The earliest phases of high-mass star formation: Opportunities with JWST

O. Krause, S. Birkmann, M. Hennemann, M. Nielbock and Th. Henning
Max-Planck-Institut für Astronomie, Heidelberg

Introduction

Massive stars play a key role in the evolution of the universe. Although our knowledge of their formation has significantly advanced during the past years mainly by studies of infrared-bright ultracompact HII regions, hot molecular cores and high-mass protostellar objects (HMPOs), the understanding of the "infrared-dark" earliest phases of formation is still sketchy (Zinnecker & Yorke 2007). Recent work is suggesting that an accretion-based formation scenario in turbulent cloud cores is a likely way to build most stars of all masses (Beuther+ 2007), but it has also become clear that high-mass star formation is not just an up-scaled version of low-mass star formation. Among the major scientific questions are:

1. *What are the initial conditions leading to the formation of high-mass stars?* Do massive prestellar cores exist? What is their density structure? How fast do they evolve?
2. *Are high-mass stars formed via monolithic collapse?* Does competitive accretion play a role after early-stage fragmentation? Does coalescence of massive cores and/or young high-mass stellar objects occur?
3. *How is material accreted onto a forming high-mass star?* How fast do initial hydrostatic cores accrete material ? How does the accretion rate evolve? What are the properties of the formed accretion disks? How is the accretion process stopped?
4. *Do forming high-mass stars exhibit collimated jets during early accretion phases?* How are jets driven and collimated? Do they originate from the surface of the disk? Is there an evolutionary sequence from collimated to un-collimated outflows?

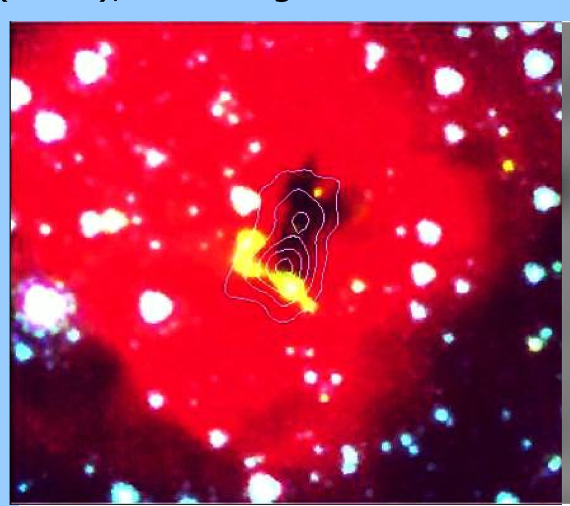
To answer these questions, detailed studies of a statistical sample of massive "protostars" are an observational challenge for the next decade. As discussed in the following examples, JWST will provide sufficient sensitivity and spatial resolution to perform breakthrough observations of these objects. However, since high-mass stars are rare and evolve quickly, it its difficult to identify them during their earliest evolution which is obscured by high dust extinction. Short evolutionary timescales (< 10^3 yr) are indicated by the absence of starless, IR-quiet high-mass cores in recent surveys of specific massive star forming regions (Motte+ 2007) and the absence of circumstellar disks around the most massive O-stars (Cesaroni+ 2007).

In order to find and characterize massive pre-stellar cores and protostars we have compiled a sample of high–mass targets based on careful preparatory studies including unbiased large-scale far-infrared and submm imaging surveys (Krause+ 2003; Klein+ 2006) as very promising target sources. Observations with radio interferometers and Spitzer suggest an the early evolutionary stage of star formation in these regions (Beuther+ 2007; Birkmann+ 2006; Birkmann+ 2007; Nielbock+ 2007).

