European Organisation for Astronomical Research in the Southern Hemisphere

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Important Notice:

1. Title Category: **C–4**

Characterizing the lowest mass freely floating objects in star forming regions

2. Abstract

This proposal aims at the spectroscopic characterization of the lowest mass freely-floating objects selected in wide-area imaging surveys of young star forming regions, carried out with either survey telescopes or large format infrared imagers at 8-m telescopes. It is likely that the physical properties of such objects, as little massive as one or a few Jupiters, can be derived only from the comparison of spectra covering diagnostic atomic and molecular lines to the next generation of ultracool atmospheres. Therefore, the determination of the shape of the lowest-mass end of the substellar initial mass function may be only possible by using relatively high signal-to-noise spectroscopy that can only be provided by ELTs. Besides, spectroscopic monitoring will yield information on the meteorology of these objects, which are expected to display complex weather patterns. The goal of this project is to obtain near-simultaneous spectroscopy of the lowest-mass objects in star forming regions, in the wavelength interval ranging from the red (0.6 μm) spectral region dominated by the opacity in alkali lines, to the near-infrared (4 μm) dominated by molecular opacities (H_2, H_2O, CH_4, NH_3.)

3. Run	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	Single-IFU	100h	any	n	n	THN	s
B	MIR-I/S	100h	any	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: Infrared survey telescopes have the potential of producing a complete census of the entire stellar and substellar contents of all nearby star forming regions down to at least the hypothetical mass where core fragmentation stops, set by the opacity limit at a few Jupiter masses (Rees 1976, MNRAS, 176, 483; Bate 2005, MNRAS, 363, 363, and references therein). The actual limit is uncertain, as some studies have shown that it depends on the initial conditions and may be lower in turbulent cores (Boyd & Whitworth 2005, A&A, 430, 1059). On the other hand, freely floating objects of truly planetary masses well below the opacity limit may exist as a consequence of the dynamical ejection from planetary systems in the earliest evolutionary stages (de la Fuente Marcos & de la Fuente Marcos 1999, New Astron., 4, 21), particularly if planets can form in the circumstellar disks around the individual components of binary systems where ejection is easier (Zinnecker 2001, ASP Conf. Ser. 239, 223). By the time the E-ELT enters operations, it is likely that complete initial mass functions down to giant-planet masses will be available for at least some of the nearest star forming regions thanks to the next generation of infrared wide-field surveys to be carried out by VISTA (e.g. Alcalá et al. 2004, Mem. Soc. Astron. Italiana Suppl., 5, 89), by pencil-beam deep observations with instruments like HAWK-I, and by other surveys of specific regions already ongoing (Caballero et al. 2007, A&A, 470, 903). Those imaging surveys may be able to show the existence of a cutoff to the lower end of the initial mass function of freely-floating objects and check theoretical predictions against actual statistics, but their quantitative results will be limited by the lack of spectroscopic information allowing accurate the determinations of their physical properties.

The faint end of the substellar mass range represents an as yet uncharted region of the parameter space populated by objects with low temperatures ($T < 1000$ K) and low surface gravities ($\log g < 3$); Baraffe et al. (2003), A&A, 402, 701). However, objects with similar temperatures, classified as late T dwarfs, are already known (e.g. Geballe et al. 2001, ApJ 556, 373; Saumon et al. 2007, ApJ, 656, 1136, and references therein) and have been theoretically modeled (Burrows et al. 2001, Rev. Mod. Phys., 73, 719; Marley et al. 2002, ApJ, 568, 335; Burrows et al. 2003, ApJ, 596, 587; 2006, ApJ, 640, 1063). These are typically evolved brown dwarfs found in the field, or in orbit around higher mass companions. Their masses are a few tens of a Jupiter mass, and they have had time during their evolution to cool down to the low temperatures observed now. The atmospheres of such objects are rich in chemistry, mineralogy, and meteorology, truly bridging the gap between the domain of stellar and planetary atmospheres. The formation of molecules and grains at such low temperatures is coupled to large-scale convection extending well into the atmosphere (Helling et al. 2008, A&A, in press), sedimentation of grains below the photosphere, raindown of chemical species, and the formation of clouds and of large-scale weather patterns (Burgasser et al. 2002, ApJ, 571, L151). Observationally, this means that the spectral features of brown dwarf atmospheres must display time variability. Photometric monitoring of T dwarfs has indeed revealed so far that aperiodic brightness variations with amplitudes of up to 0.3 mag and characteristic timescales ranging from several hours to a few days are frequent (Enoch et al. 2003, AJ, 126, 1006; Artigau et al. 2003, in "Brown Dwarfs", IAU Symp. 211, ASP Conf. Ser.). This variability has been attributed to the formation and evolution of cloud decks.

