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Low Mass Stars and Brown Dwarfs in Cepheus OB3

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Abstract.

An initial analysis suggests a surprising dearth of stars below the hydrogen burning threshold in the young unbound OB association, Cepheus OB3b. Evidence has been collected from two deep imaging surveys, covering 1.12 square degrees in the optical (RI_cZ) bands, and 0.13 square degrees in the near infra-red (JHK_s). The limiting magnitudes are approximately 23.5 in I and 20.0 in J. Suspected cluster members have been selected initially from an I v I-Z colour magnitude diagram. By matching the positions of these sources with the corresponding NIR counterparts, we have completed a catalogue of optical and NIR magnitudes for candidate members of the association. Following individual de-reddening of these stars, masses have been derived from the J magnitudes using model isochrones. Our conclusions are complicated by both incompleteness due to the crowded nature of the region and an apparent age spread.

1. Introduction

OB3b is the younger sub-cluster of the stellar association, Cepheus OB3, and has a mean age of 5.5 Myrs (Jordi et al. 1996) and a distance of 900 pc (Moreno-Corral et al. 1993), making it one of the closest OB associations to the Sun. Through the detection of their coronal x-ray emission, low-mass stars have been discovered forming in a cloud previously thought to be producing exclusively high-mass stars (Naylor & Fabian 1999). Cepheus OB3b has a small spatial distribution and a favourable viewing perspective with new born stars emerging perpendicular to our line of sight. The region is therefore ideally suited for a study into the initial mass function and the continued search for very low-mass stars and brown dwarfs. Until now, the majority of work on the mass functions of OB associations has concentrated on the Orion region. Cepheus OB3 therefore gives us the opportunity to contrast and compare results. This contribution details an optical and near infra-red (NIR) survey of the sub-cluster and the subsequent construction of luminosity and mass functions.

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2. Observations

The first observations of the area were of 4 deep RI_cZ fields totalling 1.13 square degrees, taken using the wide field camera on the 2.5-m Isaac Newton Telescope during 5 nights in October 1999. Hour long exposures were taken through the R and I_c bands, and two hours through the Z band, along with observations of appropriate Landolt standards. The limiting magnitudes are $R \sim 24.5$, $I_c \sim 23.5$, $Z \sim 22.5$. Four of the five nights were photometric. Optimal photometry was performed on the data using routines devised by Naylor (1998). Statistical errors are negligible until $I_c \sim 20.0$ and grow to 0.1 magnitude at $I_c \sim 23.0$. As no set of standards exist for the Z filter, we simply used instrumental magnitudes. Candidate members of the association were selected from the I_c vs $I_c - Z$ diagram, by selecting stars redder than a straight line positioned to lie through the obvious area of 'clear water' that lies between the background contamination and the cluster pre-main sequence (figure 1). From this, 3472 cluster candidates were catalogued in the first optical field, named INT11 (figure 2). The $I_c - Z$ colour is used in preference to the $R - I_c$ colour to prevent incompleteness caused by a lack of depth in the R band, as compared to the I_c band.

Follow-up observations were then performed on INT11 by imaging 26 fields in the NIR (JHK_s), using the INGRID camera on the 4.2-m William Herschel Telescope in 2000. Coverage was 473 square arc-minutes or just under 50% of INT11. NIR fields were concentrated in areas in which high numbers of cluster candidates were found. Calibration of the data was undertaken using magnitudes taken from the 2MASS survey. Limiting magnitudes are $J \sim 20.0$, $H \sim 19.0$, and $K_s \sim 18.0$. With the exception of a very small number of stars that lay close to the edge of an INGRID field (< 20), all optical cluster candidates within the scope of the NIR survey, were found to have a NIR counterpart. In this way, a catalogue of optical and NIR magnitudes for cluster candidates has been compiled.

Individual de-reddening of the cluster candidates was achieved using an approximately age independent, H vs J-H model isochrone, and by tracing stars on this diagram back along the relevant reddening vector. The mean reddening for the area covered by the INGRID survey is $A_v = 2.87 \pm 0.06$ ($A_H = 0.52 \pm 0.01$), which is in agreement with the figure derived by Moreno-Corral et al. (1993). The reddening was found to be significantly variable, however, and the value of A_v rises to as high as 5 in the NIR fields closest to the edge of the molecular cloud (figure 2).

