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Formation and early evolution of massive stars

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Abstract: The early evolutionary stages of high-mass star formation have been subject to intense research for more than a decade now. Because several comprehensive reviews exist, here I focus on a few results obtained in the last two years. Specific questions to be addressed are: What can we learn about the initial conditions of high-mass star formation from recent Herschel observations? How important are magnetic fields for high-mass star-forming clumps and cores? Do we find genuine massive accretion disks? Do high-mass stars form first, last or simultaneously with the low-mass stars during cluster formation?

1 Introduction

Since this conference deals with the birth, life and death of high-mass stars, it appears superfluous to stress the importance of them again. Therefore, I just like to point out that the formation and early evolution of high-mass stars has been one of the most important topics in star formation research over the last decade. This is also manifested in a loose series of conferences targeting this topic over recent years (e.g., Joint discussion at Manchester IAU 2000 "Massive Star Birth"; Boulder 2001 "The Earliest Phases of Massive Star Birth"; Sicily 2005 "Massive Star Birth: A Crossroads of Astrophysics"; Heidelberg 2007 "Massive Star Formation: Observations Confront Theory"; Townsville 2010 "Great Barriers in High-Mass Star Formation"). For more general reviews about the topic with extensive introductions and state-of-art discussions at the given time, I refer to two big reviews (Zinnecker & Yorke 2007; Beuther et al. 2007) as well as the conference proceedings from the 2005 and 2008 meetings aforementioned (Cesaroni et al. 2005; Beuther et al. 2008). Here, I like to concentrate on recent results obtained in that field over the last two years. In particular, I like to outline the progress made toward four sub-topics of that field: (a) the earliest evolutionary stages, in particular with respect to new Herschel results obtained toward infrared dark clouds (IRDCs), (b) the characterization of magnetic field structure by means of polarization and Zeeman measurements, (c) the properties of rotating toroids and/or potential massive accretion disks, and (d) discuss whether high-mass stars form first, last or simultaneously during the cluster formation process.

2 The earliest evolutionary stages of high-mass star formation

The initial conditions for, and the onset of the formation of massive stars has for a long time been largely elusive to observational research because already the identification of the right targets was difficult. This situation changed tremendously at the end of the last century when several mid-infrared surveys became available allowing us to identify the youngest and coldest molecular clouds as dark shadows against the brighter background. While first ground-breaking work was conducted with the satellites *ISO* and *MSX* (e.g., Perault et al. 1996; Egan et al. 1998; Carey et al. 2000; Rathborne et al. 2005; Sridharan et al. 2005; Simon et al. 2006), the higher spatial resolution of *Spitzer* allowed additional great progress in that field (e.g., Vasyunina et al. 2009; Peretto & Fuller 2009). However, even with the *Spitzer* IRAC bands up to 8 μm as well as with MIPS in the 24 μm band, the peak of the spectral energy distribution was still out of reach, and any characterization of young massive star-forming regions had to be limited. The launch of *Herschel* in May 2009 again changed the picture considerably. The accessibility of all wavelength bands between 70 and 500 μm wavelength now allows us to study and characterize the birth sites and initial conditions of high-mass star formation in unprecedented detail.

There are several guaranteed and open time key projects which aim at characterizing these early evolutionary stages – e.g., EPOS, PI O. Krause; HiGAL, PI S. Molinari; HOBYS, PI F. Motte. While the first of the three mentioned projects is a targeted study toward a large sample of already well-characterized very young regions, the second aims at observing a large fraction of the Galactic disk (similar to GLIMPSE and MIPSGAL, Churchwell et al. 2009; Carey et al. 2009), and the third project targets most well-known regions within 3 kpc distance from the Sun, including all evolutionary stages.

Here, I like to focus on early results obtained within the EPOS project - The Early Phase of Star Formation. Within this guaranteed time key project, we observed a sample of 44 very young high-mass star-forming regions selected from different sub-samples. One third of the sources consists of 170 μm emission sources selected from the *ISO* Serendipity Survey (e.g., Krause et al. 2004; Birkmann et al. 2006; Hennemann et al. 2008), the second third is based on the sample identified by Sridharan et al. (2005) in the fields of high-mass protostellar objects (HMPOs), and the last third contains well-known IRDCs previously studied by, e.g., Carey et al. (2000). What all sources have in common is that they are already previously well characterized from ample observations at other wavelengths, and for most of the regions, we also have higher-spatial-resolution information from interferometer observations. Therefore, these regions allow us an in-depth study of the initial conditions important for the high-mass star formation processes. In the following, I will show a few early results.

