Proceedings of 12th Cambridge Workshop on Cool Stars, Stellar Systems, & The Sun, 2003 University of Colorado.

The mass function and mass segregation in NGC 2516

R. D. Jeffries[1], M. R. Thurston[2], N. C. Hambly[3]

Abstract. We present the results of a 0.86 square degree BVI_c survey of the open cluster NGC 2516, which has an age of 150 Myr and may have a much lower metallicity than the similarly-aged Pleiades. We select 1254 low mass ($0.2 < M < 2.0 M_{\odot}$) cluster candidates, of which 70–80 percent are expected to be genuine. We find that 26 ± 5 percent of A to M-type stars in the cluster are binaries with mass ratio $q > 0.6$, in good agreement with the Pleiades. The mass function is slightly model and metallicity dependent, but consistent with a Salpeter-like law ($dN/d\log M \propto M^{-\alpha}$) with $\alpha = +1.6 \pm 0.2$ for $0.7 < M < 3.0 M_{\odot}$. At lower masses ($0.3 < M < 0.7 M_{\odot}$) there is a sharp fall, with $\alpha = -0.75 \pm 0.25$, which is inconsistent with the flatter mass functions seen in the Pleiades and field populations. We explain this by showing mass segregation has been at work in NGC 2516 – more than half of cluster stars with $M < 0.6 M_{\odot}$ are expected to be outside our surveyed area. The mass of NGC 2516 stars with $M > 0.3 M_{\odot}$ inside our survey is $1000 M_{\odot}$. Correcting for mass segregation and binarity increases this to $\sim 1400 M_{\odot}$, about twice that of the Pleiades.

1. Introduction

NGC 2516 is a rich, southern open cluster with a nuclear turn-off age similar to the Pleiades and a distance of 390 pc. However, it probably has a metallicity around half-solar – with consequences for stellar properties that depend on convection zone depth. NGC 2516 has therefore become a key object for studying X-ray emission and lithium depletion in cool stars (e.g. Jeffries et al. 1997, 1998; Harnden et al. 2001; Sciortino et al. 2001). A pre-requisite in such studies are optically selected samples of F to M-type stars, which avoid biasing the deduced stellar properties. This paper details an optical survey we have performed, from which we have selected low-mass cluster candidates and investigated the global properties of the cluster, such as the mass function, binary fraction, mass segregation and total mass.

