Interactions in Massive Colliding Wind Binaries

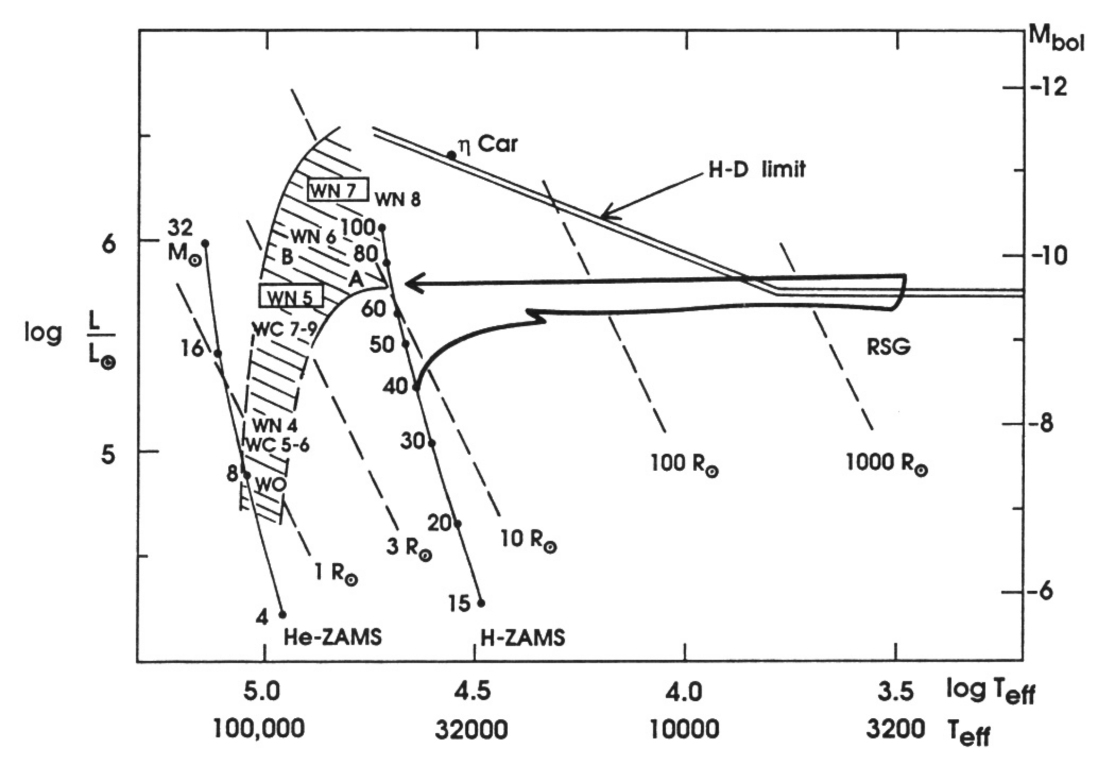
Michael F. Corcoran (CRESST/USRA/NASA-GSFC)

With lots of help from: K. Hamaguchi (CRESST/UMBC/NASA-GSFC), T. Gull (NASA-GSFC), S. P. Owocki, C. M. P. Russell (U. Delaware), A. M. T Pollock (ESA), J. M. Pittard (U. Leeds), E. R. Parkin (ANU), A. F. J. Moffat (U. Montreal), Atsuo Okazaki (Hokkai-Gakuen University)... and of course RHK

Overview

- Importance of Mass and Massive Stars (>30 $M_\odot$)
- Interactions with RHK and others
- Colliding Wind Binaries: A shocking way to study mass loss
- Two Prime Examples
  - WR 140
  - Eta Carinae
- Conclusion and future work

Mass: The Fundamental Parameter



Mass is the fundamental stellar parameter which determines the fate of the star;

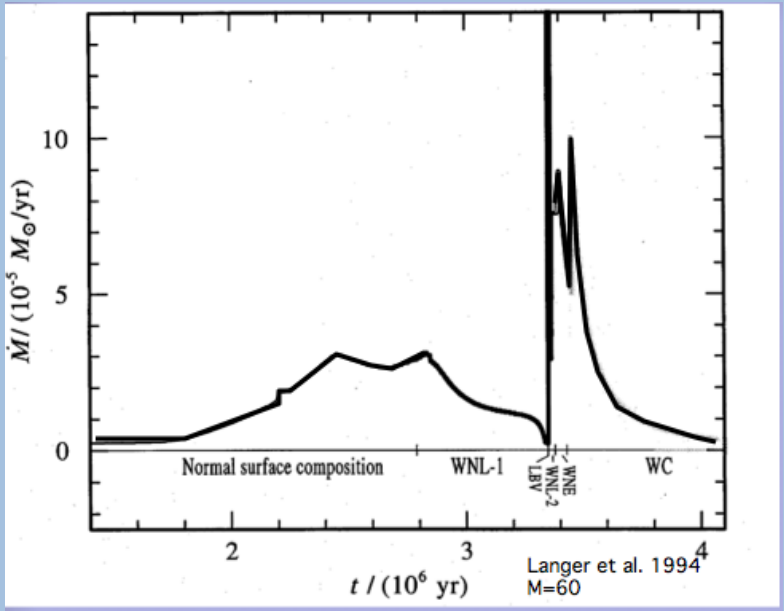
but in the upper HRD it becomes (observationally) less well constrained

AND mass changes with time

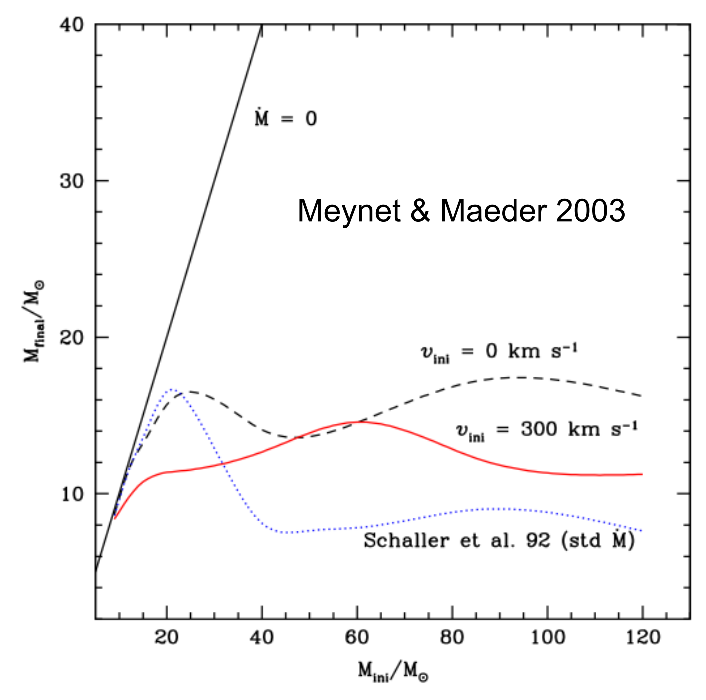
Moffat 1989

Weight Loss by the Heaviest Stars

- Mass is lost due to
  - radiatively driven stellar winds
  - Transfer/Roche Lobe leaks
  - Eruptions
  - Explosions…

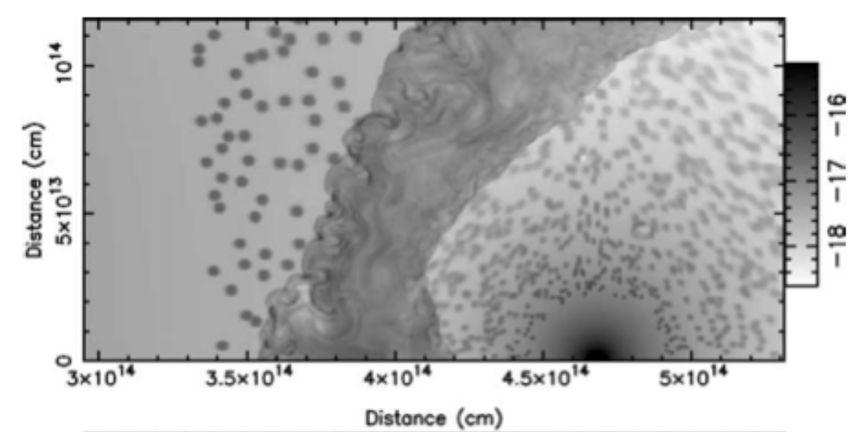


Langer et al. 1994
M=60



Meynet & Maeder 2003

Colliding Winds as a Means to Mass Loss



Stellar winds will hit something:

- Interstellar medium
- another star
- wind from another star

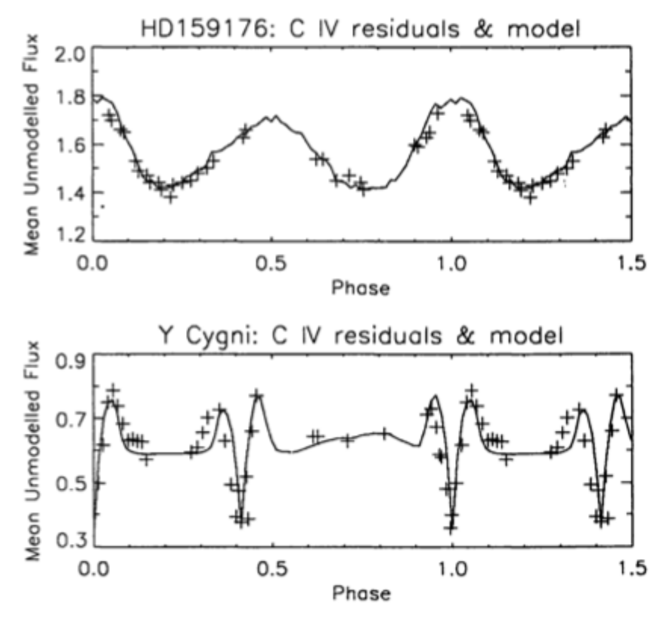
Colliding winds provides:

- – in-situ probe of mass loss
- – “Clumping-free” estimator? (Pittard 2007)
- – way to probe the stellar parameters
- – “laboratory” physics of astrophysical hypersonic shocks

Binary Interactions with RHK & others

- My interest in massive stars began with Bob’s guidance
- Bob published important work on mass loss studies (especially with IUE)
- Bob, Ray Pfeiffer and Ioannis Pachoulakas also did some significant work on radiation transfer in massive binary winds and 3-D modeling

Example: HD 159176 & Y Cyg



- Modeling of residuals in C IV and Si IV P-Cygni wind lines compared to a best fit binary model profile.

- The phase-dependent residuals were modeled to constrain amount of emission from the wind-wind interaction zone

- “We conclude with the belief that comprehensive studies of main sequence binaries like the ones presented herein ... provide a foundation for the understanding of the significantly more extravagant interactions which are of interest in evolved systems”

Koch et al., 1996, “Winds of Massive, Main Sequence Close Binaries”

More Extravagant Interactions

Two important “colliding wind binary shock laboratories”:

- WR 140, a carbon-rich Wolf-Rayet star + a “normal” O-type companion in a peculiar orbit: 8 year period, eccentricity = 0.88

- Eta Carinae: an LBV + unseen companion, in a peculiar orbit: 5.5 year period, eccentricity ~ 0.9

Both went through periastron passage **within 5 days** of each other in January 2009

Both are **bright in X-rays**

Observing and modeling campaigns were organized around these events to provide a pan-chromatic variability study to refine the orbital, wind and stellar parameters

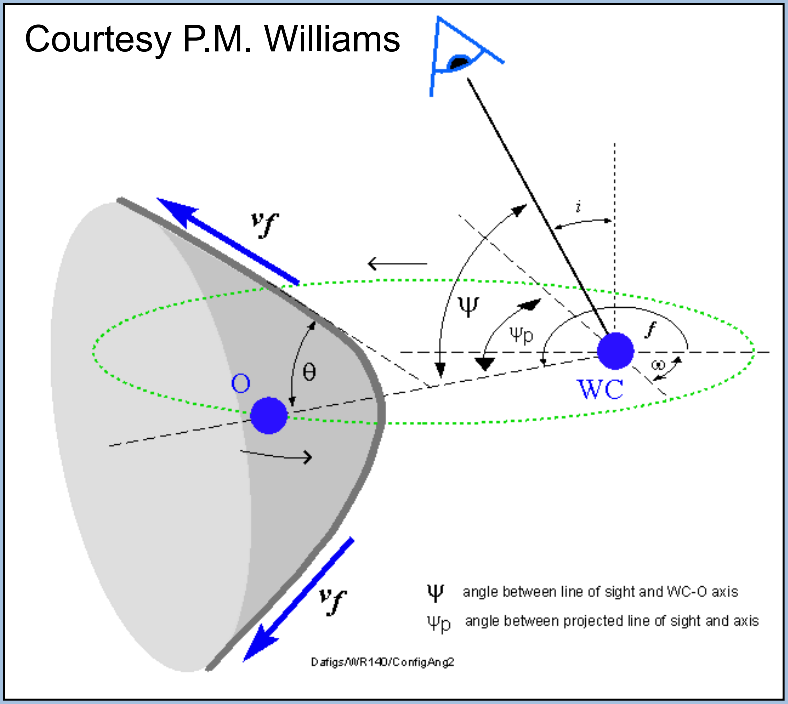
X-rays as a Probe of Colliding Wind Systems

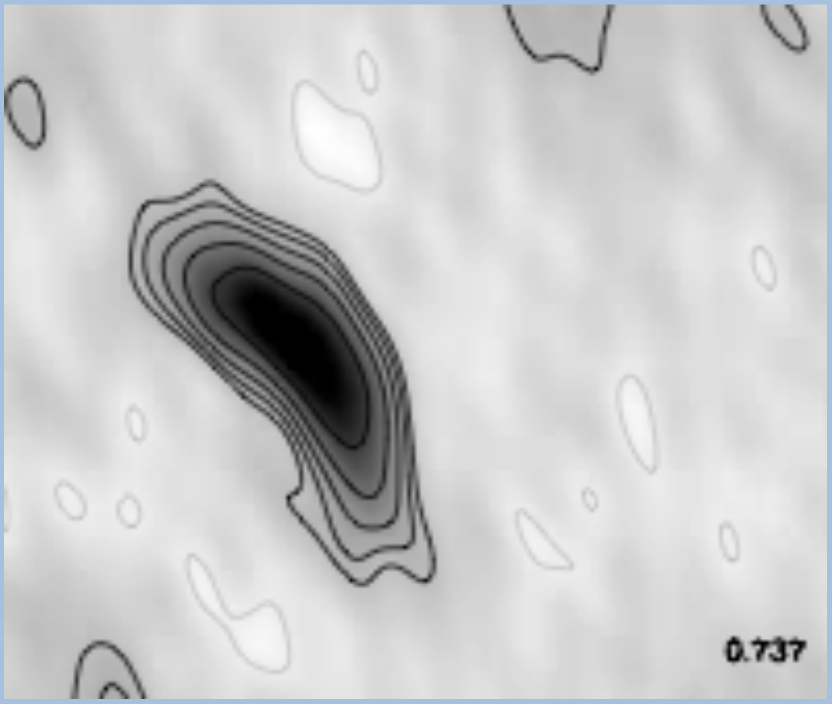
Wind velocities of 1000’s of km/s ➔ X-ray emission

X-ray studies can provide:

- wind terminal velocities (i.e. escape velocities) through temperatures
- density information via column depth measurements
- detailed flow information from X-ray emission lines
- D^{-1} variation – orbital parameters and masses

