The Formation and Early Evolution of Massive Stars

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The enormous influence exerted by massive stars on their environment can affect the evolution of entire galaxies. It manifests itself most strongly during their formation in molecular clouds and their deaths as supernovae. We give examples for current observational results that shed light on the formation of these fascinating objects. We examine how this knowledge has been achieved and how it can be extended with the help of the latest observational methods.

The birth and death of high-mass stars play a major role in shaping the morphological, dynamical, and chemical structure of many galaxies. How dramatic the effects of the formation of massive stars can be is best seen in starburst galaxies, whose structure is entirely determined by the almost explosive formation of OB stars. From which mass upwards is a star called massive? The lower mass limit can be set quite well to be 8–10 $M_{\odot}$. Only stars at least that massive are capable of producing enough UV photons to ionise the surrounding gas and to form H II regions, to create supersonic winds, and finally to explode as supernovae. Moreover, it is known that the accretion phase is longer than the contraction period for stars exceeding roughly 8 $M_{\odot}$. Thus, newly forming massive stars are still deeply embedded in their parental molecular cloud. Therefore, no optically visible massive pre-main-sequence stars are observed. This is in strong contrast to the low- and intermediate-mass pre-main-sequence stars – the so-called TTauri and Herbig-Ae/Be stars. It is obvious that especially this fact has a large impact on observational strategies; to overcome the large extinction one has to go to longer wavelengths, mainly the near- and thermal infrared. For the earliest phases even this is not sufficient, and new knowledge has to be extracted from far-infrared and (sub-)millimetre observations.

The formation of massive stars represents one of the major astrophysical problems which is still unsolved despite the crucial role these stars play in the evolution of galaxies (see the proceedings of the recent IAU Symposium 227, Cesaroni et al. 2005). The single key question is how these stars manage to accumulate that much matter during their birth process. Even during the main accretion phase, they already exhibit very high luminosities. This is a severe problem since the immense radiation pressure on dust grains counteracts the accretion, and the growing ionisation further pushes the gas to expand. It is not clear whether spherical accretion on the one hand can compete against the strong radiation, and on the other hand can cope with the vastly growing ionising flux of the forming star in order to quench an H II region for many dynamical times. The formation of massive stars by spherically symmetric mass infall therefore seems rather unlikely.

However, if the material is accumulated from a circumstellar disc the problem *may* disappear. The reason is that due to the presence of a disc, a highly anisotropic radiation field is produced, with different energy flows parallel and perpendicular to the disc's axis. First evidence for such accretion discs was thought to be found in the bipolar morphologies of the ionised regions around some well-known massive young stars or by the existence of very energetic and massive molecular outflows. We now have accumulating evidence that at least early B and late O stars (up to probably 20 $M_{\odot}$) form via disc-accretion processes similar to their low-mass counterparts. The characterisation of massive accretion discs is often considered as the missing link in the understanding of massive star formation.

An alternative theory to explain the formation of massive stars is based on the merging of lower-mass stars. The 'coalescence' scenario implies that tidal friction in close binary systems and dense clusters 'melt' a number of lower-mass stars into one high-mass star. In its originally proposed form, this scenario implied a broken mass distribution function in the cluster (due to missing lower-mass stars that already underwent merging), which is not observed in 'normal' clusters. The concept of coalescence may still play a role in very dense clusters especially in starburst regions, but observational indications such as the omnipresent outflows and even more collimated jets cannot be easily explained in this scenario and thus are in favour of a more conventional accretion scenario for more typical galactic environments.

A related issue is the question of what the observational characteristics of the earliest stages of massive stars are. Do they always form in clusters? What is the initial mass function (IMF) in these clusters? How important is competitive accretion? When do the outflows start? What are the spectral properties of the very young massive stars? Answers to these questions can only be obtained by disentangling the complex structure of massive star-forming regions, using near-infrared adaptive optics and long-baseline infrared interferometry, sensitive thermal infrared observations, and interferometry at millimetre and radio wavelengths. In this article, we will give examples of such observations and concentrate on recent results where ESO instrumentation has provided important contributions.

