European Organisation for Astronomical Research in the Southern Hemisphere

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Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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Important Notice:

1. Title — Category: **C–4**

Giant-planet-mass objects in the Large Magellanic Cloud

2. Abstract

The goal of the proposal is to probe the complete substellar mass regime of a young star forming region in the LMC down to 5 M_{Jup}. This mass may be below the opacity limit setting the minimum mass of objects formed by fragmentation at the metallicity of the LMC. Therefore, the observations proposed here have the potential of revealing the opacity limit in a low-metallicity environment such as that of the early Milky Way, thus providing a data point that cannot be obtained from observations in our own Galaxy. The determination of the lowest-mass IMF, and eventually of the location of the opacity limit at low metallicity, will be helpful to constrain the volume density of evolved giant-planet-mass objects lurking in our own galactic disk, which have faded into invisibility since a long time ago. The challenge of these observations is set by the very small size of a typical star forming region, the crowdedness, and the coexistence of the main targets with much brighter stars that can be located a fraction of an arcsecond away.

3.

Run	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	DLI	25h	0.4	n	n	THN	s

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CoI(s): H. Zinnecker (Potsdam, D)

5. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

6. Description of the proposed programme

A) Scientific Rationale: One of the main goals of current observational studies of the stellar and substellar content of star forming region is the detection of the lightest objects that can form in isolation (Lucas et al. 2000, MNRAS, 314, 858; 2006, MNRAS, 373, L60). The lower limit to the mass function of compact objects formed through molecular core fragmentation (stars, brown dwarfs, and isolated planetary mass object) is thought to be related to the opacity limit, i.e. the conditions under which a collapsing and fragmenting core becomes opaque to its own radiation, thus halting further fragmentation. Theoretical estimates for the opacity limit (Rees 1976, MNRAS, 176, 483; Bate 2005, MNRAS, 363, 363, and references therein) lie around 10 M_{Jup}, but simulations including realistic environment conditions of cores have shown that the opacity limit can be overcome to form objects of even smaller masses (Boyd & Whitworth 2005, A&A, 430, 1059). Indeed, observations of very young aggregates have revealed members with masses probably in the range of a few Jupiter masses only (e.g. Zapatero Osorio et al. 2002, ApJ, 578, 536; Luhman et al., 2005, ApJ 635, L93; Jayawardhana & Ivanov 2006, ApJ, 647, L167). As wide-field, deep infrared surveys of star forming regions are carried out in the next years, it may be expected that the existence and location of the lower limit to the substellar mass function will be firmly established.

Nevertheless, even if the lower limit to the initial mass function can be observationally derived soon, it will be so only for the young clusters of the solar neighborhood, all of which have virtually solar metallicity. Since the limit depends on the cooling curve of dense, cold molecular gas and the cloud opacity, metallicity is expected to play a major role in determining it. This has rather far-reaching consequences concerning the evolution of the mass function of galactic disks, since during most of its history the disk our Galaxy has been forming stars at subsolar metallicity. Therefore, knowing the shape of the lower end of the initial mass function at solar metallicity, and knowing the location of its lower mass cutoff, is of limited value for the purpose of estimating the numbers of extremely low mass objects that may exist nowadays in the galactic disk, since an extrapolation of their present-day formation rates would not be possible towards the low-metallicity ages of our Galaxy.

Can this problem be addressed observationally? It seems unlikely at present. Available models at solar metallicity (Baraffe et al. 2003, A&A, 382, 563) indicate that a 5 M_{Jup} object (similar to the lowest-mass ones detected in the σ Orionis cluster; Caballero et al. 2007, A&A, 470, 903) coeval with the Sun would have cooled down to 220 K of surface temperature having $M_J = 29.8$, $M_H = 28.8$, $M_K = 41$. The exotic colors, caused by ethane and ammonia absorption in the K band, would make the object easily identifiable as a K-band dropout (even if the sense of the dropout would be opposite to the common one, i.e., the object disappearing at the long wavelength). However, the faint absolute magnitudes mean that next-generation surveys reaching down to $J \sim 23$ could not detect them beyond 0.4 pc -or about 100,000 AU. Objects of the same mass formed at the beginning of the life of the Galaxy would have faded to $M_J = 34$, and would not be detected beyond 13,000 AU. Somewhat younger objects (ages less than ~ 3 Gyr) of the same mass could be detectable if present at a distance of a few parsecs, but their metallicities would be practically solar and thus not relevant to the determination of the evolution of the low-mass cutoff with metallicity.