WR 140

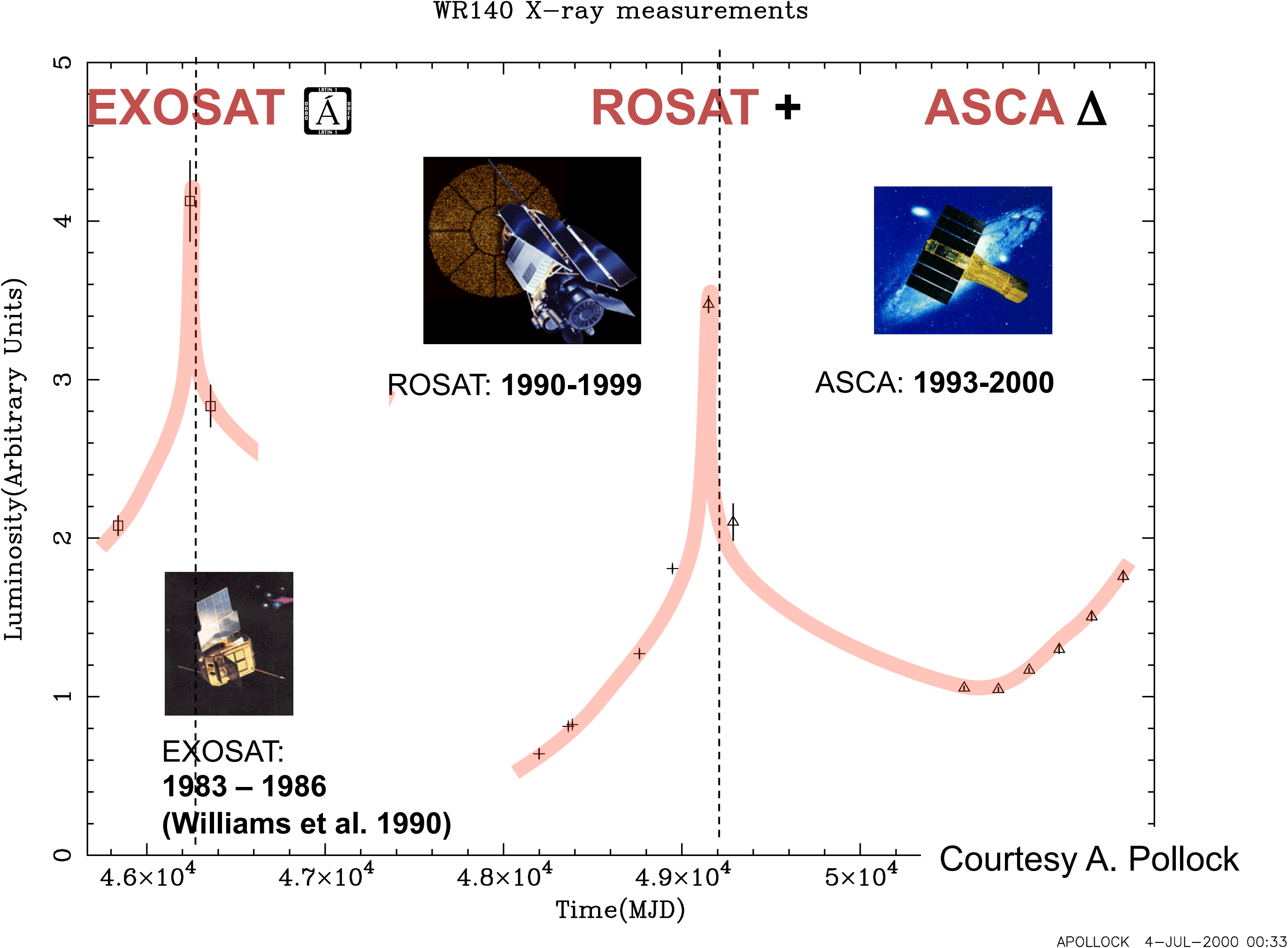




Radio - Dougherty et al. 2005

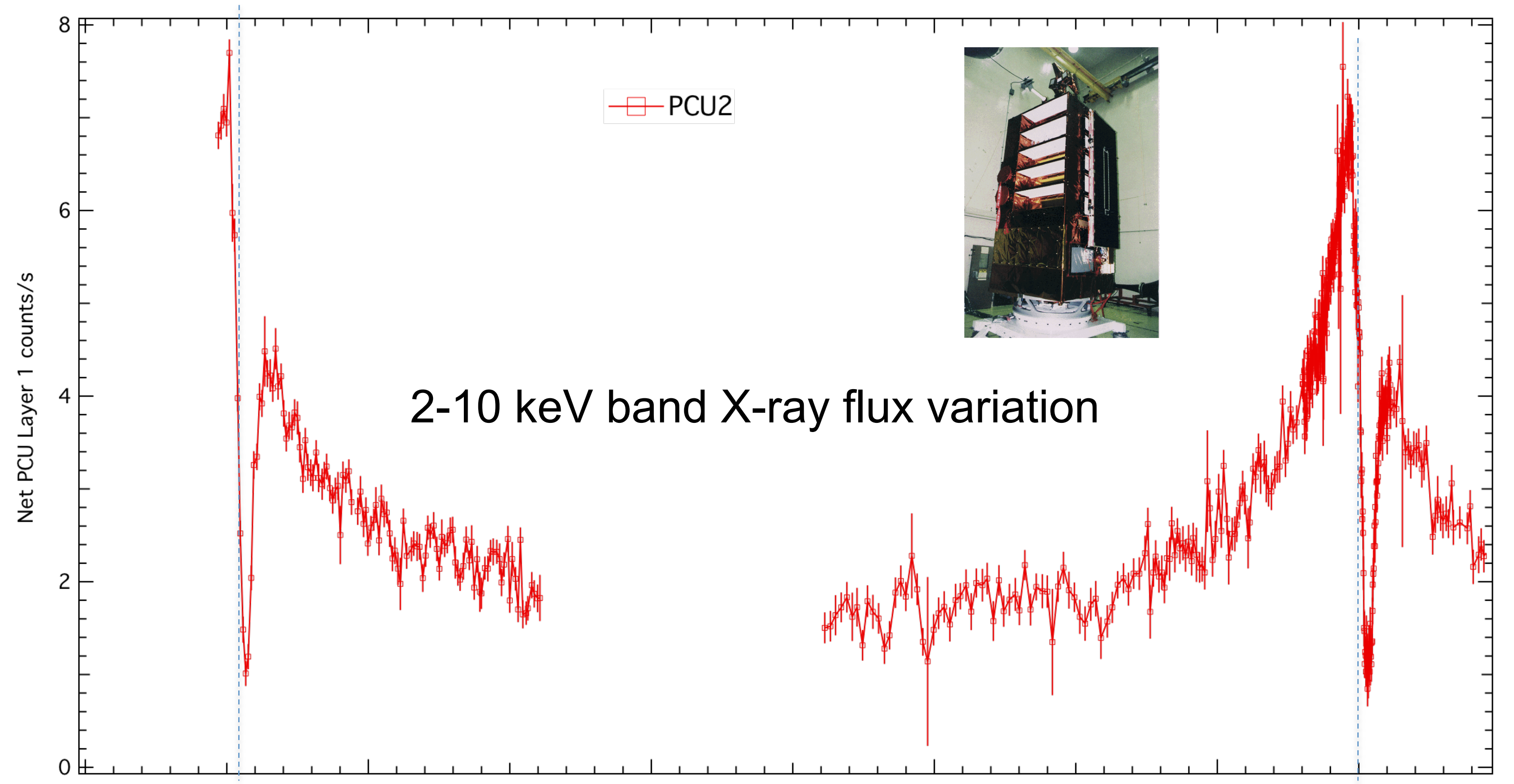
WC7 (20 solar masses) +O4-5 (50 solar masses)

WR 140: “Historical” X-ray Variability

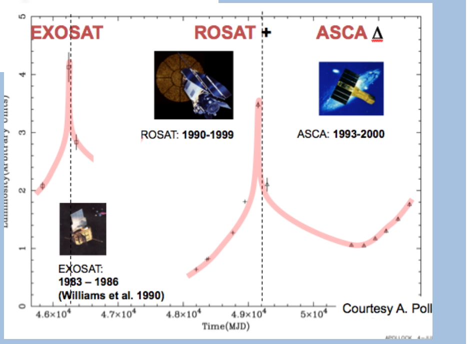


Courtesy A. Pollock

Detailed Observations of WR 140 with RXTE

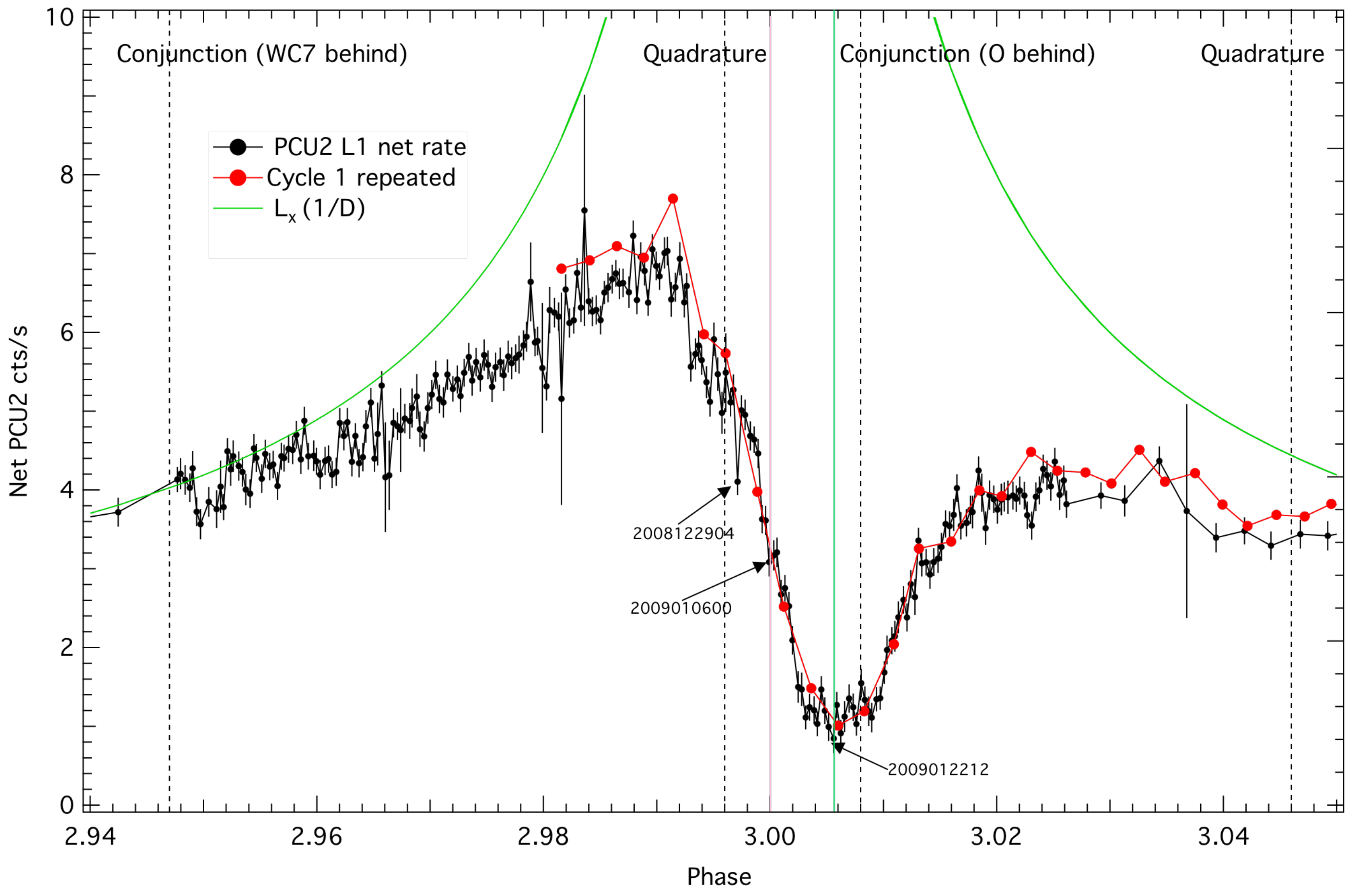


RXTE = Rossi X-ray Timing Explorer, launched Dec 1995
TBT Dec 2011

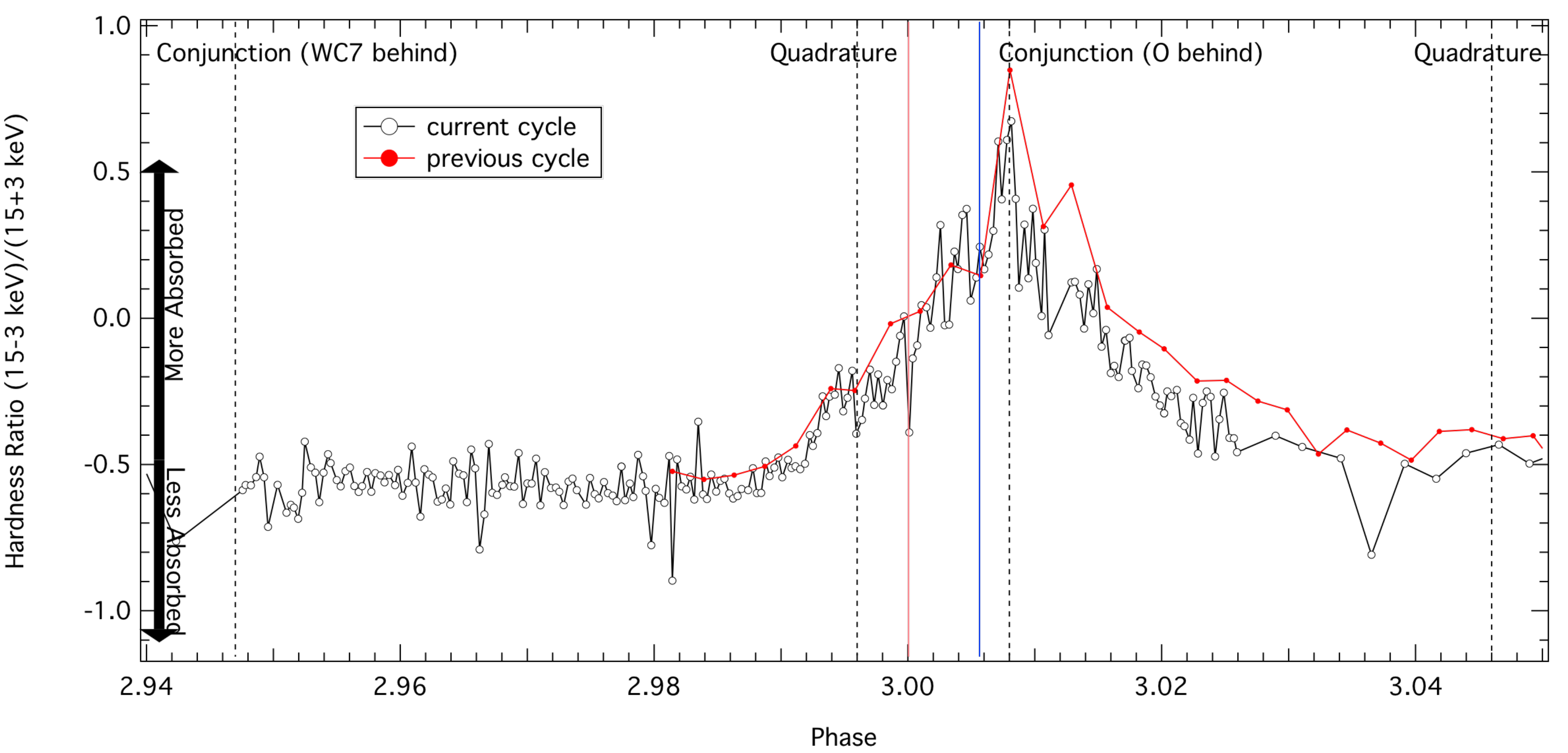


“Historical”

