3D Structure and Dynamics of the Homunculus of Eta Carinae: an Application of the Fabry Perot, ADONIS and AO Software

II. SPIKES AND BULLETS

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1. Summary

Eta Carinae is an extremely massive and highly evolved member of the Carinae starburst region. It has undergone numerous eruptions over the past millennium. In 1841, a giant eruption ejected several solar masses or more of material. Most of this material is currently in the dusty nebula denoted as the "Homunculus".

In an initial article (*The Messenger* No. 101, September 2000, p. 24), we presented results on the 3-dimensional structure and dynamics of the nebula. In addition to the smoothly distributed light from the nebula, there are sharp spikes or "jets" extending far beyond the Homunculus and very small condensations or "bullets".

This second article presents new results on these features obtained as an application of two new software packages developed in the frame of the PAPAO programme (*The Messenger* No. 100, June 2000, p. 12).

The first is STARFINDER (*The Messenger* No. 100, June 2000, p. 23) that has been developed for use with AO data (as well as other types of data) by ESO and Emiliano Diolaiti of the University of Bologna[3]. The second is LINEPHOT developed at ESO by B. Svensson[5] and S. Tordo. In order to test the performance of these software packages for astrometric applications, we require observations in which there is significant and known relative motion of the objects in the field. In the short life of the PAPAO[2] programme, the collection of such data has not been feasible. Therefore, we have conducted these tests on observations of eta Carinae obtained by WFPC2 IDT on the Hubble Space Telescope[1]. We also present results of observations obtained by D. Currie with VLT FORS1.

2. Spike (or "Jets") and Bullets

David Malin obtained colour images of eta Carinae and the surrounding nebula using the Anglo-Australian Telescope[4]. John Meaburn[6] noticed a peculiar red Spike in this image, and performed a series of spectroscopic measurements on this "Spike". The Doppler velocities or red shifts of the clumps in this "Spike" indicated very high velocities. Later Weis et al.[7] again observed the Spike and other similar features about eta Carinae. The motions along the spikes have the remarkable and unique property that the velocities increase towards larger distances from the star[7]. At the time that we measured the astrometric motion of the Homunculus in the WFPC2 images[1], it was difficult to measure the astrometric motion of Spike. However, a later review of the images following some special processing techniques found that there were two very faint, barely resolved objects at the head of the Spike[1]. The astrometric measurements on these two "Bullets" could be performed and they were found to be moving at almost 1% the speed of light (i.e. 3000 km/sec. This led to the application of the special capabilities of the STARFINDER programme, that has been developed in a joint programme between University of Bologna and ESO[2, 3]. The STARFINDER programme is especially adapted to perform astrometric and photometric measurements on adaptive optics observations of target fields in which there is a large contamination with background radiation. Using this programme, we were able to re-determine the earlier measurement of the astrometric motion of the two Bullets, as well as measure the astrometric or Plane-of-the-Sky (PoS) motion of the individual knots or clumps within Spikes. In addition, it was possible to measure the motion of the components of the other Spikes and many other such Bullets were discovered that were moving at a velocity that implied that they, like the original Bullets and the clumps within the original Spike, were emitted in 1841, at the same time as the clumps that compose the Homunculus. Most of the results presented here address the Spike #1 with the 2 bullets at its tip (Fig. 1). Very detailed results have also been obtained on spike #2. As we shall discuss, the diameters of these Bullets and the Spikes are unresolved in the Planetary Camera images, so they have a diameter of less than the extended solar system. Comparison with the diameter of stellar images indicates that these diameters (FWHM) are 100 AU or less in the direction perpendicular to the long axis of the Spike. By comparing the plane-of-the-sky (PoS) velocity component (i.e. the astrometric velocity) with the line-of-sight (LoS) velocity compo-

