ETA CARINAE: BULLET STREAMS AND COLLIDING WIND SHOCKS

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RESUMEN

El resumen será traducido al español por los editores. eta Carinae, the most massive and most luminous star in our galaxy, erupted in 1842 with an energy rivaling a supernova. It ejected material, approximately two solar masses, that appears as an extended bipolar nebula, the homunculus, a variety of massive "bullets" (NN and NS knots and the South Bar) and finally the spikes (long narrow strings of bullets). We have performed spatial and spectral astrometry on all of these features, but we shall concentrate on our observations and analysis of the spikes and homunculus. The different spikes were emitted at various angles with respect to the axis of symmetry of the homunculus and the equatorial disk. These spikes may be a astrophysical realization of the recent magneto-hydrodynamical simulations by López, Steffen and Garcia-Segura. The latter use a wind and magnetic structure and for certain values of the parameters, produce, for planetary nebula parameters, several features that resemble the spikes including their velocity distribution. We will discuss the properties of the spikes, the relation to the HD and MHD simulations and the speculations on the nature of eta Carinae.

ABSTRACT

eta Carinae, the most massive and most luminous star in our galaxy, erupted in 1842 with an energy rivaling a supernova. It ejected material, approximately two solar masses, that appears as an extended bipolar nebula, the homunculus, a variety of massive "bullets" (NN and NS knots and the South Bar) and finally the spikes (long narrow strings of bullets). We have performed spatial and spectral astrometry on all of these features, but we shall concentrate on our observations and analysis of the spikes and homunculus. The different spikes were emitted at various angles with respect to the axis of symmetry of the homunculus and the equatorial disk. These spikes may be a astrophysical realization of the recent magneto-hydrodynamical simulations by López, Steffen and Garcia-Segura. The latter use a wind and magnetic structure and for certain values of the parameters, produce, for planetary nebula parameters, several features that resemble the spikes including their velocity distribution. We will discuss the properties of the spikes, the relation to the HD and MHD simulations and the speculations on the nature of eta Carinae.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — STARS: VARIABLES: LBVS**

1. GENERAL

The extraordinary energy of the Great Eruption (GE) of eta Carinae (approaching the energy released in a supernovae) while preserving the star has both caused many phenomena that have not been seen elsewhere in the galaxy and has facilitated the study of these phenomena. Astrometric studies of eta Carinae have been conducted using both spatial astrometry in the plane of the sky (Walborn 1988; Walborn 1978; Currie 1996; Dowling 1996), and spectral astrometry (Walborn 1988; Walborn 1978; Hillier 1996; Dowling 1996) addressing the Doppler shifts in the locally emitted and locally reflected radiation have allowed us to detect, measure and analysis many of these phenomena. The results of the spatial and spectral astrometry (S&SA) have then been combined to determine the three-dimensional structure, velocity and history of the system (Currie 1995; Dowling 1996). We will now review some of the phenomena specifically related to the eruption(s) that raise a host of interesting theoretical and observational challenges. The new instrumentation of the Wide Field/ Planetary Camera (WFPC) on NASA's Hubble Space Telescope and the Ultraviolet Spectrograph (UVES) on ESO's Very Large Telescope at Paranal, Chile has allowed our group at the University of Maryland to attack these issues. We will address the spikes (a.k.a. "whiskers" or "strings") and the homunculus, which both consist of debris that was ejected in 1842 during the GE. Other material from later eruptions is addressed elsewhere in these proceedings (Dorland 2003).

2. SPIKES

General Description: The spikes were first observed by Meaburn in images obtained by Malin who suggested a "Hubble flow" with radial velocity from

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the central star that increases as a function of distance. This can be explained by postulating simultaneous ejection of "bullets" at the time of the GE (Currie 2000c). WFPC observations show that (Currie 2000c; Morse 1998) these long spikes are presumably composed of the same combination of dust and gas as the homunculus. The length is of the order of 3/4 of a parsec, a width of less than 200 AU (i.e., the resolution of WFPC) and with a velocity at the tip of up to 2000 km sec^{-1}.

