Three newly-discovered M-dwarf companions of Solar Neighbourhood stars

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ABSTRACT

[1]Portions of the data presented here were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. We also make use of data obtained with the Palomar 60-inch telescope, owned jointly by the California Institute of Technology and the Carnegie Institution of Washington.

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We present low-resolution spectroscopy of newly-discovered candidate companions to three stars in the Solar Neighbourhood. All three companions are M dwarfs, with spectral types ranging from M4 to M9.5. In two cases, G85-55'B' (M6) and G87-9'B' (M4), we have circumstantial evidence from spectroscopy, photometry and limited astrometry that the systems are physical binaries; in the third, G216-7B (M9.5), comparison of POSS II IIIaF plate material and the 2MASS image indicates common proper motion. The primary star in this system, G216-7A (M0), is itself an unresolved, nearly equal-mass binary. All three low-mass companions are highly likely to be stellar in nature, although G216-7B lies very close to the hydrogen-burning limit.

Subject headings: stars: low-mass, brown dwarfs; Galaxy: stellar content

1. Introduction

The constituents of the immediate Solar Neighbourhood provide a snapshot of the average population of the Galactic Disk. Identifying and characterising those constituents has been a major focus of stellar research since the early twentieth century, yet our current catalogues patently remain incomplete, even for distance limits as small as 10 parsecs. The last few years have seen a renewed emphasis on this issue with, in particular, the emergence of the NASA/NSF NStars initiative (Backman *et al.*, 2000). As part of that project, the present authors, together with other collaborators, are using a variety of techniques to exploit the potential of the new generation of near-infrared sky surveys, notably 2MASS (Skrutskie *et al.*, 1997), in searching for previously-unrecognised nearby stars and brown dwarfs. This paper presents some of our first results.

As with any census, nearby star catalogues are most incomplete for the least prominent members of the community: some, like brown dwarfs, are born to insignificance; others, like white dwarfs, acquire insignificance; still others, through their proximity to more massive and more luminous companions, have insignificance thrust upon them. Here, we describe observations of stars in the last category: three M dwarfs, each a candidate companion of a Solar Neighbourhood late-K/early-M dwarf. Section 2 outlines the identification of those candidates and our spectroscopic observations; section 3 describes the three systems; and section 4 summarises our conclusions.

2. Target identification and observations

The three M dwarfs discussed in this paper were identified as candidate companions of nearby dwarfs based on photometry from the 2MASS database. All three potential primaries have annual proper motions of $\mu \sim 0.3$ arcsec yr^{-1} and were discovered in the course of the Lowell Observatory proper motion survey (Giclas, Burnham & Thomas, 1971). Two of the fainter stars (the candidate companions to G85-55 and G87-9) were found (by JDK) as part of a larger survey aimed specifically at searching the environs of known nearby stars for candidate companions; the third (G216-7B) was uncovered (by KLC) as part of an NStars photometric survey for candidate M and L dwarfs within 20 parsecs of the Sun. Table 1 lists 2MASS astrometry and photometry of each component of these candidate binary systems and Figure 1 plots their location on the ((J-H), (H-K_S) plane. The three brighter stars have colours consistent with late-type K or early-type M dwarfs, while the fainter stars lie on the M-dwarf sequence, with G216-7B close to the M/L boundary.

2.1. Spectroscopy

The three candidate companions were observed spectroscopically using the Low-Resolution Imaging Spectrograph (LRIS, Oke *et al.*, 1995) on the Keck I 10-metre telescope. The instrumental set-up matches our previous observations of ultracool dwarfs: we use the 400 line mm^{-1} grating blazed at 8500Å with a 1 arcsecond slit to provide coverage from 6,300 to 10,100Å at a resolution of 9Å. The spectra were extracted, wavelength- and flux-calibrated using standard techniques described by Kirkpatrick *et al.* (1999), and Figure 2 plots the resultant spectra.

All three stars are clearly M dwarfs. We have determined spectral types using the TiO5 index defined by Reid *et al.* (1995),

$$\mathrm{TiO5} \;=\; \frac{\langle F(7126-7135)\rangle}{\langle F(7042-7046)\rangle}$$

measuring the overall depth of the 7050Å TiO bandhead. As shown in their Figure 2, this index has a bimodal distribution with spectral type, decreasing in a near-linear manner from TiO5$\sim$ 0.9 at K7 to a minimum value of $\sim$ 0.15 at M6.5, but increasing at later types as VO absorption erodes the peak of the bandhead. Considering the three M dwarfs observed here, G87-9'B' has TiO5=0.39, corresponding to spectral type M4. G85-55'B' is of later spectral type, with the TiO5 ratio of 0.23 consistent with spectral type M6 or M7.5; based on the appearance of the VO bands at 7000 and 7400Å the earlier type is more appropriate. G216-7B is the latest of the three dwarfs, with strong VO and TiO5=0.51, indicating a spectral type of M9.5. The two later-type dwarfs exhibit Hα in emission, with equivalent widths of 9Å in G85-55'B' and 0.7Å in G216-7. Visual inspection of the spectra (by JDK) results in nearly identical spectral types (JDK estimates M6.5 for G85-55'B'). We have also checked for the 6708Å absorption line due to neutral lithium; none of the three dwarfs show detectable absorption, with an upper limit on the equivalent width of 0.3Å for G87-9'B' and $< 3\mathring{A}$ for the two cooler dwarfs.

2.2. Near-infrared astrometry

As discussed further below, the 2MASS scans provide the earliest-epoch imaging of G85-55'B' and G87-9'B'. We therefore supplemented these data with K-band images of both systems, obtained on January 19, 2001 using NSFCAM on the NASA Infrared Telescope Facility. Conditions were photometric, with 0.7 arcsecond seeing. We used the 0.148 arcsec pix^{-1} platescale, taking images in a five-point dither pattern, with each image the sum of 25 $\times$ 0.08 second exposures. This configuration provided unsaturated images of both the primary star and the potential companion, allowing accurate measurement of their relative positions.

3. The systems

The individual stars in each system are discussed in more detail in this section. Table 2 collects published photometric and astrometric observations of the potential primaries. Table 3 gives the derived luminosities, masses and level of chromospheric or coronal activity.

3.1. G85-55

The brighter star in this system is also known as HD 248184, BD +19 872, LTT 11613 and GJ 3338. As Table 2 shows, this is the bluest of the three potential primaries. Although the SIMBAD database lists a spectral type of K5, there is no recent published spectroscopy and the optical/near-infrared colours suggest that the spectral type is closer to K4. Heintz (1994) has determined an absolute trigonometric parallax of 42 ± 6 milliarcseconds (*mas*). As Figure 3 shows, this places G85-55'A' slightly below the (M_V, (V-K_S) main sequence, although Sandage & Kowal's (1986) UBV measurements indicate near-solar metal abundance. Figure 4 shows similar agreement in the (M_J, (J-K_S) plane.

