The Physical Structure of the Outer Ejecta and the Strings

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Abstract

The outer ejecta is part of the nebula around η Carinae. They are filamentary, shaped irregularly and larger than the Homunculus, the central bipolar nebula. While the Homunculus is mainly a reflection nebula, the outer ejecta is an emission structure. However, we showed with kinematic analysis that the outer ejecta (as the Homunculus) expands bi-directional despite of its complex morphology. Radial velocities in the outer ejecta reach up to 2000 km s$^{-1}$ and give rise to X-ray emission. An analysis showing the distribution of the soft X-ray emission and its comparison to the optical emitting gas is presented here. X-ray maxima are found in areas in which the expansion velocities are highest. The temperature of 0.65 keV determined with the CHANDRA/ACIS data and thermal equilibrium models indicates post-shock velocities of 750 km s$^{-1}$, about what was found in the spectra. In addition analysis of the new HST-STIS data from the Strings—long, highly collimated structures in the outer ejecta—are presented. The data show that the electron density of the Strings is of the order of $10^4$ cm$^{-3}$. The same value was detected for other structures in the outer ejecta. With this density String 1 has a mass of about $3 \times 10^{-4}$ M$_\odot$ and the total ejecta could be as massive as 0.5 M$_\odot$.

1 The outer ejecta: Introduction and background

The first images of the nebula around η Carinae were made by Gaviola (1946, 1950) and Thackeray (1949, 1950). Gaviola named the nebula according to the geometry he identified at that time the Homunculus. It had a size of somewhat larger than 10$''$. Nowadays we know that the Homunculus is highly symmetric—bipolar—and is larger. The Homunculus is only the central part of the nebula around η Carinae (e.g. Walborn 1976), which in total extends to a diameter of 60$''$ (0.67 pc). While we still call the central bipolar structure the Homunculus, all outer filaments are combined into what is known as the outer ejecta. The sizes and morphology of structures in the outer ejecta are manifold. In contrary to the Homunculus the outer ejecta not symmetric, nor is it a coherent object but consists out of quite a number of filaments, bullets or knots. Fig. 1 (left) shows an HST image taken with the F658N filter of the nebula around η Carinae. Besides the different morphology of the Homunculus

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Figure 1: Left: An HST/F658N image of the nebula around η Carinae, the brightest regions, the Homunculus, are additionally overplotted with intensity contours, for a better illustration and comparison. Right: Same HST image but with radial velocities overplotted at certain regions. The font size is larger for larger velocities. Red and blue (plus underlined) colors indicate red- (positive) and blueshifted (negative) radial velocities.

and the outer ejecta, it illustrates also the large difference in brightness. Therefore the Homunculus is additionally plotted with contours. If instead we compare the kinematics of Homunculus and outer ejecta, they seem more alike. The Homunculus, according to his bipolarity expands with about 650 km s$^{-1}$ (Davidson & Humphreys 1997, Currie et al. 1996) and with the south-east lobe approaching and the north-west lobe receding. The outer ejecta has on average similar velocities, the majority of the structures expanding with $|v_{\text{exp}}| = 600$ km s$^{-1}$ (e.g. Meaburn et al. 1996, Weis et al. 2001a). But note that a significant fraction of the filaments move much faster, they reach velocities as high as 2000 km s$^{-1}$ (Weis 2001a,b). So in velocity space nevertheless the outer ejecta are more ordered than expected from the morphology. In the south-eastern region most filaments are blueshifted, while in the north-west the clumps are redshifted, see right panel in Fig. 1. Compared to the movement of the Homunculus the expansion of the outer ejecta is along a very similar symmetry axis. As the Homunculus the outer ejecta has a bi-directional (bipolar) movement.

2 X-ray emission from the outer ejecta

As expected from the expansion velocities, the nebula around η Carinae is detected in X-rays, as is the central object. Originally barely resolved with the EINSTEIN satellite (Chlebowski et al. 1984) the higher spatial resolution of ROSAT and CHANDRA makes it possible to better separate the emission of the nebula from that of the harder central source. Already with ROSAT it was found that the softer emission is roughly hook shaped (e.g. Corcoran et al. 1994, Weis et al. 2001) and agrees in its dimensions with the extension of the outer ejecta (Weis et al. 2001). The CHANDRA/ACIS data are so far the images with the highest spatial resolution and at the same time had decent spectral resolution. In Figure 2 (left) this image is shown color-coded with red is the soft emission and blue the hard emission. The central source—which might be slightly extended—is very hard and as known from other observations variable (e.g. Corcoran et al. 1995, Ishibashi et al. 1999, Weis et al. 2001).
Figure 2: *Left:* This figure shows a color composite image of η Carinae and its nebula in X-rays. The images was taken with CHANDRA/ACIS. Color coding: Green 0.2-0.6 keV (predominantly the Nitrogen line at 0.5 keV); Red 0.6-1.2 keV; Blue 1.2-11 keV. *Right:* The CHANDRA emission in the 0.6-1.2 keV regime overlayed on the HST/F658N image. The softer emission agrees with the outer ejecta. Again the expansion velocities are added, and the highest expansion velocities are situated on X-ray emission maxima.

