CCD PHOTOMETRY OF OPEN CLUSTERS

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ABSTRACT. CCD photometry of globular clusters is a vigorous field, and it is clear from even a casual perusal of the literature in that field that accurate photometry from CCD's has greatly contributed to our understanding of globular clusters. On the other hand, much of the excitement in open cluster research centers on spectroscopy (vsini's, lithium abundances, chromospheric activity, etc.). However, there is is an important role for accurate photometry in open clusters also. I will review a few of the exciting current activities involving photometry in open clusters, and in particular will emphasize programs which are still in progress or which have not yet reached the stage of formal publication.

1. Introduction

Open cluster photometry using electronic detectors dates back at least to 1957, and thus this general topic of open cluster research is now marking its 40th anniversary. It is still a very active field, however. In this review, I intend to concentrate on three areas where accurate photometry of open cluster stars is providing important contributions to our understanding of stellar structure and evolution. These three areas are: (1) color-magnitude diagrams and cluster ages and distances, particularly with respect to the open cluster distance estimates provided by the Hipparcos satellite; (2) time series photometry of low mass stars in young clusters to identify spotted stars and determine their rotational periods and light-curve shapes; and (3) the use of CCD-mosaic cameras to extend the determination of the initial mass function to very low mass stars and to search for brown dwarfs in young open clusters.

2. Open Cluster Distances - Main Sequence Fitting or Hipparcos Parallaxes

Just a few days prior to our meeting this week in Palermo, The European Space Agency hosted another meeting in Venice where the initial results from the Hipparcos satellite were discussed. One of the most heavily publicized sets of papers dealt with open clusters. Mermilliod et al. (1997), Perryman et al. (1997), Robichon et al. (1997) and van Leeuwen and Ruiz (1997) presented the Hipparcos parallaxes for $\sim$12 open clusters. The Hyades was by far the best-studied cluster, with $\sim$200 cluster members having parallaxes measured by Hipparcos; for the other clusters, the number of stars observed ranged from 7 to 51. The derived mean cluster distances were disturbing in the sense that they often disagreed with the pre-Hipparcos distances by amounts that were larger than could be easily explained away. If the errors in either or both the Hipparcos distances or the previously published cluster distances have not been underestimated, then there are serious and unexplained problems with the interpretation of color-magnitude diagrams for clusters (both open and globular). Because this has such potentially far-reaching implications, I will devote much of my time here to summarizing some of the material presented in Venice; for more details, see the papers referenced above.

Except for the Hyades, open clusters are too distance to derive useful parallaxes using existing ground-based telescopes. Therefore, with only a few exceptions, the traditional distances normally quoted for open clusters are derived from main-sequence fitting. By definition, the cluster main-sequences are thus "aligned" when one plots absolute magnitude versus reddening corrected color, except for metallicity effects. To derive accurate distances in this manner, it is necessary to have good photometry (with both small random errors and small systematic errors), accurate reddening corrections, and accurate metallicities. The photometry must extend faint enough to cover the portion of the cluster color-magnitude diagram where stars are still essentially on the ZAMS. An additional requirement is a zero-point for the distance scale. This is usually provided by the Hyades, which is near enough to allow other distance determination techniques to work - for example, the moving cluster method (Gunn et al. 1988). Alternatively, the zero-point can be set by constructing a field star color-magnitude diagram using only stars with accurate parallaxes and appropriate photometry. A slightly subjective listing of the "traditional" distances, reddenings and metallicities is provided in Table 1 for the clusters for which there are Hipparcos parallaxes for at least 10 cluster members.

By contrast, the Hipparcos satellite measured direct parallaxes for a sample of members for 12 nearby open clusters. One difficulty with this was that Hipparcos could only determine parallaxes for a limited number of stars in a given area of the sky. Only the Hyades was near enough - and thus dispersed enough over the sky - so that a large sample of the cluster members ($\sim$200 stars) could be measured by Hipparcos. It is also true only for the Hyades that the individual parallaxes are large enough so that useful distances to individual stars cold be determined ($\pi/\sigma_\pi \sim$25). For all of the other clusters, $\pi/\sigma_\pi \sim$5-10, resulting in errors in M_V or M_I of 0.2 to 0.4 mag (or larger). However, by combining the parallaxes for the entire sample of stars observed in each cluster, the error in the derived mean distance to the cluster could be reduced to less than 5% for several of the clusters. The derived distances, their errors, and the number of stars used for the Hipparcos open cluster program are also listed in Table 1.