G85-55'B' lies only 9.4 arcseconds from G85-55'A', and is not detectable on either POSS I or POSS II. The 2MASS observations, made on 3 November 1997, therefore provide the first epoch astrometry of this system. Our IRTF observations provide a baseline on 3.2 years, allowing a first test for common proper motion [3] . The relative offset between the two stars ('A' to 'B') in the 2MASS observations is $\Delta\alpha = 2.8 \pm 0.44$ arcseconds, $\Delta\delta = 9.0 \pm 0.20$ arcseconds; the proper motion of the primary is 0.31 arcsec yr^{-1}, $\theta = 131^o$, corresponding to relative motion of +0.265 arcsec in Right Ascension and -1.23 arcsecond in Declination if 'B' is stationary with respect to 'A'; our measured offsets from the IRTF data are $\Delta\alpha = 3.1 \pm 0.25$ arcseconds, $\Delta\delta = 8.8 \pm 0.25$ arcseconds. With such a short time baseline, these data do not provide conclusive evidence, but the observations are at least consistent with common proper motion between the two stars.

We can check whether the spectroscopic parallax of the companion is consistent with the near-infrared photometric properties. If we assume a parallax of 42 ± 6 *mas*, the 2MASS photometry implies $M_K(B) = 9.7 \pm 0.3$. In comparison, the nearby M5.5 dwarfs, Gl 65A and GJ 1116A have M_K=8.78 and 8.83; the M6 dwarfs Gl 406 (Wolf 359) and Gl 65B (UV Ceti) have M_K = 9.18

[3]With a projected separation of $\sim$ 225AU, the binary system would have a period exceeding 2000 years, and orbital motion has a negligible effect on the relative proper motions. The same circumstances hold for the other two binaries considered in this paper.

and M_K = 9.17; and the M6.5 dwarfs LHS 3003 and GJ 1111 have M_K=9.96 and 9.46; thus, an association with G85-55'A' is broadly consistent with the observed spectral type. Placing G85-55'B' at 42 parsecs also gives good agreement with the main sequence in the (M_J, (J-K_S)) plane, as illustrated in Figure 4.

While statistical arguments are always vulnerable when considering one object, we can also consider the probability of random association. Given the (M_K, spectral type) results listed above, we assume that our spectral type estimate, M6±0.5, corresponds to $M_K = 9.2 \pm 0.5$. In that case, we derive a spectroscopic distance of $r_{spec} = 39.8^{+10.3}_{-8.2}$ parsecs and place the star within a spherical shell of volume $\sim 4 \times 10^5$ pc^3. There are 13 dwarfs with spectral types between M5.5 and M6.5 in the northern 8-parsec sample (Reid & Hawley, 2000: RH2000), corresponding to a space density of $\rho_{M6} = 0.008$ stars pc^{-3}. Our sampling shell therefore contributes a surface density of 0.078 M6 dwarfs sq.deg.$^{-1}$ with the appropriate apparent magnitude. There is a corresponding probability of 1.9×10^{-6} of finding an M6 dwarf within 10 arcseconds of a randomly-chosen position on the sky. While not conclusive, these result are strongly suggestive of a physical association between the K5 dwarf, G85-55'A', and the M6 dwarf, G85-55'B'. If so, the physical separation is $\sim$ 225 astronomical units.

Considering G85-55'B' itself, the spectral type of M6 implies an effective temperature of 2800$\pm$ 150K (Leggett *et al.*, 1996). Figure 5 matches those limits against theoretical tracks from Burrows *et al.* (1993, 1997) and Baraffe *et al.* (1998). Briefly comparing those model predictions, the former tracks (Arizona models) predict higher temperatures (at a given age) than the latter (Lyon) tracks for masses above $\sim 0.08 M_\odot$, but lower temperatures for masses below $\sim 0.07 M_\odot$. The hydrogen-burning limit lies at a slightly lower mass in the Lyon models, with a $0.075 M_\odot$ Lyon dwarf falling above the limit, while a 0.075$M_\odot$ Arizona dwarf is a transition object. Considering G85-55'B', our spectroscopy failed to detect Li I 6708Å, but sets an upper limit of only 3Å equivalent width, while the expected equivalent width for no depletion at these temperatures is 1 to 2 Å. However, our temperature estimates allow us to set upper limits on the mass of G85-55'B': if we adopt the Arizona models, we infer $M \leq 0.1 M_\odot$; in the case of the Lyon models, $M \leq 0.11 M_\odot$.

We can refine the mass estimate by considering the level of chromospheric activity, measured by the flux ratio, $\frac{F_\alpha}{F_{bol}}$; youthful dwarfs can be expected to have above average activity, and Figure 5 shows that we require $\tau < 0.25$ Gyrs for $M < 0.075 M_\odot$. We can derive the Hα line flux directly from our spectrum as $F_\alpha = 3.5 \times 10^{-15}$ $erg\ cm^{-2}\ s^{-1}$. Previous experience has shown that the J-band bolometric correction provides a robust method of estimating luminosities in M and L dwarfs (Reid *et al.*, 2001). Leggett *et al.* (1996) derive BC_J=1.99 mag. for the M5.5/M6 binary Gl 65AB and BC_J=2.06 mag. for the M6.5 dwarf GJ 1111. Given these results, we adopt $BC_J = 2.0$ mag. for G85-55'B' and calculate $m_{bol} = 14.5$. Taking $M_{Bol}(\odot) = 4.75$, we find a ratio of $\frac{F_\alpha}{F_{bol}} = 8.6 \times 10^{-5}$ (Table 3). This is $\sim$ 10% below the average activity level of M6 dwarfs in both the Hyades cluster (Reid & Mahoney, 2000) and the general field (Gizis *et al.*, 2000). This suggests that G85-55'B' has an age $\tau > 0.6$ Gyrs and a mass exceeding 0.08 $M_\odot$.

3.2. G87-9

The supposed primary of this system is also known as G103-65, LP 254-40, GJ 3411 and HIP 32723. Reid *et al.* (1995) derive a spectral type of K5 based on a TiO5 index of 0.94. This is consistent with the optical/near-infrared colours listed in Table 2. The Hipparcos parallax indicates a distance of 27.6 ± 1.3 parsecs and $M_V = 8.4 \pm 0.1$. As Figures 3 and 4 show, this places the star close to the main sequence.

