The Eta Carinae Homunculus in Full 3D with X-shooter and Shape

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Massive stars like Eta Carinae are extremely rare in comparison to stars such as the Sun, and currently we know of only a handful of stars with masses of more than 100 $M_\odot$ in the Milky Way. Such massive stars were much more frequent in the early history of the Universe and had a huge impact on its evolution. Even among this elite club, η Car is outstanding, in particular because of its giant eruption around 1840 that produced the beautiful bipolar nebula now known as the Homunculus. In this study, we used detailed spatio-kinematic information obtained from X-shooter spectra to reconstruct the 3D structure of the Homunculus. The small-scale features suggest that the central massive binary played a significant role in shaping the Homunculus.

Introduction

In August 2014 the stars of the η Car binary system were at their closest approach. The observable changes in the weeks around periastron are rather dramatic, because of the highly eccentric orbit. Therefore, many groups had been preparing to observe η Car, looking for changes that might help us learn more about this complex system of high-mass stars and interacting stellar winds, and its effect on the surrounding gas and dust, including the famous Homunculus Nebula. A comprehensive overall review by many authors on different aspects of η Car and its surroundings can be found in Davidson & Humphreys (2012).

In recent work (Steffen et al., 2014), based on spectroscopic observations with X-shooter on the Very Large Telescope (VLT), we found the first strong evidence for a direct impact of the binary system on the structure of the bipolar Homunculus Nebula that was ejected in the giant eruption around 1840. Here we briefly describe the motivation, observations and results of this work. It is particularly interesting how the rather simple geometric results connect to sophisticated theoretical simulations of the interacting winds of the central binary (Madura et al., 2013).

Owing to the large difference in brightness and closeness to the primary, the existence of the secondary can only be inferred indirectly, mainly through the 5.5-year periodicity in the X-ray band and spectroscopic changes in the ultraviolet, optical and infrared bands (Damineli et al., 2008). Finding direct evidence of the binary interaction in the Homunculus Nebula would therefore shed some light on the eruption process itself and would help to further constrain the orientation of the highly elongated orbits. The fact that there are two nebulae, the Little Homunculus (Ishibashi et al., 2003) located within the Homunculus, and the fast-moving ejecta outside the Homunculus, both exhibiting the same elongated shape, provides hints that the binary system played a role in shaping the eruptions.

To achieve these goals, the structure of the Homunculus needed to be derived in more detail than that provided by the available axi-symmetric models. Spatially resolved kinematic data with full coverage were needed in the infrared, since in the visible spectrum the Homunculus is optically thick, greatly obscuring the far sides of the bipolar lobes.

Observations

The X-shooter spectrograph mounted on the VLT's Kueyen Unit Telescope (UT2) is ideally suited for mapping the Homunculus. The 0.4 by 11 arcsecond slit provided seeing-limited spatial resolution with spectral resolving power of 11 300, which is well matched to the approximately ten-arcsecond-wide bipolar structure. Since the structure expands at velocities up to 650 km s^{-1} along the line of sight, image slices with 50 km s^{-1} separation provided detailed maps of the structure along the line of sight. While the spectral range of the data extended from 2999 Å to 24 790 Å, for this particular work we focussed on a single emission line of molecular hydrogen, the v = 1-0 S(1) line at 2.12125 μm.

The Homunculus was mapped with a total of 92 dithered positions orienting the slit perpendicular to the projected bipolar axis (position angle [PA] = −41 degrees). To provide a suitable dynamic range for each slit position, the exposure times ranged from 30 seconds in the outer regions to 0.067 seconds over the central star. Multiple images at each position were then combined to yield a total exposure time from 30 seconds in the central region to 150 seconds in the outer lobes.

After standard processing for individual spectra, a datacube was generated on a regular position–velocity (P–V) grid interpolating between actual slit positions. Figure 1 shows an optical Hubble Space Telescope (HST) image of the Homunculus with the observed slit positions in grey and the interpolated slit positions for modelling in red. For the 3D modelling process, 16 slit positions were selected from the combined datacube based on significant structural changes. These 16 P–V images are displayed in Figure 2 together with P–V images synthesised from the model.