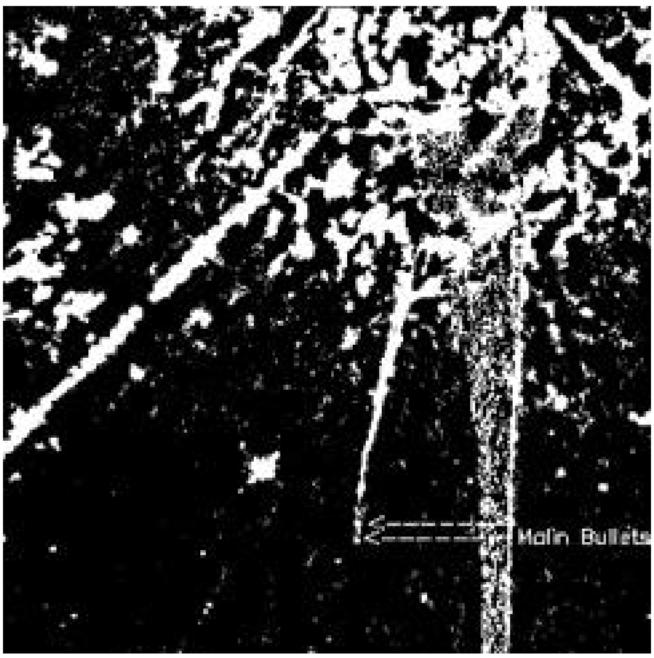

Figure 1: HST image of the southern edge of the nebula of Eta Carinae, the Homunculus, with Malin Spike #1 and its 2 bullets at the end. The 2 brighter spikes are diffraction effects.

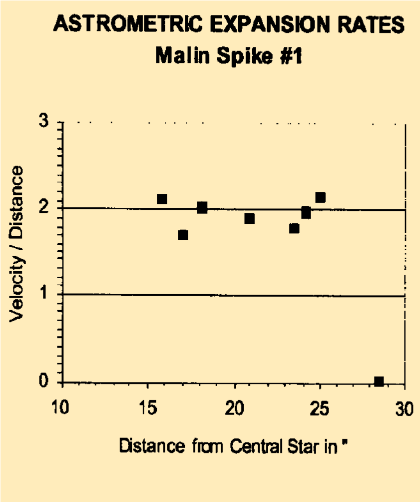

Figure 2: Astrometric motions (on the plane of the sky) of knots and clumps which compose spike #1. Abscissa: distance from central star in arcsec. Ordinates: velocity, in pixel per year, divided by radial distance in arcsec. By combining the astrometric and spectroscopic data, one obtains a consistent picture in which all the clumps in the spike left the star about 165 years ago, that is in 1841. The point at 28.4″ is a (stationary) background star.

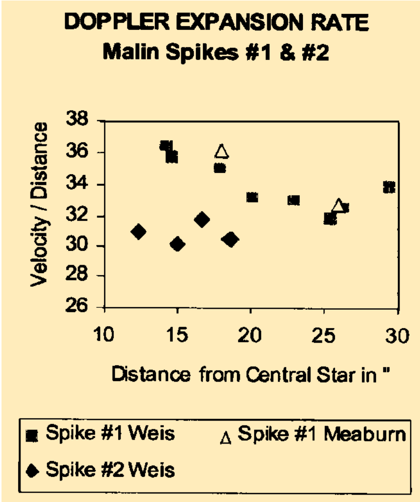

Figure 3: Line-of-sight velocity of the clumps divided by the distance from the star plotted as a function of the distance from the star. The velocity increases with distance from the star[6, 7].

nent (i.e. the Doppler velocity) we can determine that the angle from the line of sight is about 65 degrees from the line of sight.

The PoS motion was detected by using pairs of images of eta Carinae that were recorded using the WFPC2 on the HST in 1990, 1991, 1994, 1995 and 1997. Positional measurements of the clumps or knots in these images, using STARFINDER, have been used to derive the astrometric velocities of the bullets and of the clumps that compose the Spikes. In Figure 2, the astrometric velocity (PoS) measurements for Spike #1 are plotted as a function of the distance to the central star (in the PoS). In Figure 3, the Doppler velocities (i.e. LoS) of Spikes #1 and #2, determined by spectroscopic measurements of the Spikes[7, 8], are plotted as a function of the PoS distance from the central star. The relatively uniform values of the linear expansion rates (i.e. the velocities/distances) imply a relatively smooth linear increase in the velocity with distance. In addition, there is very little spreading of the ejecta. The mechanics of the generation and propagation of such features is unknown. Finally, this in turn implies that each of the clumps was ejected from the central star at the same time in different directions, again a phenomenon for which the physics is not understood.

In the past, the direct analysis of properties of width and straightness for the Spikes have been confused by the changes in brightness along the Spikes and the existence of non-uniform nebulosity surrounding the Spike. To allow the extraction of this information, we have developed a programme, LINEPHOT, to fit the peak intensity, the width and central position of the Spike with a Gaussian function along a line that is orthogonal to the long dimension of the Spike. We have separately estimated the various parameters describing the background nebulosity, in order to reduce their influence on the parameters of the Spike[4]. The results of such an analysis applied to our WFPC2 image (HST Proposals 1138, 2887, 5239, 7253 by Westphal, and the IDT) is shown in Figure 4. A similar analysis of the FORS1 data from the VLT (VLT Proposal 63.I-0619(A) by Currie, et. al.) is shown in Figure 5. In both of these figures, the uppermost plot shows the total brightness of the Spike (peak intensity times twice the Gaussian width). The second plot shows the position of the centroid of the Gaussian, more precisely, the component of the position that is orthogonal to the Spike, illustrating the deviations from straight-line motion. Finally the last curve shows the width of the Spike, where the width of a stellar image in the same frame, obtained with the same fitting programme, is shown by the dashed line.