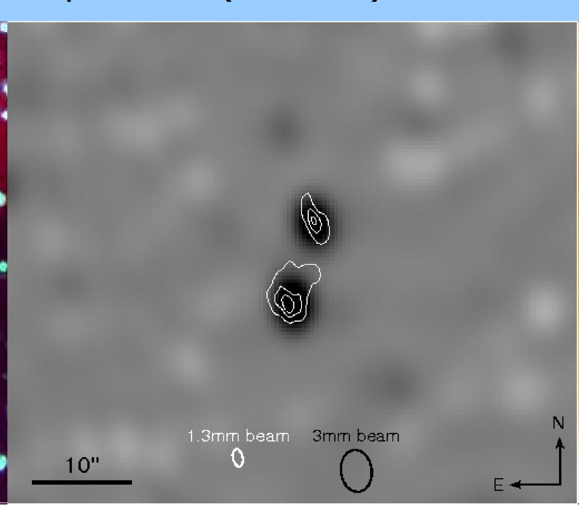
Although high-resolution observations of the cold dense gas have revealed important information (which will be further improved with a dedicated HERSCHEL GT key program) and SPITZER data have constrained the properties of embedded protostars, only JWST will ultimately provide both sufficient sensitivity and spatial resolution to characterize the physical properties of the massive protostars itself. In the following we discuss some of the capabilities of JWST on the basis of four case studies from our sample.

Case 1: The high-mass star forming clump ISOSS J18364-0221E

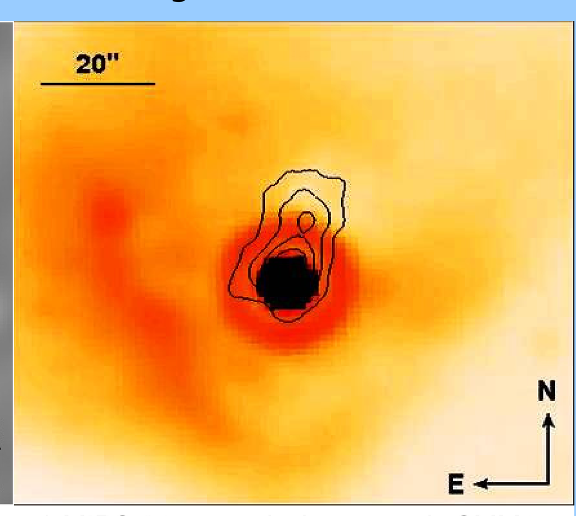
This region was identified by a systematic search for early evolutionary stages of high-mass stars using the 170 µm ISOPHOT Serendipity Survey (ISOSS), has a total mass of 3200 $M_\odot$ and is located at a distance of 2.2kpc (Birkmann+ 2006). Submm continuum and molecular line measurements revealed two compact clumps within this region. We focus on the eastern clump SMM1 here, which is resolved into two cores at 450 µm separated by 20 000 AU (panel a), confirmed by PdB interferometry at 1.3 and 3 mm (b). At 1.3mm the core sizes are 10000 x 7400 AU (south) and 11400 x 3400 AU (north). The core masses are 70 $M_\odot$ for the southern and 50 $M_\odot$ for the northern one, based on optically thin dust emission between 70 and 850 µm (κ_{1mm} = 1 cm²/g; gas-to-dust ratio 100). Masses derived from interferometry (where an spatially extended component is suppressed) are 25 $M_\odot$ (south) and 15 $M_\odot$ (north), assuming the same dust temperature (T ~ 19K) derived from the single-dish data.



