View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Clemson University: TigerPrints

Clemson University
TigerPrints

Publications

Physics and Astronomy

9-1-1998

The Problem of HIPPARCOS Distances to Open Clusters. II. Constraints from Nearby Field Stars

David R. Soderblom
Space Telescope Science Institute

Jeremy R. King
Clemson University, jking2@clemson.edu

Robert B. Hanson
University of California

Burton F. Jones
University of California

Debra Fischer
San Francisco State University

See next page for additional authors

Follow this and additional works at: https://tigerprints.clemson.edu/physastro_pubs

Recommended Citation

Please use publisher's recommended citation.

This Article is brought to you for free and open access by the Physics and Astronomy at TigerPrints. It has been accepted for inclusion in Publications by an authorized administrator of TigerPrints. For more information, please contact kokeefe@clemson.edu.

Authors
David R. Soderblom, Jeremy R. King, Robert B. Hanson, Burton F. Jones, Debra Fischer, John R. Stauffer, and Marc H. Pisonneault

This article is available at TigerPrints: https://tigerprints.clemson.edu/physastro_pubs/259

THE ASTROPHYSICAL JOURNAL, 504:192–199, 1998 September 1
© 1998. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE PROBLEM OF *HIPPARCOS* DISTANCES TO OPEN CLUSTERS. II. CONSTRAINTS FROM NEARBY FIELD STARS[1]

DAVID R. SODERBLOM AND JEREMY R. KING
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore MD 21218; soderblom@stsci.edu, jking@stsci.edu
ROBERT B. HANSON AND BURTON F. JONES
University of California Observatories/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz CA 95064; hanson@ucolick.org, jones@ucolick.org
DEBRA FISCHER
Department of Physics and Astronomy, San Francisco State University, San Francisco CA 94132; fischer@stars.sfsu.edu
JOHN R. STAUFFER
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge MA 02138; stauffer@cfa.harvard.edu
AND
MARC H. PINSONNEAULT
Astronomy Department, Ohio State University, 174 West 18th Avenue, Columbus OH 43210; pinsono@astronomy.ohio-state.edu
Received 1997 December 23; accepted 1998 April 3

ABSTRACT

This paper examines the discrepancy between distances to nearby open clusters as determined by parallaxes from *Hipparcos* compared to traditional main-sequence fitting. The biggest difference is seen for the Pleiades, and our hypothesis is that if the *Hipparcos* distance to the Pleiades is correct, then similar subluminous zero-age main-sequence (ZAMS) stars should exist elsewhere, including in the immediate solar neighborhood. We examine a color-magnitude diagram of very young and nearby solar-type stars and show that none of them lie below the traditional ZAMS, despite the fact that the *Hipparcos* Pleiades parallax would place its members 0.3 mag below that ZAMS. We also present analyses and observations of solar-type stars that do lie below the ZAMS, and we show that they are subluminous because of low metallicity and that they have the kinematics of old stars.

Subject headings: open clusters and associations: individual (Pleiades) — solar neighborhood — stars: distances — stars: evolution — stars: Hertzsprung-Russell diagram

1. DISTANCES TO OPEN CLUSTERS

The results of the *Hipparcos* mission have recently appeared (European Space Agency 1997), and they provide unprecedented astrometric precision and accuracy for a very large sample of stars. Analyses of these results are just beginning, of course, but to us some of the most intriguing *Hipparcos* measurements are those of nearby open clusters, such as the Hyades, Pleiades, Praesepe, and α Persei.

Open clusters are critical laboratories for testing stellar evolution models, since they provide large samples of stars of a single age and composition (as near as we can tell, anyway) over a broad range of mass. Those models are calibrated against the Sun, the one star for which we know fundamental properties with very high accuracy. Thus, we construct stellar models, adjust them to match the Sun, and then test them against open clusters, because those clusters have near-solar composition, making it possible to work differentially. Having passed those tests, we have some confidence that the models can then be applied to significantly different conditions, such as globular clusters, that are vital for establishing the cosmic distance scale.

This paper and the companion paper by Pinsonneault et al. (1998; hereafter Paper I) are motivated by concern over the accuracy of the *Hipparcos* results. Nearly all the *Hipparcos* cluster distances disagree with conventionally determined values, although in most cases the differences do not conflict with the estimated uncertainties. But the Pleiades is an especially egregious case. The *Hipparcos* estimates of the Pleiades parallax range from 8.54 to 8.65 mas, depending on the solution used: Robichon gets 8.54 ± 0.22 (see Table XXVI of van Leeuwen 1997); Mermilliod et al. (1997) get 8.60 ± 0.24; van Leeuwen & Hansen Ruiz (1997) quote 8.61 ± 0.23 as their solution A (this value also appears in van Leeuwen & Evans 1997 and van Leeuwen 1997) and 8.65 ± 0.24 as their solution B. These correspond to a distance of about 116 pc, or a distance modulus of 5.33 mag. Traditional determinations of the cluster's distance (e.g., VandenBerg & Bridges 1984; Soderblom et al. 1993, hereafter SSHJ) are based on a comparison of the cluster's main sequence to that of nearby stars, which leads to a distance modulus of about 5.6. The same value of 5.6 has been derived by fitting a spectroscopic binary to isochrones (Giannuzzi 1995). Boesgaard & Friel (1990) show that the Pleiades has $[\mathrm{Fe/H}] = -0.034 \pm 0.024$, i.e., that it has essentially solar metallicity. Thus, the *Hipparcos* results suggest that Pleiades members are about 0.3 mag fainter than we have thought up to now. Can these different estimates be reconciled? Can a zero-age main-sequence (ZAMS) star with solar metallicity be 30% fainter than our current models predict? These are the essential questions that we address here.

