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# Low-Mass Stars and Brown Dwarfs Around $\sigma$ Orionis

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**Abstract.** We present optical spectroscopy of 71 photometric candidate low-mass members of the cluster associated with $\sigma$ Orionis. Thirty-five of these are found to pass the lithium test and hence are confirmed as true cluster members, covering a mass range of $\leq 0.055$-$0.3\,M_\odot$, assuming a mean cluster age of $\leq 5$ Myr. We find evidence for an age spread on the $(I,\ I-J)$ colour magnitude diagram, members appearing to lie in the range 1-7 Myr. There are, however, a significant fraction of candidates that are non-members, including some previously identified as members based on photometry alone. We see some evidence that the ratio of spectroscopically confirmed members to photometric candidates decreases with brightness and mass. This highlights the importance of spectroscopy in determining the true initial mass-function.

## 1. Introduction

$\sigma$ Orionis is the brightest member of a young ($< 7$ Myr) stellar cluster of the same name, located in the Orion OB1b association at a distance modulus of 7.8-8.3 (Béjar et al. 2001). Assuming that all members of this cluster are coeval, it represents an ideal hunting ground for very low-mass stars and brown dwarfs, since such objects are at their most luminous when young. When combined with the fact that the cluster is unlikely to have undergone any dynamical evolution, such as evaporation or mass segregation, $\sigma$ Orionis seems like an ideal candidate for studying the initial mass function. The mass function can be determined from photometry but it is possible that contaminating objects, such as foreground M-dwarfs, bias the result. One way of eliminating these polluting objects from the colour magnitude diagram (CMD) is to perform a spectroscopic survey of cluster candidates. Since the cluster is very young all low-mass members should retain their initial lithium.

## 2. Observations

The INT wide-field camera was used to obtain $R$ and $I$ band photometry of a one square degree area of the $\sigma$ Orionis cluster during October 1999. Complete to $I \sim 21$ and centered on the star after which the cluster is named, the photometry was used to select 82 cluster candidates for follow-up spectroscopy.

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Unfortunately, eleven of these targets were "lost" from the dataset because they fell down fibres of poor transmission (see below). The targets covered an $I$ magnitude range of 14.9-18.1, the fainter end of this scale corresponding to an object with an age-dependent mass of 0.03-0.06$M_{\odot}$ (at 1-7 Myr), i.e., just into the realm of brown dwarfs ($\lesssim$ 0.075$M_{\odot}$). Figure 1 shows the spectroscopic targets as triangles on an ($I$, $R-I$) colour-magnitude diagram.

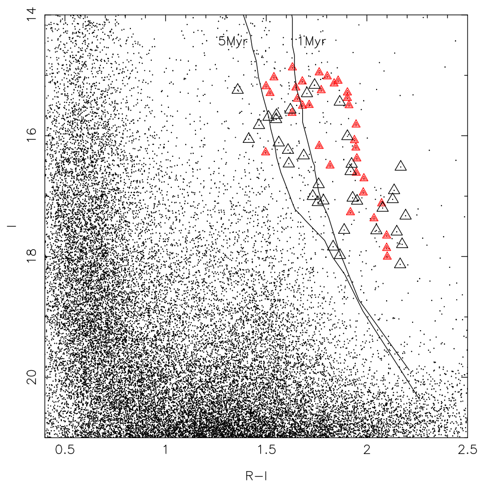


Figure 1. (I, $R-I$) colour magnitude diagram for one square degree around $\sigma$ Orionis. Spectroscopic targets are shown as triangles - filled ones indicating cluster membership, open indicating no evidence of lithium. Baraffe et al. (1998) isochrones are also shown.

During December 1999 we obtained follow-up high-resolution (1Å FWHM) optical spectroscopy for the photometric members using the Wide Field Fibre Optic Spectrograph (WYFFOS) on the 4.2m William Herschel Telescope. The large-fibre module was used (2.7$''$ diameter fibres) with spectra being recorded via the TEK 6 1024 pixel CCD. The 6625Å echelle filter was selected, giving a spectral coverage of approximately 6400-6800Å, with a nominal dispersion of 0.4Å pixel$^{-1}$. Spectra were taken over two nights and of the 71 targets observed, 29 were common to both of these runs. Total exposure times were; 4.25 hours per target on the night of December 12, and 4.33 hours on December 13. Arc spectra were obtained using a Tungsten lamp and sky exposures were taken following each target frame.

