Multi-conjugate adaptive optics observations of the Orion Trapezium Cluster

M G Petr-Gotzens, M F Sterzik, R Köhler, J Kolb, E Marchetti, V D Ivanov, D Nürnberg, H Bouy, N Huélamo, E L Martín and D Barrado y Navascués

1 European Southern Observatory, Karl-Schwarzschild-Str.2, D-85748 Garching, Germany
2 European Southern Observatory, Alonso de Córdoba 3107, Casilla 19001, Santiago, Chile
3 ZAH, Landessternwarte, Königstuhl, 69117 Heidelberg, Germany
4 Instituto de Astrofísica de Canarias, C/ Víñ Láctea s/n, E-38200, La Laguna, Tenerife, Spain
5 LAEFF-INTA, PO Box 78, E-28691, Villanueva de la Cañada, Madrid, Spain

E-mail: mpetr@eso.org

Abstract. We obtained very deep and high spatial resolution near-infrared images of the Orion Trapezium Cluster using the Multi-Conjugate Adaptive Optics Demonstrator (MAD) instrument at the VLT. The goal of these observations has been to search for objects at the very low-mass end of the IMF down to the planetary-mass regime. Three fields in the innermost dense part of the Trapezium Cluster, with a total area of ~3.5 sq.arcmin have been surveyed at 1.65µm and 2.2µm. Several new candidate planetary mass objects with potential masses < 13MJup have been detected based on their photometry and on their location in the colour-magnitude diagram. The performance of the multi-conjugate adaptive optics correction is excellent over a large field-of-view of ~ 1'. The final data has a spatial resolution of < 0.1arcsec over most of the area covered, enabling us to study the brown dwarf binary fraction, which is tightly linked to the brown dwarf formation process in dense stellar clusters. Only one brown dwarf binary was found, which is a newly detected system. Confirmation of the substellar nature of the faintest objects detected in our observations (potentially 3-10MJup), however, must await future confirmation by spectroscopic and/or photometric observations.

1. Introduction

The study of the very low-mass end of the initial mass function (IMF) is an important task in star formation research. The distribution of objects’ masses beyond the stellar/brown dwarf limit at 0.075M☉ towards the regime of the so-called planetary mass objects (< 0.013M☉) provides crucial constraints for any star formation theory. Of similar importance as the shape of the sub-stellar IMF is its limit, and key questions are: Is the process of star formation via hierarchical cloud core fragmentation incapable of producing objects beyond a specific lower mass limit? And, if yes, lies this limit at 0.001 – 0.010M☉ (or 1 – 10MJup), as predicted by theory (e.g. [1, 2, 3]). Similarly, the properties of young brown dwarf/planetary-mass binaries are tightly linked to their formation process and must, therefore, be thoroughly studied and analysed in the context of current theoretical models (e.g. [4, 5]).

In recent years extensive observations of nearby star forming regions and young stellar clusters have begun to investigate the sub-stellar IMF in great detail (e.g. [6, 7, 8]). The Orion Nebula Cluster (ONC), which is the most populous young stellar cluster within 1kpc, serves as a
benchmark to study the full dynamic range of the IMF from \( \sim 50M_\odot \) down to Jupiter mass objects. Its low-mass IMF was found to rise with decreasing mass until it forms a peak near \( \sim 0.2M_\odot \) and then declines sharply through the brown dwarf regime and beyond the deuterium burning limit at \( \sim 0.013M_\odot \) [9, 6, 10]. Interestingly, a secondary peak in the substellar IMF possibly appears at \( \sim 0.013 - 0.025M_\odot \) [6, 11].

However, none of these studies reached a sensitivity high enough to detect potential \( 3-5M_{Jup} \) objects in the innermost central region of the Trapezium Cluster, because large stellar crowding and significant amounts of background nebulosity from the Orion Nebula diminish the detection limit as compared to non-crowded regions. High spatial resolution is a key to overcome these limitations, and it is needed to survey the central part of the ONC, the central Trapezium Cluster, for the lowest mass objects. High angular resolution is also mandatory to resolve very close binaries, and to detect faint sub-stellar companions by enhancing the contrast to brighter, higher mass, stars.

