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Multiplicity Among Very Low Mass Stars and Brown Dwarfs in the Pleiades

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Abstract. We present initial results of an HST WFPC-2 photometric survey of selected very low-mass (VLM) stars and brown dwarf candidates in the Pleiades. With a sample size of 23 objects, only one is definitively resolved as a binary with a separation of less than 12 AU for a given distance of 125 pc. Three others were found to have elongated PSFs, but could not be resolved. Of these candidates, CFHT-PL-19 was assessed to be a non-member based upon the proper motion survey of Moraux, Bouvier and Stauffer (2001). These results complement those of Martín et al. (2000) in which an HST NICMOS and CFHT adaptive optics survey of 34 Pleiades members found no resolved pairs with separations greater than 27 AU. Combining the new observations with those of Martín et al. (2000), we find that a dearth of VLM binaries with separations of greater than 15 AU (P$\sim$184 yr) exists within the Pleiades. These findings provide tentative evidence that the period distribution of VLM binaries in the Pleiades is significantly different from that of the cluster F5-K0 stars and the field solar analogues.

1. Introduction

It has long been recognized that a significant fraction of stars in the Galactic disk are multiple in nature. Numerous studies have been conducted in the field as well as within open clusters to investigate multiplicity among various spectral types including: early B stars, Abt and Levy (1990), nearby solar analogues, Duquennoy and Mayor (1991), and low-mass M-dwarfs, Henry and McCarthy (1990) and Fischer and Marcy (1992). In the last decade, large-scale optical and infrared imaging surveys (DENIS, 2MASS, SDSS) have greatly increased the number of identified brown dwarf candidates within the field and galactic clusters. These findings have permitted the opportunity to conduct a statistically meaningful study of physical properties, including binarity, for objects below the hydrogen-burning limit.

The reasons for undertaking multiplicity studies in VLM stars and brown dwarfs include: 1) to place theoretical constraints upon their formation mechanisms by studying binary frequencies, mass-ratio distributions and the variation of orbital elements, 2) the opportunity to measure dynamical masses of VLM objects through continued observations, 3) the detection of fainter companions of known brown dwarfs which will likely be less massive objects 4) to allow

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for corrections of the cluster initial mass function by accounting for binarity among its members and 5) to correct ages derived from theoretical isochrones by accounting for binarity.

Having similar ages and metallicities as well as higher luminosities, the members of young galactic clusters provide ideal samples for multiplicity studies among VLM stars and brown dwarfs. Additionally, the youngest, most massive clusters are typically still in the process of dynamically relaxing, ensuring that most members have not dissipated into the field. Clusters previously targeted for low-mass binary surveys include the Hyades, the Pleiades, α Persei, and the Chamaeleon I dark cloud. The Pleiades, with an age of 120 Myr and a distance of 125 pc, is perhaps one of the best studied young clusters with a well-defined mass function down to approximately 40 M_J, Hambly et al. (1993), Meusinger et al. (1996), and Bouvier et al. (1998). In the following sections, this paper will review previous binarity studies in the Pleiades, briefly address target selection and the HST WFPC-2 observations and discuss the initial results of the survey. Finally, the paper will summarize the implications of the findings thus far, emphasizing the differences in the period distribution diagram for the VLM Pleiades members and the F5-K0 stars of the Pleiades and the nearby solar analogues. A more complete version of this paper is in preparation for publication in the *AstrophysicalJournal*.

2. Previous Investigations

Many early binary studies in the Pleiades were spectroscopic surveys of the most luminous members conducted to identify radial velocity variables. Recent investigations, however, have focused upon later spectral types. Stauffer (1984) conducted an optical and infrared photometric survey of late-type Pleiades members and derived a binary frequency of 26%, consistent with Abt and Levy's (1976) work with field G stars. Mermilliod et al. (1992) conducted radial velocity observations of 100 F5-K0 stars yielding a multiplicity frequency of 36% and a flat mass-ratio distribution. Bouvier et al. (1997) found that the binary frequency of G-K stars in the Pleiades is consistent with that of the field as derived by Duquennoy and Mayor (1991). Additionally they found that the orbital periods and mass-ratios were distributed similarly to the field G and K-dwarfs.