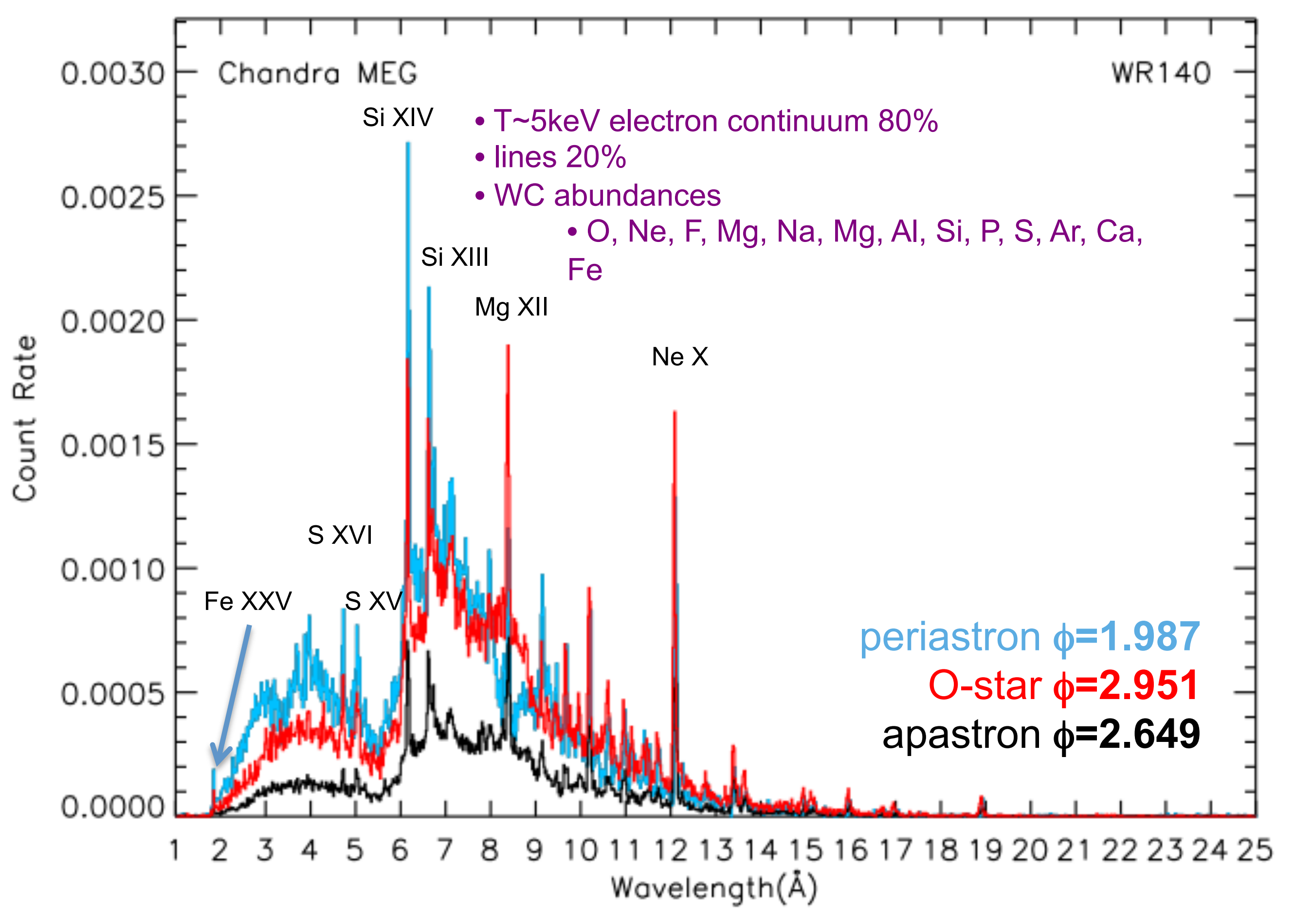
Comparison of Periastra



X-ray Color Change Near Periastron



WR 140 X-ray Emission Line Spectra with Chandra

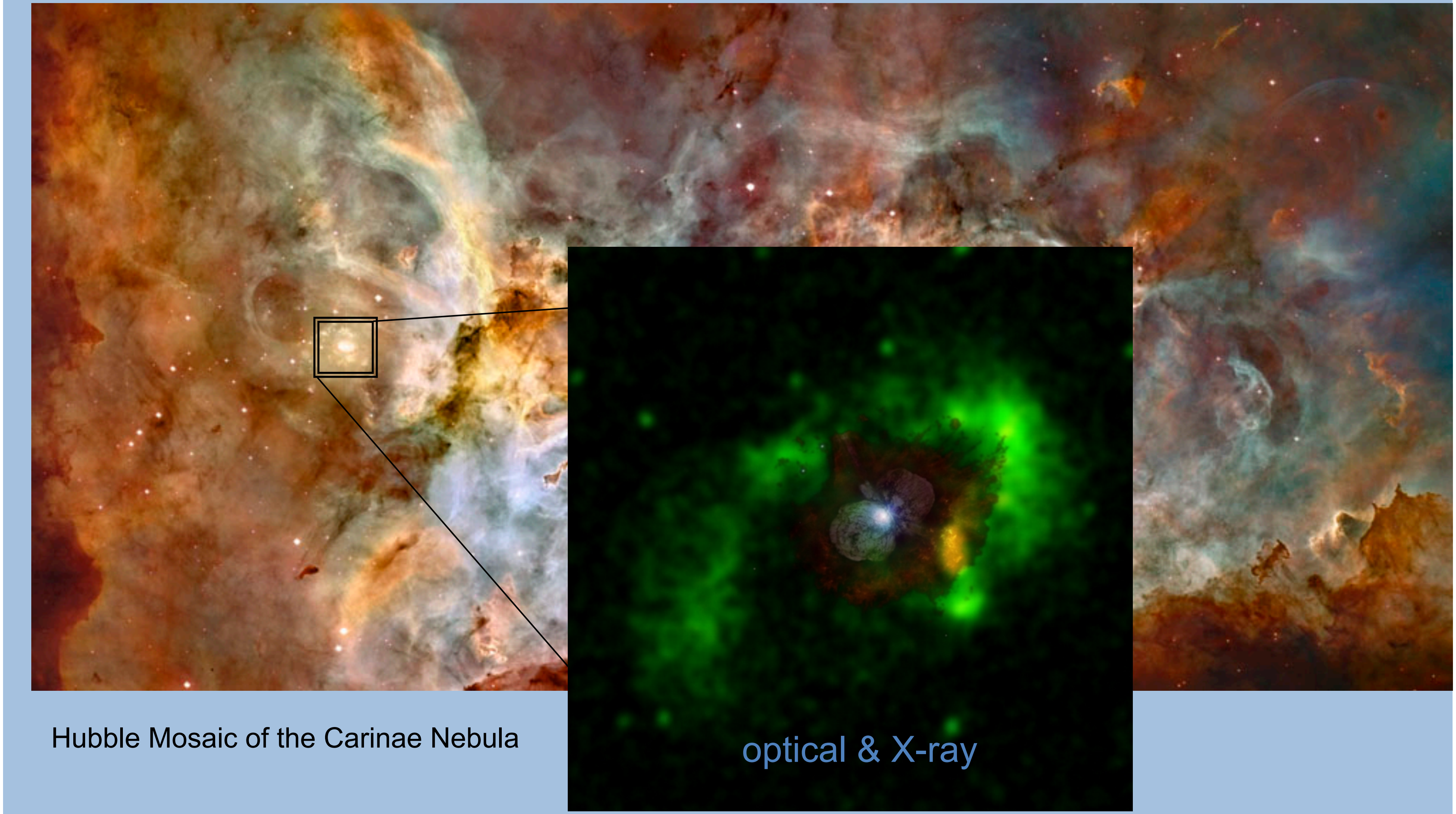


- T~5keV electron continuum 80%
- lines 20%
- WC abundances
  - O, Ne, F, Mg, Na, Mg, Al, Si, P, S, Ar, Ca, Fe

Courtesy Andy Pollock

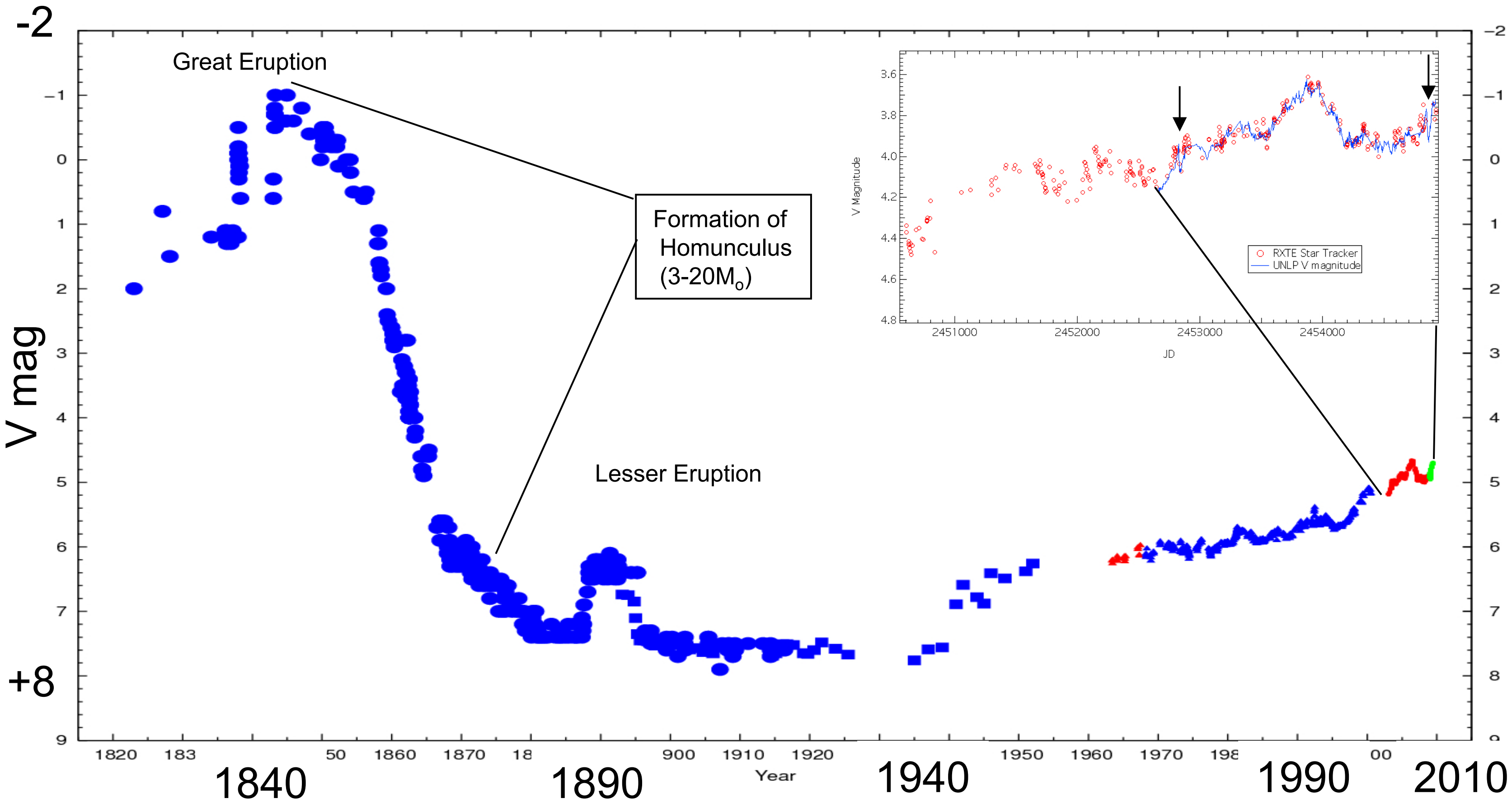
Eta Carinae

η Car is one of the most luminous (massive) stars in the Galaxy (most luminous, massive star within 3 kpc.)



