Deep in a star forming region with the VLT: looking for sub-Jupiter mass objects

F. Comerón

European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany

Abstract. A remarkable result of evolutionary models for isolated objects with temperatures of $\sim 1,000$ K is the prediction of near-infrared fluxes orders of magnitude larger than they would have if emitting like black bodies. Model predictions of exotic near-infrared colors due to prominent molecular bands have been confirmed by very cool evolved objects discovered in a variety of surveys, implying that such very cool objects are both detectable as well as relatively easy to identify. While such cool objects in the field are relatively evolved, with masses in the range of tens of a Jupiter mass, objects with similar temperatures in star forming regions should have masses in the Jupiter-Saturn range and could be detectable in deep imaging of nearby star forming complexes. Their identification would be essential both to demonstrate their existence and to test the input physics and chemistry of the models.

Here I report on a deep JHK survey carried out with ISAAC at the VLT of a selected area in the Chamaeleon I complex. The vast majority of the objects detected have the colors expected from background high-z galaxies, but one faint object stands out because of its nearly zero $H - K_s$ color, while being undetected at J_s. The $(H - K)$ color suggest a temperature of order of 1,000 K. The blue $(H - K_s)$ color may be due methane and molecular hydrogen absorption in the K_s band, while the non-detection at J_s might indicate an abundant presence of dust in the photosphere.

1 Introduction

The search for the least massive substellar objects has been so far in the domain of very wide field or all-sky imaging surveys, aiming at the detection of freely-floating nearby objects, or of targeted observations searching for companions to known objects. With few and rather serendipitous exceptions ([6]), the coolest substellar objects known to date have been discovered in dedicated searches falling in those categories, rather than in deep field searches. By a fortunate chance, direct identification and follow-up spectroscopy of objects as cool as 1,000 K and even less ([2]) is taking place at a time when precise modeling of objects with masses intermediate between those of the lowest mass stars and of giant planets ([9], [3], [4]) is producing far-reaching predictions testable by observations. The intense interaction between theory and observations over the last decade provides one of the most spectacular recent examples of mutual feedback leading to an accelerate pace of developments in a field of astrophysics.

The masses of the coolest objects directly detected either in the field or as companions are typically in the range of a few tens of a Jupiter mass. The recent discovery of very late-type objects in the young aggregate around σ Ori ([10]) pushes this limit towards even smaller masses, just a few times the Jupiter mass. This narrows down the tantalizing gap between the masses of the lightest freely-floating, directly detectable objects, and those of the giant planets in our own Solar System and in the rapidly growing number of extrasolar planetary systems ([8]).

Deep fields are needed to close this gap. Here I report on a deep infrared image of a field in the Chamaeleon I star forming region where the first object with a mass of the order that of Jupiter or even less may have been found.

2 Model predictions

The emergent flux redistribution due to molecular opacities at temperatures in the 1,000 K range, mainly H_2 and H_2O, enhances the flux in the near-infrared to values several orders of magnitude above those expected from a blackbody at the same temperature and luminosity. At the same time, the strong enhancement at J_s and the depression of the K band due to broad CH_4 and H_2O absorption bands gives these objects a uniquely blue infrared color. These predictions have been essentially confirmed by observations of T dwarfs ([1]) in the field and as companions to low mass stars.

Table 1. Expected photometric properties for isolated planetary-mass objects at the ages of star forming regions (from Burrows et al. 1997)

Mass ($M_\odot$)	Age (Myr)	M_H	$(H-K)$
5	1	9.3	1.22
1	1	13.2	0.08
1	5	16.1	-0.22
0.5	1	15.9	-0.48

The small sensitivity of these features to surface gravity ([3]) suggests that objects with T-dwarf-like spectra in star forming regions should be also easy to detect and identify, but their masses should be much lower at any given temperature. Table 1 gives representative results with giant-planet-like masses at typical ages in star forming regions ([3]). They should be taken as a qualitative approximation, as large offsets in both absolute magnitude M_H and color $(H-K)$ may be expected due to incompleteness in model input quantities, in particular CH_4 linelists. As an aside, it must be said that strong disagreements exist among different groups on whether or not such objects should be called "freely-floating planets" (as their masses are in the giant planet range) or "low-mass brown dwarfs" (as they are isolated and have formation histories and environments different from those of actual planets). To avoid entering such discussions, I am hereafter referring to these objects as "young, isolated planetary-mass objects", or YIPMOs for short.