a) IRAC 3-color composite of SMM1. Contours: 450µm continuum

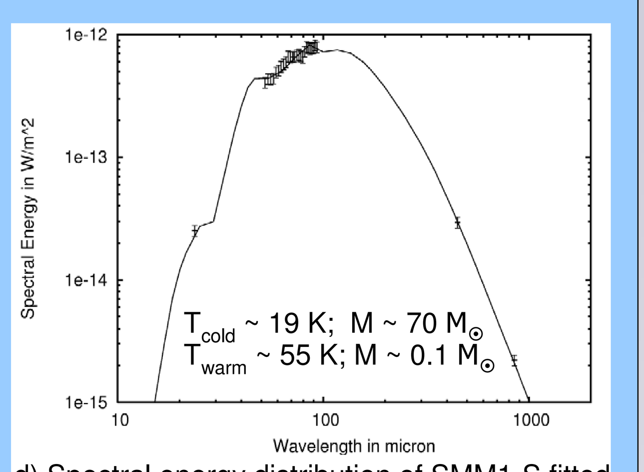


b) Greyscale 3.4 mm continuum Contours 1.3 mm continuum

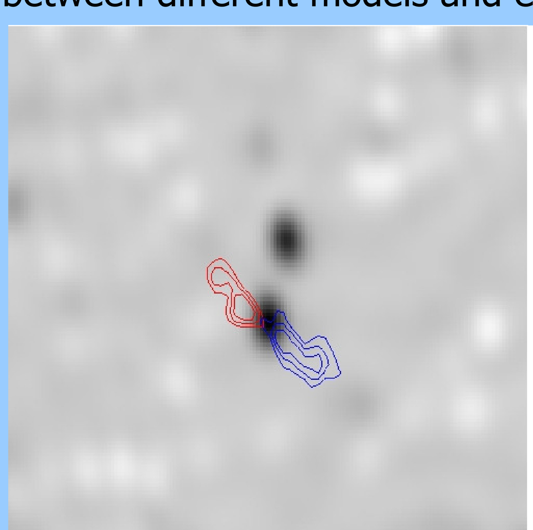


c) MIPS 24 µm emission towards SMM1. Contours: 450µm continuum

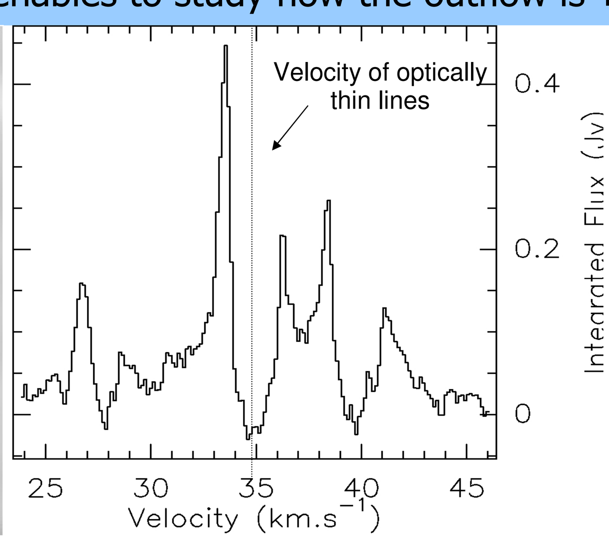
What is the evolutionary stage of the two high-mass cores? The submm continuum emission coincides with absorption of 8 µm background emission in the IRAC image (a), confirming large column densities N(H) > 5 $\cdot 10^{23}$ cm^{-2}. No counterparts of the cores are detected between 4 and 8 µm. However, IRAC 4.5µm excess emission is seen east and west of the southern core, suggesting a bipolar outflow. This is confirmed by PdBI CO(2-1) observations (e). MIPS observations reveal a 24 µm counterpart of the southern core (c) which shows infall signatures in HCN(1-0) emission, too. SMM1-S appears to be a accreting protostar. Radiative transfer models by Whitney+ 2004 constrain the central source mass to 5-6 $M_\odot$ with T=5000K and an envelope mass between 70-170 $M_\odot$. As shown in (g) imaging with JWST-MIRI will allow to break the degeneracy between different models and enables to study how the outflow is launched from the disk-interface.



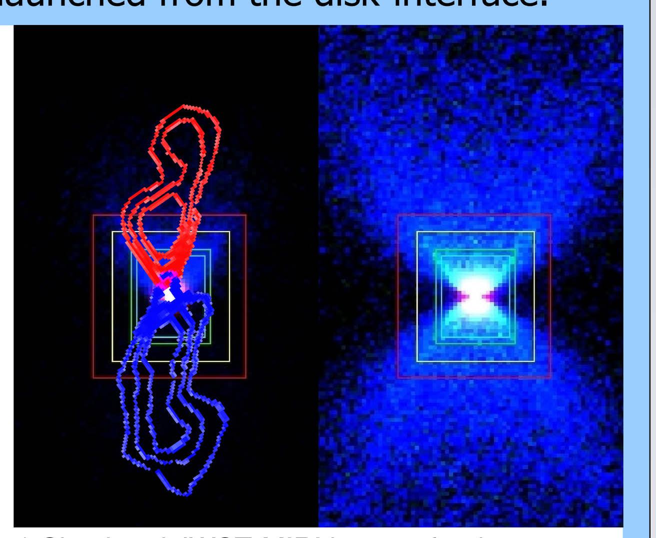
d) Spectral energy distribution of SMM1-S fitted by two optically thin components. 24,50-90 µm data are from MIPS; 450,850 µm from SCUBA.



