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Letter to the Editor

A search for young solar system analogues with the VLT*

Hans Zinnecker[1], **Alfred Krabbe**[2], **Mark J. McCaughrean**[1], **Thomas Stanke**[1], **Bringfried Stecklum**[3], **Wolfgang Brandner**[4], **Deborah L. Padgett**[5], **Karl R. Stapelfeldt**[6], **and Harold W. Yorke**[6]

[1] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
[2] German Aerospace Center, Institute of Space Sensors and Planetary Research, Rutherfordstrasse 2, 12489 Berlin, Germany
[3] Thüringer Landessternwarte, Sternwarte 5, 07778 Tautenburg, Germany
[4] University of Hawaii, Institute for Astronomy, 2680 Woodlawn Dr., Honolulu, HI 96822, USA
[5] SIRTF/IPAC–Caltech, Mail Code 100–22, Pasadena, CA 91125, USA
[6] Jet Propulsion Laboratory, Caltech, 4800 Oak Grove Drive, Mail Stop 169–506, Pasadena, CA 91109, USA

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Abstract. The VLT/UT1 telescope has been used with its facility near-IR camera ISAAC to obtain 1–2.5 μm wavelength images at $0\farcs4$ spatial resolution of six southern young low luminosity sources associated with extended reflection nebulosity. Two are in the Chamaeleon I dark cloud (Cha IR nebula, Cederblad 110 IRS4), and the other four in the Gum Nebula (HH 46/47, CG 30, Re 4, Re 5). Complex structure is seen, including in most cases bipolar blue and red scattering lobes likely due to the illumination of outflow cavities by the central star(s), hidden by a flattened circumstellar disk or envelope. In one object (Re 4), a double jet appears to be emanating from the central source, suggestive of a binary system with nearly aligned disks. These images, when supplemented by polarimetry maps, will help determine the structure and geometry of the young stellar objects, and will also be compared to 3D radiative transfer models to match both the surface brightness distribution of the extended emission and the spectral energy distribution of the central source. Applied to a series of such objects, these analyses will lead to an improved evolutionary sequence for the formation of solar system analogues.

Key words: telescopes – stars: formation – stars: pre-main sequence – ISM: jets and outflows

1. Introduction

A major motivation for the study of low-mass star formation is to improve our understanding of the origin of the Sun and our solar system, and the nearby star-forming regions in the southern sky provide rich hunting grounds for the discovery of early solar system analogues. Accordingly, a survey was proposed to use the VLT and its near-IR camera ISAAC to image the surface brightness distribution of selected young stellar objects (YSOs) at high spatial resolution. Selection criteria were designed to favour the discovery of nearly edge-on circumstellar disks accompanied by scattering lobes above and below the disk plane. Namely, the targets should be highly reddened with strong far-IR emission, should be associated with optical nebulosity, but should not have a bright near-IR point source, such that the central star would hopefully be hidden behind a near edge-on disk. In this paper, the initial results of this exploratory survey are reported, including six sources: two in the Chamaeleon I dark cloud (the Cha IR nebula and Cederblad 110 IRS4), and four in the Gum Nebula (HH 46/47, CG 30, Re 4, and Re 5) at distances of ~ 150 pc and ~ 450 pc respectively. Similar sources were recently studied in Taurus by Padgett et al. (1999) using NICMOS on the HST.

2. Observations and data reduction

Near-IR (J, H, and K broad-band) images were taken on 28 April 1999 with the 8.2 m VLT/UT1 (Antu) at Cerro Paranal (Chile) in visitor mode, on a night of constant good seeing ($0\farcs5$ and $0\farcs4$ in the V and K bands respectively). The short-wavelength channel of the facility near-IR camera ISAAC was used, its 1024×1024 pixel HgCdTe array covering a field-of-view of $2\farcm5 \times 2\farcm5$ at $0\farcs147$/pixel. By taking the data in visitor mode, it was possible to examine the images in real-time, and to optimise the total integration times, which were typically on the order of 7 min in the J and H bands, and 3 min in the K band. Equal integration time images were made of nearby blank sky. For each object, five frames were obtained: a central one and four others dithered by $\sim 10''$ each to the north, south, east, and west. The ESO pipeline reduction software was used to sky subtract, flat-field, and mosaic. Finally, the data were scaled logarithmically and combined with J as blue, H as green, and K as red, to obtain the true-colour composite images shown in Figs. 1 and 2. The typical fields-of-view shown are roughly $2' \times 2'$, cor-

