Mass Accretion in the Binary Star η Carinae

Amit Kashi and Noam Soker, Technion – Israel Institute of Technology, Haifa, Israel
kashia@physics.technion.ac.il

Quick Summary

- **We present the *accretion model* for the behavior of the supermassive binary system η Car close to periastron passages.**
- **The model assumes that for 10 weeks near periastron the secondary star accretes mass from the slow dense wind blown by the primary star.**
- **This Assumption is examined theoretically.**
- **The main findings are:**
  1. **Accretion is indeed likely to take place, with an accretion rate in the range $0.4\text{–}3.3\times10^{-6} M_\odot$**
  2. **This mass possesses enough angular momentum to form a thick disk, or a belt, around the secondary.**
  3. **The viscous time is too long for the establishment of equilibrium, and the belt must be dissipated as its mass is being blown in the reestablished secondary wind.**
  4. **This processes requires about half a year, which we identify with the recovery phase of η Car from the spectroscopic event.**

Background

η Car is a massive, highly eccentric ($e \simeq 0.9 – 0.95$) binary system with some basic undetermined parameters and open questions. Its 5.54 year periodicity is observed from the radio, through the IR, visible and to the X-ray. The X-ray cycle (Fig 1) presents a deep minimum lasting ~70 days and occurring more or less simultaneously with the spectroscopic event, defined by the fading, or even disappearance, of high-ionization emission lines. Afterwards a slow and gradual recovery is observed. The X-ray minima and the spectroscopic events are assumed to occur near periastron passages. The winds blown by both stars creates a colliding wind cone.

In a series of papers we proposed that the fast variations during the spectroscopic event are caused by the collapse of the winds interaction region onto the secondary star. The secondary then accretes mass for ~10 weeks, and its fast wind is blown only along the polar direction. One of the results is that the secondary wind is very weak, explaining the fast variation and minimum of the X-ray emission. The accretion phase can explain also the fast changes of some spectral lines, and the IR emission.

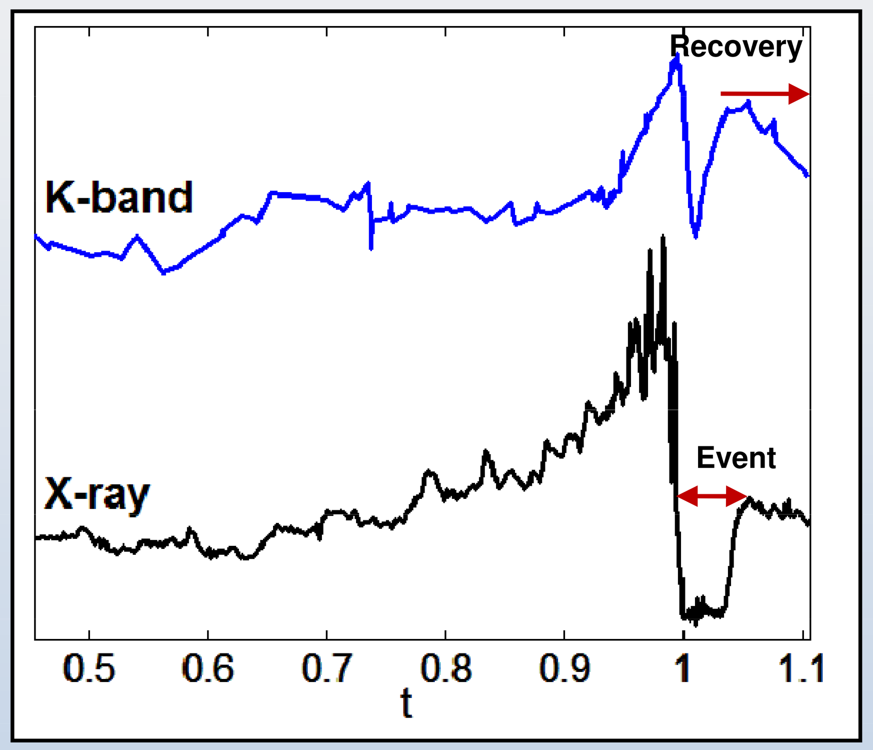


Fig. 1 – The K- band (Whitelock et al. 2004) and X-ray (Corcoran et al. 2005) variability along the binary orbit. The X-ray minimum begins at phase 1 (29 June ,2003).
The spectroscopic event and recovery phase are marked on the figure.