Unless we are extremely lucky and one of those objects happens to be in the close vicinity of the Solar System, there is no possibility of detecting a real low-metallicity isolated planetary-mass objects in our Galaxy. Yet these objects might be extremely abundant if the early, low-metallicity Galaxy was at all able to form them.

Interestingly, the ELT will make barely possible the observation of low metallicity brown dwarfs and may answer the question of whether or not they formed, and in which amounts, in the early Galaxy. In principle old galactic planetary mass objects may be detectable with the ELT by carrying out deep surveys reaching up to a few parsecs from the Sun, but the chances to serendipitously detect one such object would be vanishingly small. However, the Magellanic Clouds are places where low-metallicity brown dwarfs are being formed *today*, and are thus many orders of magnitude brighter than their old counterparts of the same metallicity in the disk of our Galaxy. In a 1 Myr old star forming region of the LMC, our 5 M_{Jup} planetary-mass object would still have a temperature of 1900 K and magnitudes $M_J \simeq 10.6$, $M_H \simeq 10.2$, $M_K \simeq 9.7$, with a spectral type probably around mid L. At the distance modulus of the LMC ($DM = 18.5$), this implies $J \simeq 29.1$, $H \simeq 28.7$, $K \simeq 28.2$. The numbers are approximate only for several reasons. First, large uncertainties plague evolutionary models as such early ages (Baraffe et al. 2002, A&A, 382, 563), especially in the giant-planet-mass regime (Marley et al. 2007, ApJ, 655, 541). Secondly, these models are calculated for solar metallicity, whereas the atmosphere characteristics, interior opacities, and evolutionary tracks should be expected to vary sensibly for significantly subsolar metallicity.

B) Immediate Objective: The goal of this proposal is to constrain the low-mass luminosity function down to the giant planet-mass regime in some star forming regions of the Large Magellanic Cloud, with the hope of determining the as yet uncertain location of the opacity limit at the metallicity (40% solar; Hunter et al. 2007, A&A, 466, 277) of the LMC. Typical low-mass star forming regions of the solar neighbourhood like Lupus 3 or ρ Ophiuchi would subtend an angle $\sim 2''$ at the distance of the LMC, thus being appropriate for extreme AO observations which would provide diffraction-limited, high contrast, and deep imaging of the whole stellar and substellar content of the cluster. The instrument of reference is the XAO imager. The regions to be observed could be selected on the basis of their thermal infrared emission detected by other facilities, and would

6. Description of the proposed programme (continued)

normally contain stars of much higher masses, up to a few solar masses for a low-mass aggregate containing Herbig Ae/Be stars at the top end of its mass function, as is the case of well-known nearby star forming regions like Chamaeleon I, Lupus 3, or ρ Ophiuchi. The object density is unknown, as the initial mass function is unknown down to the masses of interest in this proposal, but a rough guess based on the extrapolation of the IMF of galactic star forming region (Chabrier 2003, PASP, 115, 763) yields about 20 members of the aggregate per square arcsecond.