The HST and the FORS1 observations were conducted in narrow-band filters at the wavelength of the Hα emission or slightly longward. In this region, we are seeing primarily the 6583 locally emitted, blue-shifted [NII]6583 radiation, with a small component (i.e. at the edge of the filter band pass) of locally emitted, blue-shifted Hα emission. In addition, there would be expected to be some components of the Hα radiation emitted by the central star and scattered by the dust contained in the Spike. Recent observations on the FORS1 instrument on the VLT at Paranal, taken at the wavelength selected for maximum sensitivity show that the Bullets are indeed the leading elements of the Spikes, with no component beyond the Bullets. This starts to give us information to address the physics of the generation and dynamics of these remarkable objects.

The similarly detected results obtained for Spike #2 illustrate the contrast in the apparent and physical properties of the different Spikes that surround eta Carinae. The lengths differ by almost a factor of two. Spike #1 is rather “knotty” while Spike #2 is relatively smooth. Spike #1 shows a number of small bends, while Spike #2 shows a single large bend, and the rest of the motion is straight. Spike #1 has a leading bullet, while Spike #2 does not. In both cases, the width of the Spike is beyond the resolving power of the telescope/camera/atmosphere at the time.

Finally we wish to address the width of the original Spike (Spike #1) and Spike #2. Discussion in the literature either states or implies that these features were well resolved. However, the LINEPHOT programme allows a much more quantitative consideration of this issue. The major portions of the Spikes are essentially unresolved by FORS1 and by the WF camera. In order to obtain a better estimate for the width (or at least a better upper limit), we apply the LINEPHOT procedures to the images obtained in the Planetary Camera of HST. The result is that the Spikes are essentially unresolved, with the resolution of the telescope empirically determined by the measurement of stellar images, i.e., about 100 milli-arc-seconds (mas). This value was determined using a nearby star from the same frame, and using our same LINEPHOT programme. (Spike #2 is especially smooth). That indicates a width of less than 50 mas, or less than 120 AU. In particular, the widths of the Spikes are essentially unresolved from their emergence out of the glare of the central star to their tip. Thus the Spikes are very thin features that have a (length)/(width) ratio of over 600.

Analysis of the FORS1 images have also resulted in the discovery of several new Spikes that have a very high redshift, such that neither the locally emitted nor the locally reflected radiation was admitted by the Hα or the [NII] filters on HST. The FORS1 images also allow a rough red shift determination and thus a classification of the Spikes, as well as a guide for interpreting the spectroscopic measurements. Data reduction and analysis is continuing on the other Spikes, as well as the many Bullets that have been found in the outer regions beyond the Homunculus.

3. Conclusions: Adaptive Optics Operation and Data Reduction Techniques

In conclusion, we have demonstrated that the very large velocities of the Spikes and Bullets indeed represent

