EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME — PERIOD: **78A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of COIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title — Category: **B–2**

The Centers of Massive Dense Young Clusters: deep ELT infrared imaging and 3D spectroscopy

2. Abstract

We propose to use the 42 m ELT at 2 – 5 microns (broad band and narrow-band filters) to probe the the number density and brigthness of deeply embedded massive stars and protostars just formed in dense Galactic protocluster clouds (ultracompact HII regions, hot cores, outflow and maser sources), penetrating as much as 200 mag of visual extinction. The combination of astrometric, proper motion (1 mas/yr) and spectroscopic, radial velocity ($R \sim 10^4$) data are crucial to study dynamical processes associated with cluster formation, such as tight binary formation and gravitational interactions followed by stellar ejections. Integral field spectroscopy is needed for these dense and severely crowded clusters (up to 1000 objects per square arcsec at $K = 25 - 30$).

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	79	ISAAC	20h	any	d	$\leq 0.4''$	PHO	v
B	79	SINFONI	66h	any	d	$\leq 0.4''$	PHO	v

4. Number of nights/hours — Telescope(s) — Amount of time

a) already awarded to this project:

b) still required to complete this project:

5. Special remarks:

In order to establish feasibility we need detailed simulations to determine the dynamic range of deep infrared LTAO imaging in a crowded field. Similarly, we need to determine the accuracy of sub-mas proper motion AO observations. The simulations should take into account the extra noise contribution due to infrared "cloudshine".

6. Principal Investigator: H. Zinnecker (AIP Potsdam, D, hzinnecker@aip.de)

CoI(s): F. Comeron (ESO, D), M. McCaughrean (Exeter, UK)

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

8. Description of the proposed programme

A) Scientific Rationale: Massive stars ($M > 20\,M_\odot$) represent powerful engines of change/evolution within their galactic and extragalactic environment. When they die and explode as supernovae, they dramatically deposit lots of kinetic energy and chemically enriched material in the interstellar medium. Yet despite their enormous overall importance for galactic dynamical and chemical evolution, their origins and birth processes remain poorly understood (Bally & Zinnecker 2005; Zinnecker & Yorke 2007).

In this DRM proposal, we outline how future ELTs (> 30 m diameter) help to understand the formation and early dynamical evolution of massive stars embedded in highly obscured very compact HII regions. The wavelength range of 2 − 5 microns (K-,L-, and M-bands) is required to penetrate the visual extinction (up to $A_v = 200$ mag) in the dense molecular clumps ($N_{H2} = 3{\cdot}10^{23}\,cm^{-2}$) where massive stars are born. Note that J-band (1.2 micron) and H-band (1.6 micron) observations do not peer into such dense dusty birthplaces while K-band observation do ($A_J = 0.28\,A_V$, $A_H = 0.18\,A_V$, $A_K = 0.11\,A_V$; $A_V = 200$). The L- and M-band ($A_L = 0.06\,A_V$, $A_M = 0.02\,A_V$) data are needed to probe the hot and warm circumstellar matter (disks/envelopes) by means of the detection of infrared excess (K-L, L-M); the Pfund gamma (3.76 micron) and Brackett alpha (4.05 micron) recombination lines also fall into these L and M bands, respectively, and allow us (in conjunction with their flux ratio to Brackett gamma at 2.17 micron and via Menzel Case B recombination line theory) to determine the extinction towards resolved ionizing stellar sources, i.e. massive stars, in ultra-compact (size 0.1 pc) and hyper-compact (size 0.01 pc) radio HII regions, which indicate the deeply embedded sites of high-mass star formation. If we know the extinction, we can correct the K-band and V-band magnitudes and can determine the luminosities and masses of the bright central cluster stars. These massive stars are born on the Main-Sequence and are not dominated by accretion luminosity anymore (Zinnecker & Yorke 2007). They typically originate in dense, crowded stellar clusters or Trapezium systems, with linear star-to-star separations of the order of 1000 − 5000 AU (inferred from aperture synthesis radio observations of ultra- and hyper-compact HII regions). At the typical distances to massive star forming regions of 2 to 10 kpc, such linear separations translate into angular separations of 0.1 to 0.5 arcsec. Considering that there up to to a dozen embedded massive stars in such dense protocluster clumps implies a central surface density of 20 to 1000 objects per square arcsec! To convincingly resolve such crowded stellar systems, we need 10 mas angular resolution observations, the same as ALMA in the submm regime. Thus, these observations need 5 times better angular resolution at 2 microns than JWST will provide, while WFC3 on HST does not cover the required 2 − 5 micron domain but stops at 1.6 micron. HST/WFC3 may thus detect and resolve near-infrared sources in less extincted ($A_V = 50 - 100$ mag) less crowded regions (at a later stage of evolution), while JWST can go to higher extinction but only in more nearby protoclusters at 500 − 1000 pc, such as the Orion-KL region, not at 5 − 10 kpc, i.e. the Galactic Center region. The number of massive star formation sites is very limited in the solar neigborhood and grows with distance squared. Thus, ELT (together with ALMA) will be the telescope of choice, when it comes to study the variety of high-mass birthplaces in dense incipient clusters in the inner Galaxy. In the more nearby massive star formation regions (1 − 2 kpc) the angular resolution of the ELT may help to detect short-period binary and multiple systems by way of precise astrometric signatures in the reference frame of bright cluster stars and study their mass ratios. Close binary evolution of massive stars depends to a great deal on the initial binary mass ratio and is relevant as input for understanding the origin of low-mass and high-mass X-ray binaries. Finally, gravitational interactions will occur in such dense protoclusters and some heavyweights may be ejected at speeds in excess of 50 km/s (Blaauw's runaways). 50 km/s is 10 mas/yr at 1 kpc or 1 mas/yr at 10 kpc; this again shows we need 10 mas spatial resolution to catch these dynamical ejection phenomena in the distant clusters (e.g. near the Galactic Center).

