European Organisation for Astronomical Research in the Southern Hemisphere

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

VISITING ASTRONOMERS DEPARTMENT • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: visas@eso.org • Tel. : +49-89-32 00 64 73

APPLICATION FOR OBSERVING TIME PERIOD: 80A

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: **C–7**

Dynamics and chemical evolution of circumstellar disks

2. Abstract

We propose near- and mid-infrared (2-20 microns) spectroscopy of young circumstellar disks using the E-ELT in order to study their internal dynamics and the chemical processing of dust, gas, and ices. These observations would ideally be carried out via near-diffraction limited integral-field imaging covering a FOV of 2-5 arcsec.

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	80	SINFONI	100h	any	n	$\leq 0.6''$	CLR	s
B	80	VISIR	100h	any	n	$\leq 0.6''$	CLR	s

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:

This is an E-ELT observing program, with SINFONI and VISIR acting as placeholders for diffraction-limited, small-field near- and mid-IR IFU spectrographs, respectively.

6. Principal Investigator: **M.J. McCaughrean** (University of Exeter, UK, mjm@astro.ex.ac.uk)

CoI(s):

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: In the paradigm of the formation of low-mass stars and their planetary systems, circumstellar disks are a critical component, as they provide a conduit to channel material onto the forming star (Hartmann et al. 1997, ApJ 475 770) and supply a reservoir of material from which planets may form (Bodenheimer & Pollack 1986, Icarus, 67 391). They are also directly involved in the formation and collimation of jets and outflows, generally thought to be implicated in the key process of angular momentum removal (e.g., Coffey et al. 2004, ApJ 604 758).

After centuries of speculation that our own solar system must have formed from a rotating disk of gas and dust, the existence of circumstellar disks around other young stellar objects (YSOs) is now firmly established (Beckwith et al. 1990, AJ 99 924; Strom et al. 1993, Protostars & Planets III, 837; Beckwith & Sargent 1996, Nature 383 139). Disks are found around $\sim$30–50% of all low-mass (0.3–3 $M_\odot$) young (0.3–10 Myr) stars, with radii $\sim$10–1000 AU, and masses $\sim$0.01–0.1 $M_\odot$. Most of these results are based on indirect measurements (e.g., spectral energy distributions, asymmetric wind profiles, polarization mapping), but in the past decade, well-resolved direct images of circumstellar disks have become available and can provide us with important information on the structure of the disks and how they are affected by their ambient environment (e.g., Burrows et al. 1996, ApJ 473 437; McCaughrean & O'Dell 1996, AJ 111 1977; Watson et al. 2007, Protostars & Planets V, 523).

Over 10–100 Myr, these optically-thick young disks lose their original gas and dust through accretion onto the central star or through agglomeration and accretion to form planets and planetesimals. This transition between young, optically-thick, gas-dominated disks and older, residual dust debris disks is crucial to our understanding of the planet formation process (e.g., Meyer et al. 2007, Protostars & Planets V, 573). In particular, it is important to study the dynamical structure and the chemical and physical evolution of the gas in the inner disk regions as it is incorporated into planetary bodies (Najita et al. 2007, Protostars & Planets V, 507).

B) Immediate Objective: We propose high spectral and spatial resolution near- and mid-IR imaging spectroscopy of gas and dust in young and transition disks, in order to trace their chemical and dynamical evolution. The E-ELT is fundamental to such studies, inasmuch as its very large collecting area and AO systems will yield the required high spectral resolution, high angular resolution, and high sensitivity.

Gas in the inner disk: In order to understand the formation of our Solar System, it is important to examine the inner regions (<10 AU) of young gas- and dust-rich circumstellar disks. In particular, it is important to study the gas, which can give direct indications of the dynamical state of the material. The key tracers of inner disk gas are the CO bandhead lines at 2.3 and 4.6μm (Carr et al. 1993, ApJ 411 37; Najita et al. 2003, ApJ 589 931), H_2 lines at 2, 17, and 28μm (Weintraub et al. 2000, ApJ 541 767; Bary et al. 2002, ApJ 576 73; Thi et al. 2001, ApJ 561 1074), and H_2O rotational-vibrational lines at 2μm (Najita et al. 2000, Protostars & Planets IV, 457).

