesting loose end, 
in that the primary shows a $U-B$ blue excess of 0.3 mag rel-
ate to either main-sequence or giant colors. A giant model 
selected to match the dereddened primary $B-V$ color is 
shown in Table 6; the $U-B$ color of this model is signifi-
cantly redder than derived for the primary star. The $U-B$ 
color of a main-sequence star of the same $B-V$ is 0.89. Both 
The $U$-band measurements of Sanders (1989) and 
Montgomery et al. (1993) support such an excess, although 
their measurements differ by 0.07 mag and possibly indicate 
variability. This excess ultraviolet light may in fact be asso-
ciated with the primary star, or it may derive from elsewhere 
in the system.

Since the gravity of the primary star is weakly constrained 
by the spectroscopy, we use both main-sequence and giant 
models of the same $B-V$ color as the primary to provide 
bolometric corrections and luminosities at the distance of 
M67. The giant model implies a luminosity for the primary 
of 2.0 $L_\odot$ and an effective temperature of 4534 K. The main-
sequence model provides a luminosity of 2.1 $L_\odot$ and 
effective temperature of 4726 K. Both of these temperatures are 
somewhat lower than the spectroscopically determined 
effective temperature of 4800 K (§ 3.1).

Unlike the secondary star, the model for the primary star 
inferrred from these photometric arguments is markedly dif-
ferent from the model for the primary developed from the 
geometrical arguments. The photometric radius for the pri-
mary of 2.0 $R_\odot$ is significantly smaller than the geometric 
radius of 4.0 $R_\odot$, or equivalently the photometric luminosity 
of 2.0 $L_\odot$ is substantially smaller than the geometric lumi-
nosity of 7.7 $L_\odot$.

This discrepancy between the primary luminosities derived 
from geometric and photometric arguments can be cast in a 
distance-independent manner. The geometric argument 
provides a distance-independend prediction for the ratio of 
primary to secondary $V$ flux. Continuing to assume synchro-
nization and alignment of axes, the ratio of primary to sec-
dary radii is the same as the ratio of $v\sin i$. Using also the 
ratio of our spectroscopically determined effective tempera-

4 Turning this argument around, we adopt a 4 Gyr, 5500 K star as a 
model for the secondary. The implied mass is 0.95 $M_\odot$ with an absolute $V$ 
magnitude of $M_v = 5.3$. Unreddened, the distance modulus to such a star is 
10.0 mag; given reddening, this is an upper limit. Thus, if the secondary 
is a main-sequence star, S1113 cannot be located far beyond M67.

6. DISCUSSION

6.1. S1063

The binary S1063 is remarkable in three ways: low appa-
rent brightness compared with M67 subgiants of similar 
color, enhanced reddening compared with Galactic extinct 
tion along the line of sight, and weak H$\alpha$ emission observed 
at a velocity different from the primary star velocity. In 
addition, the long timescale light variations are not easily 
explained if they are aperiodic. If they are periodic on time-
scales longer than 18 days, then they likely are due to star 
spots on the primary star and indicate that the primary is 
not rotating pseudosynchronously.

Given both its close kinematic association with M67 and 
projection upon the core of the cluster, we have explored ex-
planations for S1063 in the context of cluster membership. 
In this context, we have previously inferred a radius of 
2.4 $R_\odot$ for the primary star. As such, the primary star does 
not approach its critical surface at periastron passage. Thus, 
the radius of the star is not confined by the presence of the 
secondary, nor is there motivation for present mass transfer. 
Similarly, the eccentricity of the orbit does not suggest 
either a large evolved star or mass transfer in the past, both 
of which would likely have circularized the orbit.

We have explored the possibility that, rather than being 
an underluminous subgiant, the primary star is instead an 
ouerluminous main-sequence star. For example, a recent 
merger of two main-sequence stars would deposit kinetic 
energy into the merging stars. Here we consider two types 
of mergers: coalescence and collision. In the coalescence sce-
nario, the S1063 system was originally a triple system in 
which the present secondary was the tertiary star. If we 
assume that the orbital period that we observe now is 
equal to the period of the original tertiary star, we can use 
stability arguments to place an upper limit on the period of 
the original inner binary star. Using the coplanar formula-

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three of the stars involved in the binary-binary encounter, two having merged into the primary and a third being the present secondary. An eccentric orbit is a natural result of such a resonant encounter.

