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VERY LOW MASS STARS AND SUBSTELLAR OBJECTS IN THE PLEIADES[1]

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ABSTRACT

We have identified a small number of faint, red stars in optical and infrared frames taken near the center of the Pleiades cluster. The sampled masses range from 0.25 to 0.04 $M_\odot$. The Pleiades mass function in linear units is consistent with a M^{-1} power law or with a flat dependence in logarithmic mass units. This dependence is consistent with studies of other young open clusters and suggests that massive brown dwarfs and low-mass stars do not contribute significantly to the dark matter.

Subject headings: dark matter — open clusters and associations: individual (Pleiades) — stars: low-mass, brown dwarfs — stars: luminosity function, mass function

1. INTRODUCTION

Despite years of effort, the search for brown dwarfs has been mostly a failure (see Stevenson 1991, and references therein). This lack of success primarily is in regard to searches for brown dwarfs as binary companions to higher mass stars. We have chosen a different approach. Our goal is to locate single brown dwarfs as members of a young, nearby, relatively rich, unembedded cluster. This paper reports a deep optical/infrared search for such objects in the Pleiades.

The most difficult part of a cluster survey for low-mass members (hence dim members) is determining membership probabilities. Classical methods for determining membership probabilities are based on proper motion studies and spectroscopic follow-up. However, for the very low luminosity sources this method is impractical because existing first epoch plates do not reach faint enough magnitudes. Williams, Reike, & Stauffer (1995b) discuss a photometric technique using a very large wavelength baseline [V (0.55 μm) to K (2.22 μm)], that is efficient, complete, and reliable. We have used this same approach in the work reported here.

Stauffer et al. (1989, hereafter SHPRM) imaged $\sim$900 arcmin^2 of the Pleiades at V and I, with follow-up K photometry of a very few members. They identified 12 Pleiades brown dwarf candidates. To extend this survey to lower masses, we have added K photometry of 300 arcmin^2 of this region, plus 100 arcmin^2 of new V, I, and K data. In addition, we report new K photometry of two additional sources from SHPRM.

2. OBSERVATIONS AND DATA REDUCTION

CCD observations at V and I were obtained of fields in the Pleiades using the 4-shooter on the Hale 200 inch telescope. Details of the data and reduction have been described by Stauffer, Hamilton, & Probst (1994a). One field was imaged at V at the Steward 2.3 m telescope in 1993 January and reduced using standard IRAF techniques and calibrated using the standards of Odewahn, Bryja, & Humphreys (1992).

Infrared images of 8.5 of these fields were obtained in 1991 October and December on the Steward Observatory 2.3 m telescope. These data used a camera with a NICMOS2 128 × 128 HgCdTe array; the pixel size was set to $\sim 1\farcs2$, and the field of view was $\sim$6.55 arcmin^2. Most of each CCD field was covered with a mosaic of 3 × 3 infrared frames; the total area included in the survey is 400 arcmin^2. Each field was observed twice, either in October and December or on different nights during December. K photometry of source 4 from SHPRM was taken in 1995 April on the Steward Observatory 2.3 m telescope using a camera with a NICMOS3 256 × 256 HgCdTe array.

Standard procedures were used to remove the instrumental signature and calibrate the infrared frames, and are described in detail in Williams et al. (1995b); all steps were under IRAF. Sources were extracted with DAOPHOT, after adjusting procedures carefully to maximize signal to noise and photometric repeatability (determined by comparing results on the two independent sets of images). The frames reach $m_K > 17$ in October, and $m_K > 17.5$ in December.

The infrared and CCD source extractions were cross correlated and all sources detected at K and either V or I were extracted. For the remaining K-only sources, we compared

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[1] Observations reported here were obtained at the Multiple Mirror Telescope Observatory, a facility operated jointly by the University of Arizona and the Smithsonian Institution.

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the two sets of images and extracted all objects that were detected twice. The slightly poorer limit of the October data was not a serious limitation, since sources below the S/N ratio required for independent identification could still be used for confirmation of a detection in December.

We obtained near-infrared spectra of brown dwarf candidates 1 and 2 of SHPRM on the Multiple Mirror Telescope on 1989 December 11 and of candidate 6 on 1993 October 3. We used the Steward Observatory germanium diode spectrometer with a 150 lines mm^{-1} grating and a 3″ entrance aperture, giving a Nyquist-sampled resolution of $\lambda/\Delta\lambda = 200$. The spectra were flat-fielded and corrected for atmospheric extinction by comparison with similar spectra obtained of solar-type stars close to the Pleiades on the sky. Details of the data reduction procedure are described in Rix et al. (1990).

3. ANALYSIS

3.1. *Extraction of Pleiades Members*

Figure 1 shows the m_V, $V-K$ color—magnitude diagram for our data. We also plot a young disk main sequence at the distance of the Pleiades (126 pc), based on Table 6 of Leggett (1992), as a solid line. The isochrone for stars and substellar objects at the age (taken to be 70 million years), and distance of the Pleiades is indicated by the dotted line. This line is based on theoretical calculations provided by W. B. Hubbard (private communication), which in turn are based on Model X of Burrows et al. (1993). The theoretical effective temperatures were converted to photometric colors by applying the work of Kirkpatrick et al. (1993) to relate T_e to M dwarf spectral type. Colors for the appropriate M dwarfs in the Cousins system were taken from Leggett (1992); we assumed that the colors of pre–main-sequence objects would be identical to those of M dwarfs of identical effective temperature. This procedure provides an observationally based set of colors and absolute magnitudes even for objects with masses well below the bottom of the main sequence, since at the age of the Pleiades these objects have not yet cooled below the temperatures of evolved M dwarfs. We have indicated the masses of objects along the Pleiades isochrone.

Models and observations of very low-mass stars have generally been in disagreement when placed in a color-magnitude diagram (or the theoretical equivalent HR diagram). The majority of comparisons, no matter the source of the data nor the choice of models, show that the models are systematically hotter than the observed stars by several hundred degrees (e.g., Burrows & Liebert 1993; Tinney, Mould, & Reid 1993). Kirkpatrick et al. (1993) indicate that it is the conversion of photometric colors to $T_{\rm eff}$ that is likely the problem, where their determinations of $T_{\rm eff}$ were determined from spectroscopic data, and in general are in much better agreement with the theoretical models. Observations of sets of coeval stars are now needed to constrain further both the models and the temperature scale.