2.1 The Snake or G11.11

One of the most famous IRDCs is the so-called Snake, a.k.a. G11.11. This region was previously observed by Carey et al. (2000) and has been subject to investigations since then (e.g., Johnstone et al. 2003; Pillai et al. 2006). Within the EPOS key project, the whole region was observed in all Herschel PACS and SPIRE continuum bands between 70 and 500 μm wavelengths (see Fig. 1 for a few example images, Henning et al. 2010). An image comparison allows us already interesting insights for the cloud being an absorption feature below 100 μm, then becoming nearly indistinguishable from the background at 160 μm, and turning into emission at longer wavelengths. More importantly, the data reveal many point-source-like protostars along the snake-filament. An SED analysis of these sources reveals dust temperatures below 20 K and masses usually of the order a few $M_{\odot}$, hence no massive protostars yet. It appears that most of the mass is still distributed over the cold envelopes and the entire filament. While for each individual sub-source, one cannot conclude whether it will be a high-mass star at the end of its evolution, it is a reasonable assumption that some will because the entire gas reservoir is sufficient to form massive stars. Furthermore, we detect an entirely new population of very young objects that was undetected even at 24 μm, but which become clear point-source emission features from 70 μm onwards. While the SED does not allow us to distinguish these sources from genuine starless cores, the fact that they appear as point sources in the 70 μm image with

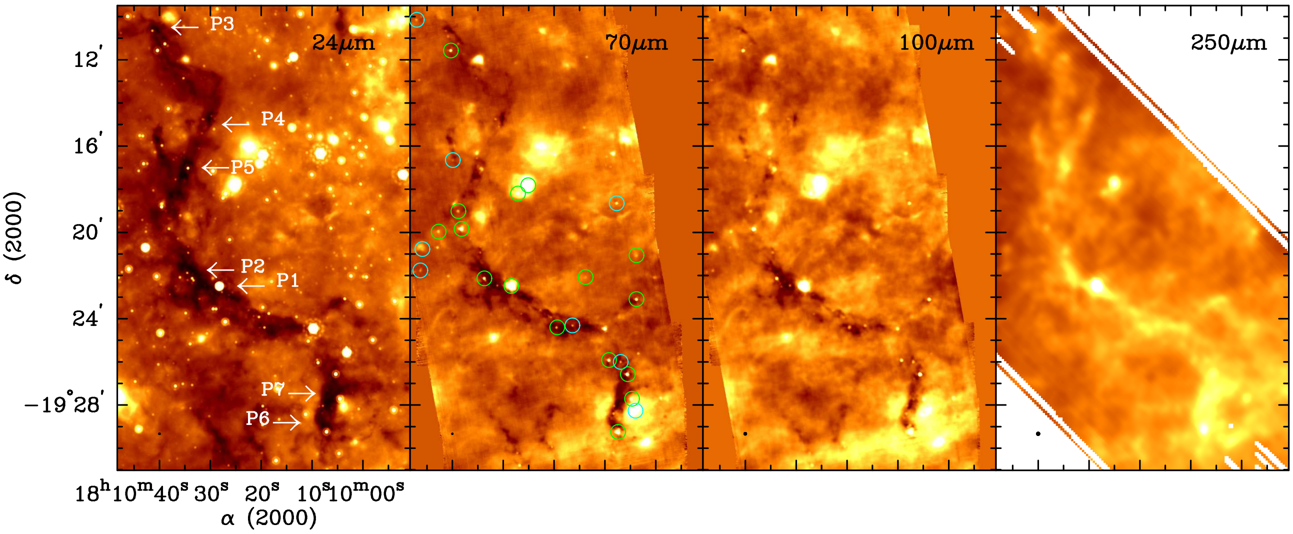

Figure 1: The Snake a.k.a. G11.11. The left panel shows the *Spitzer* 24 μm data, and the other three panels present different wavelengths bands from *Herschel* as marked (Henning et al. 2010). The labels in the left panel identify submm continuum sources from Johnstone et al. (2003), and the circles in the 2nd panel outline identified point sources.

a spatial resolution of $\sim 6''$ ($\sim$21000AU) is indicative of an inner heating source already. Therefore, one may speculate whether these new detections may be the observational manifestation of the first hydrostatic cores in the star formation process.

2.2 The infrared dark cloud complex IRDC 18223

This cloud complex started to be investigated because of its IRAS identification as a high-mass protostellar object (HMPO) by Sridharan et al. (2002). However, it was quickly realized that not just the HMPO is interesting but that the whole complex presents a region with several evolutionary stages in close proximity (Fig. 2, Sridharan et al. 2005; Beuther et al. 2005; Beuther & Steinacker 2007). Right south of the strong IRAS source, one finds a dark filament that contains only weak 24 μm emission sources. These sources represent high-mass cores with embedded low-to intermediate-mass protostars that may (or may not) be destined to become massive at the end of their evolution. Further south, we identify another region that is dark at 24 μm, and now with Herschel also at 70 and 100 μm, but that becomes a strong emission source at longer wavelengths due to the cold dust emission. Hence, this region comprises all evolutionary stages ranging from high-mass starless cores up to HMPOs. The Herschel data now allow us a detailed evolutionary characterization of the different evolutionary stages. Fig. 2 presents spectral energy distributions (SEDs) for four different cores representing these stages and their properties (Beuther et al. 2010a). While the starless cores are only emission sources longward of 100 μm that can easily be fitted by single-component modified blackbody functions, as soon as an internal heating source starts modifying the environment, one finds excess emission at shorter wavelengths and additional warmer components are required to fit the data. The 70 μm emission source from that point of view is a borderline object, because it shows a clear point source at that wavelength but can still be fitted with a single component. That may again be a candidate source in an evolutionary stage of the first hydrostatic core, similar to the G11.11 case discussed above. While excess emission at 24 μm becomes evident early in the evolutionary sequence, it appears that for some time the luminosity of this warmer component remains still relatively low, from an observational point of view at least as long as the sources are infrared dark in the Spitzer IRAC

