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

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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**

Imaging the planet-forming regions of circumstellar disks

2. Abstract

We propose to investigate the spatial structure of circumstellar disks via direct near- and mid-IR imaging with the E-ELT. The goal is to search for gaps and non-axisymmetric structure such as spirals and hotspots in the young and more mature disks indicative of ongoing or completed planet formation. In particular, it is important to reach as far as possible into the zone where putative terrestrial-mass habitable planets may be forming or have already formed. The key E-ELT requirements will be near-diffraction limited spatial resolution at 1–20 microns, with core wavelengths 2–10 micron. A diffraction-limited 42m telescope will yield a linear resolution of 2 AU at 150 parsecs, allowing access to young disks in nearby star-forming regions as seen in scattered light. Similar resolution will be achieved at 10 microns out to 30 parsecs for imaging of self-emission from dust in debris disks around nearby stars.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	80	NACO	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 NACO and VISIR acting as placeholders for diffraction-limited, small-field near- and mid-IR imagers, 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, which 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. The reservoir of small dust grains is then replenished by collisions between rocky planetesimals, leading to the so-called dusty "debris disks" seen around older, nearby stars such as Better spatial resolution is possible for residual, dusty "debris disks" around older, nearby stars such as Vega, β Pictoris, Fomalhaut, ε Eridani, AU Microscopii, and HD 107146. There is considerable evidence that non-axisymmetric structures in these debris disks can be used to infer the presence of planetary systems (e.g., Kalas et al. 2005, Nature, 435 1067)

The 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, high spatial resolution direct imaging of disks from 1–100 Myr in age has a crucial role to play, as protoplanets and mature planets can leave tell-tale signatures in the disks in terms of radially axisymmetric structures such as gaps and belts, and non-axisymmetric structures such as resonances and spiral density waves (Kalas et al. 2006, ApJ 637 57; Wyatt 2006, ApJ 639 1153): see also Figure 1.

However, such direct imaging studies, particularly in the crucial regions where analogue gas giants like Jupiter and terrestrial-mass planets like the Earth are expected to form. This is simply a matter of the available spatial resolution: the 5 AU radius orbit of Jupiter would subtend only 33 mas at 150 pc, the distance to the nearest low-mass star-forming regions, while a search for signs of Earth-like planets forming in a potentially habitable zone would require just 7 mas resolution at the same distance.

Matters are somewhat improved for the older, nearby debris disks, which have been probed in optical/near-IR scattered light with HST, VLT, Gemini, and Keck, and in direct thermal emission from dust grains by Spitzer and ground-based sub-mm/mm telescopes. The same fiducial distances of 5 AU and 1 AU subtend 170 mas and 35 mas at 20 pc: such resolutions are achievable at optical/near-IR wavelengths with HST and ground-based AO, but not by Spitzer or single dish sub-mm telescopes.

A fully diffraction-limited E-ELT should yield angular resolutions of 13 mas at 2μm, 60 mas at 10μm, and 120 mas at 20μm, enabling very substantial gains in disk imaging, both in terms of scattered light at the shorter wavelengths and direct thermal emission from dust at the longer wavelengths.

Images obtained of scattered light and warm (100–300 K) thermal emission from disks at near- to mid-infrared wavelengths, respectively, with the E-ELT would be directly complementary to those obtained at sub-mm/mm wavelengths with ALMA of the colder dust and gas at larger distances from the parent star, with a spatial resolution of $\sim$0.1 arcsec at 1 mm, equivalent to 15 AU at 150 pc.

Complementary spectroscopic E-ELT studies of the dynamics of gas and the chemical and physical evolution of gas and dust in the inner regions of circumstellar disks are presented in another DRM case.

B) Immediate Objective: The E-ELT will be used to obtain direct near- and mid-IR images of young and more mature circumstellar disks in search of gaps and non-axisymmetric structure such as spirals and hotspots indicative of ongoing or completed planet formation. In particular, it is important to reach as far into the zone where putative terrestrial-mass habitable planets may be forming or have already formed.

High quality, high contrast adaptive optics over a limited field (few arcsec) is required: in many cases, the parent star can be used for on-axis wavefront sensing, although a near-IR wavefront sensor would be highly recommended for more embedded sources. Post-wavefront sensing coronography will be required at short wavelengths in order to suppress the central star, with a trade-off necessary between the diameter of the occulting disk, the level of suppression, and the minimum distance from the star that can be probed. Coronography will likely not be needed at longer wavelengths, where the dust emission should far outweigh the stellar flux. Particular care should be taken to analyse the sensitivity and 'believability' of the AO system when imaging extended nebulosity with only minor structural inhomogeneities.