The early stages of evolution

The earliest stage of star formation is the collapse and fragmentation of a molecular cloud to (a) protostellar object(s). These objects are rather cold and usually not detected at near- or mid-infrared wavelengths. The search for massive and cold (pre-)protostellar cores only recently led to the detection of the first good candidates.

The best tool to find such cold and massive molecular cloud cores is an unbiased, large survey at far-infrared and sub-millimetre wavelengths. With more than 15 % sky coverage, the ISOPHOT 170 μm Serendipity Survey (ISOSS) is cur-

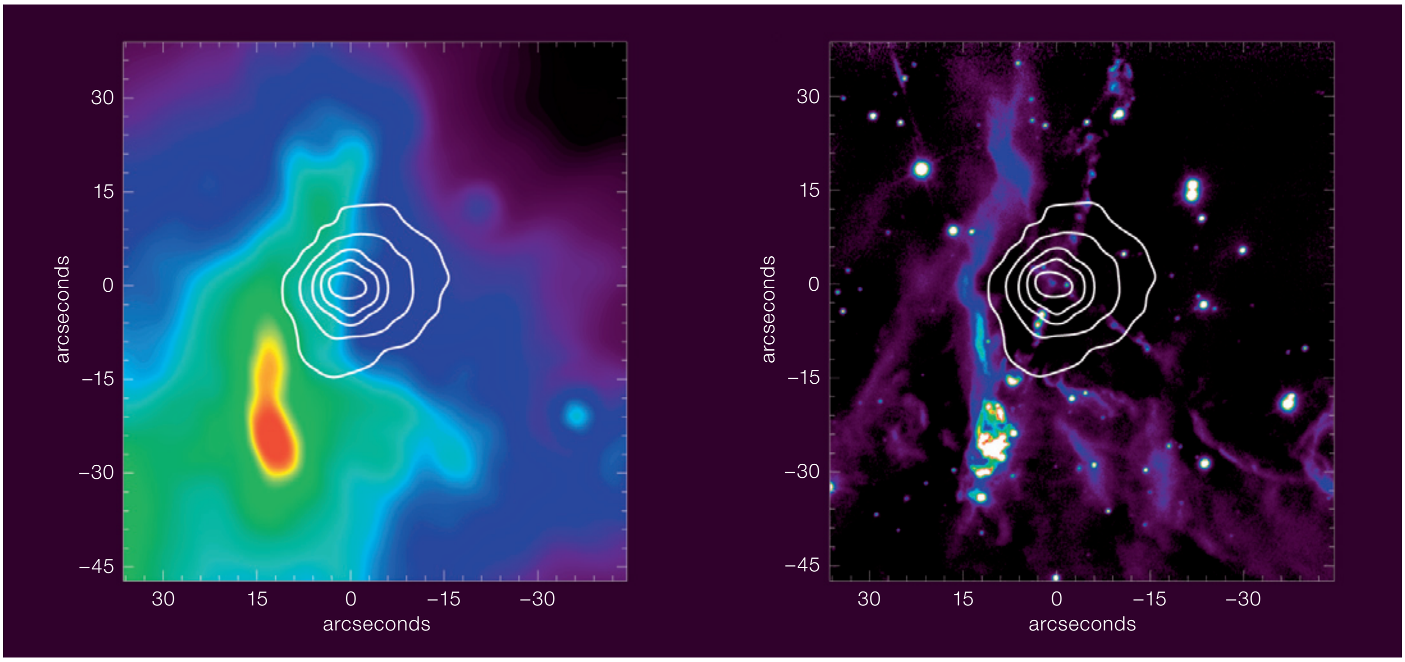

Figure 1: The cold core UYSO1 detected at the edge of the molecular cloud near IRAS 07029-1215. (Reference position R.A. $07^h05^m10^s.80$ Dec $-12°18'56''.8$ (J2000).) **Left:** Spitzer 24 µm image of the region with superimposed SCUBA 450 µm contours tracing the actual young core. **Right:** VLT ISAAC near-infrared image of the same field in the H_2(1-0)S1 narrow-band filter before continuum subtraction (from Forbrich, Stanke et al. in preparation). In particular, it features two crossed arms of near-infrared H_2 emission whose intersection point (close to the reference position) is compellingly near to the peak of the 450 µm emission. Note that the near-infrared emission visible at the respective core centre is not a continuum source but an H_2 knot.