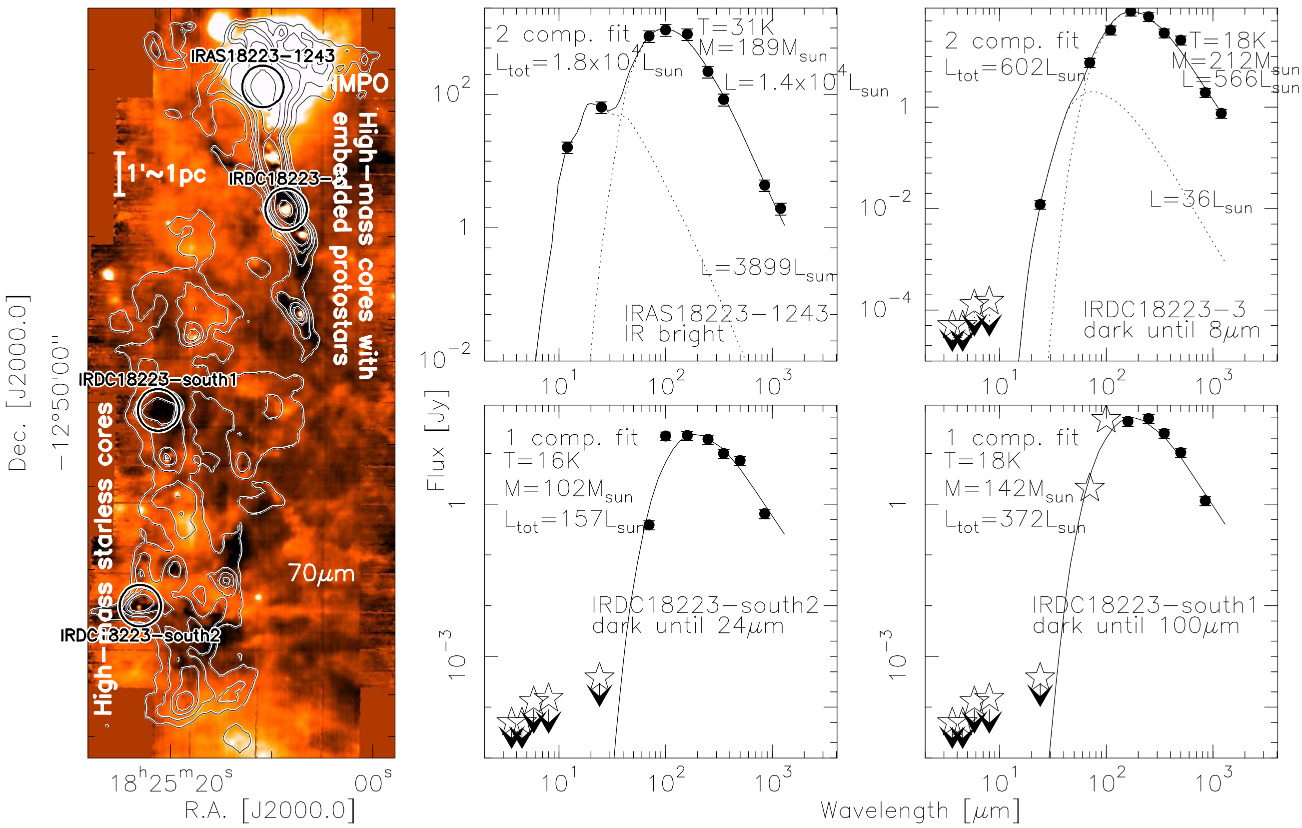

Figure 2: Composite of *Herschel* observations toward IRDC 18223 (Beuther et al. 2010a). The left panel presents in color the 70 μm continuum emission with the submm 850 μm contours on top. The evolutionary sequence as well as the four sources where spectra were extracted are marked. The other four panels show the corresponding SEDs and the associated fits. Fit parameters are given in each panel.

bands up to 8 μm. To quantify the time-scales of the different evolutionary stages will be one of the important questions in that field in the coming years. However, with the high-quality Herschel data available, a lot of progress is expected.

2.3 High-mass starless cores in the vicinity of a mini-starburst

The infrared dark clouds associated with the cloud complex IRDC 18454 are in the immediate vicinity of the galactic mini-starburst W43 (Motte et al. 2003; Sridharan et al. 2005). It is noteworthy in itself that one finds 70 μm dark extinction sources with masses of several 100 $M_\odot$ in such close proximity of one of the most active star-forming regions of our Galaxy (Fig. 3). Hence, it appears that the luminosity and energy output of W43 does not straight away trigger either the collapse or the dispersal of nearby cloud cores, but that some of them may stay around for some (unknown) amount of time. A detailed analysis of the Herschel dataset is currently being conducted (Beuther et al. in prep.). However, here we like to point out another curiosity of that region, namely some kinematic characteristics. It was early on recognized that some of the cores showed different velocity features in their spectra about 50 km s^{-1} apart. One component at $\sim$ 100 km s^{-1}, approximately the rest velocity of W43, and one component at 50 km s^{-1}. Is the latter just a chance alignment along the line of sight or may it be associated with the peculiar location of that region right at the interface of the inner Galactic bar and a spiral arm? Figure 3 also shows N_2H^+ emission maps integrated over the two velocity components. While the 100 km s^{-1} component clearly confirms the association of the