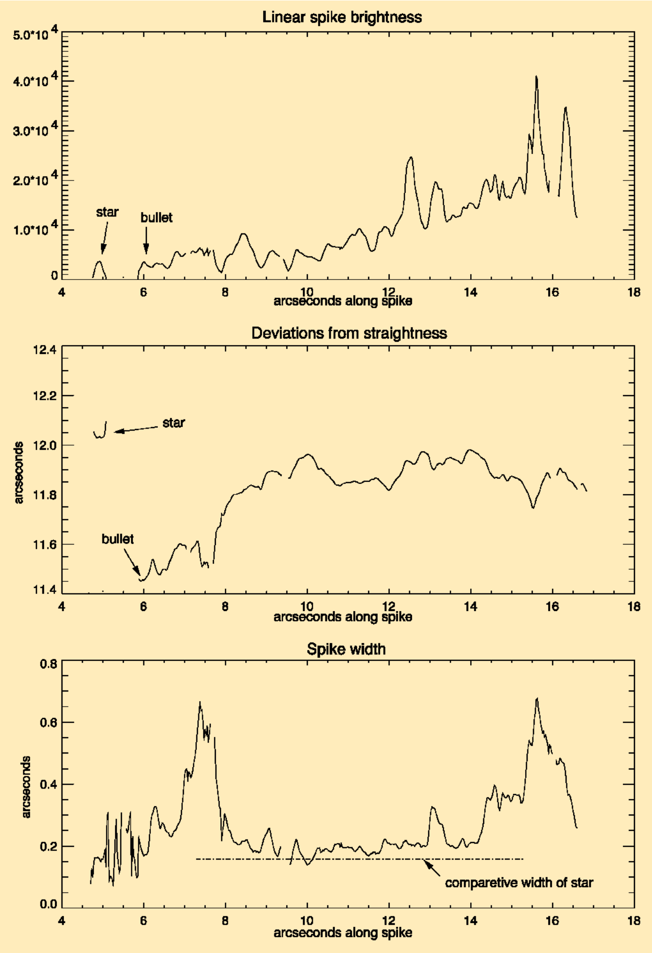

Figure 4: Intensity, position and width of Spike #1 as obtained with LINEPHOT applied to HST/WFPC2 images taken through an Hα filter, and all plotted as a function of distance from centre. Upper plot: intensity (i.e. peak values times width); middle plot: position of the centroid as compared to a straight line, i.e. deviation from straightness; lower plot: width (dashed line: width of a star). Date of the observations: 1997.

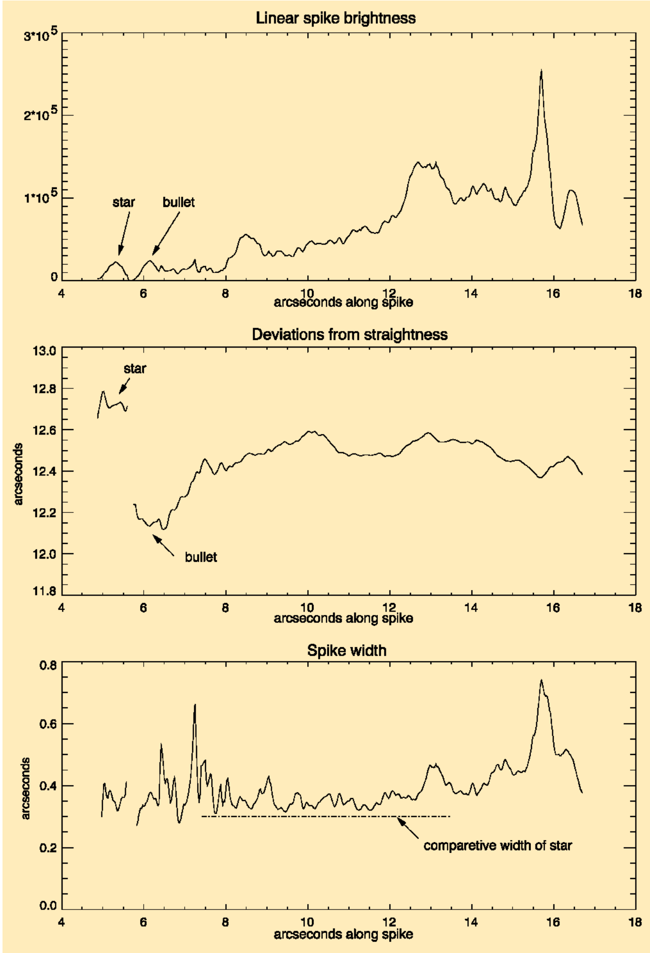

Figure 5: Same as Figure 4, but from LINEPHOT applied to Hα images taken with VLT/FORS1. Date of the observations: 1999. The small differences with Figure 4 are mostly due to the difference in angular resolution and filter band-pass.

actual physical motions of clumps of material. The individual clumps, both in terms of the astrometric and spectroscopic velocities, move in a manner to indicate that all of the elements of the Spikes were emitted in 1841. We have also shown that the Bullets are the leading elements of these strange structures, that is, there is no fainter extension of the Spike that lies beyond the bullets. The width of the Spikes and the diameter of the Bullets are less than 120 AU.

The astrophysical results presented here and in article I have been made possible by the combination of the unique capabilities of ADONIS, the WFPC2 of the Hubble Space Telescope and the FORS1 instrument on the VLT. This programme also shows the importance of the auxiliary instrumentation on an AO system, specifically the Fabry-Perot Interferometer and the Coronographic Occulting Spot.

The final point concerns the data reduction and analysis methods that are used, and that are discussed in considerably more detail in *The Messenger* No. 100, p. 12, and in other papers[2,3], and references therein. Present methods of data reduction and analysis for adaptive optics data have intrinsic photometric errors that are significantly larger than the basic limitations imposed by the photon noise in the target, the skirts or wings of nearby objects, and the sky and the read noise. An unknown portion of this is due to errors in the flat fielding. Addressing and solving these issues can either greatly improve the science that can be obtained from AO data, or can result in a significant reduction in the telescope time required to achieve a given science goal. As we proceed with the AO systems on the 8–10-metre-class telescopes, this will become an even more critical issue.

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