The completeness of the survey was studied by adding synthetic stars to our images using the DAOPHOT routine 'addstar'. After re-running the images through the star finding algorithm, the percentage of synthetic stars detected can be calculated. The result of this process showed that completion is low (50-70%) in the range $0.04 < M_\odot < 0.12$, but stays roughly constant and only drops sharply at $I_c \sim 22.0$. This effect is due to the crowded nature of the surveyed area rather than photon statistics. The completion limit marked on figure 3, represents the fall off at $I_c \sim 22.0$ ($0.04 M_\odot$ at 5.5Myrs).

3. Mass Function

Candidate members have been excluded if their extinction is larger or smaller than $\bar{A_H} \pm 0.1$ around the mean extinction to the cluster candidates in each of the 26 4.2'x4.2' NIR fields. Hence, despite differential reddening in the region studied, we are confident that the vast majority of non-members have been excluded. The mass function is constructed by selecting candidate members to the right of a 30Myr model isochrone (Baraffe et al. 1998) on the intrinsic J_o vs $(I_c - J)_o$ diagram and by plotting a J-band luminosity function as illustrated below (figure 3). The luminosity function was then transformed to a mass function using a 5.5Myr model isochrone (Baraffe et al. 1998).

The mass function (in the form $dN/dM \propto M^{\alpha}$) can be divided into three parts. The power law from $0.65 M_{\odot}$ to higher masses has been found to be significantly steeper than that of Salpeter (1955)($\alpha = -2.35$), and has a value greater than -3. In the range $0.14 < M_{\odot} < 0.65$ the slope is -0.35 ± 0.14, but below $0.14 M_{\odot}$ and across the sub-stellar boundary, the slope of the power law is $+0.57 \pm 0.34$. There is evidence for only 20 objects around or below the hydrogen burning threshold, the least massive of which has $J_o = 18.45 \pm 0.07$, and a mass of between 0.02 and $0.03 M_{\odot}$.

4. Discussion

Initial results suggest that for the mass interval, $0.14 < M\odot < 1.2$ in which we believe our catalogue to be nearly complete, the shape of the mass function closely agrees with that found for the Orion Molecular Cloud (OMC) (Luhman et al. 2000, Hillenbrand & Carpenter 2000). The mass function rises across the hydrogen burning threshold and turns over at approximately $0.65 M_{\odot}$ becoming a power law steeper than that described by Salpeter. Below $0.14 M_{\odot}$, however, our results show a significant dearth of very low mass stars. This differs markedly from results in the ONC where the mass function across the hydrogen burning threshold is shown to be still rising with a slope of -0.43 to at least $0.025 M_{\odot}$ (Hillenbrand & Carpenter 2000). The result is also very different from that obtained through a recent survey of the σ Orionis cluster where $\alpha \sim -0.8$ (Bejar et al. 2001), and from results for the field population ($-1 < \alpha < -2$) (Reid et al. 1999).

The study of the OB3b sub-cluster has been complicated by two important factors. Completion has been hampered by the crowded nature of the survey area. The low level of completion at faint magnitudes is, however, not expected to drastically alter our results. An initial investigation into the effect of a correction for incompleteness, points to the slope of the mass function across the hydrogen burning threshold being effectively unchanged, or at least remaining within the error bars already obtained. There is also an apparent age spread around the mean age of 5.5Myrs (Jordi et al. 1996) (see figure 3), along with evidence that the brighter, more massive members of the sub-cluster are older, and hence formed prior to the formation of the low-mass members and brown dwarfs. This, if confirmed, could be a highly significant result, and is predicted by some star formation mechanisms.

