The Birth of a Massive Star

New results from ESO and IRAM suggest that massive stars form in the same way as their low-mass counterparts. In the Omega nebula, a young stellar object of more than ten solar masses is surrounded by a huge rotating disc with at least 100 solar masses of gas and dust. Part of the gas that falls onto the growing star is ejected perpendicularly to the disc, producing a bipolar jet and an hourglass shaped nebula.

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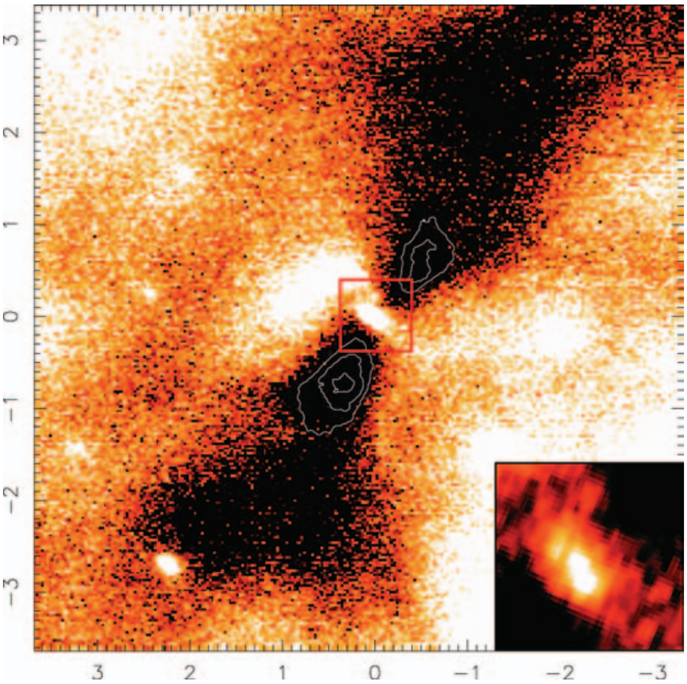

Figure 2: High-resolution adaptive optics 2.2 µm image of the accretion disc. The field size is about 7 × 7 arc seconds; the effective spatial resolution is about 0.057 arc seconds. The disc silhouette is seen in absorption against the bright background of the HII region; the white contours delineate the densest parts of the inner disc. A bipolar outflow emerges from the central object. The insert shows the inner region in more detail suggesting that there is an elongated – possibly binary – source of about 450 × 250 AU whose major axis is tilted by about 15 degrees with respect to the disc axis.

There is general consensus that stars condense from clouds of gas and dust within a mass range from about a tenth to a hundred solar masses. The formation of stars up to ten solar masses (1 solar mass [$M_{\odot}$] = 1.989 × 10^{33}g) can be explained by the gravitational collapse of a cloud fragment and the subsequent accretion from the surrounding interstellar medium onto a so-called protostar (Shu et al. 1987). The associated density enhancement of the order of 10^8 implies that the protostar becomes optically thick at some point and starts to increase its temperature: the object is on its way to becoming a low-mass hydrogen burning star. Closely connected with the accretion phase is the formation of a circumstellar disc which provides the necessary material and, eventually, the conditions for the creation of planets and life. Another associated phenomenon is a bipolar outflow of mass that expands perpendicularly to the plane of the disc and is believed to be a direct consequence of the accretion process. Most of the above theoretically expected stages could be verified observationally, and as such the formation of low-mass stars is a fairly well-understood process.

Theoretical considerations, however, show that the accretion scenario may work only for stars of up to about 10 $M_{\odot}$ (Wolfire & Cassinelli 1987). Beyond that, a massive protostar evolves so rapidly into a hydrogen burning core that its radiation pressure onto the in-falling dust and gas can halt or even reverse the accretion process, and thus can prevent the formation of stars of higher mass. Details depend on the geometry of the parent cloud and on the physical properties of the dust grains. Given this theoretical limit of 10 $M_{\odot}$ and the observational fact that most massive stars are born in dense clusters where they occur as multiple systems, it was suggested that high-mass stars might be the result of the merging of lower mass stars (Bonnell et al. 1998). This merging process requires extremely high stellar densities which have never been observed in today's star clusters, but which could have existed during their early history. Recently, theoretical calculations have shown that – depending on the original cloud mass and the opacity of the grains – stars between 20 and 40 $M_{\odot}$ can in principle be formed via accretion through a disc (Yorke & Sonnhalter 2002).