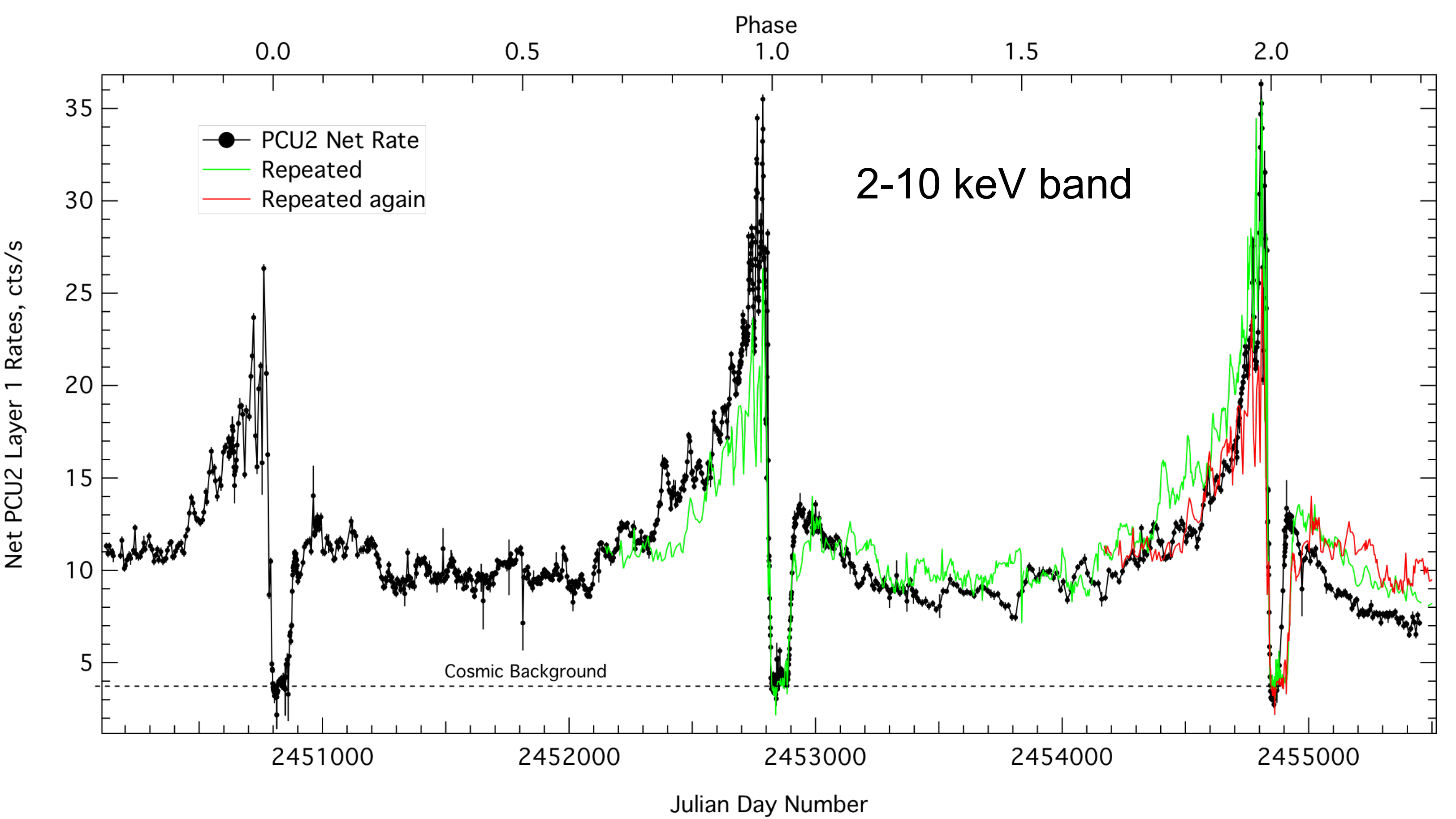
Hubble Mosaic of the Carinae Nebula

The Great Eruption and After

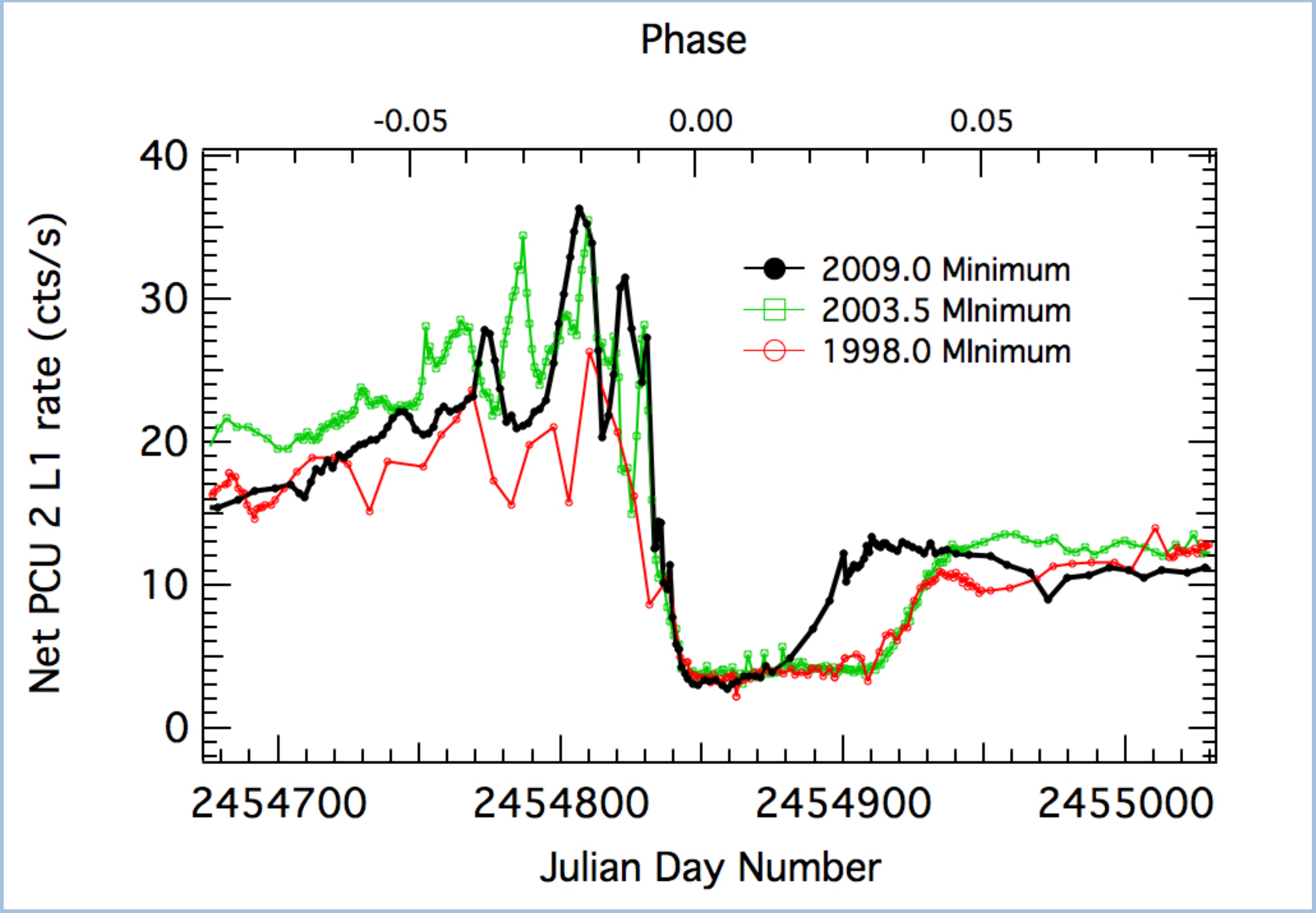


see Ferndez Lajus et al. (2009, A&A, 493, 1093)

The RXTE Lightcurve of Eta Car

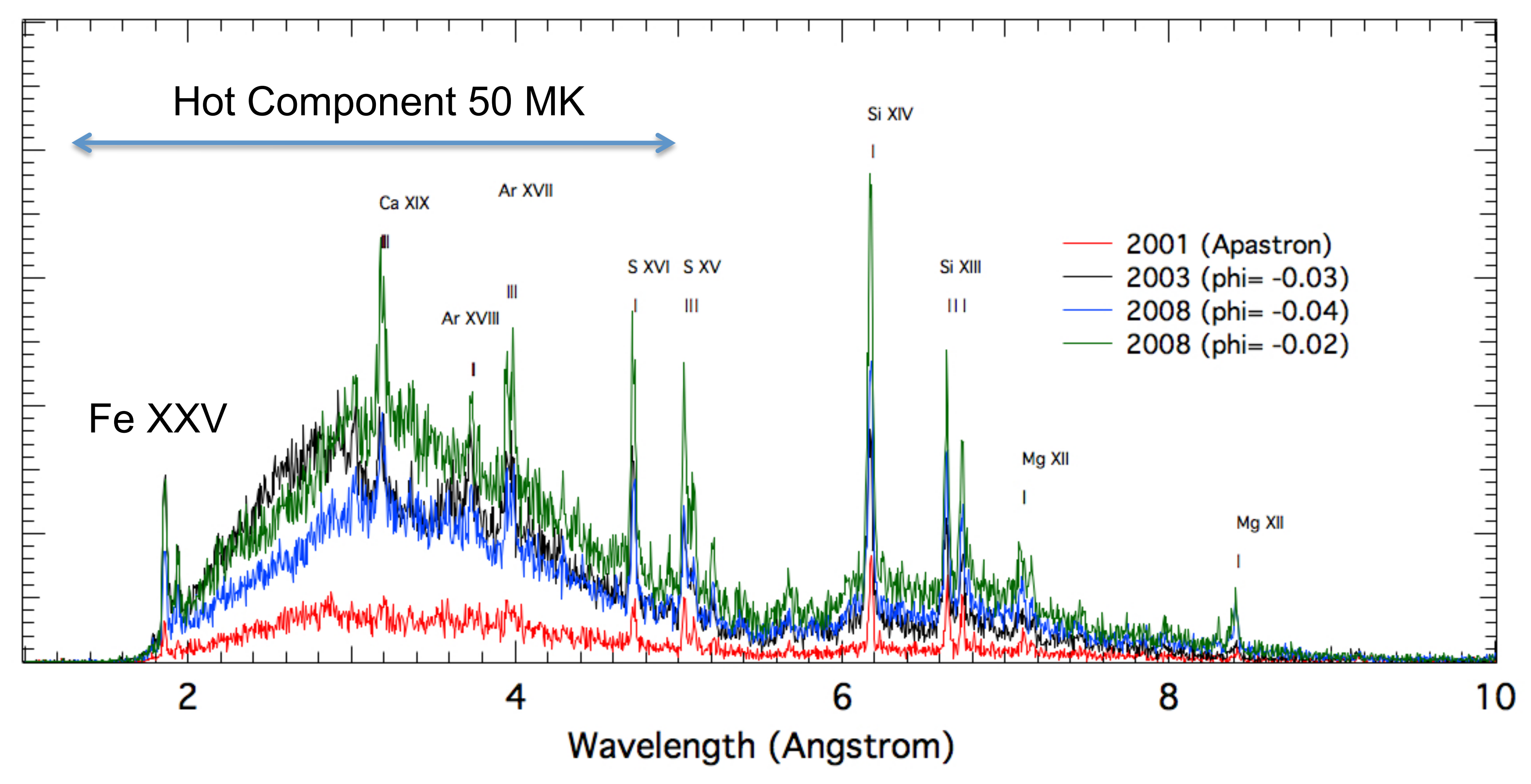


Comparison of Minima



…what happened in 2009?

X-ray Spectrum



Results: Eta Car

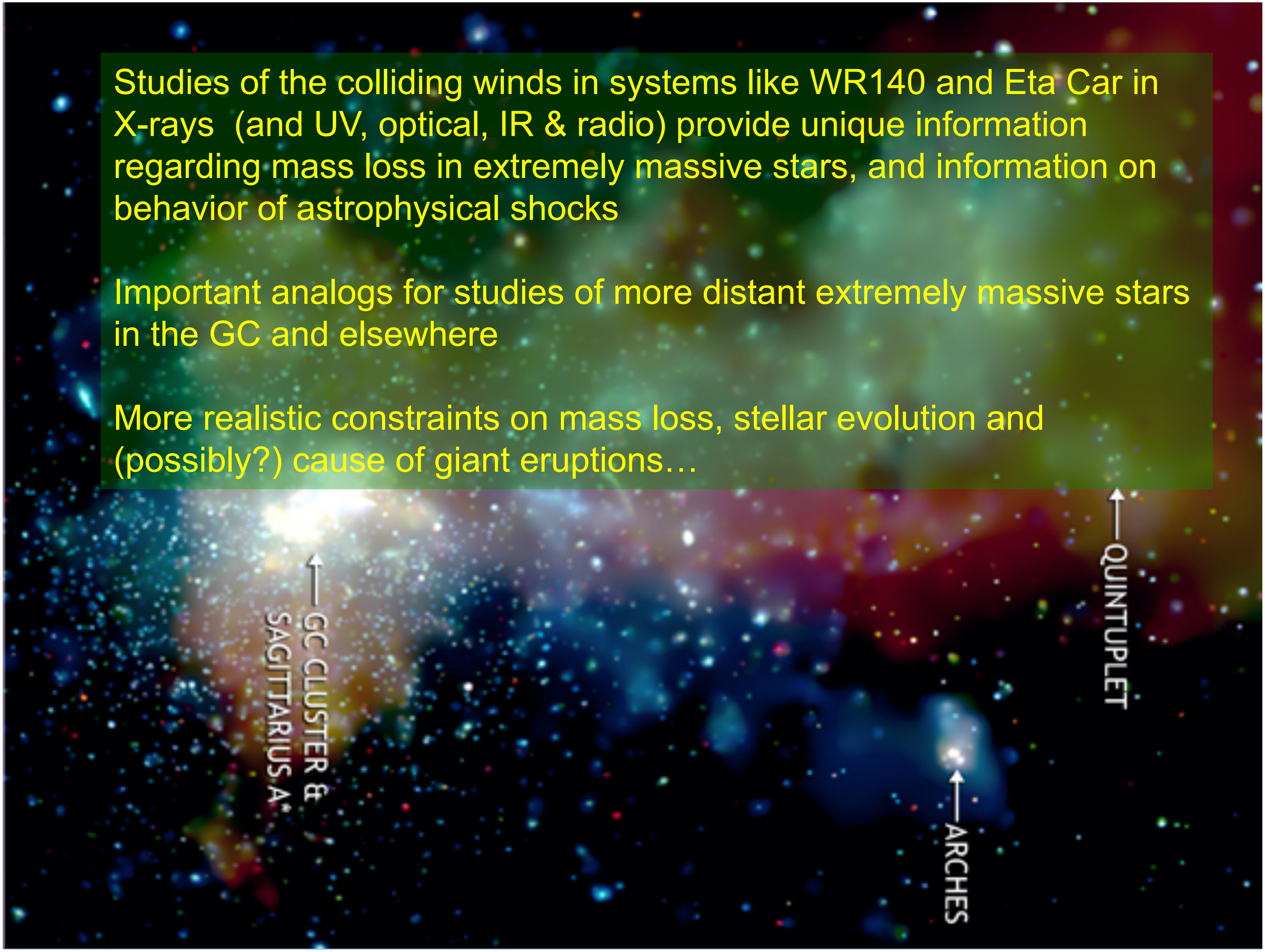
	X-ray Value	**Non-X-ray Value**
Mass Loss Rate	2.5×10^{-4} & 10^{-5}	10^{-3} & ?
Terminal Velocity	500 & 3000	500 & ?
Escape Velocity	200 & 1200	200 & ?

- Point source approximation near periastron can reproduce depth of minimum
- More realistic distribution of hot gas along the shock boundary (“extended emission model”) does *not* reproduce the X-ray minimum as well…
- radiative cooling near periastron vs. adiabatic cooling near apastron?
- shift in X-ray temperature near periastron?

Studies of the colliding winds in systems like WR140 and Eta Car in X-rays (and UV, optical, IR & radio) provide unique information regarding mass loss in extremely massive stars, and information on behavior of astrophysical shocks

Important analogs for studies of more distant extremely massive stars in the GC and elsewhere

More realistic constraints on mass loss, stellar evolution and (possibly?) cause of giant eruptions…



THANKS!

End

Mass Measurement & Uncertainties in the Upper HRD

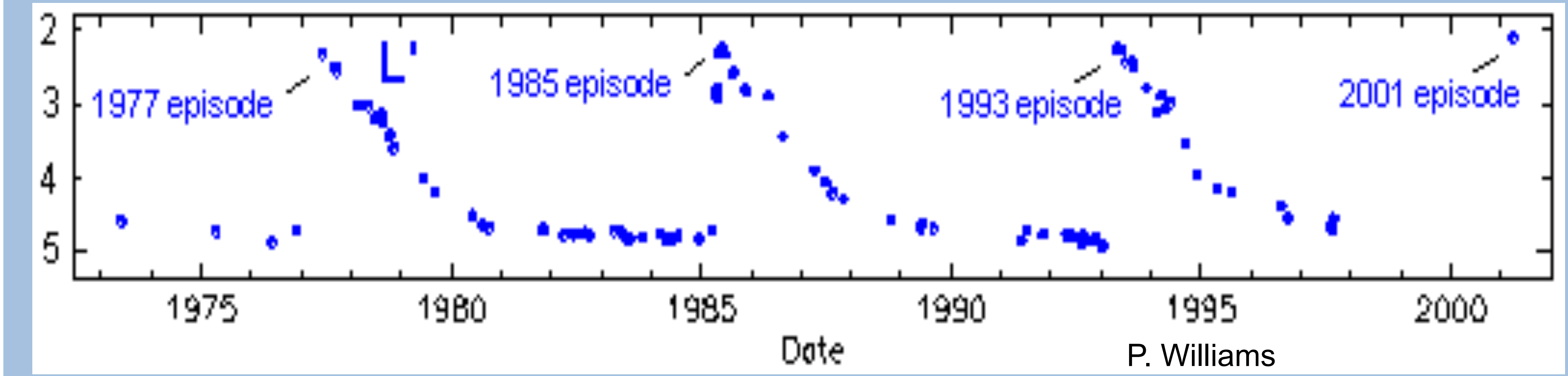
Mass Determination Method	**Potential Pitfalls**
Evolutionary: Placement on HR diagram & comparison to evolutionary tracks	model uncertainties (rotation, abundance, overshooting); extinction correction
Spectrometric: fit line profiles to determine log *g*	Contamination by “moving envelopes” at high luminosities/ high mass loss rates; line blanketing
Terminal velocities to measure escape velocities	multiple scattering, strong/weak line mix
Dynamical: classical analyses of binary stars	Contamination by circumstellar material, line broadening, rarity

$$M \propto g \frac{L}{T^4}$$

$$M \propto V_\infty \frac{R}{1-\Gamma}$$

$$\frac{M_1}{M_2} = \frac{V_2}{V_1} \; ; \; M_1 + M_2 \propto \frac{a^3}{P^2}$$

WR 140: “Canonical” Massive Long Period Binary



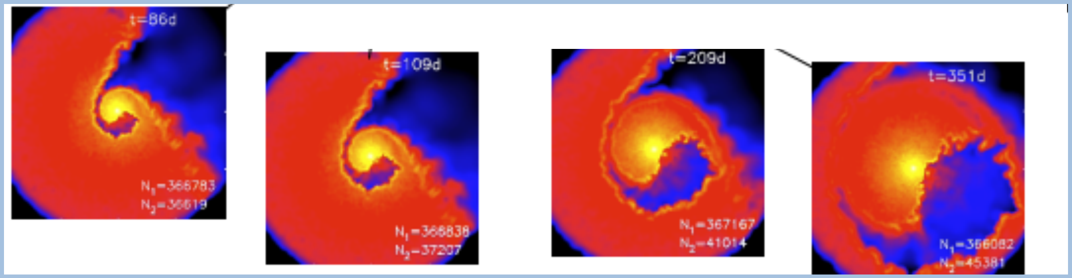
P. Williams

- Coordinated variability at wavelengths from cm to 10^{-8} cm
- all driven by wind-wind collision between the two stars

What Shortened the 2009 Minimum?