G87-9'B' lies only 6.5 arcseconds from G87-9'A' so, as with G85-55, the 2MASS observation, made on 23 November 1998, provides first epoch relative astrometry. We measure $\Delta\alpha = +2.5 \pm 0.3$ arcseconds ('A' to 'B') and $\Delta\delta = -6 \pm 0.3$ arcseconds. Our IRTF observations provide a baseline of only 2.145 years, during which time the primary ($\mu = 0.32$ arcsec. yr^{-1}, $\theta = 153^o$) is predicted to move 0.31 arcseconds East and 0.6 arcseconds South; we measure offsets of $\Delta\alpha = +3.1 \pm 0.25$ arcseconds and $\Delta\delta = -5.8 \pm 0.25$ arcseconds. As with G85-55, the recent measurements are consistent with common proper motion, but do not set strong constraints on the relative motion.

If we assume that the two stars are associated, then the absolute magnitude is M_K(B)=8.0. The (M_J, (J-K_S) colour-magnitude diagram offers no discriminatory power for mid-type M dwarfs, but we can compare the absolute magnitude for consistency against the measured spectral type, M4±0.5. There are fifteen M4 dwarfs in the northern 8-parsec sample (RH2000), eleven of which have K-band photometry; the average absolute magnitude is $\langle M_K \rangle = 7.50$, with an rms dispersion of $\sigma_K = \pm 0.46$ magnitudes. In comparison, we derive $\langle M_K \rangle = 7.80$, $\sigma_K = \pm 0.69$, from K-band data for nine of the 13 M4.5 dwarfs listed by RH2000, and $\langle M_K \rangle = 7.27$, $\sigma_K = \pm 0.61$ from observations of nine of the 15 M3.5 dwarfs. While the constraints are relatively weak, the inferred absolute magnitude of G87-9'B' for $r = 27.6$ parsecs is consistent with the observed spectral type.

As with G85-55, we can calculate the probability of a chance association. Given the ($\langle M_K \rangle$, spectral type) values listed above, we take our spectral type estimate as corresponding to limits of $6.8 < M_K < 8.1$. These place a K_S=9.8 magnitude M4 dwarf at a distance between 39.8 and 21.9 parsecs, within a spherical shell of volume 2.2×10^5 parsecs. There are 45 dwarfs in the RH2000 8-parsec sample with spectral types between M3.5 and M4.5, giving a space density $\rho_{M4} = 0.028$ stars pc^{-3}. This implies an expected surface density of 0.149 stars sq.deg.$^{-1}$, and a probability of $\sim 1.8 \times 10^{-6}$ of finding an M4 dwarf at the appropriate apparent magnitude within 7 arcseconds of a randomly chosen point.

Again, the available constraints favour the identification of G87-9'B' as a binary companion of G87-9'A' at a physical separation of 200 AU. Given the spectral type and the absence of both lithium absorption and Hα emission, G87-9'B' is likely to be a disk dwarf with $\tau > 1$ Gyr. and a mass of $\sim 0.18 M_\odot$.

3.3. G216-7

This is the best studied of the three systems and the only confirmed binary. The primary is also known as G189-30, BD+38 4818, LTT 16634, HIP 111685 and GJ 4287. Reid *et al.* (1995) measure a spectral type of K7 based on a TiO5 index of 0.81. Our LRIS spectrum of the secondary provides an opportunity for an independent measurement through the presence of scattered light from G216-7A; we measure TiO5=0.75, corresponding to a spectral type of M0. Weis (1987) has obtained VR_KI_K photometry, and those colours are more consistent with the later spectral type.

G216-7A was observed by Hipparcos (ESA, 1997) and lies at a distance of $18.89^{+0.72}_{-0.65}$ parsecs, within the 25 parsec limit of the NStars project. At that distance modulus, the star lies significantly above the main sequence in the (M_V, (V-K_S) plane (Figure 3), and, even allowing for the parallax uncertainties, is brighter than the earlier-type G87-9'A' in both M_V and M_J (Figure 4). In fact, Hipparcos has resolved the star as a binary with separation 0.144 ± 0.019 arcseconds (PA = 355^o, epoch 1991.25), with a magnitude difference $\Delta H_P = 0.44 \pm 0.96$ magnitude. If we assume a V-band flux excess of 0.5 magnitudes above the single-star main-sequence, then the two components have absolute magnitudes of M_V(Aa) $\sim$ 8.5 and M_V(Ab) $\sim$ 9.1.

Given the relatively small magnitude difference, G216-7A might be resolved as a double-lined spectroscopic binary, while a close binary system might be expected to have unusually high chromospheric and coronal activity. Gizis, Reid & Hawley (in prep.) have a single high-resolution echelle spectrum, taken using McCarthy's spectrograph on the Palomar 60-inch telescope, but there is no evidence for line doubling. Those data do permit measurement of the radial velocity, $V_r = -53.1 \pm 1.5$ km s^{-1}. Combined with the Hipparcos astrometry, this gives heliocentric space motions (U, V, W) of (20.8, -56.6, -11.1), where U is positive towards the Galactic Centre. These motions are consistent with membership of the old disk population.

The echelle spectrum also provides a measure of chromospheric activity: there is no detectable Balmer emission, with Hα absorption with equivalent width 0.69Å (comparable to Hyades M0 dwarfs); emission is present at Ca II H and K, with equivalent widths of 3.71 and 2.45 Å respectively, but activity at this level is not unusual for late-K/early-M dwarfs. Huensch *et al.* (1999) derive an X-ray luminosity of 7.7×10^{27} erg s^{-1} from ROSAT observations. Combined with our estimate of M_{bol} (Table 3), we derive $\log \frac{L_X}{L_{bol}} = -4.88$, a low level of coronal activity for early-type M dwarfs.

Turning to the companion, G216-7B lies 33.6 arcseconds from the primary and, at that distance, is clearly visible on the POSS II IIIaF survey plate; indeed, the companion may be barely visible on the POSS I E plate (Figure 6). In any case, the time baseline between the POSS II F plate (3 September 1989) and the 2MASS observation (10 October 1998) is sufficient to show that the position angle and separation between G216-7A and G216-7B remains unchanged, despite motion of almost 3 arcseconds, confirming G 216-7B as a physical companion at a separation of 635 AU.