Observation and Analysis Methods: The plane of the sky position and velocities are obtained by analysis of WFPC data from the HST and FORS1 data from the VLT spatial astrometry (Currie 2002c). The positions at two or more different epochs are used to determine the velocity. The spectral astrometry is performed by obtaining medium or high resolution observations (Meaburn 1996; Weis 1999; Currie 2000b). The velocity is then determined by observations of both the locally reflected and locally emitted line emission (Currie 2000a). These data are then combined to obtain the 3D orientation of the spikes (Currie 2000c). The spikes are emitted at apparently random places on the surface of the star.

Puzzle or Challenge: We know of no ejection mechanism that would produce such events at various paces on the surface of the star. This ejection mechanism must, at a "random" location on the surface of the star, produce a family of bullets, all emitted in the same direction, with a sufficiently smooth distribution of velocities so as to create, in some cases, an apparently continuous distribution of "bullets" to form a spike that is more or less uniform in distribution of radial brightness. The second puzzle is the propagation mechanism. The width of the spikes remains unresolved. At the tip, this means that the ratio of the expansion velocity to the radial propagation velocity is less than 600 to 1. While this is compatible with the expansion velocity associated with a temperature of 10,000K, it does require that the ejection mechanism that produces bullets with a radial velocity of 2000 km sec^{-1} but with essentially no azimuthal velocity.

Possible Solution: One part of the ejection puzzle can perhaps be explained by either of the approaches described by Garcia-Segura (2000) and Steffan (2002). They have produced models that can produce narrow jets or knots that have increasing velocities. Joint investigation is now proceeding to determine if the velocity in the models is indeed a linear Hubble flow and if appropriate results can be obtained for the various parameter ranges of interest in eta Carinae. The lifetime and expansion velocity of the bullets in these proposed approaches also needs to be investigated. The remaining puzzle concerning the random distribution of the "points of origin" over the surface of the star will be addressed toward the end of this paper.

3. HOMUNCULUS AND DIMPLE

Description: The conclusion from the S&SA of the homunculus is that the lobes are shaped like a "Double Flask" (Currie 1995; Dowling 1996). All the material composing the homunculus as well as the North Jet and the South Bar was emitted during the eruption centered on 1841.9. By projecting the motion of the clumps back in time, using the assumption of ballistic motion, we can determine the date of origin for each clump. This analysis implies that the eruption occurred over a period of less than 15 years. The other notable feature for our current discussion is the dimple (when seen in velocity space) or the "dark spot" (when seen in direct images). This is a region in the center of the base of the "Double Flask" model of reduced intensity and velocity.

Observations and Method of Analysis: The homunculus has been analyzed using S&SA in the manner described above (Dowling 1996; Currie 1996). The spatial astrometry was carried out on bright clumps. The spectral astrometry was carried out on data from the AAT (Hillier & Allen 1992). The S&SA was then combined to obtain the three dimensional structure in the form of the Double Flask model (Currie 1995; Dowling 1996).

Puzzle: The dimple is difficult to explain with current understanding and simulations. A similar structure has been seen in some planetary nebula (Corradi 1993) so this process may have broader astrophysical significance than just for eta Carinae. In addition, most of the hydrodynamical and magnetohydrodynamical simulations of the development of the homunculus do not have a detailed agreement with the combination of the observed shape and velocities of the homunculus.

Possible Solution: Concerning the shape, new physics needs to be added to the models and a detailed comparison made with the observational information. On the other hand, the role of the dimple will be discussed in the last section.

4. PRECESSION OF THE SPIN AXIS

Objective: We have addressed a possible explanation of the generation mechanism of the spikes, but have not yet addressed their origin from random places on the surface of the star. Nor have we addressed the origin of the dimple. Both of these phenomena may be explained by assuming a precession of the spin axis of the central star. Thus we may accept the implicit presumption of Garcia-Segura and of Steffan that their spikes originate along the spin axis of the star. If the spin axis is precessing about the angular momentum vector, then the spin axis will move along in a circle on the sky.

Spike Explanation: Under this scenario, the spikes should lie on a circle about the nominal axis of symmetry. To date, we have the three dimensional orientation of only two spikes, so this hypothesis is confirmed, but only weakly. Further observations will be necessary to provide a strong confirmation of this hypothesis.

Dimple Explanation: A number of simulations (e.g., Garcia-Segura 2000) indicate an elliptical shape for the homunculus but without a dimple and much narrower than the double flask. However, if we have emission that is narrow and the axis of the ellipse is moving about the conserved angular momentum vector, they would create a flask-like shape with the dimple.