The emission which results from the outer ejecta is much softer and shows a hook shape, plus a bridge like connection which crosses the central object from the south-west end of the hook to the ridge in the north-east. This is best seen in the contours shown in Fig. 2 (right). Still with CHANDRA's higher resolution an overlay of the optical image and the X-ray emission (Fig. 2 right) shows only a few correlations between the optically emitting and the hot X-ray gas. While the dimensions of the outer ejecta in the optical and X-ray are roughly the same, individual knots rarely agree. One exception is the so called *S condensation* (Walborn 1976), here the brightest X-ray feature agrees with the bright optical filament. A much stronger conformance was found comparing the image with the radial expansion velocities. The expansion velocities are derived from our optical Echelle spectra (see Weis 2001a,b) and are plotted in Fig. 2 (right). We find that areas with higher X-ray emission, show in general higher expansion velocities, so the faster the gas is moving the more intense is the X-ray emission found in that region. Therefore we can explain the morphology of the extended soft X-ray emission from η Carinae by shocks formed through the interaction of the faster moving filaments. Since CHANDRA/ACIS-S has good energy resolution we have the possibility to extract spectra. A spectrum of the emission in connection with the outer ejecta was extracted and modelled. Using a one temperature, thermal equilibrium model (Mewe-Kaastra-Liehdal) and a fixed column density (log $N_H \sim 21.3$), yielded already reasonable good fits to the data, with a temperature of $\sim 0.65$ keV (Weis et al. 2002, Weis et al. in prep.). That indicates post-shock velocities of around 750 km s$^{-1}$ and agrees quite well with the detected average expansion velocities. Besides the temperature, the nitrogen abundance was determined, which was possible because a very prominent nitrogen line at about 0.5 keV was visible in all spectra. In general the values indicate a roughly 6 times higher nitrogen abundance. A similar enhancement of Nitrogen was detected in optical spectra of the outer ejecta.
Figure 3: Left: This image shows a section of the HST/F656N image of η Carinae in the region were three of the 5 identified Strings are. String 1 is the longest of all. Right: Part of the HST-STIS spectrum of String 1 between 6450 and 6780 Å.

3 HST-STIS observations of the Strings—first results

The Strings are long, highly collimated structures that point nearly radially away from η Carinae and emerge from the outer ejecta region that is closest to the Homunculus, partly that is the S ridge (Walborn 1976). The largest of all is String 1 (Fig. 3 with a total length 0.177 pc and a width of equal or less than 0.003 pc). String 4 (0.13 pc), String 3 (0.085 pc), String 5 (0.058 pc), and String 2 (0.044 pc) follow, all with similar width. For a detailed description of the basic parameters of the Strings see Weis et al. (1999). The Strings are nearly aligned with the long axis of the Homunculus and their radial velocity increases as the String move outwards. For String 1 this increase ranges from −522 to about −995 km s\(^{-1}\) (Weis et al. 1999). Here I will discuss new results from a first analysis of the HST-STIS spectra taken of 4 of the Strings; due to the space limitation only the case of String 1 is discussed in detail.

We observed the Strings with the HST-STIS and the G750M first order grating and the 52 × 0.5 aperture. The slit was successfully aligned with each String. The spectra ranged from 6295 to 6867 Å. In all spectra the Strings are identified in emission in the following lines: [N\(_{II}\)] at 6548 Å and 6583 Å, H\(_\alpha\), He\(_{I}\) at 6678 Å and both [S\(_{II}\)] lines at 6716 and 6731 Å. Figure 3 shows String 1 in these lines. This imaging-spectroscopic display of String 1 shows that the String is very homogeneous, is not subdivided and that there is no brighter structure at the front. The bullets originally believed to be the head of String 1 are visible and appear detached from the String—below the continuum of the star in Fig. 3 (right)—nevertheless they follow the linear velocity increase well. From these spectra it is obvious that the String is more of a steady flow rather than bullets along a chain. The origin of String 1 is sudden, within the southern part of the S ridge. It looks as it does not extend back into the Homunculus, see top of Fig. 4 right panel. The velocities determined from the STIS spectra range from −290 km s\(^{-1}\) at the beginning to −950 km s\(^{-1}\) further out. The slightly different values compared to Weis et al. (1999) result mainly because of the lower spectral resolution of STIS (∼50 km s\(^{-1}\) compared to 14 km s\(^{-1}\)) and as for the much lower starting value due to the better tracing of the string inwards giving the higher spatial resolution. We therefore trace the String longer than in our Echelle spectra. Also a
split which was suggested to occur in String 1 (Weis et al. 1999) was confirmed with the STIS data, see Figs. From the lines detected we derived line ratios for String 1, see table 1. The line ratios are very similar for string 2-4, the other Strings observed. Using the [S\text{II}] line ratio and assuming a temperature of about 14000 K (a typical value for the S ridge, Dufour et al. 1997) we obtain an electron density of about $1.2 \times 10^4$ cm$^{-3}$. Since the ratio lies close to the high density limit this is more of a conservative lower limit and might be higher. The results agree well with electron densities in the outer ejecta (S ridge) determined by Dufour et al. (1997) using the Si\text{III] lines. With the help of the electron density and kinematics of String 1 one can calculate the mass and determine the kinetic energy associated with the String. With an electron density of about $10^4$ cm$^{-3}$, which corresponds to a mass density $\rho$ of $1.6 \times 10^{-23}$ kg cm$^{-3}$ (using cosmic abundances) and a volume of the String of $3.7 \times 10^{49}$ cm$^3$, the mass $M$ of String 1 is about $3 \times 10^{-4}$ $M_{\odot}$ if it is completely filled. With a lower limit on the average expansion velocity of $v \sim 450$ km s$^{-1}$ the total kinetic energy $E = \frac{1}{2}M v^2$ is about $6 \times 10^{43}$ ergs. Or using the cross section $A$ of the String and its density flow we can estimate the power in sense of a kinetic Luminosity $L = \frac{1}{2} \rho v^2 A v$ which is about $1 L_{\odot}$. Several mechanism have been proposed to explain the Strings, like trails left by a bullet (Weis et al. 1999, Redman et al. 2002), shadowing effects (Soker 2001) or a steady gas flow (Weis et al. 1999) are only a few to name. The new STIS data show that the Strings are dense (but might be hollow) objects with $10^4$ cm$^{-3}$ and that there is no density contrast detected along the String which could give rise to a denser leading head. There still might be a density difference to much higher densities which we would not detect since we are close to the high density limit of the [S\text{II}] line ratio. But this is unprobable since than at the same time the surface brightness should also increase in this denser knot, and this is not see in the spectra.

