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Chandra meets Eta Carinae

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Abstract. In its X-ray characteristics as in other respects, η Car does not quite match any other easily observed object. Two very different problems arise: the origin of the hard central X-ray spectrum, which probably involves a colliding-wind binary but may yet prove to be something quite different; and the softer X-rays produced by gas flows which, somehow, exist far outside the familiar Homunculus ejecta-nebula. Chandra has just begun to make an impact on these questions. Its spectral resolution may prove especially valuable for them.

1. A role model, enigma, and basket of omens, all in one place

What's so special about η Carinae? We've all seen the public X-ray image from Chandra, and Eta was also among the best early-observation objects for IUE twenty years ago, for five different HST instruments in the 1990s, and for other telescopes. I suppose it will be among SIRTF's first targets, too. Its extraordinary scientific appeal ranges from radio to X-rays; the reasons concern not only physics, but also the styles in which we do astronomical research.

To the general public (and, perhaps to most astronomers) η Car is The Mysterious Bipolar Astronomical Thing *par excellence* that People Are Vaguely Aware Of. Thus, a few years ago the HST/WFPC2 color image of its "Homunculus" ejecta-nebula apparently inspired a new fashion for Hollywood's space explosions: bipolar with equatorial debris, not the old-fashioned spherical kind! The name itself appeals: "Eta Carinae" has been a race horse, at least one rock band, an Italian amateur astronomers' society, etc.; ETA Car is a British automobile broker, and one shudders to imagine what else might be found on the internet. Like the public, the professional research community more or less recognizes Eta by name and appearance, but few astronomers know much about its physical character.

Eta's unique role in astrophysics arises from a combination of circumstances:
• An extreme set of parameters. It's the most luminous and massive star that we know much about ($> 100\ M_\odot$, maybe around $130\ M_\odot$); loses mass at a terrific rate (of the order of $10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$); site of the biggest non-terminal stellar explosion that we know much about (it ejected several $M_\odot$ in the 1840s, while radiating as many visual-wavelength photons as a SN); extremely large present-day IR luminosity; unusually hot thermal X-rays; etc.
• The associated scientific problems are diverse and relate to several branches of astrophysics: Stellar structure, evolution, and chemical processing; dense

stellar winds and the fundamental nature of the Eddington limit; exotic nebular excitation processes in the ejecta; unfamiliar gasdynamic structures; etc. Some of these have relevance to cosmological topics.

• Many of the observed facts are *not understood* at a surprisingly basic level; to note just one example, we still don't know what caused the Great Eruption of the 1840s. Some of these questions are profoundly disturbing because we would not know about them if this object were not so accessible for observation! It's a counter-paradigm; theorists have repeatedly failed to predict crucial effects for very massive stars in general and η Car in particular. These may, therefore, be omens that critical phenomena are missing from models needed in other branches of astronomy (some of them extragalactic).

• One might add that the object and its problems have been unusually well suited to some modern instruments. Spatial resolution of the complex structure has been especially rewarding.

This isn't a good place to recite details; for general information and references see Davidson & Humphreys (1997), Morse et al. (1999), Davidson (2000), and Gull et al. (2001). The important point is that *good physical reasons make η Car extraordinarily significant.* It isn't merely one more picturesque object.

Here I'll sketch just two current scientific problems where Chandra has begun to help: The hard X-rays near η Car itself, and softer, more diffuse X-rays from ejecta more than 100 years old. With apologies to many X-ray pioneers and those who have developed Chandra, I'll describe mainly the context rather than observational details. My own credentials relate to the former, and my informants on the latter have been Mike Corcoran, Kazunori Ishibashi, and, lately, Kerstin Weis. (No blame attaches to them if I have misunderstood some of the data.) So far, at least, Chandra's effect on this topic has been evolutionary – greatly improving upon earlier work with the Einstein, ROSAT, ASCA, RXTE, etc., instruments, but not overturning any of their discoveries.

2. Relatively hard X-rays near the star

Earlier instruments found a substantial 2–10 keV flux coming from near η Car itself, i.e., not from the entire Homunculus Nebula (Seward et al. 1979; Seward & Chlebowski 1982; Chlebowski et al. 1984; Corcoran et al. 1995, 1998, 2000; and other refs. cited therein). Being thermal, it most likely arises in one or more shock fronts. Plenty of thermal and kinetic energy is available (Table 1).

Table 1. Likely Power & Luminosity Budget of η Carinae

	$L/L_\odot$	$\log_{10}$(ergs/s)
• Total:		
Luminosity...	5×10^6	40.2
Kin. power in wind...	2×10^4	37.9
Hα emission...	2×10^4	37.9
X-rays...	~ 25	35.0
• Hypothetical companion star:		
Luminosity...	$< 10^6$	< 39.5
Kin. power in wind...	1000 ?	36.6?

