THE NATURE OF FAINT COMPANIONS TO G-TYPE STARS FROM ADAPTIVE OPTICS

A. CHAKRABORTY, J. GE, AND J. H. DEBES

Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802; abhijit@astro.psu.edu, jian@astro.psu.edu, debes@astro.psu.edu

ABSTRACT

High spatial resolution (0′′.30) near-IR photometric observations using the adaptive optics of the Mount Wilson 100 inch (2.5 m) telescope and the Penn State IR Imager and Spectrograph have revealed faint companions to HD 190067 and HIP 13855. HD 190067B is found to be of mass 0.075–0.1 M⊙ with an age from 0.5 Gyr to a few gigayears. HIP 13855B is a low-mass star (age 100–500 Myr) of mass between 0.1 and 0.2 M⊙. Further near-IR spectroscopic observations will be necessary to classify their spectral types precisely.

Key words: instrumentation: high angular resolution — stars: low-mass, brown dwarfs — techniques: photometric

1. INTRODUCTION

Substellar dwarfs or brown dwarfs are objects whose masses are too low to burn hydrogen at their cores. The mass can range between 0.075 and 0.002 M⊙ (late M, L, and T-type stars; see, e.g., Kirkpatrick & McCarthy 1994; Burrows et al. 1997; Kirkpatrick et al. 1999a; Basri 2000). In the last few years, ultracool dwarfs have been discovered from the 2MASS, Sloan, and DENIS surveys (Kirkpatrick et al. 1999a, 2000; Strauss et al. 1999; Fan et al. 2000; Delfosse et al. 1997). These extensive works have helped to establish the spectral signatures of ultracool dwarfs and the classifications of M, L, and T spectral types (see also Reid et al. 2001; Leggett et al. 2002).

However, determining the intrinsic properties of brown dwarfs is difficult because their luminosity and effective temperatures are functions of age and mass (Burrows et al. 1997; Baraffe et al. 1998). Therefore, finding such objects in binary systems containing a main-sequence star would be of great interest because both these parameters can be determined reasonably accurately. Indeed, the first discovered undisputed brown dwarf is a companion to the M1 V star Gl 229 (Nakajima et al. 1995). Also, the coronagraphic Palomar survey (Oppenheimer et al. 2000), which goes 4 absolute magnitudes fainter than Gl 229B, discovered at least seven new faint companions to nearby stars.

We have started a high angular resolution (0′′.30) search for faint companions at near-IR wavelengths around G- and K-type stars in the solar neighborhood, as well as in nearby young star clusters, such as MBM 12 and MBM 20 (Hearty et al. 2000a, 2000b). The list consists of stars with ages from 100 Myr to a few gigayears, and we are using ground-based telescopes equipped with adaptive optics. In this paper, we report the discovery of two faint companions to main-sequence stars: HD 190067 and HIP 13855. This is a result of our first, limited survey, conducted using the 100 inch (2.5 m) telescope on Mount Wilson.

2. OBSERVATIONS AND DATA ANALYSIS

The H and K photometric observations were performed in 2001 October at the 100 inch Mount Wilson telescope using its natural guide star adaptive optics (AO) system (Shelton et al. 1995) and the Penn State IR Imager and Spec-trograph (PIRIS; Ge et al. 2002a). The detector is a 256 × 256 PICNIC array with pixel size of 40 μm. The gain and read noise of the camera are 4.0 e− ADU−1 and 20 e−, respectively. The plate scale was 0′′.082 pixel−1, providing a field of view of 21′.0. The filters used were standard astronomical H and K filters. A cold pupil mask located in the pupil plane inside the dewar reduces the thermal background, particularly in the K band. The camera will soon be equipped for near-IR spectroscopy at R = 200 by use of commercially available fused silica grisms and at high R = 5000 resolution using silicon grisms developed at Penn State (Ge et al. 2000, 2002b).

We observed six young solar analogs from Gaidos, Henry, & Henry (2000), a couple of main-sequence stars with faint companions (Turner et al. 2001), and six main-sequence stars toward the MBM 12 star-forming cloud (Hearty et al. 2000a, 2000b). The observations were done under photometric condition with subarcsecond seeing. The average FWHM of the point-spread function (PSF) was 0′′.30 after the AO correction.