In particular, CO fundamental $\delta v = 1$ bandhead emission at 4.6μm should be a key tracer of the gas across the whole potentially terrestrial planet-forming regions of a disk from the co-rotation radius outwards (0.05–2 AU), given the required excitation temperatures and densities (Figure 1). The 2.3μm CO overtone bandhead tends to trace only hotter, denser material at smaller orbital radii (<0.5 AU).

High spectral resolution is required to trace the gas dynamics: R=100,000 yields a velocity resolution of a 3 km s^{-1} (*cf.* the 30 km s^{-1} orbital velocity of the Earth). Similarly, high signal-to-noise of a few hundred is required to measure the CO line profiles accurately (Figure 2). The diffraction-limited angular resolution of a 42 m E-ELT is 28 mas at 4.6μm, yielding 4 AU at 150 pc, and thus typically the inner disk region cannot be spatially resolved. Nevertheless, a combination of a high Strehl ratio and a large collecting area is needed to deliver the high signal-to-noise observations required.

The formation of gas giant planets: It is also important to study the evolution of warm molecular gas in disks as the building material for giant planets. Diffraction-limited integral field imaging spectroscopy in a number of rotational lines of H_2 simultaneously will make it possible to determine the radial distribution of mass and temperature and, in tandem with ALMA studies in the dust continuum, the gas-to-dust ratio. Wide spectral coverage is necessary here in order cover many lines simultaneously and, in general, high dynamic range spectroscopy is required in order to allow the tracing of faint features against the bright continuum of the central young star.

Astrochemical evolution of gas and dust: The gas and dust in a circumstellar disk undergo significant processing en-route to planet formation. Near- to mid-infrared spectroscopy allows access to tracers from a wide variety of gas-phase molecules, amorphous and crystalline silicates, PAHs, ices, and organic materials. It is important to trace the processing of these materials by UV radiation, X-rays, and thermal radiation from the central protostar and other, more massive stars in the local environment. These materials cycle back and forth between gas and solid phases as a disk evolves and by studying the astrochemical evolution in detail, it will be possible to trace the formation history of planetesimals and other solid bodies, their composition, their processing, and search for signs of complex organic molecules, the precursors of life. Spectral resolutions should range from R=300 to 3000 for the broad solid and gas phase species, respectively.

8. Description of the proposed programme (continued)

Near- and mid-IR E-ELT spectroscopy would be directly complementary to that obtained at sub-mm/mm wavelengths with ALMA of colder gas at larger distances from the parent star.

Complementary diffraction-limited near- and mid-IR imaging E-ELT studies of scattered light and direct thermal emission in the inner 1–30 AU of circumstellar disks in search of gaps, bands, and non-axisymmetric structures is presented in another DRM case.

C) Telescope Justification: A very large, filled aperture telescope is needed in order to achieve the required high signal-to-noise at high spectral resolution. Excellent Strehl ratio is needed in order to provide maximum sensitivity at thermal-IR wavelengths (see below).

D) Observing Mode Justification (visitor or service): Low, medium, and high resolution spectroscopy is needed from 2–20μm, preferably at high spatial resolution. This would permit resolved imaging of the nearest disk systems and for more distant, unresolved systems, greatly enhanced point source sensitivity in the face of high thermal backgrounds (the time to reach a given point source flux limit is inversely proportional to D^4 for background-limited, diffraction-limited telescopes with diameter D). Ideally, integral field spectroscopy would be used to ensure access to multiple lines across a resolved source simultaneously. Only a relatively small field is required: a 100 AU diameter disk subtends 0.7 arcsec at 150 pc.