A number of general features of Figure 1 need comment. Because the CCD saturated above $m_V = 17.5$, we base the following discussion on sources with $m_V > 17.5$. For the Pleiades, $m_V = 17.5$ corresponds to a star of $M = 0.25\,M_\odot$, so our discussion will include no stars more massive than this value. The boundary to the distribution of detected sources extending from $m_V = 19.5$, $V-K = 2$ to $m_V = 24$, $V-K = 6.5$ arises from the K detection limit of $m_K \sim 17.5$. We believe the survey is complete for $m_K \lesssim 17$. The V limit of the survey is $m_V = 22.5$ to 23. However, where a K detection was achieved, we examined the CCD frames for a faint source below the limit for independent detection. We believe a typical limit for source detection at K is $m_V = 23.5$.

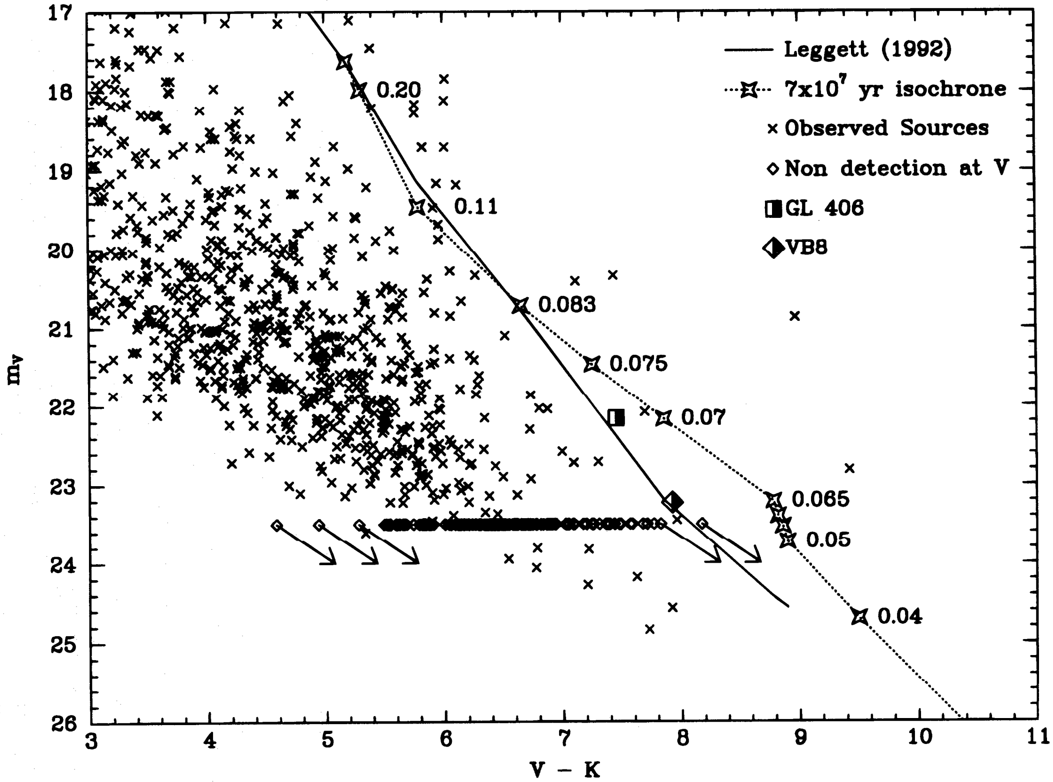

FIG. 1.—Color-magnitude m_V, $V-K$ for the Pleiades

Sources not detected at V but detected at K or at I and K are shown as upper limits corresponding to $m_V = 23.5$ with tails extending in the direction they would move as m_V is made larger than 23.5. For a given spectral type, changes in distance move points vertically in Figure 1. Therefore, the great majority of stars, which fall below the Pleiades isochrone for their colors, are dwarfs that lie behind the cluster. There may be a contamination of these counts by red giants at much greater distances than the dwarfs; however, because the Pleiades are at relatively high Galactic latitude (24°), this contamination should be very small. Stars far above the isochrone are likely to be foreground dwarfs. Based on the counts of stars within 8 pc by Henry & McCarthy (1992) with $11 < V < 18$, we estimate that there should be about one low-mass dwarf between us and the cluster; four stars appear well above the Pleiades isochrone, in rough agreement with this expectation.

We draw attention to the excellent separation of the background stars from the Pleiades isochrone in the m_V, $V-K$ diagram. It is tempting to base low-mass star investigations on colors redder than V because cool objects should be more easily detectable in that manner. However, we find that separation of cluster members from the background population is compromised unless the full V to K baseline is utilized. This point is discussed in more detail by Williams et al. (1995b).

Based on our estimates of photometric errors, on the diameter of the Pleiades, and on the uncertainty of the distance to this cluster, we estimate that any object within 0.35 mag of the isochrone in Figure 1 could be a single-star member of the cluster. Unresolved double stars of equal magnitude could lie as far as 1.15 mag above the isochrone. Objects that meet the +1.15, −0.35 mag criterion are plotted on a $V-I$, $I-K$ color–color diagram in Figure 2. In addition to objects with full V, I, and K detections, we also include an object without V information, shown as the appropriate limit. This is the second reddest limit shown in Figure 1, which is just outside the selection band, but the sense of the limit quickly makes it a candidate.

In Figure 2, the solid line is the locus of dwarfs, from Leggett (1992) (given the way we estimate the colors of Pleiades members, they should fall on this line). The dashed line shows the locus of red giants. With the exception of two objects, the potential Pleiades members all fall on the dwarf locus within the photometric errors, which is consistent with their being true cluster members. The two exceptions ($I-K \sim 3.0$, $V-I \sim 2.75$, $m_V \sim 18.3$, $V-K \sim 5.75$) are assumed to be background giants and will be dropped from further discussion. Two additional sources fall below the m_V, $V-I$ isochrone (not shown) and are also assumed to be background sources. The remaining candidate Pleiades members are listed in Table 1. K-band finder charts for objects not previously identified in Stauffer et al. (1989) or Hambly, Hawkins, & Jameson (1993) (see below) are given in Figure 3.