The technique of multi-conjugate adaptive optics (MCAO) enables us to achieve very high, and often diffraction-limited, spatial resolution over a large field of view. The total observing time spent to survey a region of interest is therefore reduced with respect to normal adaptive optics studies, where several small fields must be observed individually and stitched together at the end. In this contribution we present a high angular resolution MCAO study of the central Orion Trapezium Cluster aiming at the detection of planetary mass objects and close sub-stellar binaries.

2. Observations with MAD/MCAO

The Trapezium Cluster has been observed with the MAD (Multi-Conjugate Adaptive Optics Demonstrator) instrument installed on UT3 of ESO’s Very Large Telescope on Cerro Paranal. MAD was built by ESO with major contributions of consortia from the University of Lisbon, and the Arcetri and Padova Observatories, and it is a test instrument for evaluating the feasibility of multi-conjugate adaptive optics for ground-based telescopes [12, 13]. This technique shall provide (almost) diffraction-limited imaging in the near-infrared over a wide field-of-view, where wide refers to \( 1' - 2' \) diameter fields. This is achieved by sensing and correcting the atmospheric turbulence not only in a single direction above the telescope (as regular adaptive optics techniques do), but simultaneously along several different directions within the field-of-view. In the case of our MAD observations the sensing of the atmospheric turbulence was done on the light of 3 reference stars that fed 3 wavefront sensors. A real-time computer analyses the light received by each wavefront sensor at a frequency of 400 Hz, and reconstructs the wavefront errors created by the turbulence. Then, respective corrections are applied via two deformable mirrors (optically conjugated to 0 and 8.5 km atmospheric altitudes, known to contain strong layers of turbulence) in order to obtain an optimized image quality over the whole field-of-view. With a pixel scale of 0.028"/pix the near-infrared camera of MAD provides a field-of-view of approximately 57.5" \( \times \) 57.5".

Table 1. Coordinates (J2000.0) of the observed fields, approximate total integration time per filter, and magnitude of the MCAO guide stars.

| Field central coordinates | \( T_{int} \) in sec | V-magnitude of guide stars |
|---------------------------|----------------------|----------------------------|
| 05 35 16.86, -05 23 07.20 | 2400(H),720(Ks) | 11.4\(^m\),11.1\(^m\),12.5\(^m\) |
| 05 35 18.78, -05 22 09.78 | 2100(H),720(Ks) | 9.6\(^m\),10.6\(^m\),11.4\(^m\) |
| 05 35 18.71, -05 21 17.44 | 2600(H),720(Ks) | 11.9\(^m\),9.6\(^m\),10.6\(^m\) |
Since at least three optically bright wavefront sensing stars must be present within a circle of 2' diameter, the target fields suitable for observations with MAD are limited, even in the high stellar density Trapezium Cluster. Moreover the magnitude difference between these reference stars shall not exceed 3 magnitudes. Searching the whole Orion Nebula Cluster we identified 3 target fields for which we proposed observations at H and Ks-band. The observations were obtained during 2 MAD runs that took place in November 2007 and January 2008. Furthermore, we complemented our observations of the Trapezium central field with observations taken during an earlier commissioning run of the instrument in April 2007, and which are published in [14].

Table 1 lists the central coordinate for each field, the approximate total integration time, and the magnitude of the reference stars used for wavefront sensing. Due to a small dither inbetween individual short exposure images taken per target field, each final mosaic has a size of roughly 65'' x 65''. The total area surveyed thus comprises about 3.5arcmin².

