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The WIYN open cluster study: A new color-magnitude diagram for M35 - a twin of the Pleiades?

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Abstract. M35 (NGC 2168) is rich, young, and in some regards a better laboratory for stellar cluster research at 100 million years than the Pleiades. Yet, while M35 has been the subject of intriguing photometric, astrometric, and theoretical studies, to the best of our knowledge no published CCD-based photometry exists for this cluster. We have obtained relatively wide-field (23' ×23') precise UBVRI CCD photometry for M35 as part of the WIYN Open Cluster Study (WOCS) at the 0.9m telescope at Kitt Peak National Observatory. The photometry extends from the main sequence turn off to beyond V = 19. We find that M35 is ∼ 100 Myrs old, with $(m\text{-}M)_V = 10.25$, and E(B-V)=0.3 based on fitting Yale isochrones. We also perform a differential comparison between M35 and the Pleiades, and we explore the cluster dynamical state.

1. Introduction

M35 has drawn attention because of its richness and an age similar to the Pleiades. While a number of astrometric studies have been done of this cluster (McNamara & Sekiguchi 1986a, Cudworth 1971, Ebbighausen 1942) modern photometric studies are limited to the work of Sung & Lee (1992). Sung & Lee obtained photoelectric UBV photometry of 112 field plus cluster stars to V=14, approximately the same limiting magnitude as the two more recent proper motion studies. Sung & Lee derived a true distance modulus of 9.3, an age of 85 Myr, and internal differential reddening of $0.26 \leq E(B\text{-}V) \leq 0.44$. The differential reddening and a population of cluster binaries cause a spread in the cluster main sequence (see Fig. 1). Reimers & Koester (1988) derived a cluster age of 70 to 100 Myrs based on a reanalysis of older photometry and on the cooling age of two cluster white dwarfs. The cluster metallicity is unknown. Leonard & Merritt (1989) performed a dynamical analysis and found M35 is close to dynamical equilibrium, its dynamical mass within the central 3.75 pc is 1600 to 3200 $M_\odot$ (95% confidence), and its IMF slope is 2.7 ± 0.4 between 1 and

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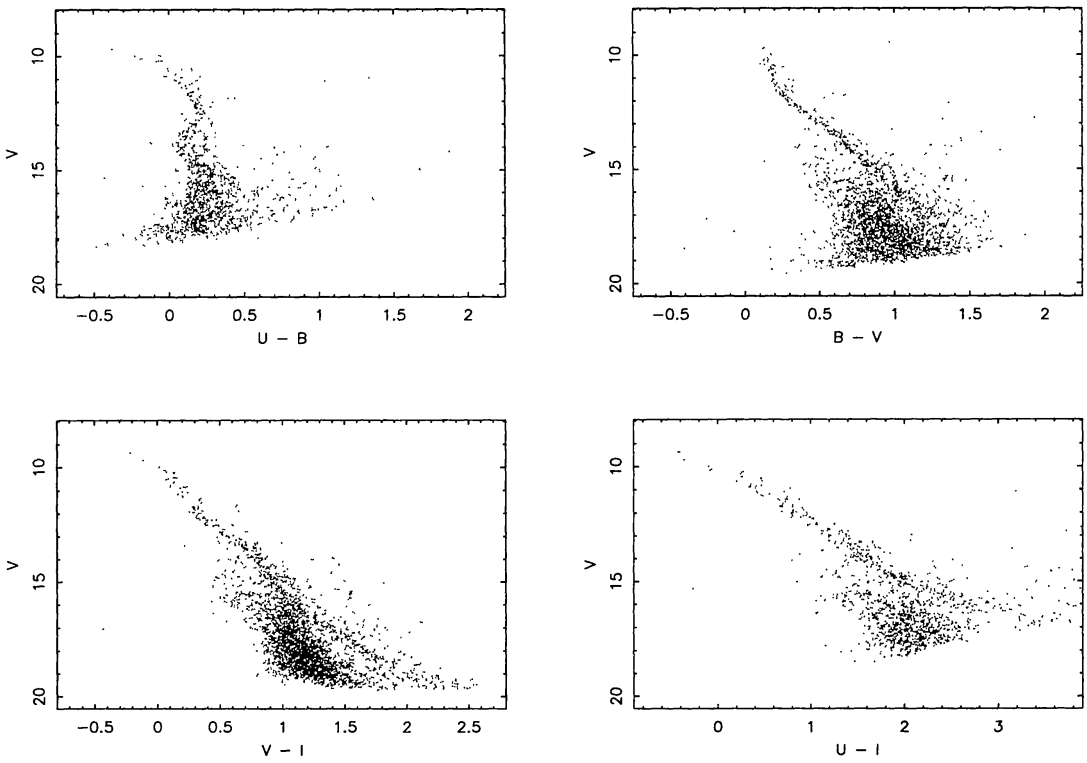