Our K images should be complete for brown dwarfs with masses $\gtrsim 0.02\ M_\odot$, including objects with V upper limits with masses $\gtrsim 0.035\ M_\odot$. Unfortunately, we have no way of sorting these very low mass objects out from the contaminating background stars. However, our survey should be complete and relatively uncontaminated for Pleiades members with $0.04\ M_\odot < M < 0.25\ M_\odot$. Using the +1.15, −0.35 mag tolerance, we find 11 potential members more massive than $0.08\ M_\odot$, i.e., stars, and two potential members (including the V limit) between 0.04 and $0.08\ M_\odot$, i.e., brown dwarfs.

We can estimate the contamination level in this sample from a reference field at the same Galactic latitude but

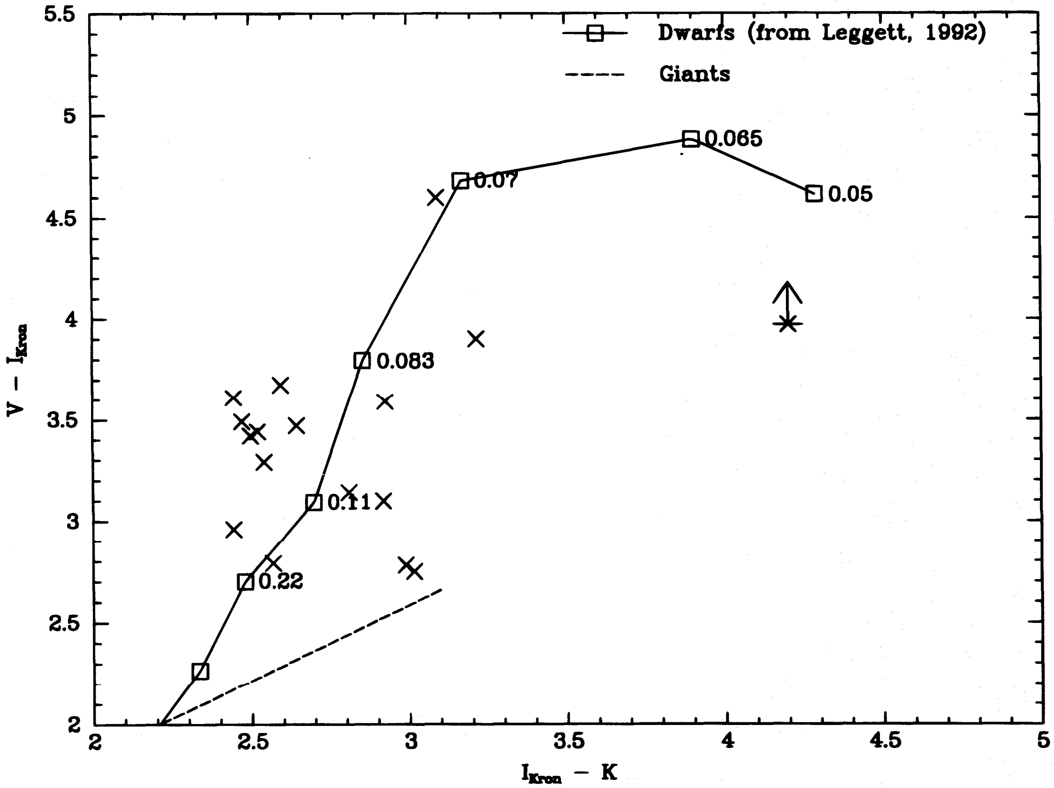

FIG. 2.—Color–color $V-I$, $I-K$ for the Pleiades. Only sources within +1.15, −0.35 mag of the 70 Myr isochrone are plotted.

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TABLE 1

Probable Pleiades Members

Number	R.A.[a]	Decl.[a]	m_V	m_I	m_K	Previous ID[b]
1........	$03^h45^m34^s.2$	23°43′31″.8	18.22	15.26	12.82	
2........	03 44 11.8	23 16 42.0	18.71	15.61	12.69	
3........	03 45 31.2	23 48 59.2	18.71	15.42	12.88	HHJ 132
4........	03 42 27.0	23 47 37.4	19.16	16.02	13.21	
5........	03 42 40.7	23 47 44.2	19.18	15.71	13.07	
6........	03 45 43.5	24 18 13.7	19.47	16.05	13.55	HHJ 44
7........	03 46 02.9	23 29 10.1	19.68	16.19	13.72	
8........	03 40 56.9	23 37 35.5	19.87	16.43	13.91	
9........	03 41 01.5	23 38 35.1	20.28	16.67	14.22	PPl 9
10	03 42 16.3	23 12 08.9	20.33	16.66	14.06	
11	03 42 14.4	23 44 26.4	20.41	16.51	13.30	PPl 7; HHJ 14
12	03 42 43.0	23 44 50.3	22.08	17.48	14.39	PPl 1
13	03 42 16.9	23 45 13.6	...	19.53	15.34	

[a] All coordinates are for the 1950.0 equinox and accurate to ~3″.

[b] (PPl) Stauffer et al. 1995; (HHJ) Hambly et al. 1993.