3D modelling

The 3D modelling was done with the virtual astrophysical modelling laboratory Shape (version 5, Steffen et al., 2011)[1]. The general assumption for the reconstruction of the position information along the line of sight is that the nebular material was ejected in a short interval of time in the relatively distant past and is expanding homologously (i.e., the position vector of each volume element

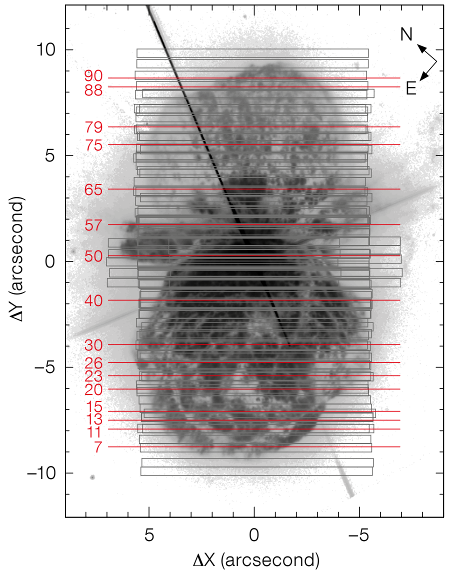

Figure 1. Observed X-shooter slit positions (horizontal rectangles) superimposed on an optical Hubble Space Telescope image of the Homunculus Nebula. The spectra were combined to generate a continuous datacube. The red horizontal lines show the positions at which position–velocity images were extracted from the datacube for modelling (see Steffen et al. [2014] for more detail).

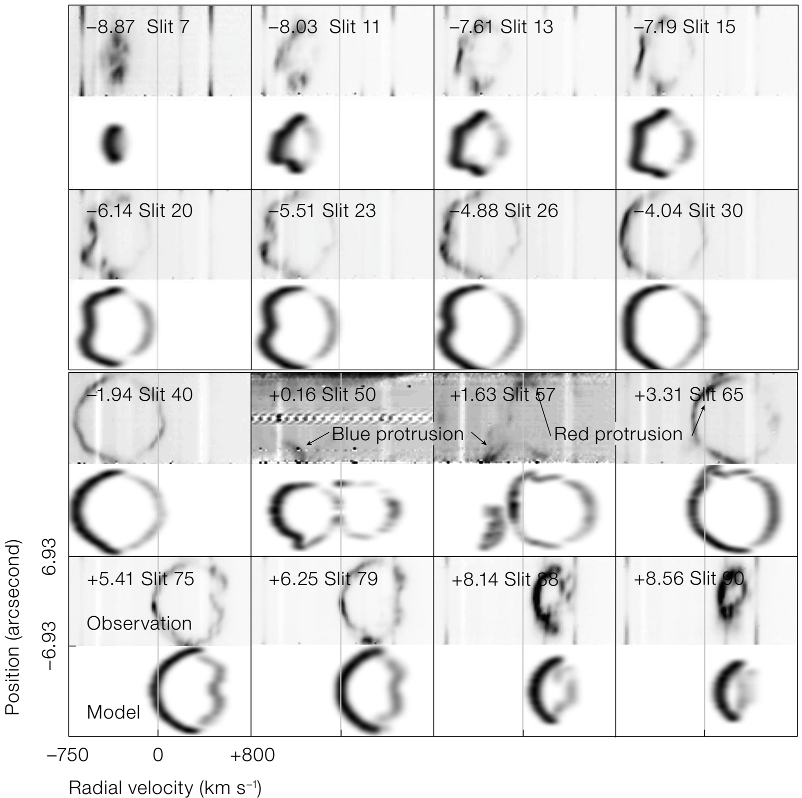

Figure 2. The 16 observed position–velocity images that have been used for 3D modelling are shown (rows 1, 3, 5, 7), together with the corresponding model position–velocity images (rows 2, 4, 6 and 8) beneath (from Steffen et al., 2014). The slit numbers and offset along the Homunculus long axis (Figure 1) are indicated.

is proportional to its velocity vector). Physically, such an expansion pattern is expected from an explosion or eruption in which the gas is accelerated very quickly and then expands with constant speed radially outwards. Furthermore, the process of ejection must be short compared to the time that has elapsed between the eruption and the observation in order to allow the matter to sort itself out according to its velocity.

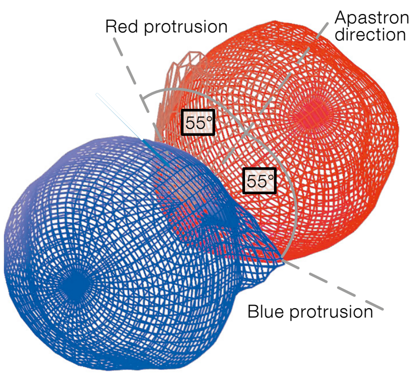

Figure 3. The 3D model mesh of the Homunculus as seen from Earth. The direction of binary apastron and its angular relation to the newly discovered protrusions are marked with dashed lines (adapted from Steffen et al., 2014).