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Send offprint requests to: Hans Zinnecker (hzinnecker@aip.de)

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Fig. 1. VLT/UT1–ISAAC JHK observations of two young stellar objects in Chamaeleon. The objects are the Cha IR nebula (top) and Ced 110 IRS4 (bottom). North is up and east left in both images; the field sizes (in arcsec) are 166×125 and 136×100, respectively

responding to linear dimensions of ~ 0.1 pc at the distance of the Chamaeleon cloud and ~ 0.3 pc at the Gum Nebula.

3. The Chamaeleon objects

3.1. The Cha IR nebula

This well-known object was discovered by Schwartz & Henize (1983), and has since been studied extensively (for an overview see Schwartz 1991). However, it has never been imaged with the clarity and dynamic range seen in the VLT image (Fig. 1, top panel). The nebula is believed to harbour a YSO with an estimated luminosity of 14 $L_\odot$ (Cohen & Schwartz 1984), which is obscured by a nearly edge-on disk.

The present image reveals clearly for the first time that the innermost nebula is bisected by a dark lane, i.e. the putative edge-on disk. The image is dominated by a large east-west biconical structure, with dimensions probably close to that of the original protostellar cloud (~ 0.1 pc). The hour-glass shaped lobes are known from previous optical/near-IR polarisation studies (Scarrott et al. 1987; Ageorges et al. 1996), although the fainter western lobe, seen clearly here, is almost totally obscured at optical wavelengths. The surface brightness distribution of the lobes may reflect the distribution of optically thin dust in the remnant protostellar core from which this star-disk system was born. Alternatively, they may delineate an outflow cavity illuminated by the hidden central source, although there is presently no evidence for a molecular outflow, jet, or Herbig-Haro objects associated with the Cha IR nebula. Overall, the reflection nebulosities appear rather smooth, except for one or two small semi-circular holes near the centre which may allow certain beams of light to escape. The inner nebula is limb-brightened in the north-east and south-west, and more X-shaped than parabolic, reminiscent of the predictions of the X-wind model for outflows from young stars (Shu et al. 1997).

High spatial resolution (0.″2) H band speckle polarimetry images of the Cha IR nebula were presented by Ageorges et al. (1996). They noted 4 intensity knots named A, B, C, and D, forming an arc-like structure just to the east of the centre: the VLT image confirms this structure and shows an apparent counterpart dark hole in the western lobe. Ageorges et al. (1996) modelled the polarised surface brightness distribution and inferred a disk inclination of 20° from edge-on and a minimum disk radius of 1000 AU for a total dust plus gas disk mass of about 0.01 $M_\odot$ as derived from 1.3 mm data (Henning et al. 1993). Feldt et al. (1998) presented K' band imaging and spectroscopic data, and made a 2D radiative transfer model of the system as a spherical envelope with two 45° biconical holes. They obtained a fit of the spectral energy distribution and, accounting for the anisotropy/beaming of the radiation field, recalculated the luminosity to be an order of magnitude higher (170 $L_\odot$) than previously; they also confirmed the disk inclination of about 20° from edge-on (see also Stecklum et al. 1994).

Feldt et al. (1998) also supported the speculation by Gledhill, Chrysostomou, & Hough (1996) that there may be a binary system inside the dust lane, although no direct detection of two stars was made in their images. The brightest central region of the reflection nebula breaks up into knots A and B of Ageorges et al. (1996), separated by some 2.″5, and both knots still appear extended in the present images. Ageorges et al. (1996) suggested they were just circumstellar clumps without addressing the nature of their illumination. However, it is possible that each is illuminated by one of the hidden binary stars, a hypothesis that can be tested against models of reflection nebulae from deeply embedded binary stars that should soon be possible using new 3D radiative transfer techniques.