Discriminating between both formation scenarios observationally is rather difficult due to several reasons: first, high-mass stars are extremely rare objects. Second, massive stars are generally far away and deeply embedded within dust clouds which diminishes their light substantially. Third, they usually occur in the centres of stellar clusters where source confusion is a major problem. Finally, their lifetimes are only a few million years and their early evolution is accordingly short. In particular, massive stars start the hydrogen burning process at a point where they still have not yet reached their final mass. Thus, depending on the formation scenario, one either has to observe the merging process between two or more young stars or one has to witness the accretion through a disc; both observations require high spatial resolution and kinematic information that is almost impossible to achieve with present day instrumentation.

Looking into the cradle

The Omega nebula (M 17) is a well-known region of star formation in our Galaxy (Chini & Wargau 1998) at a distance of 2200 parsec (1 parsec = 3.086 × 10^{18} cm). Figure 1 is part of a three-colour infrared mosaic of the area which was the initial observation leading to our investigation. It consists of 9 individual, partly overlapping fields at 1.25, 1.65 and 2.2 µm and was obtained with the infrared camera ISAAC at the ESO Very Large Telescope (VLT) in September 2002. The composite image shows a dense cluster of young stars embedded in clouds of gas and dust with unprecedented detail and depth; several high-mass stars, whose total energy output exceeds that of our sun by almost a factor of 10^7 ionise the surrounding hydrogen gas. Adjacent to its south-western edge, there is a cloud of molecular gas which is a site of ongoing star formation. Due to the sensitivity of our measurements the molecular cloud was largely transparent and the nebular emission of the HII region could shine through the dust. Against this nebular background, we discovered a tremendous opaque silhouette, associated with an hourglass shaped nebula and surrounded by a larger disrupting dust envelope. As we will show in the following, this object resembles theoretical predictions of a newly forming high-mass star surrounded by a huge accretion disc and accompanied by an energetic bipolar mass outflow.

◀ **Figure 1:** Three-colour ISAAC mosaic of the star forming region M 17. The field size is about 7 × 7 arc minutes, the effective spatial resolution is about 0.6 arc seconds; wavelength coding: blue 1.25 µm, green 1.65 µm, red 2.2 µm. A similar image from SOFI was released some years ago as ESO-Press-Photo 24/00.

The accretion disc

After the discovery of the object, we applied for discretionary time in order to study the morphology of the system in more detail. In June 2003 we obtained three extremely rewarding hours with NAOS-CONICA at the VLT; Figure 2 shows the corresponding high-resolution 2.2 µm image of the new object. Due to the adaptive optics technique – which eliminates atmospheric turbulence – the morphology of the silhouette was nicely resolved into two triangular shaped dust lanes that resemble a flared disc, seen nearly edge-on. The disc has a diameter of about 20,000 AU (1 astronomical unit [AU] = 1.496 × 10^{13} cm) which is about 200 times the size of our solar system and by far the largest circumstellar disc ever detected. When going from the centre towards its outer edges the disc widens substantially. Using the background nebular light as a homogenous source of illumination, the extinction and thus the column density of interstellar matter within the disc can be