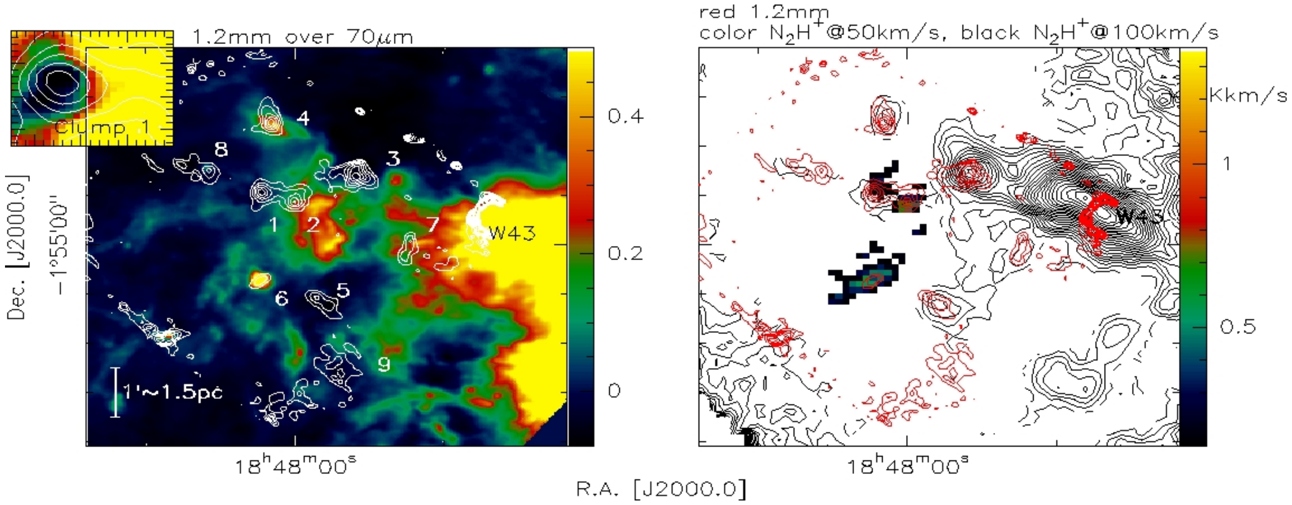

Figure 3: Composite of data toward the dark cloud complex IRDC 18454. The left panel shows in color the 70 μm emission with white contours of 1.2 mm continuum. The inlay presents a zoom into clump 1 (tick-marks there are arcseconds). The right panel shows the same region, this time the N_2H^+(1–0) and 1.2 mm continuum emission as labeled on top of the panel.

IRDC complex with the mini-starburst W43, the 50 km s^{-1} component is confined to only a few of the sub-sources. However, the nearly indistinguishable character of the submm sources between the different velocity components as well as the close spatial association let us speculate whether the two components may not be spatially interacting, maybe between the galactic bar and the spiral arm? The IRAM large program studying the whole region on much larger scales in ^{13}CO emission may shed more light on this question (PI F. Motte).

3 Magnetic field structure during high-mass star formation

The morphology of the magnetic field structure, in particular on the smallest spatial scales for high-mass star formation, has largely been elusive to observations. While Zeeman measurements with high-density tracers like CN or CH_3OH maser emission toward larger samples reveal magnetic field strengths on core scales (several 1000 to 10000 AU) of order mG (e.g., Falgarone et al. 2008; Vlemmings 2008), high-spatial-resolution polarization measurements of masers as well as the recent advent of polarization capabilities at mm interferometers has allowed us significant progress studying also the field morphology.

While VLBI OH maser observations revealed polarized emission at the edges of ultracompact HII regions, barely any evident morphological signature could be derived (e.g., Fish & Reid 2006). Vlemmings (2008) recently started exploring the polarization and Zeeman properties of the class II CH_3OH maser emission which traces the densest cores in high-mass star-forming regions. Toward the disk-outflow system Cepheus A, Vlemmings et al. (2010) were now able to trace the 3D morphology distribution of the maser polarization, and hence the magnetic field, via MERLIN VLBI observations at 6.7 GHz. They find that the magnetic field is predominantly aligned along the protostellar outflow and perpendicular to the disk (Fig. 4). A detailed analysis indicates that the core is collapsing and that the gas likely falls in along the magnetic field lines.