The *Hipparcos* parallax of van Leeuwen & Hansen Ruiz (1997) is based on measurements of 54 Pleiades members, ranging in m_V from about 3 to 11, so it represents a good cross section of the cluster. *Hipparcos* observations are reduced to an absolute reference frame, but the measure-

[1] Based on data from the European Space Agency *Hipparcos* astrometry satellite.

ments are correlated within a limited region of the sky as the satellite swept out great circles. These correlated measures have been corrected for (van Leeuwen & Hansen Ruiz 1997) as part of the effort to reduce all the *Hipparcos* observations in a consistent and systematic way. Reconciling the *Hipparcos* distance with the traditional estimate would imply systematic errors larger than the quoted uncertainties. There is, therefore, no obvious reason to believe that the *Hipparcos* distance to the Pleiades contains a systematic error that is large enough to bring it into accord with the traditional distance.

The traditional distance measure appears, on the face of it, to be just as sound. It is based on the comparison of a Pleiades color-magnitude diagram (CMD), corrected for a small amount of reddening, to a CMD created from nearby stars with large parallaxes, or to a CMD of the Hyades suitably corrected for the difference in metallicity. Theoretical isochrones can also be converted to observational coordinates using a color calibration, and the offset between the isochrone and the cluster can be used to infer the distance modulus. This technique is used in Paper I and yields similar results. In this paper, we reexamine the comparison of the Pleiades to nearby stars. Our hypothesis is that the stars of the Pleiades cannot be completely unique in our Galaxy and that there must be nearby examples of stars that share the same unknown stellar physics or unusual parameters that result in the Pleiades stars being so faint. It should therefore be possible to find examples of anomalously faint ZAMS stars that are so close to the Sun that errors in parallax cannot account for their faintness. If no such stars exist, as we will show, then either we have failed to account for some fundamental aspects of stellar physics adequately, or there are unappreciated errors in the *Hipparcos* parallaxes.

2. AN OBSERVATIONAL ZAMS USING NEARBY SOLAR-TYPE STARS

We start by showing that nearby solar-type stars that are known to be young do not lie below the usual ZAMS. The idea of comparing a cluster main sequence to one constructed from nearby stars with large parallaxes is not new, but the nearby stars are of many ages and evolutionary states, which spreads the apparent main sequence considerably. The appropriate comparison, of course, is to very young nearby stars, since the clusters in questions are essentially ZAMS themselves.

In this case, by young we mean very active, as determined from observations of the Ca II H and K lines. Table 1 lists our sample. The northern stars have been observed as part of the Mount Wilson survey of chromospheric emission in late-type dwarfs (Vaughan & Preston 1980; Soderblom 1985; Soderblom & Mayor 1993), from which we have taken the R'_{HK} index of HK emission. To the extent that they have been measured, these stars have metallicities near solar (Cayrel de Strobel et al. 1992). The photometry of the northern stars is from Mermilliod & Mermilliod (1994). We divided these northern stars into two subsets. The first consists of the most active of the stars, those with $\log R'_{HK} > -4.40$, to which we added a few others that are slightly less active but so well studied that there is no ambiguity about their youth (HD 39587 = χ^1 Ori is an example). The second subset of northern stars is also active, but not as much so or not as well studied; these have $\log R'_{HK}$ values from -4.41 to -4.44. We have also included some southern stars from the HK survey of Henry et al. (1996) that have $\log R'_{HK}$ values from -4.20 to -4.40; that paper provides the photometry.

The parallaxes given in Table 1 are from *Hipparcos* (European Space Agency 1997). We kept only those stars with $\sigma_\pi/\pi \lesssim 0.1$, so that parallax error could not accidentally place a star significantly below the ZAMS. We also excluded stars with known companions unless we were confident that the companion is not influencing the HK observations or the photometry.

Our young stars are shown in Figure 1. The large filled circles represent the first subset; i.e., the stars most likely to be bona fide ZAMS objects. The small filled circles represent the other northern stars, and the open circles are the southern stars. The solid line shows a theoretical ZAMS from D. A. VandenBerg (1997, private communication). This has been calibrated to reproduce the solar temperature and luminosity (represented by the diamond) at the Sun's age, and to fit the M67 cluster main sequence at its age. The dashed line shows the ZAMS transformed to the CMD using the color-temperature relation of Bessell (1979). For reference, the long-dashed line shows the same ZAMS (for 100 Myr age and [Fe/H] = 0.0) used in Paper I. About half the difference between the VandenBerg and Paper I isochrones arises in the color-temperature relations used.

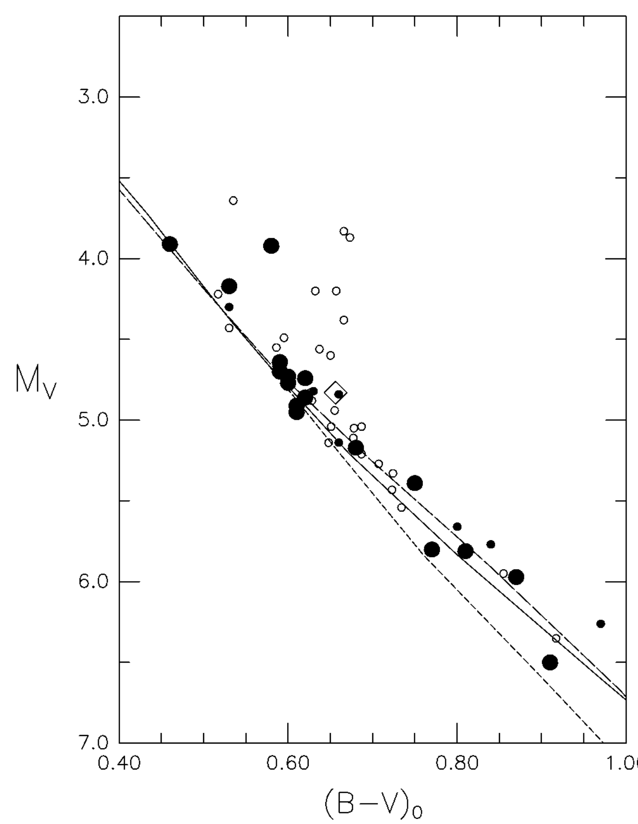

FIG. 1.—Absolute V magnitude vs. $B-V$ color for nearby young solar-type stars. Parallaxes are from the *Hipparcos* output catalog, while colors and magnitudes are from Mermilliod & Mermilliod (1994). The large filled circles represent stars with high levels of chromospheric activity, taken to represent the ZAMS. The smaller filled circles are also active stars, but less so. The open circles show active stars from the HK survey of Henry et al. (1996). The solid line shows a theoretical ZAMS from VandenBerg, calibrated as described in the text. The dashed line shows the same ZAMS, but using the color-temperature relation of Bessell (1979). The diamond shows the position of the Sun. For reference, the long-dashed line shows the ZAMS used in Paper I.