The observations are challenging because of the high density of objects and the fact that they will cover a wide range in magnitudes, from $K \sim 18$ to $K \sim 29$. Simulations should determine whether meaningful photometry of the faintest members given the anticipated degree of crowding can be achieved, or whether the faintest members may be rendered completely undetectable because of the combined wings of the PSFs of (much) brighter members of the star forming region. Simulations can be made more realistic by assuming the presence of a variable background due to reflection nebulosity, especially in the J band, and variable extinction along the line of sight to each aggregate member. Photometric accuracy should be at the 0.1 mag level in order to confirm the low masses of the faintest detected objects on the basis of their colors. Another aspect that may be considered in the simulations is the fact that the LMC, at $\delta = -69°$, is observable at most only at high zenith distance ($> 45°$) from any of the potential ELT sites.

A possible result of the execution of this program could be the observational determination of an opacity limit lying at masses significantly above that of our fiducial 5 M_{Jup} object. Due to the steep mass-magnitude relationship at the lowest masses, an opacity limit located at 10 M_{Jup} would result in the non-detection of objects fainter than $J \sim 27.8$, $H \sim 27.4$, $K \sim 27.0$ (assuming no extinction), well above the limits that we require in this proposal.

The prescription for a realistic simulation should contain the following ingredients:

- A distribution of stellar masses drawn from the Chabrier (2003) initial mass function, whose most up-to-date analytical form (log-normal) can be found at Chabrier 2005, in "The initial mass function 50 years later", eds. Corbelli, Palla, and Zinnecker, Springer. Since we will consider only low-mass star forming regions analogous to the nearby ones, the mass function should be truncated in the high mass end to 2 $M_{\odot}$. The normalization factor will be chosen so that 100 objects are simulated.
- The mass is transformed to J, H, K absolute magnitudes using the evolutionary tracks of Baraffe et al. 2003 for an age of 5 Myr.
- A distance modulus of 18.50 is added to the absolute magnitudes, plus a random extinction in K, A_K, for each star drawn from a uniform probability distribution ranging from 0 to 1. The corresponding extinction in J and H are respectively taken as $A_J = 2.52 A_K$, $A_H = 1.61 A_K$.
- The simulated stars are scattered at random in a circle of $1''$ radius.
- Stellar light reflected by dust is introduced as an increase in the background of the region. Assuming reflection nebulosity with a total reprocessed emission in the K-band equivalent to 1/10 of the solar luminosity in that band, and typical emission nebulosity blue colors $(J - H) = -0.9$, $(H - K) = -0.6$, we obtain a background level of ~ 23.9, ~ 24.8, and ~ 25.4 mag per square arcsecond in the J, H, and K bands, respectively. It is proposed to simulate this contribution as 1- *a uniform background* level over the $1''$ radius of the star forming region, and 2- *a variable background* in which the emission per pixel takes a random value drawn from a uniform probability distribution going from zero background to a brightness that is twice the one corresponding to the values given above. This latter case, in which the background emission is taken as unresolved, is expected to be fundamental in determining limiting the detectability of the faintest sources.

C) Telescope Justification: This program may be marginally feasible only, even for a 42m ELT.

D) Strategy for Data Reduction and Analysis: Crowded field photometry will be needed to analyze the resulting images. Again, the simulations should determine the feasibility.

7. Justification of requested observing time and lunar phase

Lunar Phase Justification: This is broad-band infrared imaging, virtually unaffected by the presence of the Moon in the sky.

Time Justification: (including seeing overhead) To reach the limits $J = 29.1$, $H = 28.7$, $K = 28.2$ at $S/N = 10$, necessary exposure times according to the ETC are: 7h in J, 8h in H, and 10h in K (5 milliarcsecond sampling). The total time per region is thus 25 hours, plus overhead. Observation of several star forming regions is desirable, since their actual member surface densities will vary. The feasibility of this project is expected to be limited by a combination of factors that include the presence of too bright members, excessive crowding, excessive extinction, and variable background emission.

Calibration Request: Standard Calibration

8. Instrument requirements

Diffraction limit imager (DLI):
Wavelength range required: from 1.1 μm to 2.4 μm.

9. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	LMC	05 20 00	-69 00 00	25				

Target Notes: Accurate positions of low-mass star forming regions to be chosen on the basis of thermal infrared imaging available.