3.2. Cederblad 110 IRS4

Cederblad 110 (also known as Glass F or T 21) is one of three well-known optical reflection nebulae in the Chamaeleon I dark cloud (see Schwartz 1991). Sensitive high spatial resolution IRAS images of the region revealed some nine far-IR sources, with IRS 2, IRS 4, and IRS 6 aligned along a filament (Prusti et al. 1991). Of these, IRS 4 (IRAS 11051−7706) appears to be the youngest object, apparently driving a CO outflow and most likely also the HH 49/50 Herbig-Haro complex. IRS 4 is a low-luminosity source ($L_{\rm bol} = 1.4\,L_\odot$; Prusti et al. 1991), and its cold dust emission of ~ 100 mJy at 1.3 mm is roughly 3–4 times weaker than that from the Cha IR nebula (Henning et al. 1993). Subsequent 1.3 mm mapping confirmed IRS 4 as a protostellar candidate (Cha–MMS1) responsible for the observed outflow activity (Reipurth, Nyman, & Chini 1996).

The present image (Fig. 1, bottom panel) shows Ced 110 IRS4 to be a north-south reflection nebula bisected by a patchy east-west dark lane with a highly reddened central point source. The source is unseen at optical wavelengths and thus must be embedded in a dense cloud core: a large-scale gradient in the extinction is indicated by the absence of background stars in the southern part of the image. The central dust lane appears too wide (5″ or 750 AU) to be a thin edge-on disk, and is more likely a flared disk or flattened envelope, or perhaps a toroidal structure formed from a sheet collapse (Hartmann, Calvet, & Boss 1996). In the latter scenario, a non-rotating sheet-like gas layer condenses to form a protostar surrounded by a toroid in the plane of the layer, with infall proceeding faster at the poles than at the equator. This produces a relatively evacuated cavity, even in the absence of any bipolar outflow, thus naturally explaining the wide opening angles of the reflection nebula lobes. The southern, bluer part of the nebula (named IRS 4A here) would be the near side, while the northern, redder part (IRS 4B) would be material deeper inside the cloud, tilted away from us. Polarisation measurements and radiative transfer modelling are needed to clarify the geometry of this object.

A previously unknown pair of point sources (here IRS 4C & 4D) is seen about 1.4′ to the south-east of IRS 4A/B. Also, another very red stellar object (here IRS 4E) is seen halfway between IRS 4A/B and IRS 4C/D. The nature of these additional objects is unclear from the present data: they may be just reddened background objects, but it is worth noting that all three sources (AB, CD, and E) lie along the filament defined by IRS 2, IRS 4, and IRS 6, with CD coincident with IRS 6, and thus they may be associated with the same Ced 110 cloud core.