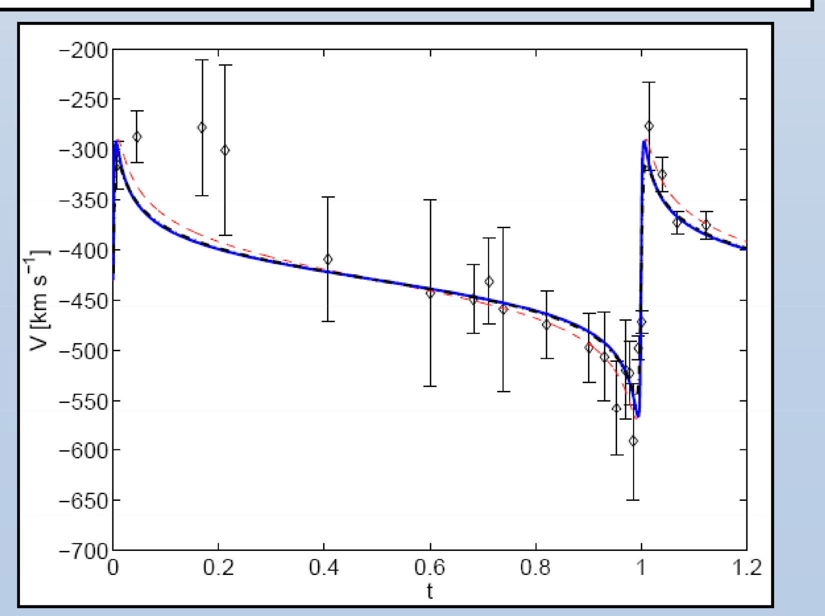


Fig. 2 – The Doppler shift of the He I lines. In our model the source of the He I lines is the acceleration zone of the secondary`s wind. The inclination angle is 45°, and the secondary is oriented toward us at periastron. Diamonds and errorbars: He I lines data from Nielsen et al. (2007). Red thin line: A mathematical fit made by Nielsen et al. (2007). Blue line:
Our Doppler shift model for eccentricity of e = 0.90, Black dot-dashed line for e = 0.93.

Accretion Time Scales

While the orbital period is P = 5.54 years, the duration of the strong interaction near periastron passage is much shorter. We evaluate the periastron passage time:

$$t_{\rm pp} = \frac{2R_1}{v_{\rm orb2,per}} \simeq 6\left(\frac{R_1}{180R_\odot}\right)\left(\frac{v_{\rm 2,per}}{470{\rm kms^{-1}}}\right)^{-1} {\rm days}$$

The Keplerian period on the secondary equator is:

$$t_{\rm Kep} = 1.89\left(\frac{R_2}{20R_\odot}\right)^{3/2}\left(\frac{M_2}{30M_\odot}\right)^{-1/2} {\rm days}$$

Despite the fact that the Keplerian period is much shorter than t_{pp} , a geometrically thin accretion disk cannot be formed, since the viscosity time scale in the disk is very long. In the α-disk model where the viscosity is $\nu=\alpha C_s H$, where C_s is the sound speed and H(R) the disk height, the viscosity time scale is given by:

$$t_{\rm visc} = \frac{R^2}{\nu} = \frac{R^2}{\alpha C_s H} \simeq t_{\rm Kep}\left(\frac{R}{H}\right)^2 \frac{1}{2\pi\alpha} = 30\left(\frac{R}{10H}\right)^2\left(\frac{R_2}{20R_\odot}\right)^{3/2}\left(\frac{M_2}{30M_\odot}\right)^{-1/2}\frac{1}{\alpha}{\rm days}$$

where the equation was scaled near the secondary equator, where the viscosity time scale is the shortest. Since we expect α < 1, the viscosity time is not short enough to make a geometrically thin disk during the accretion time. However, the viscosity is not completely negligible and the accreted mass will form a thick accretion disk attached to the secondary–a *belt.*
The relation among the timescales is such that:

$$t_{\rm Kep} < t_{\rm pp} \ll t_{\rm acc} \sim t_{\rm visc} \ll P$$

During the strong interaction phase, lasting ~10 days, when the accretion rate is very high the accretion belt will be far from equilibrium. During the entire accretion phase, lasting ~10 weeks, a thick accretion disk might be formed.