8. Description of the proposed programme (continued)

It would also be highly advantageous to be able to image in multiple narrow-band filters spanning a range of infrared wavelengths, in order to use emission lines in H II regions to provide high contrast images of disks seen in silhouette, as in Orion (Figure 2). Here the aim would be to image the outer edge structure of the disks to obtain insight into truncation mechanisms and the potential evidence for grain growth from the wavelength dependence of disk diameter and structure (*cf.* Throop et al. 2001, Science 292 1686).
Polarimetry may be useful for the scattered-light near-IR observations.

C) Telescope Justification: A very large, filled aperture telescope is required in order to achieve full u, v-plane imaging at the highest possible spatial resolutions. The "information content" of the images is directly proportional to the resolution (arguably even to the square of the resolution), and thus smaller telescopes such as the JWST will simply yield less detail. Interferometers such as the VLTI may have the edge in terms of raw resolution, but they are relatively poor when it comes to imaging structures on a variety of scales and any substantial degree of asymmetry.

D) Observing Mode Justification (visitor or service): Fully diffraction limited imaging is needed from 2–20μm, but covering a relatively small field only: a 100 AU diameter disk subtends just 5 arcsec at 20 pc and 0.7 arcsec at 150 pc.
(That having been said, there are disks which range up to almost 1000 AU in diameter and thus if they are nearby, as with Vega, are rather large on the sky, up to an arcminute.)

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

8. Attachments (Figures)

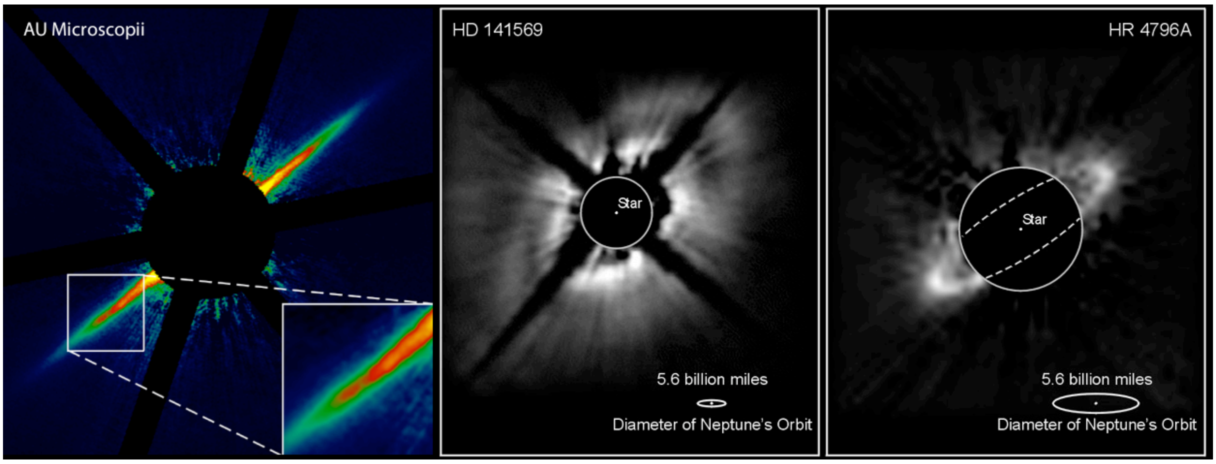

Figure 1: Near-infrared scattered light coronographic images of representative circumstellar disks. From left to right: AU Microscopii (Keck image, resolution ~0.1 arcsec, 1 AU at 10 pc; Kalas et al. 20XX, Science 303 1990); HD 141569 (NICMOS image, resolution ~0.2 arcsec, 20 AU at 100 pc; Weinberger et al. 1999, ApJ 525 L53); HR 4796A (NICMOS image, resolution ~0.2 arcsec, 15 AU at 70 pc; Schneider et al. 1999, ApJ 513 127)