Tab. 1 - Open Clusters with Hipparcos Distance Estimates

Cluster	Standard Distance	[Fe/H]	E(B-V)	Age	Hipp. Distance	N(Hipp.)
Hyades	47.5	0.14	0.00	600	46.3	190
Pleiades	127	0.00	0.04	100	116 $\pm$ 3	51
Alpha Per	159	0.00	0.10	50	184 $\pm$ 8	32
Praesepe	162	0.07	0.00	800	177 $\pm$ 10	24
IC2602	155	0.	0.02	35	147 $\pm$ 5	13
Blanco 1	250	0.03	0.02	50	252 $\pm$ 30	11
NGC 2516	370	-0.3	0.12	100	348 $\pm$ 25	15
NGC 6475	250	0.11	0.06	220	291 $\pm$ 25	21
Coma Ber	80	-0.05	0.00	450	88 $\pm$ 2	26

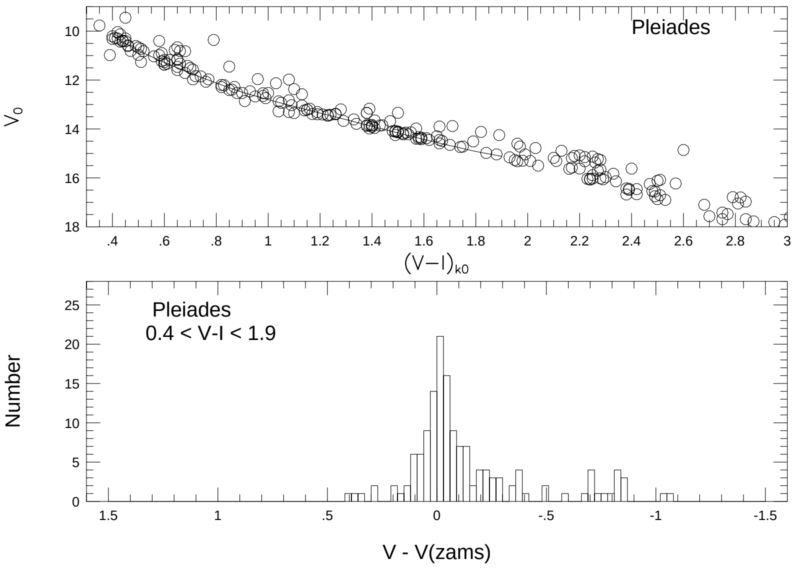

Fig. 1. Color-magnitude diagram for the Pleiades derived from data in Stauffer (1984) and references therein, and a histogram of the displacement of these stars relative to the empirical main-sequence curve shown in the figure. The binsize for the histogram is 0.03 mag.

A first reaction to Table 1 might be that things don't look too bad. That is, the MS fitting distances are in some cases essentially equal to the Hipparcos distances, and the worst-case difference is only about 15%. For only three of the clusters is the difference between the Hipparcos and MS-fitting distance more than twice the estimated RMS uncertainty of the Hipparcos distance. For most kinds of astronomy, a 15% uncertainty in any quantity would correspond to a high accuracy measurement. However, in this case, disagreement at that level is in fact unexpected. That is because the ability to determine relative distances between two clusters by the main-sequence fitting technique is in principle much more accurate than that. For two nearby, rich clusters, one should be able to determine the relative differential distance modulus to 0.05 mag (or about 2.5% in distance). This is illustrated in Figure 1, which shows a CM diagram for the Pleiades and a histogram of the vertical displacement of the stars in the figure relative to a ZAMS curve fit to the lower envelope. The figure illustrates that for a well-populated nearby cluster with little reddening and good photometry, one should be able to define the location of the main sequence to 0.05 mag or better.