[1]Department of Physics, Keele University, UK

[2]School of Physics and Astronomy, University of Birmingham, UK

[3]Institute for Astronomy, Edinburgh, UK

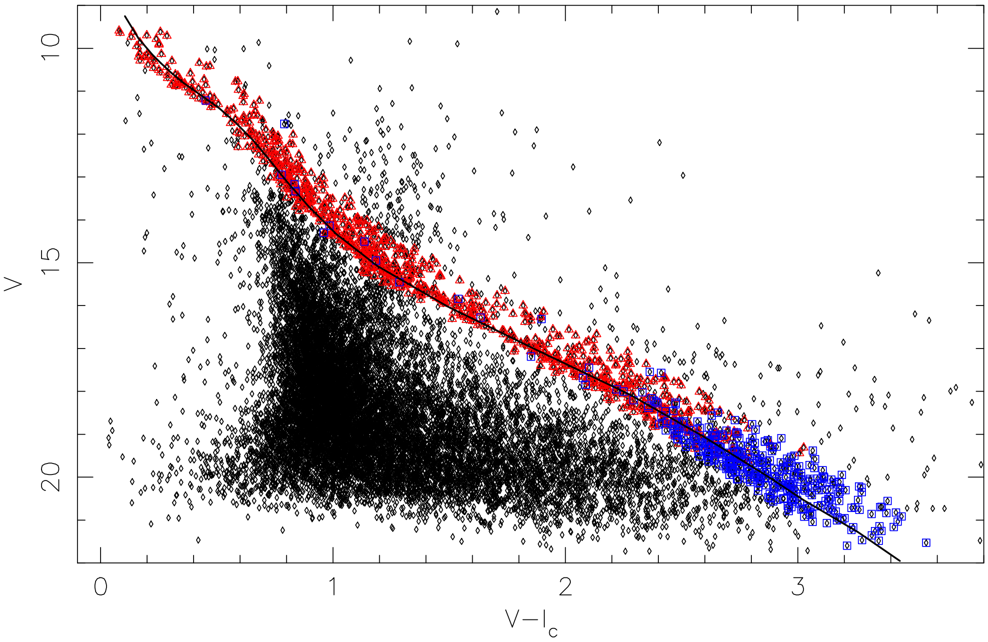

Figure 1. The V vs $V - I_{\rm c}$ CMD for our survey. The solid line shows the Siess et al. (2000) isochrone we used to select members of the cluster. Objects selected as cluster members are shown as red triangles (where both $B - V$ and $V - I_{\rm c}$ were available) or blue squares (where only $V - I_{\rm c}$ was available – for 368 objects).

2. Observations

A $BVI_{\rm c}$ survey of a 0.86 square degree area centered on the bright stars of NGC 2516 was performed on the CTIO 0.9-m in January 1995. A set of 25 overlapping fields were observed with a short and long exposure through each filter. Many Landolt standards were observed, the nights were photometric and the overall calibration is excellent out to $V - I_{\rm c} = 2.8$, with external errors no bigger than 0.02 mag. Aperture photometry was performed in 3 arcsec radius apertures (6 arcsec radius for the brighter stars) to yield the two colour-magnitude diagrams (CMDs). Photometry errors are negligible until $V = 17$ and grow to 0.1 magnitude at $V = 20$. Astrometry was based on the SuperCOSMOS sky surveys (Hambly et al. 2001), linked to Tycho-AC standards. Typical rms positional uncertainties are less than 0.3 arcsec. By recovery of simulated stars, we have established that for faint, red cluster members, our photometry is > 90 percent complete to $V = 20$ in the V vs $V - I_{\rm c}$ CMD and to $V = 18.2$ in the V vs $B - V$ CMD. The catalogue contains 15 495 objects with $9.7 < V < 21.7$ and was supplemented with 55 brighter objects catalogued in Jeffries et al. (1997).

Cluster candidates were selected based on their proximity to the 150 Myr isochrone from the models of Siess et al. (2000) in both the CMDs (see Fig. 1) and the colour-colour diagram. The $T_{\rm eff}$-colour relations were calibrated by forcing a 120 Myr isochrone to fit the observed Pleiades CMDs. A star that