Figure 1. The calibrated CMDs for M35. From top left to bottom right the four panels display the U-B, B-V, V-I, and U-I CMDs. Our observations trace the cluster main sequence as deep as V $\sim$ 18 in the V-I CMD, $\sim$ 4 magnitudes fainter than previous work.

6 $M_{\odot}$. Mathieu (1983) and McNamara & Sekiguchi (1986b) noted that M35 exhibits mass segregation, though it is unclear whether this is due to relaxation or initial conditions. Mathieu (1983) further noted that the cluster age is close to the expected relaxation time of the intermediate mass component, though the relaxation timescale is uncertain by a factor of $\sim$ 2.

In summary, past observations of M35 demonstrate that it is nearby and massive (e.g. rich) with great potential for stellar evolution and cluster dynamical studies at $\sim$ 100 Myr. While the Pleiades is the standard bearer at this age, M35 has the distinct advantage of being at a distance more appropriate for both CCD photometry and multi-fiber spectroscopy.

2. Observations and reductions

The observations were made at the Kitt Peak National Observatory's 0.9m telescope using the T2KA CCD. The T2KA is a 2048^2 pixel device with 0.68″ pixels, yielding a field of view of 23 × 23 square arc minutes. A single set of observations totaling 100, 30, 20, 15, and 40 seconds in UBVRI are presented here. M35 is larger than the T2KA field of view but the cluster was approximately centered on the CCD. Standard reductions, aperture photometry, and photometric calibrations were performed using IRAF.

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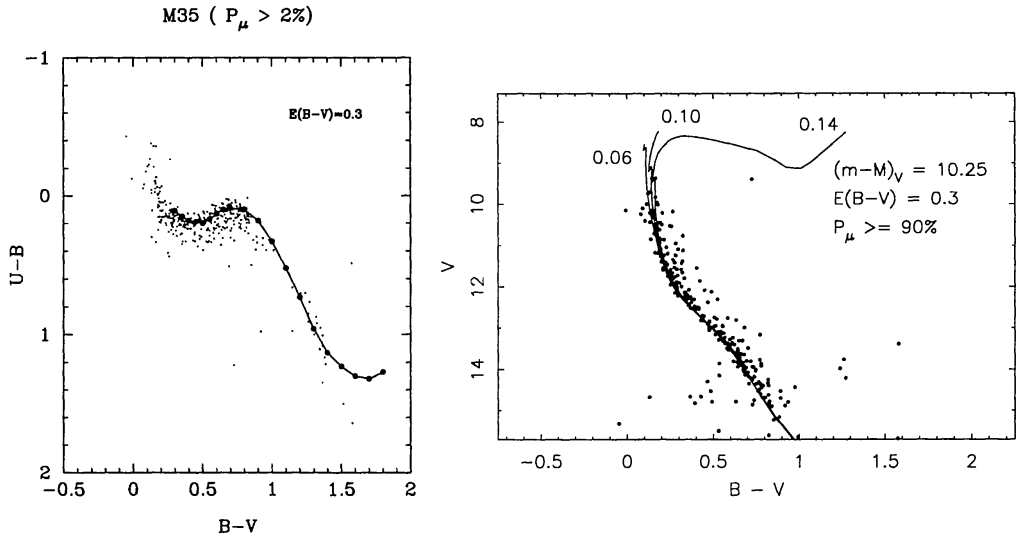

Figure 2. The left panel displays the UBV two color diagram for cluster stars with proper motion membership probabilities $\geq$ 2% and with the Hyades fiducial sequence superimposed. The fit gives E(B-V)=0.3. We find from the two color diagram and from our isochrone fits to the lower main sequence that the cluster metallicity is $\sim$ 50% solar. The right panel displays the cluster CMD for stars with membership probabilities, P $\geq$ 90%. The overplotted Yale isochrones are for ages 0.06, 0.10, and 0.14 Gyrs. In this data subset the turn-off is poorly defined, but the cluster is clearly young, with an age in the range of 100 Myrs.