e) CO(2-1) emission contours at 27 km/s and 41 km/s



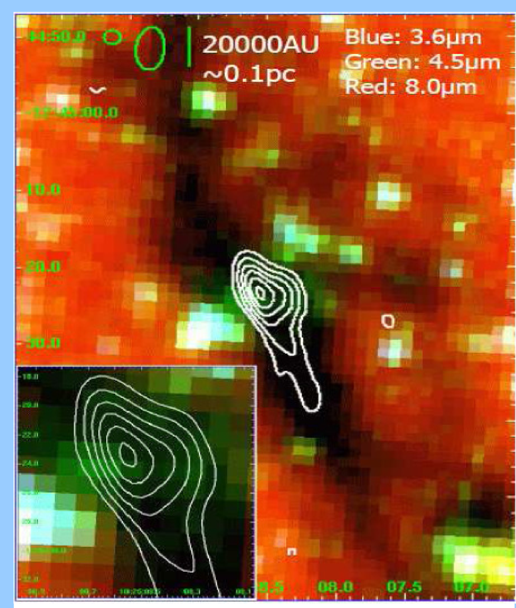
f) HCN(1-0) spectrum towards SMM1-S with PdBI shows red-shifted self-absorption.



g) Simulated JWST-MIRI images for the two radiative transfer models for SMM1-S: Blue: 5.6 µm, green: 7.9 µm, red: 21 µm. (color ranges 0-160nJy; 0-760 nJy; 0-780 µJy/pix. Extension of CO outflows and MIRI IFU shown for comp.

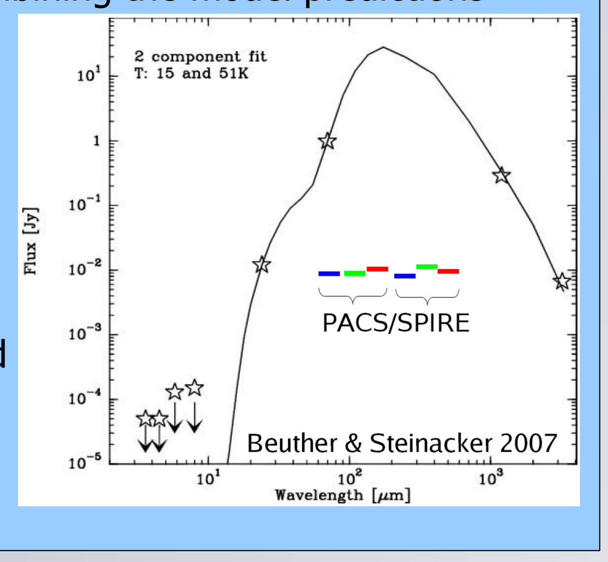
After subtraction of the southern 24 µm source, no counterpart but rather a 24 µm absorption feature is visible at the northern core, making it a good candidate for a high-mass prestellar core. MIRI will allow to test this scenario by sensitive mid-infrared imaging. With a 10σ limit of 28 µJy at 25.5 µm (10 000s), MIRI is sensitive enough to even detect the thermal emission of the cold core in case no embedded source is detected. NIRCAM and MIRI will allow to map the density structure of the core with < 200 AU resolution from the absorption of background emission.

