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SIGNATURES OF THE 3-D WIND-WIND COLLISION CAVITY IN η CAR

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RESUMEN

Discutimos esfuerzos recientes al aplicar simulaciones de hidrodinámica de partícula alisada (SPH) para modelar la colisión binaria de vientos en η Carinae, centrándonos en el efecto del agujero del borde, en donde el viento rápido de la estrella secundaria caliente talla una cavidad en el denso viento primario, permitiendo aumentar el escape de la radiación de las capas más calientes/profundas de la fotósfera extendida de la primaria. Este modelo puede proporcionar pistas de cómo/dónde la luz UV está escapando del sistema, la iluminación del material distante en varias direcciones y los parámetros/orientación de la órbita binaria. También se discute el papel de observaciones interferométricas para probar los modelos.

ABSTRACT

We discuss recent efforts to apply 3-D Smoothed Particle Hydrodynamics (SPH) simulations to model the binary wind collision in η Carinae, focusing on the Bore Hole effect, wherein the fast wind from the hot secondary star carves a cavity in the dense primary wind, allowing increased escape of radiation from the hotter/deeper layers of the primary's extended photosphere. This model may provide clues on how/where UV light is escaping the system, the illumination of distant material in various directions, and the parameters/orientation of the binary orbit. The role of interferometric observations in testing the models is also discussed.

Key Words: hydrodynamics — stars: atmospheres — stars: individual (**η** Carinae) — stars: winds, outflows

1. BINARITY AND THE BORE HOLE EFFECT

The 5.54 year periodicity seen in the He I λ10830 line, as well as the infrared and X-ray fluxes, suggests η Car is a binary system (Whitelock et al. 1994; Corcoran 2005; Damineli et al. 2008). Recently, Okazaki et al. (2008) modeled the *RXTE* X-ray light curve of η Car using a 3-D SPH simulation of the binary wind-wind collision. A key point of Okazaki et al. (2008) is that the fast wind of the secondary star carves a cavity in the dense wind of the primary, allowing X-rays that would otherwise be absorbed to escape into our line-of-sight. If the primary wind is sufficiently optically thick in the optical or IR waveband, then the low-density secondary wind may likewise carve or "bore" a cavity or "hole" in the associated wind photosphere, allowing increased escape of radiation from the hotter/deeper layers. Such a "bore hole" should depend on (1) how close the cavity carved by the secondary gets to the primary and (2) the apparent size of the primary photosphere. If at some point (2) > (1), there is a bore hole.

The minimum distance from the primary to the head of the shock cone formed by the two colliding winds occurs at periastron and is given by $R_{\rm min} \approx a(1-e)/(1+1/\sqrt{\eta}) \approx 1$ AU, where e is the orbital eccentricity (0.9), a is the orbital semi-major axis length (15.4 AU), and η is the momentum ratio of the two winds (≈ 4.2, Okazaki et al. 2008). A simple way to define the apparent size of the primary wind photosphere is to use the radial photospheric radius $R_{\rm phot}$ at which the optical depth $\tau = 1$. This has the form $R_{\rm phot} = \kappa \dot{M}/4\pi v$, where κ is the opacity ([cm^2 g^{-1}], assumed constant), $\dot{M}$ is the mass loss rate of the primary (2.5×10^{-4} $M_\odot$ yr^{-1}), and v is the terminal speed of the primary's wind (500 km s^{-1}). A bore hole effect occurs whenever $R_{\rm phot} > R_{\rm min}$. Even for low values of κ of order unity, this is the case. Increasing κ (or $\dot{M}$) results in a larger primary star and a bore hole at phases other than periastron.

To investigate the bore hole effect, we use the 3-D SPH simulation of Okazaki et al. (2008), combined with a modified version of the visualization program SPLASH (Price 2007), to generate renderings of the surface brightness of the primary star for various values of κ from 0.34–80 cm^2 g^{-1} as a function of orbital phase for a binary system orientation whose observer's line-of-sight is the same as the best-fit from Okazaki et al. (2008), i.e., inclined 45° and rotated 27° prograde relative to the orbital semi-major axis (see Figure 1). Our models reveal three possible bore hole scenarios. The first is the "no cavity" scenario that occurs for low values of κ (0.34 cm^2 g^{-1}) where the primary's photospheric