TABLE 1

ABSOLUTE MAGNITUDES AND COLORS OF ACTIVE SOLAR-TYPE STARS

HIP No.	HD No.	$(B-V)$	V	π (mas)	M_V	$\log R'_{HK}$
Most Active Stars						
544	166	0.75	6.10	72.98 ± 0.75	5.39	−4.33
8486	11131	0.61	6.75	43.47 ± 4.48	4.91	−4.44
13402	17925	0.87	6.04	96.33 ± 0.77	5.97	−4.30
25278	35296	0.53	4.99	68.19 ± 0.94	4.17	−4.38
27913	39587	0.59	4.40	115.43 ± 1.08	4.70	−4.44
28954	41593	0.81	6.76	64.71 ± 0.91	5.81	−4.42
42438	72905	0.62	5.63	70.07 ± 0.71	4.86	−4.33
46843	82443	0.77	7.00	56.35 ± 0.89	5.80	−4.20
54745	97334	0.60	6.40	46.04 ± 0.90	4.73	−4.40
62512	111456	0.46	5.85	41.39 ± 3.20	3.91	−4.43
64532	115043	0.60	6.83	38.92 ± 0.67	4.77	−4.43
64792	115383	0.58	5.21	55.71 ± 0.85	3.92	−4.33
71631	129333	0.61	7.54	29.46 ± 0.61	4.95	−4.23
73869	134319	0.68	8.42	22.59 ± 0.68	5.17	−4.33
88694	165185	0.62	5.94	57.58 ± 0.77	4.74	−4.39
92919	175742	0.91	8.08	46.64 ± 1.03	6.50	−4.21
107350	206860	0.59	5.94	54.37 ± 0.85	4.64	−4.42
Other Active Stars						
1803	1835	0.66	6.39	49.05 ± 0.91	4.84	−4.42
26779	37394	0.84	6.22	81.69 ± 0.83	5.77	−4.43
29525	42807	0.66	6.44	55.20 ± 0.96	5.14	−4.44
46580	82106	1.01	7.20	78.87 ± 1.02	6.68	−4.43
66704	119124	0.53	6.33	39.64 ± 0.71	4.30	−4.42
80337	147513	0.63	5.39	77.69 ± 0.86	4.82	−4.43
103859	200560	0.97	7.69	51.65 ± 0.72	6.26	−4.43
115331	220182	0.80	7.36	45.63 ± 0.83	5.66	−4.41
Southern Stars from Henry et al. (1996)						
490	105	0.595	7.51	24.85 ± 0.92	4.49	−4.36
14007	18809	0.677	8.47	21.21 ± 0.88	5.11	−4.33
26990	38397	0.586	8.18	19.17 ± 0.73	4.55	−4.26
28764	41700	0.517	6.35	37.46 ± 0.50	4.22	−4.35
30001	44135	0.632	8.14	16.29 ± 0.88	4.20	−4.33
36948	61005	0.734	8.20	28.95 ± 0.92	5.54	−4.26
36832	61033	0.724	7.59	35.27 ± 0.65	5.33	−4.34
37563	62850	0.637	7.20	30.07 ± 0.56	4.56	−4.30
42808	74576	0.917	6.56	89.78 ± 0.56	6.35	−4.31
43290	75519	0.651	7.98	27.71 ± 0.70	5.04	−4.37
59315	105690	0.707	8.18	26.43 ± 1.03	5.27	−4.27
63862	113553	0.678	7.90	22.11 ± 1.15	5.05	−4.30
66765	118972	0.855	6.93	64.08 ± 0.81	5.95	−4.39
69781	124784	0.650	8.77	15.36 ± 1.12	4.60	−4.23
78505	142033	0.657	8.00	17.22 ± 0.79	4.20	−4.35
82431	151598	0.673	8.23	13.42 ± 1.12	3.87	−4.40
95149	181321	0.628	6.48	47.95 ± 1.28	4.88	−4.31
96334	183414	0.648	7.92	28.22 ± 0.98	5.14	−4.23
98704	188480	0.535	8.22	12.05 ± 0.98	3.64	−4.35
98839	190102	0.626	8.18	21.56 ± 1.08	4.83	−4.39
99137	190422	0.530	6.25	43.08 ± 0.79	4.43	−4.38
101432	195521	0.666	6.80	25.48 ± 0.89	3.83	−4.31
105612	202732	0.687	7.88	29.21 ± 0.75	5.21	−4.40
105384	203019	0.687	7.84	27.49 ± 1.18	5.04	−4.36
105712	203244	0.723	6.97	140.88 ± 3.09	5.43	−4.39
113579	217343	0.655	7.48	31.22 ± 0.93	4.94	−4.27
117596	223537	0.666	8.03	18.64 ± 0.64	4.38	−4.36

Their zero-points are close (the VandenBerg isochrone is, on average, 0.04 mag fainter in the range of 0.5 to 0.9 in $B-V$), and there is a slight difference in the slopes of the main sequences. Differences in the color-temperature relations are a larger source of uncertainty for the cooler stars, as the increasing difference between the VandenBerg and Bessell lines indicates.

The theoretical isochrones are clearly an excellent representation of the observations. We anticipate finding stars above the ZAMS by modest amounts because they are photometric binaries, but we note that none of the young stars fall below the ZAMS. Thus, there is no hint in this small sample that there are any nearby young stars that are 0.3 mag below the usual ZAMS.