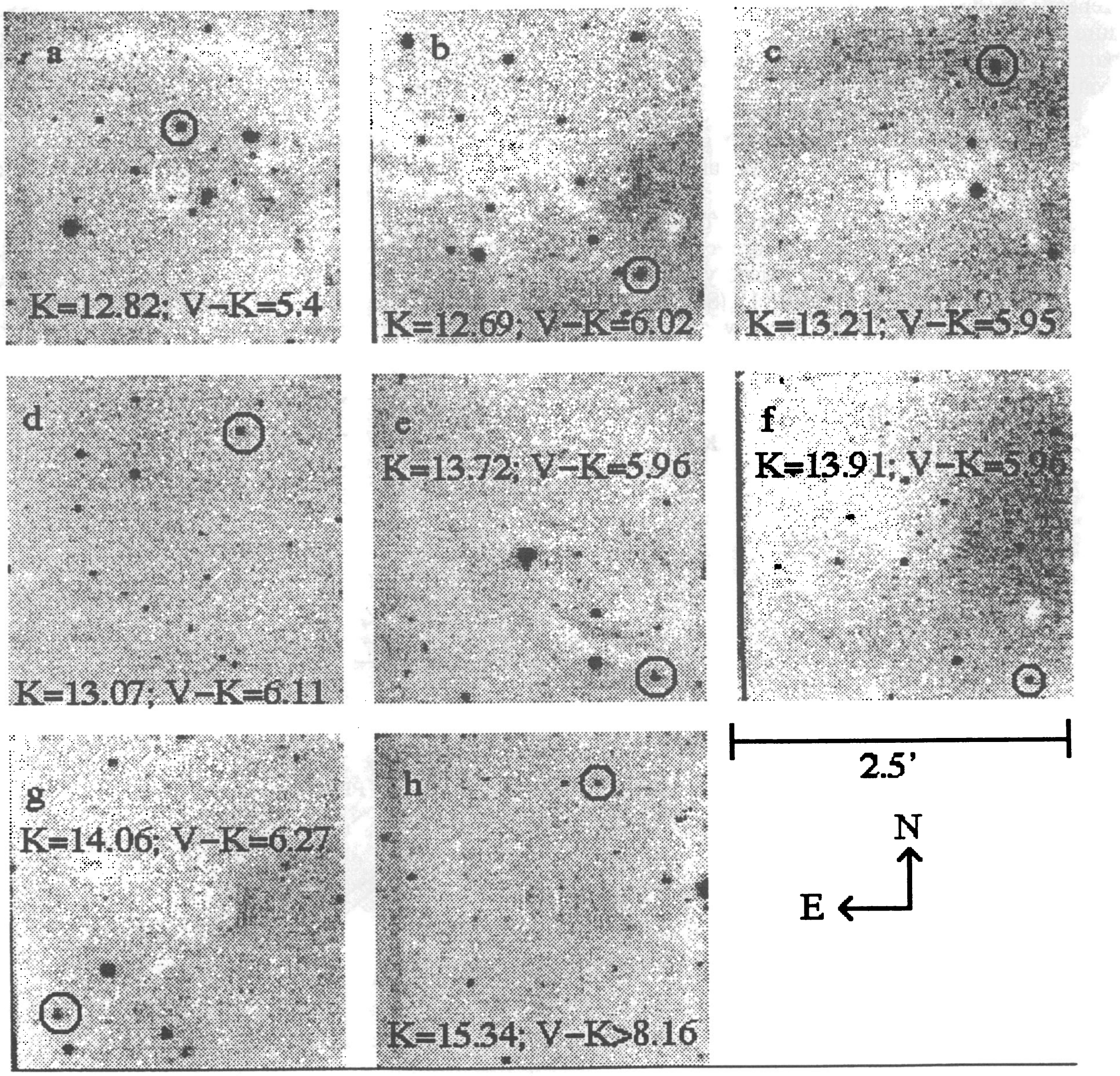

FIG. 3.—*K*-band finder charts for objects not previously identified. Each image is 2′.5 on a side, with north up and east to the left; (*a*) object 1; (*b*) object 2; (*c*) object 4; (*d*) object 5; (*e*) object 7; (*f*) object 8; (*g*) object 10; (*h*) object 13.

removed from the Pleiades by 5°, which contains approximately half the size of our Pleiades survey (~ 175 arcmin^2), and which we imaged in V, I, and K and have analyzed using techniques identical to those used for the Pleiades. We find zero stars in the reference field that pass all the tests that would have led us to associate them with the Pleiades. A second class of contamination is from true low-mass stars not associated with the Pleiades, which happen to be located within the volume sampled by our tolerance to define Pleiades members. Using the luminosity function of Henry & McCarthy (1992) for stars within 8 pc, we expect to find four non-Pleiades low-mass stars with $11 < M_V < 16$ interloping in the volume for the $+1.15$, -0.35 mag tolerance, where we find 11 potential stellar members, so the background-corrected estimate is 7 ± 3.9. The possibility that the brown dwarf candidates are contaminating sources is discussed below and found to be unlikely.

3.2. *Tests of the Extraction Technique*

Particularly for the brown dwarf candidates, our technique depends on the theoretical model calculation and the procedure we have used to convert it into isochrones. For these particular fields, we note there are essentially *no* additional viable brown dwarf candidates on the m_V, $V-K$ diagram, even should the isochrone be in error by a significant amount. However, a test of the procedure is still of interest and will be important in terms of future applications.

Although we have assigned the locus for substellar objects from our own conversion of theoretical models to observed colors, strong support is provided by the location in m_V, $V-K$ and $V-I$, $I-K$ of PPL 15 (Stauffer et al. 1994a), which falls almost exactly where we would predict in Figures 4 and 5. Basri, Marcy, & Graham (1995) have detected lithium absorption in this object, which supports its identification as a brown dwarf just below the bottom of the main sequence (Stauffer et al. 1994a). Although Basri et al. (1995) suggest from the apparent depletion of lithium in PPL 15 that the age of the Pleiades may exceed 70 Myr by as much as a factor of 2, we have not adjusted our analysis pending further understanding of this discrepancy. In any case, the adjustment would be small and would not significantly affect any of our conclusions about the shape of the IMF. However, an increase in the assigned age for the Pleiades would slightly increase the masses of faint objects and might bring the brown dwarf status of PPl 1 and 2 into question.

We have examined two possible systematic errors: (1) the age of the Pleiades and (2) the temperature scale. The temperature scale for very red stars remains an outstanding challenge as described by Burrows & Liebert (1993). We have adopted the temperature scale of Kirkpatrick et al. (1993), which yields the hottest temperature for a given spectral type (see Berriman, Reid, & Leggett 1992; Bessel 1991). The effects of both assigning an older age to the Pleiades and using a cooler temperature scale both bring the isochrone for Pleiades objects closer to the zero-age main sequence. While our tests cannot rule out either of these two individual effects, we can rule out the combination of both an assumed age of 120 Myr and a temperature scale that is 150 K cooler at a specific spectral type than Kirkpatrick et al. (1993), as this combination eliminates virtually all of the PPl sources (including PPl 15).