While we have classed G216-7B as spectral class M9.5, it clearly lies very close to the L dwarf régime, as Figures 1 and 4 illustrate. With M_J=11.97 and M_K=10.77, it is over half a magnitude fainter than the archetypical M9.5 dwarf, BRI0021, and within 0.1 magnitudes of the absolute magnitude of the L0.5, 2M0746+20 (making due allowance for the fact that 2M0746 is an equal-mass binary). Like most ultracool dwarfs, G216-7B exhibits a low level of chromospheric activity. The weak Hα emission, equivalent width 0.7Å, corresponds to a line flux of $F_{\alpha} = 4.2 \times 10^{-17}$ erg s^{-1}. Assuming BC$_J \sim 2$ magnitudes, we derive $m_{bol} = 15.35$, giving $\frac{F_{\alpha}}{F_{bol}} = 2.5 \times 10^{-6}$.

Based on the spectral type, we estimate the effective temperature as 2100 ± 150K. Those limits are superimposed on the theoretical tracks plotted in Figure 5. As with G85-55'B', our non-detection of lithium sets only weak constraints on the mass, since the expected equivalent width is only 0.5 to 1Å, as in the M9.5 brown dwarf, LP 944-20 (Tinney, 1998). However, the inactivity of the M0 companion suggests an age at least comparable to that of the Hyades, and probably exceeding 1 Gyr. Under those circumstances, G216-7B is likely to have a mass in the range 0.065 to 0.08$M_{\odot}$, regardless of whether one uses the Arizona or Lyon models as the reference. If $\tau > 1.25$ Gyrs, G216-7B is a transition object or a star, rather than a brown dwarf.

4. Summary and conclusions

We have presented spectroscopic observations of three candidate low-mass companions to known nearby stars. Each was identified from the 2MASS catalogue based on their near-infrared colours. All three prove to be M dwarfs with spectral types M4, M6 and M9.5. None has detectable lithium absorption and, based on their characteristics (luminosity, colours, activity) and the characteristics of the potential primaries, all three are almost certainly stars rather than brown dwarfs. However, the M9.5 dwarf, G216-7B, lies close to the hydrogen-burning limit.

Based on our spectroscopy, together with literature astrometric and photometric data, two of the three systems, G85-55'A'/'B' and G87-9'A'/'B', can only be classed as probably binaries; the third, G216-7A/B, is confirmed as a common proper motion system based on comparison of POSS II plate material and 2MASS images spanning a baseline of 9.1 years. With annual proper motions of ~ 0.3 arcsec yr^{-1}, similar confirming observations of the probable systems will be possible in the near future.

The available data indicate distances of 24 ± 3.5 parsecs for G85-55, 27.6 ± 1.4 parsecs for G87-9 and 18.9 ± 0.7 parsecs for G216-7, all based on trigonometric parallax measurements. In each case, the distance is derived from observations of the (hypothetical) primary. We note that, while all three are included in the latest version of the Nearby Star Catalogue (as indicated by the GJ designation), only G216-7 is unequivocally within 25 parsecs of the Sun and therefore eligible for inclusion in the NStars Database.

These three candidate binaries were uncovered in the first stages of our search through the 2MASS database for unrecognised members of the Solar Neighbourhood. At present, the parent samples are not defined with sufficient precision, nor do we have sufficient examples in hand, to permit a reliable estimate of how many similar systems remain to discovered. Nonetheless, it is likely that further examples will be discovered, particularly by the targetted wide-companion search (the van Biesbroeck project).

Finally, if confirmed, all three of these systems have component separations exceeding 150 AU. Elsewhere, we have discussed a possible correlation between the maximum separation of binary components and the total system mass (Reid *et al.*, 2001). The systems discussed here include a K4+M6 (0.7+0.1 $M_\odot$) binary at $\Delta = 225$AU, a K5+M4 (0.65+0.18 $M_\odot$) binary at $\Delta \sim 200$AU and an (M0+M0)+M9.5 (0.6+0.6+0.08) triple at $\Delta \sim 635$ AU. All three fall within the hypothetical $(log(\Delta), M_{tot})$ limits outlined in Figure 11 of Reid *et al.* (2001).

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Fig. 1.— The ((J-H), (H-K_S)) diagram: crosses are data for nearby stars, spectral types A to M; L dwarfs are plotted as open squares; the T dwarfs Gl 229B and Gl 570D are plotted as five-point stars. The extremely red M dwarf is 2M0149+20 (M9.5 pec.). The six points with errorbars plot the 2MASS colours for the six stars discussed in this paper: open circles for G85-55'A'/'B'; open triangles for G87-9'A'/'B'; and solid points for G216-7A/B.

Fig. 2.— Keck LRIS spectra of the three M-dwarf companions discussed in the text. The spectra have been sky-subtracted, but not corrected for telluric absorption.

Fig. 3.— The (M_V, (V-K_S)) colour-magnitude diagram: the three primary stars are plotted, using the same symbols as in Figure 1. Note that G 216-7A, the reddest object, lies significantly above the main sequence at its colour ((V-K_S)=3.55).

Fig. 4.— The location of the six stars discussed in this paper in the (M_J, (J-K_S)) colour-magnitude diagram; the symbols have the same meaning as in Figure 1.

Fig. 5.— A comparison between observed parameters for the two cool M dwarfs, G85-55'B' and G216-7B, and theoretical models. The upper panel plots (T_{eff}, τ) evolutionary tracks calculated by Burrows *et al.* (1994, 1997) for a range of masses (0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.075, 0.08, 0.09, 0.10 and 0.11 $M_\odot$), with the heavy line indicating the approximate location of lithium depletion to 1% primordial abundance. The horizontally hatched regions mark the observational locations of G85-55'B' (2800$\pm$150K) and G216-7B (2100$\pm$150K); both have depleted lithium. The lower panel plovides the same comparison against the Baraffe *et al.* (1998) models (masses of 0.02, 0.025, 0.04, 0.05, 0.06, 0.07, 0.072, 0.075, 0.08, 0.09, 0.10 and 0.11 $M_\odot$.

Fig. 6.— The G216-7 system: the upper left and upper right figures plot 5×5 arcminute regions from the POSS I E and POSS II F plates; the lower images plot the 2MASS J (left) and K_S data on the same scale. North is up and east to the left. The arrow indicates the location of G216-7B on each image.