Figure 2 shows a similar CMD for the Pleiades, taken from SSHJ and corrected for reddening of 0.04 mag in $B-V$ and 0.12 mag in V. The lines in this figure are the same as in Figure 1, but displaced by 5.6 mag. This com-

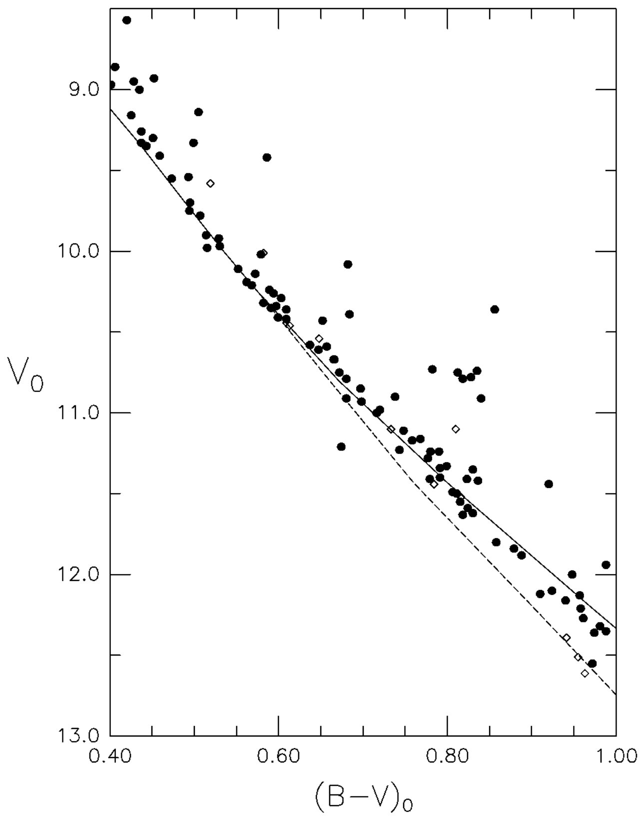

FIG. 2.—CMD for Pleiades solar-type stars. The derivation of the photometry is described in Soderblom et al. (1993) and is already corrected for reddening of 0.04 mag in $B-V$ and 0.12 mag in V. The lines are the same as in Fig. 1, but displaced by a distance modulus of 5.6 mag. The diamonds represent Pleiads that are ultrafast rotators, meaning stars with $v \sin i \geq 30$ km s^{-1}.

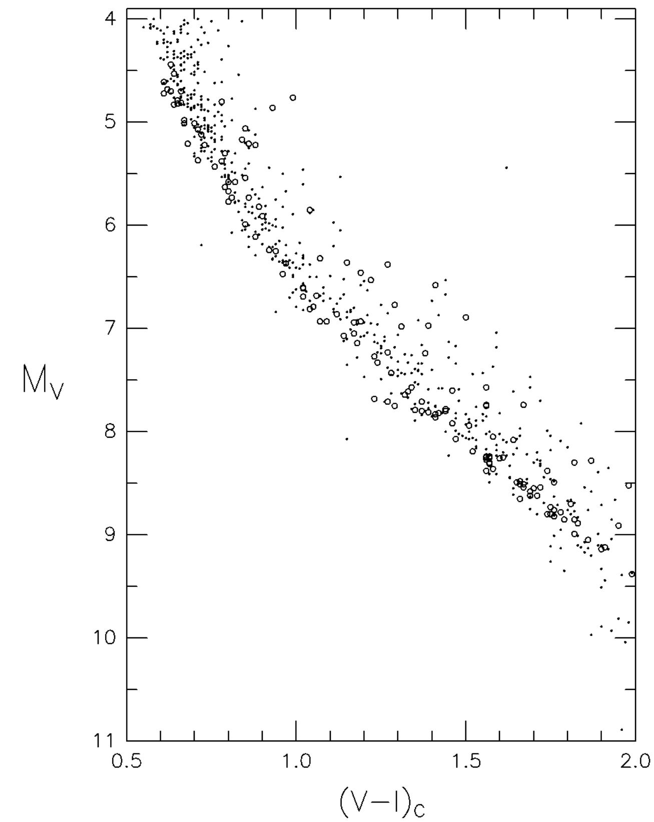

FIG. 3.—CMD for the Pleiades and for nearby stars, using Cousins $V-I$ colors. The colors and parallaxes for the nearby stars (*small filled circles*) are from the *Hipparcos* catalog, and we have used only those stars for which actual measured $V-I$ colors exist. The Pleiades photometry (*open circles*) is from Stauffer, and his Kron $V-I$ colors are transformed to Cousins colors using the Bessell & Weis (1987) relation. The Pleiades colors have been corrected by 0.06 mag for reddening. The Pleiades magnitudes assume a distance modulus of 5.6 and $A_V = 0.12$ mag.

parison shows that different isochrones can differ from one another and from the cluster by 0.1 mag or more for $B-V \gtrsim 0.7$. The Bessell relation is clearly too blue, while both the VandenBerg and Paper I isochrones are too red for $B-V \gtrsim 0.8$. Note, however, that these theoretical ZAMS lines deviate from the Pleiades in the same way that they deviate from the field stars of Figure 1, underscoring the comparability of the two samples.

To emphasize that the traditional distance to the Pleiades does not depend on assumptions of age, in Figure 3 we show a CMD for nearby stars and the Pleiades, for $(m-M) = 5.6$. The color used in Figure 3 is $V-I$ in the Cousins system, in order to have an index that is less sensitive to metallicity than $B-V$, and field stars of all ages are represented. The nearby star parallaxes and colors are from the *Hipparcos* Catalog, and we used only stars with measured $V-I$, excluding those where $V-I$ had been estimated from $B-V$ or other colors. The Pleiades data are from J. R. Stauffer (1997, private communication), who transformed his observations of Pleiads in the Kron $V-I$ color (Stauffer 1984) to Cousins $V-I$ using the relation of Bessell & Weis (1987), correcting for reddening in the process. The Pleiades V magnitudes have been shifted by 5.6 for distance and by 0.12 to correct for extinction. Both main sequences overlap for $V-I \lesssim 1.7$. The Pleiads redder than this depart from the field-star sequence simply because they are so young that they lie above the main sequence. There are essentially no nearby stars below the ZAMS defined by the Pleiades.

