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The Substellar Domain in the ϵ Orionis Cluster

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Abstract. We present an IZ photometric survey covering a total area of about 1000 arcmin^2 around the ϵ Orionis young massive star ($\sim$10 Myr, d=412 pc) and reaching a limiting magnitude I=22. From the resulting I, $I-Z$ color-magnitude diagram we have selected 123 red candidates in the interval I=15–22 mag, which according to evolutionary models corresponds to masses between 0.40 and 0.020 M$_\odot$, i.e, approaching the deuterium burning mass limit. We have obtained follow-up J-band photometry for half of our photometric candidates. The I, $I-J$ color-magnitude diagram and low-resolution optical spectroscopy of four of them suggest that we have identified a rather abundant population of young low-mass stars and brown dwarfs. We compare our findings with previous works in other young clusters.

1. Introduction

The B0-type star ϵ Orionis is located in the Orion belt (OB1b subgroup). Its Hipparcos distance modulus is $m-M$=8.1 (412 pc, Perryman et al. 1997). The extinction towards this star is very low, A_I=0.13 mag (Lee 1968). Previous studies based on ROSAT pointed observations (Wolk & Walter 2000) led to the discovery of a numerous stellar population around ϵ Orionis, for which the authors estimated an age about 7 Myr. Here we present an IZ survey covering a large area located to the south-east of the ϵ Orionis star (see Figure 1). Follow-up J-band photometry and optical spectroscopy allow us to investigate the membership status of our photometric candidates.

2. Observations

Our far-red optical survey has been carried out using the IZ bands and the Wide Field Camera (WFC) attached to the prime focus of the Isaac Newton Telescope (INT, Roque de los Muchachos Observatory) on 1998 November 15. The camera consists of a mosaic of four 2×4 K CCD detectors (plate scale: 0.33 arcsec/pix). We observed one WFC field (1006 arcmin^2, see Figure 1) exposing one hour total integration time per filter. Images were processed (bias-substracted and flat-fielded) within the IRAF environment. Aperture and psf photometry were performed with routines of the DAOPHOT task. Instrumental magnitudes were

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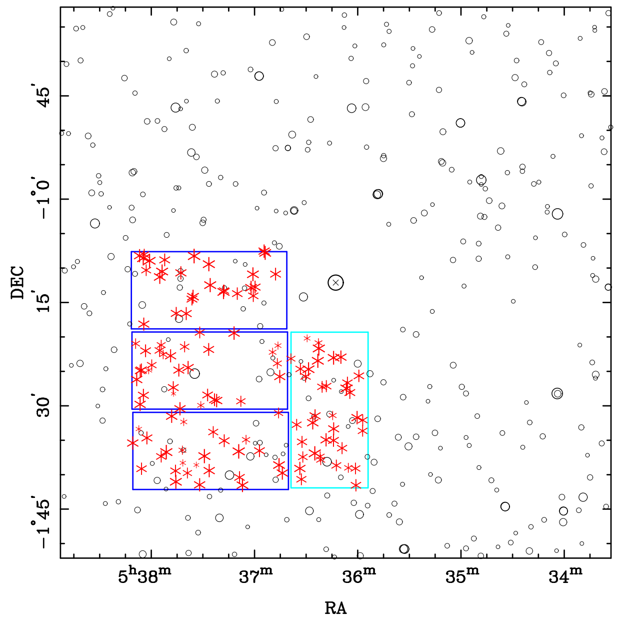

Figure 1. Our IZ WFC survey around the ϵ Orionis star (central cross). The four CCDs of the WFC are denoted by blue rectangles. IZ candidates are indicated with red asterisks. Open circles stand for field stars brighter than V = 13.

calibrated into observed magnitudes using I-band images of Landolt (1992) photometric standard stars collected with the IAC-80 telescope (Teide Observatory) a few nights later. Seeing conditions at the INT were 1.8 arcsec on average. The completitude and limiting I-band magnitudes of our survey are 21 and 22, respectively. From the resulting I, $I-Z$ color-magnitude diagrams (illustrated in Figure 2) we have selected 123 candidate members of the ϵ Orionis cluster. They define a photometric sequence that is redder and brighter than that of older objects in the field. According to state-of-the-art evolutionary models (Chabrier et al. 2000), I=22 mag corresponds to a mass of 0.02 $M_\odot$ at the age of 10 Myr.