We report here the observations of two stars, HD 190067 (spectral type G8; Duquennoy & Mayor 1991) and HIP 13855 (spectral type G0; Hearty et al. 2000a, 2000b), that are associated with faint companions (HD 190067B and HIP 13855B). We discuss the nature of these faint companions and determine their possibility of being substellar, transition, or late M dwarfs close to the hydrogen burning limit.

The total integration in the H and K bands for HD 190067 was 20 s (five co-added 4 s exposures), and 50 s (five co-added 10 s exposures) for HIP 13855. An appropriate number of sky frames (five) were observed immediately after the object observations for proper sky subtraction. Flats were made by combining several (15) sky frames. Two standard stars, HD 225023 and SAO 56596, from the UKIRT standard-star list and Hunt et al. (1998), respectively, were observed to determine the zero point of the camera in each filter before or after the observations of the program stars. Each frame was sky-subtracted and flat-fielded before co-adding. Photometry was performed on individual frames as well as on the total co-added frames to estimate the total photometric error. Photometric analysis was carried out using the standard DAOPHOT routines in IRAF. While primarily we did aperture photometry after determining the width of the PSF using the PHOT task, we
also performed photometry of the faint companion HIP 13855B after subtracting the PSF-fitted bright primary HIP 13855A using the tasks PSF and ALLSTAR. This procedure was necessary because the separation between the A and B components of HIP 13855 is only 0.5. A Gaussian PSF was constructed considering an isolated bright star. The photon noise corresponded to an error of \( \pm 0.02 \) mag in the individual images. However, we estimated the maximum error by computing the magnitudes from five different frames to be \( \pm 0.1 \) mag, and the mean magnitude from five frames is the same as the magnitude estimated from the co-added frames. This relatively high error could be due to the AO system, and in the present work we will limit the uncertainty to \( \pm 0.1 \) mag. Table 1 gives the magnitudes estimated from the co-added frames.

We note that the source seen as a faint companion to HIP 13855 at a separation of 0.5 is real and not an artifact-like ghost. Other stars observed under similar conditions, including the standard stars, do not show any such point source that is 5 mag fainter than the primary.

We compared our \( H \) and \( K \) photometry of HIP 13855A with that given in the 2MASS Point Source Catalog. The 2MASS \( H \) and \( K \) magnitudes of HIP 13855 (A+B) are 7.29 and 7.25, respectively. We find that if we consider a larger aperture (3") comparable to the 2MASS PSF, then we do obtain similar values in the \( H \) and \( K \) bands (7.4 and 7.3, respectively) within the photometric errors stated earlier.

### TABLE 1

| Name            | \( H \) (mag) | \( K \) (mag) | Separation (arcsec) | P.A. (deg) |
|-----------------|--------------|--------------|---------------------|------------|
| HD 190067A      | 6.6          | 6.4          | ...                 | ...        |
| HD 190067B      | 10.7         | 9.6          | 2.9                 | 75         |
| HIP 13855A      | 7.8          | 7.7          | ...                 | ...        |
| HIP 13855B      | 12.6         | 12.6         | 0.5                 | 243        |

Note.—The overall photometric error in each band is \( \pm 0.1 \) mag, as discussed in \S 2. The error in the position angle is about \( \pm 0.4 \) deg.

3. RESULTS AND DISCUSSION

The photometric results for HD 190067, HIP 13855, and their respective companions are presented in Table 1. The absolute magnitudes of the faint companions were calculated assuming the distances given in the Hipparcos Catalogue (ESA 1997). The \( A_V \) values toward these sources from the literature are negligible compared with the overall photometric error (\( \pm 0.1 \) mag) and hence are not considered for absolute magnitude estimation. The \( A_V \) values were estimated from the \( A_v \) values found in the literature for HIP 13855 (Luhman 2001); for HD 190067, mean extinction in the Galaxy was considered for a distance of 19 pc (Glass 1999) and using the relation \( A_H/A_K = 0.142 \) (Rieke & Lebofsky 1985). Thus the estimated \( A_H \) values for HIP 13855 and HD 190067 were 0.028 and 0.01 mag, respectively. Figures 1 and 2 show \( H \) and \( K \) images of HD 190067 and HIP 13855, respectively, along with their faint companions.