3. SUBLUMINOUS STARS

We have just shown that nearby young stars lie on or above the usually accepted ZAMS and that none lie below it. We now show that those stars that do lie below the ZAMS are old stars of low metallicity, not young stars analogous to Pleiads.

We began by extracting from the *Hipparcos* catalog all stars within 60 pc. We kept only those stars with $\sigma_\pi/\pi < 0.050$ and $\sigma(B-V) < 0.025$. The portion of these stars that lie below the ZAMS is shown in Figure 4. We observed six of these stars, which are shown by squares in Figure 4. We used the Hamilton spectrograph on the Lick 3 m Shane reflector, reducing the data in the usual way within IRAF (see SSHJ for details). The stars and the spectroscopic results are listed in Table 2. [Fe/H] was determined from the strength of the Fe I 6750 Å line in comparison to a solar spectrum of similarly high resolution. This is a small number of stars, due to poor observing conditions, but they were chosen randomly from the stars that lie about 0.3 mag below the ZAMS.

As we anticipated, most of these stars have unresolved rotation and subsolar metallicities, which accounts for their locations in the CMD. (Carney et al. 1994 show [Fe/H] = −0.61 for HIP 23431, in accord with our value.) There is one star, HIP 25127, that has obvious filling-in of the Hα line (Fig. 5). This star also has relatively strong Li,

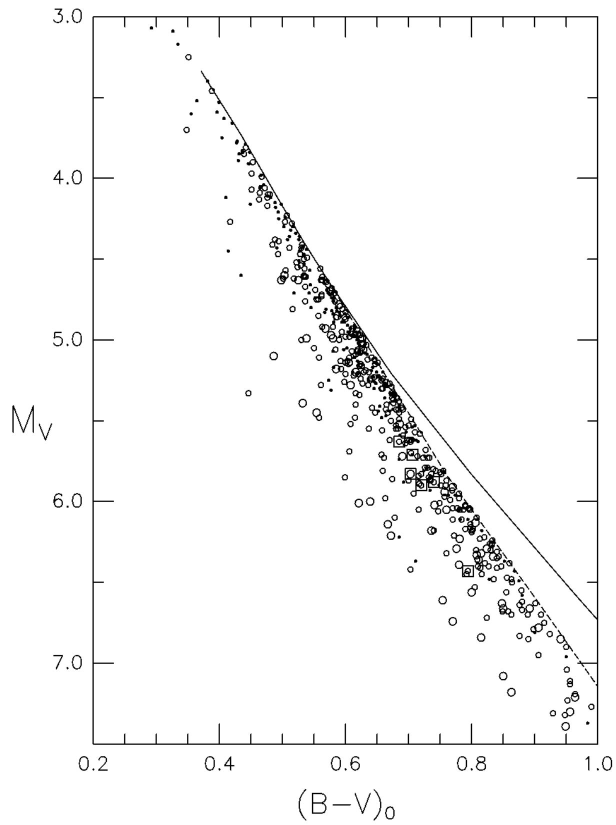

FIG. 4.—CMD for solar-type stars within 60 pc, with parallaxes good to 10% or better, and with $\sigma(B-V) < 0.05$ mag. Only those stars lying below the ZAMS are shown. The symbols denote different ranges of the transverse velocity (v_{trans}). Dots have $v_{trans} < 30$ km s^{-1}, small circles have v_{trans} from 30 to 100 km s^{-1}, and large circles denote $v_{trans} > 100$ km s^{-1}. The stars in squares were observed at high resolution and are listed in Table 2. The lines are the same as in Fig. 2.

the indicated equivalent width implying log N(Li) ≈ 2.35. We also estimate $v \sin i$ for HIP 25127 to be approximately 7 km s^{-1}, based on a comparison of line breadths in this star to others in the sample. All these factors suggest youth, but this star's position in the CMD is due to its low metallicity of -0.3, and so HIP 25127 validates models of ZAMS stars by confirming that low-metallicity stars appear to lie well below the solar-metallicity ZAMS, even if they may be young.

The symbols in Figure 4 indicate the transverse velocities of the subluminous stars, calculated from the *Hipparcos* proper motions and parallaxes. Small filled circles indicate $v_{trans} < 30$ km s^{-1} (the median velocity for all stars within 50 pc). Small open circles indicate $30 \leq v_{trans} < 100$ km s^{-1} (the 95th percentile), while the large open circles have transverse velocities that exceed 100 km s^{-1}. The scarcity of low-velocity stars and the higher velocities of the more subluminous stars strongly suggest that the objects in Figure 4 represent an old population, lying below the ZAMS because of low metallicity. The lack of subluminous stars with $B-V \lesssim 0.5$ also indicates an old population.

A more detailed examination of the kinematics of these stars requires radial velocities to provide the third dimension, and a more strictly limited sample to minimize the effects of observational errors. For this purpose, we extracted stars within 50 pc from the *Hipparcos* Catalog, accepting only those stars with $\sigma_\pi/\pi < 0.05$ and $\sigma(B-V) < 0.025$. Binaries and stars with other astrometric problems were rejected using flag H59 (European Space Agency 1997, Vol. 1, p. 126). This left a clean sample with 3345 stars. Of these, we found radial velocities in the *Hipparcos* Input Catalog for 1799, and these were used to calculate Galactic space motions U, V, and W. Correction to the local standard of rest (LSR) was done using the new solar motion $(U, V, W)_\odot^{LSR} = (+10, +5, +7)$ km s^{-1} from *Hipparcos* data (Dehnen & Binney 1997).