A prediction of either of these merger scenarios is that the resulting star will rotate rapidly. In the coalescence scenario, rapid rotation is expected as a result of synchronous rotation prior to the merger. With respect to the collision scenario, the simulations of Sills et al. (2001) show that a collision product is born with a high rotation rate. We argued in § 5 that for aligned rotation and orbital axes, the true equatorial rotation velocity could be as large as 13 km s\(^{-1}\), and for a primary radius of 2.4 \(R_\odot\), the rotational period could be as short as 10 days. However, such a rotation period is still long compared with those expected from mergers or collisions. In the collision scenario, of course, the primary rotation axis and the orbital axis need not be aligned, particularly since tidal circularization has not come to completion. As such, the surface rotation velocity of the primary could be significantly higher. A high inclination angle could also possibly explain a lack of periodic photometric modulation.

Most problematic, these impulsive origins must face the challenge that—even if the merger product would briefly have the properties of the S1063 primary star—the thermal timescale of the primary is very short compared with the cluster lifetime. If, for the sake of example, we adopt a primary mass of 0.7 \(M_\odot\), the present thermal timescale \(E_{\text{pot}}/L\) is only 3.4 Myr. A merger product would be expected to readjust to its new mass on such timescales (and perhaps become a present or future blue straggler depending on the combined mass). Given such short timescales, the probability of observing the primary prior to its new equilibrium state is very low. On the other hand, should a star be found shortly after a merger, the presence of residual circumstellar material resulting from the merger might also be expected, and it represents a possible explanation for the enhanced reddening of this system. Lastly, if formed recently, such a system may not yet be pseudosynchronized.

We stress that the nature of the secondary is unknown; we know only that it is substantially fainter than the primary at \(V\). Thus, the secondary is permitted to be a white dwarf. An isolated white dwarf of the cluster age would have a mass on the order of 0.6–0.7 \(M_\odot\) (Wood 1992; Richer et al. 1998); a white dwarf deriving from a prior mass transfer scenario could be much different. A hot source of radiation might help explain the weak \(H\alpha\) emission observed at a velocity different from the primary star velocity. How the secondary could become a white dwarf without circularizing the orbit during its prior post–main-sequence evolution would need to be explained; again, a dynamical exchange might play a role.

6.2. S1113

In § 5, we derived the properties of the stars in S1113 from two independent lines of reasoning, geometric and photometric. The two arguments produced quite different conclusions regarding the luminosity ratio of the stars or, similarly, regarding the nature of the primary star. To bring these two lines of reasoning into agreement, we must give up a basic premise of at least one of the arguments. Here we explore two possibilities and then discuss the measurement uncertainties.

1. Both the geometric and photometric arguments converge on a 0.9 \(M_\odot\), main-sequence secondary. This suggests that the resolution of the contradiction in luminosity ratios might be found in the primary star. Under the assumption of membership in M67, the geometric argument must be found wrong, for its implied 4800 K primary star of radius 4.0 \(R_\odot\) would be 1.2 mag more luminous in \(V\) than observed. The problem cannot be solved with extinction, since the reddening vector for the S1113 primary does not pass through an M67 4.0 \(R_\odot\) giant.

Examining the premises of the geometric argument, we first note that relaxing the assumption of alignment of orbital and rotational axes cannot in itself resolve the problem. Even if the inclination angle of the primary rotation axis is taken to be 90°, its radius is reduced only to 3.0 \(R_\odot\). (Recall that the primary radius derived from the photometric argument is 2.0 \(R_\odot\).)

Supersynchronous rotation of the primary leads to more success. Specifically, a rotation period of 1.4 days—or supersynchronous rotation by a factor of 2—would bring the primary radii derived from both the geometric and photometric arguments into agreement on a primary radius of 2.0 \(R_\odot\).

Such supersynchronism is not expected theoretically given the close proximity of the stars, the primary’s large radius, and the surface convection zones on both stars. Unless continuously driven, the duration of a supersynchronous state would be short. Furthermore, supersynchronous rotation of the primary would also require that the observed variability of the composite light at the orbital period must derive from elsewhere in the system. A cool spot on the secondary seems an unlikely origin. Given a secondary/primary \(V\) luminosity ratio of 0.35, a 38% light modulation from the secondary would be required to reproduce the observed 10% variation in the composite light at \(V\).