4 Summary and general remarks

The nebula around $\eta$ Carinae can be divided into two quite different parts, the Homunculus a bipolar reflection nebula about 0.2 pc across and the 0.67 pc large outer ejecta, a filamentary emission nebula. We have shown that the kinematics of the outer ejecta indicate that also this part of the nebula expands bi-directional, or bipolar. The symmetry axis is similar to that of the Homunculus.

Historically we know that $\eta$ Carinae und its nebula emit X-rays. With CHANDRAs unprecedented spatial resolution a very accurate comparison of the X-ray emission with the optical emission could be made. The X-ray emission is more homogeneous and smoother than the optical nebula, which is more of an accumulation of filaments, knots and bullets. While the sizes match, that is we find X-ray emission in regions where there is optical emission we barely find an agreement of individual knots, except for the S condensation. Comparing the intensity maxima of the X-ray emission with the velocities of the optical filaments yields a much better consensus. We conclude that in the case of $\eta$ Carinae’s outer ejecta the faster moving filaments are able to form stronger shocks and therefore stronger X-ray emission. The temperature of 0.65 keV indicates post-shock velocities of 750 km s$^{-1}$, in agreement with the measurements.

From the new HST-STIS spectra of the Strings we obtain a first analysis of new parameters of the Strings. We can see that the Strings starts abruptly and does not extend back into the Homunculus. The slowest velocity of String 1 was denoted with $-290$ km s$^{-1}$. The fastest is similar to the previous measurements with about $-950$ km s$^{-1}$. We determined several line ratios for String 1, the

|       | $\text{[S\text{II}]}/\text{[N\text{II}]}$ | $\text{[S\text{II}]}/\text{H}\alpha$ | $\text{He}\text{I}/\text{H}\alpha$ | $\text{He}\text{I}/[\text{S\text{II}}]$ |
|-------|------------------|-----------------|----------------|----------------|
|       | $I(6716)/I(6731)$ | $I(6583)/I(6563)$ | $I(6716+31)/I(6563)$ | $I(6678)/I(6563)$ | $I(6678)/I(6716+31)$ |
| 0.5   | 1.7-3            | 0.07            | 0.03           | 0.5            |
most interesting of which is the [S II] ratio, a density indicator. For String 1 this ratio is about 0.5 ± 0.1. Within the errors the ratio is steady along the String. The ratio is close—but clearly not always at—the high density limit of the line, so we still can determine an electron density of 10^4 cm^{-3}. The density, as the line ratios in general are for all Strings alike. The Strings are more of a denser steady flow rather than ablating bullets, shadows or knots on chains. Since the HST-STIS spectra we have taken for the Strings also contain information of the immediate surrounding—that is the outer ejecta, mainly the S ridge and W Arc—we could also determine the density of several filaments in this region. Measurements in these spectra show that the filaments in the outer ejecta have a density of the order of 10^4 cm^{-3}, thus about the same as the Strings. This value does not change significantly—at least in the regions which are covered by our HST-STIS observations. If we assume that all filaments in the outer ejecta have roughly this density, and take a reasonable filling factor for the knots in the ejecta of 1% within the total (0.67)^3 pc^3 volume of the outer ejecta, the total mass is at least 0.5 M☉.

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