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Evidence for disks around young high-mass stars

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Abstract: The formation of high-mass stars remains a poorly understood process despite growing observational evidence in favour of accretion from a circumstellar disk onto a protostellar core. The high fraction of multiple stellar systems among the most massive stars and the fact that these stars are usually born in dense clusters can alternatively be explained by merging of intermediate-mass stars. Here we review some observations that provide direct evidence for large ($\sim 10,000 - 20,000$ AU) disks and/or dusty envelopes seen in emission and absorption around high-mass stars. The objects are all members of the young cluster in M 17 and have been investigated by multicolor photometry and spectroscopy.

1 Introduction

M 17 is a region of active high-mass star formation at a distance of 2.1 kpc. It consists of a luminous H II region, a huge adjacent molecular cloud and an embedded young cluster with an age of about 5×10^5 years (Hoffmeister et al. 2008). About 74% of the investigated cluster members show infrared excess indicating the presence of dense circumstellar material. Spatially resolved images of circumstellar disks and shells have been obtained for a number of high-mass sources, suggesting the accretion scenario to work also in the high-mass regime. The present paper reviews two of the most outstanding high-mass sources with circumstellar dust and introduces a new candidate in M 17. Further similar sources exist in this young region and are subject to ongoing investigations.

2 IRS 15 - a B0.5 V star with an emission disk

Due to the rapid evolution of a new-born massive star and the early sublimation of circumstellar dust in the vicinity of these hot objects it is hard to find a high-mass star which is still surrounded by a remnant disk. Chini et al. (2006) reported on the rare case of such an optically visible star in the southwestern area of M 17, hereafter IRS 15, which is still associated with circumstellar dust.

Imaging from $0.4 - 2.2\,\mu$m shows a point-like object whose optical spectrum resembles type B0.5 V. Beyond 2.2 μm extended circumstellar emission becomes increasingly prominent around this high-mass star (Fig. 1). Eventually, at 10 μm the nebula attains its largest size of $17,400 \times 12,500$ AU. While usually, early embedded B stars are associated with blue reflection nebulae that disappear with increasing wavelengths, IRS 5 shows the opposite behavior, i.e. the extended emission becomes more

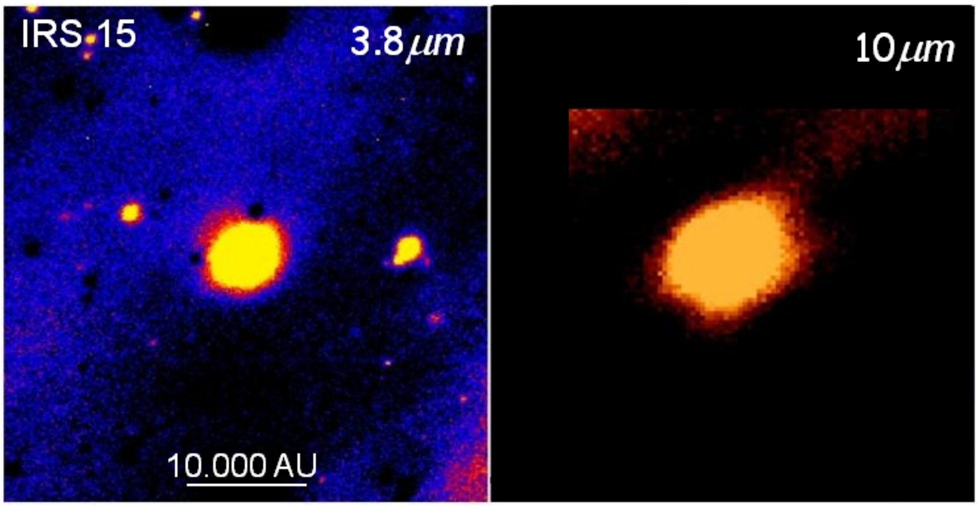

Figure 1: While at shorter wavelengths IRS 15 is point-like and its circumstellar neighborhood is inconspicuous, extended thermal emission of dust dominates at 3.8 and 10 μm; the disk has a total projected size of $17,400 \times 12,500$ AU (lowest 3σ intensity contour at 10 μm) and is seen under an angle of about 53 degrees with respect to the line of sight.

prominent at longer wavelengths. This indicates that the nebulosity is not due to scattering by micron-sized circumstellar dust grains but arises from their thermal emission. The photometric data at 3.8 and 10 μm (Chini et al. 2006), a 20 μm study by Nielbock et al. (2001) as well as the 8 μm data from the Spitzer archive, yield a mean color temperature of 220 K, indicative of warm dust.

