Multi-wavelength Observations of Colliding Stellar Winds

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Outline of Talk

- Statement of the Problem
- Massive Stars as Colliding Wind Labs
  - Wind Characteristics
  - Types of Interactions
- A (non) canonical Example: Eta Car
- New high resolution tools
- Colliding winds in Single Stars
- Conclusions

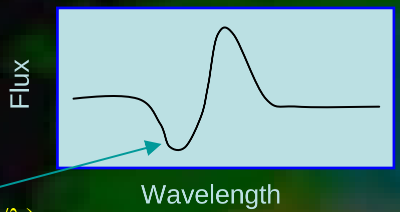
Statement of a General Problem:

- An “engine” loses mass into its surroundings
- the surroundings are “messy” and the outflow collides with nearby “stuff”
- by observing the results of this collision, we can learn about the engine, its environment, and the relation between the engine and the environment
- Concentrate on: Massive outflows from massive (non-exploding) stars
- neglect interesting phenomena like magneto-hydrodynamic interactions in winds of lower mass stars and AGB

Massive Stars ($10<M/M_{\odot}<100$): Colliding Wind Labs

- Wind parameters (mass loss rates, wind velocities) can be characterized (UV, radio)

P-Cygni profiles



$V_{\infty}=(\Delta\lambda/\lambda)c$

$$S_{\nu} = 23{\cdot}2 \left(\frac{\dot{M}}{\mu v_{\infty}}\right)^{4/3} \frac{\nu^{2/3}}{D^{2}} \gamma^{2/3} g^{2/3} Z^{4/3} \text{ Jy}$$

- Stellar parameters (masses, temperatures, radii, rotational velocity) can often be estimated
- They are nearby
- Generate X-ray & Radio emission

Stellar Wind Characteristics

- For Massive Stars Near the Main Sequence

$$\dot{M} > 10^{-6} M_{\odot} \mathrm{yr}^{-1}$$
$$V_{\infty} \sim 1000 \mathrm{~km~s}^{-1}$$
$$L_{wind} \sim 10^{36} \mathrm{ergs~s}^{-1}$$

•Lots of energy to accelerate particles and heat gas
•Evolutionary scenario: O⇒WR (⇒LBV)⇒WR⇒SN
•Winds evolve as the star evolves:

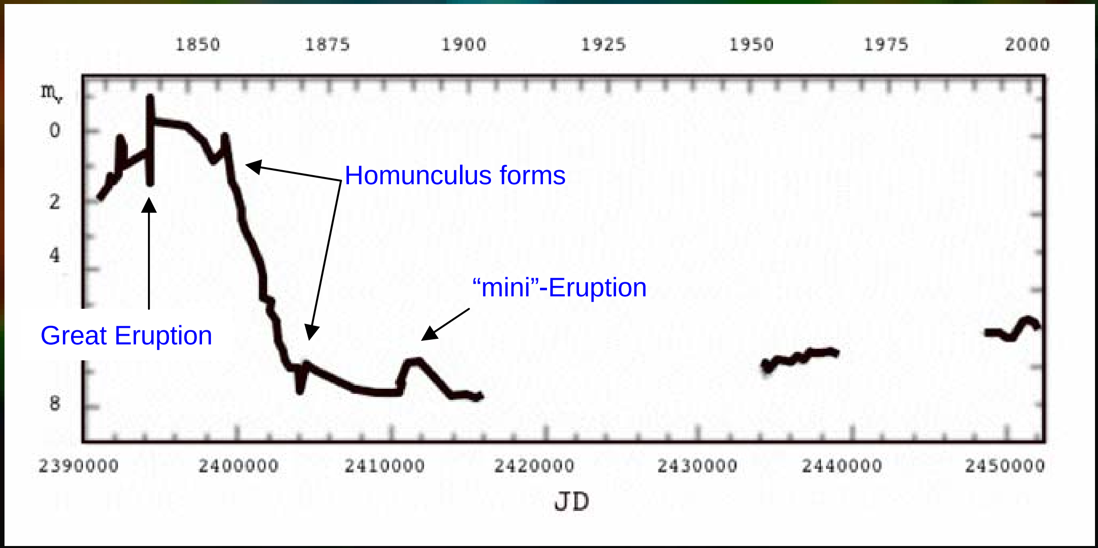
$$\text{Luminous Blue Variable}: \dot{M} \sim 10^{-3} M_{\odot} \mathrm{yr}^{-1}, V_{\infty} \sim 500 \mathrm{~km~s}^{-1}$$
$$\text{Wolf-Rayet}: \dot{M} \sim 10^{-5} M_{\odot} \mathrm{yr}^{-1}, V_{\infty} \sim 2000 \mathrm{~km~s}^{-1}$$