One likely cause of thermal shocks forcibly presented itself when Damineli (1996) identified a 5.5-year periodicity in Eta's visual-wavelength spectrum: the massive star may have a companion in a 5.5-year orbit, so two stellar winds collide (Damineli et al. 1997, 2000; Corcoran et al. 1998, 2000; Pittard et al. 1999; Ishibashi et al. 1999b). The secondary star must have a wind speed above 2000 km s^{-1} in order to produce the observed X-ray temperatures. The primary star's side of the collision interface contributes little to the observed flux, because its slower wind (300–1000 km s^{-1}) implies relatively soft photons which are mostly absorbed by intervening material. In late 1997, when Damineli's 5.5-year period had predicted an "event," the X-ray flux suddenly crashed almost to zero (Ishibashi et al. 1999a,b; Corcoran et al. 2000); this was widely interpreted as some sort of eclipse. Various observers (cited below) then reported visual-to-infrared data which, in their views, supported the colliding-wind binary model.

Unfortunately, this development has been very untidy. Here I venture some unfashionable remarks: Though a hypothetical companion star seems plausible for η Car, it has *not* been confirmed and the idea presents difficulties that enthusiasts usually don't acknowledge. Single-star alternatives remain possible and, though perhaps less likely than a binary, will be far more interesting if true. The awkward part is that advocates often assert that some particular binary scenario (not always the same one!) has been confirmed and that the problem is essentially solved. In fact it is still fluid.

Let me illustrate with a mischievous parable, the twelfth recension of an Elephant Story. A committee of blind researchers take turns examining a pachyderm. One, feeling the beast's trunk, exclaims, "A snake! A muscular, flexible serpent." Whereupon the second expert, embracing a leg, interprets it as an extremely heavy, stiff snake. The blind man assigned to the tail finds a wriggling, light snake. The fourth researcher explores one of the elephant's tusks and pronounces it a *fossilized* snake. Having been assured that they all examined the same animal, they report: "We all agree. Our observations reveal this creature to be a snake."

– Well, the discussion of binary models for η Car has been a little like that. Good observers, finding valuable clues, have often forced them into the mold of one or another binary scenario, disregarding contradictions. For instance, when ground-based spectroscopy seemed to indicate orbital velocity variations (Damineli et al. 1997, 2000), some astronomers cited them as conclusive evidence. In fact the data were misleading (Davidson et al. 2000); but aside from that, the derived orbit orientation would have predicted X-ray behavior in 1997–1998 different from what actually happened. Another binary model was inspired by near-infrared photometry (Feast et al. 2001); the X-rays are cited in its support even though it appears to contradict some aspects of a colliding wind model. There's dialectic hysteresis, too; I fear that astronomers, having been convinced by observation A that theory B is correct, often remain convinced when they later hear that A was a mistake.

In my view the X-ray data remain the only good evidence for a binary system. We can easily imagine a "best bet" model with the following characteristics (Davidson 1999, 2000).

• Each sudden "event" in the 5.5-year cycle occurs near periastron in the orbit, when the companion star either enters or evokes dense gas near the primary.

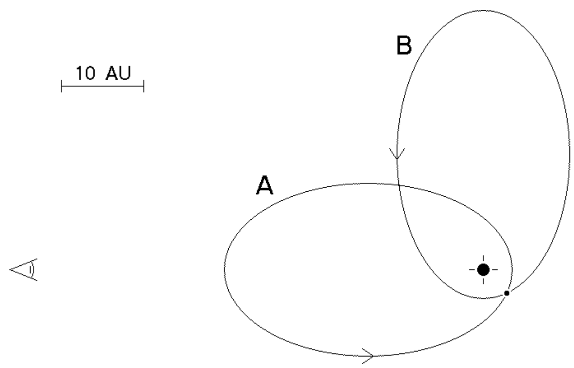

Figure 1. Orbit orientation makes a big difference for X-ray behavior during a periastron event. Here our viewpoint is at the left of the figure (although we're not in the orbital plane). Most authors have assumed an orientation close to 'A', but 'B' seems more consistent with the 1997 observations.

This would seem consistent enough with our HST/STIS data and ground-based observations. The word "eclipse," though often used, is probably wrong or at least misleading.

• Why does the X-ray flux rise tremulously and then abruptly plummet, as observed in 1997? The gradual increase is familiar in colliding-wind theory: as the two stars approach each other the wind interface becomes denser, increasing the efficiency of radiative (as opposed to expansion) cooling. I've suggested that the sudden decline occurs when radiative cooling dominates enough to make the shock viciously unstable. As the surface corrugates or breaks up, most parts of it become quite oblique to the stellar wind, thus decreasing the maximum temperatures so the X-rays become too soft to observe through the increased amount of surrounding material.