We note that making the secondary subsynchronous would imply a larger, more luminous secondary, which would also resolve the flux ratio discrepancy. However, the consequent change in mean density moves the secondary off the main sequence into a domain not occupied by standard stellar evolution (Fig. 7). While perhaps this is the case, this path permits essentially unconstrained modeling of the binary.

Finally, the unusual color-magnitude diagram position of S1113 is not easily solved by enhanced extinction of a cluster member. Large extinctions (in excess of 1 mag) along a standard reddening vector would imply a primary star near the top of the M67 main sequence, with much higher effective temperatures than found spectroscopically.

2. Alternatively, we consider arbitrarily discounting the spectroscopically determined flux ratio at \(V\) of 0.32 (§ 3.1) and adopt the geometric model for the system. This model indicates a secondary/primary flux ratio at \(V\) of 0.11. Corresponding decomposition of the composite \(V\) magnitude leads to a primary with \(V = 13.88\) and a secondary with \(V = 16.31\). The geometric model indicates a 0.9 \(M_\odot\), main-sequence secondary, and so, without considering additional reddening, the secondary \(V\) magnitude places the binary 1 mag beyond M67. A similar conclusion is reached by comparing the luminosity of a 4800 K, 4.0 \(R_\odot\) primary star with the composite light. At this distance, the 1.3 \(M_\odot\) primary becomes very similar to a star at the base of the M67 giant branch and, as such, can be explained by standard stellar evolution theory (albeit not as a cluster member).
The larger primary radius of 4.0 $R_\odot$ implied by the geometric model represents a large fraction of the primary Roche radius. The Roche radii are 4.5 and 3.8 $R_\odot$ for the primary and secondary, respectively. An equipotential surface about the primary whose volume equals that of a 4.0 $R_\odot$ sphere extends 74% of the way to the $L_1$ point. Thus, within the geometric model, the role of mass transfer in the evolution of S1113 merits consideration. Evidently, the 0.9 $R_\odot$ main-sequence secondary lies well within its Roche radius.

Interestingly, both the phasing of the periodic photometric variation and the ultraviolet excess are suggestive of a hot spot near the secondary star powered by an accretion stream. Such spots are formed on the following side of the primary. Adopting the spot parameters above, a temperature variation can also be well modeled by a large cool spot on the surface of the secondary star.

We note that at present no spectral signatures of such a hot spot have been seen. Van den Berg et al. (1999) did find broad Hα from S1113, but this emission was kinematically associated with the primary star. They argued that this emission could be consistent with the higher chromospheric activity driven by the rapid rotation of the star, in analogy to V711 Tau. In this context, we note that the photometric variation can also be well modeled by a large cool spot on the primary star. For example, we have reproduced the light variations with the addition of a cool spot in the upper hemisphere of the primary and located 90° from the major axis of the orbit. Specifically, the spot properties are as follows: latitude 40°, longitude 270°, radius 27°, and temperature 0.82 of the stellar surface temperature. The location of the spot at 270° longitude is motivated by the observations rather than an independent physical argument.

The large extent to which the primary star fills its Roche lobe in this model implies that its shape is significantly asymmetric. Using the Wilson-Devinney formalism, we have investigated the expected magnitude of photometric variations due to the anticipated ellipsoidal shape of the primary. Adopting the spot parameters above, a temperature of 4800 K for the primary star, a limb-darkening coefficient (linear law) of 0.6 for each star, a gravity-brightening coefficient of 0.32, and a reflection coefficient of 0.5, we find the peak-to-peak ellipsoidal variations to be 0.06 mag in $V$. Most importantly, these ellipsoidal variations produce a double-peaked light curve over the orbital period, in marked contrast to the observed single-peaked light curve. It is possible that these small ellipsoidal variations have gone undetected in contrast to the larger photometric variations of the system. For example, in Figure 8 we show the light curve combining both the cool spot described above and the ellipsoidal variations. Evidently, the ellipsoidal variations are lost to inspection in this synthetic light curve, which in fact looks very similar to the observed light curve.

To summarize, the geometric line of reasoning suggests that S1113 is a field binary located behind M67. In this scenario, it may be a detached RS CVn whose rapid rotation is producing the several emission diagnostics of enhanced chromospheric activity, as well as a large spot. Alternatively, mass transfer may be underway, producing a hot spot in the vicinity of the secondary star. However, to adopt this interpretation of the system, both the kinematic association with M67 and the agreement of the primary mass with the M67 turnoff mass must be taken as merely coincidental. In addition, the measured $V$ flux ratio must be ignored. As we discuss below, we find this last requirement to be a serious counterargument.