To summarize: We plan to exploit the ELT's near- and mid-IR enhanced sensitivity and angular resolution to peer through huge amounts of dust extinction, and take direct nearly diffraction limited infrared images, in order to determine the stellar density in the centers of deeply embedded, massive clusters (e.g. the progenitor of NGC3603), before the gas has been expelled and the cluster hatches. This will allow us to infer if stellar collisions are likely in the formation of the most massive stars and perhaps, in combination with ALMA submm observations, if such clusters form as a result of global collapse of molecular clouds.

As an example, we derive the scientific requirements for an ELT to resolve a cluster of four massive stars (Trapezium system) embedded in a dense hypercompact HII region with radius 1000 AU at 2 kpc distance (diameter 1") behind 200 mag of visual extinction (22.5 mag extinction in the K-band at around 2 μm and 4.5 mag in the M-band at around 5 μm; see the relations given above based on the interstellar extinction law of Rieke & Lebofsky 1985). High proper motion (several mas/yr), including dynamical ejections at velocities in excess of 30 km/s due to close encounters (ca. 20 AU), in such multiple systems can be monitored over a 1 − 2 year timeline. We can also work out that we need to reach a limiting apparent magnitude of K = 28 (S/N = 5; 1 hr), to see deeply embedded early O-stars assuming an absolute O-star magnitude of M_K = -6 and a distance modulus of 11.5 (2 kpc). These requirements can be met by a giant telescope of 42 m diameter, if a natural near-IR bright guide star can be found, within 10 − 30", perhaps in the adjacent compact HII region, on which the wavefront sensing can be performed. Alternatively, a laser guide star must be used (LTAO).

Follow-up integral field spectroscopy of the incipient cluster will also be required. The first goal here would be to derive the extinction to the individual massive stars by measuring the flux ratio of the Brackett gamma

8. Description of the proposed programme (continued)

(2.17 μm) to Brackett alpha (4.05 μm) line, which changes with extinction from its intrinsic Menzel Case B value (1/3). Secondly, we expect to detect collimated H_2 jets (2.12 μm) if the stars are in a phase of active disk accretion. Also, CO bandhead emission and absorption (both the fundamental at 4.6 μm and the first overtone at 2.3 μm) must be searched for to determine the temperature of the warm gas near the stellar photosphere and its kinematics (rotation, infall). A velocity resolution of 30 km/s is required, i.e. $R = 10^4$. This would also allow us to detect radial velocity variations and orbital motion of massive close binaries, making use of near-IR photospheric absorption lines. Many visible massive OB stars are double-lined short-period spectroscopic binaries, but the question is whether they are born as close binaries or if they form by disk-assisted grazing collisions (Moeckel & Bally 2007).
The requirements on the integral field spectroscopy are as follows: we would hope to use 4 k × 4 k IR-arrays, which at 5 mas/pixel provide a FOV = 20" for imaging, thus catching the wider cluster core (0.1 pc). For IFU spectroscopy, we can concentrate the unit on the central or other 2" × 2" fields, requiring 400 × 400 = 160,000 fibers. Given the desired spectral resolution of 10,000, we need 2000 pixels to disperse the whole K-band. If we use only 1/2 of the K-band (2.10 − 2.18 μm for H_2 and Brg, and 2.29 − 2.31 μm for 2-0 CO bandhand), we can fit 4 spectra in one spectral row. As we have 4 k spectral rows, we can fit 16 k spectra or spexels on one IR array detector, hence we need 160,000/16,000 = 10 IR chips to match our scientific requirements. Similar for the M-band. Not impossible, by 2015.
Finally we mention that ALMA will have a similar resolution of 10 mas at submm wavelengths as the E-ELT in the near- and thermal infrared. Hence, while ELT will be particularly good at detecting OB stars at the end of their main accretion phase, ALMA should see OB protostars, i.e. massive stellar objects in their early or main mass assembly phase. Together ELT and ALMA are a powerful combination to reveal one of the most hidden but most important secrets of stellar astrophysics: the origin of massive stars.