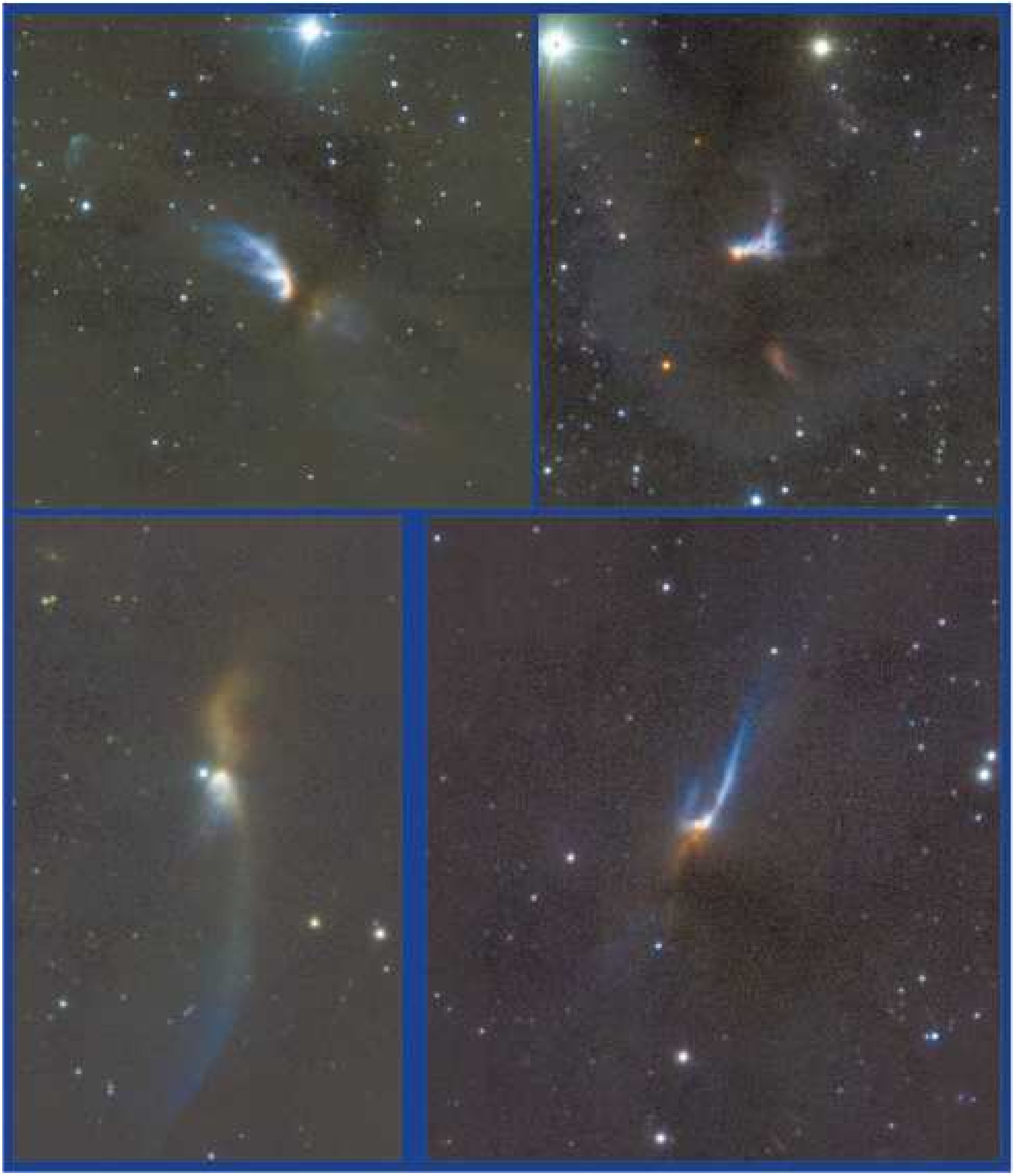

Fig. 2. VLT/UT1–ISAAC JHK observations of four young stellar objects in the Gum Nebula. The objects are HH 46/47 (upper left), CG 30 (upper right), Re 4 (lower left), and Re 5 (lower right). North is up and east left for HH 46/47, CG 30, and Re 4; Re 5 has north right and east up. The field sizes are (in arcsec): 143×123, 121×130, 86×143, 125×140, respectively.

4. The Gum Nebula objects

The four sources shown in Fig. 2 are embedded in cometary globules in the Gum Nebula (Reipurth 1983; Zealey et al. 1983). All four appear in the IRAS Point Source Catalog and their spectral energy distributions were shown by Graham & Heyer (1989), who also obtained early near-IR images for the sources, covering a relatively small field-of-view ($\sim 20'' \times 20''$). Summary descriptions for all four sources were given by Pettersson (1991).