Case 2: The protostar in the IR dark cloud IRDC 18223-3



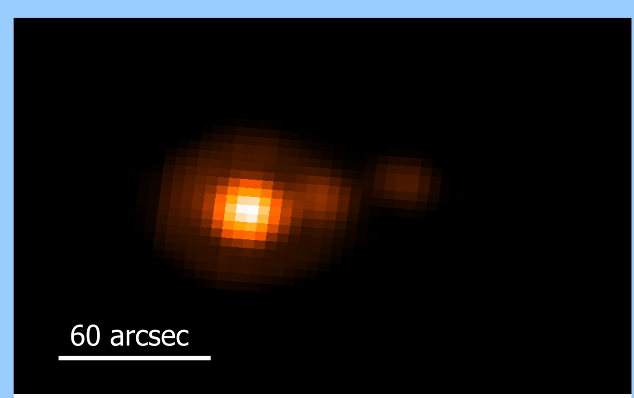
a) IRAC composite; Contours 3mm continuum

The infrared dark cloud IRDC18223-3 (d=3.7 kpc) contains a massive core that shows no protostellar emission below 8 µm. Beuther+ 2005 calculated from the 3.2mm continuum flux a mass and column density of the gas core with T=15K, M=576$M_\odot$ and 10^{24} cm^{-2} (A_V~1000). The central protostar, which is detected longwards of 24 µm source shows a steeply rising SED. Combining the mid- to far-infrared data with previous mm continuum observations and the upper limits below 8 µm (a), one can infer physical properties of the central source. Its derived luminosity of 177 $L_\odot$ is reached in simulations by Krumholz+ 2007 already at very early times when the protostellar mass is still well below half a solar mass. The corresponding accretion rates are of the order 10^{-4} $M_\odot$ yr^{-1}. 4.5 µm (a) emission indicates molecular outflows (supported by CO and CS line observations) and provides further evidence for the onset of massive star formation. Although combining the model predictions with the observed properties of this object from integral photometry indicates that the massive gas core harbors an embedded, accreting protostar with accretion rates that are high enough that it will eventually form a massive star, further IR observations with high spatial resolution are urgently required to understand the system. Analogous to case 1 JWST-MIRI will be able to study the conditions of the outflow emission with sufficient sensitivity and resolution to further constrain the critical mid-infrared continuum for a detailed and Spatially resolved 3D radiative transfer calculations based on mid-infrared emission and absorption.

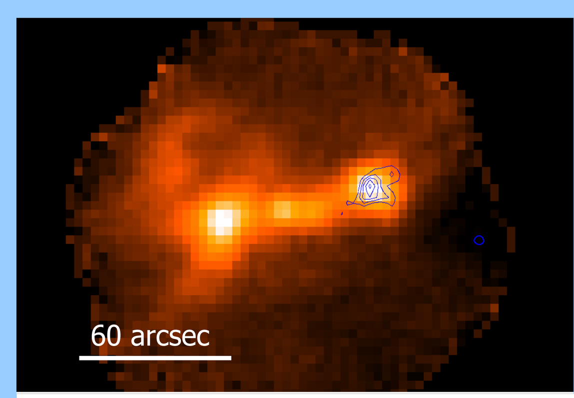


Case 3: The massive prestellar core ISOSS 04225+5143W

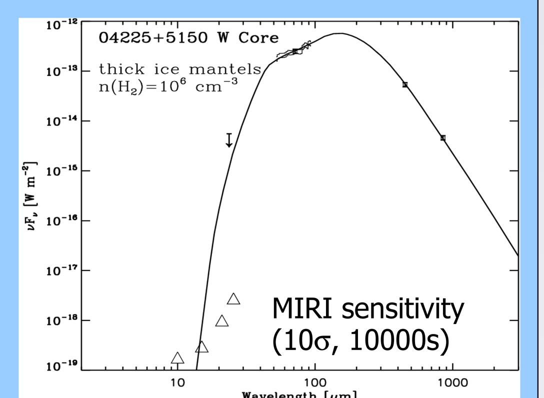
This is another region identified by the 170 µm ISOPHOT Serendipity Survey. Located at a distance of 6 kpc, follow-up observations with SCUBA and MIPS revealed two massive cores. While the western one is faintest at 70 µm, the situation is reversed at 450 µm indicating a low dust temperature T ~ 15 K. VLA NH_3 (1,1) and (2,2) observations confirm a dense ammonia core coinciding with the FIR/submm peak (T_{kin} < 20 K). The spectral energy distribution of this core (including MIPS SED mode data) is shown in (c). The core mass calculated assuming optically thin dust emssion (T ~ 15K) is 700 $M_\odot$ which is comparable to the core in IRDC18223-3 discussed above.