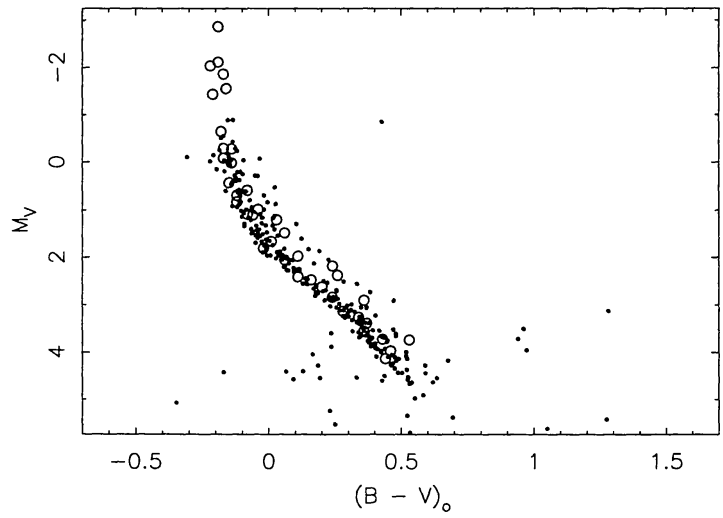

Figure 3. A differential comparison between M35 members (P $\geq$ 90%) and the Pleiades. The Pleiades data of Erro (1969) are plotted as "o" symbols. We employ $(m-M)_V = 5.74$ for the Pleiades and 10.25 for M35, and E(B-V)=0.1 for the Pleiades and 0.3 for M35. Photometric binaries are apparent in both clusters. The differential comparison indicates that M35 is somewhat older than the Pleiades.

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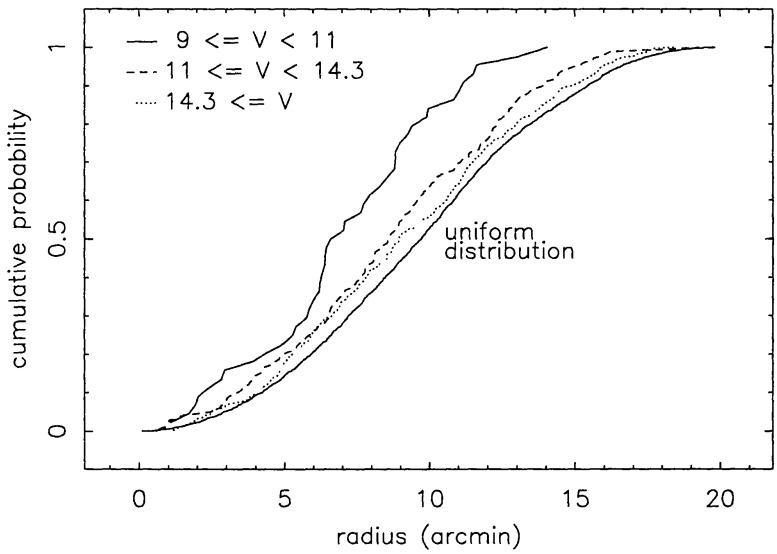

Figure 4. The radial distribution of M35 stars with $4 \geq M/M_{\odot} \geq 2$ ($9.25 \leq$ V < 11), $2 \geq M/M_{\odot} \geq 1$ ($11 \leq$ V < 14.3), $1 \geq M/M_{\odot} \geq 0.55$ ($14.3 \leq$ V ≤ 19), and a hypothetical uniform distribution. In order to include the faintest cluster members, stars were selected by color rather than proper motion. This process selected effectively against field stars in the brighter two magnitude ranges only. KS tests indicate that the V=9-11 distribution is different from the V=11-14.3 distribution at the 94.7% level, from the V>14.3 distribution at the 99.7% level, and from the uniform distribution at the 99.9% level. The V=11-14.3 distribution differs from the V>14.3 distribution at the 64.5% level and from the uniform distribution at the 97.1% level. The V>14.3 distribution is different from the uniform distribution at the 89.8% level. The cluster radial profile is evident (the distributions are non-uniform). The massive stars are more centrally concentrated than the intermediate mass stars. Whether mass segregation continues to the lowest mass stars in unclear.

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