In addition, we have obtained near-infrared J-band images covering an area of $\sim$ 600 arcmin^2 in the ϵ Orionis cluster using the infrared camera (CAIN, field of view of 18 arcmin^2) attached to the Carlos Sánchez Telescope (TCS, Teide Observatory) on 2000 November 23, 25, 28, 30 and December 9, 10. This surveyed region overlaps with our optical IZ search. Total integration times in the J-band were typically 1200 seconds per CAIN field. Weather conditions were fairly photometric, and the average seeing ranged from 1.7 to 3.3 arcsec. Raw frames were sky-substracted and flat-fielded within the IRAF environment. We have obtained aperture photometry for 61 candidates out or the total IZ sample. Figure 3 illustrates the resulting I, $I-J$ color-magnitude diagram where no-dusty and dusty, 5 Myr and 10 Myr isochrones of the Lyon group (Chabrier et al. 2000) are included for comparison. From the Figure it is observed that the majority of our candidates ($\sim$ 75%) do follow a well-delineated photometric sequence in the optical and near-infrared wavelengths. We consider them as very

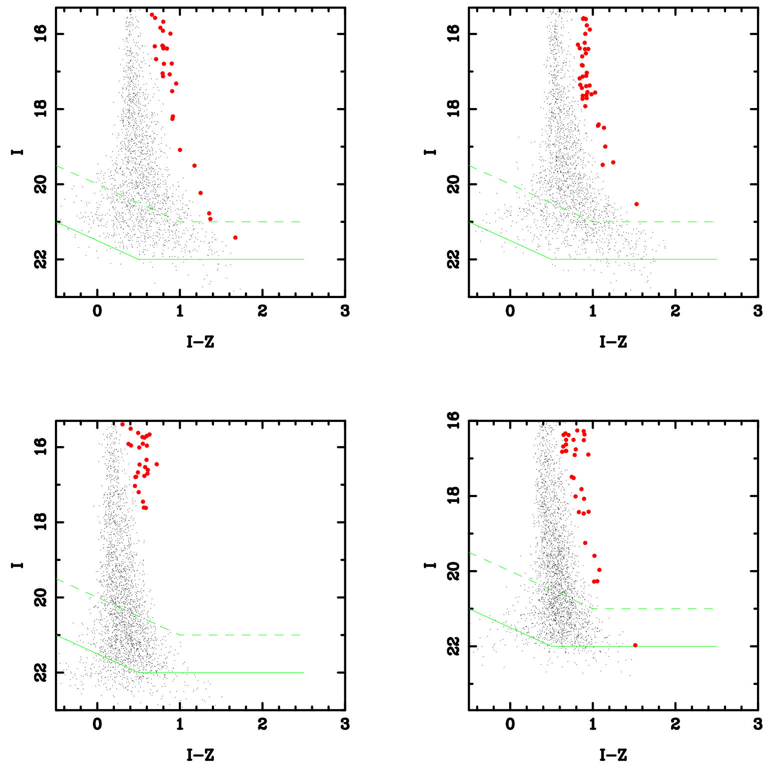

Figure 2. I, $I - Z$ color-magnitude diagrams: The 123 photometrically selected candidates are indicated with red circles. The completitude and limiting magnitudes are shown with dashed and solid lines, respectively.

likely members of the ϵ Orionis cluster. As inferred from the models, our IZJ candidates have masses between 0.4 $M_\odot$ and 0.030 $M_\odot$ at the age of 10 Myr. The remaining 14 objects that deviate from the sequence (displaying rather blue $I - J$ colors) are likely cluster nonmembers.