Types of Interactions:

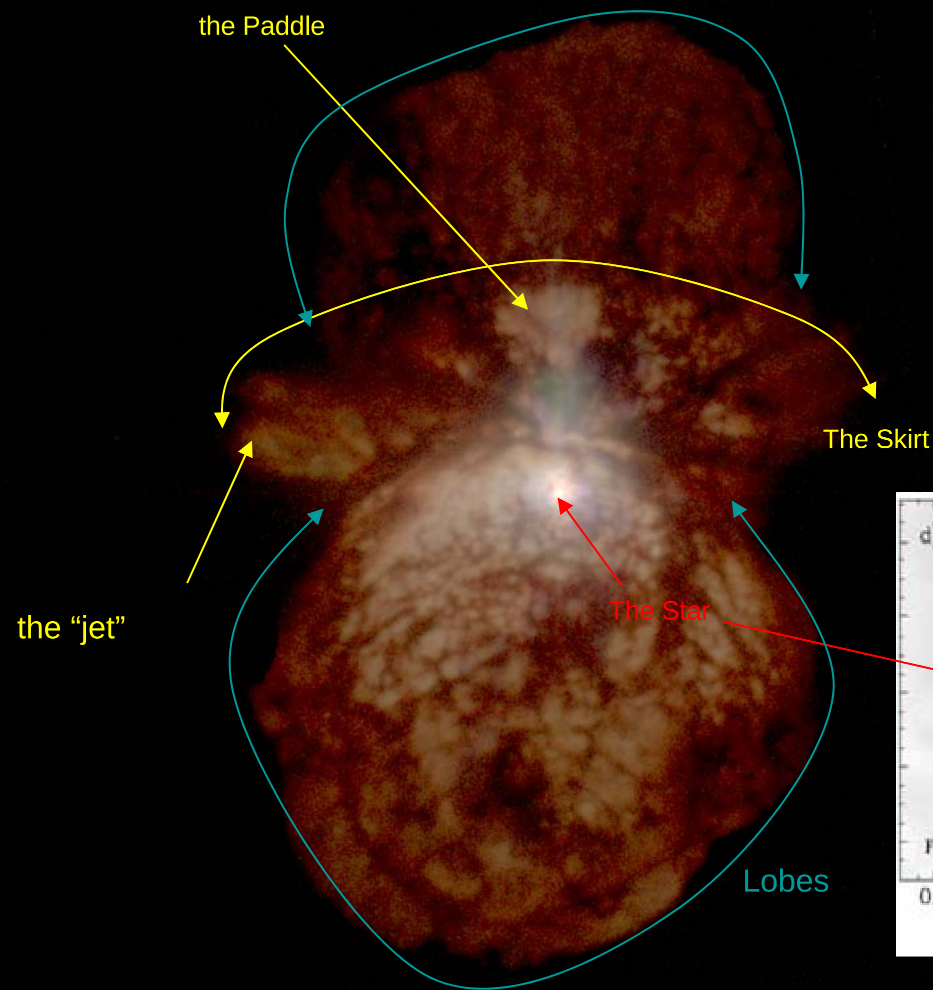
- Stellar outflows can collide with
  - pre-existing clouds
  - earlier ejecta
  - winds from a companion
  - a companion
  - itself
- All these collisions can produce observable emission from shocked gas
- Typical velocities 100-1000 km/s $\Rightarrow$ T ~ 10^6 K