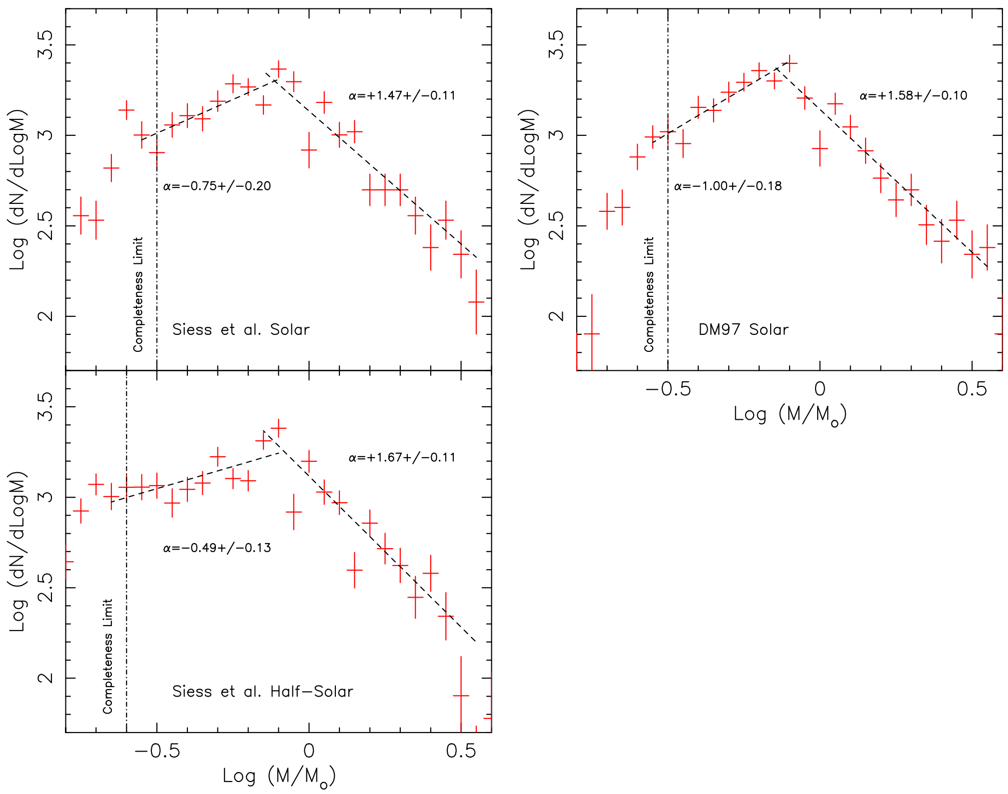

Figure 2. Mass functions for NGC 2516 derived using different models and metallicities (D'Antona & Mazzitelli 1997; Siess et al. 2000). The completeness limit is shown along with power law fits to the mass functions and the power law index values.

does not fail any of the tests is classed as a cluster candidate and any candidate more than 0.3 mag. above the cluster locus in the V vs $V - I_c$ CMD (or V vs $B - V$ CMD for $V < 11$) is classed as a probable unresolved binary with mass ratio, $q > 0.6$. We find 1254 cluster candidates, of which 403 are possible binary systems. Our complete catalogue with photometry, positions and membership/binarity classification is available in electronic format from ftp://cdsarc.u-strasbg.fr/pub/cats//J/A+A/375/863.

Contamination by foreground/background stars is assessed by modelling the stellar density along strips of colour in the V vs $V - I_c$ CMD, after removing the cluster candidates. By integrating the fitting function (a constant plus exponential) over the region occupied by members we gain an excellent estimate of the likely contamination. Separate estimates are made for single stars and binaries. The numbers of contaminants varies significantly with colour (as may be seen in Fig. 1). We determine that between 50 percent (at $V - I_c \simeq 1.0$) and 95 percent (at $V - I_c < 0.7$ and $1.3 < V - I_c < 2.4$) of our candidates are genuine cluster members.

3. Mass Function

The mass function (MF) is derived using mass-colour relationships from the model isochrones. The identified binaries are treated as two stars with the same colour (and mass) and corrections are applied for contamination by non-members. There is some model and composition dependence of masses derived from colours. We have calculated MFs based on both the solar and half-solar metallicities of Siess et al. (2000) and from the solar metallicity models of D'Antona & Mazzitelli (1997) (see Fig. 2).

We can summarise the results by saying that for $0.7 < M < 3.0M_{\odot}$, the MF (expressed in the form $dN/d\log M \propto M^{-\alpha}$) is slightly model and metallicity dependent and has a power law slope with $\alpha \simeq +1.6 \pm 0.2$, which is close to the canonical Salpeter (1955) value of $+1.35$. In fact our partial inclusion of binaries has increased α by 0.2 over an analysis (like Salpeter's) where binarity is neglected, so the comparison is even closer. At lower masses ($0.3 < M < 0.7M_{\odot}$) the MF turns over and falls with $\alpha \simeq -0.75 \pm 0.25$. This contrasts sharply with the rather flat MFs found for field stars ($-0.1 < \alpha < +0.3$ – Gould et al. 1997, Kroupa 2001) and the Pleiades ($\alpha \simeq 0$ – Meusinger et al. 1996) in this mass range. Roughly speaking, there is a deficit of a factor of 2 in the numbers of NGC 2516 members at around $0.3M_{\odot}$ compared with a scaled Pleiades MF, and this deficit is also clearly apparent in the luminosity function.