4.1. HH 46/47

This is a spectacular bipolar Herbig-Haro jet complex with multiple bow-shocks (Reipurth & Heathcote 1991), originally discovered by Schwartz (1977). The jet is associated with a small bipolar molecular outflow from a dense ammonia core (Olberg et al. 1992), and is driven by a deeply embedded source (IRAS 08242−5050) which has a total luminosity of 24 $L_\odot$ (Cohen & Schwartz 1987) and a 1.3 mm dust continuum flux of $\sim 0.15\dot{\mathrm{J}}\mathrm{y}$ (Reipurth et al. 1993): the source was recently found to be a binary separated by $0\farcs15$ in HST NICMOS images (Reipurth, personal communication).

The present images show both outflow lobes mostly in scattered light, although line emission is also clearly seen, with some red knots from shocked H_2 at 2.122 μm in the broad-band K filter, and green knots due to high excitation [Fe II] at 1.644 μm in the H filter (see, e.g., Eislöffel et al. 1994). An interesting property of the reflection nebulosity is its asymmetry with respect to the outflow axis, suggesting that scattering material is only present on the northern side of the outflow cavity. This may be related to the gradual change in flow direction towards a more northerly direction (Reipurth & Heathcote 1991; Stanke, McCaughrean, & Zinnecker 1999), which suggests that there may be a gradient in the density of the surrounding material. This might reflect the primordial state of the local medium, or perhaps the fact that jet is precessing due to the presence of a binary system, and that the northern side of the cavity has more recently been excavated by the jet, leaving more material there at present. Because of the high surface brightness sensitivity, the present data may provide some clue as to the mechanisms responsible for cavity clearing.

4.2. CG 30

CG 30, cometary globule no. 30 of Zealey et al. (1983), contains a central reflection nebula (Reipurth 1981) and a bright low-excitation Herbig-Haro knot, HH 120 (Pettersson 1984). Optical polarisation mapping (Scarrott et al. 1990) confirmed that the reflection nebula is illuminated by an embedded source, IRS 4, for which a spectral type of K5 III was inferred from the colours of the nebulosity (Pettersson 1984). CG 30 also contains IRAS 08076−3356, a strong sub-mm/mm dust continuum source (1.20 and 0.47 Jy at 850 and 1300 μm, respectively; Reipurth et al. 1993), with a total luminosity of $\sim 19\,L_\odot$ (Cohen & Schwartz 1987), characteristics which suggest it may be a very young Class 0 source. Cohen, Schwartz, & Williams (1987) showed near-IR spectroscopy demonstrating the presence of shocked H_2 emission in CG 30, and subsequent imaging by Hodapp & Ladd (1995) revealed two orthogonal well-collimated H_2 jets, neither with its axis of symmetry apparently passing through IRS 4. Thus it seems likely that IRS 4 and IRAS 08076−3356 are distinct, the former illuminating the optical reflection nebula, and the latter, invisible at near-IR wavelengths, driving the jets (Hodapp & Ladd 1995).

The present images have a large enough field-of-view to show the confines of the ~ 0.3 pc diameter dark globule clearly, with IRS 4 the very red source seen at the centre, just below the bluer nebulosity. The various H_2 emission knots discussed by Hodapp & Ladd (1995) are also seen as red, coming through in the K filter, with four sets of knots located around the periphery of the globule delineating where the two orthogonal jets break out of the globule. The high spatial resolution of the present images shows a very peculiar structure in the blue reflection nebulosity, with a braid-like or helical appearance. We speculate that several hitherto unseen deeply embedded sources in addition to IRS 4 and IRAS 08076−3356 may be involved in creating the two or more overlapping flows and reflection nebulae. Infrared imaging polarimetry and thermal-IR imaging are required to reveal all the embedded sources in CG 30.

4.3. Reipurth 4

Re 4 is a small nebula discovered by Reipurth (1981) associated with IRAS 08194−4925, with a bolometric luminosity of $\sim 30\,L_\odot$ (Cohen & Schwartz 1987). It is believed to be a small multiple system, in which low-excitation Herbig-Haro objects and a reflection nebula are observed next to a K5 V foreground star (Graham 1986).