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Table 1
2MASS astrometry and photometry

Name	2MASSI	J	H	K_S	$(J-K_S)$
G85-55‘A’	J0514169+195258	7.40 ± 0.01	6.88 ± 0.03	6.74 ± 0.01	0.66 ± 0.01
G85-55‘B’	J0514171+195307	12.53 ± 0.07	11.90 ± 0.05	11.58 ± 0.03	0.95 ± 0.08
G87-9‘A’	J0649358+350826	7.68 ± 0.01	7.09 ± 0.02	6.90 ± 0.01	0.78 ± 0.02
G87-9‘B’	J0649360+350820	10.61 ± 0.03	10.10 ± 0.08	9.76 ± 0.03	0.85 ± 0.04
G216-7A	J2237298+392251	6.63 ± 0.01	6.04 ± 0.03	5.86 ± 0.02	0.77 ± 0.02
G216-7B	J2237325+392239	13.35 ± 0.03	12.68 ± 0.03	12.15 ± 0.03	1.20 ± 0.04

Table 2
Published photometry and astrometry

Name	V	(U-B)	(B-V)	$(V\text{-}R)_C$	$(V\text{-}I)_C$	$(V\text{-}K_S)$	μ	θ	π	sources
							“ yr^{-1}	^{o}	mas	
G85-55‘A’	9.47	1.11	1.17			2.73	0.31	131	42 ± 6	1, 3, 4
G87-9‘A’	10.18	1.27	1.33	0.79	1.54	3.28	0.348	132	36.16 ± 1.82	1, 2, 5
G216-7A	9.41			0.83	1.68	3.55	0.341	176.4	52.94 ± 1.94	2, 5

Reference sources: 1. Sandage & Kowal, 1986: UBV
2. Weis, 1987: VRI (transformed to Kron-Cousins following Bessell & Weis (1987)
3. Giclas, Burnham & Thomas, 1965: μ, θ
4. Heintz, 1994: π
5. ESA, 1997: μ, θ, π

Table 3

Luminosities, Masses and Activity

Name	M_V	M_J	M_{bol}	Src.	Mass	Src.	$\log(\frac{F_\alpha}{F_{bol}})$	$\log(\frac{L_X}{L_{bol}})$
G85-55‘A’	7.58 ± 0.25	5.5	7.1	1	0.70	1		
G85-55‘B’		10.65	12.6	2	0.07 to 0.10	2	-4.07	
G87-9‘A’	8.41 ± 0.11	5.91	7.6	1	0.65	1		
G87-9‘B’		8.84	10.6	2	0.18	3		
G216-7A	8.03 ± 0.07	5.25	6.8	3	0.6+0.6	1		-4.88
G216-7B		11.97	14.0	2	0.06 to 0.08	2	-5.60	

Reference sources:

Bolometric magnitudes: 1. Flower (1996), ((B-V), BC_V)

2. BC_J data from Leggett *et al.* (1996) and Reid *et al.* (2001)

3. (BC_I, (V-I)) relation from Reid & Mahoney (2000)