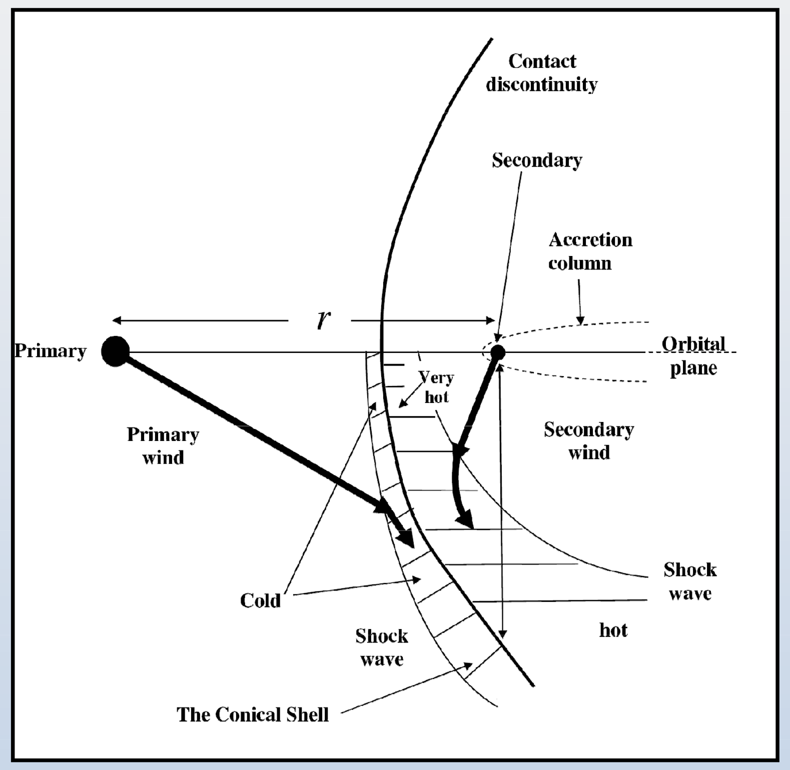


Fig. 3 – A schematic drawing of the collision region of the two stellar winds. There is an axial symmetry around the line through the two stars. The two thick lines represent winds' stream lines. The two shock waves are drawn only in the lower half. The post-shock regions of the two winds are hatched. The shocked primary wind region is referred to as the 'conical shell'. The dashed line shows the accretion column which exists, according to the accretion model, only for ~70 days during the accretion period which corresponds to the X-ray minimum and the spectroscopic event.

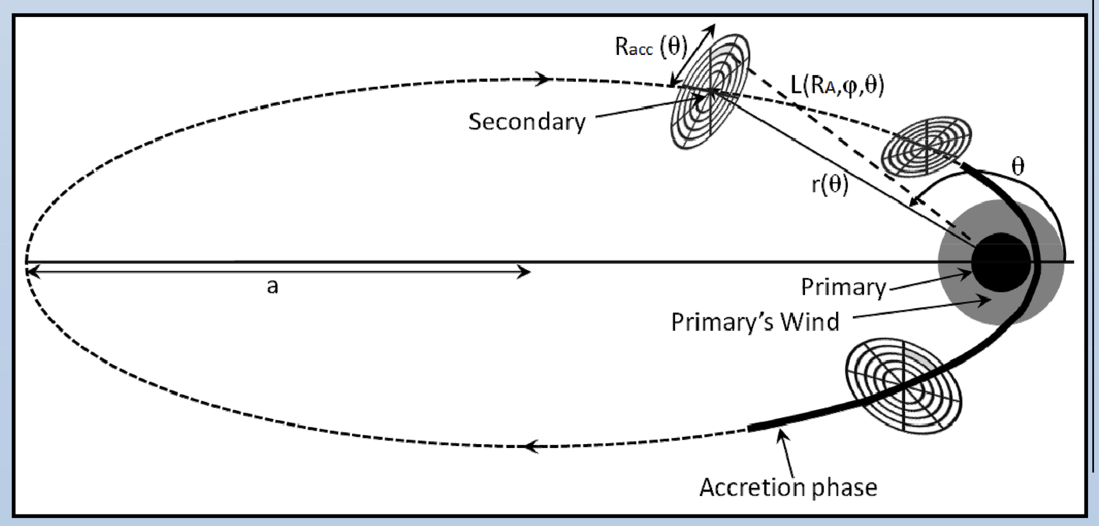


Fig. 4 – A schematic drawing of the geometry of the orbit and the accretion cross section used in the calculations. The gray donut around the primary represents the radius where the primary's wind accelerated to 100 km s^{-1}, for wind profile with β = 3. The orbit and binary star are drawn for scale for the case e = 0.93 and R1 = $180R_\odot$.