rently still the largest survey performed beyond the IRAS 100 µm band at medium spatial resolution. It provided very good candidates for massive cold cores (e.g., Birkmann et al. 2006) which we are presently investigating with millimetre and Spitzer observations. Another related class of objects are the so-called infrared dark clouds which appear as dark regions even at mid-infrared wavelengths and were first detected with the MSX satellite and in the ISOGAL survey.

We performed another survey for massive protostellar cores and protoclusters in the outer Galaxy using SCUBA and IRAM bolometers (Klein et al. 2005). These (sub-)millimetre observations yielded the detection of a particularly interesting object (Figure 1): near to IRAS 07029-1215, which itself is an object with a luminosity of 1700 $L_\odot$, located at a distance of 1 kpc, a deeply embedded object ('UYSO1') was discovered. This object appears to be in a particularly early evolutionary stage, since it has no detectable continuum counterpart in the near- or thermal infrared. Yet, it is already driving a high-velocity bipolar CO outflow with a total mass of $M_{outflow} = 5.4\ M_\odot$. Mass estimates and subsequent empirical relations as well as considerations of the spectral energy distribution (SED) point to the object being an early B star surrounded by an envelope of 30–40 $M_\odot$ (Forbrich et al. 2004). To investigate the content of this core, we subsequently utilised the Spitzer MIPS camera. As can be seen in Figure 1, no 24 µm point source associated with the core is detected. This is a rare finding among the presently known objects of this class since the vast majority of cores from the surveys mentioned above apparently already exhibit such localised 24 µm emission. The near-infrared data for the UYSO1 region, taken recently with the VLT (see Figure 1 right), show an intensity gradient towards the cold core similar to the 24 µm data. In addition, they reveal the presence of two crossed H_2 jets which both more or less intersect the cold core. The orientation of the north-south arm is very similar to the one of the previously revealed CO outflow. Thus, one can speculate that UYSO1 is associated with at least one of these jet features. This means in turn that star formation has already turned on in the core. A next step will be high spatial resolution interferometric observations at (sub-)millimetre wavelengths which can be achieved with the Plateau de Bure Interferometer and with the SMA. Furthermore, UYSO1 is certainly a good candidate for ALMA observations for the future in order to pinpoint the mass distribution in the interior of the core and to sort out whether additional low-mass sources are present that introduce independent jet activity.

The hot core phase

The next stage in the evolution of a massive star towards the main sequence is the so-called hot-core stage. Here, massive stars are located within dense molecular cloud cores and – because of the high extinction – are neither visible in the