3. Resulting images

For each field and filter we obtained a final stacked mosaic after some basic data reduction was applied to the individual exposures, e.g. sky subtraction, electronic offset correction, and bad/hot pixel cleaning. For all mosaics the image quality, measured in terms of FWHM on point-sources is < 0.1'', and in the best cases ~ 0.07'', which is achieved for the H and Ks observations of the central Trapezium field (see Figure 1). Certainly, the image quality varies over the field-of-view and typically degrades towards the edges of a mosaic. However, the overall improvement in spatial resolution as compared to the seeing-limited case, but also as compared to the single star normal AO observation, is significant. Figure 2, for example, shows that the measured FWHM of point-sources in the H mosaic of the central Trapezium field (left hand side image of Figure 1) is ≤ 0.15'' over a 50'' x 50'' wide field-of-view. This demonstrates the excellent performance of MAD during our observations.

In a next step we used Starfinder [15] to identify stellar and substellar sources in the mosaic images. However, strong electronic cross-talk caused by bright saturated stars created artifacts.
that could easily be misinterpreted as fainter stellar/substellar objects. Therefore, special care was taken not to misidentify an artifact with a star, and cross-checks via visual inspection of objects on the images with the object lists delivered by Starfinder had to be made. In the end, a total number of almost 250 sources has been compiled in our survey.

4. Photometry and candidate substellar mass objects

We applied aperture photometry to all non-saturated objects that have been identified in the H and Ks-band mosaics. Aperture photometry was preferred over PSF photometry, because the PSF strongly varies over the field, due to a non-homogeneous correction achieved by MAD (see also Figure 2). The instrumental magnitudes were calibrated upon the 2MASS HKs-magnitudes [16] and other available HKs-photometry from the literature [17, 6]. The overall detection limits reached are \( \sim 21.0 \) (10\( \sigma \)) at H and \( \sim 19.8 \) (10\( \sigma \)) at Ks, with slightly brighter limits in the Trapezium Cluster center field. These sensitivities confirmed our expectations of being able to detect candidate planetary mass objects in the central part of the Trapezium Cluster: according to the DUSTY evolutionary models of [18], a 3\( M_\text{Jup} \) object at the age of 1 Myr and at the distance of the Trapezium Cluster (440 pc) shielded by \( A_V = 5 \) of extinction has H=20.5 and Ks=19.0, and is therefore well within reach in our highly sensitive MAD observations.

In Figure 3 we show the colour-magnitude diagram for about 200 sources detected in our survey with measured H and Ks magnitudes. Also plotted is the 1Myr isochrone from the DUSTY evolutionary models [18]. Clearly visible in the colour-magnitude diagram is the presence of a large range of intrachannel extinction, as the sources populate a range in H-K colour.
from $\sim 0.5 - 3$ mag. In order to derive an individual source mass, assuming it is a member of the Trapezium Cluster(!), one would have to shift it back along the line of interstellar reddening until it intersects the 1 Myr isochrone. The direction of reddening is presented by the two solid lines, one starting at 75Mjup, the other at 13Mjup, and extending to the lower right. The total length of the reddening lines are equivalent to $\sim 40$ mag. Assuming that the sources are members of the Trapezium all sources between the two reddening lines are potential brown-dwarf objects, while every source below the lower reddening line is a candidate planetary mass object. About 8 candidate planetary mass objects have been detected, which are all new detections. Also some of the $\sim 30$ brown dwarfs detected in our survey have not been reported by any previous observations. These new detections prove the superiority of highest angular resolution images that boost the signal-to-noise ratio in crowded nebulous regions: In Figure 4 we show for comparison a deep, combined, 15min ISAAC image of the Trapezium center, which was obtained under 0.5" seeing [9]. None of the faint sources detected in our MAD observations (right image in Figure 4) have been detected in the ISAAC image.

However, without further photometric and/or spectroscopic observations it is impossible to conclude on the nature and mass of these candidate brown-dwarfs and planetary mass objects. Contamination of our observations with foreground or background objects cannot be excluded. In principle it should be possible to use an astrometric study in a couple of years to differentiate cluster members from background objects based on proper motions. However, as Orion is essentially moving radially away from us, the proper motions are extremely small. Nevertheless, a very simple quick-look approach to the shape of the substellar IMF can be taken by calculating the number ratio of brown dwarfs (13-75Mjup) to planetary mass objects (3-12Mjup). Taking the
purely observed numbers without any corrections, this ratio is $\sim 3.5$ for our MAD observations of the Trapezium cluster center. Interestingly, a very similar value (3.2) has been obtained from a deep survey of brown dwarfs in the periphery of the Orion Nebula Cluster by [11].