4. Binarity

Unresolved binarity will affect estimation of the mass function and total cluster mass. Our method of identifying unresolved binaries will result in finding those systems with $q > 0.6$. Allowing for contamination by non-members, we find that the binary fraction (number of binary systems divided by the total number of systems) for this range of mass ratios is 26 ± 5 percent. There is only marginal evidence for any variation of this as a function of mass/colour as we move from A to M-type stars. The equivalent binary fractions in the Pleiades and in field stars are 26 percent (Stauffer et al. 1984) and 21 percent (Duquennoy & Mayor 1991). Integrating the field q distribution down to zero, we would estimate a total binary fraction of 85 percent in NGC 2516.

5. Mass Segregation

After excluding the candidate binary systems with $q > 0.6$, we determined the surface density of stars as a function of radial distance from the cluster centre of gravity. The sample was split into four colour/mass bins to investigate mass segregation. Fig. 3 shows the results, where the dashed line shows the (assumed constant) level of contamination and the solid lines show King profile fits to the surface density distributions after this contamination has been subtracted. There is a dramatic increase in the cluster core radius below $0.86M_{\odot}$, from about 0.9 pc to 1.9 pc, and then to 3.5 pc for the lowest mass bin. This evidence for mass segregation is completely robust to our assumptions about the size of the cluster tidal radius (about 15 pc) and the level of background contamination.

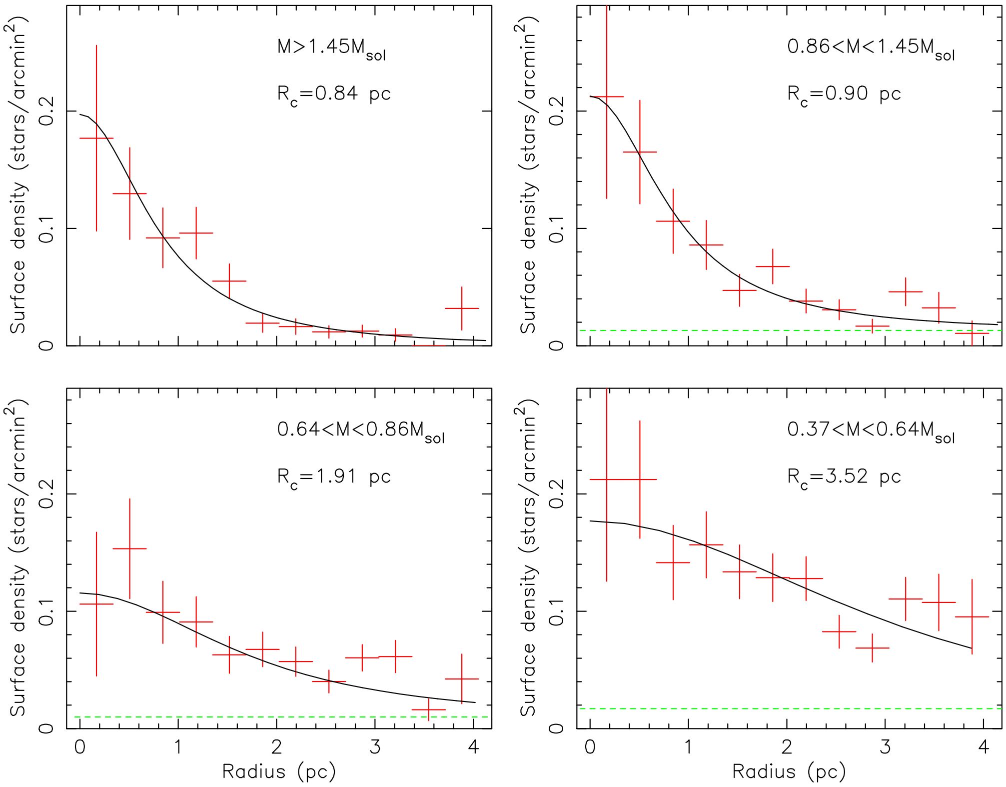

Figure 3. Mass segregation in NGC 2516. The plots show the radial profile of the stellar density for four mass bins, with King model fits (tidal radius 15 pc). The green dashed lines indicate the surface density of non-member contaminants that were subtracted before fitting. The core radius grows dramatically as we move to lower mass stars.

