RevMexAA (Serie de Conferencias), **15**, 59–61 (2003)

ETA CARINAE: BULLET STREAMS AND COLLIDING WIND SHOCKS

D. G. Currie

Department of Physics, University of Maryland, USA

RESUMEN

Eta Carinae, la estrella más masiva y luminosa de nuestra galaxia, hizo erupción en 1842 con una energía parecida a la de una supernova. Eyectó aproximadamente dos masas solares de material para asi formar una nebulosa bipolar extendida (el homúnculo), una variedad de "balas" masivas (nudos NN y NS y la Barra Sur) y las "púas" (unas hileras largas y delgadas de balas). Hemos hecho astrometría espacial y espectral en todos estos componentes, pero voy a concentrarme en nuestras observaciones y análisis de las púas y el homúnculo. Las púas fueron emitidas a una variedad de ángulos con respecto al eje de simetría del homúnculo. Estas púas podrían ser una manifestación astrofísica de las simulaciones magnetohidrodinámicas de las nebulosas planetarias hechas por J. A. López, W. Steffen, G. García-Segura y colaboradores. Ellos utilizan un viento y una estructura magnética y para ciertos valores de sus parámetros producen varios componentes que se asemejan a las púas. Discutiremos las propiedades de las púas, su relación a las simulaciones hidro- y magnetohidrodinámicas y especularemos sobre la naturaleza de η 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 approximately two solar masses of material to form an extended bipolar nebula (the homunculus), a variety of massive "bullets" (NN and NS knots and the South Bar) and the "spikes" (long narrow strings of bullets). We have performed spatial and spectral astrometry on all these features, but I shall concentrate on our observations and analysis of the spikes and homunculus. The spikes were emitted at various angles with respect to the axis of symmetry of the homunculus. These spikes may be an astrophysical realization of the recent magnetohydrodynamical (MHD) simulations of planetary nebulae by J. A. López, W. Steffen, G. García-Segura and collaborators. They use a wind and magnetic structure and, for certain values of their parameters, produce several features that resemble the spikes. We will discuss the properties of the spikes, the relation to the hydrodynamic (HD) and MHD simulations and speculate on the nature of η Carinae.

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

1. GENERAL

The extraordinary energy of the Great Eruption (GE) of η Carinae (approaching the energy released in a supernova), 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 η Carinae have been conducted using both spatial astrometry in the plane of the sky (Walborn, Blanco, & Thackeray 1978; Walborn & Blanco 1988; Currie et al. 1996a; Dowling 1996), and spectral astrometry (Walborn et al. 1978; Walborn & Blanco 1988; Hillier & Allen 1992; Dowling 1996). The latter addresses the Doppler shifts in the locally emitted and locally reflected radiation and has allowed us to detect, measure, and analyze many of these phenomena. The separate 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 1996b; 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* (*HST*) 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 et al. 2003).

2. SPIKES

General Description: The spikes were first observed (Meaburn et al. 1996) on images obtained by Malin, suggesting a "Hubble flow" with radial velocity from 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 et al. 2000c). WFPC observations indicate that (Currie et al. 2000c; Morse et al. 1998) these long spikes are presumably composed of the same combination of dust and gas as the homunculus. Their length is of the order 0.75 parsec, with a width of less than 200 AU (i.e., the resolution of WFPC) and with a velocity at the tip of up to $2000\,\mathrm{km\,s^{-1}}$.

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 et al. 2000c). The positions at two or more different epochs are used to determine the velocity. The spectral astrometry is performed using medium- or high-resolution observations (Meaburn et al. 1996; Weis, Duschl, & Chu 1999; Currie et al. 2000b). The Doppler velocity is then determined by observations of the locally reflected and/or locally emitted line emission (Currie et al. 2000a). These data are then combined to obtain the 3-D orientation of the spikes (Currie et al. 2000c).

Puzzle or Challenge: We know of no ejection mechanism that would produce such events at various places 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 free expansion velocity associated with a temperature of 10,000 K, it does require that the ejection mechanism produce bullets with a radial velocity of $2000\,\mathrm{km\,s^{-1}}$ 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 García-Segura & López (2000) and Steffan, López, & Lim (2002). They have developed models that can generate narrow jets or knots that have increasing velocities. Collaborative investigations are 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 η 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 et al. 1996b; 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 et al. 1996a). The spatial astrometry was carried out on bright clumps. The spectral astrometry was carried out using AAT data (Hillier & Allen 1992). The S&SA data were then combined to obtain the three-dimensional structure in the form of the "double flask" model (Currie 1996b; Dowling 1996).

Puzzle: The dimple is difficult to explain with current understanding and simulations. Similar structures have been seen in some planetary nebulae (Corradi & Schwarz 1993) so this process may have broader astrophysical significance than just for η Carinae. In addition, most of the hydrodynamical and magnetohydrodynamical simulations of the development of the homunculus do not have a detailed agreement with both the observed shape and velocities of the homunculus.

Possible Solution: Concerning the shape, new physics may need 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: I 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 I 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 assumption of García-Segura & López (2000) and of Steffan et al. (2002) 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, compatible with this hypothesis, but only a weak validation. Further observations will be necessary to provide a strong confirmation of this hypothesis.

Dimple Explanation: A number of simulations (e.g., García-Segura & López 2000) suggest 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 during the emission, a flask-like shape with the dimple would be created.

Physics of the Precession—Nature and Origin:

(a) Free Precession: The most favored possibility at present consists of a free precession. The expected periods of this motion allow a number of precessional cycles within the 15 years during which the spikes were formed. As to how this motion is generated, we have performed a 3-D analysis of the debris (Currie et al. 2000b,c; 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. The initial studies of the free precession of non-rigid bodies (Lewis 1993; Lewis & Simo 1994), have not yet addressed the detailed parameters of η Carinae.

(b) 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 η Carinae (Daminelli, Conti, & Lopes 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 the determination of the motions and locations of the debris from the GE. Here we have addressed 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.

I wish to thank ESO, STScI, and NASA for use of the VLT and *HST*, and also thank NASA, ESO-Garching, ESO-Vitacura and the University of Maryland for support during data analysis activities.

REFERENCES

Corradi, R. L. M., & Schwarz, H. E. 1993, A&A, 269, 462
Currie, D. G., Le Mignant, L., Svensson, B., Diolaiti, E., Tordo, S., & Naesgarde, K. 2000a, in Adaptive Optical Systems Technology, ed. P. L. Wizinowich, SPIE, 4007, 1
Currie, D. G., Le Mignant, D., Svensson, B., Tordo, S., & Bonaccini, D. 2000b, ESO Messenger, 101, 24
__________. 2000c, ESO Messenger, 102, 25
Currie, D. G., et al. 1996a, AJ, 112, 1115
Currie, D. G., et al. 1996b, in The Role of Dust in the Formation of Stars, eds. H. U. Kaufl & R. Siebenmorgen (Berlin: Springer-Verlag), 89
Damineli, A., Conti, P. S., & Lopes, D. F. 1997, New Astronomy, 2, 107
Dorland, B. N., Currie, D. G., Kaufer, A., & Bacciotti, F. 2003, RevMexAA(SC), 15, 70 (this volume)
Dowling, D. M. 1996, Ph.D. thesis, University of Maryland
García-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., 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. 1988, PASP, 100, 797
Walborn, N. R., Blanco, B. M., & Thackeray, A. D. 1978, ApJ, 219, 498
Weis, K., Duschl, W., & Chu, Y.-H. 1999, A&A, 349, 467

Douglas Currie: Department of Physics, University of Maryland, College Park, MD 20742, USA (currie@umd.edu).