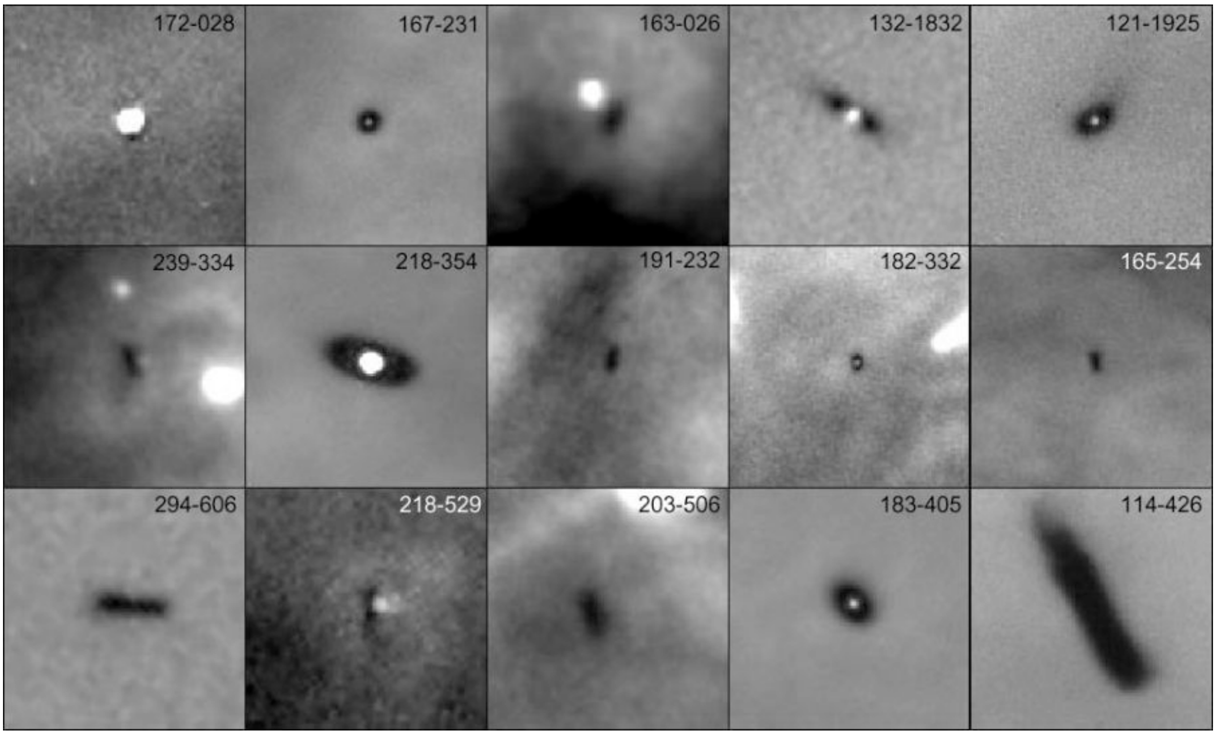

Figure 2: A gallery of young circumstellar disks seen in silhouette against the background nebulosity of the Orion Nebula H II region, as imaged at optical wavelengths with the HST. Narrow-band filters are used to obtain high contrast silhouettes against individual bright lines. Each square is 1200 AU (2.4 arcsec) across and the spatial resolution is ~0.1 arcsec or 50 AU at the 500 pc distance to Orion. (Bally, O'Dell, & McCaughrean 2000, AJ 119 2919).