A graphic illustration of the problem posed by the Hipparcos cluster distances is shown in Figure 2, where stars in the Pleiades and Alpha Persei clusters are plotted

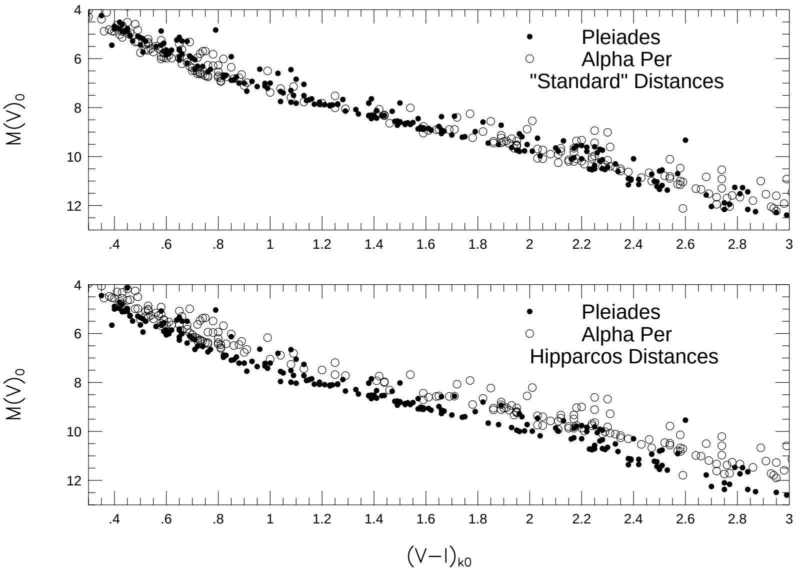

Fig. 2. HR diagrams for the Pleiades and Alpha Persei clusters using distance moduli from main-sequence fitting (top) or from the Hipparcos parallaxes (bottom).

together in an HR diagram, using first the main-sequence fitting distances and then the Hipparcos distances. The two clusters are nearly the same age, and both are essentially solar metallicity, so one would expect the two main sequence loci to be coincident (except for the lowest mass stars - Alpha Persei is slightly younger than the Pleiades, and so one would expect to see the locus of Alpha Per stars slightly above the Pleiades locus for the faintest stars).

Clearly, using the Hipparcos distances for the Pleiades and Alpha Per results in an apparently discrepant result when one plots absolute magnitude vs. color. Qualitatively the same sort of displacement exists when comparing several of the other clusters in Table 1. Are there any “benign” explanations for this? Possibilities might include: improperly calibrated photometry; errors in the calculated reddening; errors in the metallicity; or some combination of the three. At least individually, I do not believe those explanations are viable. Concerning the photometry, the main point is that for most of these well-studied clusters it is not a question of any one study or any one photometric system - most of these clusters have photometry available in several different photometric systems. Often, the same author or group has studied several of the clusters, thus making it likely that at least internally they do not have significant systematic errors in the photometry. Robichon et al. (1997) and Mermilliod et al. (1997) have shown that the displacement in the color-magnitude diagrams is essentially independent of what photometric system is used (both qualitatively and quantitatively). Similarly, the reddening estimates for the better known clusters in Table 1 have usually been determined in several ways, and using stars with spectral types from A to M, and the results are usually in very good agreement ($<$ 0.05 mag in A_V). Metallicities are not as well-determined, but even in that case there are often several determinations and the qualitative ordering by metallicity for the clusters in Table 1 is well-established (except possibly for Blanco 1 and perhaps NGC2516). The difference between the MS-fitting distance and the Hipparcos distance does not correlate well with metallicity, thus suggesting that metallicity is not a big contributor to these problems. Nissen (1988) has reported a somewhat similar problem in the interpretation of Stromgren photometry data for several of the Hipparcos clusters (often referred to as "the Hyades anomaly" although several clusters appeared to have the affliction). However, the Pleiades and Alpha Per both appear normal according to the Stromgren photometry, and thus the "Hyades anomaly" and the Hipparcos anomaly are not synonymous.