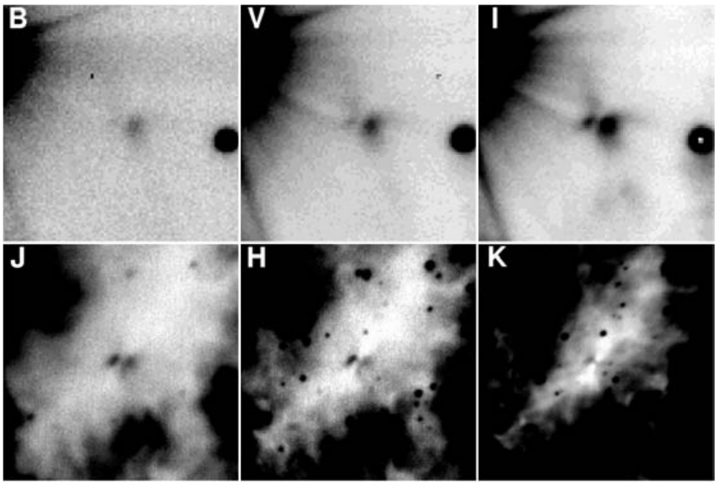

Figure 3: Multi-colour sequence of the hourglass-shaped nebula. The change in morphology is displayed as a function of wavelength; the upper row was taken at optical (0.44, 0.55, 0.78 µm), the lower row at infrared (1.25, 1.65, 2.2 µm) wavebands. In the upper row, the nebula is dominated by reflected light from a bipolar cavity; the south-western (right) lobe is much stronger while the north-eastern (left) lobe is obscured by the disc. The lower row is dominated by more compact emission from a bipolar jet (see also Fig. 2). Each frame has a size of 30 × 30 arc seconds.

determined at each point along the line of sight. The maximum column density of hydrogen inferred from the optical depth at 2.2 µm is ~ 6×10^{22} atoms cm^{-2}; the associated dust produces a visual obscuration of a factor of 10^{23} towards the central object.

Further physical properties concerning the mass and the kinematics of the disc and its surroundings can be obtained from millimetre observations. We have observed the region in molecular line transitions of several CO isotopomeres like ^{12}CO, ^{13}CO and $C^{18}O$ and in the adjacent continuum at 1.3 and 3 mm with the IRAM Plateau de Bure Interferometer. The molecular spectroscopy indicates that the system rotates with a velocity of about 0.85 km/s at a radius of 15,400 AU; its north-western part is approaching the observer. From ^{13}CO we derive a gas mass of at least 100 $M_{\odot}$.

The bipolar nebula

Perpendicular to the plane of the disc there is an hourglass shaped nebula visible throughout the entire spectral range from 0.4 to 2.2 µm; Figure 3 shows a corresponding sequence of images, where the optical data have been obtained with EMMI at the ESO NTT. Obviously, the two nebular lobes show different wavelength dependent intensities. The fact that optical light is detectable throughout the huge amount of foreground extinction can only be explained if the emission is – at least partly – due to reflected light scattered by dust grains. The nebular light consists of two separate components, a diffuse extended shimmer and a more compact emission in the central region.

Firstly, the diffuse emission – particularly prominent at optical wavelengths – is symmetric and seems to mark the walls of an hourglass shaped cavity. It extends at least up to 5×10^{17} cm above the plane of the disc towards both sides with a maximum width of about the same size (see Fig. 3.); the image of the NE lobe is fainter and somewhat distorted by stray light from a nearby bright star. The emission of this hourglass feature is due to scattered light from the walls of a bipolar cavity that has probably been cleared by an energetic mass outflow. From the fact that the NE lobe becomes brighter with increasing wavelength while the intensity of the SW lobe remains almost constant we conclude that the former suffers from more extinction. This suggests an inclination of the disc of about 15 degrees with respect to the line of sight which hides the NE lobe partly behind the disc. Vice versa we are facing the disc slightly from below and thus are looking into the SW cavity. The hourglass morphology of the SW cavity is supported by two curved dusty ejecta that end in typical bow-shocks as a result of their interaction with the ambient medium. This picture is further corroborated by our CO data which, in part, also seem to trace the walls of both cavities.

Secondly, there is a more compact emission at both sides of the innermost disc. Both blobs show strong wavelength dependence with the western one being bright in the optical and almost vanishing in the infrared; at about 1 µm the clumps are of equal intensity and attain simultaneously their maximum brightness. Beyond 1 µm the eastern blob is stronger by 10% at *J* and *K* and by 40% at *H*. This is in contrast to what one would expect from the extinction which is higher along the eastern line of sight due to the inclination of the disc. We therefore conclude that there must be intrinsic intensity differences between the two features which are most probably caused by an asymmetric outflow. Likewise, we speculate that additional line emission contributes to the different morphological shapes.