Masses: 1. Henry & McCarthy (1993), (M_V, log(mass)) relation

2. Figure 5, this paper

3. Henry & McCarthy (1993), (M_K, log(mass) relation

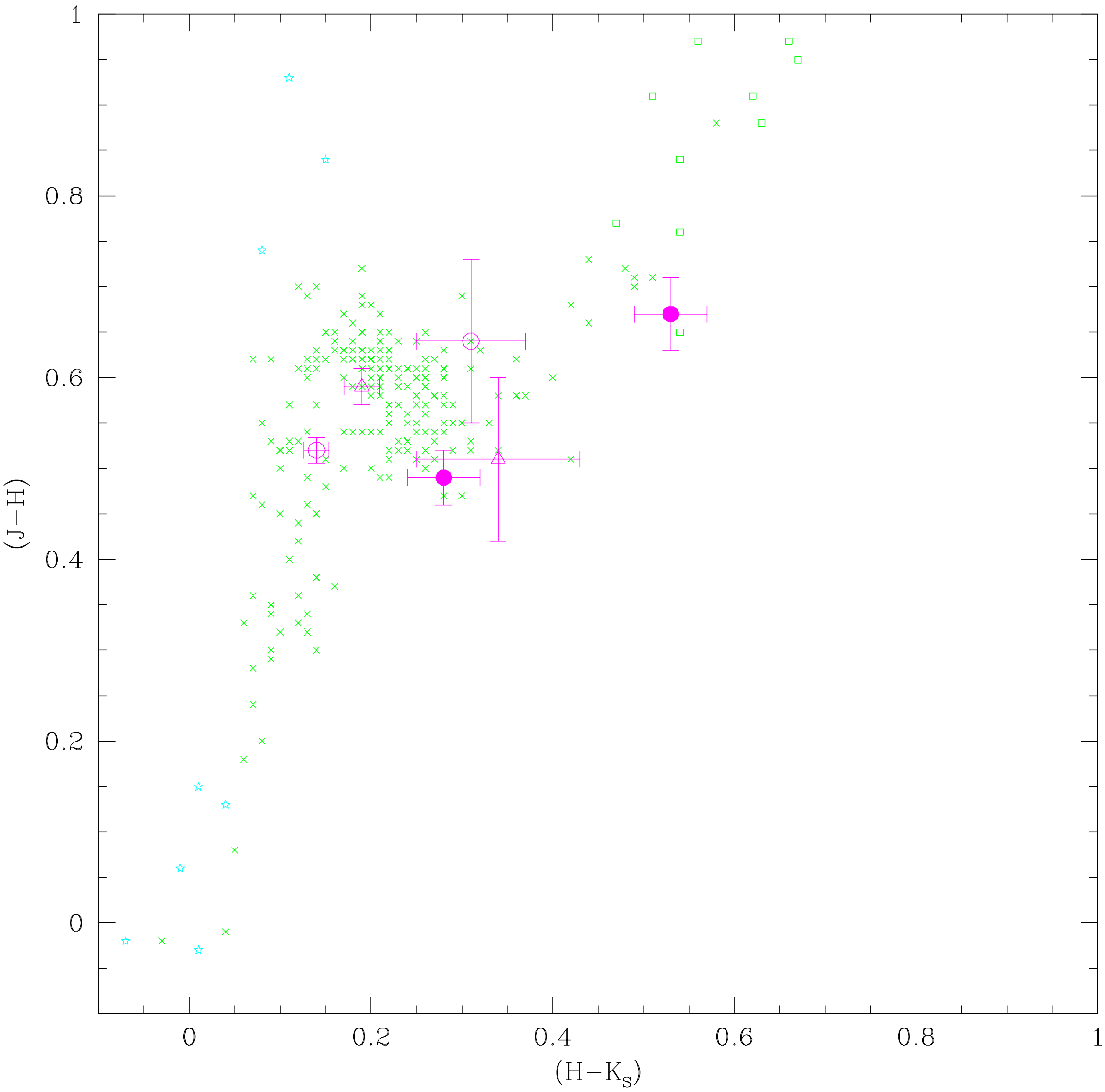

Fig. 1.—

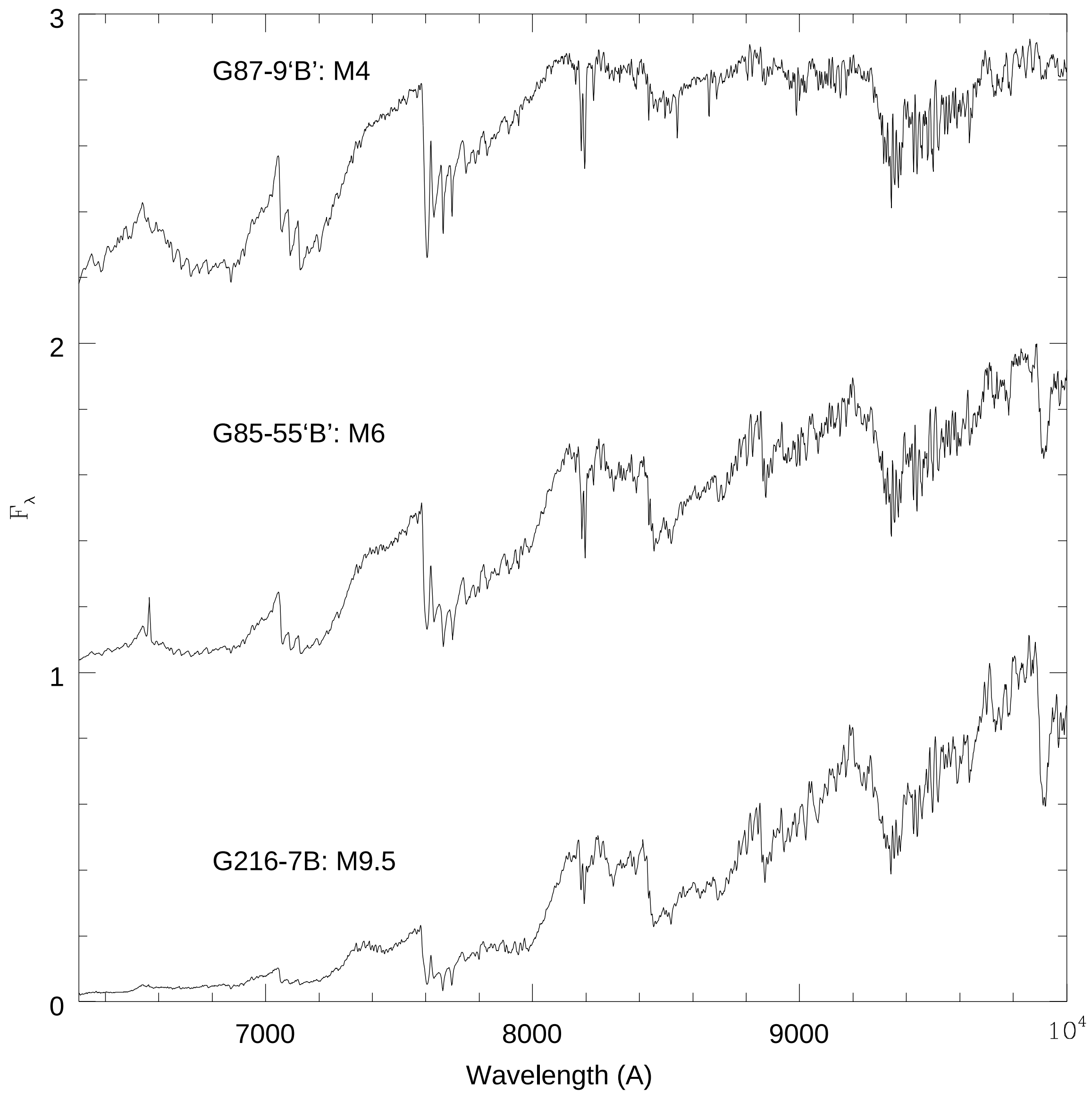
G87-9‘B’: M4
G85-55‘B’: M6
G216-7B: M9.5
3
2
1
0
F_λ
7000
8000
9000
10^4
Wavelength (A)