The present data show an S-shaped reflection nebulosity, blue in the south, red in the north, probably indicating that the northern lobe is further from us and more embedded in the parent cloud. Simple dust scattering models in a star-disk system with excavated cavities in an axisymmetric surrounding envelope can explain the S-shaped appearance (Wolf, personal communication), although alternatively, it may indicate a precessing outflow, perhaps due to a young obscured binary system with two circumstellar disks near the centre (Terquem et al. 1999) or possibly due to the Lorentz force of an external magnetic field on the outflow (Fendt & Zinnecker 1998). The binary hypothesis is strengthened by what appears to be a binary jet emanating from the obscured centre, with an offset angle between the two jets of 5–10°. The two jets are apparently visible mostly in reflected light as indicated by their blue colour, but each also contains a red knot which is likely to be shocked H_2 in the K band: the knots are roughly equidistant along the jet axes, perhaps indicating synchronised accretion and outflow events at the binary stars. An alternative possibility is that these jets are in fact just "light house" beams escaping through holes in the inner structure, similar to those observed in the Egg Nebula (Sahai et al. 1998).

4.4. Reipurth 5

Re 5 is another small nebula first listed by Reipurth (1981), apparently a pure reflection nebula illuminated by an obscured star, without any associated outflow or T Tauri activity, as evidenced by the lack of emission lines in the reflected optical spectrum (Graham & Heyer 1989). Its near- to mid-IR spectrum is similar to that of the Cha IR nebula (Gürtler et al. 1999), which also lacks any evidence for outflow, as discussed in Sect. 3.1. Re 5 is associated with IRAS 08196−4931, with fluxes of 7 Jy and 53 Jy at 12 and 60 μm, respectively: no bolometric luminosity has been given in the literature, but we estimate it to be on the order of $\sim 30\,\mathrm{L}_\odot$.

The new images show separated blue and red reflection nebulae, extending at least $20''$ ($\sim$ 0.05 pc) on either side of the nominal centre, reminiscent of bipolar outflow cavities, albeit very narrow ones. There is no trace of the central illuminating source in these data: the compact source at the apex of the blue lobe is extended, and is probably a clump in the local dust distribution. Thus IRAS 08196−4931 may be a Class I or 0 YSO whose precise location should be revealed by follow-up mid-IR and/or millimetre imaging. Again, the geometry and surface brightness distribution of the Re 5 system appear to be simple enough to make it possible to infer the main system parameters, including inclination and luminosity, via detailed radiative transfer modelling.

5. The present and the future

The large collecting area of the VLT, combined with the superb image quality delivered by its active optics system and the high throughput of ISAAC, make it possible to trace the surface brightness of the circumstellar environment of YSOs to very faint levels and large distances from the illuminating source, in fact to distances comparable to the radius of the original protostellar core prior to its collapse. The high spatial resolution also makes it possible to disentangle the structural details of the innermost regions of scattered light, important when hoping to reveal multiple sources of illumination. Equivalent resolution near-IR polarimetry and and thermal-IR imaging are needed to clarify further the number and position of the obscured sources. In addition, monitoring of the nebulae is worthwhile, as it is likely that these reflection nebulae will undergo changes both in structure and brightness within timescales as short as a few months, as clumpiness in the inner circumstellar disks causes the stellar light to escape through new channels.

Further progress in imaging capability may lead to a more detailed classification of the evolution of YSOs based on morphological criteria, rather than just the spectral energy distribution (SED) classes currently in use (Classes 0–III; cf. André, Ward-Thompson, & Barsony 1993). While the SED fit alone does not yield a unique model (see, e.g., Hartmann et al. 1996 for HL Tau, and Men'shchikov & Henning 1997 for L 1551 IRS5), it should constrain the model parameters fairly convincingly when combined with models of the extended emission from the objects via self-consistent 3D Monte Carlo radiative transfer simulations (Wolf, Henning, & Stecklum 1999). The extended structure of these circumstellar nebulae will also guide future sensitive far-IR observations, e.g., with SOFIA and FIRST, to study the chemical composition of the dust grains and possibly magnetic fields through polarised sub-mm dust emission, as well as the presence and nature of complex chemical species, plausibly even organic molecules.

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