3. Measurement uncertainties: We have explored whether the discrepancy between the conclusions of the geometric and photometric analyses are the result of our measurement uncertainties. On the photometric side, broadband photometric measurements of S1113 are several and corroborative. The effective temperature for the primary derived from photometric colors is similar to the effective temperature derived from our high-resolution spectra, indicating that both determinations of the effective temperature are reasonable. Finally, we find it unlikely that the bolometric correction for the primary star overestimates the luminosity by a factor of 3, particularly given the observed excess flux in the $U$ band. However, given that only $UBV$ photometry is available, photometry over a wider range of wavelength is much needed.

The geometric luminosity ratio can be brought into accord with the observed $V$ ratio if the effective temperatures and projected rotation velocities of both stars are all adjusted by 1.5 $\sigma$ in the appropriate senses. While ad hoc and improbable, the required adjustments are small enough relative to their uncertainties that further precise measurements of these quantities are in order.

The measured flux ratio at $V$ is pivotal in this discussion. External checks of this quantity on other eclipsing binary systems, using similar spectroscopic material and with the same techniques used here, have not shown significant systematic errors. For example, a comparison with independent determinations available from the light-curve solutions of double-lined eclipsing binaries typically agree within 10% or better with our spectroscopic determinations (see, e.g.,

Fig. 8.—Synthetic light curves for S1113, phased against the binary orbit period. The top curve shows expected light variation due to the expected ellipsoidal shape of the primary, given synchronous rotation. The bottom curve shows the same light curve combined with the photometric variation due to a spot at longitude 270°. The resulting light curve is very similar to that seen for S1113 (Fig. 4), and the ellipsoidal variations are no longer evident.
Lacy et al. 1997, 2000). Thus, we have no reason to believe that our flux-ratio measurement for S1113 would be in error by as much as a factor of 3. Nonetheless, given the importance of this measurement we encourage additional observational study.

In closing, we note that Hurley et al. (2001) have suggested that S1113 is subluminous due to an evolutionary response to mass transfer. Alلب et al. (2001) identify stars below the subgiant branch of the globular cluster 47 Tuc that they note are similar to S1063 and S1113. They suggest that such systems may result from mass transfer, with the subsequent contraction of the primary Roche radius deflating the primary star and making it less luminous. Our analyses indicate that, considered as a cluster member (i.e., the photometric model), both stars in S1113 currently fall well within their Roche radii. Put another way, if the primary of S1113 fills its Roche lobe (e.g., the geometric model) and has an effective temperature of 4800 K, the observed brightness places it behind M67 (and as noted above this conclusion of nonmembership cannot be removed via extinction arguments). Thus at least currently S1113 would not seem to be a candidate for a Roche-filling cluster binary.

7. SUMMARY

The stars S1063 and S1113 in the field of the old open cluster M67 have attracted attention for their location in the cluster color-magnitude diagram roughly 1 mag below the cluster subgaint branch (Fig. 1). Comprehensive photometric (optical and X-ray), spectroscopic, and astrometric studies have shown them to be RS CVn-like systems with observed three-dimensional motions that are the same as that of the cluster to high precision. Their location in the color-magnitude diagram has led us to describe these stars as candidate sub-subgiant cluster members.

Specifically, S1063 is a single-lined spectroscopic binary with a period of 18.4 days and an eccentric orbit ($e = 0.2$). The primary effective temperature is 5000 K. Spectroscopic surface gravity measurements indicate a subgiant with a surface gravity log $g \approx 3.5$. $UBVIIIJK$ colors indicate a reddening of $E(B-V) = 0.14-0.18$, higher than the cluster reddening of $E(B-V) = 0.032$. Since the entire Galactic reddening in the direction of M67 is only 0.03 mag, the enhanced reddening of S1063 is likely not interstellar. There is no evidence in the near-infrared colors for warm circumstellar dust in this system. The strong X-ray emission suggests rapid rotation of the primary, although the measured $v \sin i$ is only 6 km s$^{-1}$. Pseudosynchronous rotation at a period of 14.64 days is permitted by existing observations, but there is no evidence for photometric variability at this period. Photometric variability is seen on longer timescales, with no evident periodicity for periods less than 18 days.