The morphology of the dust distribution at 10 μm complies with two extreme cases: an oblate envelope seen edge-on (with a minimal axis ratio of about 2:1) or a flat disk seen under an inclination angle of about 53 degrees with respect to the line of sight. Adopting a disk-like configuration with a scale height ratio of 0.1, an inner radius of 130 AU, an outer radius of 10,000 AU and 0.1 μm-sized silicate dust particles, Chini et al. (2006) could reproduce the observed radial flux profiles at 3.8 and 10 μm fairly well. The dust density distribution displays a flattening in its inner part. Compared to standard accretion disk models a substantial fraction of the inner disk must have been already eroded. This may indicate a similar mass removal process as observed for older disks around lower-mass objects. Another argument in this direction comes from $K-$band spectra where the CO band-heads beyond 2.29 μm - usually arising at the inner disk from hot and dense material - are missing. The model requires a total dust mass of at least 5×10^{-4} $M_{\odot}$.

IRS 15 is very likely a star on the main sequence which has stopped accretion. This is corroborated by the absence of typical accretion indicators like emission lines of Hα, Ca II and He I. On the other hand, IRS 15 must be extremely young because the time span during which a massive star can maintain a circumstellar disk that has not yet been completely destroyed by the strong stellar winds must be of the order of a few Myr. In summary, IRS 15 is a fortunate coincidence where the newly-born high-mass star is already optically visible while its circumstellar disk (or envelope) is not yet dispersed and still glowing at infrared wavelengths.

3 A hyper-compact H II region with a dark lane

M 17-UC1 was discovered as a cometary ultra-compact H II region displaying a shell structure with a diameter of 6.9×10^{15} cm. The number of stellar Lyman continuum photons of $\simeq 2 \times 10^{47}$ s^{-1} requires a B0 - B0.5 V star as the ionising source. Meanwhile, M 17-UC1 is regarded as a hyper-compact H II region (HCHII) with broad ($\geq$ 35 km s^{-1}) radio recombination lines and a rising spectral index between 1.4 and 43 GHz. Numerous infrared studies have proven M 17-UC1 to be a strong source at 10 μm and beyond. Nielbock et al. (2007) presented deep NIR/MIR high-resolution imaging and spectroscopy as well as radio interferometry to study the morphology of M 17-UC1 with unprecedented detail.

While being extremely weak at short IR wavelengths, M 17-UC1 becomes prominent in the K band and beyond. Nielbock et al. (2007) resolved the source into two K band emission blobs, separated by 0.46" and a position angle of $54°$. A dark lane separates the two K band nebulae (Fig. 2). At L band the source attains a spherical shape with a radius of $\sim 1.0''$ corresponding to 2100 AU. The N band data show a similar – although less resolved – double structure as in the K band with a FWHM of 0.7×0.5; the brightness maximum is centred on the southwestern K band peak (Fig. 2). The total circumstellar emission ($\sim 10,500 \times 6300$ AU) is relatively complex with a noticeable extent to the northwest.

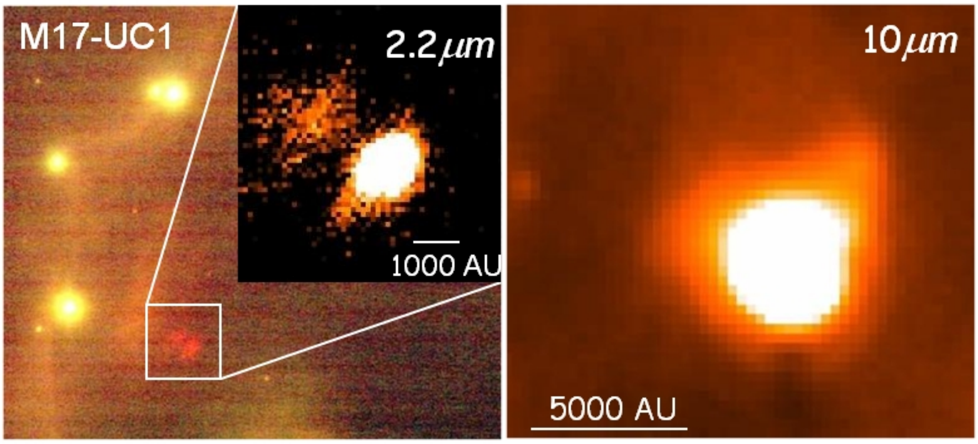

Figure 2: *Left:* Three-color image (*JHK*) of the Arc region in M 17. The inset at 2.2 μm shows the bipolar emission of M 17-UC1 and the associated absorption lane in between. Its symmetrical triangular shape on both sides resembles a circumstellar disk. *Right:* 10 μm image of the extended dust emission around M 17-UC1.

