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The relationship between two periodicities observed in Eta Carinae

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Abstract

An 85-day periodicity in the X-ray emission of Eta Carinae has been reported, while spectrocopic events recur with a period of 5.5 years (Corcoran et al., 1997 [Natur, 390, 587]; Damineli, 1996 [ApJ, 460, L49]). If the hot X-rays are produced by colliding winds in a 5.5-year binary system, then the interval of 85 days between X-ray flares is likely to represent pulsation or rotation of the primary star, or conceivably the orbit of a third object. *In a broad class of models, the 85-day recurrence interval is predicted to lengthen drastically in 1998 after the two stars pass periastron.* If this effect does occur, then it can give information about the nature of the system. If it does not, then specific types of models are ruled out. © 1998 Elsevier Science B.V.

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1. Introduction

Astronomers have long sought to identify periodicities in the behavior of η Carinae (e.g., Wolf, 1863; Feinstein & Marraco, 1974; Van Genderen et al., 1995). Recently, and somewhat surprisingly, distinct values of 5.5 years and 85 days have both emerged, each supported by reasonably definite evidence (Damineli, 1996; Corcoran et al., 1997). The purpose of this paper is to note that in the most ‘‘obvious’’ types of model that interpret 5.5 years as an orbital period, the 85-day apparent X-ray period should not continue in 1998.

The 5.5-year period was proposed by Damineli (1996), who noticed it as a recurrence interval between spectroscopic events occasionally observed during the past 50 years. Damineli et al. (1997) later reported systematic wavelength fluctuations of certain emission lines, consistent with the Doppler shifts expected in a 5.5-year binary star orbit. The most promising orbit based on their data has been described by Davidson (1997): its eccentricity is $e=0.80$, and the periastron separation, though not

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directly derivable from the data, is most likely about 3 or 4 a.u. Conjunction, periastron passage, and the next ''spectroscopic event'' are all expected to occur during the first few weeks of 1998. This orbit is sketched in Fig. 1. **(See also the ''movie'' version of this figure.)**[4] X-ray observations seem consistent with an orbital model for the 5.5-year periodicity. If η Car is a binary system, then its hot thermal X-rays (Corcoran et al., 1998) may originate in a colliding-wind zone, the shocked interface between stellar winds of the two very massive component stars. In such a model the column density along the line of sight through the stellar wind, indicated by absorption in the X-ray spectrum, should increase as the stars approach conjunction and periastron. The X-ray flux should also increase until a time when absorption has become quite serious. As this is written (1997, early December), results of X-ray monitoring with the RXTE satellite have been fairly consistent with the predictions (Corcoran et al., in preparation). Therefore a 5.5-year binary orbit model now seems appealing, though single-star models are still possible (Davidson, 1997).

However, the RXTE monitoring has also revealed fluctuations in the X-ray brightness, and peaks or ''flares'' have occurred at an average interval of 84.8±1.2 days (Corcoran et al., 1997). Fig. 2 is a simplified plot of the data. Some of the peaks occurred a few days before or after a strict 84.8-day schedule, and there were other intermediate events, usually smaller; but the basic periodicity is very credible because, after being noticed in 1997 April, it accurately *predicted* the times of two major peaks in the sequence. (Corcoran et al. mentioned only the predicted 1997 July event, but another flare also occurred on schedule near the end of September. These were events 6 and 7 in Fig. 2.) During the last half of 1997 the behavior has become more complex, with intermediate peaks growing more prominent.