Fig. 2.—

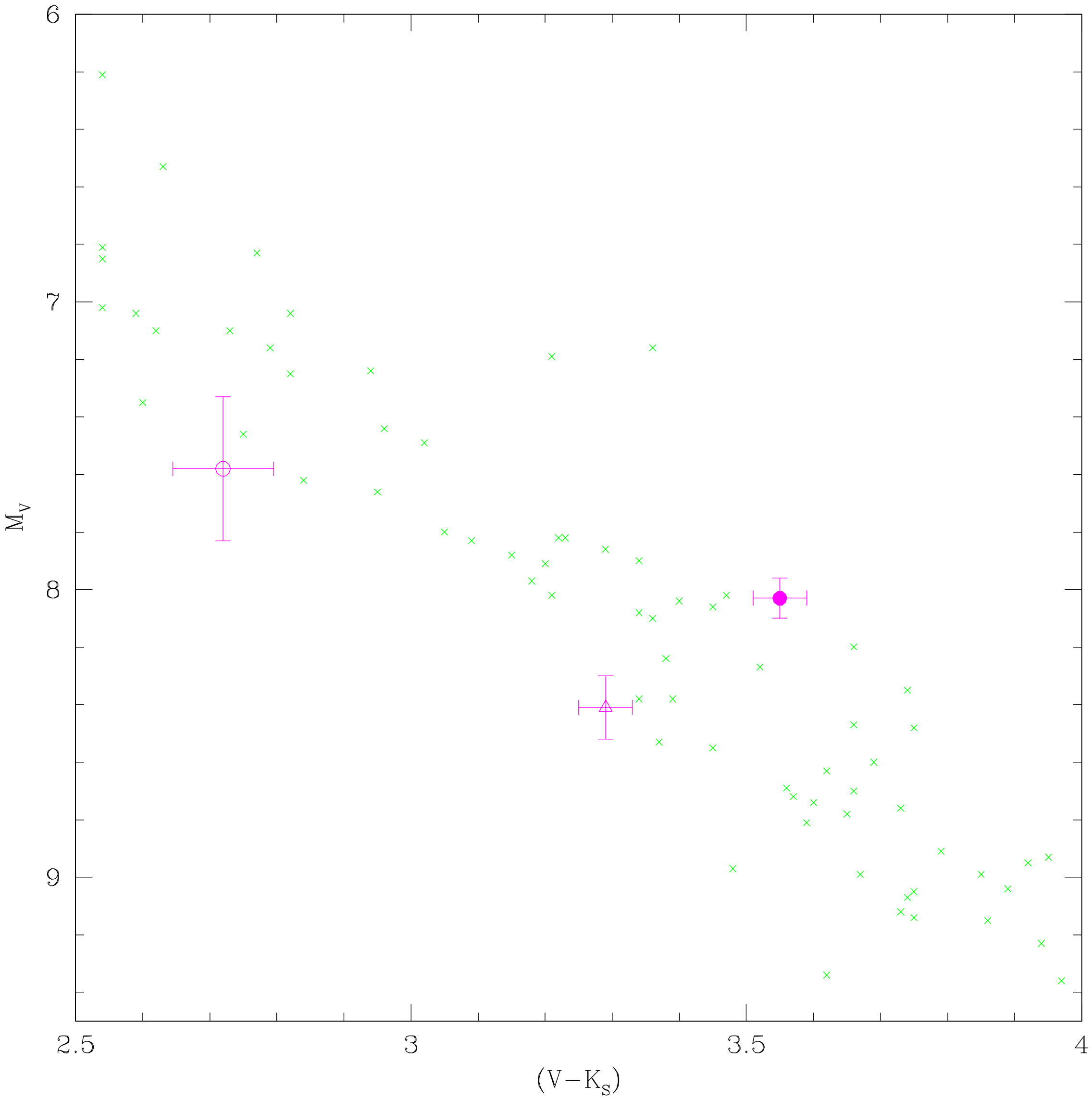

Fig. 3.—

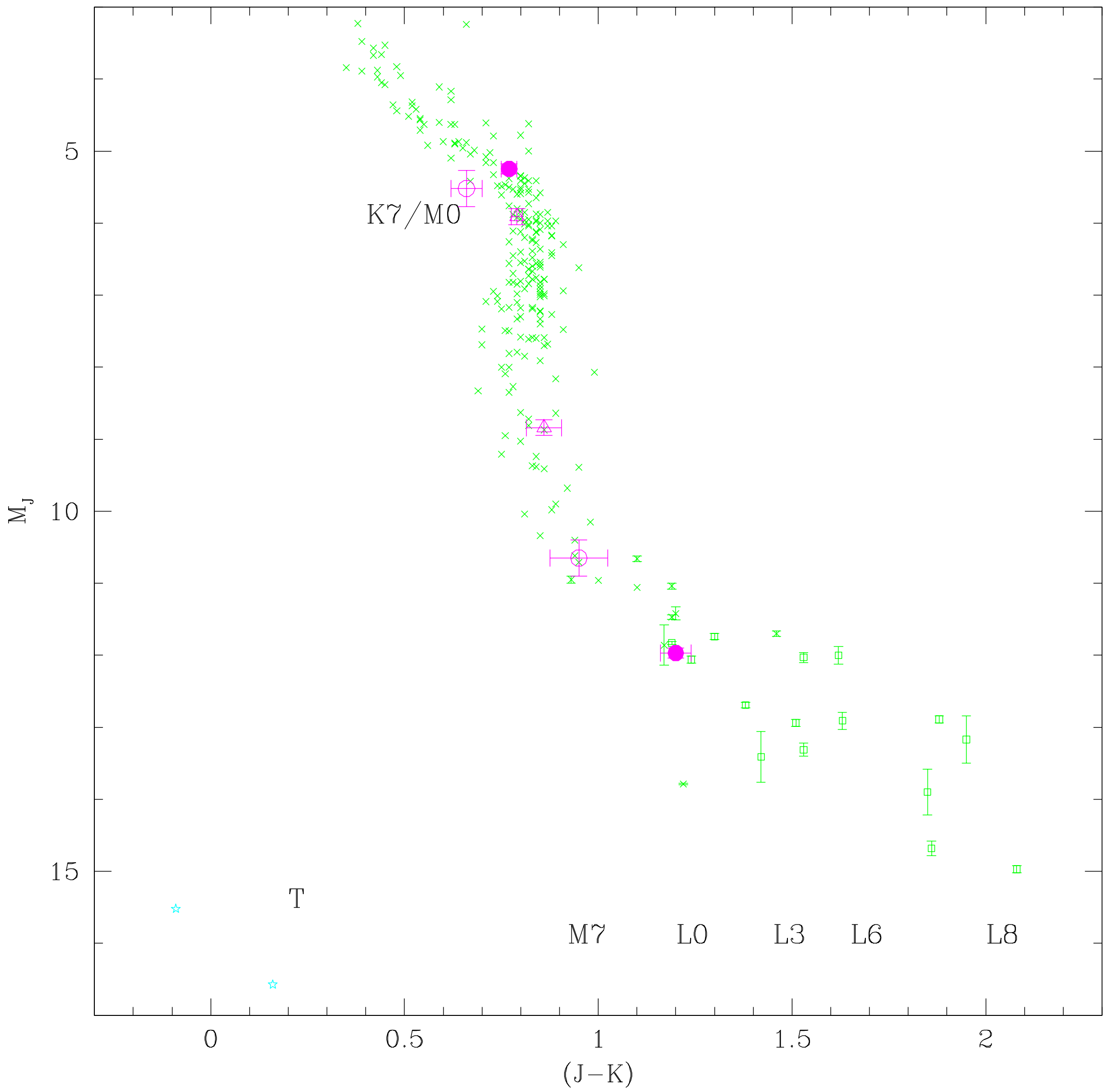

Fig. 4.—

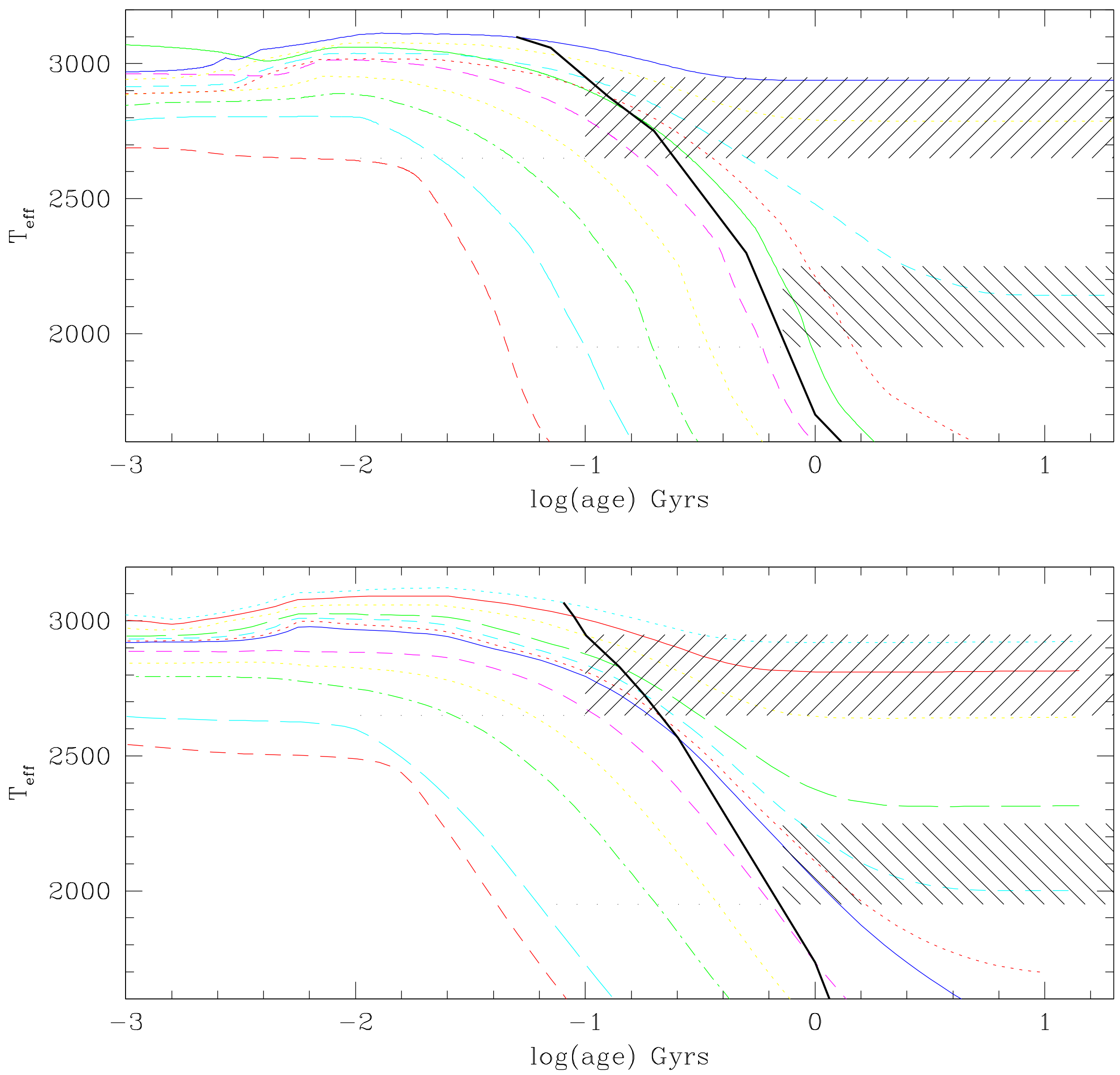
3000