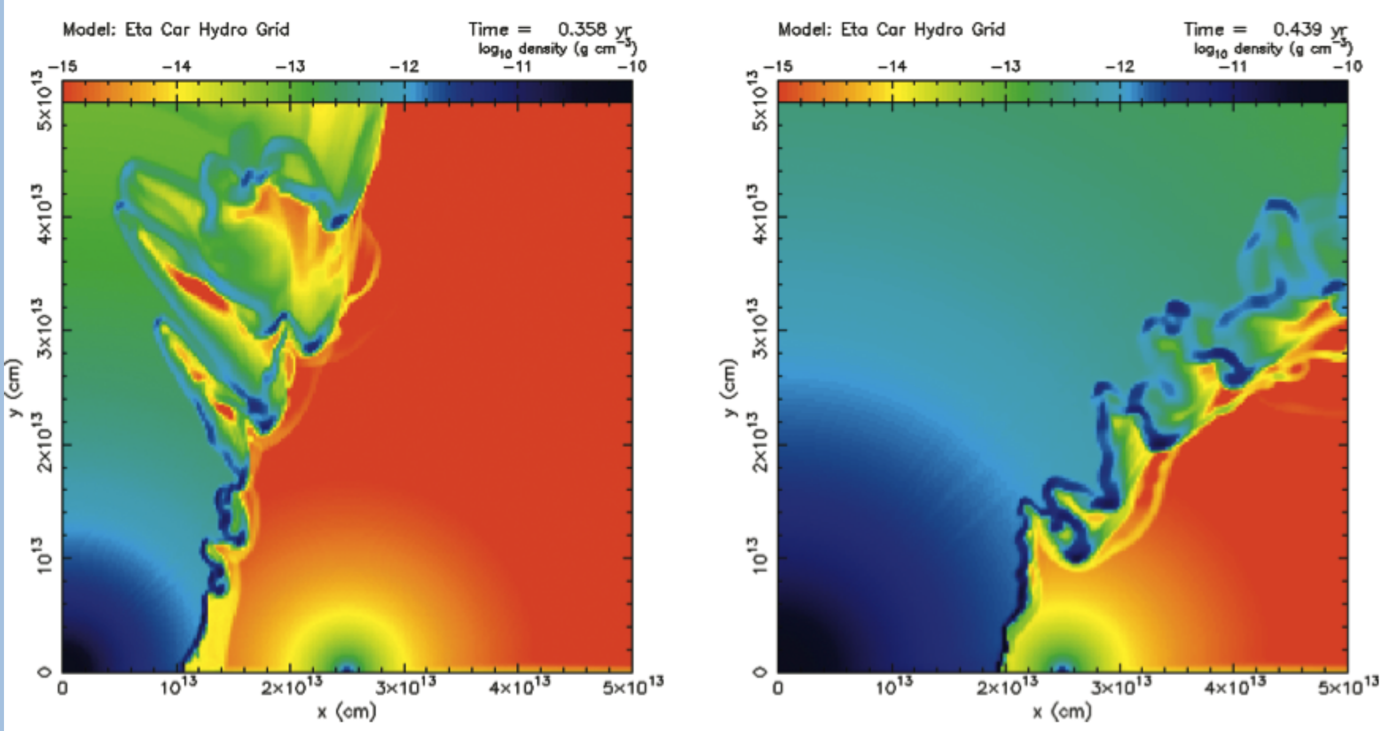
Minimum depends on:

- ➔ intrinsic 2-10 keV emission of shock near periastron (radiative instabilities important)
- ➔ amount of absorption around the “bubble”



A decrease in the LBV’s mass loss rate could make the shock less radiative (more stable) and less absorbed ➔ shorter X-ray Minimum

“Reality is Complicated”– Hideki Yukawa

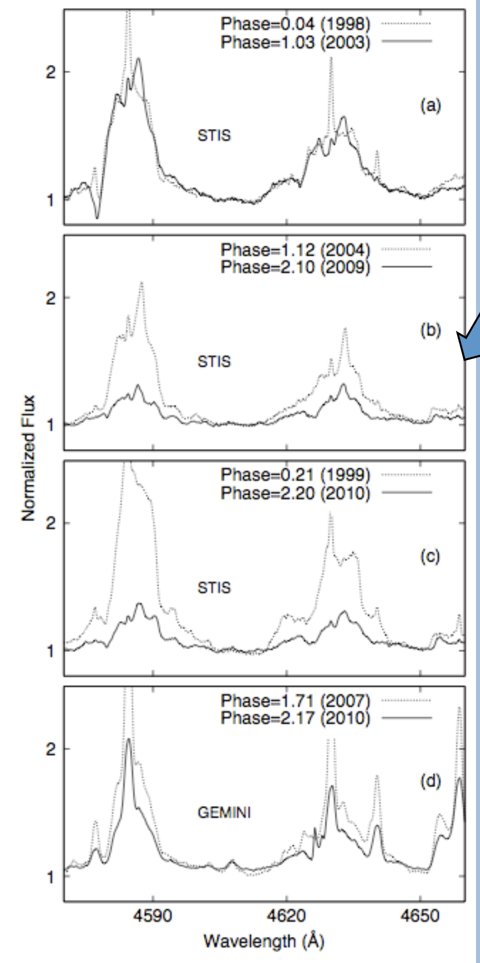


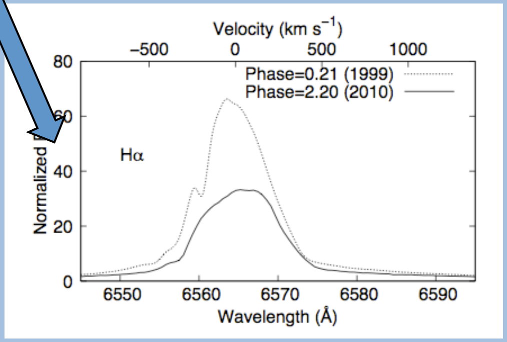
Importance of radiative instabilities at wind-wind interface (thin shell, etc, Parkin et al. 2009, Pittard & Corcoran 2002)

A (Sea) Change in Mass Loss Rate

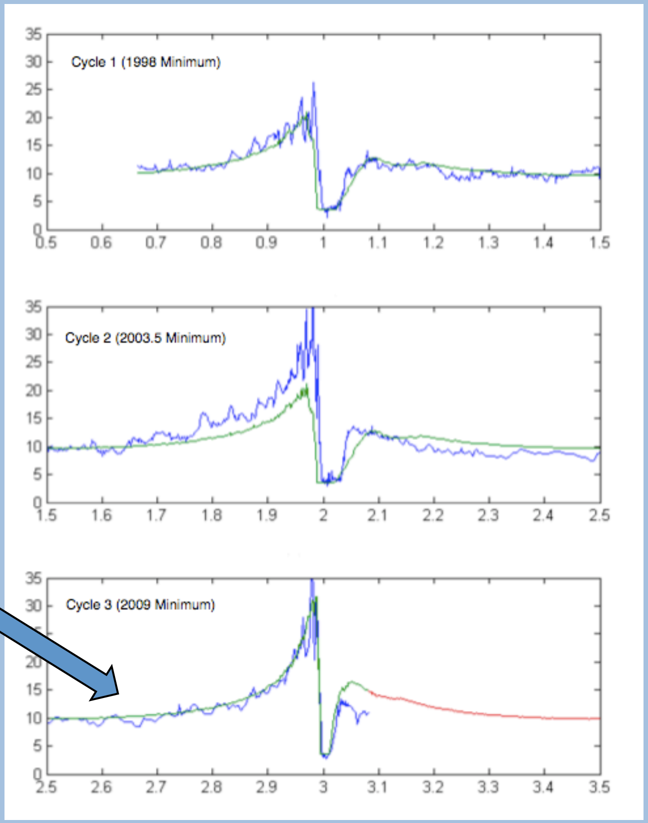
STIS, Gemini reveal weakening of emission lines in 2009 (Mehner et al. 2010)

Large decrease in Mdot from LBV?

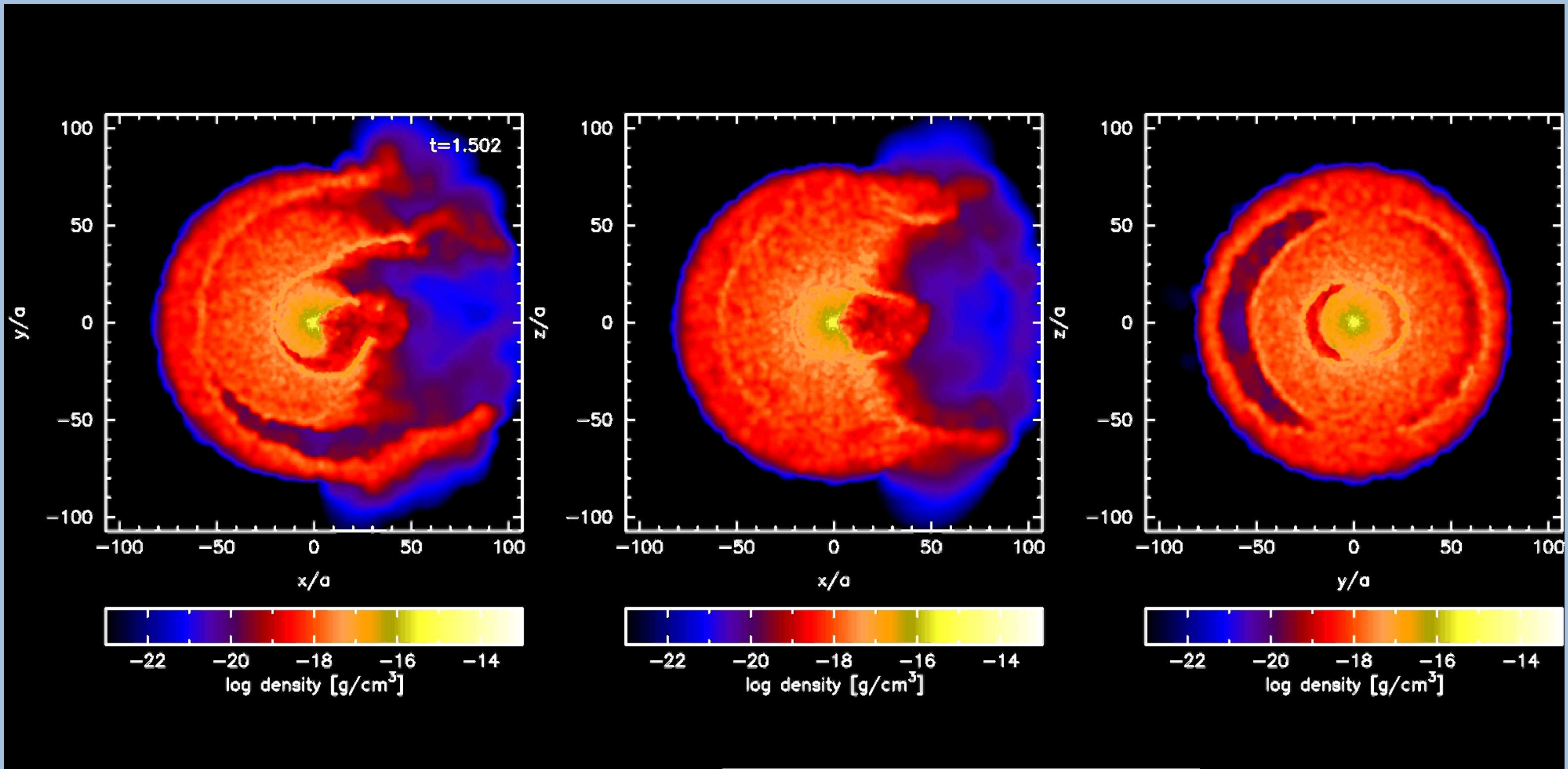




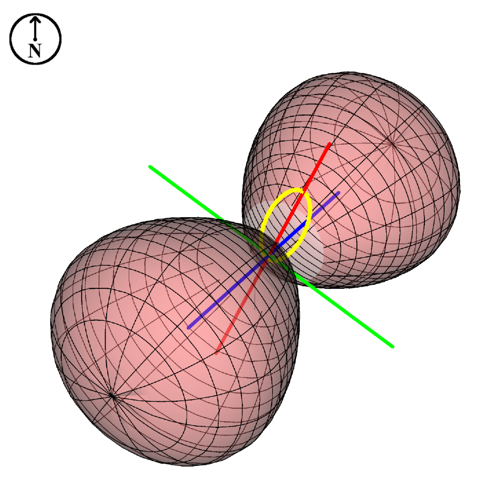
Decrease in Mdot may also explain the decrease in duration of X-ray minimum (See C. Russell, Poster P5.20; Kashi & Soker 2009)