Physics of the Precession—what is the nature and origin of the precession?

Free Precession: The most favored possibility at present is that this is a free precession. The expected periods of this motion allow a number of precesional cycles within the 15 years during which the spikes were formed around 1842. On how this motion is generated, we have done a 3D analysis of the debris (Currie 2000b, 2000c; Dowling 1996) and confirmed the visually apparent asymmetry in the outer debris from the previous eruption. Thus we need only the continuation of the precession for a few hundred years. Initial studies of the free precession of non-rigid bodies have been published (Lewis 1993, 1994), but not yet for the detailed parameters of eta Carinae.

Binary Driven Precession: Another candidate is that the generation of the precessional motion is interaction between the central star and a binary companion. The forces acting between the companion and the "tidal bulge" of the central star will produce a "binary driven" precession. Since there is a considerable body of evidence suggesting a companion to eta Carinae (Daminelli 1997) this is an interesting possibility. However, for reasonable parameters, the precessional periods are too slow to complete a few revolutions in the fifteen years. Therefore this does not seem viable at this time.

5. CONCLUSIONS

eta CAR is a unique laboratory for the study of extreme physics in our galaxy. Accurate astrometry, both spatial and spectral, allows accurate determination of the motions and locations of the debris that was the result of the GE. However, the central star and the details are beyond our reach for direct observation. Here we address some possibilities of the underlying physics that are compatible with the recent observations and analysis in order to guide future observations and to challenge the authors of the simulations.

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REFERENCES

Corradi, R., Schwarz, L. & Hugo, E. 1993, A&A, 269, 462

Currie, D. G., Dowling, D., Shaya, E., Hester, J., HST WFPC IDT & WFPC2 IDT 1996, Proceedings of the ESO Workshop: "Role of Dust in the Formation of Stars", Kaufl, H. U. and Siebenmorgen, R. (ed.) Springer-Verlag, Garching bei Muenchen, 89

Currie, D. G, Dowling, D. M., Shaya, E. J., Hester, J. J., Scowen, P., Groth, E. J., et al. 1996, AJ, 112, 1115

Currie, D. & Dowling, D. 1999, ASP Conf. Ser., Morse, J., Humphries, R. & Damineli, A. (eds.), 179, 79

Currie, D. G., Le Mignant, L., Svensson, B., Diolaiti, E., Tordo, S., & Naesgarde, K. 2000a, SPIE Vol. 4007 AO Systems Technology, P. Wizinowich (ed.), 1

Currie, D. G., Le Mignant D., Svensson, B., Tordo, S., & Bonaccini, D. 2000b, ESO Messenger, 101, 24

Currie, D. G., Le Mignant D., Svensson, B., Tordo, S., & Bonaccini, D. 2000c, ESO Messenger, 102, 25

Damineli, A., Conti, P. S., & Lopes, D. F. 1997, New Astronomy, 2, 107

Dowling, D. M. 1996, "The Astrometric Expansion and 3-D Structure of eta Carinae", PhD Thesis, University of Maryland, College Park, MD

Dorland, B. N., Currie, D. G., Kaufer, A., Bacciotti, F. 2003, these proceedings

Glover, T., Dufour, R., Hester, J., Currie, D., van Orsow, D. & Walter, D. 1998, RMxAA(SC), 7, 158

Garcia-Segura, G. & López, J. A. 2000, ApJ, 544, 336

Hillier, D. J. & Allen, D. A. 1992, A&A 262, 153

Lewis, D. 1993, Nonlinearity, 6, 4

Lewis, D. & Simo, J. C. 1994, J. Nonlinear Sci., 4, 253

Meaburn, J., Boumis, P., Walsh, J. R., Steffen, W., Holloway, A. J., Williams, R. J. R., et al. 1996, MNRAS, 282, 1313

Morse, J. A., Davidson, K., Bally, J., Ebbets, D., Balick, B. & Frank, A., 1998, AJ 116, 2443

Steffen, W., López, J. A., & Lim, A. J. 2002, RevMexAA (SC), 13, 150

Walborn, N. R., Blanco, B. M. & Thackeray, A.D. 1978, ApJ 219, 498

Walborn, N. R. & Blanco, B. M. 1988, PASP, 100, 797

Weis, K., Duschl, W., & Chu, Y.-H. 1999, A&A, 349, 467

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