Reduction was carried out predominantly within the IRAF environment, using the WYFRED procedure. All images were initially bias subtracted by interpolating the overscan region across the whole of the frame. Flats were then used to remove the instrumental signature of the CCDs. WYFRED employed an optimal method to extract the spectra from a frame, each spectrum was dispersion corrected and wavelength calibrated using a function determined from the arc spectra. Finally, a fibre-to-fibre throughput correction was applied using offset-sky frames, and sky subtraction performed with mean sky spectra obtained with dedicated sky fibres. Spectra from the same night were co-added to increase the signal to noise ratio, but the decision was made not to combine spectra from the two nights as this could mask any short period binaries.

## 3. Lithium

The "lithium test" exploits the fact that objects with masses $M \lesssim 0.065M_{\odot}$ never attain the high internal temperatures ($\gtrsim 2.6 \times 10^6$K) required to burn lithium as a nuclear fuel. Stars above this mass-limit will consume the element, the age at which lithium destruction begins is determined by the mass of the star - the lower the mass, the longer until the onset of burning. The current work investigates the cluster surrounding $\sigma$ Orionis, members of which are believed to have ages of $\lesssim 7$ Myr. At this age, stars in the approximate mass range 0.4-$0.7M_{\odot}$ will have consumed most of their initial lithium. All of our spectroscopic targets are believed to be less massive than $0.3M_{\odot}$, hence if the true cluster age is $\leq$ 7Myr, and there is little or no age spread, one would expect all the genuine cluster members to contain lithium.

Each spectrum was visually inspected for the characteristic 6707.8Å Lithium I doublet, and equivalent widths calculated. Briefly, thirty-five objects were found to contain significant lithium and are classified accordingly as definite cluster members. Assuming a cluster age of $\sim 5$ Myr, they range in mass from 0.055-$0.3M_{\odot}$. A selection of these are shown in Figure 2, labelled with their $I$ magnitudes.

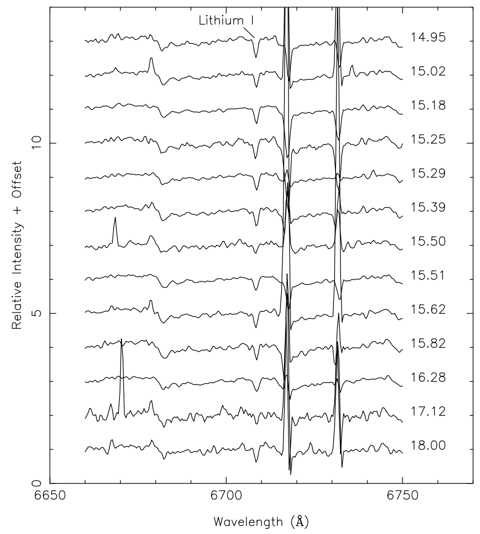


Figure 2. Selection of cluster members' spectra, highlighting the Lithium I absorption feature at 6708Å. All spectra have been normalised and had a constant offset applied, labels are $I$ magnitudes

## 4. Discussion

Figure 1 shows an ($I$, $R-I$) CMD with the lithium members drawn as closed triangles and non-members as open triangles, isochrones are calculated from the Baraffe et al. (1998) models. There appears to be little correlation between the isochrones and the observed cluster sequence. This seems to confirm the known mis-match between model calculations of $R-I$ colours and their empirical counterparts. 2MASS $J$ band photometry was obtained for all but two of our targets, allowing us to construct an ($I$, $I-J$) CMD, see Figure 3. Comparison between the identified cluster members and $I-J$ isochrones does provide a better match but suggests an age spread of $\sim$ 1-7 Myr, even allowing for unresolved binary systems.