We have also obtained low-resolution optical spectroscopy for four of our IZ candidates with the red arm of the ISIS spectrograph mounted on the William Herschel Telescope (WHT, Roque de los Muchachos Observatory) on 2001 February 3. The R158R grating and the TEK 1024×1024 pixels detector (0.36 arcsec/pix) were used, providing a wavelength coverage from 550 nm up to 850 nm and a nominal dispersion of 2.9 Å. A 1.5 arcsec slit width was used. Exposure times ranged from 1200 to 2000 seconds. Spectra were bias-substracted, flat-fielded and optimally extracted within the IRAF environment. Wavelength calibration was performed using terrestrial emission lines. The spectra were flux calibrated by observing the spectrophotometric star G191-B2B. Our final data are shohwn in Figure 4, where the most prominent spectroscopic features

are indicated. We have derived spectral types by comparing our spectra to optical spectra of well-known field dwarfs and, and by measuring the PC3 index (Martín et al. 1999). We provide our results as well as equivalent widths (EWs) of Hα and Na I at 819.5 nm in Table 1.

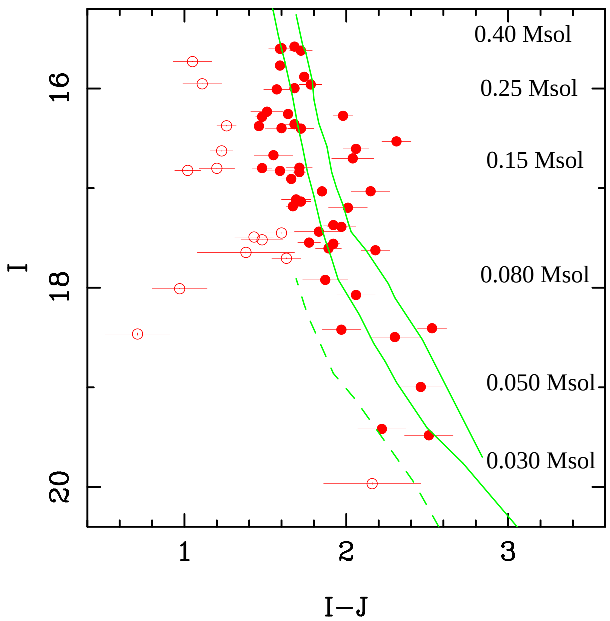

Figure 3. I, $I - J$ color-magnitude diagram: candidates following the expected photometric sequence of the ϵ Orionis cluster are indicated with red filled circles, while those objects (probably cluster non-members) with rather blue $I - J$ colors are plotted with open circles. The 5 Myr and 10 Myr no-dusty isochrones (solid lines) and the 10 Myr dusty models (dashed line) of the Lyon group are included for comparison.

Table 1. Spectral data of ϵ Orionis candidates

Name	I	Sp Type	EW H_α (Å)	EW Na (Å)
Eori2-1328	16.23	M4.5	8.2	3.4
Eori1-1644	16.79	M5.0	7.6	6.5
Eori1-388	17.32	M6.0	6.5	3.9
Eori1-726	18.20	M6.0	<3	<8.5