3.1. Ages of HD 190067 and HIP 13855

HD 190067 is a disk star (Eggen 1987), and based on the velocity components in its disk, it seems that its age could be anything from 0.5 Gyr to a few gigayears (Eggen 1987; Mihalas & Binney 1981).

HIP 13855, at a distance of 74 pc (ESA 1997), is a foreground star toward the star-forming cloud MBM 12, whose distance is estimated to be somewhere between 90 and 275 pc (Luhman 2001). The MBM 12 cloud contains very young stars, with ages from 10 to 100 Myr (Hearty et al. 2000a). Some members of the MBM 12 cluster, however, are much closer; for example, HD 17332 is at a distance of 33 pc (ESA 1997). HD 17332 is a young G1 V star, since lithium is detected in its spectrum (Hearty et al. 2000a). We qualitatively argue on the basis of its proximity that HIP 13855 could be associated with the MBM 12 cluster; however, there is no record of lithium detection in its spectrum. So we assume a lower limit for the age of HIP 13855 could be 100 Myr (Hearty et al. 2000a).

Burrows et al. (1997) developed models for young substellar dwarfs of various ages that show a similar trend of absolute magnitudes versus near-IR colors for such stars that are younger than 1.0 Gyr. Similar models of the evolution of brown dwarfs and low-mass stars with a timescale from less than 100 Myr to 10 Gyr have shown that the hydrogen burning limit is somewhere between 0.072 and 0.075 \( M_\odot \), and that the corresponding spectral type varies with age (from M6.5 at 100 Myr to L4 at 10 Gyr; Baraffe et al. 1998, 2002; Kirkpatrick et al. 1999b; Basri 2000). Figure 3 shows such evolutionary model curves from Baraffe et al. (1998, 2002), and overlaid on it are the results of the present work. We discuss below the nature of the newly discovered companions based on their ages and absolute \( H \) magnitudes.

3.2. HD 190067

HD 190067 is at a distance of 19 pc (ESA 1997). Its possible binary nature was first reported by Turner et al. (2001). However, they could not confirm it, because of lack of information on common proper motion. We detect the binary component HD 190067B at a separation of 2.90, which is 0.04 more than the separation observed previously in 1996 by Turner et al. (2001). HD 190067 should have moved by 0.51 between these two sets of observations as a result of its proper motion alone. Thus, it appears that HD 190067 and its faint companion have similar proper motion, and this establishes that HD 190067B is a physical binary. However, the observed position angle in 1996 was 82°, while in 2001 (present work) we found it to be 75° (see Table 1). This difference could be due to the orbital motion of the secondary. We will need more such observations to determine the orbital period and the mass of the secondary.

We estimate an absolute \( H \) magnitude \( M_H = 9.3 \pm 0.1 \) and an \( H-K \) color of 1.1 ± 0.2. Kirkpatrick & McCarthy (1994) have shown from \( R IJHK \) photometry and optical spectroscopy that young stars (<0.5 Gyr) of spectral types M6.5 and later cannot burn hydrogen in their cores. These measurements suggest that HD 190067B could be a transition candidate if it is young (<0.5 Gyr). However, if it is older then it is a low-mass star close to the hydrogen burning limit. From Figure 3, the mass of HD 190067B may be 0.08–0.1 \( M_\odot \). The high \( H-K \) color (1.1 ± 0.2) is intriguing. A high \( H-K \) color is common for late L-type substellar dwarfs (Reid et al. 2001), but a late L-type source is expected to be more than a magnitude fainter in \( M_H \) (Kirkpatrick et al. 2000). Near-IR spectroscopic observations will be necessary to accurately determine the spectral type.
3.3. HIP 13855

We find a faint companion to HIP 13855 with a separation of 0".5 whose \( H \) and \( K \) magnitudes are 12.6 and 12.6, respectively. These yield an \( M_H \) of 8.3 ± 0.1 for HIP 13855B. Figure 3 shows that the companion could have a mass in the range 0.1–0.2 \( M_\odot \). We find the \( H-K \) color of HIP 13855B to be 0.0 ± 0.2 mag. Therefore, if the system is a physical binary (common proper motion yet to be confirmed), then HIP 13855B is a young late M dwarf. Spectroscopic observations will be helpful to probe further into its nature.