S1113 is a double-lined spectroscopic binary with a period of 2.8 days, a circular orbit, and a mass ratio of 0.7. Effective temperatures of 4800 and 5500 K are found for the primary and secondary stars, respectively. The photometric properties of S1113 are well modeled by a binary with a 0.9 $M_\odot$, main-sequence, secondary star and 1.3 $M_\odot$, a subgiant primary star (2.0 $R_\odot$) at a distance similar to M67. However, this model does not easily explain the large projected rotation velocity (53 km s$^{-1}$) of the primary star. Supersynchronous rotation of the primary is required, in contrast to the short synchronization timescales, the circular orbit, and the observed variability of the composite light with the orbital period.

Alternatively, mean densities for both stars are derived geometrically assuming a tidally relaxed system. These densities indicate a 0.9 $M_\odot$, main-sequence, secondary star and a 1.3 $M_\odot$, 4.0 $R_\odot$, primary star that very nearly fills its Roche lobe. In this model, S1113 would be an RS CVn (possibly transferring mass) located behind the cluster. However, the $V$ flux ratio derived from this model differs by a factor of 3 from the spectroscopically measured flux ratio. In addition, the observed light curve shows no evidence for asymmetry of the nearly Roche-filling primary star. Thus, neither the photometric nor the geometric analyses are able to provide a fully consistent model for the S1113 system.

The issue of cluster membership is pivotal for understanding both S1063 and S1113. Given their low apparent luminosity, the interpretation of both binaries as background field RS CVn’s is a natural solution. This interpretation runs counter to the very close kinematic three-dimensional association of both binaries to the cluster. Still, our statistical analyses indicate that the probability of one of the two being a background binary is not entirely negligible, although both being background stars is improbable. Equally important, we have not yet been able to create model background binaries that reproduce all of the observed properties of either S1063 or S1113.

Star clusters have long been recognized as dynamically active environments, particularly in the form of binary encounters with both single stars and other binaries. It would be no surprise if we were to find products of such encounters that run counter to single-star evolutionary theory. Nor would it be a surprise if the products of such encounters were binary stars. S1063 and S1113 may be recent products of such encounters, and as such may define alternative evolutionary tracks in the cluster environment. Regrettably, we have not yet been able to explain their low luminosities, although we conjecture that their evolutionary histories include mass transfer episodes, mergers, and/or dynamical stellar exchanges.

Alلب et al. (2001) have noted stars in the globular cluster 47 Tuc that fall in a similar domain of the color-magnitude diagram as S1063 and S1113. Their finding of more examples of stars like S1063 and S1113 emphasizes the need for searches for sub-subgiants in other clusters.

Finally, the primaries of both S1063 and S1113 are candidates for future mass transfer. It is intriguing to consider these binaries as progenitors of the blue stragglers, and particularly of the short-period binary blue straggler F190 in M67.