B) Immediate Objective: Our ELT measurements will be directed to regions with signs of active massive star formation, such as the Orion BN/KL hidden source(s), Spitzer infrared dark clouds with UCHII regions as as well as hot molecular cores with methanol (or H_2O/OH) masers, all known to pinpoint massive stars in the process of formation. These measurements have the following immediate objectives: (1) see the photospheres of deeply embedded stars and protostars and determine the stellar number density in these dense molecular cloud clumps. This is important to estimate the likelihood of stellar collisions, a process under discussion for the growth of very massive stars (Bonnell, Bate & Zinnecker 1998); (2) check if the cluster center is mass segregated at birth, i.e. whether all bright massive stars are actually located near the cluster center, a profound prediction of the theory of massive star formation by competitive accretions including the merging of subclusters (Bonnell, Bate & Vine 2003). (3) from proper motion astrometric measurements at two epochs (1 year apart) find evidence for dynamical interactions, such as gravitational slingshot effects and stellar ejections at speeds characteristic of OB runway stars, i.e. some 40 − 100 km/s corresponding to (1 − 2 mas/yr) at 4 − 8 kpc distances of typical massive star forming regions; (4) integral field spectroscopic follow-up, as described above, to complement the proper motion data with radial velocity information, also relevant to catch the close spectroscopic massive binary population at birth. It is the interactions with these "hard" binaries that give rise to the ejection of single massive stars from the cluster (e.g. de Wit et al. 2005 and "runaway" O-stars references therein). (5) try to observe the subfragmentation of a centrally-peaked, dense molecular core destined to form a massive star in its center by identifying column density fluctuations on very small sub-arcsec scales, using the NICE method of Alves, Lombardi & Lada (2007) which measures the near-infrared color excess of background stars through the cloud core in question (here K_{long} vs. K_{short}, or even K-L). Such data would settle an ongoing debate between two schools of massive star formation: Dobbs & Bonnell (2005) vs. Krumholz & McKee (2005). The former authors predict fragmentation occurs, the latter disagree and predict a monolithic collapse without fragmentation.

C) Telescope Justification: The ELT is needed because of its sheer penetrating power into dusty protocluster clouds and because of its very high angular resolution. The latter is also instrumental for measuring the expected small proper motions (sub-mas astrometry).

D) Observing Mode Justification (visitor or service): Commissioning time, science verification is needed for DRM proposals. (visitor or service).

E) Strategy for Data Reduction and Analysis: Data reduction will be non-standard, cloudshine (Foster & Goodman 2006) maybe a noise-source compromising the photometric and astrometric precision.