5. Close binaries
The high spatial resolution and high sensitivities achieved allow us further to search for any binaries with component separations $< 1''$. At the distance of the Trapezium Cluster such a limit corresponds to $\sim 450$ AU physical separation. In particular, faint sources close to bright primaries can be more easily detected thanks to the enhanced contrast and the significant depth of our survey. A total of 20 binaries have been detected. However, only one system is a new detection and this is actually a potential brown-dwarf binary system with components’ separation of $\sim 0.12''$. It likely escaped detection so far simply because the area wasn’t observed yet with high enough spatial resolution. None of the other potential brown-dwarf sources show a companion, neither do any of the planetary-mass candidates. Although this result awaits further statistical proof from studying a larger sample size, our findings are consistent with previous findings for the binary frequency of low-mass stars in the Orion Trapezium Cluster [17, 19] and with the apparent lack of brown dwarf binaries in the outer regions of the Orion Nebula Cluster [11].

5.1. Acknowledgments
The authors wish to acknowledge the support and assistance from the MAD team from ESO Garching and ESO Chile, who made MAD work efficiently and who operated MAD in the best possible way to provide high quality scientific data. The data for this study has been obtained during science verification time of the MAD instrument.
References
[1] Low C and Lynden-Bell D 1976 *MNRAS* **176** 367
[2] Boss A 2001 *ApJ* **551** L 167
[3] Boyd D F A and Whitworth A P 2005 *A&A* **430** 1059
[4] Bate M R, Bonnell I A and Bromm V 2002 *MNRAS* **336** 705
[5] Bate M R, Bonnell I A and Bromm V 2003 *MNRAS* **339** 577
[6] Muench A A, Lada E A, Lada C J and Alves J 2002 *ApJ* **573** 366
[7] Lucas P W, Weights D J, Roche P F and Riddick F C 2006 *MNRAS* **373** L60
[8] Caballerio J A, Béjar V J S, Rebolo R, Eislöffel J, Zapatero Osorio M R, Mundt R, Barrado y Navascués D, et al. 2007 *A&A* **470** 903
[9] McCaughrean M J, Zinnecker H, Andersen M, Mees G and Lodieu N 2002 *ESO Messenger* **109** 28
[10] Slesnick C L, Hillenbrand L A and Carpenter J M 2004 *ApJ* **610** 1045
[11] Lucas P W, Roche P F and Tamura M 2005 *MNRAS* **361** 211
[12] Marchetti E, Brast R, Delabre B, Donaldson R, Fedrigo E, Frank C et al. 2006 *ESO The Messenger* **129** 8
[13] Marchetti et al. 2007 *SPIE* 6272
[14] Bouy H, Kolb J, Marchetti E, Martín E L, Huélamo N and Barrado y NAVASCUES D 2008 *A&A* **477** 681
[15] Diolaiti E, Bendinelli O, Bonaccini D, Close L, Currie D and Parmeggiani G 2000 *A&A* **347** 335
[16] Skrutskie M F, Cutri R M, Stiening R, Weinberg M D, Schneider S, Carpenter J M, Beichman C et al. 2006 *AJ* **131** 1163
[17] Petr M G, Coudé du Foresto V, Beckwith S V W, Richichi A and McCaughrean M J 1998 *ApJ* **500** 825
[18] Chabrier G, Baraffe I, Allard F and Hauschildt P 2000 *ApJ* **542** 464
[19] Köhler R, Petr-Gotzens M G, McCaughrean M J, Bouvier J, Duchêne G, Quirrenbach A and Zinnecker H 2006 *A&A* **458** 461