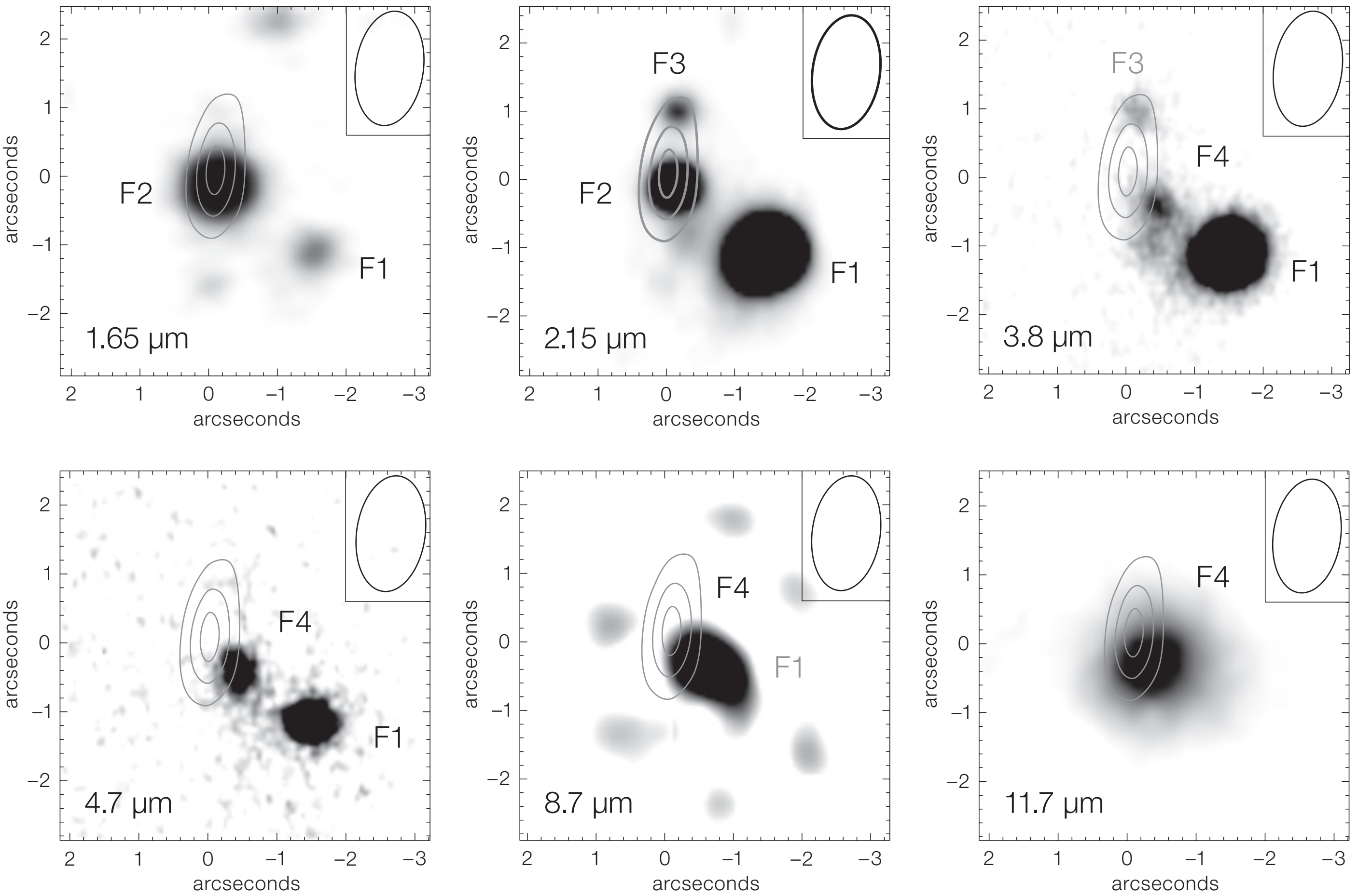

Figure 2: Central region of the Hot Core G9.62+0.19-F, as seen with VLT/ISAAC (1.65–4.7 μm), 3.6-m/TIMMI2 (8.7 μm), and 5-m (Mount Palomar)/SpectroCam-10 (11.7 μm) (Reference position R.A. $18^h06^m14^s.88$ Dec −20°31′39″.4 (J2000)). The contours in each panel trace the NH_3(5,5) radio emission from the hot core. Drastic changes in the infrared appearance of the region are obvious. While F2 seems to be a foreground star detached from the actual hot core, the nature of F1 and F3 is not fully clarified. We presume that the feature F4 is closely associated with the hot core itself (from Linz et al. 2005).