8. Attachments (Figures)

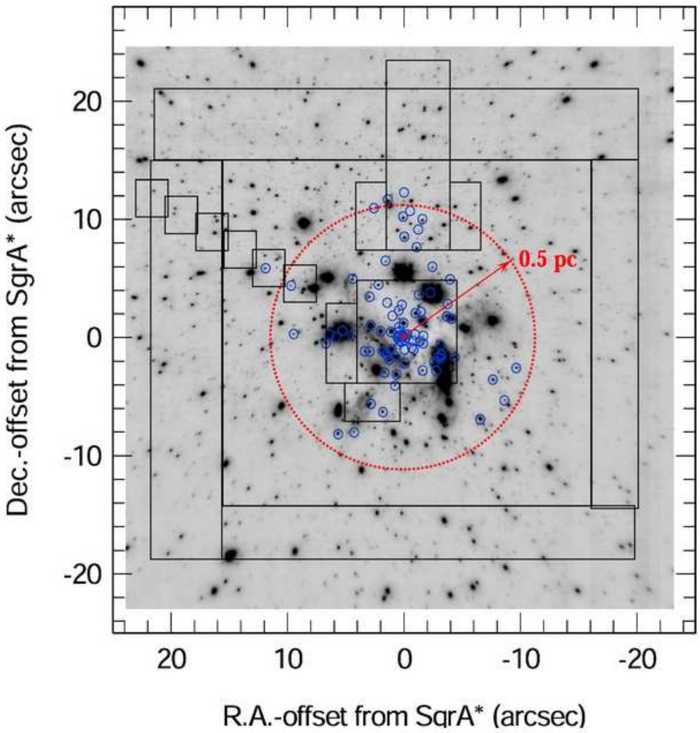

Fig. 1: Outline of the various 2003 – 2005 SPIFFI/SINFONI H+K- and K-band cubes, superposed on a $\simeq 100$ mas resolution, L-band NACO image (logarithmic scale). Small circles denote the 90 quality 1 and 2 early-type stars (OB I – V, Ofpe/WN9, W-R stars. A dotted circle denotes a 0.5 pc (20 arcsec) radius zone centered on Sgr A*, within which essentially all OB stars we have found appear to lie (from Paumard et al. 2006).

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: Our infrared observations don't necessarily need dark time.

Time Justification: (including seeing overhead) Using the ELT- Experimental ETC (Version 2.4WG) assuming that Laser tomography Adaptive Optics is available, and 5mas pixels for an average star (e.g., A0), we can obtain point sources images down to a magnitude $K = 28$ in approximately 1 hour of integration ($S/N = 5$). We await detailed simulations to see how crowding and cloudshine will affect the limiting K-magnitude. L and M band limiting magnitudes are even more unclear, no information yet from the ETC at this point.
For the $6-8$ targets selected ($3-4$ in the Galactic Center region) we estimate a total of 200 hr for the wide- and narrow-band infrared adaptive optics observations (24 hours or 2 nights per star forming region).

Calibration Request: Special Calibration -

10. Report on the use of ESO facilities during the last 2 years

Test observations with VLT/NACO

11. Applicant's publications related to the subject of this application during the last 2 years

Alves, Lombardi, & Lada 2007, A&A 462, L17; Bally & Zinnecker 2003, AJ 128, 2381; Bonnell, Bate, & Zinnecker 1998, MNRAS 298, 93; Bonnell, Bate, & Vine 2003, MNRAS 343, 413; de Witt et al. 2005, ASPC 347, 389; Dobbs & Bonnell 2005, PPV, 8170; Foster & Goodman 2006, ApJ 636, L105; Krumholz & McKee 2005, ApJ 630, 250; Megeath, Wilson, & Corbin 2005, ApJ 622, L141; Moeckel, N. & Bally 2007, ApJ 656, 275 Paumard et al. 2006, ApJ 643, 1011; Rieke & Lebofsky 1985, ApJ 288, 618; Zhang & Ho 1997, ApJ 488, 241; Zinnecker 2006, IAU-S232 Cape Town; Zinnecker & Yorke, Annual Review A&A 45, 481 − 563 (and 480 references therein)

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	name	RA	DEC	time(hrs)	mag	DM	ang diam(")	note
A	BN/KL	06 00	-05 00	12	M = 4	8.5	10"	Orion-IRc2 protostar
A	SgrA*	17 59	-29 00	24	10–25	14	40"	Galactic Center OB cluster
A	W51-IRS2	19 24	+14 30	8	10–25	14	10"	dense embedded cluster
A	G10.6-0.4	18 10	-19 56	8	10–25	14	10"	dense embedded HII region
B	BN/KL	06 00	-05 00	24	10–25	8.5	10"	Orion-IRc2 protostar
B	SgrA*	17 59	-29 00	24	10–25	14	40"	Galactic Center OB cluster
B	W51-IRS2	19 24	+14 30	8	10–25	14	10"	dense embedded cluster
B	G10.6-0.4	18 10	-19 56	8	10–25	14	10"	dense embedded HII region

Target Notes: Other targets near the Galactic Center include: Arches and Quintuplet clusters, a Spitzer protocluster in SgrB2; heavily obscured, deeply embedded protoclusters in infrared dark clouds (IRDC) including IRAS, ISO, MSX, and Spitzer selected regions (TBD; from Beuther/Garay) weakly obscured dense young clusters: NGC 3603, Tr14 and Tr16 in the Carina regions, and the dense center of 30 Dor (R136) in the Large Magellanic Cloud.
The targets in run A are for LTAO imaging, the targets in run B are for IFU imaging/spectroscopy.

12b. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If yes, explain why the need for new data.

13. Scheduling requirements

14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
79	ISAAC	A	IMG	KLM
79	SINFONI	B	IMG	KLM