No thorough binary surveys of M-dwarf Pleiades members have been conducted for comparison to Henry and McCarthy's (1990) or Fischer and Marcy's (1992) field population studies. Young et al. (1987) conducted a spectroscopic survey of 48 dM and 15 dMe star in the field. Of the 15 dMe stars, two were found to be binary and all possessed space motions consistent with that of Pleiades members. Recently Martín et al. (2000) presented results from an HST NICMOS imaging survey and an adaptive optics survey of VLM stars and brown dwarf candidates in the Pleiades. Their findings will be discussed in detail in the Discussion section of this paper.

3. Observations

3.1. Sample Selection Criteria

The targets were compiled from several lists of Pleiades VLM candidates (M< 0.1 $M_\odot$): CALAR objects from Zapatero Osario et al. (1997), HHJ objects from Hambly et al. (1993), ROQUE objects from Zapatero Osorio et al. (1999), CFHT-PL objects from Bouvier et al. (1998), HHCJ objects from Hambly et al. (1999) and NPL objects from Festin (1998). These compilations include most of the known Pleiades VLM stars and brown dwarf candidates. Of the 27 objects originally proposed for this program, 24 have been observed. One of these observations was affected by the WFPC-2 shutter anomaly which prevented accurate photometry from being obtained for this candidate. The remaining 3 targets have yet to be scheduled for observation.

3.2. HST WFPC-2 Observations

The targets were observed as part of an HST Snapshot (SNAP) program designed to fill short intervals between accepted GO observations. Each of the brown dwarf candidates was centered in the PC chip of the Wide-Field Planetary Camera. With a plate-scale of $0''.0455$ per pixel, the PC has a field of view of $36''$ in diameter. Assuming a distance of 125 pc for the Pleiades, this provides a physical separation of 2250 AU from each of the candidates to search for companions. The three Wide-Field cameras with plate-scales of $0''.0996$ per pixel and fields of view of approximately $80''$ in diameter were used to identify other brown dwarf candidates in the vicinity of the primary targets. The observations were made in two broadband filters, the F814W and the F785LP with central wavelengths at $7924\mathring{A}$ and $8621\mathring{A}$ respectively. The filters were chosen to provide high throughput and a clear color separation between brown dwarfs and background stars and galaxies. Two exposures were taken in each filter to allow for proper cosmic ray rejection, yielding total integration times of 600 and 280 seconds in the F814W and F785LP filters respectively. Image reduction and aperture photometry was accomplished using the IRAF STSDAS package and the PHOT task in DAOPHOT.

4. Results

Photometry was completed for objects in each of the four chips of the WFPC-2 array. The limiting magnitude for the survey is approximately $I_C \sim 22.5$ and was constrained by the lower throughput and shorter exposure times of the F785LP images. The instrumental color-magnitude diagram for the 23 fields observed is shown in Figure 1. The VLM candidates are denoted by red triangles with photometric error bars indicated for both axes. From their position in the color-magnitude diagram, away from the brown dwarf sequence, three objects are probable non-members: ROQUE-23, NPL-43, and ROQUE18. Additionally, three previously unknown VLM candidates were identified in the images. Transformation of the F814W magnitudes to the I_C bandpass was accomplished by linearly fitting the instrumental magnitudes of several candidates with previously published photometry. The right vertical axis in Figure 1 shows the