The main difference between the already well known evolved T dwarfs and objects with similar temperatures in a star forming region concerns the mass and the surface gravity. Assuming that such objects do form at all, Baraffe et al.'s (2003) models predict that a $T = 1000$ K object in a 5 Myr young star forming region should have a mass $M = 3$ $\mathrm{M_{Jup}}$ and a surface gravity $\log g = 3.6$, to be compared to $M = 55$ $\mathrm{M_{Jup}}$ and $\log g = 5.3$ for a 5 Gyr-old T dwarf of the same temperature. Observations of a handful of T dwarf-like objects in star forming regions (e.g. Zapatero Osorio et al. 2002, ApJ, 578, 536) indicate colors and spectral features that are similar, but not identical, to those of field T dwarfs, whereas recent atmosphere models clearly identify gravity-dependent spectral features (Burrows et al. 2006). On the other hand, an intriguing possibility currently under theoretical investigation is that the spectrum may contain as well telltale signatures of the formation mechanism. Such signatures would be the consequence of the differences in composition and internal structure between those objects formed in isolation by collapse and fragmentation, and those formed in an accretion disk around a star and subsequently ejected into interstellar space.

While they will be within the detection limits of imaging surveys, spectroscopy of these objects will require EELT capabilities due to their faintness even in the nearest star forming regions at a distance of ~ 150 pc. Expected magnitudes for a 5 Myr object of 1 $\mathrm{M_{Jup}}$ ($T_{\mathrm{eff}} \simeq 640$ K) are $I = 26.2$, $J = 22.7$, $H = 22.5$, $K = 22.9$, $L = 19.4$ (Baraffe et al. 2003). Interestingly, these same models predict that, for objects in the range of exotic colors of interest, a color-absolute magnitude relationship exists that is virtually independent of age over the entire range from 1 Myr up to 10 Gyr. The existence of such *pseudo-main sequence* provides a simple way to estimate the contamination of this region of the color-magnitude diagram of young aggregates due to non-members: objects with the same colors but brighter apparent magnitudes provide a direct measurement of the volume density of evolved objects of any age in the same color range between us and the aggregate. One should note however that luminosity estimates at such young ages are at present extremely uncertain and may fall considerably below those indicative values, as recently shown by Marley et al. (2007, ApJ, 655, 541).

Spectroscopy at moderate resolution is needed in order to analyze the composition of the dust clouds that form in the atmospheres of these objects. The main spectral regions of interest are the J, H, K, and L bands, where the dominant sources of opacity (H_2O, NH_3, CH_4) appear, and also the far red (0.6-1.0 μm) where lines from neutral alkali elements (Li, Na, K, Cs, Rb) dominate the flux depression shortwards of 1 μm (Burrows et al. 2000, ApJ, 531, 438) and together with refractory elements (Al, Ca, Cr...) provide important diagnostics on temperature and pressure (Lodders 1999, ApJ, 519, 793) that can be extremely useful to constrain the evolutionary tracks where the objects lie. Distances to nearby star forming regions, which currently are the dominant source of uncertainty in the observational determination of luminosities, will be known to an accuracy better than ~ 1 % by the time the E-ELT enters operations thanks to the results provided by GAIA.

Time monitoring of ultracool objects will be important, as it will enable the observation of global weather pattern evolution and the development and disappearance of local atmospheric features, thus providing information on the atmospheric circulation, the timescale for the formation of local instabilities, or the role of rotation. The changing cloud coverage in these objects, the complex chemistry in their atmospheres, and the rotational modulation probably makes their spectrum evolve continuously, thus requiring integration times limited to a few hours in order to obtain meaningful snapshots. We expect rotation to be the main factor in limiting the duration of exposures, based on recent results by Zapatero Osorio et al. (2006, ApJ, 647, 1405) that show that field T dwarfs have rotation periods of 12.5 h or less and that the spin-down timescale at such low masses is very slow. Furthermore, with the advances in the modeling of the atmospheres and interiors of these objects expected in the coming decade, it may be foreseen that the spectroscopic characterization will be an even more valuable tool than it is today to relate the properties of ultracool young objects to their masses, thus becoming essential to determine the shape of the IMF at its lowest end.