References

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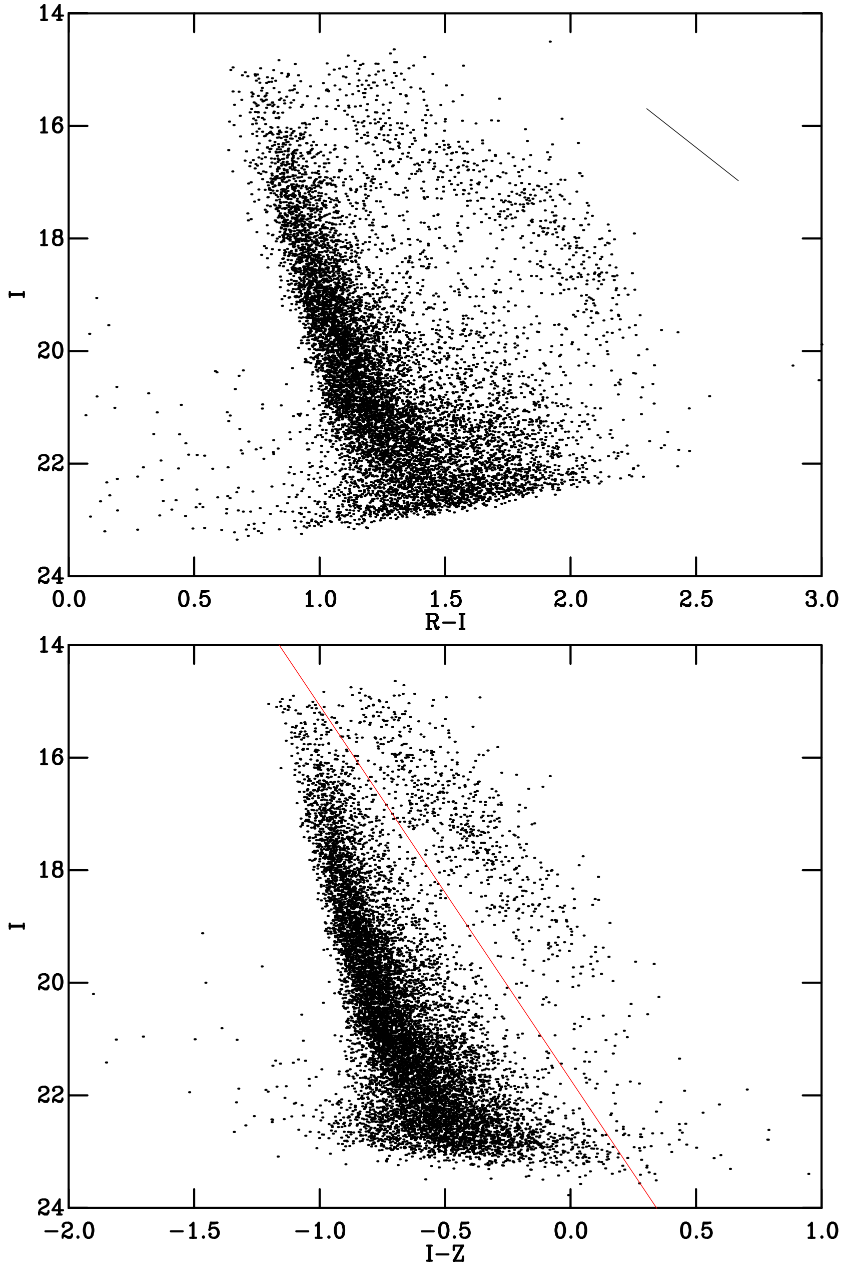


Figure 1. Colour-magnitude diagrams for the optical field INT11. The cluster pre-main sequence is clearly evident to the right of the background contamination. The line to the right of the pre-main sequence on the I_c vs $R - I_c$ diagram is the reddening vector. The red line shown on the I_c vs $I_c - Z$ diagram is the lower left boundary for those objects we consider to be cluster candidates. The stars which have been plotted have $s/n > 5$.