Assuming that the King profiles are a correct representation of the stellar distribution and extrapolating beyond the bounds of our survey, we estimate that while 81 percent of stars with $M > 1.45M_{\odot}$ are included in our survey, only 44 percent of stars with $0.37 < M < 0.64M_{\odot}$ are present. This huge difference over a relatively short mass interval can completely explain the falling mass function at low masses, determined from our limited survey area. Such a large effect is greater than predicted simply by equipartition of energy and dynamical mass segregation. We believe there is strong evidence for primordial mass segregation, which has yet to be erased even though the cluster age is similar to the relaxation timescale.

6. Conclusions

- The luminosity function of NGC 2516 is consistent in shape with the Pleiades and field populations for $M_V < 8$. For fainter stars, the luminosity function of NGC 2516 flattens and contains a factor of two fewer stars than a scaled Pleiades luminosity function.

- The derived mass function is Salpeter-like for $M > 0.7M_{\odot}$, but turns over and falls quite sharply at lower masses, with $\alpha = -0.75 \pm 0.25$.
- Mass segregation is clearly apparent when comparing the radial distributions of stars above and below about $0.8M_{\odot}$. From extrapolation of simple models we deduce that more than half the lower mass stars lie outside our survey area, whilst the vast majority of high mass stars are included. This discrepancy means that the whole-cluster mass functions of NGC 2516 and the Pleiades (and the field) could be similar at least down to $0.3M_{\odot}$.
- The cluster core radius increases more rapidly with decreasing mass than expected simply by equipartition. We suggest this is evidence for primordial mass segregation, with high mass stars being formed closer to the cluster centre.
- The binary fraction for mass ratios $q > 0.6$ in NGC 2516 is 26 ± 5 percent and is comparable with that in the Pleiades and field populations.
- Integrating the derived mass function we obtain a total cluster mass of about $1000M_{\odot}$. Correcting for unresolved binarity and mass segregation would increase this estimate to $1400M_{\odot}$, about twice the mass of the Pleiades.
- If the whole-cluster mass functions of the Pleiades and NGC 2516 are similar then we expect about 100-200 brown dwarfs to be present in our surveyed area, and 300-450 in the cluster altogether.

References

D'Antona, F. & Mazzitelli, I. 1997, Mem. Soc. Astr. It., 68, 807

Duquennoy, A. & Mayor, M. 1991, A&A, 248, 485

Gould, A., Bahcall, J. N. & Flynn, C. 1997, ApJ, 482, 913

Hambly, N. C., Davenhall, A. C., Irwin, M. J. & MacGillivray, H. T. 2001, MNRAS, 326, 1315

Harnden, F. R. et al. 2001, ApJ, 547, L141

Jeffries, R. D., James, D. J. & Thurston, M. R. 1998, MNRAS, 300, 550

Jeffries, R. D., Thurston, M. R. & Pye, J. P. 1997, MNRAS, 287, 350

Kroupa, P. 2001, MNRAS, 322, 231

Meusinger, H., Schilbach, E. & Souchay, J. 1996, A&A, 312, 883

Salpeter, E. E. 1955, ApJ, 121, 161

Sciortino, S. et al. 2001, A&A, 365, L259

Siess, L., Dufour, E. & Forestini, M. 2000, A&A, 358, 593

Stauffer, J. R., Hartmann, L., Soderblom, D. R. & Burnham, N. 1984, ApJ, 280, 202