The situation is evidently peculiar. If the 5.5-year periodicity were unknown, then most astronomers would probably interpret the 85-day X-ray effect as evidence for a close binary system (see Section 5 of

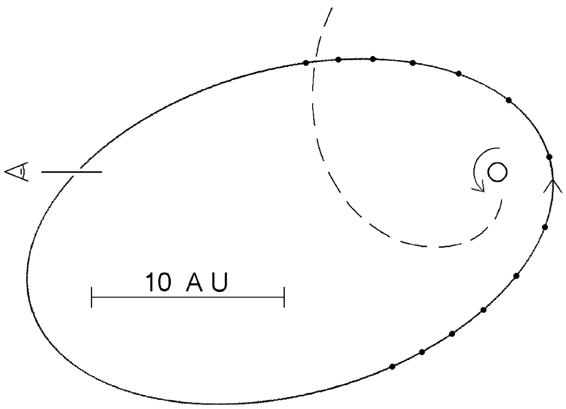

Fig. 1. Plan view of one proposed 5.5-year orbit for η Car. (A ''movie'' version can be seen in the electronic version of this article (http://www.elsevier.nl/locate/newast).) This is the model described by Davidson (1997), with eccentricity $e=0.8$ and periastron passage near 1998 January 30. The ellipse represents the approximate path of the hypothetical X-ray emission region; this is somewhat smaller than the secondary star's orbit. Positions at 60-day intervals are marked. Our viewpoint, projected onto the orbit plane, is to the left of the figure. A dashed line represents the approximate shape of the spiral pattern for the ''rotation'' sample model described in Section 2 of the text.

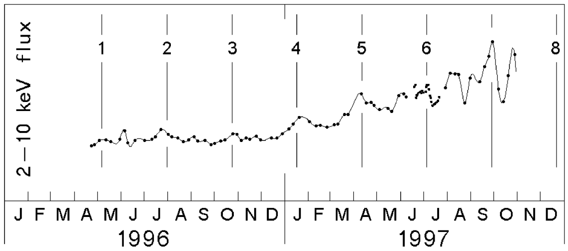

Fig. 2. Approximate plot of the net 2–10 keV X-ray flux of η Car observed with the RXTE satellite between 1996 April and 1997 November; see Corcoran et al. (1997). No corrections for intervening extinction have been made. The numbered vertical lines indicate 84.8-day intervals, the ''constant period'' model in Table 1; a peak in the data occurred close to each of these times. It is possible that some intermediate peaks also tend to recur. The interval between RXTE observations was smaller during event number 6 because this event was given special attention, having been predicted on the basis of the suspected 85-day periodicity.

[4] http://ast1.spa.umn.edu/bish/reschcs.html

Davidson & Humphreys (1997), and references cited therein). What does the shorter period represent, and are the two different periods likely to interact? These questions are discussed in Section 2 below, for models in which 5.5 years is an orbital period. In most such cases, we find, the steadiness of the shorter period has been largely fortuitous, and in early 1998 it should become dramatically longer than 85 days. If this change does not occur, then a class of likely-seeming models will be ruled out.

2. The role of the 85-day interval in a long-period binary model

The main point of our discussion here is that the 85-day X-ray flare interval need not be equal to the period of the underlying phenomenon that causes it. In the most obvious type of model (see below), recurrent ‘‘disturbances’’ move outward in the primary star’s wind, and an X-ray flare occurs when each disturbance encounters the shocked interface between the two stellar winds. But this localized site of X-ray emission (the wind-collision zone) moves along an elliptical path related to the 5.5-year binary orbit; therefore the interval between X-ray flare events is modified by a quasi-Doppler effect, involving the relative velocities of the orbital motion and the primary star’s wind. For instance, when the X-ray emission region is approaching the primary, then the time between flares is less than the interval at which disturbances are created in the primary star’s wind. This effect obviously varies during the 5.5-year orbital period, but it also depends on whether the underlying recurrence period represents stellar rotation, pulsation, etc., as noted below.