There do not seem to be any simple explanations of the problem when one looks at the photometric and spectroscopic data. A final possibility would then be to question the Hipparcos parallaxes (or the error bars attached to the cluster distances). Most of these clusters have distances of order 150 pc, and therefore the individual parallaxes are only of order 7 milli-arcsec (compared to the standard one-sigma accuracy for Hipparcos measurements of order 1 milli-arcsec). Because of the method whereby Hipparcos scanned the sky, stars in a given small region of the sky can have correlated errors and thus it would be possible that even though many stars go into the mean parallax for a given cluster the errors might not cancel out and there could be position-dependent systematic errors in the cluster parallaxes. However, this effect was well-known to the groups that derived the Hipparcos open cluster parallaxes, and they employed a special analysis technique to minimize the effect. The error bars on the Hipparcos cluster distances in Table 1 are meant to include these possible systematic effects.

If one excludes the easy explanations, are there other possibilities? Two were mentioned in Venice. One suggestion was that the shifts are due to cluster to cluster metallicity differences, and thus that (a) there are errors in the accepted mean cluster metallicities (since the displacements do not correlate strongly with the adopted metallicities) and (b) the effect of metallicity variations is larger than predicted (since with standard models the small metallicity variations indicated in Table 1 would not lead to shifts in the HR diagram as large as needed). Even if these two assumptions were correct, it is unlikely that the shifts in the main sequence loci would be so nearly independent of stellar mass and so independent of the color index in use (as empirically seems to be the case). A second suggestion was that there are large helium differences between the clusters (not necessarily correlated with metallicity). However, to explain the required variations in helium abundance (assuming standard models) are huge - e.g. a helium abundance for the Pleiades of $Y = 0.36$ would be required (compared to $Y = 0.26$ for a standard solar model).

Determining what is going on with the Hipparcos open cluster distances has ramifications far beyond just this arena. If the Hipparcos distances are correct, it suggests that any distance derived from main sequence fitting or by use of a simple main-sequence relation has potential errors of 10-20%. This could include distances to globular clusters, and hence might affect age estimates for them (and hence the estimated age of the universe).

There are no easy answers to this question - and the resolution of the puzzle is still unsolved. However, it should be clear that a large database of accurate open cluster photometry is a necessary facet of any empirical test of the Hipparcos data.

3. Photometric Monitoring Programs

The primary technology used to determine the rotational velocity distribution of low mass stars in open clusters has been high resolution spectroscopy. However, such spectroscopy provides only upper limits to the rotational velocities of the slowest rotators and has the inherent limitation of providing only the projected rotational velocity (i.e. $v \sin i$). For young open clusters, photometric monitoring programs can provide rotation periods, thus avoiding the sini bias; with effort, such programs can determine periods even for slow rotators (thus removing uncertainties associated with including upper limits in the rotational velocity distributions). Obtaining such rotation periods is currently a very active field of endeavor - the number of clusters with good, published rotation period data will soon double and soon there will be more than a half dozen clusters with >50 low mass stars with known rotation periods. Due to lack of space, I will just mention several of the projects and their probable results.

S. Barnes (Yale/Lowell Obs.) has obtained data for several southern clusters, including NGC3532, IC2602, NGC2516, NGC2451 and Blanco 1 with good time and phase coverage. For NGC3532, he has determined periods for 50 low mass members; he has a similar photometry database for the other clusters. K. Stassun (Wisconsin) has 10-14 days of data (with approx. one hour sampling) for 4700 stars in Orion, which could potentially yield hundreds of periods for these PMS stars. B. Patten and S. Strom have a similar database for PMS stars in NGC2264. A. Krishnamurthi, S. Allain, C. Prosser and C. Grankin have obtained new periods for low mass stars in the Alpha Persei and Pleiades clusters, approximately doubling the number of periods compared to that available until now (and providing periods for a number of the stars with only $v \sin i$ upper limits).

In combination with the high resolution spectroscopic programs, the photometric periods should allow, for example, a much improved determination of the dependence of light-curve amplitude on rotation period (as a function of stellar mass), better constraints on the required distribution of PMS disk lifetimes, a better determination of the functional dependence of stellar activity indices on rotation rate, etc.