Another encouraging result can be seen from the density of possible Pleiades members along the isochrone. Because of the cooling of brown dwarfs, the theoretical isochrones in

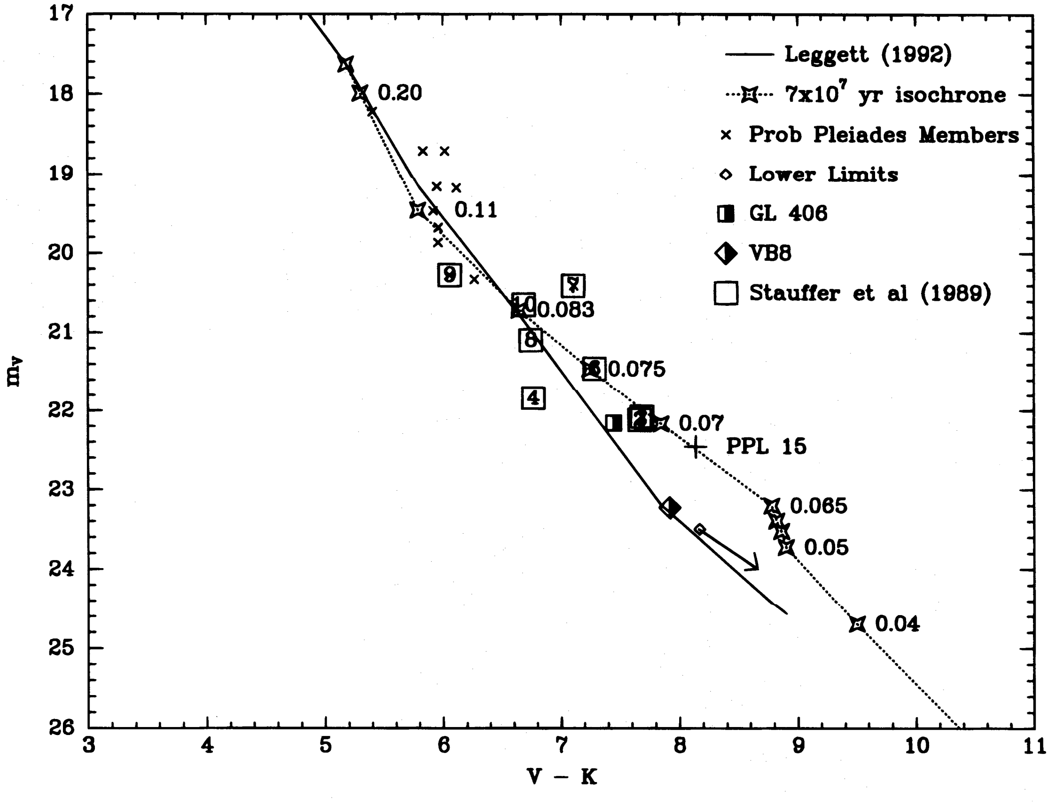

FIG. 4.—Color-magnitude m_V, $V-K$ for the Pleiades. Sources within $+1.15$, -0.35 mag of the 70 Myr isochrone are plotted. Also shown are seven sources originally identified in SHPRM, labeled as identified in that paper. Sources 1 and 2 overlap.

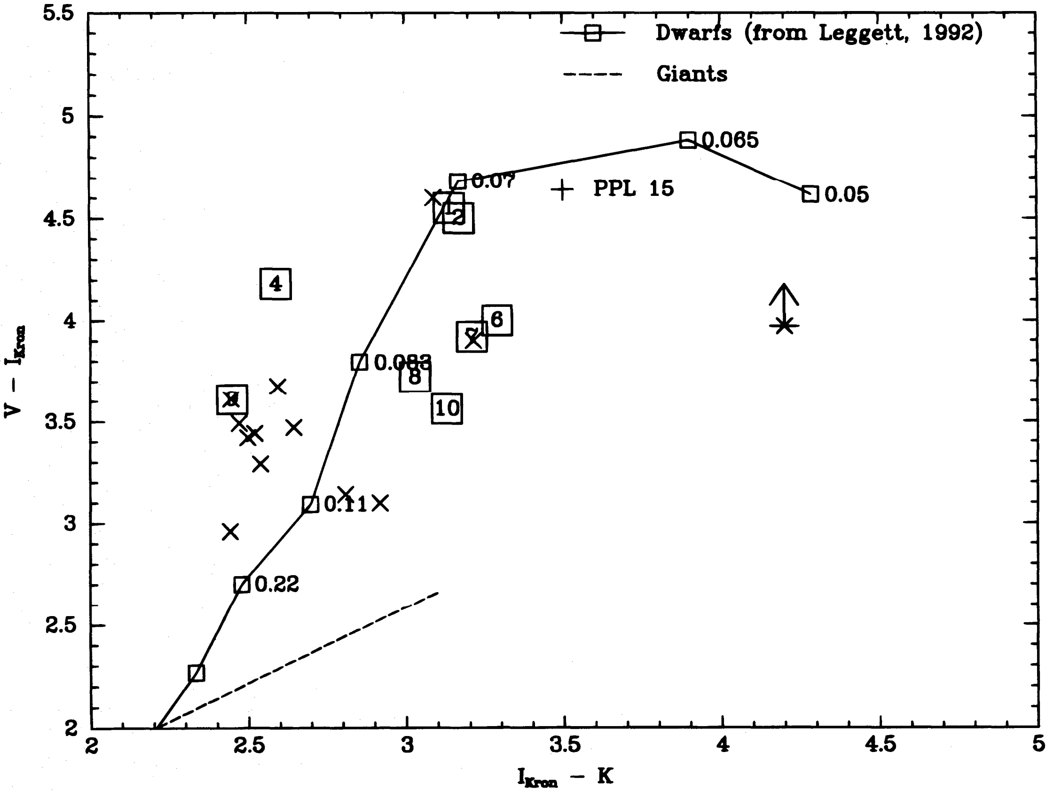

FIG. 5.—Color-color $V-I$, $I-K$ for the Pleiades. Sources within $+1.15$, -0.35 mag of the Pleiades isochrone are plotted. Also shown are seven sources originally identified in SHPRM, labeled as identified in that paper.

m_V, $V-K$ and $V-I$, $I-K$ are "stretched" below 0.08 $M_{\odot}$. That is, a given factor of change in mass below 0.08 $M_{\odot}$ corresponds to a larger interval in, say, $V-K$ than it does above 0.08 $M_{\odot}$. In agreement with this prediction, the density of candidate members along the isochrones appears to drop abruptly near 0.08 $M_{\odot}$. Figure 2 shows this effect very clearly.