optical nor in the near-infrared, but in the mid-infrared spectral region. These cores are heated by the embedded or neighbouring massive stars to temperatures between 100 and 300 Kelvin, forming 'hot cores' about 0.1 pc across, which have a density of molecular hydrogen of about 10^7 particles per cm^3. Typically, in this stage the objects are not yet surrounded by larger amounts of ionised hydrogen. The formation of H II regions is possibly suppressed by the high rate of mass infall. This also means that the youngest massive stars are only observable in the thermal infrared and the (sub-)millimetre range, whereas they are not strong centimetre radio continuum sources. The particularly interesting case of the G9.62+0.19-F Hot Core is shown in Figure 2, for which we conducted a multi-wavelength study with ISAAC at the VLT and with TIMMI2 at the ESO 3.6-m telescope (Linz et al. 2005). From classical spherically symmetric models it is *not* expected that hot cores themselves could be detected with ISAAC (wavelength range 1–5 μm) due to hundreds of magnitudes of visual extinction. However, we previously showed that the G9.62 hot core drives a massive molecular outflow roughly oriented along the line-of-sight (Hofner et al. 2001) which might severely disturb the spherical symmetry. Indeed, our ISAAC 3.8 μm and 4.7 μm observations reveal the presence of a feature (F4) not seen at shorter wavelengths which eventually dominates the emission at longer wavelengths (Figure 2). This leads to a scenario where the outflow has a 'clearing effect' so that thermal infrared radiation from the inner interior of the hot core can more easily escape through the outflow cone directed towards us. This finding clearly demonstrates the deviation from spherical symmetry which has to be taken into account in detailed radiative transfer models. Here we should note that accurate astrometry, especially between the thermal infrared images and the radio interferometry data is an important requirement to prevent misidentifications. Together with existing millimetre interferometer data, our new sub-arcsecond thermal infrared data facilitate an order-of-magnitude assessment for the luminosity of this hot core (without disturbing contributions from other sources); we estimate it to be around $1.9 \times 10^4\ L_\odot$. This is a clear indication that the G9.62 hot core harbours a young massive star. However, caution is advisable, as we see in the case of the Orion Hot Core, where on a much smaller scale than in our case several infrared sources can be distinguished. (G9.62+0.19 is more than 12 times farther away from our Sun than the Orion Hot Core.) Thus, diffraction-limited *L*- and *M*-band observations with NACO (yielding a spatial resolution of ca. 0.1″) will be a logical step to trace potential substructures in this hot core.

Ultracompact H II regions

During the next evolutionary phase of massive stars – now in or very close to the zero-age main sequence – 'ultra-compact H II regions' (UCH IIs) form around the young stars. In these ionised regions of about 0.1 pc diameter with electron densities of about 10^5 per cm^3, electrons decelerating in the plasma emit strongly at radio wavelengths (free-free emission). Thus, these objects can be best found by radio continuum surveys. These very compact objects have lifetimes of about one million years. Eventually the regions of ionised hydrogen expand, forming 'compact H II regions' of 0.5 pc diameter and electron densities up to 1000 electrons per cm^3. These then evolve into 'diffuse H II regions' which are well known to us in the form of the Orion Nebula.

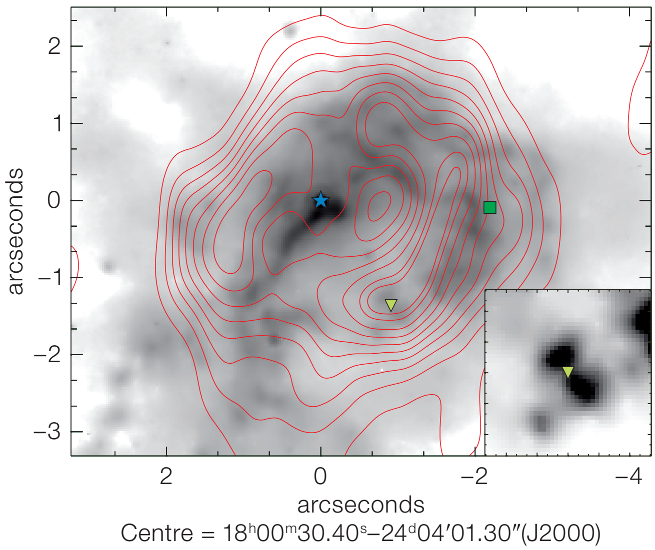

Figure 3: *L*-band image of G5.89-0.39 taken with NACO. The contours represent 2-cm emission from Wood and Churchwell (1989), the star, the triangle, and the square show the locations of the ionising star candidate found by Feldt et al. (2003), the 1.3-mm source found by Sollins et al. (2004), and the centre of a possible newly identified outflow, respectively (from Puga et al. 2006).