If the expansion can be assumed to be homologous and there is a good degree of axial symmetry, then an accurate mapping can be derived between position and observed velocity along the line of sight. The massive, dense eruption that produced the Homunculus is expected to expand nearly homologously because of its high density compared to the local circumstellar environment, which is probably a hollow cavity blown out by the earlier stellar winds. Previous work and our reconstruction are consistent with only very minor deviations from large-scale homologous expansion.

The reconstruction was done in the Shape software´s interactive mesh reconstruction mode. The general procedure for such reconstructions is to interactively generate a 3D mesh shell that represents the observed gas shell volume (Figure 3). The detailed structure of this mesh is obtained by deforming an initially spherical object using a variety of "modifier" tools. An emissivity distribution and a velocity field are then defined. Finally, the software computes spatial and position–velocity images for the synthetic slit positions that correspond to the observations. The results can then be compared directly with the observations. The differences between the observations and model output are then iteratively corrected until the result satisfactorily reproduces the observations. In Figure 2, observed and synthetic position–velocity images are shown together, which allows an estimate of the precision of the reconstructed geometry.

Results

The resultant 3D mesh structure, shown in Figure 3, provides significant details of the well-known bipolar structure seen at optical wavelengths, as imaged in Figure 1. At the poles of each lobe are holes, previously found by Teodoro et

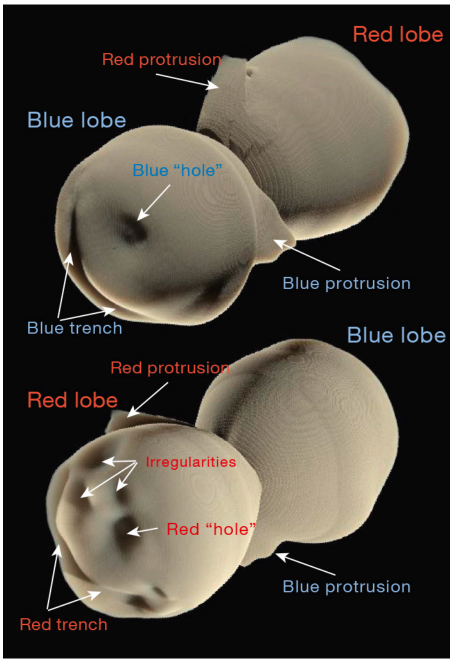

Figure 4. Two renderings of the 3D surface structure of the Homunculus model that emphasises the small-scale structure (adopted from Steffen et al., 2014). The view from Earth is shown in the upper image, whereas the lower one is a view from the opposite direction. The lobes are denoted according to their actual red or blue spectral line shift as viewed from Earth. (A 3D version is available in the online *Messenger*.)

al. (2008) from maps of the near-infrared [Fe II] 1.257 μm line. Looking more closely, these "holes" are off-centre by roughly eight degrees. Each polar cap is gouged by a trench, each of which is positioned with approximate point-symmetry, not mirror-imaged with respect to the central star. There are also red and blue protrusions extending from the lobes near the mid-plane of the nebula. One protrusion is seen on the near lobe to the right (west) and another on the far lobe pointing to the top (north). Added to Figure 3 are three lines that lie in the equatorial plane: projections of the red and blue protrusions onto the equatorial surface and the apastron direction of the binary. The latter was derived by Madura et al. (2013) based on 3D models of the extended winds mapped deep within the Homunculus by the Space Telescope Imaging Spectrograph (STIS) on board HST (Gull et al., 2009).

We initially thought that the protrusions near the equatorial region, at latitudes between about 10 degrees to 20 degrees might be due to a ring-like structure, but the modelling showed that they are quite localised, one on each lobe. Their projected separation is about 110 degrees, very close to the apparent opening angle of the wind–wind bowshock produced by the massive interacting winds of η Car when the stars are at apastron (Madura et al., 2012). The two trenches (Figure 4) have never before been identified and are similar in angular extent and position relative to the central binary.

Independently obtained and apparently disconnected results that turn out to have a strong correlation hint towards a causal relation between the interacting winds and the features of the Homunculus we have identified in our analysis. We note that the 3D reconstruction of the Homunculus Nebula was obtained without assuming the orientation of the orbit of the central binary. The apastron direction derived by Madura et al. (2013) projects between the two protrusions. Furthermore, the angular size of the trenches in the polar regions is very similar to the angular extent of the protrusions, and their orientations are also centred on the apastron direction.

In Figure 5 we compare the orientation of the two projections to 3D models of the massive interacting wind derived by Madura et al. (2013). The model is derived from the spatial structure seen in [Fe III] from detailed maps made with STIS (Gull et al., 2009). Multiple distorted shells have been created by wind–wind interaction during the current and previous orbits of the binary system; because of the high eccentricity ($e \approx 0.9$) the stars spend most of their orbits near apastron. The net result is a large cavity carved out in the apastron direction of the secondary star; the opening angle of this wind–wind interaction cone is strikingly similar to the azimuthal distance between the protrusions (see Figure 5). Obtained from a completely independent investigation, this comparison suggests a causal relation between the wind–wind interaction and the protrusions.