Although the JWST is nominally much more sensitive than even the E-ELT at thermal-IR wavelengths, JWST does not have the required spectral resolution for the dynamics experiments or the spatial resolution necessary to image disks in star-forming regions directly.

E) Strategy for Data Reduction and Analysis: Reduction and analysis of the proposed imaging spectroscopy data are relatively straightforward.

8. Attachments (Figures)

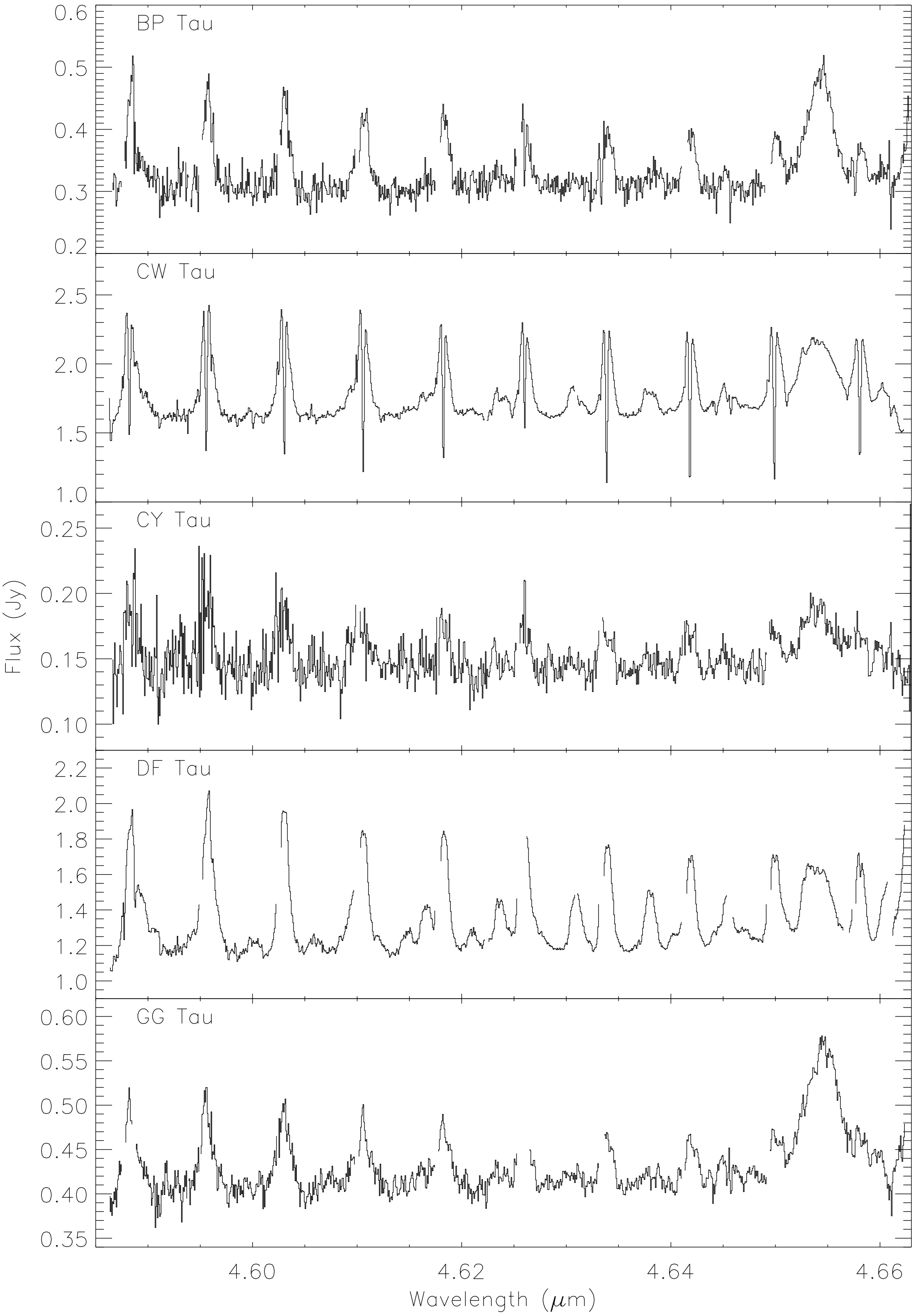

Figure 1: Keck NIRSPEC observations of the CO fundamental lines near 4.6μm for a number of classical T Tauri stars (Najita et al. 2003, ApJ 589 931).