3-D Spectro-Models: Geometry of Mass Loss



Courtesy T. Madura, Phd thesis



Synthetic Slit Spectra from 3-D SPH Sims

MODEL

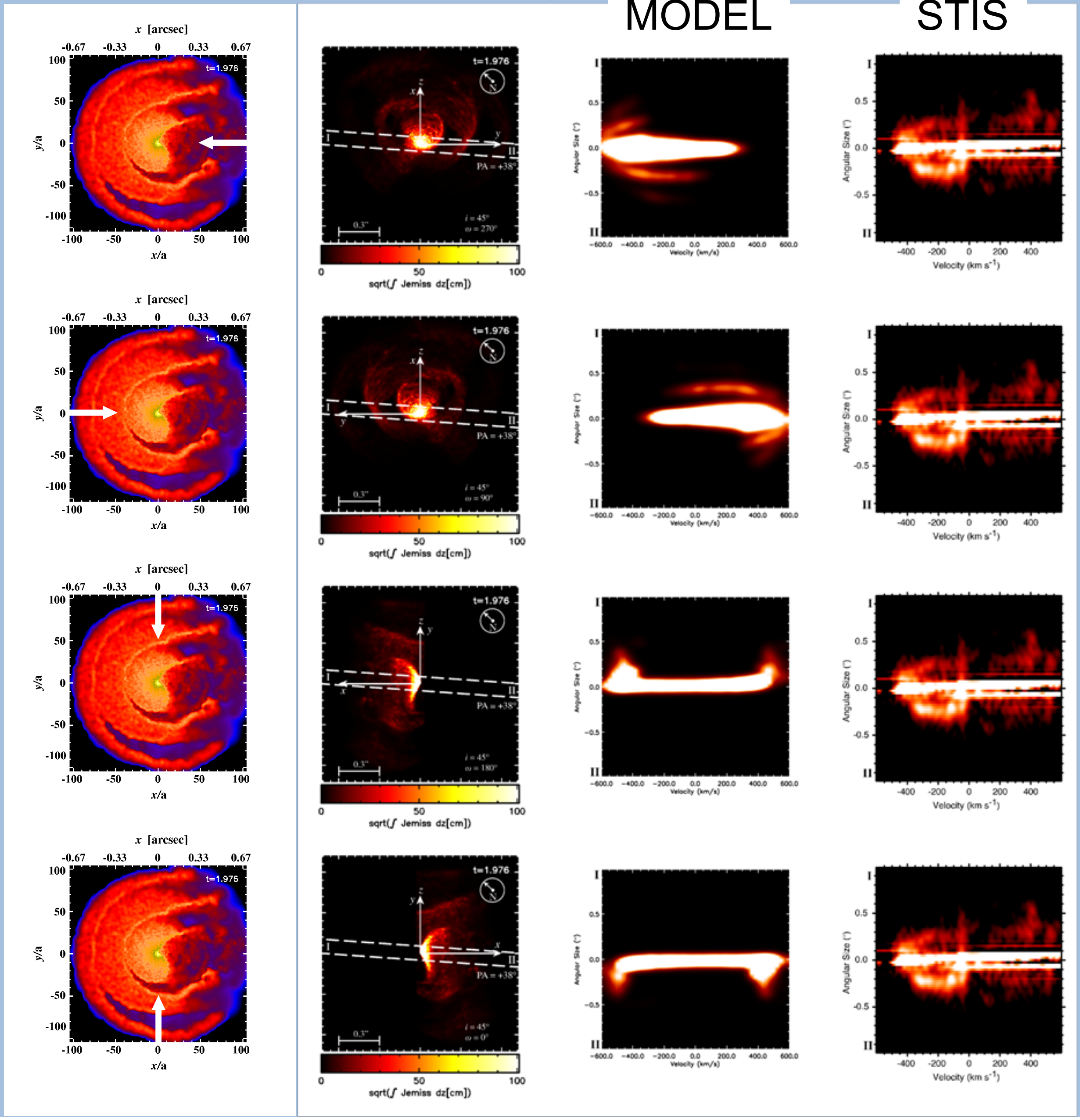
STIS

$\omega = 270°$

$\omega = 90°$

$\omega = 180°$

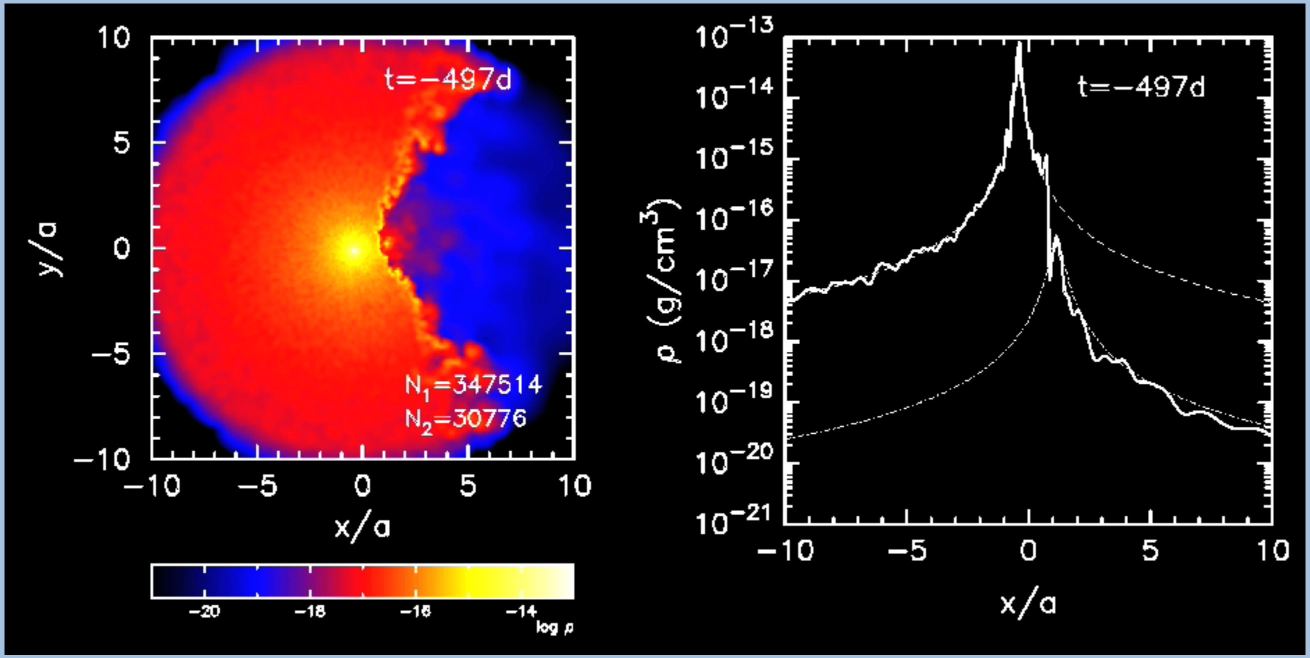
$\omega = 0°$



Courtesy
Tom Madura

Recent 3-D modeling

wind structure in orbital plane



Density profile

Okazaki et al. 2008

Bow shock shapes primary wind

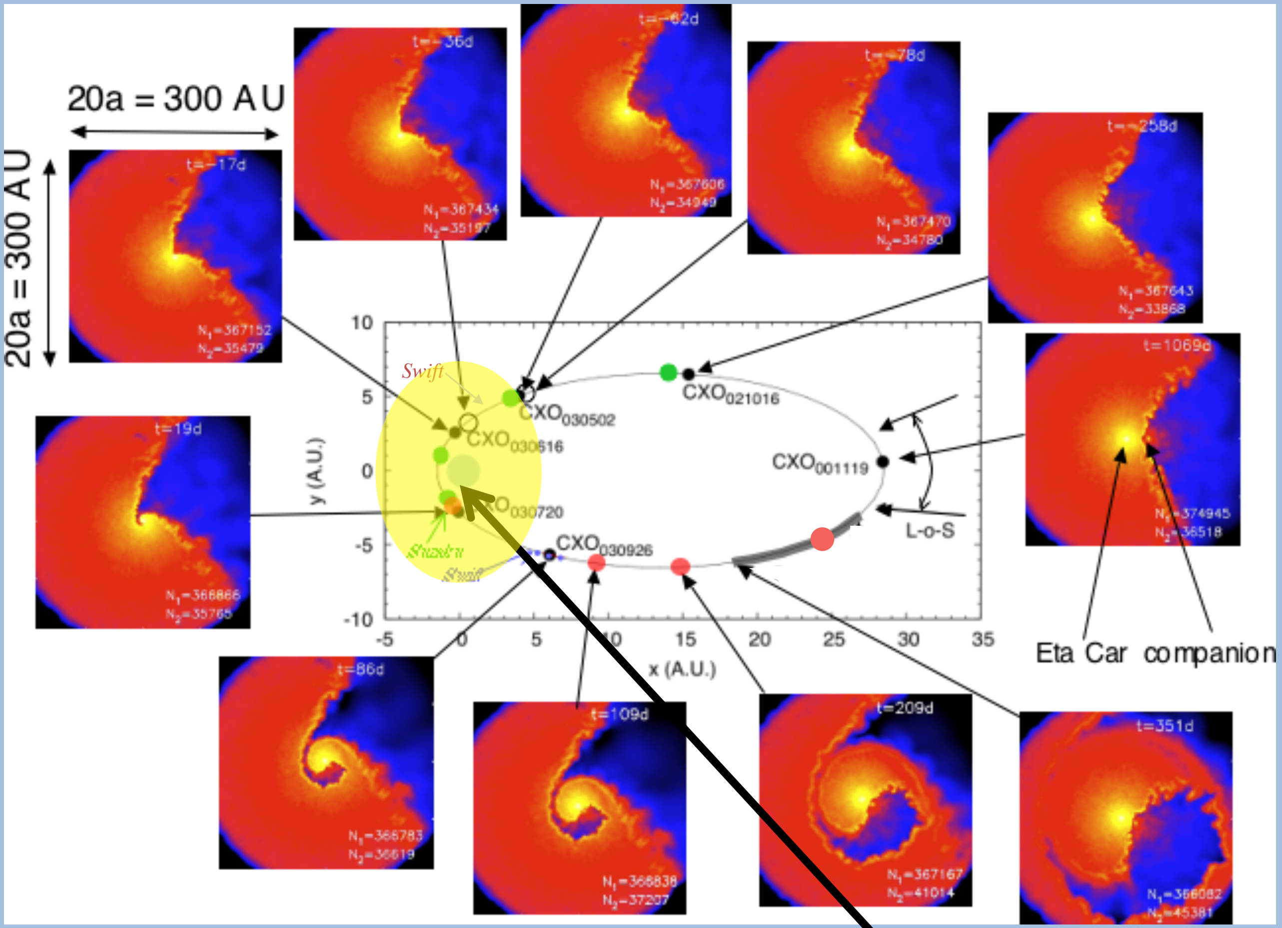
Variable ρ (N_H)

large Coriolis distortions in wind near periastron passage effects photoionization of wind/nebula by the companion

Thermalization of KE at WWC produces X-rays sensitive to orbit

“Flashlight Effect”

The Campaign



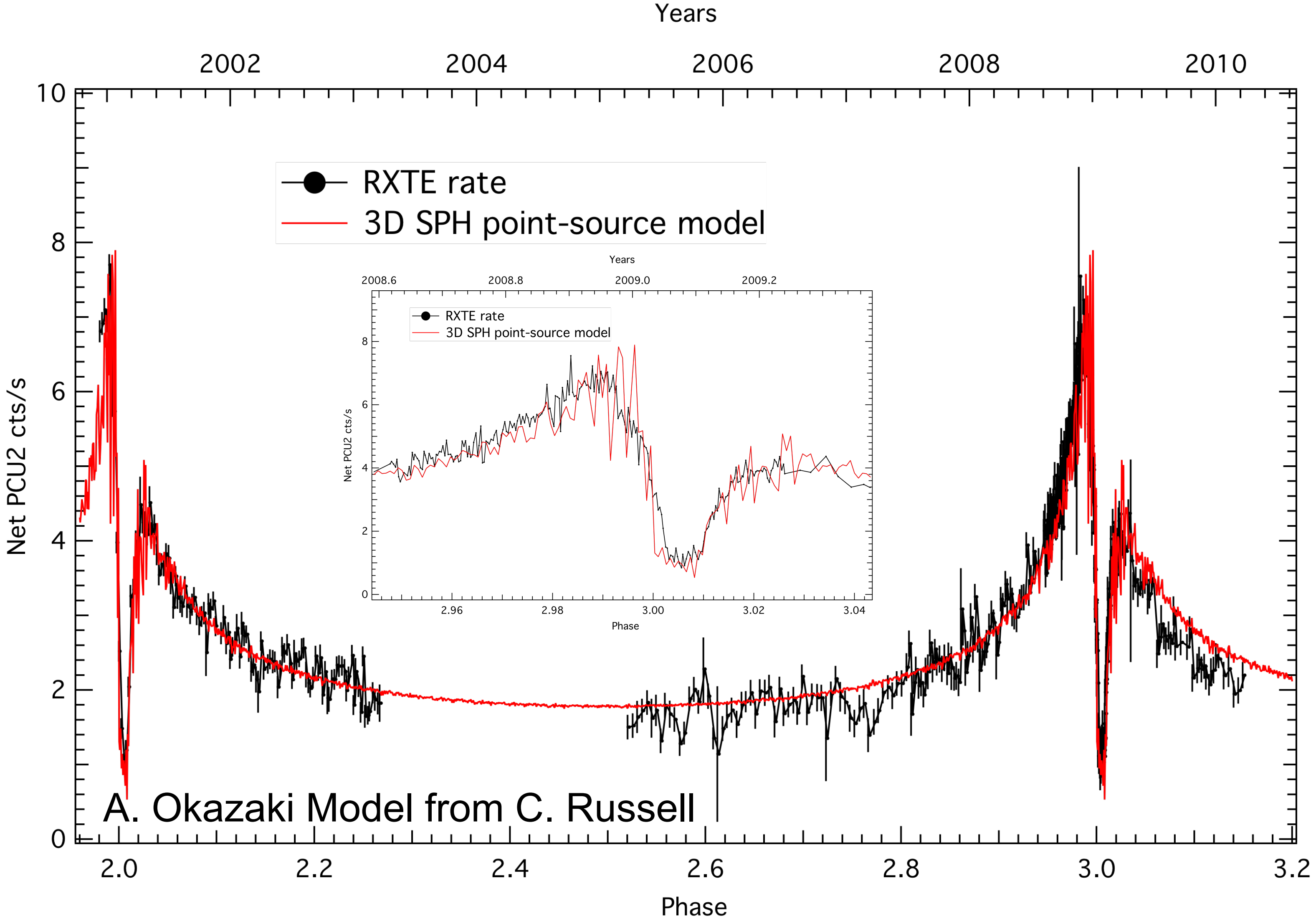
P=2024 d; e~0.9; a~15 AU; i~50^{o}

Ishibashi et al. 1998; Corcoran et al. 2001

Simulations by A. Okazaki

The Event

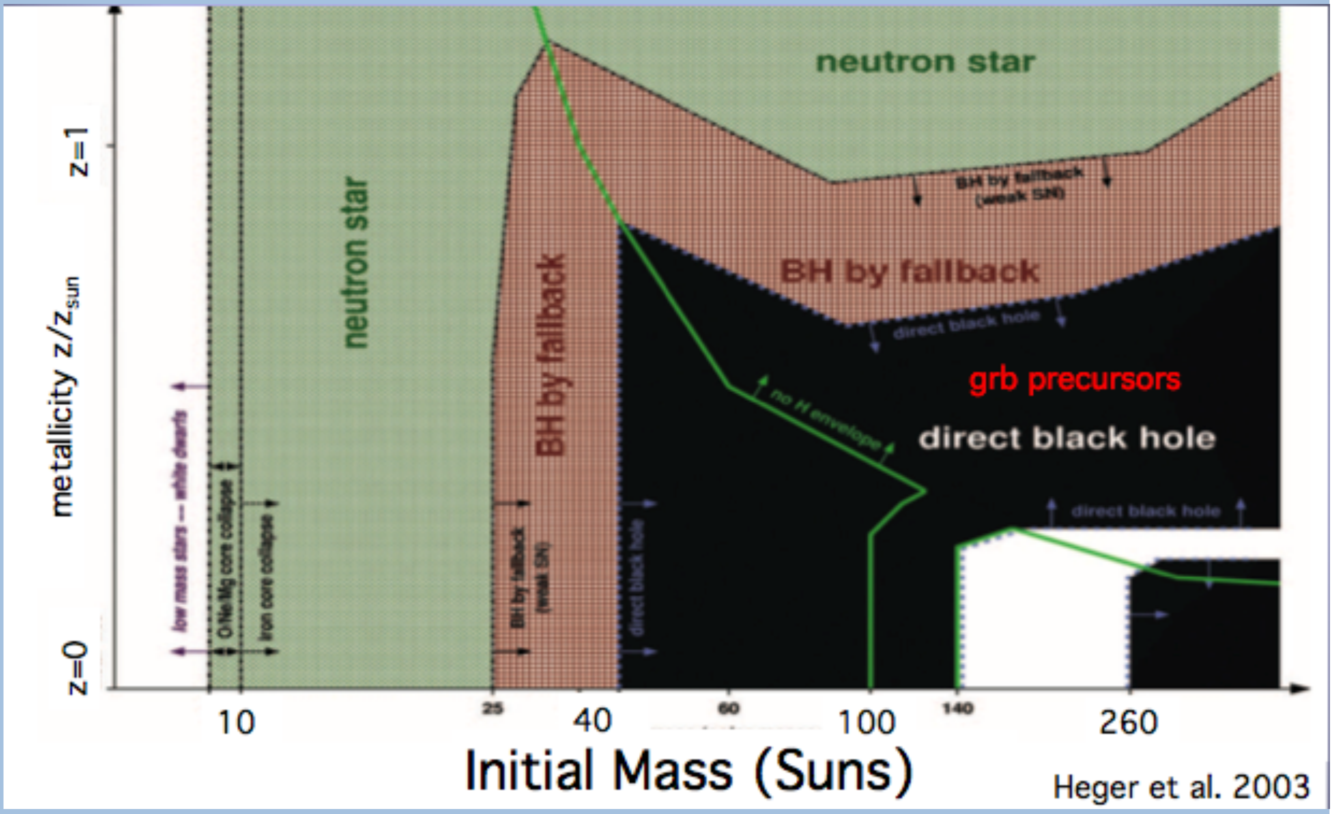
3D Lightcurve Models



A. Okazaki Model from C. Russell

Realistic Mass Loss

- Smooth wind vs. clumped?
- spherical or not?
- eruption: timescales & rates?
- explosion: core & remnant amounts?



Heger et al. 2003

Beginning to End…

Results

	X-ray Value	**Non-X-ray Value**
Mass Loss Rate $M_\odot$/yr	1.2×10^{-6} & 3.8×10^{-5}	same
Terminal Velocity (km/s)	3200 & 2860	same
Escape Velocity (km/s)§	1280 & 1144	same

- Point um

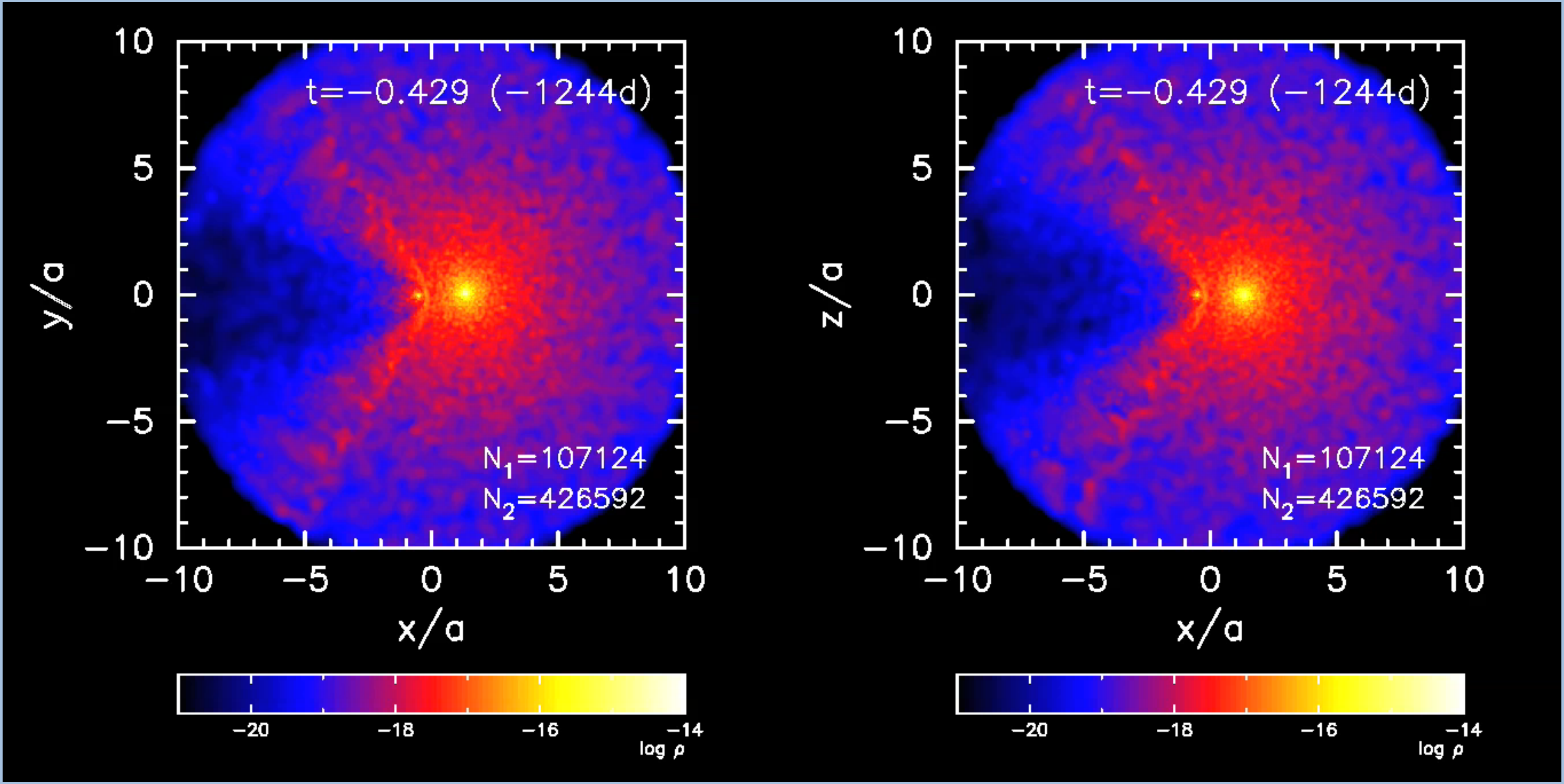
- More realistic distribution of hot gas along the shock boundary ("extended emission model") does *not* reproduce the X-ray minimum as well…

- radiative cooling near periastron vs. adiabatic cooling near apastron?