The advent of the submm continuum dust polarization capability at the Submillimeter Array (SMA) also opened the window to high-spatial-resolution magnetic field studies of the dense gas cores not just limited to the specific maser conditions. While early work revealed the predicted hour-

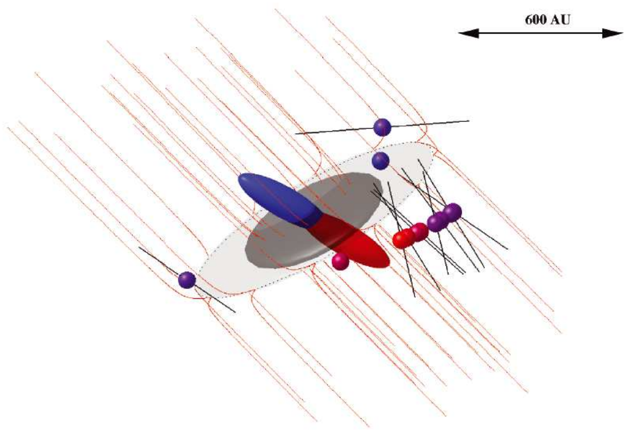

Figure 4: The three-dimensional magnetic field structure around the massive protostar CepheusA HW2 from Vlemmings et al. (2010). Spheres indicate the masers, with the black vectors indicating the true magnetic field direction. The grey region indicates the disk, and the blue and red cones the outflow. The red lines outline the magnetic field morphology.

glass shape magnetic field structure in low-mass cores (Girart et al. 2006), similar results were more recently also found in a few high-mass star-forming regions (e.g., Girart et al. 2009; Tang et al. 2009). Quantitative estimates from these data are difficult since the Chandrasekhar-Fermi method relies on the statistical spread of polarization angles in the data and is hence intrinsically prone to large error margins (Chandrasekhar & Fermi 1953). Nevertheless, current data indicate that magnetic fields are important, however, they do not seem to prevent the collapse of the cores.

Furthermore, the (sub)mm window also allows us studies of the Goldreich-Kylafis effect from molecular lines, in particular CO (Goldreich & Kylafis 1981, 1982). Since this effect relies on a combination of Zeeman-splitting and an anisotropic population of the different sub-levels, which can be achieved by anisotropic optical depth and radiation fields (for a qualitative description see Kylafis 1983), molecular outflows appear as particular promising candidates to study their magnetic field structure via this effect. Early work in this direction has been conducted by Girart et al. (1999); Lai et al. (2003); Cortes et al. (2005, 2008). Recently, we now also achieved the first spatially resolved Goldreich-Kylafis effect observations in CO(3–2) with the Submillimeter Array (SMA) toward the young massive disk-outflow region IRAS 18089-1732 (Fig. 5, Beuther et al. 2010b). Interestingly, we also find that the magnetic field structure appears to be approximately aligned with the outflow, similar to the maser data discussed above. One additional technical advantage of the CO polarization observations is that one obtains simultaneously the dust continuum polarized emission. Hence, within a single observation one can study the magnetic field of the dense core as well as that of the outflow.

One other recent very interesting magnetic field result is that Carrasco-Gonzales and co-workers measure the magnetic field of one high-mass jet via its synchrotron emission (presented in the Sept. 2010 “Great Barriers in High-Mass Star Formation” meeting in Townsville/Australia). They also find that the magnetic field is aligned with the jet. If one combines the maser, synchrotron and CO data, it appears that the magnetic field remains very organized over large spatial scales, down from the core center, along the jet and also within the entrained gas of the molecular outflow.

4 Rotation, infall and disks

The study of disks in high-mass star formation is considered as one of the cornerstones in this field. While there has been tremendous progress over the last decade (e.g., Cesaroni et al. 2007), we are

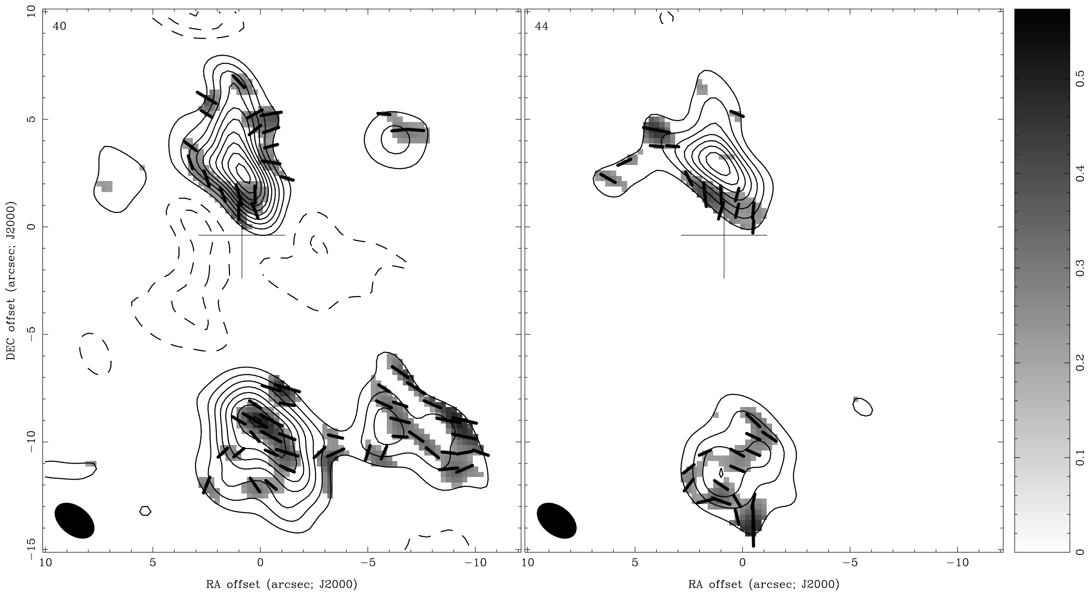

Figure 5: The grey-scale presents the linearly polarized CO(3–2) emission in two channels (central velocities are marked in the top-left corners) for the young high-mass disk-outflow system IRAS 18089-1732. The line-segments show the orientation of the polarized emission. The contours present the corresponding CO(3–2) Stokes I image. The cross marks the position of the submm continuum peak.