Proposed 5.5-year orbits require high eccentricities to explain the brief spectroscopic events. They generally predict a periastron passage near the beginning of 1998. For the purpose of discussion, we adopt a specific orbit described by Davidson (1997) and shown in Fig. 1. The eccentricity is $e = 0.80$; the longitude angle between the periastron radius vector and the projection of our line of sight onto the orbit plane is 16°; periastron passage occurs at Julian Day 2450843 (1998 Jan 30). Conjunction, when the secondary star passes beyond the primary as seen from our point of view, occurs a few days before periastron. By ‘‘primary’’ we mean the stellar component whose bright emission lines indicate a dense, roughly 500 km s^{-1} wind with a very high mass-loss rate. The hypothetical secondary star has never been detected but is presumably hotter, with a faster, much less dense wind and a relatively normal mass-loss rate; for the reasoning behind these assumptions see Davidson & Humphreys (1997), Damineli et al. (1997), Davidson (1997), and Corcoran et al. (1997). With plausible order-of-magnitude values of ρv^2 in the two winds, one finds that their collision interface is located close to the secondary star, perhaps about 20% of the distance from the secondary to the primary. The X-ray production region therefore follows a nearly elliptical path relative to the primary star; let us assume that at periastron the X-ray zone is located 2.8 a.u. (4.2×10^{13} cm) from the center of the primary. For simplicity we regard the center of the primary star as a fixed point of reference, neglecting the small effects of its orbital acceleration.

The disturbances that cause recurrent X-ray flares may originate in or near either the primary star or the secondary, or conceivably in the X-ray emission region itself. The primary star must be regarded as the first choice among these possibilities, because it is notoriously peculiar and unstable and because its physical parameters seem well-adapted to a timescale of the order of 85 days (Corcoran et al., 1997; Davidson & Humphreys, 1997). Therefore, as a working hypothesis, suppose that the primary star is the basic site of the periodicity. (The timing effects described below may help to test this assumption.) The first and simplest case to consider is a *pulsation* model, wherein a series of spherically symmetric disturbances move outward in the primary wind. Their precise nature is not critical here; it is sufficient to imagine them as density pulses or waves. A second type of model involves stellar *rotation;* for instance, if a particular region on the rotating star has a locally enhanced mass loss rate, then a spiral disturbance wave is formed in the wind. Other, more complex possibilities, such as non-radial pulsation or a close binary companion (making a triple system), would produce effects comparable to either the pulsation or the rotation case.

To illustrate the likely period-change effect, we have calculated two simple examples, one with pulsation and the other with rotation. In each case we assume that the outward velocity of a disturbance wave is $\partial r/\partial t = 500\,\mathrm{km\,s^{-1}}$. This may represent either the wind speed or radial motion of a perturbation in the wind. We suppose that an X-ray flare event occurs whenever one of the periodic disturbances reaches the location of the colliding-wind region, which follows the elliptical path described above. (The relative orbital speed is between 100 and $250\,\mathrm{km\,s^{-1}}$ at times of interest.) In our sample calculations, the intrinsic period P_0 for disturbances in the wind – i.e., either the pulsation period or the rotation period of the primary star – has been adjusted so that the third and sixth flares in the calculated series coincide with the times of X-ray peaks observed at about 1996 October 24 and 1997 July 5; this constraint gives $P_0 = 93.1$ and 91.4 days for the pulsation and rotation cases respectively. (As noted above, the 85-day flare interval was less than P_0 during 1996–1997 because the X-ray production region was then hypothetically moving inward, against the flow of disturbances in the primary's wind.) In the rotation model the star is assumed to rotate in the same direction as the orbital motion, with a rotation axis approximately perpendicular to the orbit plane. (The former assumption seems quite likely but the latter is more questionable, merely a matter of convenience for our calculations.) We neglect the angular momentum in the wind, a fair approximation for distances of interest. The shape of a resulting spiral disturbance is shown in Fig. 1 (cf. Mullan, 1984, 1986).