The eastern outflow shows a pronounced morphology which is nicely resolved by our adaptive optics image (Fig. 2); it seems to originate close to the central object and resembles a precessing flow that turns over shortly after leaving the innermost region; farther out the orientation of the flow axis is almost parallel to the disc plane. The much fainter western flow is more diffuse and has an angle of about 45° with respect to the disc plane.

In order to explore the origin of the optical nebula, we have taken spectra between 0.4 and 0.9 µm that cover both cavities and the flows (Fig. 4); the spectra were obtained

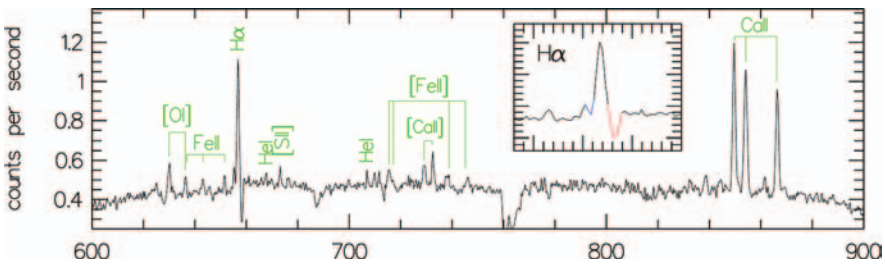

Figure 4: Optical spectrum of the bipolar nebula. The slit was oriented perpendicular to the disc plane. The emission from the HII region has been subtracted by averaging several offset positions. The various emission lines in the reflected light indicate evidence for ongoing accretion.

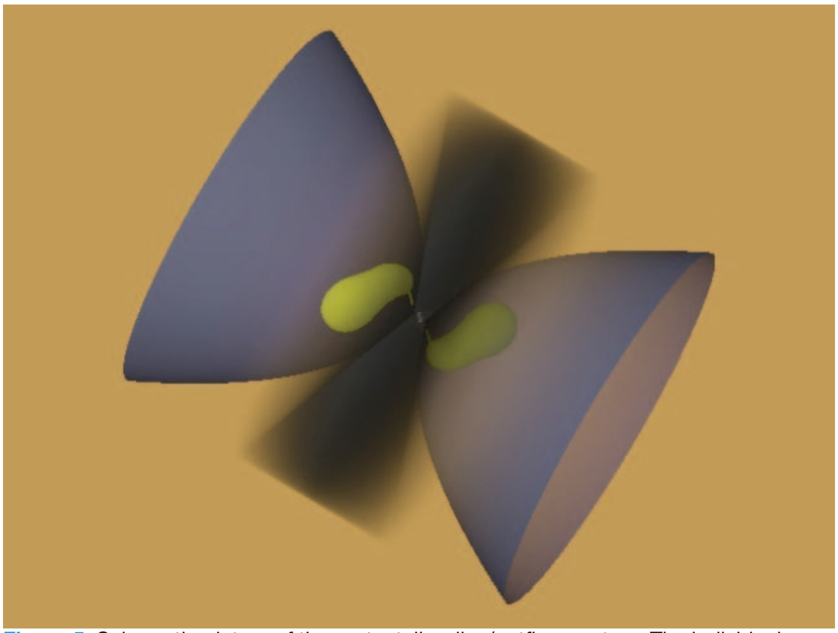

Figure 5: Schematic picture of the protostellar disc/outflow system. The individual components are drawn to scale with the suggested orientation to the observer; accretion disc (black), hourglass shaped cavity (blue), bipolar precessing jet (yellow), elongated central object (white).