nevertheless still lacking a solid understanding of the properties of rotating structures, the infalling gas and the embedded disks. Among the best disk candidates are probably IRAS 20126 and CepA (e.g., Cesaroni et al. 2005; Jiménez-Serra et al. 2007), however, their inferred central stellar masses barely exceed $10\,M_\odot$. For more massive and more luminous regions, one usually finds rotating structures perpendicular to the outflows, but their sizes (several 1000 to 10000 AU) and non-Keplerian rotation curves preclude that these are genuine disks (e.g., Beltrán et al. 2004; Chini et al. 2004; Cesaroni et al. 2007; Beuther & Walsh 2008; Beuther et al. 2009). These structures are much more likely parts of rotating and infalling envelopes – sometimes also coined toroids – that may host more genuine accretion disks at the inner center.

Recent modeling work toward the prototypical high-mass disk candidate IRAS 20126 confirmed that both a warm, dense, rapidly-rotating disk and a cold, diffuse infalling envelope are required to reproduce all the available mm spectral line data. Work toward a younger source, the IRDC 18223-3 also revealed a rotating and flattened structure perpendicular to the outflow, however, the size is much larger of the order 25000 AU (Fallscheer et al. 2009). Furthermore, only a comparably small velocity difference of $\sim$3 km s^{-1} is found over the large region. These data are consistent with a large flattened, rotating and infalling envelope structure. However, since the region also exhibits a typical bipolar outflow, it is most likely that at the inner unresolved center one finds a more typical accretion disk. Going to more evolved regions, we recently observed a dozen hot core regions in the southern hemisphere identifying rotational signatures in 6 of them (Beuther et al. 2009). Again the velocity gradients are consistent with rotating and infalling envelopes but not yet real accretion disks. Taking the spatial resolution into account, if genuine accretion disks exist at the center of these rotating structures, they should not exceed $\sim$1000 AU. Going to even higher spatial resolution and more evolved sources that are detectable in the near-infrared, Kraus et al. (2010) recently presented the first near-infrared image of an accretion disk around a massive young stellar object obtained with the VLTI/AMBER instrument. This disk-like structure of warm and compact dust extends only about 20 AU and has a dust-free inner zone of less than 9.5 AU.

Although the statistical basis for toroid and disk studies is still small, current data indicate that there is an evolutionary trend for the rotating structures: They start with very large and extended toroidal infalling envelopes at the onset of collapse (size about 20000 AU), developing into rotating and infalling envelopes (size several 1000 AU) hosting likely accretion disks < 1000 AU at their centers, and continuing into smaller and compact disks (of order several 10 AU) during the continuing formation phase. A challenging task for future observations will be to connect the warm and compact dust disks seen in the near-infrared with the colder and more extended gas and dust disks usually observed at (sub)mm wavelengths.

5 Which stars form first/last?

One of the questions often discussed in high-mass star formation research is whether the high- and low-mass stars form simultaneously, or whether the massive stars form last or first during the early cluster evolution. Although perhaps not a very scientific approach, Zinnecker & Beuther (2008) conducted a poll during a panel discussion among leading theorists within that field, and even there no agreement was achieved.

To first order, one would argue that high-mass stars form last since their strong UV-radiation and winds should severely affect the surrounding gas reservoir that the maternal cocoons may get expelled shortly after the massive stars are actually born. This picture seems to be supported by observations where Kumar et al. (2006) detect already formed low-mass clusters around a sample of still actively accreting HMPOs. In contrast to this, numerical simulations show a larger degree of clumpiness and filamentary structure (e.g., Bonnell & Bate 2005), and within such an environment, the radiation from the massive stars may more easily escape without affecting the other cores in the environment too much. Another view is proposed by Joao Alves (priv. comm.), who, based on observations of the very luminous clusters within W49 (Alves & Homeier 2003; Homeier & Alves 2005), suggests that the massive stars form first and then trigger the formation of low-mass stars in the aftermath.

During a recent multi-wavelength study of the S255 star-forming complex from near-infrared to mm wavelengths, Wang et al. (subm. to A&A) dissected the different populations of the central forming cluster in detail. They find that the most massive cluster member drives an outflow with a dynamical age of the order 10^4 years. Although these dynamical ages are very uncertain, it is unlikely that this object is older than 10^5 years. In contrast to that, the near-infrared spectra reveal a cluster of low-mass stars in the direct environment of the central massive protostars. The spectral data allow Wang et al. to spectral type and then age date these sources via stellar evolution models. The derived age is $\sim 2 \pm 1$ Myr. While the actual age is again uncertain, it is unlikely that these sources are significant younger than 1 Myr. Therefore, taking into account the uncertainties, the data indicate that there is still an age difference of about 1 order of magnitude between the already formed low-mass cluster and the just forming high-mass protostar. Hence, these data are again support for the first scenario where massive stars form last.