In Figures 4 and 5 we show on the m_V, $V-K$, and $V-I$, $I-K$ diagrams eight of the nine Pleiades objects with $m_V > 20.4$ from the study of SHPRM and PPl 15 from Stauffer et al. (1994a); the objects are labeled as listed in those papers and will be referred to with a "PPl" prefix (see Stauffer et al. 1994a). PPl 3 was omitted because it is blended with another object and its colors may be inaccurate; however, if its V magnitude is increased to correct for the blending, it does not move toward the Pleiades isochrone and we conclude it may not be a cluster member. PPl 1 is the candidate with full photometric measurements found in our survey (object 12). PPl 7 was also observed as part of this survey (object 11). We have also determined the K magnitude of PPl 4 in a follow-up observation. The sources plotted fall very close to the isochrone, lending support both to the methods we have used to derive the isochrone and to the identification of the faintest three of these six objects as candidate brown dwarfs.

Additionally, PPl 7 and PPl 10 were determined to be Pleiades members in the proper motion study of Hambly et al. (1993) (HHJ 14 and HHJ 10, respectively). Marcy, Basri, & Graham (1994) supported the membership claim of PPl 7 by observing Hα in emission; however, they feel that PPl 7 is not a brown dwarf due to the lack of a lithium 6708 Å absorption as predicted by Rebolo, Martin, & Magazzu (1992) and Magazzu, Martin, & Rebolo (1993), in very good agreement with our results. The radial velocity of PPl 7 was also shown by Basri & Marcy (1995) and Stauffer et al. (1994b) to be consistent with the radial velocity of the Pleiades. The membership claim of PPl 10 was furthered by Stauffer, Liebert, & Giampapa (1995) based on both Hα and radial velocity arguments.

One alternate hypothesis is that these objects are background sources. From their position on the $V-I$, $I-K$ diagram, we can exclude that they are either red giants or distant normal galaxies. In Figures 6 and 7 we show near-infrared spectra of PPl 1, PPl 2, and PPl 6 in comparison with the spectrum of VB 10. The presence of the steam feature at 1.3 μm requires PPl 1 and PPl 2 to be cool stars and is fully consistent with our identification of them as members of the Pleiades. PPl 6, however, does not show this steam feature. Although its bluer $V-K$ would lead us to expect a weaker feature than for the other two sources, the lack of any detection calls its status as a member of the Pleiades into question.

A second alternate explanation for the position of the two remaining candidates (PPl 1, PPl 2) is that they are independent M dwarfs close to the Pleiades.

Adopting this hypothesis, a distance of ∼90 pc for both objects can be estimated from the distance in m_V between their apparent positions in Figure 4 and the main sequence. We compute a generous upper limit to the probability that these objects are foreground by computing the volumes of pyramids extending from the Earth to these distances and with bases equal to the total area surveyed by SHPRM, i.e., 871 arcmin^2. We then multiply each of these volumes by the density of stars or pairs of stars of M6 or later type ($M_V > 15$) observed within 8 pc of the Earth by Henry & McCarthy (1992). (The photometric colors of PPl 1 and PPl

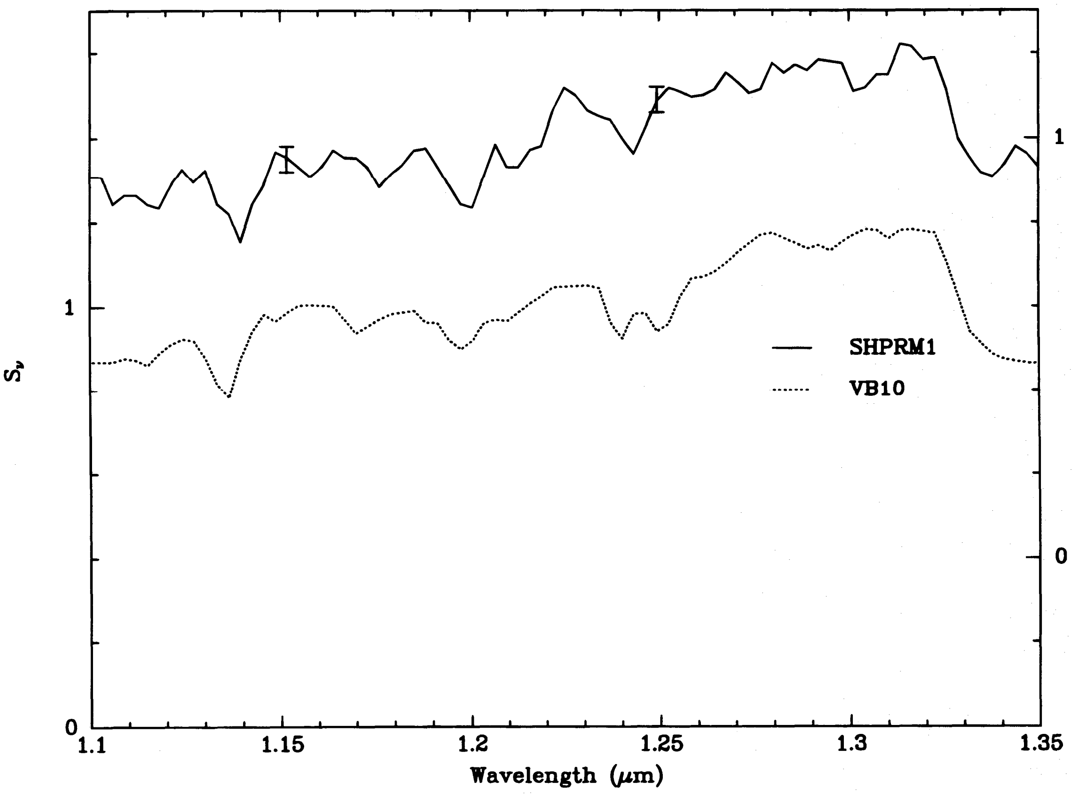

FIG. 6.—Spectra of VB 10 (*bottom*) and PPl 1 (*top*). The spectra are normalized to 1; the scale for VB 10 is shown on the left side of the frame and that for PPl 1 on the right (they have been offset for clarity). Note the steam feature at 1.3 μm.