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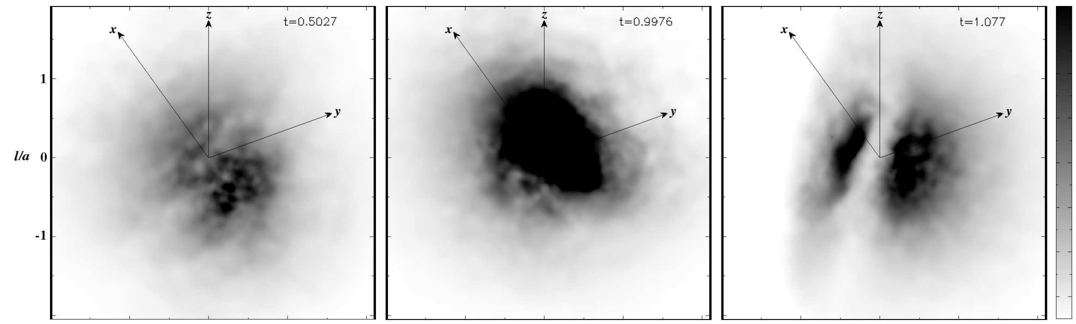

Fig. 1. 3-D renderings of the bore hole effect for $\kappa = 10$ cm^2 g^{-1} at orbital phases of apastron (left), 5 days before periastron (middle), and 155 days after periastron (right). The x and y axes are the major and minor axes, respectively, and z is the orbital axis $\perp$ to the orbital plane. Lengths are in semi-major axes and grayscale indicates surface brightness.

radius is so small the shock cone head never penetrates and there is never a bore hole. The second is the "moderate cavity" scenario for intermediate values of κ (2.5–10 cm^2 g^{-1}). In this case, when the secondary is at or near apastron, the shock cone is too far from the primary photosphere and there is no bore hole (Figure 1, left panel). But, as the secondary moves closer to the primary during its orbit, the shock cone gradually penetrates into the primary, creating a bore hole effect that increases up until periastron passage (Figure 1, middle), at which point the secondary quickly wraps around the back side of the primary and the bore hole briefly vanishes as it faces away from the observer. After periastron, the bore hole reappears on the opposite side of the primary (Figure 1, right panel) and then slowly fades as the secondary moves out back towards apastron. Finally, there is the "large cavity" scenario that occurs for large values of κ (≥ 20 cm^2 g^{-1}) where the primary photosphere is so large the shock cone penetrates at all orbital phases creating a large bore hole for the entire orbit (but briefly vanishing at periastron).

2. TESTING THE BORE HOLE MODEL

Determining whether a bore hole effect is detectable with current interferometers requires a form for the photospheric radius that depends on wavelength λ. The above analysis however assumes that the opacity κ is a constant. In reality, κ is a function of wavelength λ, density ρ, and temperature T. Assuming free-free absorption, $\kappa \sim (1.34 \times 10^{56})\rho(\lambda/c)^3 T^{-1/2}$ cm^2 g^{-1}. For a specific T, this can be written as $\kappa \equiv \alpha_0(\lambda/c)^3\rho$, where α_0 is a constant. Solving for the new photospheric radius yields $R_{\rm ff} \equiv (\alpha_0/3)^{1/3}(\dot{M}/4\pi v)^{2/3}(\lambda/c)$, which scales linearly with wavelength. If $v = 500$ km s^{-1}, $\dot{M} = 2.5 \times 10^{-4}\ M_\odot$ yr^{-1}, and $T = 10,000$ K, then $R_{\rm ff} = 0.29$, 0.73, and 1.46 AU at $\lambda = 2$, 5, and 10 μm, respectively. Therefore, the bore hole effect should be more prominent at longer wavelengths and detectable with modern interferometers.

Unfortunately, there are currently no interferometric observations of η Car's wind during periastron passage. Such observations would represent a key test of the bore hole model. Improved modeling is also needed if we are to better constrain the stellar, wind, and orbital parameters of the η Car system. Two natural improvements are to use a 3-D prolate wind SPH simulation and an improved treatment of the opacity κ that varies with ρ, T, and λ.

DISCUSSION

T. Szeifert: *If you take the current binary period of η Car, is it possible to scale back to 1840 to know if the great outburst occurred at periastron?* — η Car's binary period is very well known, to an accuracy of $\pm$ 2 days (Damineli et al. 2008). Unfortunately, the date of the great eruption is not, so I do not think we can.

D. Gies: *Could you comment on the orientation of the model semi-major axis on the sky?* — We assume an observer's line-of-sight that is the same as the best-fit from Okazaki et al. (2008). However, their models are degenerate with respect to the absolute orientation of the binary orbit. To break this degeneracy, we make the usual assumption that the orbital axis is aligned with the Homunculus symmetry axis. Thus, the projection of the semi-major axis on the sky points slightly NNW.

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