3 Searching for YIPMOs with the VLT in the Chamaeleon I star forming region

The center of the Chamaeleon I star forming region is a promising ground for the search of YIPMOs. It is only 160 pc from the Sun ([7]), and contains a low-extinction strip abundantly populated by young low-mass stars and brown dwarfs, most of which are about 2 Myr old ([5]). Deep near-infrared imaging was carried out on 27 and 28 March 2000 using ISAAC at the VLT of a field in Chamaeleon I flanked by some of the brown dwarfs reported in [5], while being sufficiently far from bright stars to avoid scattered light. Deep exposures were obtained totaling 7^h9 in K_s, 2^h5 in H, and 2^h7 in J_s. The FWHM of the combined images (0"81 at J_s, 0"71 at H, and 0"66 at K_s) is good taking into account that, due to the very Southern declination ($-77°$) of Chamaeleon I, all the observations had to be done at airmass near 2. Five-σ detection limits were $J_s = 23.0$, $H = 22.4$, $K_s = 22.5$.

A color-magnitude diagram of all detected sources down to $H = 22.5$ is shown in the left panel of Figure 1. The color distribution shows a sharp blue edge near 0.3, with many of the objects near it probably being background stars. Redder objects, most of which are clearly extended in our images, are mainly background galaxies at varying redshifts. However, one object stands out at $H \simeq 22.0$, $H - K \simeq 0.0$. Despite its large formal 1-σ error bar given by the PSF-fitting photometry (with a constant PSF derived from the brightest stars in the field), the fact that the aforementioned blue edge of the color distribution extends to magnitudes fainter than $H = 22$ suggests that the actual errors are not underestimated, and that the gap between the color of this object and the rest of the objects in the field is real. Therefore, based on its unusual blue color, this object may be considered as a candidate YIPMO in Chamaeleon I. The left panel of Figure 1 shows an image centered on it in the J_s, H, and K_s bands, where it can be seen that, while all the other objects in the field become more prominent as one goes from the H to the K_s frame due to both their intrinsic colors and the somewhat greater depth of the K_s image, the appearance of the candidate YIPMO remains similar between both frames.

The left panel of Figure 1 also shows evolutionary tracks corresponding to different masses and ages, from [3], at the distance of Chamaeleon I. The tracks plotted here correspond to ages between 1 and 10 Myr and masses between 0.5 and 5 M_{Jup}. The merging of isochrones in a fairly narrow band implies a considerable degeneracy between age and mass. More important is

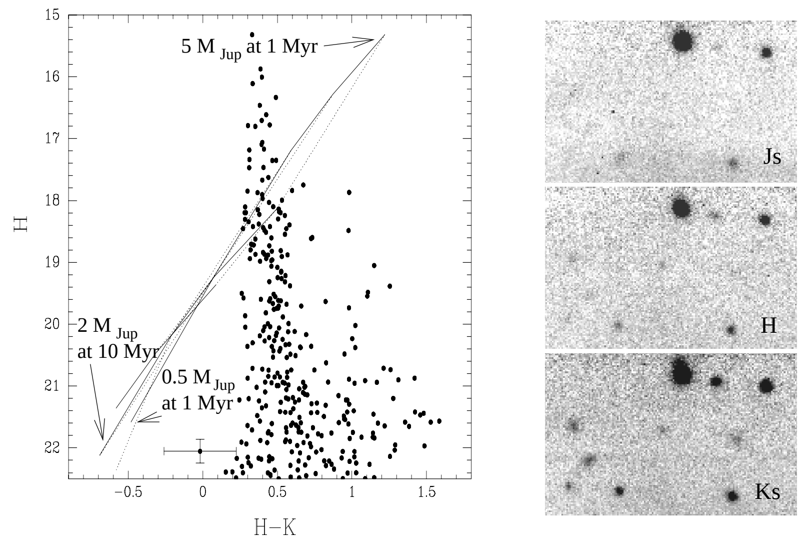

Fig. 1. *Left*: $(H - K), H$ diagram showing the position of all the objects detected in those two bands in the imaged ISAAC field. The candidate YIPMO is the point at the bottom left with formal 1-σ error bars derived from PSF-fitting photometry attached. Curves are theoretical loci of YIPMO models ([3]); solid curves are isochrones, and dotted lines mark equal masses. *Right:* a close-up view of the candidate YIPMO identified in the ISAAC field in the J_s, H, K_s bands. The extract of the image shown here measures 23" $\times$ 15", and is centered on the object.