2500
2000
T_{eff}
−3
−2
−1
0
1
log(age) Gyrs
3000
2500
2000
T_{eff}
−3
−2
−1
0
1
log(age) Gyrs

Fig. 5.—

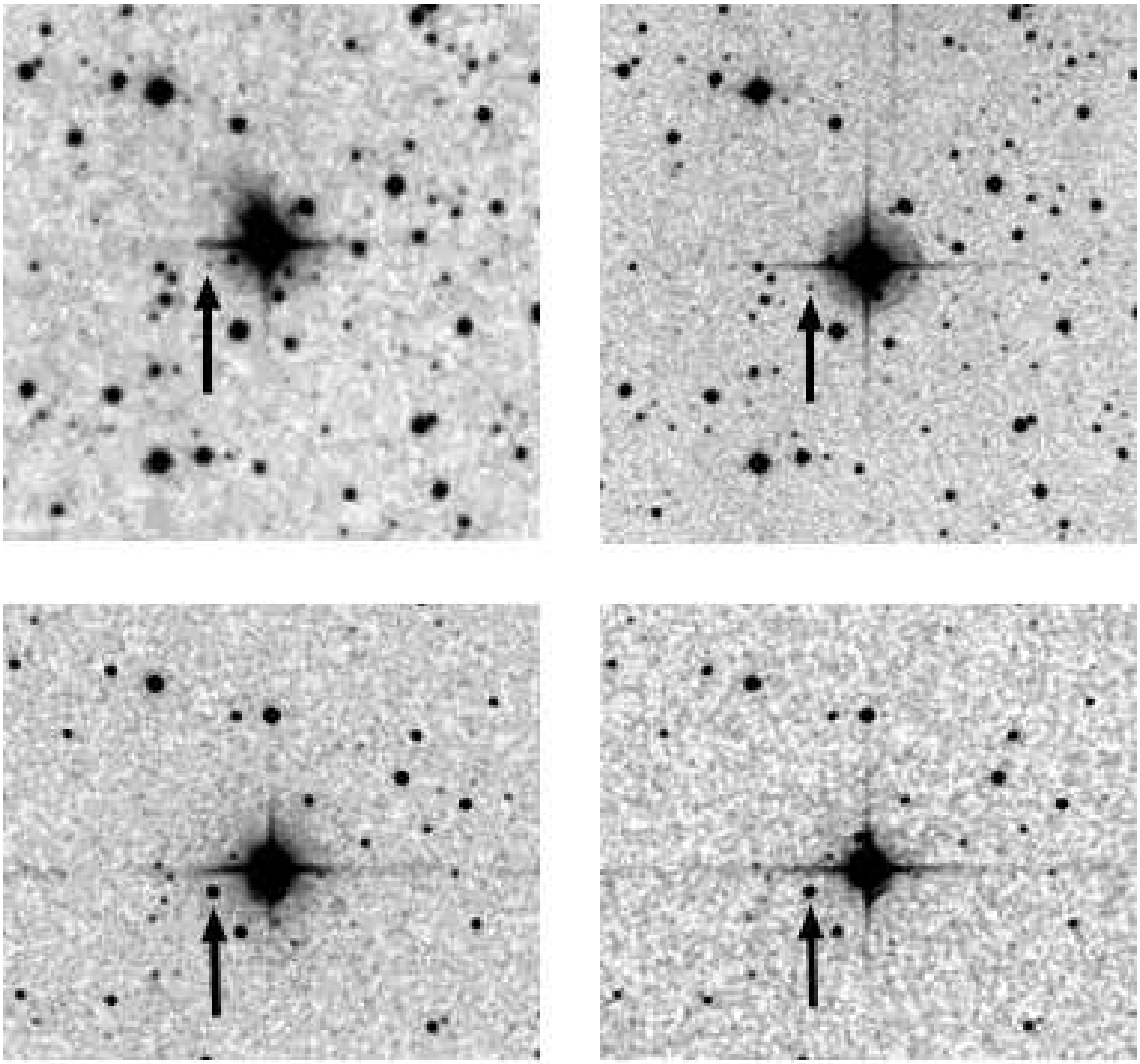

Fig. 6.—