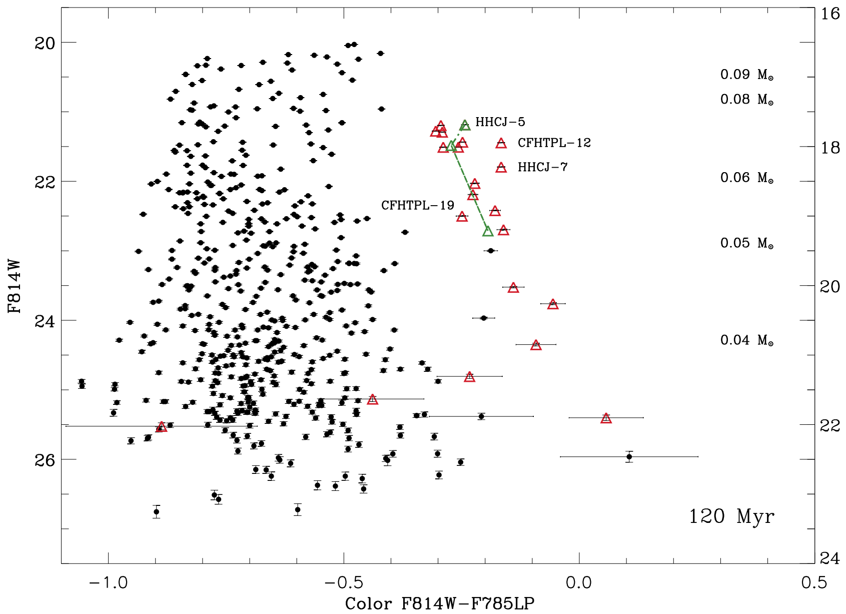

Figure 1. The instrumental color-magnitude diagram for the Pleiades brown dwarf candidate fields imaged with WFPC-2. The red triangles represent the program objects while the green triangles show the positions of the composite binary HHCJ-5, as well as the individual primary and secondary components. The mass scale shown on the right vertical axis is taken from the isochrones of Chabrier and Baraffe assuming a distance of 125 pc and an age of 120 Myr.

resulting I_C magnitudes. Also shown near the right vertical axis is the approximate mass scale as derived from the 120 Myr isochrone of Chabrier et al. (2000) assuming a distance of 125 pc.

PSF subtraction and photometry was accomplished using the PSF and ALLSTAR tasks in the IRAF DAOPHOT package. Model PSFs were constructed from isolated field stars located on the same PC image as the brown dwarf candidates. Several analytical functions were used to model the PSF, however, in most cases the MOFFAT 25 was found to yield the lowest residuals after PSF subtraction. For several program objects, however, it was not possible to create a model PSF owing to an inadequate number of bright, isolated stars in the PC field of view. It is well-understood that the PSF of WFPC-2 varies on an orbital timescale as a result of thermal breathing, pointing motions, and creeping of the telescope focal position. In spite of these difficulties, it was decided to use bright stars from other PC images to create a library of PSFs. Each of the cataloged PSFs was then subtracted from the program object and the resulting residuals were inspected to identify the best subtraction.

Of the 24 program objects observed, only one close binary was unambiguously resolved, HHCJ-5. Three others were found to have elongated PSFs, but could not be resolved: CFHT-PL-12, HHCJ-7 and CFHT-PL-19. CFHT-PL-19's membership in the Pleiades, however, is somewhat questionable based upon the proper motion study of Moraux et al. (2001). The components of HHCJ-5 are separated by only $0''.09$, implying a physical separation of 11.5 AU for a given distance of 125 pc. Although PSF photometry is difficult with such a close binary, the resulting magnitudes derived after PSF subtraction imply that HHCJ-5 is composed of 70 and 50 M_J brown dwarfs. Interestingly, CFHT-PL-12 and HHCJ-7 lie above the other program objects, further supporting their close binary nature. The only widely separated binary candidate found in this survey thus far is NPL-40. A faint object well to the right of the main sequence lies nearly $2''.5$ away. If indeed a true binary, its separation would be $\sim$312 AU and the secondary mass would be approximately 30 M_J. The photometry for this object, however, possesses large uncertainties and will require follow-up observations in the infrared as well as spectra. Proper motion analysis for this candidate will be required to confirm its cluster membership and its association with NPL-40.

5. Discussion

Nearly 60% of the field solar-analogues (F7-G9) were found by Duquennoy and Mayor (1991) to be members of multiple star systems. Fischer and Marcy (1992) found that 42% of M-dwarfs possessed companions. Reid et al. (2001) recently completed a survey of 20 field L-dwarfs using the HST WFPC-2 and found four resolved systems with physical separations of between 2 and 8 AU. Their findings suggest that a deficiency of widely separated systems ($\gtrsim$10 AU) exists among the L-dwarfs, relative to the field M main sequence stars. It is of interest to note that none of Reid et al.'s L-dwarf binaries would have been detected by this program if placed at the distance of the Pleiades.