The 10 μm spectrum of M 17-UC1 displays a deep silicate feature indicating the presence of cold dust along the line of sight. The standard relation for converting optical depths of $\tau_V \sim 17 \cdot \tau_{9.7}$ (Krügel 2003) yields a visual extinction of about 40 mag, consistent with the observed NIR spectral energy distribution of an embedded B0V star. Although the broad-band N image in Fig. 2 also includes the silicate feature, one can only see the warm emitting dust. The cool absorbing dust cannot be spatially resolved at 10 μm and is most likely located in the dark lane seen at 2.2 μm.

The absorption pattern of M17-UC1 with the scattered light nebulosities on both sides very much resembles the appearance of a young low-mass star with a circumstellar disk. Radiative transfer calculations can explain the K band image with the triangular absorption much better by a disk than by an unrelated dust filament in the foreground.

HCHIIs are very likely a transition state where the massive star has started to ionise its surroundings while the accretion process is still going on. From the results presented by Nielbock et al. (2007) it seems that a circumstellar disk can still be present during the HCHII stage and that M17-UC1 is the first example where such a disk could be directly observed.

4 IRS 5 – evidence for merging?

About 5.2” southwest of M 17-UC1 Chini & Wargau (1998) found an infrared source – hereafter IRS 5 – with a strong IR excess at wavelengths beyond 2.2 μm. It was subsequently imaged at *K, N, Q* (Nielbock et al. 2001) who presented a typical Class I SED from 1.2 to 20 μm with spectral indices of $\alpha_{K,N} = 2.5$ and $\alpha_{K,Q} = 2.4$. Kassis et al. (2002) obtained maps at 9.8, 10.53, 11.7 and 20.6 μm and performed radiative transfer code models that describe IRS 5 as a zero-age main-sequence (ZAMS) B0 type surrounded by a shell of 70 $M_{\odot}$ with an outer radius of 1 pc. Here we present deep NIR and MIR images which resolve M17-IRS 5 into several components. K and N-band spectroscopy helps to classify the stellar sources and probe the circumstellar environment.

Our NIR images resolve IRS 5 into six apparently stellar components (Fig. 3). From their location in the *JHK* color-color diagram at least three of them are heavily reddened and have IR excesses of various strengths. The brightest star (component *A*) has a visual extinction of 27 mag and displays X-ray emission. There is a fainter object *B* 0.9” west of component *A* with an extinction of 34 mag and a strong IR excess. An extremely red (component *C*) object with $K - L \sim 5$ is located 2.0” southwest of the main component; it is the only point source in the region that also shows up at 10 μm. Its visual extinction is about 34 mag – similar to that of component – *B* and it coincides with the H_2O maser No. 4 reported by Johnson (1998). The projected separations of this triple system are 2200 AU between components *A* and *B* and 4400 AU between *A* and *C*. Given that the visual extinction is fairly similar for all three stars we speculate that IRS 5 is a bound triple system of young objects.

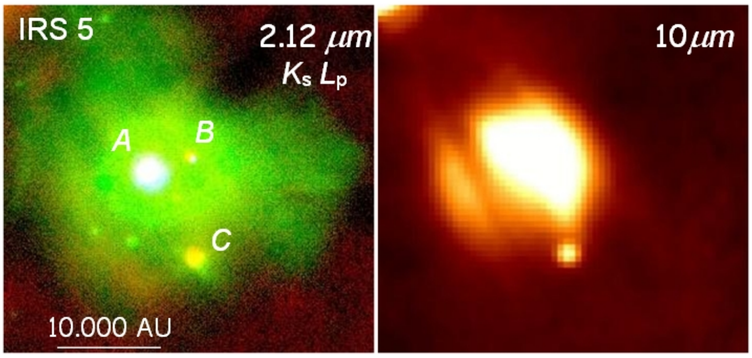

Figure 3: *Left:* Three-color image (NB 2.12 μm, *K*s, *L*p) of the IRS 5 region. The strong point source labeled ”*C*” southwest of IRS 5 coincides with an H_2O maser. *Right:* 10 μm image of the extended dust emission around IRS 5; a faint dust lane (disk?) is visible in absorption.

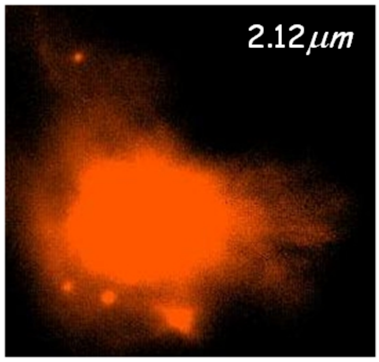

Figure 4: The H_2 emission around IRS 5 displays several filaments of shocked gas pointing away from the star.

Our K-band spectrum of IRS 5 A shows Brγ at 2.166 μm and He II at 2.188 μm in absorption. The absence of He I 2.112 μm suggests that the object is hot and probably equivalent to an O6.5 star.