A (non)canonical example: Eta Carinae

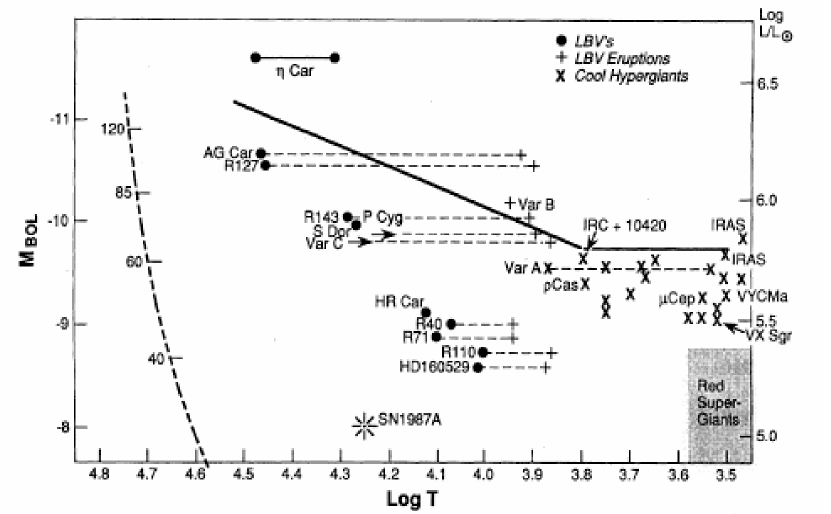
- Eta Car: perhaps the Galaxy's most massive & luminous star ($5\times10^6\ L_\odot$; $100\ M_\odot$; cf. the Pistol Star, LBV1806-20)
- An eruptive star (erupted in 1843; 1890; 1930?; now?)
- shows beautiful ejecta: outer debris field and the "Homunculus" nebula



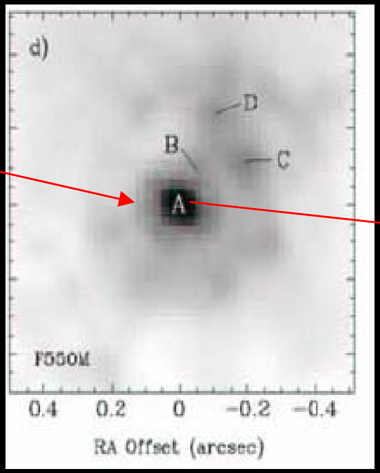
Eta Car and the Homunculus

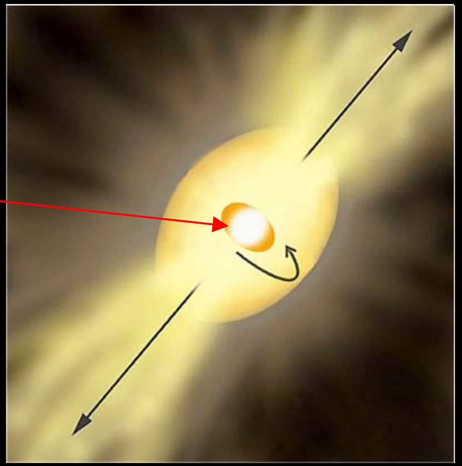


HST/ACS image of Eta Car (Courtesy the HST TREASURY PROJECT)