in April/June 2003 with EFOSC2 at the ESO 3.6 m and with EMMI at the ESO NTT. The accuracy of the wavelength calibration allows sampling velocities down to 40 km/s. The spectrum is dominated by the emission lines of Hα, the Ca II triplet 8498, 8542 and 8662 Å, and He I 6678 Å which provide unquestionable evidence for an ongoing accretion process (Hartmann et al. 1994, Muzerolle et al. 1998). Particularly the Hα line is extremely broad and shows a deep blue-shifted absorption as well as an inverse P Cygni profile; blue-shifted absorption components in permitted lines are typically associated with accretion disc-driven outflows (e.g. Calvet 1997). The same is true for forbidden emission lines such as [O I] 6300 Å and [S II] 6731 Å which are also present in our spectrum. Numerous permitted and forbidden Fe II lines which are velocity-shifted by ±120 km/s are clear signposts for high velocity dissociative shocks with velocities of more than 50 km/s. Recent spectroscopy with UVES in July 2004 shows evidence for a variation in the Hα line; the line profile varies with time and as a function of the location across the lobes. Obviously, the infall and outflow of matter is not a continuous process but the protostar takes a morsel of fuel every now and then.

The nature of the protostar

As mentioned above, the disc is deeply embedded in the molecular cloud probably behind a visual extinction of about 50 magnitudes if we take the results from our infrared photometry for stars in the immediate neighbourhood of the system as a guideline. The dust within the disc produces another contribution of about 50 magnitudes toward its centre which makes it impossible to obtain any optical information about the accreting protostellar object. Nevertheless, Fig. 2 shows an elongated 2.2 μm emission feature at the expected position of the forming star whose inclination is different from the orientation of the channel produced by the outflow, i.e. from the inner gap of the disc. One may speculate whether this elongated feature marks the starting point of the precessing massive outflow or whether it originates from a binary system that is currently born from a common accretion disc. NACO *JHKLM* measurements are scheduled for the current period to clarify the nature of this object in more detail. Assuming that the central emission is due to direct stellar light we derive an absolute infrared brightness of $K \sim -2.5$ magnitudes which would correspond to a main sequence star of about 20 solar masses and a temperature of 35,000 K. An independent mass estimate from dynamical considerations, concerning the rotation of the molecular disc, yields a mass of about 15 solar masses for the central gravitational object. Given the fact that the accretion process is still active, and that the gas reservoir of the disc still allows for a substantial mass gain, we argue that in the present case a massive protostar is on its way to becoming an O-type star. Theoretical calculations (Yorke & Sonnhalter, 2002) show that an initial gas cloud of 60 to 120 $M_{\odot}$ evolves into a star between 33 and 43 $M_{\odot}$ while the remaining mass is ejected into the interstellar medium.

From all this evidence we conclude that a massive star is currently forming via accretion through a disc while the associated energetic mass outflow disrupts the surrounding environment and ejects part of the accreted material into the ambient medium. Our observations show – for the very first time – all theoretically predicted ingredients of the star formation process directly and simultaneously with a single object and therefore improve our current understanding of such an event tremendously (Chini et al. 2004). The schematic picture of Fig. 4 summarises the individual components as revealed by our different observing techniques. A central protostar (maybe even a binary system), is surrounded by a flared, slowly rotating disc from which it accretes mass along a reconnected magnetospheric field. A considerable fraction of the transferred mass is accelerated from the polar regions of the protostar/disc interface into opposite directions along the open stellar magnetic field. This reconnection-driven jet is further accelerated magneto-centrifugally due to stellar rotation and excavates the ambient medium. Eventually, a bipolar high-velocity neutral wind forms an hourglass-like cavity which reflects light from the very inner regions of the system. Further out this neutral wind drives the observed molecular bipolar flow.

In more general terms, our data show for the first time that massive star formation via accretion is a realistic scenario. Large accretion discs can obviously withstand the harsh environment of a dense stellar cluster and are not disrupted by tidal forces. Likewise, the ionising radiation and the stellar winds of nearby massive stars do not disturb the accretion process. As a by-product of our results it follows that the star formation process which started some million years ago in M17 is still continuing and is currently producing a second generation of massive stars. Thus, it is likely that once star formation has been started in a molecular cloud, the parent generation of stars triggers the creation of a new generation.

Acknowledgements

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