2 correspond to ~M7 (Leggett 1992.) We find that the probability that both of these objects are nearby dwarfs is less than 0.08, although it is conceivable that either of them is a nearby object. A similar argument applies to the new brown dwarf candidate we have found, but which is undetected in *V*.

We conclude that the CCD survey of SHPRM did correctly identify two probable brown dwarfs in the Pleiades in

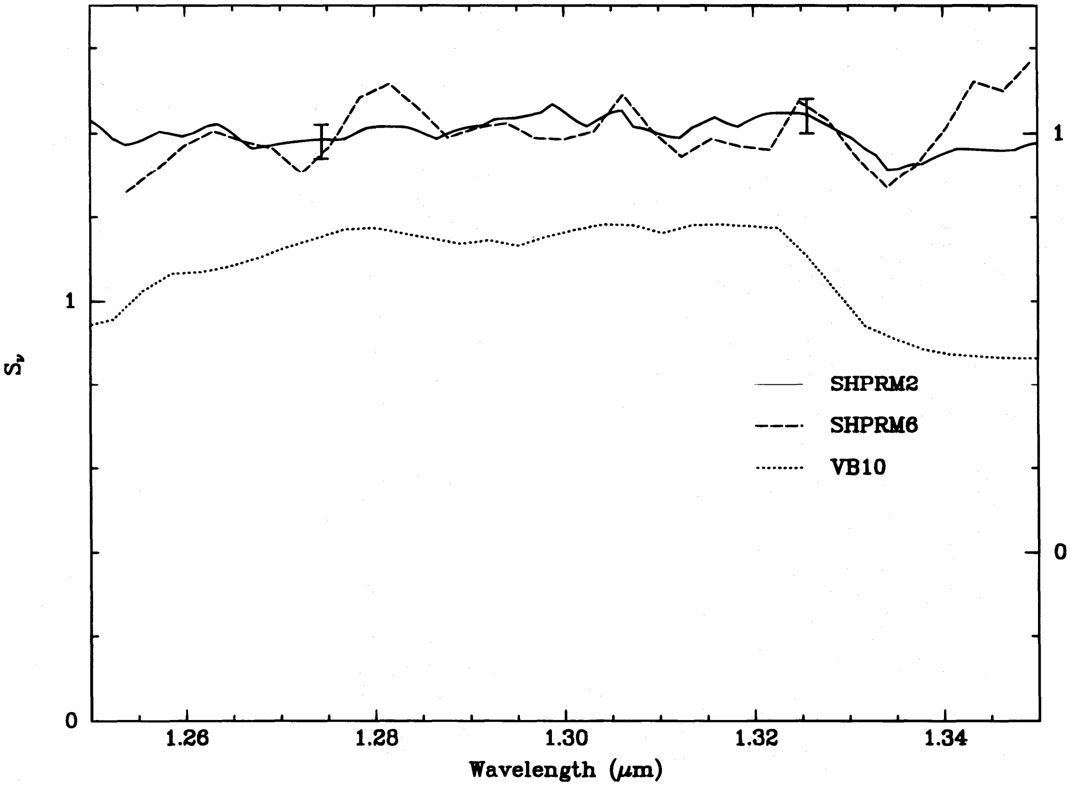

FIG. 7.—Spectra of VB 10 (*bottom*) and PPl 2 (*top, solid line*) and PPl 6 (*top, dashed line*). Details as in Fig. 6.

an angular area of 871 arcmin^2, their objects 1 and 2. Our K survey of 400 arcmin^2, although it extends to lower brown dwarf mass, has identified at most one additional brown dwarf candidate with mass $\gtrsim 0.04\ M_\odot$. The extended CCD survey of Stauffer et al. (1994a) identified one more object, PPl 15, that appears to be a confirmed brown dwarf (Basri et al. 1995) and has properties remarkably similar to PPl 1 and PPl 2. Based on their V magnitudes and $V-I$ colors, PPl 13 and PPl 14 may also be very low mass Pleiades members.

From these data, we can place constraints on the initial mass function (IMF) in the Pleiades. For simplicity, we assume that the IMF goes as $N(M)dM \propto M^{-1}dM$, including and extending into the brown dwarf regime with this same dependence (Comerón et al. 1993). This is also in good agreement with the MF of the old M dwarf population near the Sun, whose slope is between -0.70 and -1.85 (Kroupa, Tout, & Gilmore 1993). We normalize this functional dependence to the counts between 0.45 and 0.6 $M_\odot$ from Stauffer et al. (1991) (after converting their LF to a MF using Henry & McCarthy 1993), and scaling by the ratio of the 400 arcmin^2 of our survey to the 4° × 4° area of Stauffer et al. (1991). We predict 3.4 stars in our survey between 0.08 and 0.25 $M_\odot$ and 2.1 brown dwarfs between 0.04 and 0.08 $M_\odot$, where our detection rates are, respectively, seven stars and two brown dwarfs (including the limit). If we combine our counts over the entire 0.04–0.25 $M_\odot$ range and include in the statistics the subtracted contaminating stars, we find a total of 9 ± 4.1 Pleiades members where the M^{-1} IMF would predict 5.5—i.e., the agreement is within one standard deviation (see Table 2). If we consider only candidate brown dwarfs and combine the surveys of SHPRM, Stauffer et al. (1994a), and our new data, we find at least four brown dwarf candidates where seven are predicted. The observed rates are not significantly different from the 1/M IMF dependence; a larger area must be surveyed to establish any deviations. Given the small number of brown dwarf candidates, our study is probably also consistent with an IMF that flattens toward very low masses. However, our detection rates do contradict much steeper dependencies. For example, if the IMF goes as M^{-2}, then we would have predicted 13.3 stellar members and 19.5 brown dwarf members within our survey completeness limits (see Table 2).

These conclusions are unaffected by the fact that some of these Pleiades members are likely unresolved binaries. The type of binary that would lie farthest above the single star isochrone, 0.8 mag, would be a system of two identical stars. If we limit cluster members to objects that fall within ± 0.35 mag of the isochrone in the m_V, $V-K$ diagram, we would exclude three objects from our list. However, the volume included by this smaller tolerance is 4.4 times smaller than that for the tolerance that includes possible double sources, decreasing the number of expected interlopers from 4 to 1. The combined effect produces no change in the number of stellar members. Thus, our conclusions are unchanged.