Humphrey and Davidson 1994



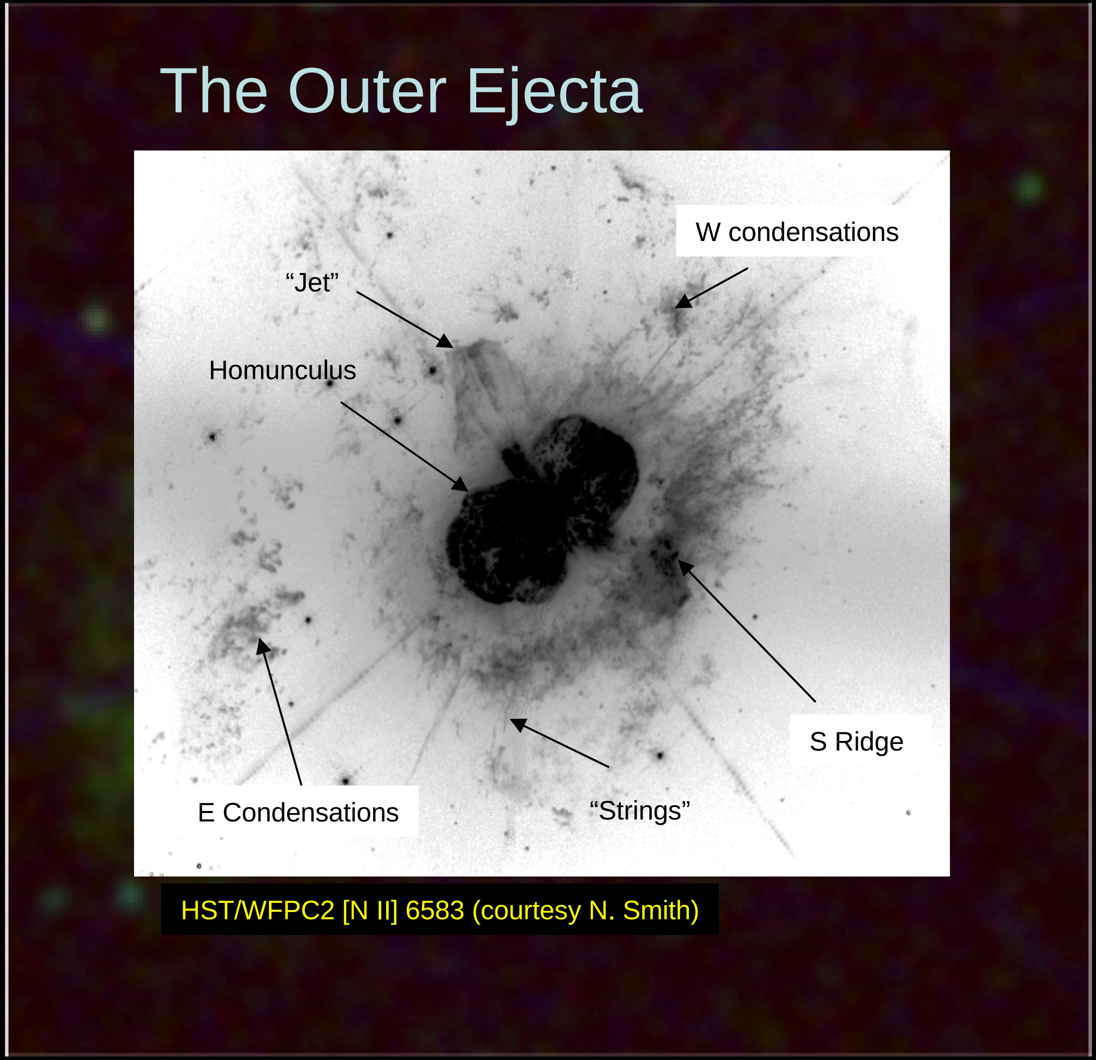


Artist rendering of Eta Carina based on Very Large Telescope Interferometer (ESO) observations