Figure 6 shows the $(U, V)_{LSR}$ and $(V, W)_{LSR}$ diagrams for these 1799 stars. The sample has been divided into 1598 stars lying on or above the ZAMS (*left panels*) and 201 stars falling 0.1 or more mag below the ZAMS (*right panels*). Table 3 summarizes the kinematic properties of these stars. The net range of velocities is roughly the same for both samples, but the ZAMS-and-above sample is highly concentrated near the LSR, and its core shows vertex deviation and clumpiness, which are characteristics of a young, low-velocity population. By contrast, these characteristics are completely absent in the diffuse velocity distribution of the

TABLE 2

SPECTROSCOPIC OBSERVATIONS OF SIX SUBLUMINOUS STARS

HIP No.	HD No.	$(B-V)$	V	π (mas)	M_V	W_λ(Li)	[Fe/H]	v_{trans}
7	...	0.740 ± 0.020	9.64	17.74 ± 1.30	5.88	≤3	−0.31	77
2128	...	0.703 ± 0.041	9.66	17.16 ± 1.47	5.83	≤3	−0.68	103
5697	7320	0.685 ± 0.003	8.95	21.71 ± 1.25	5.63	7	−0.50	47
7687	10166	0.794 ± 0.001	9.37	25.82 ± 1.56	6.43	≤3	−0.43	49
23431......	32237	0.720 ± 0.015	8.19	34.88 ± 1.46	5.90	≤3	−0.64	56
25127......	243086	0.706 ± 0.029	9.15	20.54 ± 1.22	5.71	94	−0.27	11

TABLE 3

KINEMATICS OF NEARBY STARS

Sample	N_{stars}	$\langle U_{LSR} \rangle$	$\langle V_{LSR} \rangle$	$\langle W_{LSR} \rangle$	$\sigma(U)$	$\sigma(V)$	$\sigma(W)$
All stars	1799	−2.3	−18.4	−1.1	40	31	19
>0.1 mag below ZAMS......	201	0.0	−26.4	−1.1	63	55	27
0.1 to 0.2 below ZAMS.......	63	−8.2	−18.0	+4.1	43	33	20
0.2 to 0.5 below ZAMS.......	108	−2.8	−18.4	−2.4	56	37	27
>0.5 below ZAMS	30	+27.4	−72.5	−7.6	104	104	38

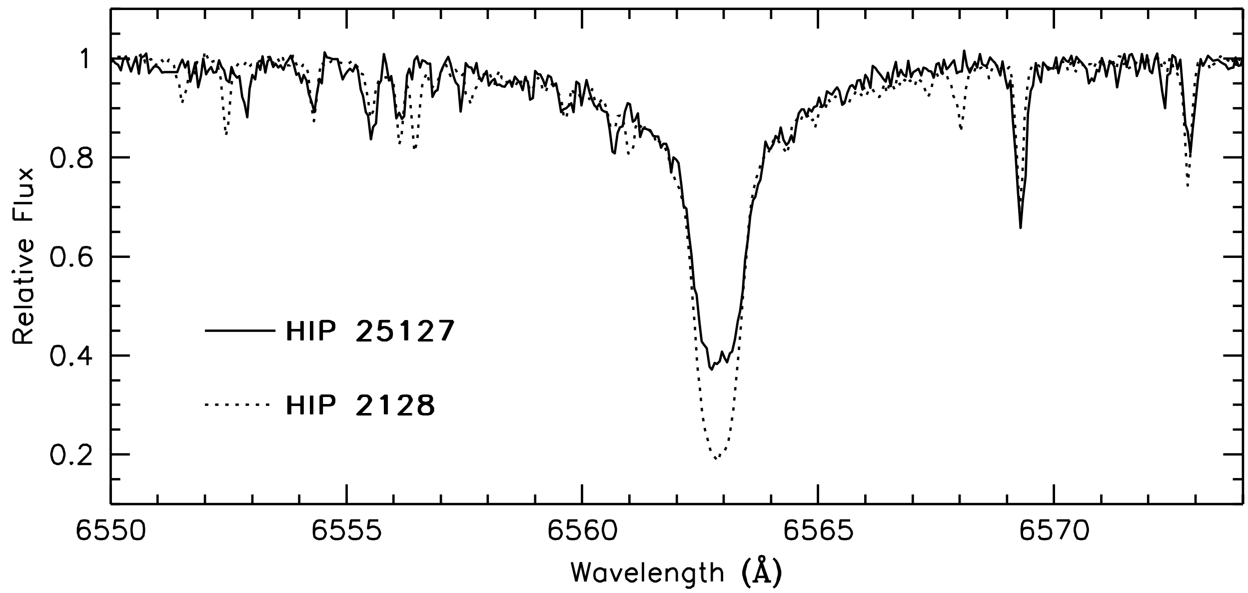

FIG. 5.—Hα profile of HIP 25217 compared to HIP 2128. HIP 2128 shows the usual deep Hα absorption profile of an old, inactive star, while HIP 25217 exhibits significant filling-in of Hα due to chromospheric activity. However, HIP 25217 has [Fe/H] ≈ −0.3.

subluminous stars. The conclusions to be drawn from Figure 6 and Table 3 are clear: the 201 stars that appear to lie below the ZAMS are dispersed in velocity space and chiefly represent the Galaxy's thick disk population, with a small admixture of halo stars. These stars are subluminous simply because this old population has metallicities substantially below solar.

It is still possible, of course, that some small fraction of these subluminous stars are, in fact, young. Such stars should have low space motions; to attempt to identify any young, subluminous stars, we selected 30 stars with $B-V < 1.2$ that lie within 1 σ of the LSR in all three coordinates. Ten of these stars, listed in Table 4, fall 0.2 mag or more below the ZAMS. We used SIMBAD to search for additional information that might indicate the ages of these 10 stars or reveal the reasons for their apparent subluminosity. As indicated in Table 4, most of these stars have low [Fe/H] or some other spectroscopic indication of old age (such as weak H and K emission or a low Li abundance). Two stars appear to have significant errors in their colors, including the only star of the 10 with any evidence of youth.