• The orbital semimajor axis must be of the order of 15 to 20 AU, consistent with the 5.5-year period and the allowable mass range. In order to make each periastron event sudden and brief as observed, the orbit must be highly eccentric, say $\epsilon \sim 0.8$; so the periastron separation is 3 or 4 AU, perhaps 5 to 10 times the radius of the primary star.

• The orbit is oriented differently than most authors have assumed. Pittard et al. (1998), running a gasdynamic computer code, assumed that the ellipse is roughly aligned with our viewpoint (orbit 'A' in Fig. 1) as suggested by Damineli et al. (1997). But that would have produced a more or less time-symmetric X-ray event in 1997–98, unlike the observed rapid fall and gradual recovery. As I noted three years ago (Davidson 1999), the orbit orientation is really a free parameter best indicated by X-ray behavior; a roughly perpendicular arrangement like 'B' in Fig. 1 seems most promising. Kazunori Ishibashi has been working on this problem lately. (Modelers must also remember that the orbit is most likely tilted by perhaps 45° relative to our line of sight.)

• Based on luminosity, the primary mass exceeds 100 $M_{\odot}$; what about the secondary star? The best clues so far are in the X-rays. The high average X-ray temperature (Corcoran et al. 1998, 2000; Seward et al. 2001) indicates a remarkably fast wind, around 3000 km/s.[1] Such a high velocity implies a high surface gravity, i.e., a very hot secondary star. Therefore it must be a main sequence or a Wolf-Rayet star, either of which entails difficulties. We would probably have detected Wolf-Rayet emission lines in the visual-wavelength spectrum; a "moderate" main sequence object (say 30 $M_\odot$) wouldn't have the wind density required in calculations by Pittard et al. (1998); and a more extreme main sequence star (say 60 $M_\odot$) would have made the surrounding Homunculus a photoionized nebula, which it isn't. Suitable possibilities may exist, but we should not regard them as obvious.

Of course errors may lurk in the above account, and theorists can find useful amusement inventing different scenarios. For the nonce, though, it seems the best (or least surprising) provisional framework for discussion.

As noted above, I don't think that the binary hypothesis has been proven. The arguments against a single-star model are essentially conservative in nature: (1) a colliding-wind binary is a good obvious way to get thermal X-rays, (2) no single stars are known to produce X-rays with luminosities and temperatures like Eta's, and (3) no definite single-star mechanism has been adduced. However, (1) colliding winds are not the only way to make shock fronts, (2) η Car is known to have physical properties unlike any other well-observed star, and (3) practically no theoretical effort has been devoted to this question. Eta's surface is so unstable that it may well generate high-velocity streams with shocks against the slower gas; indeed a speculative analogy to stellar activity (seen in cooler stars) cannot be ruled out so close to the Eddington Limit, and a 5.5-year cycle seems conceivable (Davidson 1999, 2000). If something as novel as this really is happening, then it would be extremely embarrassing to miss it just because a binary system can show approximately similar behavior.

What role will Chandra play in this story? Its most obvious advantage here is spectral resolution. Even the ASCA data were rather sketchy; now, for the first time, enough emission lines can be separated to do real spectroscopy of the shock fronts, in the same manner as classical UV-to-near-IR spectroscopy of nebulae. A few hints recently appeared in a paper by Seward et al. (2001), who report early Chandra observations of η Car and mention several emission lines. Later, more detailed work by Corcoran et al. (2002) has begun to explore the temperature distribution (rather than just one characteristic value) indicated by the emission lines, as well as density diagnostics and chemical composition. Composition may prove highly pertinent for the binary question, since the hottest material should represent the companion star whose elemental abundances should differ from the primary. However, I can't be sure about this yet; the really dramatic differences should involve C, N, and O whose emission lines are at lower photon energies. I hope the heavier elements detected in the Chandra data will be helpful. The temperature distribution will surely place useful limits on models. In summary, Chandra spectroscopy is still in its early stages and I have described the binary-

[1] Lower velocities occasionally quoted in the past were based on the maximum temperature in a shock normal to the flow. But on average the X-ray flux is produced at lower temperatures, both because the gas is cooling and because most of the wind-wind collision surface is oblique to the flow. These facts fact raise the wind speed needed to get the observed X-ray spectrum.

or-not conundrum at some length above in order to suggest one interesting and important field of application.

Finally, concerning the central object, I certainly hope that Chandra will be able to get some data in mid-2003, when the next 5.5-year "event" is predicted to occur.