Eta Car: From the Outside In

Outer debris ejected a few hundred years before the Great Eruption

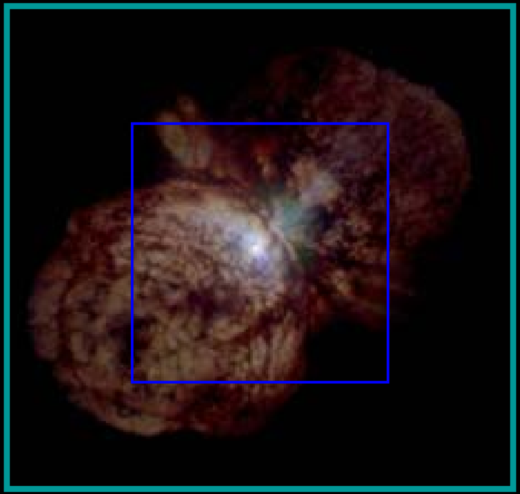
shocks from ejecta/CSM collision

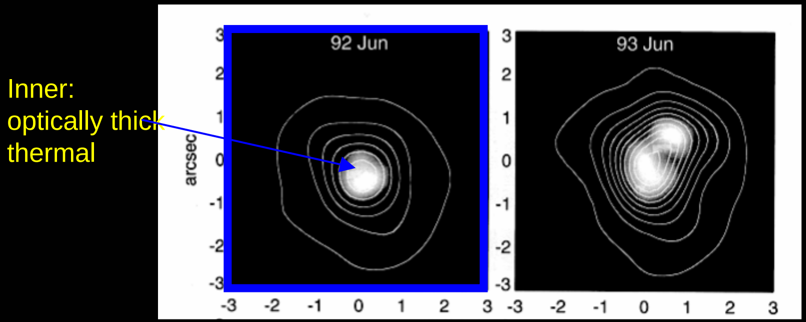


HST/WFPC2 [N II] 6583 (courtesy N. Smith)

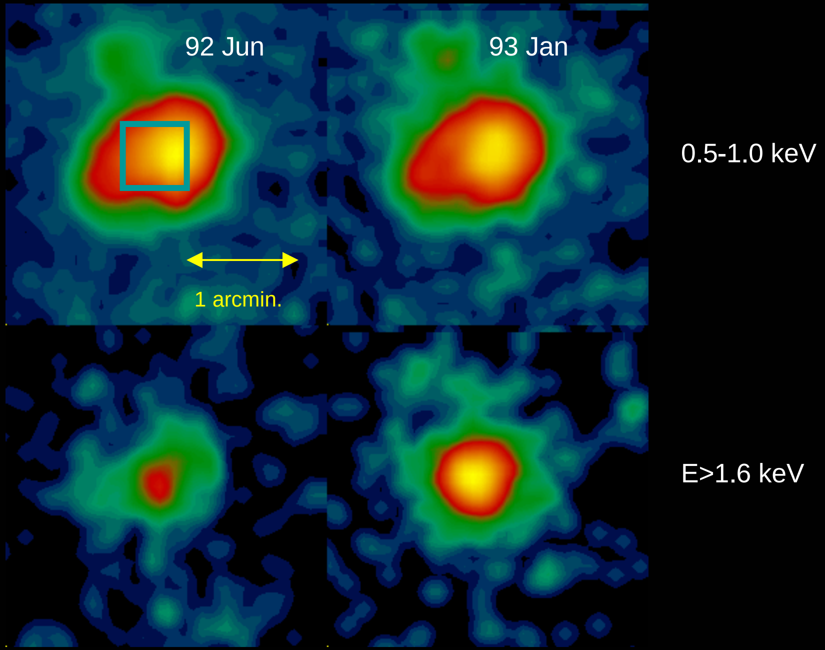
The Stellar Emission

1992: contemporaneous radio & X-ray observations saw a rapid brightening of the star





3 cm. continuum (Duncan et al. 1995)