A particularly interesting source in the context of ultra-compact H II regions is G5.89-0.39. Classified by Wood and Churchwell (1989) as a shell-type UCH II, it seemed to agree with models of a classical Strømgren sphere expansion additionally driven by the wind of a single massive star. The object is also the source of one of the most massive outflows within our Galaxy. The outflow has been studied at a variety of wavelengths and resolutions. Interestingly, also different outflow orientations and outflow velocities were derived by different groups: the east-west direction from various CO line observations, the north-south direction from the expansion of the radio shell (8 ± 2 AU/yr) and from CS and H_2O maser observations. Yet another orientation was introduced by tracing outflow motions in SiO which led to the conclusion of an NE-SW outflow. Recently, Sollins et al. (2004) confirmed this latter direction by means of SiO observations with the SMA. They also found a 1.3-mm continuum source which they proposed to be the driver of the outflow.

The driving source of 'the outflow' was always assumed to be the ionising source of the shell. A direct detection of the central ionising source was first claimed by Feldt et al. (2003), who detected a star slightly off-centre inside the shell in NACO *K* and *L*-band images. From the position in the colour-magnitude diagram, its spectral type was estimated to be O5V.

Follow-up spectroscopy of the central source is presented in Puga et al. (2006). In the long-slit *K*-band spectrum, the only remarkable line showing up at the location of the detected star is He I; this indicates that the source is hotter than 40 000 K which corresponds to a spectral type earlier than O7V. Moreover, Puga et al. (2006) present Fabry-Perot spectroscopy with the Adaptive Optics instruments ADONIS/GraF (at the 3.6-m telescope) and NACO (at the VLT UT4) as well as long-slit spectroscopy of the H_2 emission around the shell. Two prominent bow-shock-like features are detected north and south of the UCH II region equidistant from the star seen in *K* and *L*. The study of the ratio between several ro-vibrational H_2 lines confirms the shocked nature at least of the southern region. The Fabry-Perot data of this southern H_2 feature show its velocity structure to be entirely consistent with a deceleration from about 100 km s^{-1} to the ambient velocity. It appears pretty clear now that these H_2 features indeed represent terminating bow-shocks of a jet originating from G5.89-0.39. With the connecting line passing the detected O5V star at less than 0.3″, it seems reasonable to assume that this star is indeed the driving source. Also, the axis passes through the disruptions in the shell apparent in Wood and Churchwell's (1989) 2-cm image, and coincides with the direction of preferred shell expansion. The data show the power of combining high spatial resolution provided by Adaptive Optics and high spectral resolution.

But what about the other outflows? The *L*-band image in Figure 3 shows a bipolar feature at the location where Sollins et al. (2004) report their mm continuum source. The feature is elongated at a position angle matching that of the Sollins' outflow and resembles the structure of reflection lobes above and below a circumstellar disc seen edge-on (see inset in Figure 3). We concluded in Puga et al. (2006) that the *L*-band structure is the small-scale counterpart of the SiO outflow that is driven by the 1.3-mm continuum source. We also mapped the shell in the Brγ line with Fabry-Perot observations (see Figure 4). This resulting velocity map implies that another bipolar structure exists and that the shell is not as "puzzlingly symmetric and undisrupted by massive outflows" as described earlier by Ed Churchwell. The feature might be connected to an outflow in NW-SE direction – about the only direction not quoted before for an outflow from G5.89. The possible driving source would naturally be assumed to be situated between the two parabolas in Figure 4, with no detected counterpart at any wavelength yet.