8. Attachments (Figures)

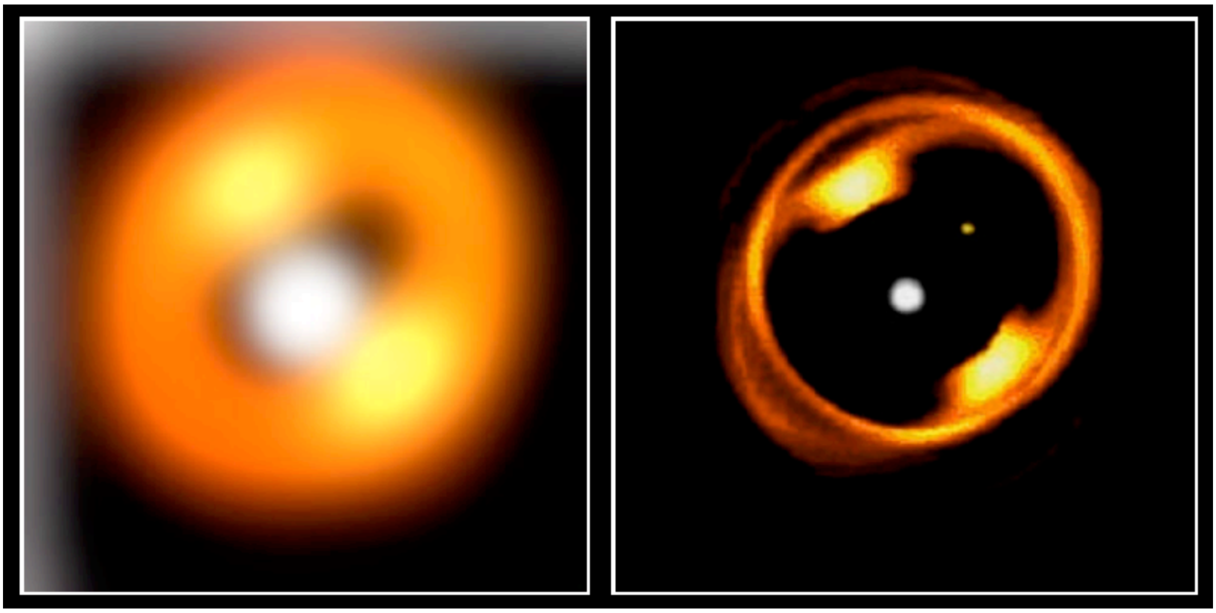

Figure 3: A representation of the gain in spatial resolution between the JWST MIRI and the E-ELT at 10μm. Both images show the simulated dust density of a Vega-like debris disk, with increased density “hotspots” in resonance with a putative planet (the yellow dot; the central star is the white dot). Although the dust density does not directly translate to mid-infrared surface brightness, it is nevertheless illustrative. The left-hand panel shows how such a system would appear to the diffraction-limited 6.5m JWST if located at a distance of 40 pc: the right-hand panel shows how it would appear with 5 times higher spatial resolution, *i.e.* to a diffraction-limited telescope with a diameter in excess of 33 m. In both cases, the ring structure is roughly 5 arcsec in diameter. Adapted from Wilner et al. (2002, ApJ 569 115) via Rieke et al. (JWST MIRI Science Case).

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: No constraints

Time Justification: (including seeing overhead) Circumstellar disks exhibit a very wide range of surface brightnesses within a given object, as a function of age, and as a function of wavelength. Thus it is hard to make a definitive statement re: surface brightness for input into an exposure time calculator. Some examples, however:
Vega: Surface brightness at 24 microns (from MIPS): 2 mJy/arcsec2 at 70AU radius; 0.2 mJy/arcsec2 at 200AU radius; 0.01 mJy/arcsec2 at 400AU radius
HD141569: Scattered light surface brightness: 0.05-0.15 mJy/arcsec2 at K over 1.5-5 arcsec radius (Boccaletti et al. 2003, ApJ 585 494); 0.05-0.3 mJy/arcsec2 at H (Weinberger et al. 1999, ApJ 525 L53)
GG Tau: L-band scattered light surface brightness (from Keck AO): peak 11.3 mag/arcsec2 dropping by factor of 5-10 (Duchene et al. 2004, ApJ 606 969) (see also McCabe et al. 2006, ApJ 636 932 for high spatial resolution imaging survey of T Tauri stars at 10–20μm)
HD97048: VISIR imaging at 8.6 and 11.3 micron PAH features; HAeBe star in ChamI at 180pc Doucet et al. 2007, A&A (astro-ph/0704.3678)
Potential sample sizes: there are 100s of disks within reach, both in terms of nearby mature debris disks and young disks in nearby star-forming regions

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	Vega	00 00 00	00 00 00	0	0			
A	Fomalhaut	00 00 00	00 00 00	0	0			
A	Eps Eridani	00 00 00	00 00 00	0	0			
A	HR4796A	00 00 00	00 00 00	0	0			
A	HD139664	00 00 00	00 00 00	0	0			
A	HD53143	00 00 00	00 00 00	0	0			
A	AU Mic	00 00 00	00 00 00	0	0			
A	Beta Pictoris	00 00 00	00 00 00	0	0			
A	HD107146	00 00 00	00 00 00	0	0			
A	HD15115	00 00 00	00 00 00	0	0			
A	HD141569	00 00 00	00 00 00	0	0			
A	HD32297	00 00 00	00 00 00	0	0			
A	BD+31 643	00 00 00	00 00 00	0	0			
A	HD97048	00 00 00	00 00 00	0	0			
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 representative and all have resolved images at optical, near-, mid-, far-IR, and/or sub-mm wavelengths. See `http://astro.berkeley.edu/~kalas/disksite/pages/gallery.htm` for a gallery of images of debris disks, for example, and Caer-Eve McCabe's catalogue of resolved circumstellar disks (young and debris) at `www.circumstellardisks.org`, which presently number 99. Many other disks are known to exist via unresolved mid-IR and sub-mm excess measurements and these too would be prime targets for the E-ELT.

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	NACO	A	IMG 13 mas/px IR-WFS	J, H, K_s
80	VISIR	B	IMG	10, 20 microns