4. CONCLUSIONS

We have been unable to find any nearby stars with solar metallicity that are very young and below the traditional ZAMS, despite the *Hipparcos* results that suggest that the Pleiades stars are 0.3 mag fainter than that ZAMS. We have also shown that nearby stars that do lie below the ZAMS show evidence of old age, as expected.

This leaves two possibilities. The first is that the *Hipparcos* parallaxes for the Pleiades and other clusters are

TABLE 4

TEN LOW-VELOCITY SUBLUMINOUS STARS

HIP No.	HD No.	$(B-V)$	M_V	Spectral Type	Note
8275	10853	1.044	7.10 ± 0.07	K5	1
12184	16232	0.51	4.12 ± 0.09	F4 V	2
44984	78661	0.355	3.60 ± 0.07	F2p	3
56998	101581	1.064	7.28 ± 0.02	K5 V	4
58863	104828	1.072	7.35 ± 0.11	K0	5
68796	123710	0.590	5.00 ± 0.06	G5	6
80366	147776	0.950	6.73 ± 0.06	K2 V	7
81520	149612	0.616	5.33 ± 0.04	G3 V	8
106231	+22 4409	1.050	7.24 ± 0.06	K8	9
114790	219249	0.695	5.54 ± 0.07	G6 V	8

NOTES.—(1) Gliese 74, dK8; Gliese & Jahreiss 1991. Marginally subluminous. (2) *Hipparcos* $B-V$ error; SIMBAD lists $B-V = 0.51$, from Tolbert 1964. (3) [Fe/H] = −0.3; Cowley & Crawford 1971. (4) Gliese 435; Favata, Micela, & Sciortino 1997 note low Li. (5) Eggen 1985 lists this star as a member of his Hyades Supercluster, with $(m-M) = 2.82$, implying $M_V = 7.03$, which is 3 σ brighter than the *Hipparcos* M_V. (6) [Fe/H] = −0.58; Cayrel de Strobel et al. 1997. (7) Gliese 621. Eggen 1986 lists this star as a member of the 4 Gyr Wolf 630 Group. (8) Inactive star; Henry et al. 1996. (9) LO Peg; $P = 0.4$ day, $A = 0.09$ mag; European Space Agency 1997; *Hipparcos* color is discrepant with spectral type of K8 ($B-V \sim 1.2$). Sterzik & Schmitt 1997 note high X-ray flux and a strong Li feature, suggesting youth.

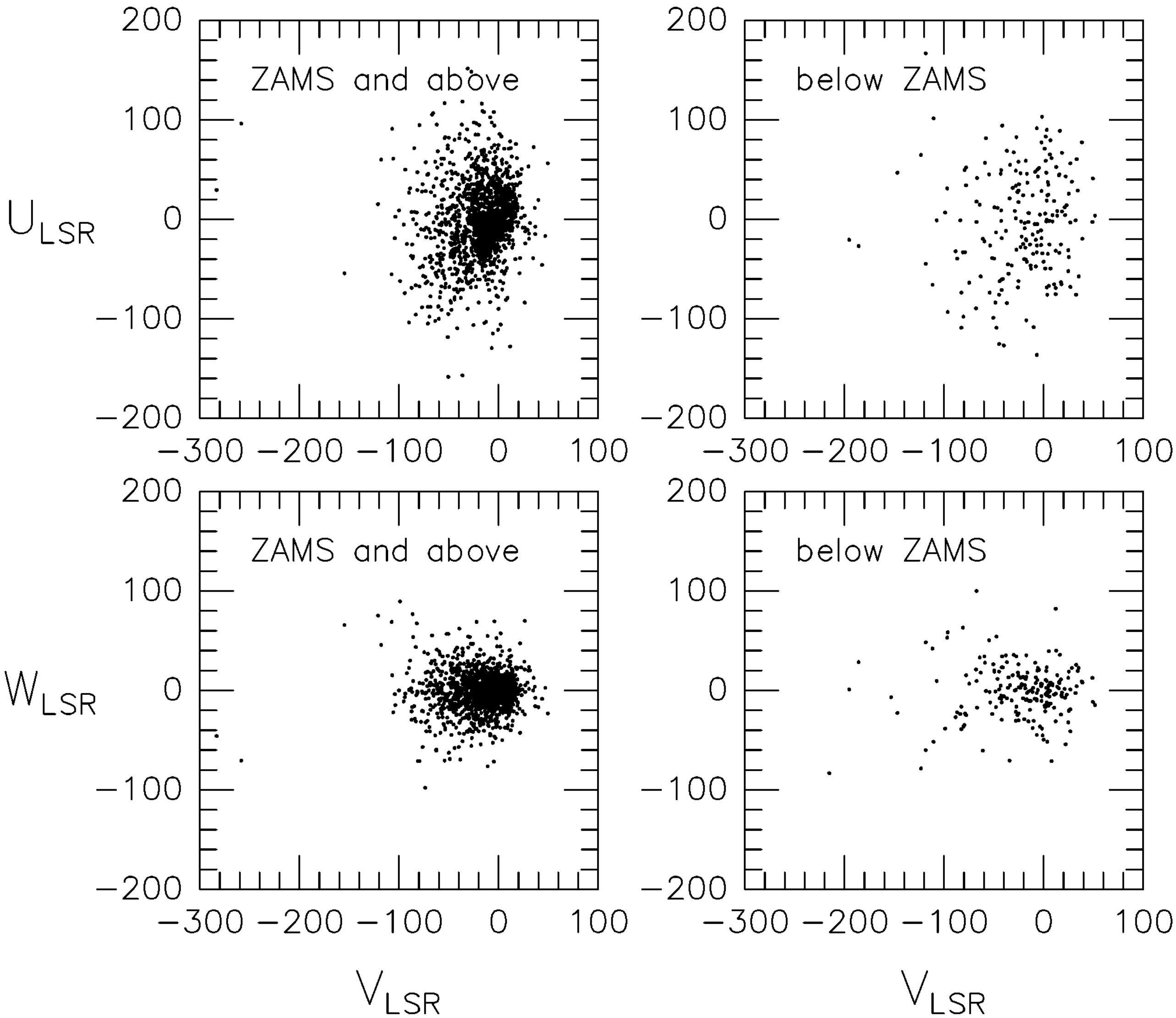

FIG. 6.—Galactic space motions for nearby stars ($d < 50$ pc). The starting sample was taken from the *Hipparcos* catalog and includes 3345 stars with $\sigma_\pi/\pi < 0.05$ and $\sigma(B-V) < 0.025$, with binaries and other problematic objects rejected. Radial velocities were available for 1799 stars from the *Hipparcos* Input Catalog, and those were used with the parallax and proper motions to calculate U, V, and W in a right-handed coordinate system. The motions have been corrected for solar motion relative to the local standard of rest. The left panels show the 1598 stars that lie on or above the ZAMS, while the right panels show the 201 stars that lie >0.1 mag below the ZAMS.