8. Attachments (Figures)

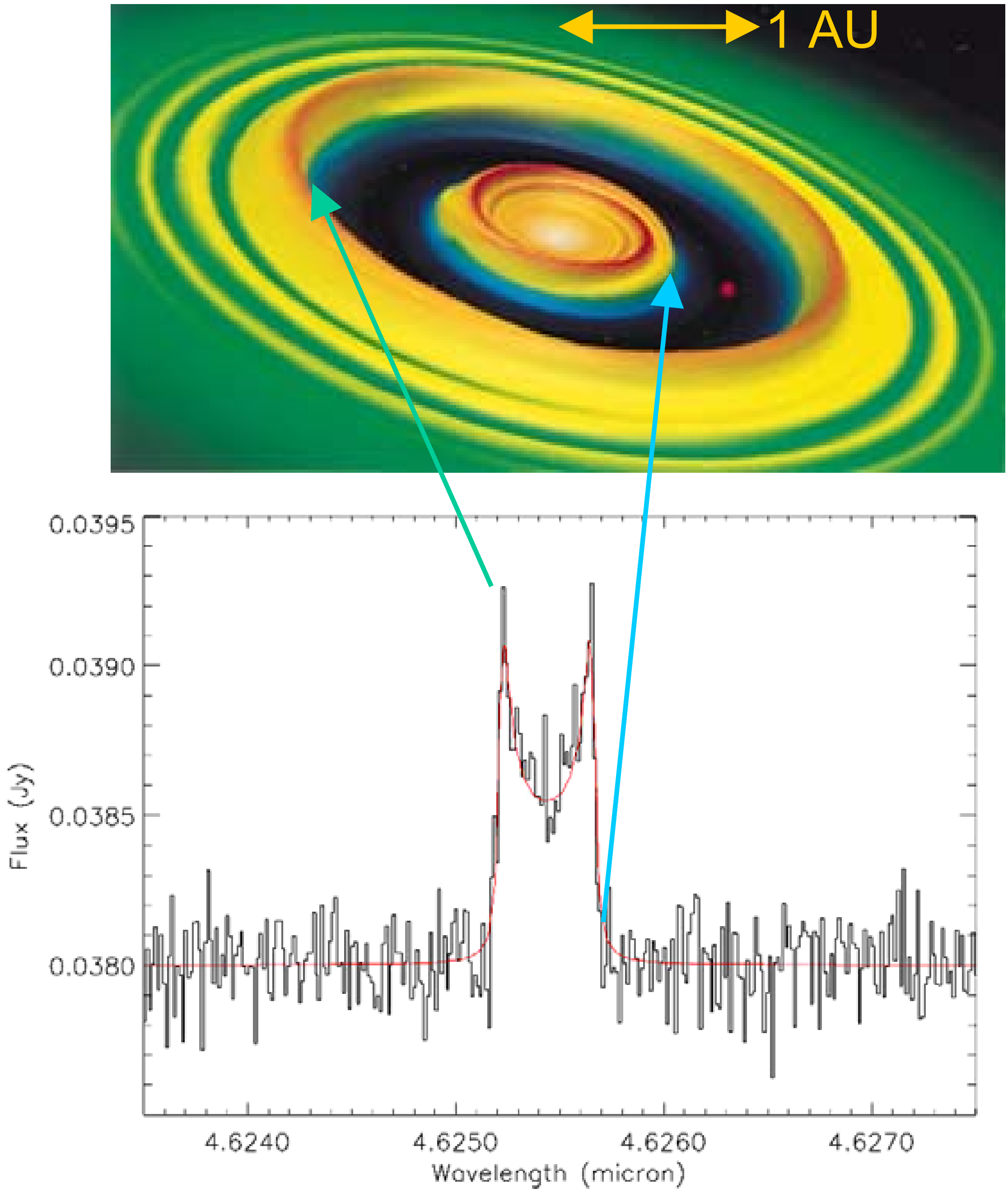

Figure 2: A numerical simulation of a young circumstellar disk with a gap created by a Jupiter-mass protoplanet orbiting a sun-like star at 1 AU (upper panel) and the corresponding simulated high resolution spectroscopic (R=100,000) profile of one of the CO fundamental lines 4.6μm from warm gas in the gap (lower panel). The wavelength separation between the two 'horns' of the CO line profile diagnoses the distance of the planet from its star, while the width of the two horns diagnoses the width of the gap which, in turn, is a measure of the mass of the planet. The simulated line profile assumes an 8 hr exposure on a 30 m telescope: the same profile should be obtained in 4 hr with a 42 m E-ELT. Adapted from the GSMT SWG report "Frontier Science Enabled by a Giant Segmented Mirror Telescope": upper panel due to Geoff Bryden; lower panel due to Joan Najita.

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: No constraints

Time Justification: (including seeing overhead) The following fiducial numbers for a 10% emissivity, 30 m GSMT (Najita et al.) need to be checked by an E-ELT specific calculation. In the read-noise limited high resolution spectroscopy, a 42 m E-ELT would be 2 times as sensitive as a 30 m assuming the same spatial resolution or 4 times if both were diffraction limited. In the background limit, equivalent sensitivity gains would be factors of $\sqrt{2}$ and 2, respectively.
Assuming a classical T Tauri star at 450 pc (Orion), a S/N=300 detection of the CO fundamental lines at 4.6μm in a 0.3 AU gap opened at 1 AU radius by a 1 $M_{\rm Jup}$ planet would be achieved in 15 minutes. This yields a total elapsed time of 45 minutes per target including calibration and overheads, and thus 1000 targets would take 100 nights.