3. Mysterious cooler (?) shocks far from the star

As Figure 2 illustrates, the structure in the well-known Chandra image is much larger than the bipolar Homunculus Nebula. Visual-wavelength images long ago showed material far outside the Homunculus (Thackeray 1949; Walborn 1976; Walborn et al. 1978; Meaburn et al. 1993, 1996; Bohigas et al. 2000). The Homunculus originated mostly in the Great Eruption of the 1840s, and we are not quite certain whether the outer condensations were ejected at that time, or earlier. Thermal X-rays from those outer regions are, in general, much softer than those from near the central star (Seward et al. 1979; Seward & Chlebowski 1982; Chlebowski et al. 1984; and other refs. cited by Weis et al. 2001). Seward et al. (2001), reporting early Chandra observations, remark that almost all of the photons are below 2 keV.

Weis et al. (2001), comparing ROSAT and ASCA X-ray data to velocities seen in visual-wavelength emission lines, found a general correlation between X-ray flux and local velocities. At this meeting Weis et al. (2002a) describe Chandra results with much better spatial resolution. The situation is moderately strange because the visual-wavelength velocities span a considerable range and some of them are quite fast. The correlation involves X-ray photons which are softer than one might expect for the highest velocities, around 2000 km s^{-1}. Therefore, what is colliding with what? And why did the Great Eruption make a wide range of ejection speeds? (Particularly in view of the fact that the Homunculus boundary is well defined.)

Also unexplained is the morphology of the structure (Fig. 2), since its brightness distribution appears ring-like rather than shell-like. An irregular ring in the equatorial plane would make sense; but instead it seems to be oriented at some odd angle. Moreover, a relatively X-ray-vacant space, above the star in Fig. 2, coincides with the "northern jet" emanating from the Homunculus, and also with a relatively faint sector of the northwest Homunculus lobe.

In addition to emission lines of iron, silicon, etc., nitrogen can be measured around 700 eV in soft X-ray region. The CNO cycle makes this element particularly overabundant in η Car (Davidson & Humphreys 1997), but not necessarily in the wind of a hypothetical companion star which has not yet been mixed. Kerstin Weis is currently attempting to measure chemical abundances in Chandra data obtained by Corcoran's group (Weis et al. 2002b). As I understand her results so far, nitrogen is plainly overabundant, but a difficulty is that it provisionally appears *too* overabundant. We shall see!

Just as for the hotter shocks near the star, Chandra will be chiefly useful for providing real spectroscopic diagnostics of temperature and density, i.e., numerous emission lines. Corcoran and others have already obtained significant Chandra data, but the analysis and interpretation have scarcely begun. Re-

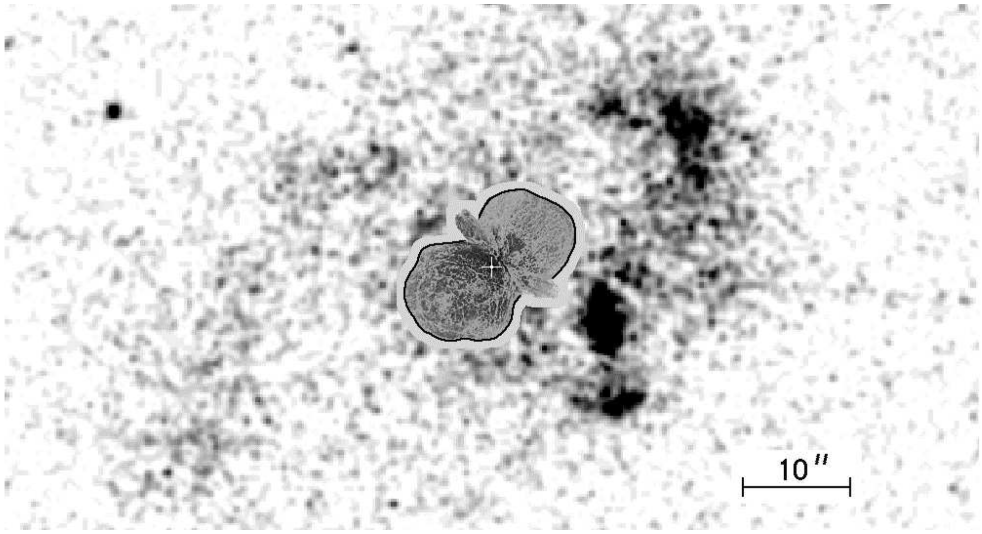

Figure 2. The outer regions here show 0.3–12 keV X-ray counts observed with Chandra (image prepared by K. Weis). However, a visual-wavelength HST/WFPC2 image of the Homunculus has been inserted in the middle in order to illustrate the difference in sizes. At the distance of η Car, 10 arcsec corresponds to a projected linear size of 0.11 pc $\approx 3.4 \times 10^{17}$ cm.

searchers in this field are making a transition from somewhat idealized models (even if they aren't labeled as such) to realistic representations of nature. This is obviously difficult and we may have to wait a few years before even the main points are truly settled.

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