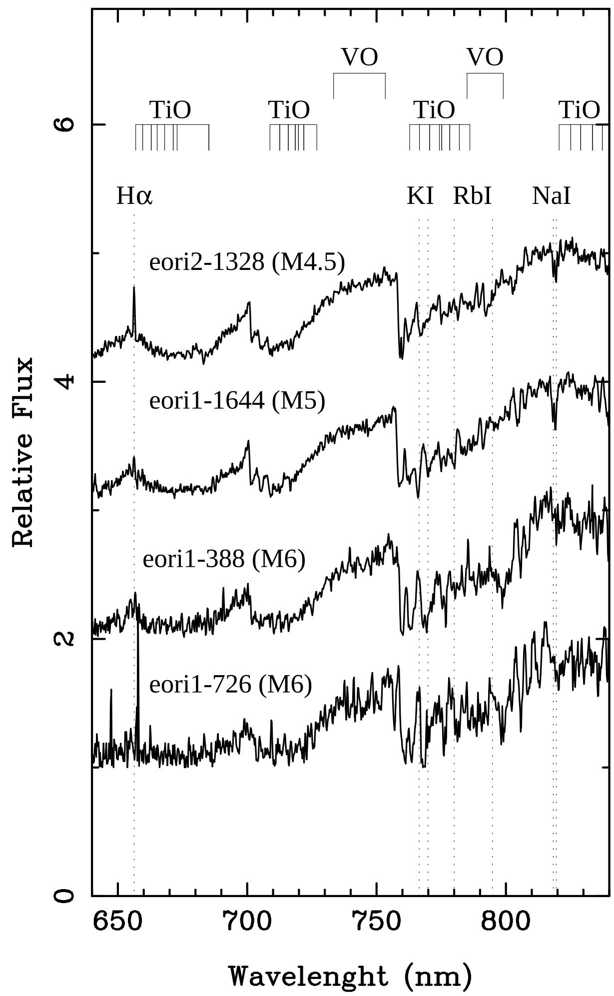

Figure 4. Optical spectra of ϵ Orionis candidates (spectral types given in brackets). Some spectral features are indicated.

3. Discussion and Final Remarks

From the I, $I - Z$ color-magnitude diagrams we have selected 123 candidates with I magnitudes between 15 and 22 mag. They most likely represent a numerous population of low-mass stars and brown dwarfs of the very young ϵ Orionis cluster. Infrared J-band photometry confirms that about 75% of our candidates do follow a well defined sequence in the I, $I - Z$ and $I - J$ diagrams, supporting their membership in the cluster. According to recent theoretical models (Chabrier et al. 2000), this photometric sequence can be explained by adopting a cluster age of 5–10 Myr. The estimated masses of our candidates are in the interval 0.4–0.02 $M_{\odot}$.

Four of our objects (with spectroscopic data available) show M4.5–M6 spectral energy distributions. They lie on the cluster borderline between stars and brown dwarfs. Hα is clearly detected in emission in three of them, while we

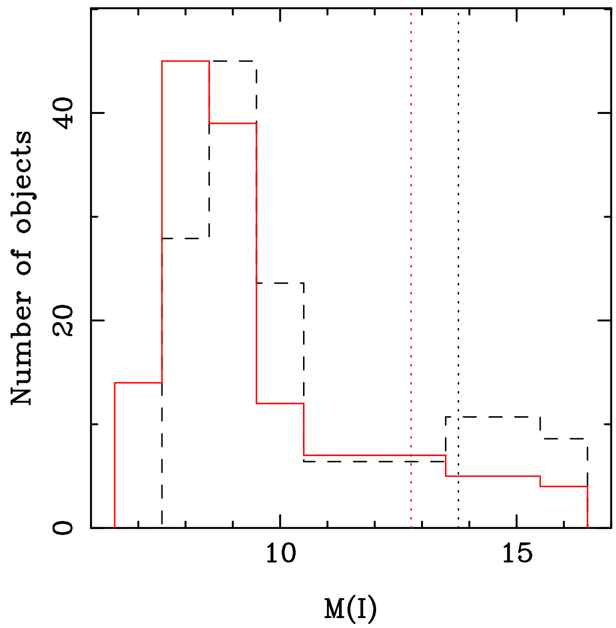

Figure 5. *I*-band luminosity function of the ϵ Orionis cluster (solid red line). The x-axis is labelled with absolute *I* magnitudes. The σ Orionis luminosity function (black dashed line) is included for comparison. Vertical dotted lines indicate completitude limits of the surveys (red — ϵ Orionis; black —σ Orionis).

can only set a modest upper limit for the fourth object given the poor signal-to-noise ratio of its spectrum (Table 1). However, Hα emission is not enough for studying cluster membership of mid-M dwarfs. Alkalies are very sensitive to gravity: the lower the gravity, the less intense alkali lines become. Of the three candidates with Hα emission, two show Na I and K I lines weaker than those of field dwarfs, indicating their low gravity and thus, supporting their membership in the ϵ Orionis cluster. The third object with EW (Na I) = 6.5 Å seems to have a larger gravity, likely being a cluster nonmember.

Assuming that the membership probability of our photometric candidates is 50–75%, and that this probability is valid through the entire magnitude interval of our survey, we can derive the luminosity function of the ϵ Orionis cluster. Figure 5 depicts our results for the *I*-band. We have included the σ Orionis luminosity function for comparison (Béjar et al. 2001). Both functions are indeed similar. Our observations of the ϵ Orionis cluster reinforces the fact that brown dwarfs are commonly formed in Nature.

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