4. Mosaic CCD Cameras and Brown Dwarf Surveys

Prior to $\sim$1995, if one wanted to do large-area imaging surveys (many square degrees), the only practical choice was to use photographic plates. The low quantum efficiency of these plates limited such surveys to moderately bright objects by current standards. However, that situation has now changed in two ways. First, Hawkins (1997) has demonstrated that by digitally stacking large numbers of photographic plates of the same field, one can reach quite faint magnitudes over large areas. Second, and more to the point for this review, CCD mosaic cameras have begun to be available on a variety of telescopes and these are now allowing - or will soon allow - large area deep surveys to be conducted. The proliferation of these cameras and their availability on modest-sized dedicated telescopes as well as large telescopes will also make it possible to conduct photometric monitoring programs not possible with single-CCD cameras (e.g. the microlensing surveys of the LMC and galactic bulge).

Table 3 provides a list of the CCD mosaic cameras of which I am aware. Most of these are already in operation; the rest are expected to be available within the next year. I have not listed the telescopes being used for microlensing surveys nor the Sloan Digital Sky Survey telescope on the assumption that these telescopes are mostly unavailable for "guest observer" type programs.

Tab. 3 - Operational CCD Mosaic Cameras

Telescope	Number of Pixels	FOV
CFHT	96,000,000	42 x 28 arcmin
CTIO 4m (BTC)	16,000,000	29 x 29 arcmin
KPNO 4m	64,000,000	36 x 36 arcmin
KPNO 0.9m	64,000,000	59 x 59 arcmin
CIDA 1m Schmidt	64,000,000	132 x 132 arcmin
USNO 1.3 m	24,000,000	78 x 60 arcmin

The mosaic CCD cameras on 4m class telescopes are particularly useful for deep imaging surveys in order to identify brown dwarfs in young open clusters. Several of us have recently used the UH 8Kx8K mosaic CCD camera to make a survey of 2.5 square degrees of the Pleiades to a limit faint enough to detect Pleiades members to 0.04 solar masses. Figure 3 shows the CM diagram for this survey (Bouvier et al. 1997). The hydrogen burning mass limit at Pleiades age is I $\sim$ 17.8; our survey should be nearly complete to approximately three magnitudes fainter than that. The large filled circles are the proposed Pleiades members, of which we believe the faintest $\sim$17 should be both Pleiades members and brown dwarfs. Because we have surveyed a significant fraction of the cluster (of order 10%), we can relatively accurately determine the IMF of the Pleiades to below the hydrogen burning mass limit (it is rising, but slowly) and we can estimate the fraction of the total mass of the Pleiades tied up in brown dwarfs ($\leq$ 2%). By conducting similar surveys of other open clusters of different ages, it should be possible to eventually determine evolutionary tracks for young brown dwarfs.

Acknowledgements

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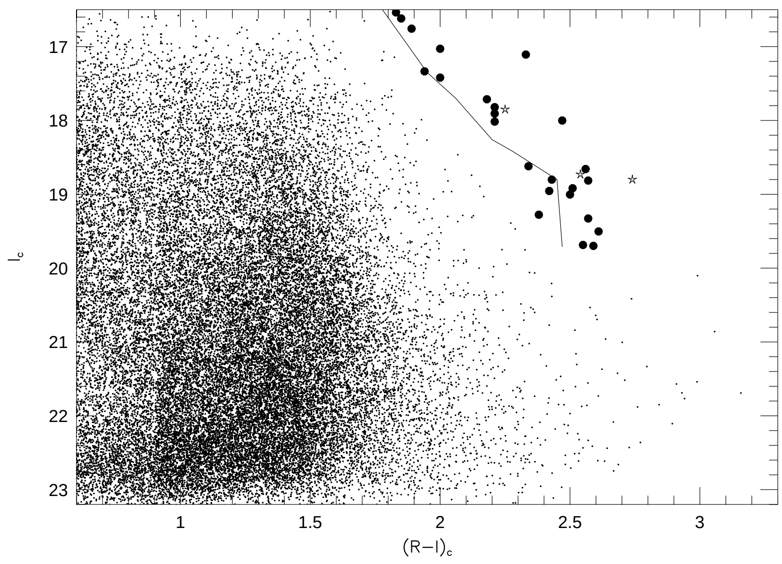

Fig. 3. Color-magnitude diagram for a 2.5 sq. degree region of the Pleiades derived from deep images obtained with the CFHT. The curved line is an empirical ZAMS, the large filled dots are the proposed Pleiades members, and the three five-pointed stars are objects "confirmed" as Pleiades brown dwarfs from lithium spectroscopy.

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