What do we learn from all this? First of all, it again appears that massive star formation is always more complex than you thought. In G5.89 everything appeared clear and matching a very simple model until a few years ago. Now we have a number of outflows confirmed in all possible directions, and we have two quite robust detections of driving sources and evidence for a third one inside a volume not larger than the shell with its diameter of about 0.05 pc. In the general notion, G5.89 has turned from a single star with an ionised shell into yet another young, massive cluster with complex interactions between the stars, the outflows, and the radiation fields and the produced H II region. This demonstrates how important it is to carefully determine and characterise the complete stellar content of any site of massive star formation, before trying to draw conclusions on the formation mechanism from integrated data like overall luminosities or outflow energies. It is also another example of massive star formation taking place at stellar densities of more than 10^4 pc^{-3}, confirming that massive stars prefer to form in very dense clusters.

Outlook

Infrared and millimetre observations of very young massive stars in the stage of cold and hot cores now complement detailed observations of slightly later stages, in particular ultra-compact H II regions. Here, the identification of the ionising and illuminating sources and the detailed study of the interaction between them and nearby molecular cloud structures have opened the way for much better modelling of these important and abundant objects.

It is clear that the riddle of massive star formation is not yet solved. However, our observational methods are getting closer to the very early stages of formation and the very immediate surroundings of young massive stars. New 3D radiative transfer models will help interpreting the data measured by interferometers, aided by input from 8-m telescope diffraction-limited observations between 1 μm and 20 μm wavelength. With these methods, we can hope to determine the mechanisms and timescales of the early evolutionary stages of massive stars within the next few years.

The currently operating Spitzer IR satellite produces a wealth of new data covering the mid- and far-infrared regime. In terms of sensitivity, it provides a major improvement with regard to its predecessors IRAS, MSX, and ISO and is of course superior to present-day ground-based observations. However, even at the smallest operating wavelength of 3.5 microns, Spitzer does not provide sub-arcsecond spatial resolution, a prerequisite to disentangle the usually crowded central regions of high-mass star formation. Hence, ground-based thermal infrared observations conducted at 8-m-class telescopes (for instance, ISAAC, VISIR, NACO, and soon CRIRES at the VLT) can contribute important knowledge about the intricate details of massive star-forming regions. Furthermore, in a few years from now, the synergy between space-based exploratory studies, especially Herschel-satellite far-infrared observations, and ground-based follow-up observations with ALMA will become a growing field of research.

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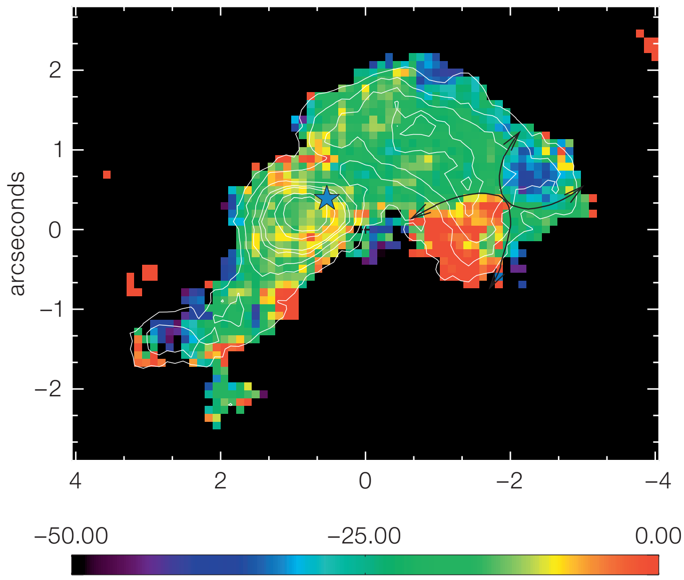

Figure 4: Peak velocities in Brγ in the upper half of G5.89's shell. The colour bar indicates the velocity range in km/s. The blue star symbol again shows the location of the ionising star candidate (see Figure 3). The overlaid thin white contours mark the velocity-integrated Brγ intensity. In the western half, a bipolar velocity structure (also indicated by the arrows) is clearly visible and recognised here for the first time (from Puga et al. 2006).