Based on this evidence for a direct influence of the interacting stellar winds on the small-scale structure of the Homunculus, we speculate that the line connecting the two protrusions defines the direction of the orbital plane, as illustrated in Figure 6. We therefore tentatively predict that the orbital plane might be tilted with respect to the equatorial plane of the Homunculus Nebula by 20 degrees. Such a misalignment between the orbital plane and axis of the Homunculus has been suggested earlier, based on the analysis of spectroscopic observations and hydrodynamical simulations (Groh et al., 2010, and references therein). However the models by Madura et al. (2013) suggest that the orbital plane appears to be closely aligned, within 10 degrees, of the Homunculus axis of symmetry. The two lobes of the Homunculus appear to be about 8 degrees out of alignment.

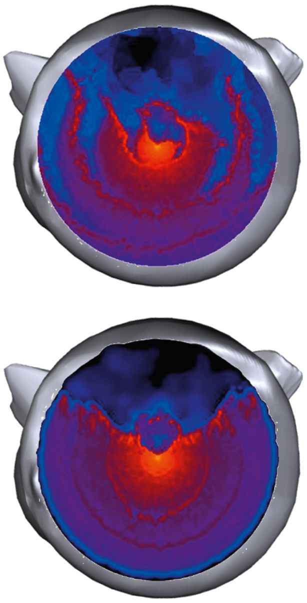

Figure 5. A comparison is shown between the opening angle of the wind–wind interaction region of the central binary star (red–blue) and the angular distance between the newly found protrusions in the Homunculus (grey). The red–blue colours depict density structures as derived by hydrodynamic simulations in the orbital plane of the binary (upper) and perpendicular to it (lower), from Madura et al. (2013). The diameter of the (grey) Homunculus section is about 6 arcseconds, while the interacting winds extend to only about 1.5 arcseconds in these images.

Based on the kinematics derived from molecular hydrogen lines observed with X-shooter and using the Shape software, several features have been revealed that are highly aligned with the orientation of the line of centres of the η Car binary system. The azimuthal angular extent and location of the features coincides with

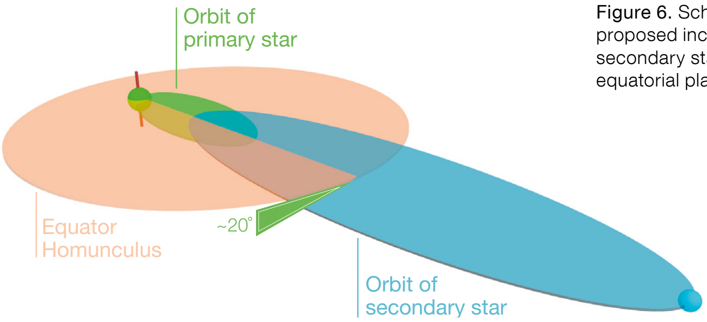

Figure 6. Schematic diagram of the proposed inclination of the orbit of the secondary star with respect to the equatorial plane of the Homunculus.

the opening angle of the conical cavity produced by the interaction of the stellar winds of the primary and secondary, previously derived by independent hydrodynamic modelling (Madura et al., 2013). We have therefore shown that the interacting winds of the central binary have had a direct impact on the surrounding Homunculus Nebulae, either briefly during the 1840's eruption, or slowly during the many orbital periods that have passed since the eruption.

Interactive and 3D printable model

We have created an interactive version of the 3D model of the Homunculus that can be accessed via Figure 5 of the original publication in Steffen et al. (2014) in PDF format. This 3D graphic is also available, as Figure 4, in this article. Furthermore, a 3D printable version in STL format is available as supplementary material to the publication[2].

Acknowledgements

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Links

[1] SHAPE software package: http://www.astrosen.unam.mx/shape

[2] Access to file for 3D printer version: http://mnras.oxfordjournals.org/content/suppl/2014/06/30/stu1088.DC1/supp.zip

Colour composite image of the star-forming complex NGC 3372, including η Carinae (lower left of centre). This image was made with the MPG/ESO 2.2-metre telescope and the Wide Field Imager by combining images in broad bands (*U, B, V* and *R*) and narrow bands (Hα and [S II]). The field of view is 33 arcminutes square (north up, east left) and the clusters Trumpler 14 and Collinder 229 can be seen to the northwest and southeast of η Car respectively. See eso0905 for more details.