But obviously, even with all these data at hand, this case is definitely not closed yet, and future studies may (or may not) shed more light on the order of star formation within young high-mass clusters.

6 Summary

While I could only address a few exciting new results here, it is obvious that much work remains to be conducted in this field. The ever evolving computational facilities promise great progress in the modeling part of high-mass star formation. In particular, there is hope that in the near future one will self-consistently model the whole evolution from the cloud formation via the fragmentation to the collapse of massive gas clumps with full 3D magneto-hydrodynamic simulations including radiation transfer as well as chemical networks. On the observational side, Herschel already now shows that we will get a wealth of new results for the earliest formation times, whereas the advent of the Atacama Large Millimeter Array (ALMA) in 2011, and JWST in the mid of the starting decade, promises exciting new insights for the cold and warm dust and gas components at the highest possible spatial resolution. Combining these observational and theoretical approaches, it is likely that within the next decade we will establish a much better understanding of the high-mass star formation processes. Among the important questions to be tackled in the future are: How do disks fragment, do they form multiples or spiral-like structures? What are the actual accretion rates, and how variable are they? On what spatial scales is the initial mass function recovered, or is low-mass star formation suppressed at the cluster centers? Are disk-winds or stellar winds dominating in high-mass star formation? How can we relate our detailed local knowledge about high-mass star formation with the extragalactic more global views?

References

Alves, J. & Homeier, N. 2003, ApJ, 589, L45

Beltrán, M. T., Cesaroni, R., Neri, R., et al. 2004, ApJ, 601, L187

Beuther, H., Churchwell, E. B., McKee, C. F., & Tan, J. C. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil, 165–180

Beuther, H., Henning, T., Linz, H., et al. 2010a, A&A, 518, L78

Beuther, H., Linz, H., & Henning, T., eds. 2008, Massive Star Formation: Observations Confront Theory, ASP Conference Series 387

Beuther, H., Sridharan, T. K., & Saito, M. 2005, ApJ, 634, L185

Beuther, H. & Steinacker, J. 2007, ApJ, 656, L85

Beuther, H., Vlemmings, W. H. T., Rao, R., & van der Tak, F. F. S. 2010b, Accepted for ApJL, ArXiv e-prints, 1010.3635

Beuther, H. & Walsh, A. J. 2008, ApJ, 673, L55

Beuther, H., Walsh, A. J., & Longmore, S. N. 2009, ApJS, 184, 366

Birkmann, S. M., Krause, O., & Lemke, D. 2006, ApJ, 637, 380

Bonnell, I. A. & Bate, M. R. 2005, MNRAS, 362, 915

Carey, S. J., Feldman, P. A., Redman, R. O., et al. 2000, ApJ, 543, L157

Carey, S. J., Noriega-Crespo, A., Mizuno, D. R., et al. 2009, PASP, 121, 76

Cesaroni, R., Galli, D., Lodato, G., Walmsley, C. M., & Zhang, Q. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil, 197–212

Cesaroni, R., Neri, R., Olmi, L., et al. 2005, A&A, 434, 1039

Chandrasekhar, S. & Fermi, E. 1953, ApJ, 118, 113

Chini, R., Hoffmeister, V., Kimeswenger, S., et al. 2004, Nature, 429, 155

Churchwell, E., Babler, B. L., Meade, M. R., et al. 2009, PASP, 121, 213

Cortes, P. C., Crutcher, R. M., Shepherd, D. S., & Bronfman, L. 2008, ApJ, 676, 464

Cortes, P. C., Crutcher, R. M., & Watson, W. D. 2005, ApJ, 628, 780

Egan, M. P., Shipman, R. F., Price, S. D., et al. 1998, ApJ, 494, L199

Falgarone, E., Troland, T. H., Crutcher, R. M., & Paubert, G. 2008, A&A, 487, 247

Fallscheer, C., Beuther, H., Zhang, Q., Keto, E., & Sridharan, T. K. 2009, A&A, 504, 127

Fish, V. L. & Reid, M. J. 2006, ApJS, 164, 99

Girart, J. M., Beltrán, M. T., Zhang, Q., Rao, R., & Estalella, R. 2009, Science, 324, 1408

Girart, J. M., Crutcher, R. M., & Rao, R. 1999, ApJ, 525, L109

Girart, J. M., Rao, R., & Marrone, D. P. 2006, Science, 313, 812

Goldreich, P. & Kylafis, N. D. 1981, ApJ, 243, L75

Goldreich, P. & Kylafis, N. D. 1982, ApJ, 253, 606

Hennemann, M., Birkmann, S. M., Krause, O., & Lemke, D. 2008, A&A, 485, 753

Henning, T., Linz, H., Krause, O., et al. 2010, A&A, 518, L95

Homeier, N. L. & Alves, J. 2005, A&A, 430, 481

Jiménez-Serra, I., Martín-Pintado, J., Rodríguez-Franco, A., et al. 2007, ApJ, 661, L187