B) Immediate Objective: This proposal relies on the expectation that theoretical modeling of cool brown dwarfs and freely-floating giant planet-mass objects in the next decade will have reached a stage in which spectroscopic diagnostics will be able to reliably constrain temperatures and surface gravities, and through them ages and masses. Therefore, spectroscopic classification will be the tool to use in order to derive the shape of the initial mass function, its possible truncation at the lowest masses, and perhaps even the origin of the lowest mass isolated objects.

We propose this project as one to be carried out under suboptimal conditions, when advanced AO capabilities of the EELT cannot be exploited. Therefore, we suggest to carry out the simulations assuming a modest level of AO performance.

This project should be rather straightforward from a simulation point of view. The red/infrared part should be carried out using the visible/infrared IFU spectrograph for the region shortwards of 2.5 μm, and the MIDIR infrared IFU at longer wavelengths. Theoretical spectra and fluxes of objects similar to those that we intend to observe are available, and the feasibility study should thus be reduced to the determination of the signal-to-noise ratio of the spectra of such objects after integrations of a (small) number of hours. The main questions that the simulation should address are:

* Given an exposure time limited to two hours by the object's rotation period, what are the limiting masses that can be reached at the nearest star forming regions (Chamaeleon, Lupus, Ophiuchus, R CrA...)?

* Given expected E-ELT performances in the infrared and the colors of the targets, what is the best spectral region for the spectroscopic study of these objects?

We will use Baraffe et al.'s (2003) predicted magnitudes at 5 Myr to set the fiducial cases to be considered. The second item above obviously involves a tradeoff between the maximization of the S/N ratio for a given integration time, and the scientific interest of the spectral features accessible in a given wavelength range. The table below summarizes the range of properties to be considered, for a distance modulus of 6.0 mag that is roughly applicable to all the regions listed in Section 12:

$M = 0.5\ M_{\rm Jup}$: $T = 455$ K, $\log g = 2.790$, $I = 28.25$, $J = 25.37$, $H = 24.91$, $K = 26.96$, $L = 21.03$
$M = 1\ M_{\rm Jup}$: $T = 644$ K, $\log g = 3.141$, $I = 26.34$, $J = 22.84$, $H = 22.57$, $K = 22.97$, $L = 19.56$
$M = 3\ M_{\rm Jup}$: $T = 1098$ K, $\log g = 3.576$, $I = 23.54$, $J = 19.89$, $H = 19.56$, $K = 16.21$, $L = 17.21$
$M = 10\ M_{\rm Jup}$: $T = 1965$ K, $\log g = 3.921$, $I = 19.61$, $J = 16.80$, $H = 16.44$, $K = 16.00$, $L = 15.06$

C) Telescope Justification: These are really faint objects, well beyond the reach of the VLT. While NIRSpec on the JWST will be highly competitive at near-infrared wavelengths longwards of 1 μm, the short-wavelength interval (< 1 μm) can be only covered by the E-ELT at the appropriate sensitivity level. The E-ELT also offers the advantage of making the monitoring aspect of this program easier to schedule. Finally, it may be noted again that this is a program with weak constraints on seeing, transparency, or adaptive optics performance, which would allow the E-ELT to keep doing unique science under worse-than-average atmosphere conditions.

The IFU capabilities offered by the instruments of choice are not directly relevant to this proposal, which would also be feasible with a long-slit spectrograph.

D) Strategy for Data Reduction and Analysis: Data reduction should be straightforward, as this is low-resolution spectroscopy of a single point source.