We thank the Mount Wilson telescope staff and the management for their help during the observations. We thank D. McCarthy for loaning us part of the optics for PIRIS, R. Brown for the PICNIC array, and A. Kutyrev for the filters.

Fig. 1.—\( H \) (top) and \( K \) (bottom) images of HD 190067. North is up, and east is to the left.
We also thank Professors Larry Ramsay, Eric Feigelson, and Donald Schneider of Pennsylvania State University for their comments on the present work, which significantly helped to improve its quality. The work was supported by NASA grants NAG 5-10617 and NAG 5-11427 and a NASA Graduate Student Researchers Program fellowship (award NGT 5-119), and the Penn State Eberly College of Science.

Fig. 2.—Same as Fig. 1, but for HIP 13855
Fig. 3.—Evolution of substellar dwarfs: absolute $H$ magnitude vs. age (Gyr). The solid lines are evolutionary model calculations for low-mass stars and brown dwarfs from Baraffe et al. (1998, 2002) with metallicity [M/H] = 0. The transition from substellar to stellar is somewhere between 0.072 and 0.075 $M_\odot$ (Kirkpatrick 1999b; Basri 2000). See text for details.

REFERENCES

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
———. 2002, A&A, 382, 563
Basri, G. 2000, ARA&A, 38, 485
Burrows, A., et al. 1997, ApJ, 491, 856
Delfosse, X., et al. 1997, A&A, 327, L25
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Eggen, O. J. 1987, AJ, 93, 393
ESA. 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200) (Noordwijk: ESA)
Fan, X., et al. 2000, AJ, 119, 928
Gaidos, E. J., Henry, G. W., & Henry, S. M. 2000, AJ, 120, 1006
Ge, J., Chakraborty, A., Debes, J. H., & Friedmann, J. 2002a, Proc. SPIE, in press
Ge, J., Lloyd, J. P., Gavel, D., Macintosh, B., Max, C. E., Ciarno, D., Kuzmenko, P., & Graham, J. R. 2000, BAAS, 197, No. 52.01
Ge, J., McDavitt, D. L., Bernecker, J. L., Miller, S., Ciarno, D. R., & Kuzmenko, P. J. 2002a, Proc. SPIE, 4485, 393
Glass, I. S. 1999, Handbook of Infrared Astronomy (Cambridge: Cambridge Univ. Press)
Hearty, T., Fernández, M., Alcalá, J. M., Covino, E., & Neuhausen, R. 2000a, A&A, 357, 681
Hearty, T., Neuhausen, R., Stelzer, B., Fernández, M., Alcalá, J. M., Covino, E., & Hambaryan, V. 2000b, A&A, 353, 1044
Hunt, L. K., Mannucci, F., Testi, L., Migliorini, S., Stanga, R. M., Baffa, C., Lisi, F., & Vanzi, L. 1998, AJ, 115, 2594 (erratum 119, 985 [2000])
Kirkpatrick, J. D., Allard, F., Bida, T., Zuckerman, B., Becklin, E. E., Chabrier, G., & Baraffe, I. 1999a, ApJ, 519, 834
Kirkpatrick, J. D., & McCarthy, D. W., Jr. 1994, AJ, 107, 333
Kirkpatrick, J. D., et al. 1999b, ApJ, 519, 802
———. 2000, AJ, 120, 447
Legett, S. K., et al. 2002, ApJ, 564, 452
Luhman, K. L. 2001, ApJ, 560, 287
Mihalas, D., & Binney, J. 1981, Galactic Astronomy (2d ed.; San Francisco: Freeman)
Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, Nature, 378, 463
Oppenheimer, B. R., Golimowski, D. A., Kulkarni, S. R., Matthews, T., Nakajima, T., Creech-Eakman, M., & Durrance, S. T. 2001, AJ, 121, 2189
Reid, I. N., Burgasser, A. J., Cruz, K. L., Kirkpatrick, J. D., & Gizis, J. E. 2001, AJ, 121, 1710
Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Shelton, J. C., Schneider, T., McKenna, D., & Balunans, S. L. 1995, Proc. SPIE, 2354, 72
Strauss, M. A., et al. 1999, ApJ, 522, L61
Turner, N. H., ten Brummelaar, T. A., McAlister, H. A., Mason, D. D., Hartkopf, W. I., & Roberts, L. C., Jr. 2001, AJ, 121, 3254