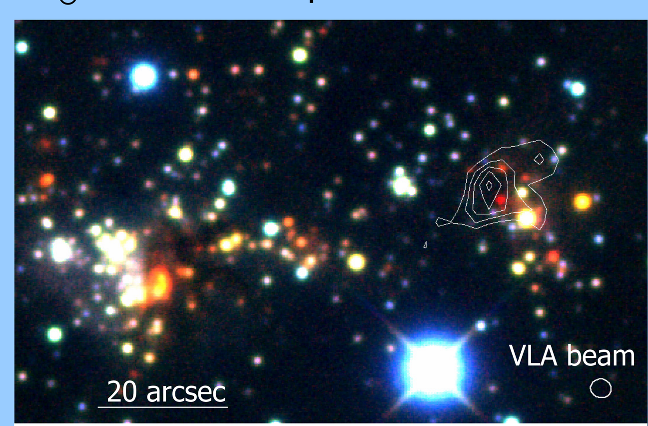
a) MIPS 70 µm map of ISOSS04225+5150



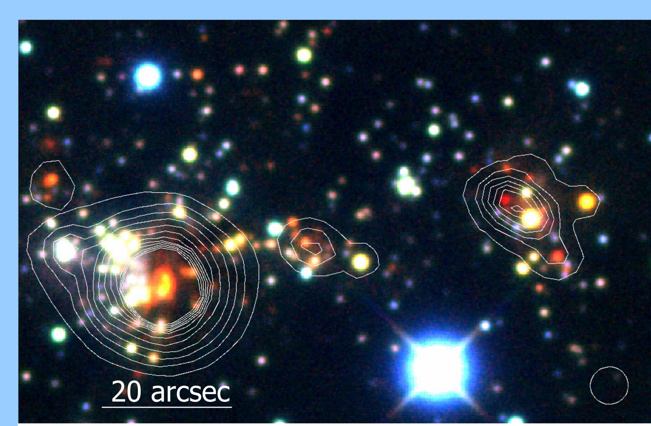
b) SCUBA 450 µm map; Contours: velocity integrated NH_3(1-1) emission



c) Spectral energy distribution of ISOSS04225+5150W



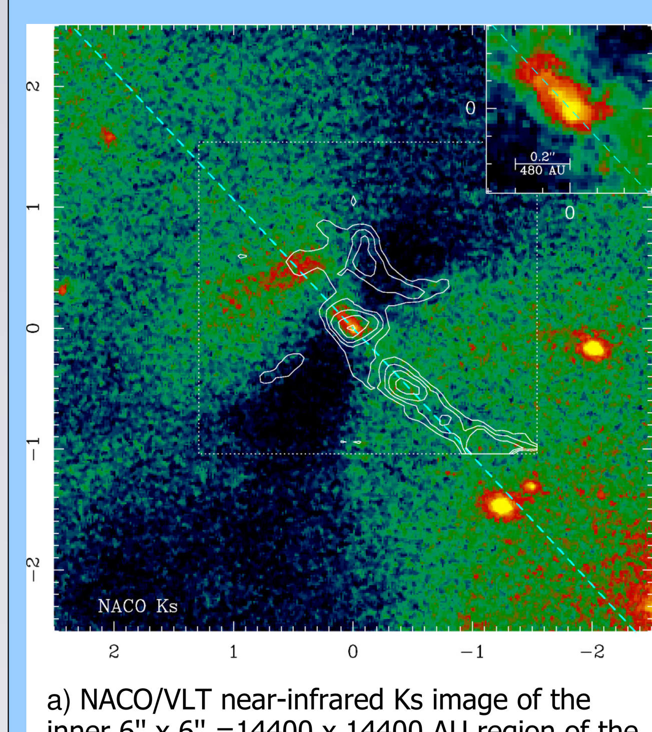
d) JHK composite; Contours: velocity integrated NH_3(1-1) emission; VLA beam is indicated