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REFERENCES

Albrow, M. D., Gilliland, R. L., Brown, T. M., Edmonds, P. D., Guhathakurta, P., & Sarajedini, A. 2001, ApJ, 559, 1060
Bailyn, C. D. 1995, ARA&A, 33, 133
Baliunas, S. L., & Guinan, E. F. 1985, ApJ, 294, 207
Belloni, T., Verbunt, F., & Mathieu, R. D. 1998, A&A, 339, 431
Belloni, T., Verbunt, F., & Schmitt, J. H. M. M. 1993, A&A, 269, 175
Bessel, M. S., & Bret, J. M. 1988, PASP, 100, 1134
Bessel, M. S., Castelli, F., & Plez, B. 1998, A&A, 333, 231
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Catalano, S., & Frasca, A. 1994, A&A, 287, 575
Claret, A., & Giménez, A. 1993, A&A, 277, 487
Dinescu, I. D., Demarque, P., Guenther, D. B., & Pinsonneault, M. H. 1995, AJ, 109, 2090
Flannery, B. P. 1975, MNRAS, 170, 325
Girard, T. M., Grundy, W. M., López, C. E., & van Altena, W. F. 1989, AJ, 98, 227
Gray, D. F. 1989, ApJ, 347, 1021
Gray, D. F., & Johanson, H. L. 1991, PASP, 103, 439
Hurley, J. R., Tout, C. A., Aarseth, S. J., & Pols, O. R. 2001, MNRAS, 323, 630
Hut, P. 1981, A&A, 99, 126
Janes, K. A., & Smith, G. H. 1984, AJ, 89, 487
Johnson, H. L., & Sandage, A. R. 1955, ApJ, 121, 616
Kaluzny, J., & Radezynska, J. 1991, Inf. Bull. Variable Stars, No. 3586
Kurtz, M. J., & Mink, D. J. 1998, PASP, 110, 934
Kurucz, R. L. 1979, ApJS, 40, 1
Lacy, C. H. S., Torres, G., Claret, A., Stefanik, R. P., Latham, D. W., & Sabby, J. A. 2000, AJ, 119, 1389
Lacy, C. H. S., Torres, G., Latham, D. W., Zakirov, M. M., & Arzumanov, G. C. 1997, AJ, 114, 1206
Landsman, W., Aparicio, J., Bergeron, P., Di Stefano, R., & Stecher, T. P. 1997, ApJ, 481, L93
Latham, D. W. 1992, in ASP Conf. Ser. 32, Complementary Approaches to Double and Multiple Star Research, ed. H. A. McAlister & W. I. Hartkopf (IAU Colloq. 135) (San Francisco: ASP), 110
Latham, D. W., Mathieu, R. D., & Milone, A. A. E. 1997, ApJ, 481, L93
Latham, D. W., Mathieu, R. D., & Milone, A. A. E. 1997, in ASP Conf. Ser. 130, The Third Pacific Rim Conference on Recent Development of Binary Star Research, ed. K.-C. Leung (San Francisco: ASP), 113
Leonard, P. J. T., & Linell, A. P. 1992, AJ, 103, 1928
Malvuto, V., & Schmidt-Kaler, T. 1997, A&A, 325, 693
Mardling, R., & Aarseth, S. 1999, in The Dynamics of Small Bodies in the Solar System, A Major Key to Solar System Studies, ed. B. Steves & A. E. Roy (Dordrecht: Kluwer), 385
Mathieu, R. D. 1983, Ph.D. thesis, Univ. California, Berkeley
Mathieu, R. D., Latham, D. W., & Griffin, R. F. 1990, AJ, 100, 1859
Mathieu, R. D., & Latham, D. W. 1986, AJ, 92, 1364
Montgomery, K. A., Marshall, L. A., & Janes, K. A. 1993, AJ, 106, 181
Morse, J. A., & Kurucz, R. L. 2003, in preparation
Nissen, P. E., Twarog, B. A., & Crawford, D. L. 1987, AJ, 93, 634
Pasquini, L., & Belloni, T. 1998, A&A, 336, 902
Racine, R. 1971, ApJ, 168, 393
Rajamohan, R., Bhattacharya, J. C., Subramanian, V., & Kupperswamy, K. 1988, Bull. Astron. Soc. India, 16, 139
Richer, H. B., Fahman, G. G., Rosvick, J., & Ibata, R. 1998, ApJ, 504, L91
Rucinski, S. M. 1998, AJ, 116, 2998
Sanders, W. L. 1989, Rev. Mexicana Astron. Astrofis., 17, 31
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schmidt-Kaler, Th. 1982, in Landolt-Börnstein New Series, Group 6: Astronomy and Astrophysics and Space Research, Vol. 2B, ed. K. Schäfers & H. H. Voigt (New York: Springer), 451
Sills, A., Faber, J. A., Lombardi, J. C., Jr., Rasio, F. A., & Warren, A. R. 2001, ApJ, 548, 323
Sparke, L. S., & Gallagher, J. S. 2000, Galaxies in the Universe: An Introduction (Cambridge: Cambridge Univ. Press)
Stassun, K. G., van den Berg, M., Mathieu, R. D., & Verbunt, F. 2002, A&A, 382, 899
Steppiën, K. 1995, MNRAS, 274, 1019
van den Berg, M., Stassun, K. G., Verbunt, F., & Mathieu, R. D. 2002, A&A, 382, 888
van den Berg, M., Verbunt, F., & Mathieu, R. D. 1999, A&A, 347, 866
Verbunt, F., & Phinney, E. S. 1995, A&A, 296, 709
Wood, M. A. 1992, ApJ, 386, 539
Yi, S., Demarque, P., Kim, Y.-C., Lee, Y.-W., Ree, C. H., Lejeune, T., & Barnes, S. 2001, ApJS, 136, 417
Zucker, S., & Mazeh, T. 1994, ApJ, 420, 806