Modeling the Accretion

The secondary accretes mass from the primary's dense wind. The effective accretion radius of the secondary depends on several parameters, in particular on the orbital separation r(θ). Since the accretion radius is very close to the primary, the primary's wind acceleration zone is taken into account as a β-model with two extreme values:1 and 3.

$$v_1(r) = v_{1,\infty}\left(1-\frac{R_1}{r}\right)^\beta$$

We consider the two limits: RLOF, taking the accretion radius as the Roche lobe equivalent radius, $R_{RL}(\theta)$, and Bondi-Hoyle-Lyttleton (BHL) accretion, where:

$$R_{BHL}(\theta) = \frac{2GM_2}{v^2_{\rm wind1}}\ ;\ v^2_{\rm wind1} = v^2_{2,\theta} + (v_1 - v_{2,r})^2$$

Full RLOF-like accretion cannot occur because the primary spin and orbital motion are not synchronized near periastron passage. Therefore, for ~10 days very close to periastron passage, the accretion process will be an hybrid of the BHL and the RLOF mass transfer processes. At the end of the accretion phase the accretion will be more of the BHL type.
To calculate the dependence of the primary's wind density on the azimuth angle and on the distance from the secondary, we slice the cross section into differential arcs. The accreted mass from each arc is calculated separately according to the density at that point, and it is added to the accreted mass.
Over all, the total accreted mass for the cases studied here is $0.4\text{–}3.3\times10^{-6}M_\odot$, with average value of $M_{acc} \sim 2\times10^{-6}M_\odot$.

Fig. 5 – The accretion rate as a function of the time near periastron passage obtained using Bondi-Hoyle-Lyttleton accretion radius (upper panel), and Roche lobe (RL) as accretion radius (lower panel). At close separation the wind's density is high. This accounts for the wide maximum in mass accretion rate around t = 0. Very close to periastron the relative velocity between the wind and the accreting star is large. As a result of that the accretion radius is small, and mass accretion low. This accounts for the local minimum at t = 0 in the three lower plots (point a′). For the case of very slow wind and close periastron (e,β) = (0.93,3), the higher density effect dominates at all times, and there is no local minimum at t = 0 (point a). As the two stars recede each other the relative velocity between the wind and accreting star reach a minimum, and therefore the accretion radius reaches a maximum (maximum at point b).

η Car – Binary Parameters

Primary - LBV	Secondary - O5 / WR
$M_1 \simeq 120{\rm M}_\odot$	$M_2 \simeq 30{\rm M}_\odot$
$R_1 \simeq 180{\rm R}_\odot$	$R_2 \simeq 20{\rm R}_\odot$
$L_1 \simeq 5\cdot10^6{\rm L}_\odot$	$L_2 \simeq 9\cdot10^5{\rm L}_\odot$
$T_1 \simeq 20{,}000{\rm K}$	$T_2 \simeq 36{,}000-40{,}000{\rm K}$
$\dot M_1 \simeq 3\cdot10^{-4}{\rm M}_\odot{\rm yr}^{-1}$	$\dot M_2 \simeq 10^{-5}{\rm M}_\odot{\rm yr}^{-1}$
$v_{1,\infty} \simeq 500$ km s^{-1}	$v_{2,\infty} \simeq 3000$ km s^{-1}
$a \simeq 16.6{\rm AU}$	$P = 2022.7 \pm 1.3$ d
$e = 0.9 - 0.95$	$i = 41^\circ - 53^\circ$
Periastron longitude $\omega \simeq 90^\circ$ (in dabate...)	