The times of X-ray flares ''predicted'' by these two models are listed in Table 1. For events 1–7 they are indistinguishable from the constant 84.8-day period mentioned by Corcoran et al. (1997). In the pulsation model the December 1997 event is predicted to occur noticeably earlier than in the constant-period case. More importantly, *both models predict very large, obvious delays in 1998 compared*

Table 1
Times of X-ray flares: modified Julian Days and calendar dates

Event number	Observed	Constant-interval model	Pulsation model	Rotation model
1	50211	50210	50204	50205
	96.05.08	96.05.07	96.05.01	96.05.02
2	50286	50295	50293	50293
	96.07.22	96.07.31	96.07.29	96.07.29
3	50380	50380	50380	50380
	96.10.24	96.10.24	96.10.24	96.10.24
4	50467	50464	50466	50466
	97.01.19	97.01.16	97.01.18	97.01.18
5	50548	50549	50551	50550
	97.04.10	97.04.11	97.04.13	97.04.12
6	50634	50634	50634	50634
	97.07.05	97.07.05	97.07.05	97.07.05
7	50719	50719	50715	50717
	97.09.28	97.09.28	97.09.24	97.09.26
8	–	50803	50793	50803
		97.12.21	97.12.11	97.12.21
9	–	50888	50885	50960
		98.03.16	98.03.13	98.05.27
10	–	50973	50999	51073
		98.06.09	98.07.05	98.09.17

to the constant-period schedule. In the rotation model the first event of 1998, event 9 in Table 1, occurs more than 2 months late! Event 10 is nearly a month late even in the pulsation model. In either type of model *the 85-day flare recurrence interval seen in 1997 should not continue in 1998.*

Of course these predictions depend on the assumed parameters, but models with plausibly different wind speeds, etc., produce qualitatively similar effects. In a pulsation model the change in the flare recurrence interval is simply a Doppler effect as noted earlier; before periastron the X-ray production zone moves inward against the wind, but after periastron the two velocities are both outward. Fig. 1 shows what happens in a rotation model. The orbital motion and the rotation of the spiral wind disturbance are both counter-clockwise in this sketch. Before periastron the spiral pattern hits the X-ray emission region approximately broadside to the orbit, minimizing the quasi-Doppler effect. But after periastron the spiral must chase the orbital movement from behind, dramatically lengthening the time that it takes to catch the wind-collision zone.

The flare events numbered 8 and 9 in Table 1 may be difficult to identify, since recent observations show that the X-ray behavior is complex near periastron (Fig. 2). But after March 1998, we hope, it should not be very difficult to determine whether or not the 85-day period seen in 1997 has ceased to exist as the general type of model assumed here predicts.

3. Implications

If a series of X-ray flare events can be timed in 1998 and if they are delayed in a manner resembling the last two columns of Table 1, then their intervals will give physical information about the situation. These intervals should indicate whether a pulsation or a rotation model (or something else) is satisfactory, and the timing will constrain the physical parameters. Perhaps the most intuitively appealing type of model is the rotation case, because a rotation period of about 90 days seems well matched to the expected characteristics of the primary star (Davidson & Humphreys, 1997); this model has the largest delays in Table 1. Mullan (1984), (1986) has described a somewhat more complex scenario for spiral disturbances in a rotating wind. Non-radial pulsations or tidal effects due to a short-period companion object would also induce effects of roughly the same magnitude as in our two idealized cases.

What shall we conclude if X-ray flares continue to occur with an 85-day period? Three assumptions in Section 2 were essential for the predicted drastic lengthening of this recurrence interval: (1) that Eta Carinae is a 5.5-year binary system, (2) that the X-rays are produced by colliding winds, and (3) that the cause of the 85-day period originates at the primary star. Quantitative details regarding (1), such as the orbital eccentricity and the time of periastron passage, are not basic assumptions in the same sense, because major changes in them would largely invalidate the quantitative rationale for the binary model. Assumption (2) seems so natural in connection with (1) that it, too, may almost be regarded as part of (1). Therefore assumptions (1) and (3) are most critical. If the 85-day period persists well into 1998, this will indicate either that the binary hypothesis is incorrect, or that the disturbances ultimately responsible for the X-ray flares do not originate at the primary star.

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