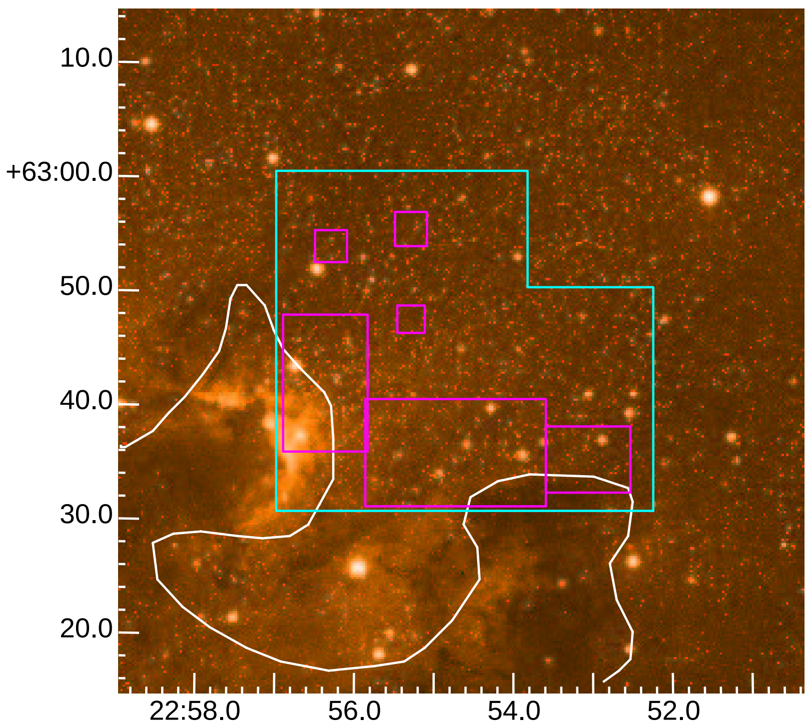
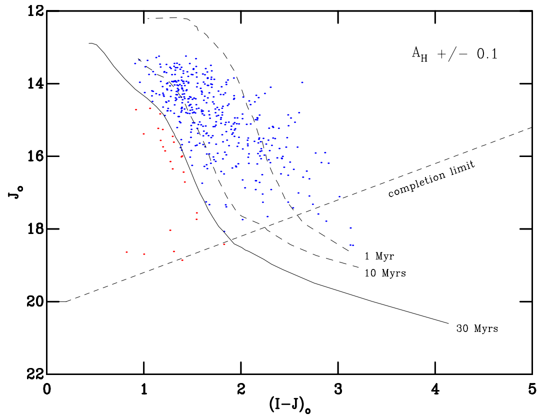
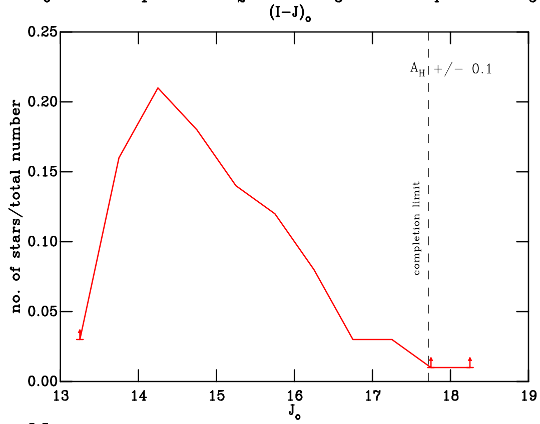


Figure 2. The area of our survey. The blue polygon represents the limit of the field INT11. The red boxes bound the areas surveyed with INGRID. The white line represents the lowest CO contour from Sargent (1977) and effectively marks the boundary of the molecular cloud.





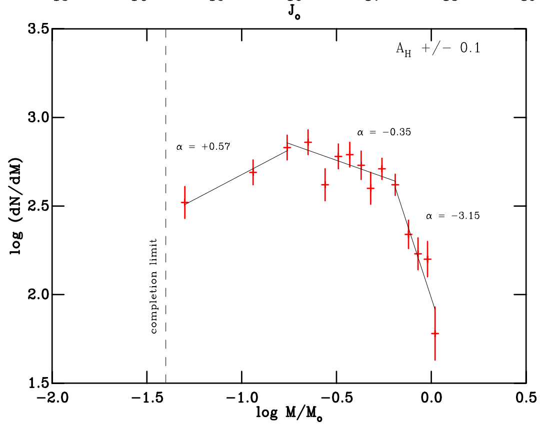


Figure 3. Top: J_o vs $(I_c - J)_o$ diagram for candidate members of the association, showing model isochrones from Baraffe et al. (1998). Rejected members are shown in red. Middle: J_o-band luminosity function. Bottom: Mass function for Cepheus OB3b.