- shift in X-ray temperature near periastron?

§assuming V_∞=2.5 V_{esc}

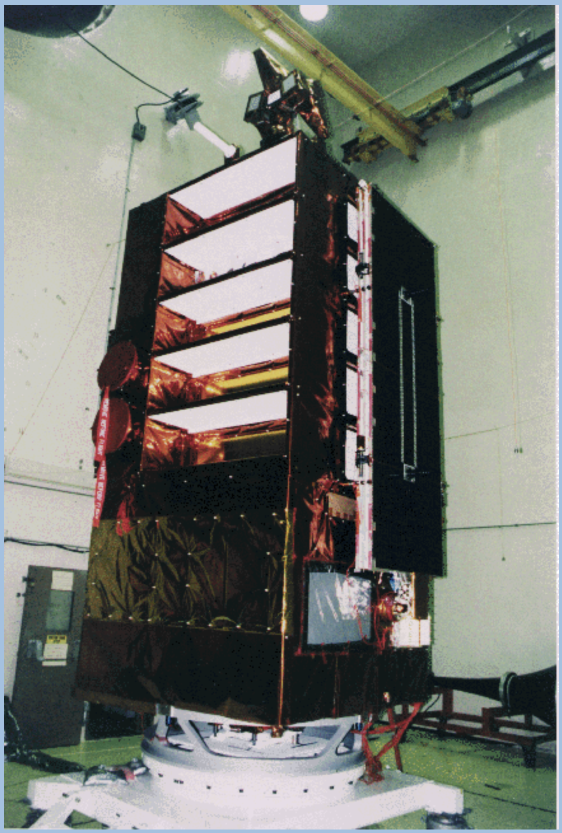
WR 140: 3D SPH models



P=2899 d; *e*~0.9; *a*~15 AU; *i*~50^o

Simulations by A. Okazaki

RXTE



- launched 1348 UTC on Dec 30 1995
- large area, micro-second time tagging capability, stable and predictable background,
- rapid slewing gives fast response time
- access to the entire celestial sphere further than 30 degrees from the sun
- 3 instruments covering the 2-250 keV band
- Still going strong, but funding cut-off expected in Fall 2011…

Dec 11, 2011: RXTE RIP?

Colliding Winds: A Simplified Approach

Early Work: Cherepashchuk (1976), Prilutskii & Usov (1976), Usov (1992), Steven, Blondin, Pollock (1992)

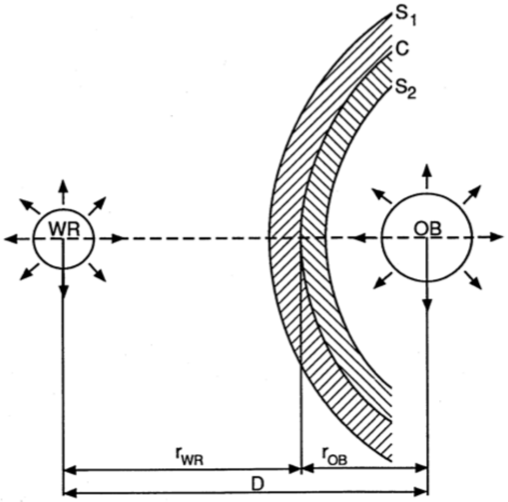


FIG. 1.—The collision of two stellar winds. S_1 and S_2 are the shock waves and C is the contact surface. The region of stellar wind collision is hatched.

$$r_{\rm WR} = \frac{1}{1+\eta^{1/2}} D \,, \quad r_{\rm OB} = \frac{\eta^{1/2}}{1+\eta^{1/2}} D$$

$$\eta = \frac{\dot{M}_{\rm OB} V_{\rm OB}^{\infty}}{\dot{M}_{\rm WR} V_{\rm WR}^{\infty}} \,.$$

$$T_s = 3\bar{m}v_w^2/16k$$

$$\chi = \frac{t_{\rm cool}}{t_{\rm esc}} = \frac{v_8^4 d_{12}}{\dot{M}_{-7}}$$

cooling parameter

c>1:
adiabatic
c<1:
radiative

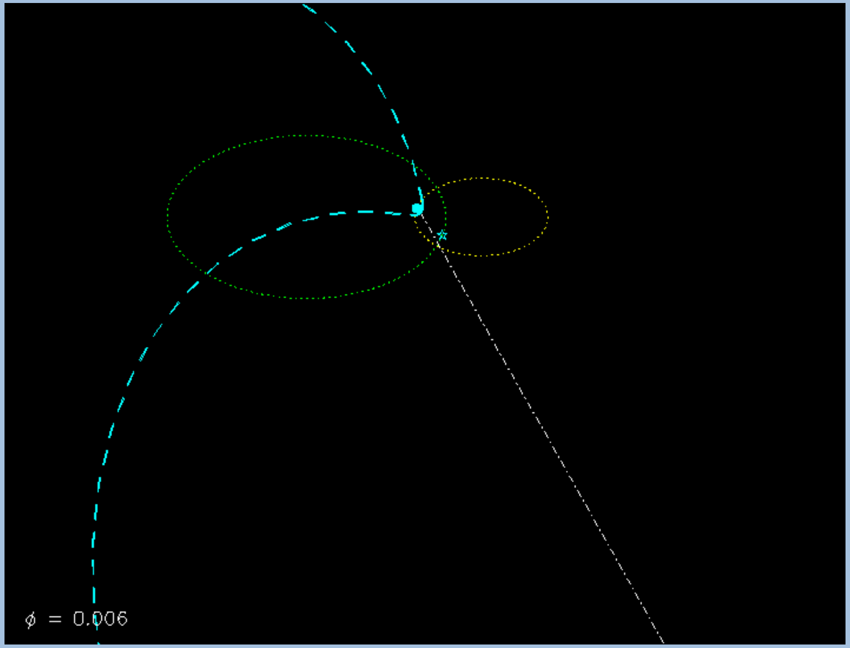
for Adiabatic shock, $Lx \propto 1/D(a, e)$

Temps of 10^7K: Thermal X-ray Emission

Colliding Winds in WR 140

Wind-Wind collisions in WR 140 allow us to probe time-variable shock physics under conditions of densities and temperatures which are difficult to reproduce on Earth

WR140: Our Shock Physics Laboratory



Courtesy P. Williams

Initial X-ray Results

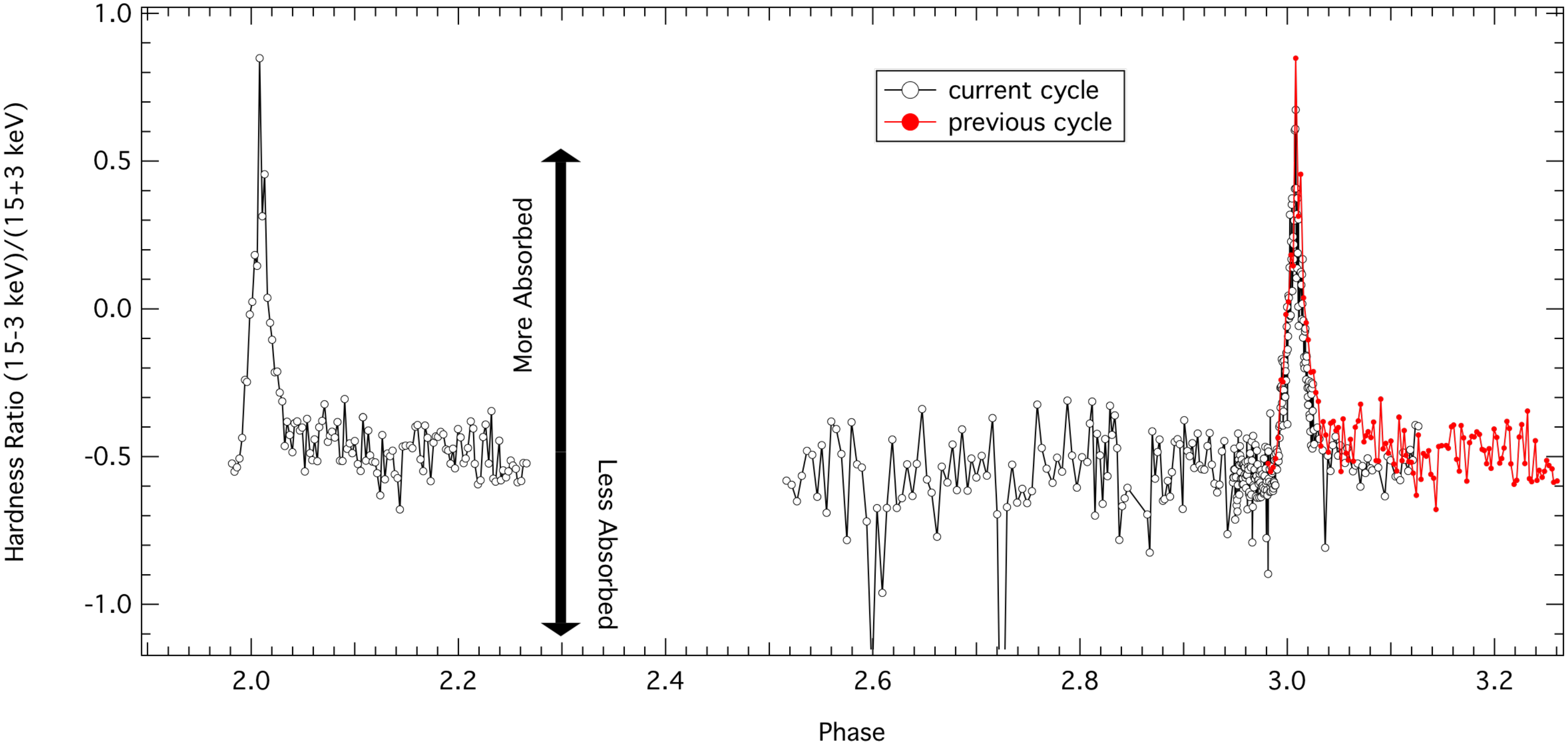
- Bright, variable X-ray source (unusual for a single massive star, even more unusual for a single WR star)

- Variable X-ray spectrum: Changes in emission measure of the hot gas, absorption to the hot gas

- Hard source: kT ~ 3-4 keV (also unusual for single massive star)

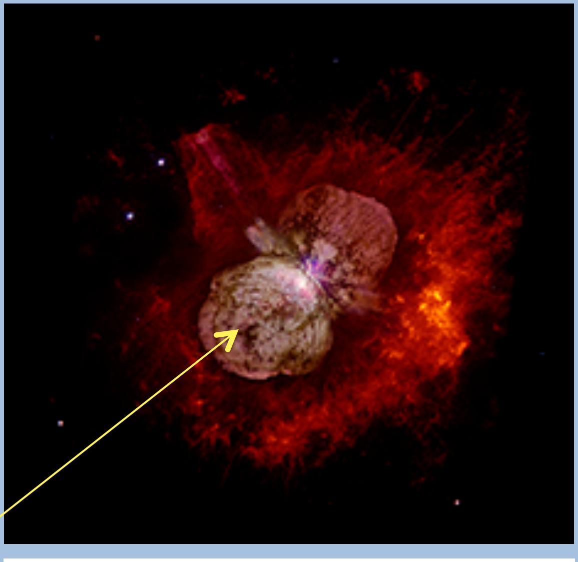
Need Detailed Monitoring:
the Rossi X-ray Timing Explorer