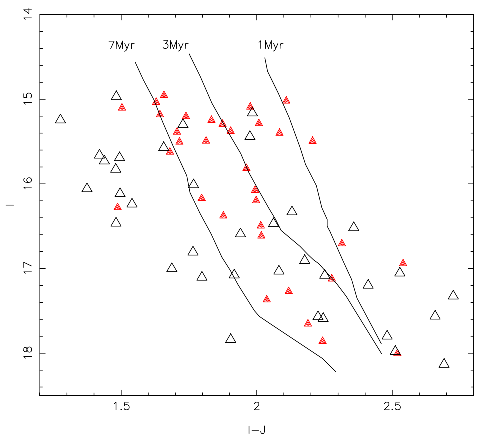


Figure 3. ($I, I-J$) colour magnitude diagram containing all but two of our 35 cluster members (filled symbols), non members are indicated by open triangles. Isochrones are from Baraffe et al. (1998).

Figure 4 shows two histograms, the blue area representing the distribution of all 71 spectroscopic targets in the survey, the red overlay corresponds to the 35 objects in which lithium was detected. The inference drawn from this figure is that photometric selection alone is insufficient to identify cluster members. In addition, the fraction of non-members appears to increase with magnitude. Thus a mass function based only on photometric criteria would over-estimate the numbers of brown dwarfs in the cluster with respect to higher mass stars. It is important to note though, that of the 36 objects classified as non-members, several have spectra which display a very small signal to noise ratio. This means that we cannot entirely rule out the presence of undepleted lithium within these objects, and consequently they may turn out to be cluster members.

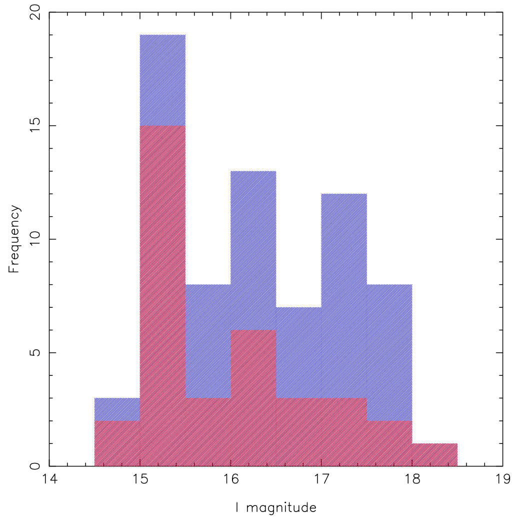


Figure 4. Histogram of cluster membership as a function of $I$ magnitude. Red columns represent the number of cluster members found per magnitude bin, shown as a fraction of the total spectroscopic targets within that bin.

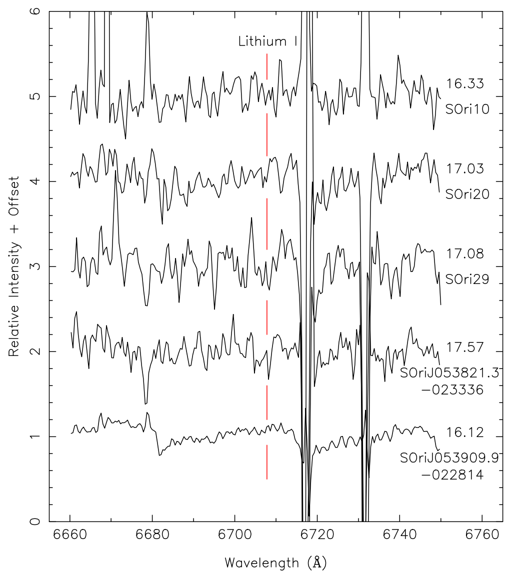


Figure 5. Objects common to this survey and Bejar et al. (2001) which we find are not cluster members, labelled with $I$ magnitudes and identifiers from Bejar et al. (2001).

Bejar et al. (2001) present 64 very low-mass $\sigma$ Orionis cluster member candidates using three colour ($I$, $Z$ and $J$) photometry. We are able to identify eighteen of their objects within our own survey, of these we are convinced that eight definitely show Lithium. However, five of their candidates show no clear evidence of cluster membership, these objects are all fainter than $I = 16$ and are shown in Figure 5. This goes some way to demonstrating the importance of backing up photometric cluster membership with spectroscopy.

We believe there is still much to be done with the dataset - current work involves determining radial velocities for all objects. This will provide a further discriminant between cluster members and contaminating objects, plus allow the detection of binary systems. To date, we have found seven potential spectroscopic binary systems among the 35 lithium-rich objects, with implied maximum orbital periods of a few days.

## References


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