3.3. *Comparison with Other Work*

Hambly et al. (1993, hereafter HHJ) located probable Pleiades members using a proper motion survey of a 5° × 5° area around the cluster center. Two HHJ objects, HHJ 344 and HHJ 440, completely saturated the arrays; thus, we cannot tell if we would have declared them members. Two of our eight objects with $m_V < 20$ appear on their list (object 3 = HHJ 132; object 6 = HHJ 44), and the coordinates agree well within the errors. The only two objects removed from our list because they were too bright (but otherwise fit our membership criteria) correspond to HHJ 255 and HHJ 315. Based on HHJ's claim of 70% completeness in this range and assuming a high completeness ratio for our survey, we would expect to see ~7 out of these 10 objects appear in both surveys, where in fact four do. HHJ 203 was one of the objects that appeared along the red giant locus in the $V-I$, $I-K$ diagram and was dismissed as a possible member. In the range $20 > m_V > 21$, where HHJ has an estimated 30% completeness ratio, we find two possible members not in their survey, and one common source (object 11 = HHJ 14 = PPl 7). There are no other HHJ sources within our sample area. As with our similar study of Praesepe (Williams et al. 1995b), we conclude that our photometric technique is in good agreement with cluster memberships assigned from proper motions.

Two other recent similar studies claim to find large numbers of brown dwarfs in the Pleiades, leading to an IMF that rises more steeply than M^{-1}. Simons & Becklin (1992) surveyed 200 arcmin^2 and a control area of 75 arcmin^2 in I and K. They used a procedure similar to ours but on the I, $I-K$ diagram to define the Pleiades isochrone and determine possible Pleiades members. After correcting for the objects extracted in the same manner from a control field, they concluded that there were 22 ± 10 objects with $\sim 0.04\ M_\odot < M < \sim 0.11\ M_\odot$, or 44 ± 20 in 400 arcmin^2. In 400 arcmin^2 we find at most 9 ± 3.3 objects with $0.04\ M_\odot < M < 0.11\ M_\odot$. First, we note that the two estimates are formally consistent. Second, the limited color baseline used by Simons & Becklin (1992) did not provide nearly as clear a differentiation of Pleiades members from the background as in our study, so we suspect that any differences between the studies may arise from contamination of their sample by background stars. Although the number counts from the two studies are consistent, the slopes of the derived mass functions are not. An MF with a slope of -1 normalized as described above predicts 3.0 objects in this mass range in this area, while an MF with a slope of -2 predicts 24.8 objects (see Table 2).

Steele et al. (1993) have also used the I, $I-K$ diagram to extract Pleiades members, so their sample may also be contaminated by background objects. In addition, age was left

TABLE 2

STAR COUNTS[a]

Method	Number of Stars	Number of Brown Dwarfs	Number of Very Low Mass Objects
This paper	7	2	9 ± 4.1
Simons & Becklin 1992......	...	...	44 ± 20
$n = -1$	3.4	2.1	5.5
$n = -2$	13.3	19.5	24.8

[a] All counts normalized to Stauffer et al. 1991 at $0.45 M_\odot < M < 0.6\ M_\odot$ and scaled to 400 arcmin^2.

as a free parameter in identifying potential brown dwarfs and many of their candidates are suggested to be much younger than the youngest well-studied stars in the cluster. More recently, Steele & Jameson (1995) reanalyzed the original data and now believe the data are best interpreted in terms of a single and a double star sequence, both of the age of the Pleiades. This effectively halves the number of brown dwarf candidates from the original analysis.

Some initial efforts to measure the IMF in embedded clusters have also been reported. One would expect these regions to have identical distributions of stellar masses to those in older unembedded clusters like the Pleiades. A comparison of the two stages in cluster formation can therefore test the assumptions made in analyzing the observations as well as providing a test of the theoretical models of low-mass stars and brown dwarfs of varying ages. Comerón et al. (1993) and Williams et al. (1995a) find that the low-mass IMF in ρ Ophiuchus goes roughly as $M^{-1.1}$ in linear mass units, or as $M^{-0.1}$, nearly flat, in logarithmic units. Strom & Strom (1994) conclude, using a different analysis technique, that the IMF in L1459E is roughly flat in logarithmic units at low masses or alternately could be fitted by an IMF with a bend at $\sim 0.3\ M_\odot$ and that falls to either side of this mass. Strom, Kepner, & Strom (1995) find the ρ Oph IMF to be flat in logarithmic units. Within the still rather large uncertainties, our results on the Pleiades, and these other studies are all consistent with each other.

Low-mass members account for a significant portion of the integrated mass of a stellar population only if the IMF in linear units is at least as steep as $N(M)dM \propto M^{-2}dM$. There is now a significant body of evidence that the IMF in open clusters for single stars and the primary members of doubles is roughly one power of mass less steep than this critical dependence. If the properties of binary systems in these clusters resembles the properties of binaries in the solar neighborhood (Duquennoy & Mayor 1991), then it can be shown that unresolved secondary stars in binaries do not contribute significantly to the integrated mass. Therefore, it appears that low-mass stars and massive brown dwarfs appear to contribute only a small portion of the integrated mass of an open cluster. If the general IMF behaves similarly, then such objects cannot be an important constituent of dark matter.

4. CONCLUSIONS

We have used optical and infrared photometry and infrared spectroscopy to identify potential low-mass Pleiades members. We conclude that the CCD surveys of Stauffer et al. (1994a) and Stauffer et al. (1989) did correctly identify at least three possible brown dwarfs in the Pleiades in an area of 1400 arcmin^2. Our K survey of 400 arcmin^2, although it extends to lower brown dwarf mass, has identified at most one additional brown dwarf candidate, and suggests that there are nine stellar members in this area with masses between 0.08 and 0.25 $M_\odot$. The initial mass function derived from these counts is consistent with a simple power law $[N(M)dM \propto M^n dM]$ with an index of $n = -1$ in linear mass units, equivalent to a flat dependence in logarithmic mass units. Our results are inconsistent with steeply falling low-mass IMFs, for example with $n = -2$, as have been found in other studies. If the IMF in open clusters is representative of star formation generally, then massive brown dwarfs and very low mass stars do not account for a very large fraction of the mass in a volume of space, i.e., such objects do not provide significant dark matter.

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