As already indicated by earlier photometric data (Nielbock et al. 2001, Kassis et al. 2002) our MIR spectrum for component *A* displays silicate absorption at 9.7 μm. Converting the optical depth at 9.7 μm into a visual extinction yields $A_V \sim 30$ mag which is consistent with the NIR photometry above and with estimates from the X-ray emission (Broos et al. 2007). Obviously, there must be cool dust in front of the extended 9.7 μm dust emission seen in Fig. 3. This absorbing dust is indeed visible at L and N as a dark lane which is reminiscent of a circumstellar disk.

Bally & Zinnecker (2005) have made some qualitative predictions of how merging of intermediate stars may lead to the formation of a high-mass star. In the following, some of their statements are compared with the properties of IRS 5:

1. "*Protostellar mergers may produce high-luminosity IR flares lasting years ...*" – The $2.2\,\mu$m flux of IRS 5 has risen by a factor of 40 from $1993-1995$ and seems to fade slowly since then.
2. "*Mergers may be surrounded by thick tori of expanding debris, impulsive wide-angle outflows, and shock-induced maser and radio continuum emission.*" – Figs. 3 and 4 display several of these features including maser emission at the position of component *C*.
3. "*Collision products are expected to have fast stellar rotation and a large multiplicity fraction.*" – IRS 5 consists of several components of which at least four are sufficiently deeply embedded to form a young multiple system.
4. "*Massive stars growing by a series of mergers may produce eruptive outflows with random orientations; ... observable as filaments of dense gas and dust pointing away from the star.*" – Fig. 4 shows several "fingers" of shocked H_2 gas emerging from IRS 5.

Although one can argue that the observed properties of IRS 5 comply with the accretion scenario one may speculate whether it is a suitable candidate to study the merging scenario for high-mass stars.

5 Conclusions

In summary, M 17 is an ideal test bed to study the early evolution of high-mass stars. The examples in the present paper show three early evolutionary stages where a massive star is associated with circumstellar dust: i) The youngest object is M 17-UC1, a hypercompact H II region, which is probably still in the process of accretion. ii) An intermediate source, IRS 5, which is a heavily embedded O-star candidate with a disk and a maser source. iii) And the latest stage IRS 15, a B0.5 main sequence star that is still surrounded by a remnant disk. M 17 harbours a number of additional candidates where dust emission is associated with massive stars; these object are currently under investigation and seem to support the accretion scenario further.

Acknowledgements

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Discussion

N. Smith: First a comment regarding these late O-type or early B-type stars which you interpreted as possible distorted disks. We found a number of similar sources in the Carina Nebula, and our analysis suggests that they are stand-off shocks between the stellar wind of the late O or early B star and a bulk flow of plasma in the H II region (see Smith et al. 2010). Also, Povich et al. found a few of these in M 17, but I'm not sure if they are the same sources you have discussed.
Also a question: regarding your potential massive merger source (I think IRS 5), which brightened by a factor of 40 over 2 years. Why do you think this is not a FU Ori outburst?
R. Chini: I agree that we cannot interpret them as remnant disks. What I wanted to show is that there exists dust close to late type O-stars. We don't find them with B-stars. I also agree that they are a result of the winds from the major ionizing sources in the center of M 17, because these rims are all pointing toward the central O4 Trapezium.
I would love to find a new FU Ori in its outburst. However, our IR spectra (with absorption lines of He and H) point toward an early type star.

H. Zinnecker: [The comment is that I did not bribe the speaker to find evidence for the Bally & Zinnecker (2005) merger scenario!]
Now the question, where did you get your O-star spectral-type vs. stellar mass calibration from? It seems to me that your mass estimates for a given spectral type are systematically too high (e.g. an O9 V star is closer to 20 $M_{\odot}$ than the 30 $M_{\odot}$ you quoted).
R. Chini: [I confirm that there was no contact before the talk between Hans and me about this paper.] I agree that the mass quotes are higher than what are published by e.g. Martins et al. (2005). However, I think that the uncertainties in this field are still much larger than the differences we are talking about here. I just learned from C. Hummel that they obtained a dynamical mass of about 27 $M_{\odot}$ for an O9.7 star which is close to the values we use.
J. Puls: I agree with Hans Zinnecker, that the typical masses of O9 dwarves should be below 20 $M_{\odot}$, and that the different calibrations should be fairly consistent.

N. Evans: The wide companions you discuss (~ 10000 AU) are very interesting. I would draw your attention to our recent Chandra observation of Polaris. X-ray observations are a very powerful way to identify low mass stars young enough to be massive stars' companions.
R. Chini: In fact, the young cluster in M 17 contains more than 800 Chandra sources. We use this information for disentangling cluster members from background stars. Interestingly, we find many X-ray sources to be associated with O- and B-type stars. Spectroscopy shows that these early-type X-ray sources are often close binaries. By the way, IRS 5 - the last source I was talking about - is coincident with ACIS 309 (Broos et al. 2007).