correct but that Pleiades-like stars are rare in the immediate solar neighborhood, or we have just been unlucky in finding them. Surveys of activity in nearby stars have been comprehensive enough to not have missed any significant number of genuinely young stars, and we cannot accept the ad hoc explanation that the Pleiades is simply bizarre. We should note here that Gatewood (1995) measured a parallax for the Coma cluster and found those stars to be subluminous to an extent similar to what is found for the Pleiades. However, Gatewood's result depends on only three stars in Coma, one of which had a particularly large uncertainty. Moreover, the proper motions of the two remaining stars differed significantly. Thus Gatewood's measurements are intriguing, but not sufficient to substantiate *Hipparcos*. (Gatewood's Coma results also differ from the traditional measures in a sense opposite to that seen by *Hipparcos*, meaning that they conflict with each other.)

If stars in the Pleiades are indeed 0.3 mag fainter than we have thought up to now, then there are significant aspects of stellar physics that have so far gone unappreciated. Paper I shows how difficult this notion is to accept, but if it is true, then we surely cannot trust our inferences of distances to the globular clusters if we cannot reproduce the behavior of stars that are nearly identical to the Sun.

The second possibility is that the *Hipparcos* parallaxes have small systematic errors. The correction needed to bring the *Hipparcos* Pleiades distance into agreement with the traditional value is almost exactly 1 mas. As shown in Paper I, the *Hipparcos* parallaxes of the brightest Pleiads in the core of the cluster are the most discrepant and weigh most heavily in the net cluster parallax, because of their low formal errors. For this reason, we suspect that the *Hipparcos* net parallax for the Pleiades is wrong.

The detection and measurement of visual binary orbits for Pleiades stars could provide an independent estimate of the cluster's distance. Such binaries would be difficult to observe, but are within the capabilities of the Fine Guidance Sensors on the *Hubble Space Telescope*, for example.

This work was supported in part by NASA grant NAGW-4837 to D. S. R. B. H. and B. F. J. acknowledge partial support from NASA grant NAG5-4830 and NSF grant AST 9530632. This research made use of the SIMBAD database, operated by the CDS, Strasbourg, France. We thank the anonymous referee for his or her remarks.

REFERENCES

Bessell, M. S. 1979, PASP, 91, 589
Bessell, M. S., & Weis, E. 1987, PASP, 99, 647
Boesgaard, A. M., & Friel, E. D. 1990, ApJ, 351, 467
Carney, B. W., Latham, D. W., Laird, J. B., & Aguilar, L. A. 1994, AJ, 107, 2240
Cayrel de Strobel, G., Hauck, B., François, P., Thévenin, F., Friel, E., Mermilliod, M., & Borde, S. 1992, A&AS, 95, 273
Cayrel de Strobel, G., Soubiran, C., Friel, E. D., Ralite, N., & François, P. 1997, A&AS, 124, 299
Cowley, A. P., & Crawford, D. L. 1971, PASP, 83, 297
Dehnen, W., & Binney, J. 1997, MNRAS, in press
Eggen, O. J. 1985, AJ, 90, 74
———. 1986, AJ, 92, 910
European Space Agency. 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200) (Paris: ESA)
Favata, F., Micela, G., & Sciortino, J. 1997, A&A, 322, 131
Gatewood, G. 1995, ApJ, 445, 712
Giannuzzi, M. A. 1995, A&A, 293, 360
Gliese, W., & Jahreiss, H. 1991, Third Catalogue of Nearby Stars (Heidelberg: Astron. Rechen Inst.)
Henry, T. J., Soderblom, D. R., Donahue, R. A., & Baliunas, S. L. 1996, AJ, 111, 439
Mermilliod, J.-C., & Mermilliod, M. 1994, Catalogue of Mean UBV Data on Stars (New York: Springer)
Mermilliod, J.-C., Turon, C., Robichon, N., Arenou, F., & Lebreton, Y. 1997, in Proc. ESA Symp., Hipparcos Venice '97, ed. M. A. C. Perryman (ESA SP-402) (Paris: ESA), 643
Pinsonneault, M., Stauffer, J. R., Soderblom, D. R., King, J. R., & Hanson, R. B. 1998, ApJ, this issue (Paper I)
Soderblom, D. R. 1985, AJ, 90, 2103
Soderblom, D. R., & Mayor, M. 1993, AJ, 105, 226
Soderblom, D. R., Stauffer, J. R., Hudon, J. D., & Jones, B. F. 1993, ApJS, 85, 315 (SSHJ)
Stauffer, J. R. 1984, ApJ, 280, 189
Sterzik, M. F., & Schmitt, J. H. M. M. 1997, AJ, 114, 1673
Tolbert, C. R. 1964, ApJ, 139, 1105
VandenBerg, D. A., & Bridges, T. J. 1984, ApJ, 278, 679
van Leeuwen, F. 1997, Space Sci. Rev., in press
van Leeuwen, F., & Evans, D. W. 1997, A&AS, in press
van Leeuwen, F., & Hansen Ruiz, C. S. 1997, Proc. ESA Symp., Hipparcos Venice '97, ed. M. A. C. Perryman (ESA SP-402) (Paris: ESA), 689
Vaughan, A. H., & Preston, G. W. 1980, PASP, 92, 385