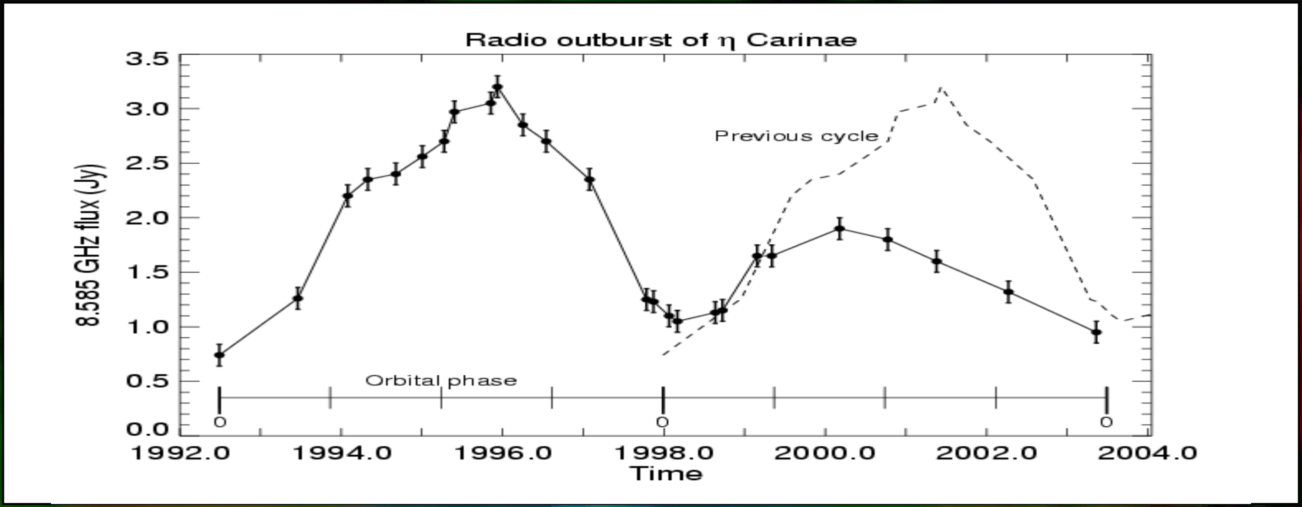


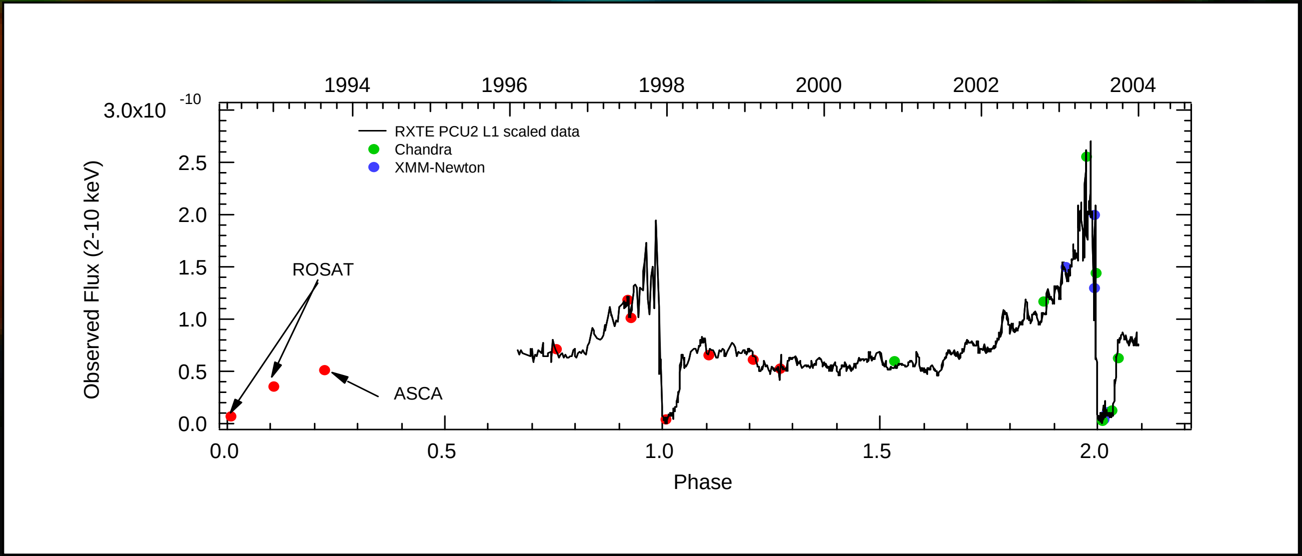
X-ray continuum (Corcoran et al. 1995)