e) JHK composite; Contours: 24 µm emission MIPS beam size is indicated

Compared to IRDC18223-3 there is however no indication of a central protostellar source. Deep NIR images obtained at the CaHa 3.5m (d,e) telescope reveal a NIR extinction feature coinciding with the submm and NH_3 core (astrometric accuracy 0.1"). A number of reddened sources is detected in the vicinity of the core but not at its center. Two of these sources are also detected at 8 and 24 µm. After PSF subtraction of the two 24 µm sources, there is no core counterpart seen at the level shown in (c), making also ISOSS04225W is an excellent candidate of a massive prestellar core. MIRI will provide sufficient sensitivity to put stringent limits on the presence of an embedded high-mass protostar in this core according to the limits shown in (c).

Case 4: The Silhouette-Disk in M17 – An O star in the making ?



a) NACO/VLT near-infrared Ks image of the inner 6" x 6" =14400 x 14400 AU region of the M17 disk. Contours denote the H2 1-0 S(1) line emission of the jet measured with SINFONI/VLT

During a systematic infrared study of the stellar content of M17, Chini+ 2004 discovered an opaque silhouette at *JHK* with a diameter of 24 000 AU against the bright background of the HII region. The flared disk is seen under an inclination angle of about 10◦ (almost edge-on) and is associated with an optically visible hourglass-shaped nebula perpendicular to the disk plane. The optical spectrum of the nebula exhibits emission lines as observed in T-Tauri stars indicative of disk accretion. Nürnberger+ 2007 found a H2 jet emerging from the disk centre, indirectly corro-borating the presence of accretion processes. However, the disk mass is still controversial, ranging from about 4 $M_\odot$ (Sako+ 2005) to 100 $M_\odot$ (Chini+ 2004). The NACO/VLT near-infrared Ks image of the M17 silhouette disk shown in (a) roughly covers the MIRI-IFU field of view. The insert shows the central 0.6" x 0.6". The central channel is resolved into a point-source of Ks=19.3 mag and a fainter tail of Ks=20.1mag extending to the northeast. This tail is coaligned with the jet detected in H_2 1-0 S(1) line emission with SINFONI/VLT (Nürnberger+ 2007). The inferred accretion luminosity from the H2 brightness is 10^{-4} $M_\odot$ yr, similar to the model for the early protostar in IRDC 18223-3 and consistent with an early B type star as central object which is still growing on it way to Becoming an O-type star. MIRI and NIRSPEC can provide new data of the jet in the interface region to the protostar. The extinction towards the closest knot detected the SINFONI observations is A_V ~ 160 mag. JWST will also allow to resolve the circumstellar disk (emission and absorption) which will allow to model the density and temperature profile using 3-D radiative transfer (Steinacker+ 2006).

References

Birkmann, Krause & Lemke 2006 ApJ 637, 380
Birkmann et al., A&A 2007 in press
Beuther & Steinacker 2007, ApJ 656, 85
Beuther et al. 2007, Proc. PRPL, 165
Beuther et al. 2005, ApJ 634, 185
Chini et al. 2004 Nature 429, 155
Nielbock et al. 2007 A&A submitted
Nürnberger et al. 2007, A&A 465, 931
Krause et al. 2003, A&A 398, 1007
Sako et al. 2005, Nature 434,995
Krumholz et al. 2007, ApJ 656, 959
Klein et al. 2005, ApJS 161, 361
Steinacker et al. 2006, A&A 456, 1013
Motte et al. 2007 astro-ph/07082774
Cesaroni et al. 2007, Proc. PRPL, 197
Zinnecker & Yorke 2007, ARA&A 45, 481