the fact that models at any age predict colors about 0.5 mag bluer than those of the candidate YIPMO at the same magnitude. This may well be however a shortcoming of models rather than a real conflict between observed and predicted properties of the YIPMO candidate: in fact, an offset in color by the same amount and in the same sense is found between model results and observations of field T dwarfs, thus supporting this interpretation.

An important discrepancy between model predictions and observations of T dwarfs on one side, and the candidate YIPMO on the other, is the very red $(J_s - H)$ or $(J_s - K_s)$ implied by the marginal detection at J_s. Models predict however $(J_s - K_s) \simeq 0.0$, which is excluded by the observations. A tentative interpretation may be based in the presence of dust in the atmosphere of the object, producing an overall reddening of the emergent spectrum ([4]). Models are somewhat uncertain about the role of dust in such objects: at the relevant temperatures discussed here, dust should condense and precipitate under the photosphere, while convection stops somewhat below the $\tau = 1$ level and in principle should not be able to bring the dust grains back into the atmosphere. Nevertheless, it has been suggested that mechanisms such as overshooting or turbulent difusion may alter the situation preventing the complete disappearance of dust grains from the atmosphere. While the blue

$(J_s - K_s)$ colors of field T dwarfs suggest that dust is indeed largely depleted from the atmosphere, it may be possible that this is not the case for objects within the ranges of ages and surface gravities discussed here. Confirmation of the YIPMO nature of the object discussed here would thus provide important constraints on the modeling of cool atmospheres.

4 Future prospects

The spectral energy distribution of the Chamaeleon I YIPMO candidate in the near-infrared is clearly different from that of any of the other objects detected in the field (where over 400 sources are detected in at least one band), and cannot be reproduced by the continuum spectrum of a star or of a normal galaxy at any redshift. While the possibility of it being a real YIPMO is very appealing in view of its location in the direction of a star forming region, alternative possibilities cannot be discarded with the available data. The only one that appears viable is that of an object having strong emission redshifted into the H and K windows. This may be the case if $z \simeq 2.4$, with Hα+[NII] appearing at K and Hβ + [OIII] at H; or of $z \simeq 3.4$, with Hβ + [OIII] at K and [OII] at H. Interestingly, although spectroscopy of such a faint YIPMO may be hard to obtain, the alternative possibility of an emission-line object may be readily confirmed or rejected with a few hours of integration with an 8-m telescope, thanks to the bulk of the emission being concentrated at a single wavelength. Spectroscopic follow-up is thus the obvious next step in trying to verify the nature of this intriguing object. If its membership in the Chamaeleon I star forming region can be confirmed, the gap between directly observed very low mass objects and objects with truly giant-planet masses will most likely have been filled.

Acknowledgements: I am pleased to thank the organizers for having allocated time to make this presentation an oral one. Valuable comments and supplementary data from Adam Burrows gratefully acknowledged, as well as remarks on this work by Isabelle Baraffe and Günther Wuchterl.

References

1. Burgasser, A.J., et al., 1999, ApJ, **522**, L65.
2. Burgasser, A.J., et al., 2000, ApJ, **531**, L57.
3. Burrows, A., et al., 1997, ApJ, **491**, 856.
4. Chabrier, G., Baraffe, I., Allard, F., Hauschildt, P., 2000, ApJ, **528**, 397.
5. Comerón, F., Neuhäuser, R., Kaas, A.A., 2000, A&A, **359**, 269.
6. Cuby, J.G., et al., 1999, A&A, **349**, L41.
7. Knude, J., Høg, E., 1998, A&A, **338**, 897.
8. Marcy, G.W., Cochran, W.D., Mayor, M., 2000, in "Protostars and Planets IV", eds. V. Mannings, A.P. Boss, S.S. Russell, Univ. of Arizona Press.
9. Tsuji, T., Ohnaka, W., Aoki, W., Nakajima, T., 1996, A&A, **308**, L29.
10. Zapatero-Osorio, M.R., et al., 2000, Science, 290, 103.