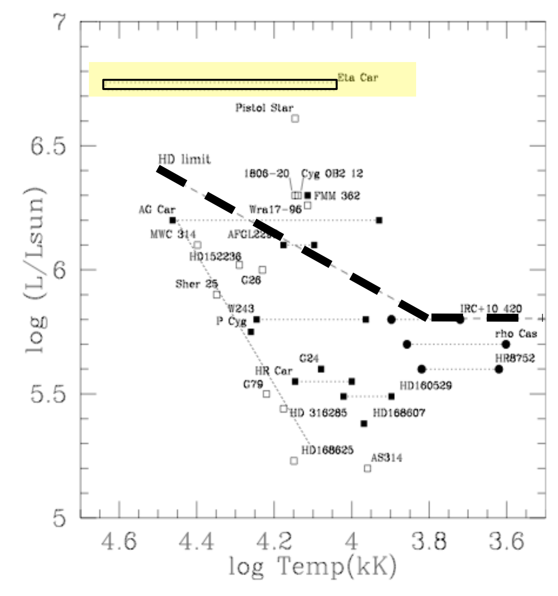
Color Change

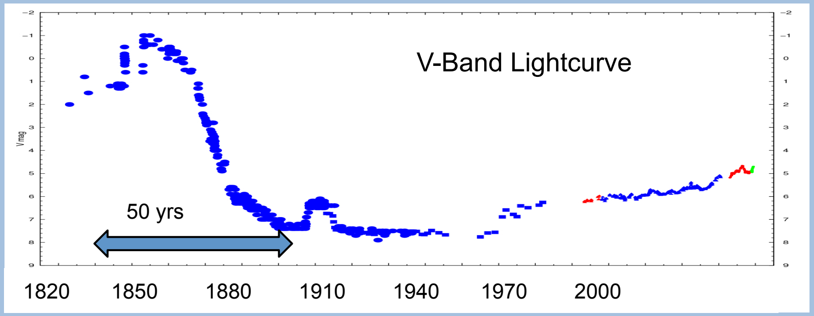


A Brief History of Eta Car

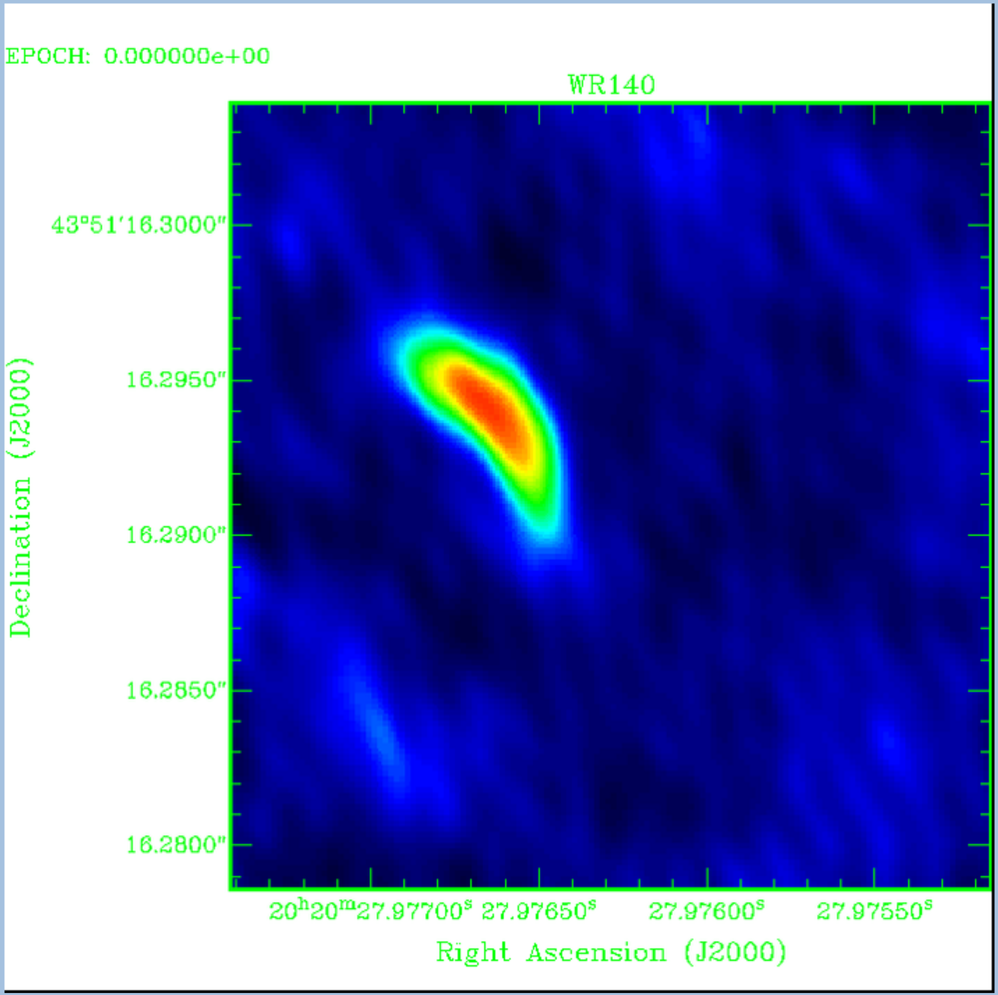
- Between $4<V<2$ from 1600s – 1800s
- 1843: $V \approx -1$ (at a distance of 2.3 kpc!): “Great Eruption”
- A supernova imposter?
- Formation of Bipolar nebula: The Homunculus
- Dust Formation
- “Lesser Eruption” in 1890
- “Little Homunculus”: bipolar inner nebula
- Growing visually brighter





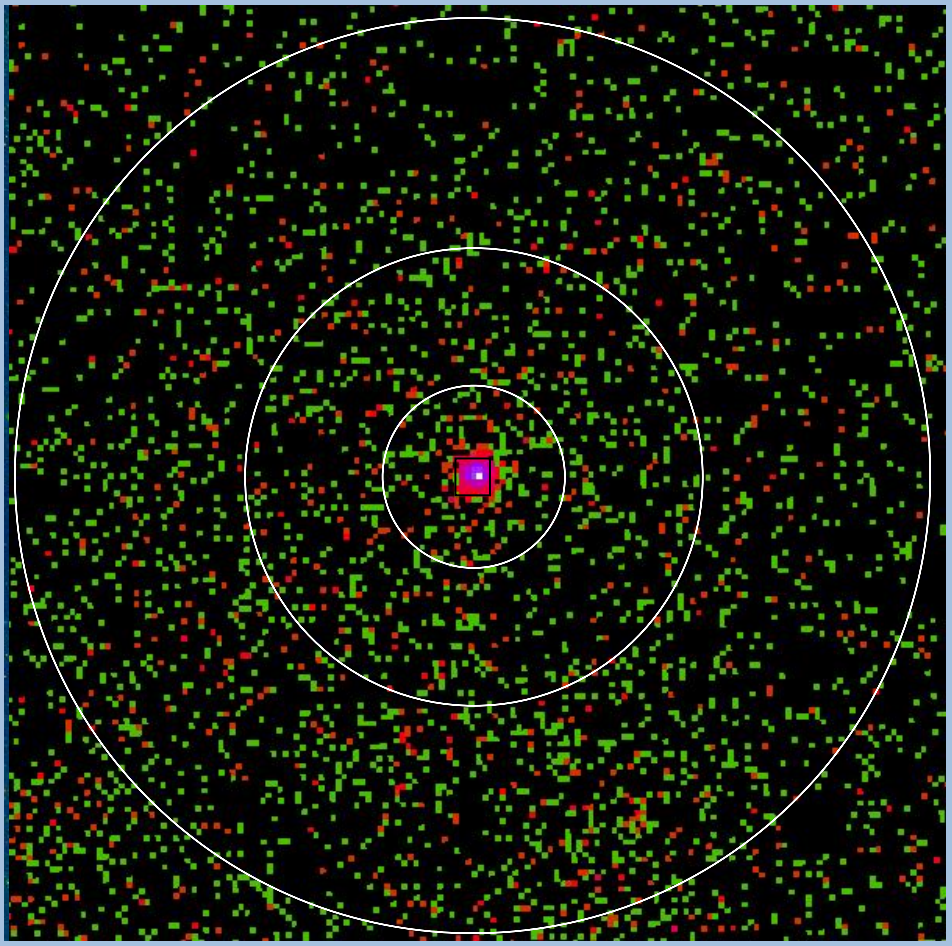


Direct Imaging



VLBA imaging courtesy S Dougherty

What RXTE Sees:



RASS 2x2 degree image of WR 140, 0.5-2 keV
(with RXTE 5%, 30% & 80% contours)

Optical: Crowded Stellar Field

X-ray: WR 140 dominant source

Dominated by WR140 CW emission above 2 keV

RXTE Instrumentation

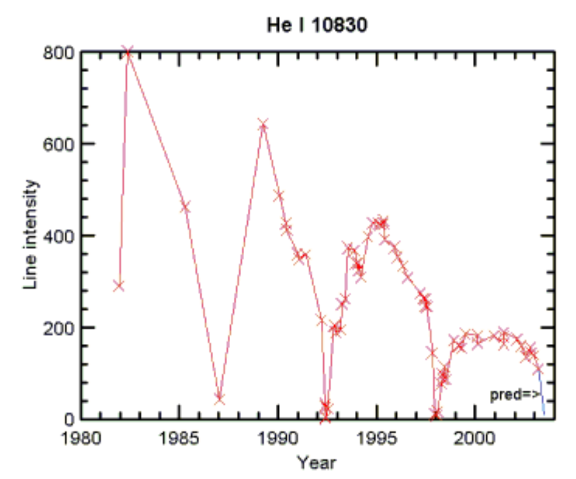
RXTE has 3 instruments:

- The Proportional Counter Array (PCA):
  - a set of five collimated Xenon-filled proportional counter units
  - 2-70 keV; 1600 cm^2
  - Most useful for WR 140

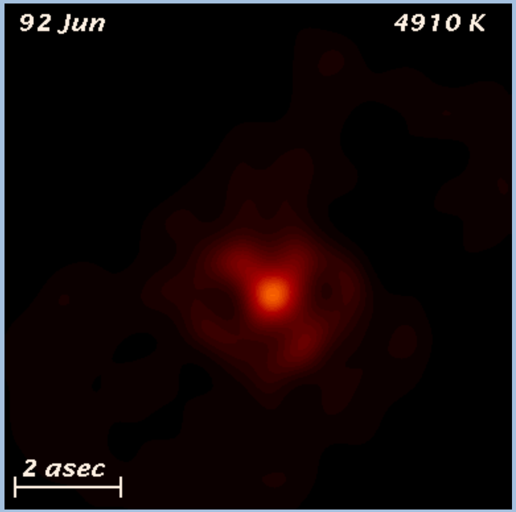
- The High Energy X-ray Timing Experiment (HEXTE)
  - two clusters of 4 NaI/CsI scintillator detectors
  - 15-250 keV; 1600 cm^2

- The All-Sky Monitor (ASM)
  - 3 shadow cameras; 90 cm^2

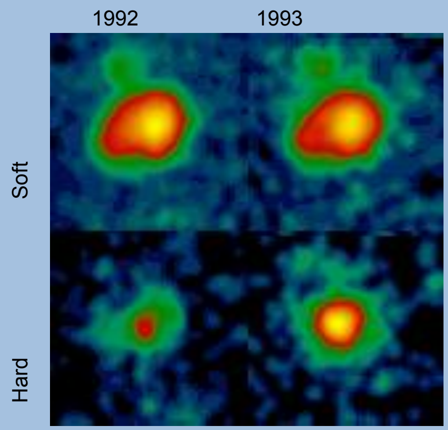
Panchromatic (?) Variability



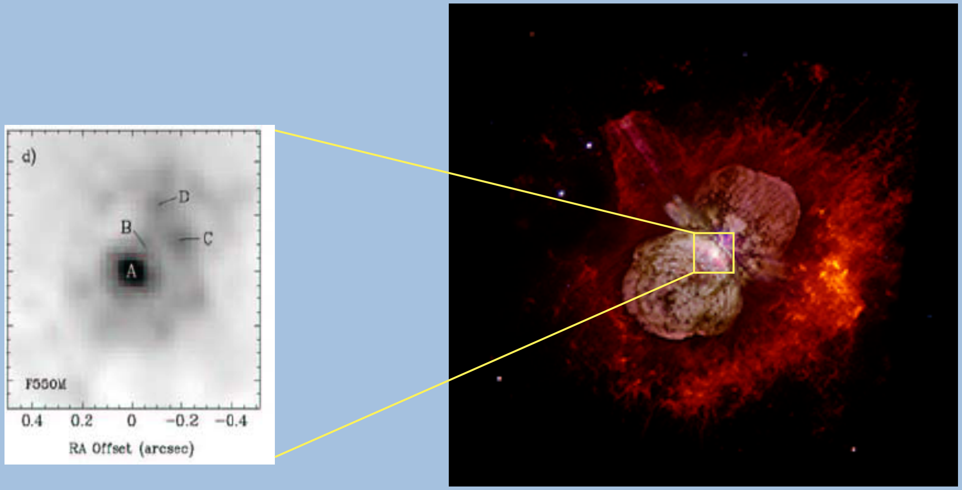
- Periodic spectral variations in He I 10830A (Damineli 1996) and other band
- due to changes in ionization/ excitation in the circumstellar material
- strict period => gravitational dynamics



Radio variability (R. Duncan, S. White et al 1995)



X-rays (Corcoran et al. 1996)



Outstanding Issues

- Cause of the “Event” (eclipse; cooling/“discombobulation”; phase-dependent mdot? Jet formation?)
- Stability of the bow shock
- Interactions near periastron
- Geometry of the inner/outer wind
- Density profile of the inner wind of Eta Car
- Radial velocities & mass ratio

Goals:

➔3-D Reconstruction of mass outflows, ejecta, photon fields

➔ Use the orbit of the companion as a probe of the fundamental parameters of Eta Car

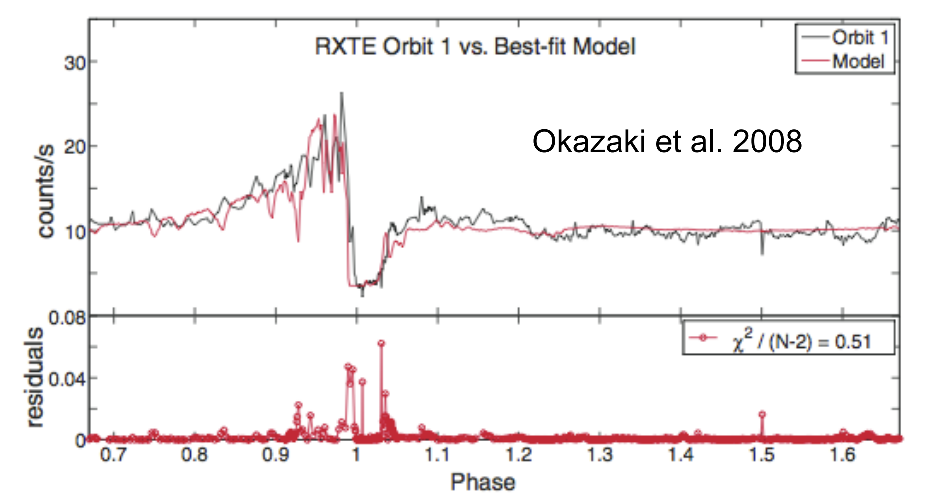
RXTE Observations

RXTE started observing 2-10 keV emission from Eta Car shortly after launch in Feb 1996

Continued monitoring with daily/weekly/monthly cadence since then

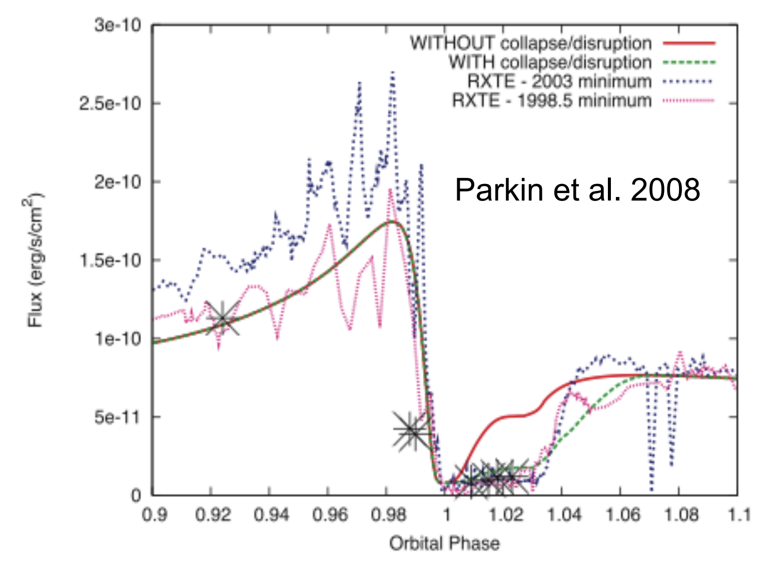
Daily monitoring near X-ray minima

Lightcurve Modeling



Okazaki et al. 2008

3-D SPH + Isothermal point source emission



Parkin et al. 2008

3-D Hydro + extended emission via 2-D hydro

Duration of X-ray minimum suggests collapse of shock
(radiative braking? radiative inhibition?)

A Coupled Problem

- Evolution effects mass loss
- Mass loss effects evolution

$$
\begin{aligned}
\log \dot{M} = & - 6.688\ (\pm 0.080) \\
& + 2.210\ (\pm 0.031) \log(L_*/10^5) \\
& - 1.339\ (\pm 0.068) \log(M_*/30) \\
& - 1.601\ (\pm 0.055) \log\left(\frac{v_\infty/v_{\rm esc}}{2.0}\right) \\
& + 1.07\ (\pm 0.10) \log(T_{\rm eff}/20\,000) \\
& + 0.85\ (\pm 0.10) \log(Z/Z_\odot)
\end{aligned}
$$

$$\text{for } 12\,500 \le T_{\rm eff} \le 22\,500 \text{ K}$$

$$
\begin{aligned}
\log \dot{M} = & - 6.697\ (\pm 0.061) \\
& + 2.194\ (\pm 0.021) \log(L_*/10^5) \\
& - 1.313\ (\pm 0.046) \log(M_*/30) \\
& - 1.226\ (\pm 0.037) \log\left(\frac{v_\infty/v_{\rm esc}}{2.0}\right) \\
& + 0.933\ (\pm 0.064) \log(T_{\rm eff}/40\,000) \\
& - 10.92\ (\pm 0.90)\ \{\log(T_{\rm eff}/40\,000)\}^2 \\
& + 0.85\ (\pm 0.10) \log(Z/Z_\odot)
\end{aligned}
$$

$$\text{for } 27\,500 < T_{\rm eff} \le 50\,000 \text{ K}$$

(rotation? magnetic fields?)

Vink et al. 2001