Removing the Belt

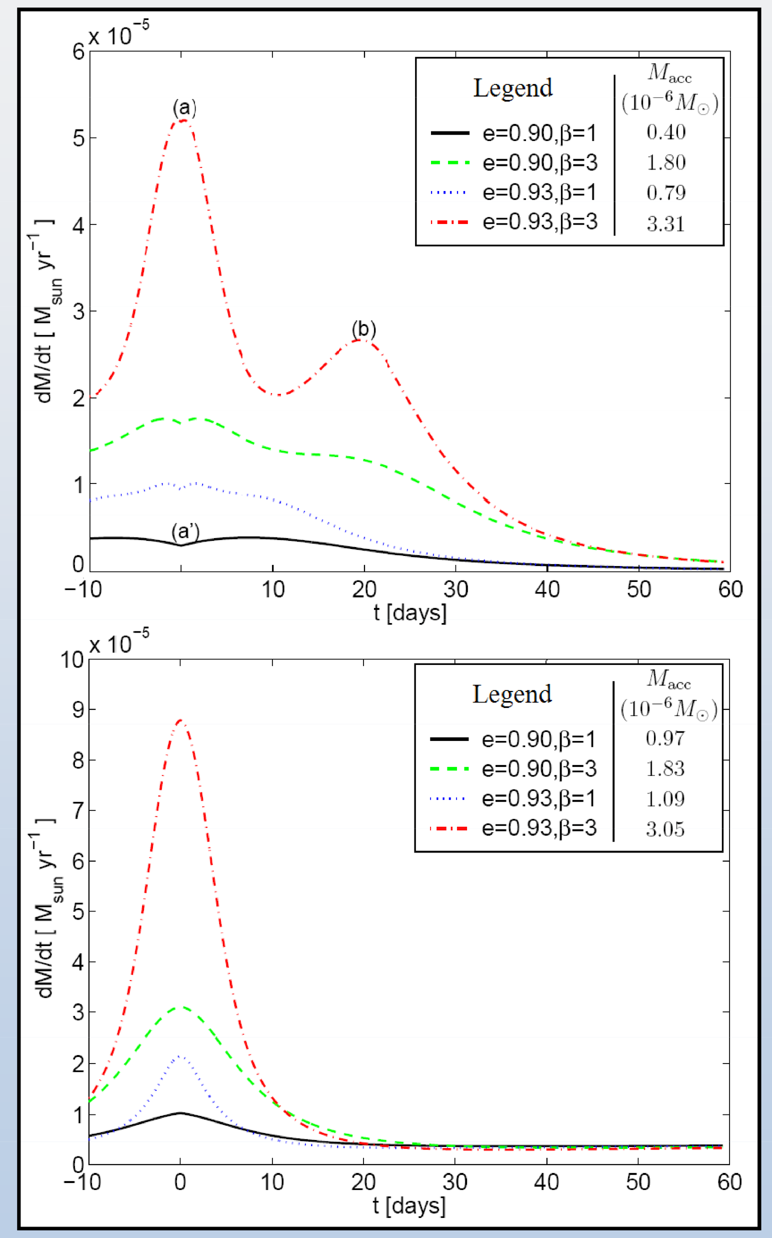
Because of the long viscosity time and the high mass loss rate, this belt is destroyed mainly by mass loss rather than accretion on the secondary. The belt covers a fraction δ of the secondary's stellar surface (for example, if this belt extends from the equator to latitudes ±30°, then δ = 0.5). We assume that the mass loss rate per unit solid angle from the belt is as that from the secondary. The belt will be blown away during a time:

$$t_{\rm belt} = \frac{M_{\rm acc}}{\delta \dot M_2} \simeq 5\left(\frac{M_{\rm acc}}{2\times10^{-6}M_\odot}\right)\left(\frac{\dot M_2}{10^{-5}M_\odot{\rm yr}^{-1}}\right)^{-1}\left(\frac{\delta}{0.5}\right)^{-1} {\rm month}$$

If the mass loss process starts ~60 days after the event starts, then the recovery ends ~7 months after the event starts. We identify this duration with the recovery phase of η Car from the spectroscopic event.

Possible Implications

The accretion from the equatorial region leaves the polar directions clear for the secondary's weaker wind, or for a polar outflow blown by the accretion disk. The visible and UV bands are obscured, but hard X-ray emission might be detected. In particular, such a polar outflow might be strong when the fast secondary's wind rebuilds itself.
The accretion disk, or belt, will survive for weeks to months after the accretion ends. During that time the accreting star will illuminate and ionize the polar directions much more than in the equatorial plane.



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