Within the Hyades, Reid and Gizis (1997) observed 53 low-mass cluster members using the HST Planetary Camera. Capable of detecting objects below the H-burning limit at separations of greater than 16 AU from their primaries, the survey yielded a binary fraction of between 17 and 23%, comparable to Fischer and Marcy's (1992) findings for local M-dwarfs having similar separations. Martín et al. (2000) surveyed 34 VLM Pleiades members using the NIC1 camera on HST as well as the PUEO AO system on CFHT. No resolved binaries were identified with separations greater than $0''.2$ or 27 AU. A previously known binary, CFHT-PL-18, was shown to be a non-member by application of the lithium test. The 6708$\AA$ resonance line was not detected and an upper limit of 200m$\AA$ was assigned, far below the initial abundance expected for a substellar object. Although no binaries were resolved, 5 were suspected based upon their placement above the 120 Myr isochrone: NOT-1, HHJ-6, CFHT-PL-6, CFHT-PL-12, and CFHT-PL-16. Prior to this study, the only confirmed binary brown dwarf in the Pleiades was PPl-15, a double-line spectroscopic binary discovered by Basri and Martín (1999). With a period of 5.8 days and component masses of 70 and 60 M_J, PPl-15 was targeted for Keck HIRES observations as a result of its location in the color-magnitude diagram. No thorough spectroscopic survey of Pleiades VLM members has yet been made to identify other short-period binaries.

Of the 24 objects included in this survey of the Pleiades, only one is definitively binary, HHCJ-5. It is apparent that although brown dwarf binaries are

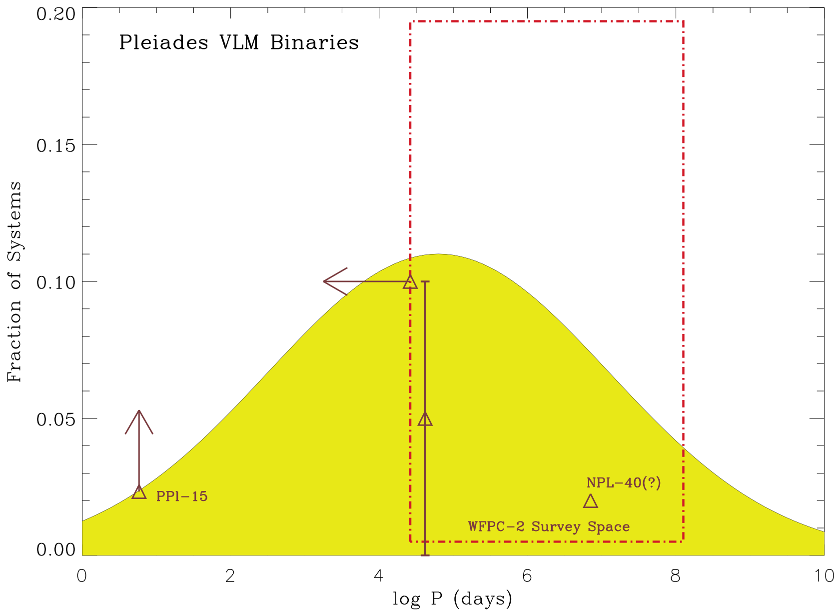

Figure 2. The period distribution diagram for the Pleiades VLM stars and brown dwarfs. The yellow gaussian represents the period distribution of solar analogues as determined by Duquennoy & Mayor (1991). The PC spatial resolution constrains the shortest period systems while the field of view limits the longest period systems for which this survey is sensitive. The two suspected binaries from this survey are represented by the point that lies on the lower WFPC-2 survey limit. The approximate position of NPL-40 is also indicated if follow-up spectra and proper motion analysis confirm its identity as a physical binary.

not rare, those with separations greater than 15-20 AU have yet to be identified within the Pleiades. This provides further evidence that the period distribution of VLM binaries in the Pleiades shown in Figure 2 is significantly different from that of field stars or of young cluster members. Whether widely separated pairs are not formed preferentially, or if they are disrupted by interactions over the cluster lifetime has yet to be resolved. Disintegrating triples could also account for the observed bias towards tightly bound systems. As the period of the closer pair shortens, the third member will be ejected from the system. Very young clusters with ages less than their crossing times would provide ideal targets to further study this problem. Not having undergone many weak interactions, the less tightly bound brown dwarf binaries should still be in existence if formed from the initial collapse of the cloud. Additionally, a thorough spectroscopic study of VLM members in the Pleiades should also be undertaken to place constraints upon the population and period distribution of the shortest period systems. This program is continuing in the Pleiades as well as the young cluster α Persei.

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