Continued Variability

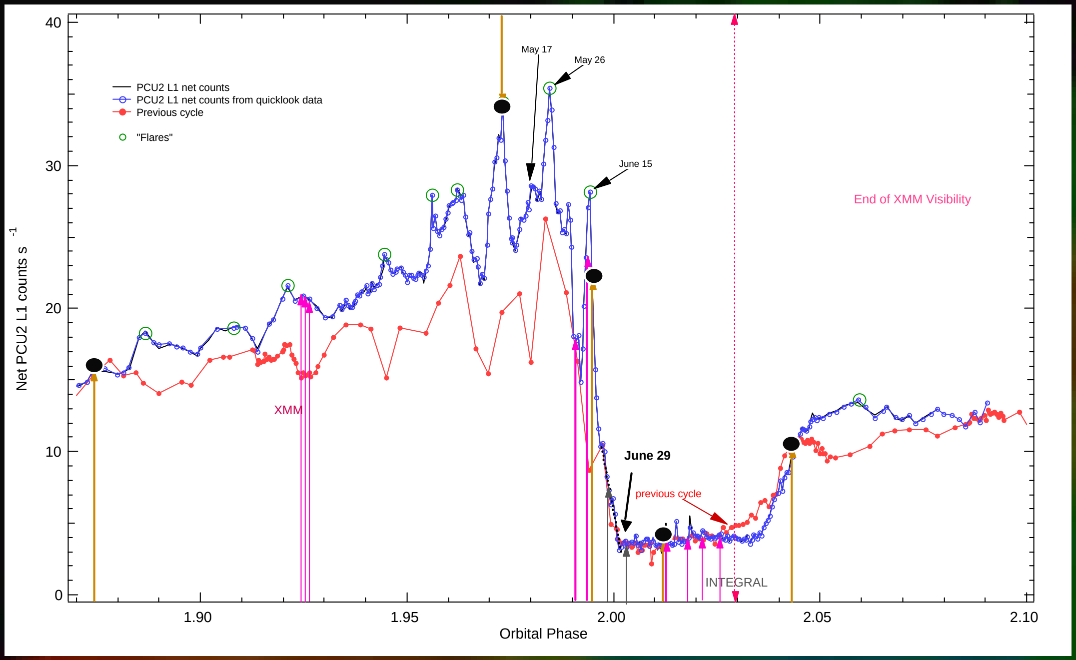
- Monitoring since 1992 in radio and X-ray regimes showed continuous variability
- Damineli (1996) showed evidence of a 5.5 year period from ground-based spectra
- apparent simultaneous variations in ground-based optical, IR, radio and X-rays suggest periodically varying emission: colliding winds?
- one star or two?

Radio and X-ray Monitoring of Eta Car

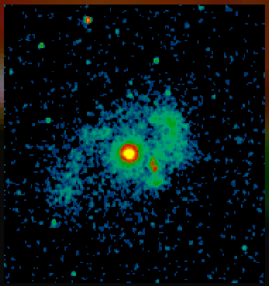


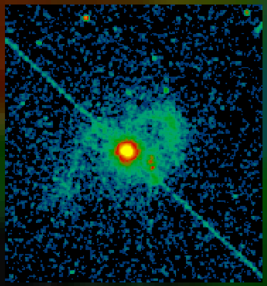


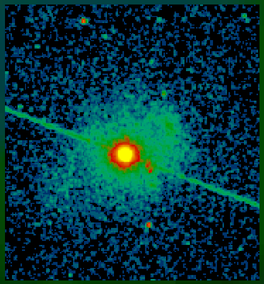
Eta Car’s Latest Eclipse (June 29, 2003): Caught in the Act

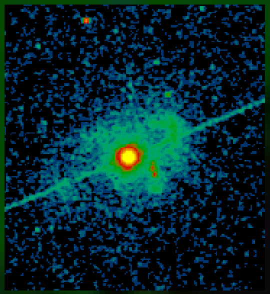


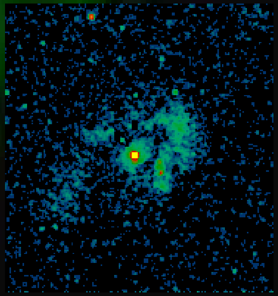
Around the time of the X-ray eclipse, snapshot monitoring of Eta Car’s X-ray emission by Chandra and the XMM-Newton X-ray Observatories