6. Attachments (Figures)

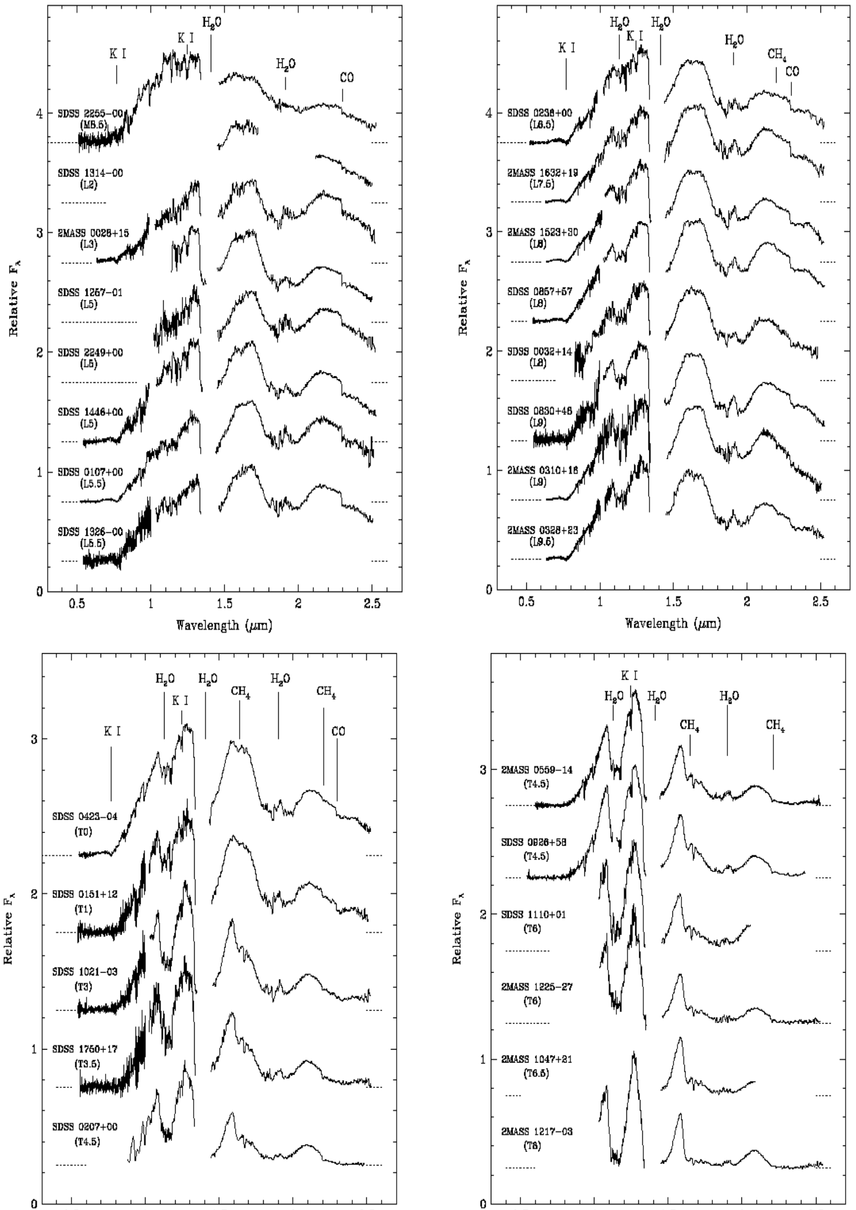

FIG. 3c FIG. 3d

Fig. 1: Examples of field (evolved) cool spectra ranging from late M-type ($T \simeq 2300$ K) to late T-Type ($T < 1000$ K). Note the strong water vapor bands and the onset of strong CH_4 absorption at early T Types. From Geballe et al. (2002), ApJ, 564, 466.

7. Justification of requested observing time and lunar phase

Lunar Phase Justification: This is low-resolution red/infrared spectroscopy limited in time by the object spectral variability. The infrared part can be done under bright conditions, whereas grey conditions would be better for the red part.

Time Justification: (including seeing overhead) Monitoring should take place on several timescales. Every time that the program is executed the observations should extend continuously for one or possibly two full nights to sample the rotational modulation (thus sampling regional variations as the object presents different hemispheres to us). Then, they should be repeated once per week and once per month to sample the evolution of the cloud coverage and weather patterns. The estimate of 100h of observing time per instrument is provided to account for these different monitoring timescales on approximately 10 objects in a given star forming region.

Calibration Request: Standard Calibration

8. Instrument requirements

AO-fed single field IFU spectrograph (Single-IFU):
Wavelength range required: from 0.6 μm to 2.4 μm.
Spectral resolution: 3,000
Simultaneous wavelength coverage over a range as broad as possible is desirable. Together with depth it takes preference over spectral resolution.

Mid-IR imager, low- and high-resolution spectrograph (MIR-S):
Wavelength range required: L' band.
Spectral resolution: 3,000
Monitoring observations should be taken as closely as possible to those obtained with the Single-IFU instrument to avoid the effects of variability.

9. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
AB	Rho Oph	16 30 00	-24 00 00	2				
AB	R CrA	19 00 00	-37 00 00	2				
AB	Lupus 3	16 10 00	-39 00 00	2				
AB	Chamaeleon I	11 10 00	-77 00 00	2				

Target Notes: These are rough positions of the nearby star forming complexes targeted by this project.