Johnstone, D., Fiege, J. D., Redman, R. O., Feldman, P. A., & Carey, S. J. 2003, ApJ, 588, L37
Kraus, S., Hofmann, K., Menten, K. M., et al. 2010, Nature, 466, 339
Krause, O., Vavrek, R., Birkmann, S., et al. 2004, Baltic Astronomy, 13, 407
Kumar, M. S. N., Keto, E., & Clerkin, E. 2006, A&A, 449, 1033
Kylafis, N. D. 1983, ApJ, 275, 135
Lai, S., Girart, J. M., & Crutcher, R. M. 2003, ApJ, 598, 392
Motte, F., Schilke, P., & Lis, D. C. 2003, ApJ, 582, 277
Perault, M., Omont, A., Simon, G., et al. 1996, A&A, 315, L165
Peretto, N. & Fuller, G. A. 2009, A&A, 505, 405
Pillai, T., Wyrowski, F., Menten, K. M., & Krügel, E. 2006, A&A, 447, 929
Rathborne, J. M., Jackson, J. M., Chambers, E. T., et al. 2005, ApJ, 630, L181
Simon, R., Jackson, J. M., Rathborne, J. M., & Chambers, E. T. 2006, ApJ, 639, 227
Sridharan, T. K., Beuther, H., Saito, M., Wyrowski, F., & Schilke, P. 2005, ApJ, 634, L57
Sridharan, T. K., Beuther, H., Schilke, P., Menten, K. M., & Wyrowski, F. 2002, ApJ, 566, 931
Tang, Y., Ho, P. T. P., Koch, P. M., et al. 2009, ApJ, 700, 251
Vasyunina, T., Linz, H., Henning, T., et al. 2009, A&A, 499, 149
Vlemmings, W. H. T. 2008, in ASP Conference Series, Vol. 387, Massive Star Formation: Observations Confront Theory, ed. H. Beuther, H. Linz, & T. Henning, 117
Vlemmings, W. H. T., Surcis, G., Torstensson, K. J. E., & van Langevelde, H. J. 2010, MNRAS, 404, 134
Zinnecker, H. & Beuther, H. 2008, in Astronomical Society of the Pacific Conference Series, Vol. 387, Massive Star Formation: Observations Confront Theory, ed. H. Beuther, H. Linz, & T. Henning, 438
Zinnecker, H. & Yorke, H. W. 2007, ARA&A, 45, 481

Discussion

Y.-H. Chu: The massive star community regards stars more massive than several tens of solar masses as 'massive stars'. What stellar mass range does your massive star formation correspond to?
H. Beuther: Most of the presented studies deal with stars in the 10-30 $M_\odot$ regime. The observational database of very young more massive regions is still relatively poor.

G. Romero: Is there any evidence for non-thermal emission in some of these SFR with strong magnetic fields?
H. Beuther: Yes, there are a few examples of non-thermal radio emission in young massive star-forming regions. The most prominent is maybe the synchrotron emission in W3 (H_2O) by Reid et al. (1995). This emission is usually associated with the jets. However, it should be stressed that thermal radio emission – from the jets and the protostars – is far more often observed.

D. Gies: Are high-mass star-formation regions usually associated with filamentary structures?
H. Beuther: Very often, yes. In particular, recent *Herschel* observations reveal filamentary structures in a very regular fashion.

R. Chini: The high-mass protostellar candidates that you find at FIR/submm wavelengths have typically a couple of hundred solar luminosities. A five-solar-mass protostar produces about thousand solar luminosities. What gives you the confidence to call them high-mass protostars if there are no additional hints like, e.g., high-mass or high-luminosity outflows?
H. Beuther: This is certainly an important point. For each individual source the answer is not easy. If we have a massive outflow with high outflow rates, that can be taken as an indirect indicator for a high-mass star-forming core. For larger samples, when we not always have such complementary data, the answer is more complicated, and one has to argue in a statistical sense. For each individual source one cannot be sure that the central object will form a massive star, it could remain low-mass star as you say. However, from a statistical point of view, some fraction is likely to form massive stars

in the end. Furthermore, an important criterion is that the mass reservoir has to be large enough to form a cluster, i.e., more than 500-1000 $M_\odot$ of gas.

H. Zinnecker: On sequential star formation in S 255-IR: in which direction is the sequence? S 255 and S 257 squeezing S 255-IR into massive star formation? Or perhaps is it the other way round: the semi-isolated B-stars powering the S 255 and S 257 H II regions could have been ejected from the S 255-IR forming cluster about 1 Myr ago, and are now pushing on their protocluster birth cloud? (cf. Zinnecker et al. 1993).

H. Beuther: While we cannot clearly exclude that idea, it still appears very unlikely to me. The age of these outer B-stars is $\sim$ 2 Myrs, whereas the B-stars still forming in the center of S 255-IR should be younger than 10^5 years. Furthermore, the morphology is very suggestive of such a squeezing and sequential star formation.