Detecting the same star at 10μm in H_2O at S/N=100 would take 4 hr. Thus including 0.5 hr overhead per target, 1000 targets would take 500 nights.
Assume a classical T Tauri star at 1 kpc: fluxes at 10 and 20μm of 9 and 16 mJy, respectively. A S/N=25 detection of H_2O at 10μm would take 5 hr; S/N=20 detection of H_2 at 20μm would take 7 hr. Total elapsed time per source 2 nights including overheads. Thus for 30 targets per cluster and 5 clusters in order to gauge disk gas content as function of age and environment would take ∼300 nights.
Potential sample sizes: there are 1000s of disks within reach across a range of masses, ages, and environmental conditions in nearby star-forming regions. A sample on the order of 1000 is needed in order to ensure that ∼100 protoplanets are detected, assuming a Jupiter-like frequency of 5–10%. In turn, achieving a sample of this size requires extending the survey distance out to Orion.

Calibration Request: Standard Calibration

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

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

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	Orion silhouette disks	00 00 00	00 00 00	0	0			
A	HH 30	00 00 00	00 00 00	0	0			
A	GG Tau	00 00 00	00 00 00	0	0			
A	DG Tau	00 00 00	00 00 00	0	0			
A	2MASS 1628−243 (Ophiuchus)	00 00 00	00 00 00	0	0			
A	TW Hya	00 00 00	00 00 00	0	0			
B	HH 30	00 00 00	00 00 00	0	0			

Target Notes: The disks given are merely representative of much larger samples of disks in the nearby dark clouds (e.g., Taurus-Auriga, Chameleon, Ophiuchus) and denser OB associations and massive clusters (e.g., Sco-Cen, Orion).

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.

No

13. Scheduling requirements

14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
80	SINFONI	A	IMG 13 mas/px IR-WFS	J, H, K_s
80	VISIR	B	IMG	10, 20 microns