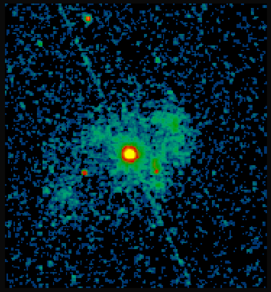

Nov 20 2000


Oct 16 2002

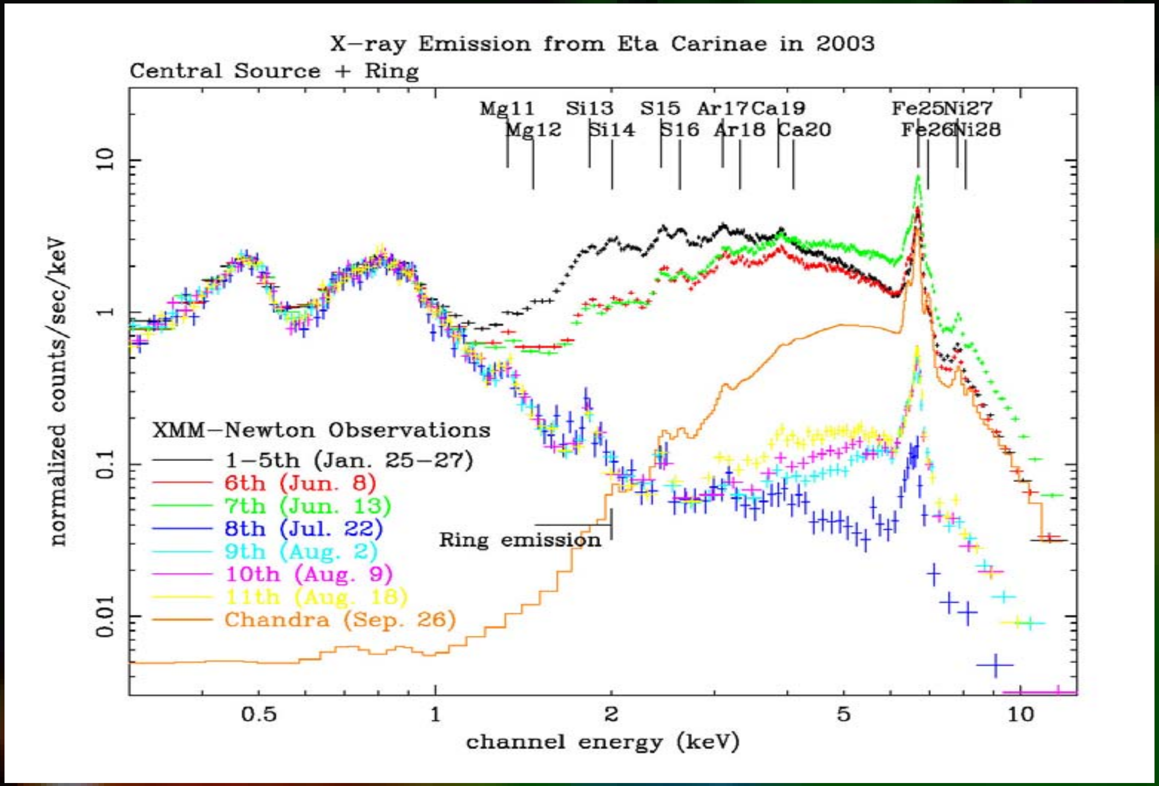

May 3 2003


Jun 16 2003

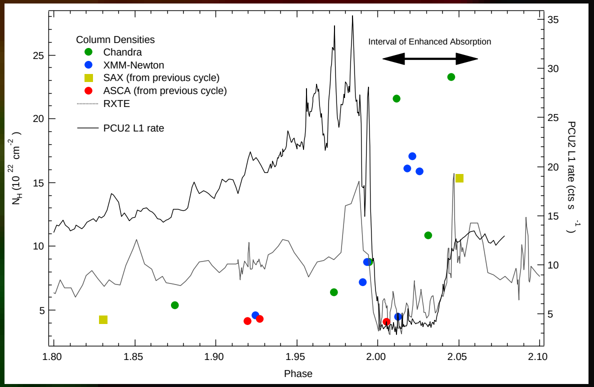

Jul 20 2003


Sep 26 2003

Absorption variations



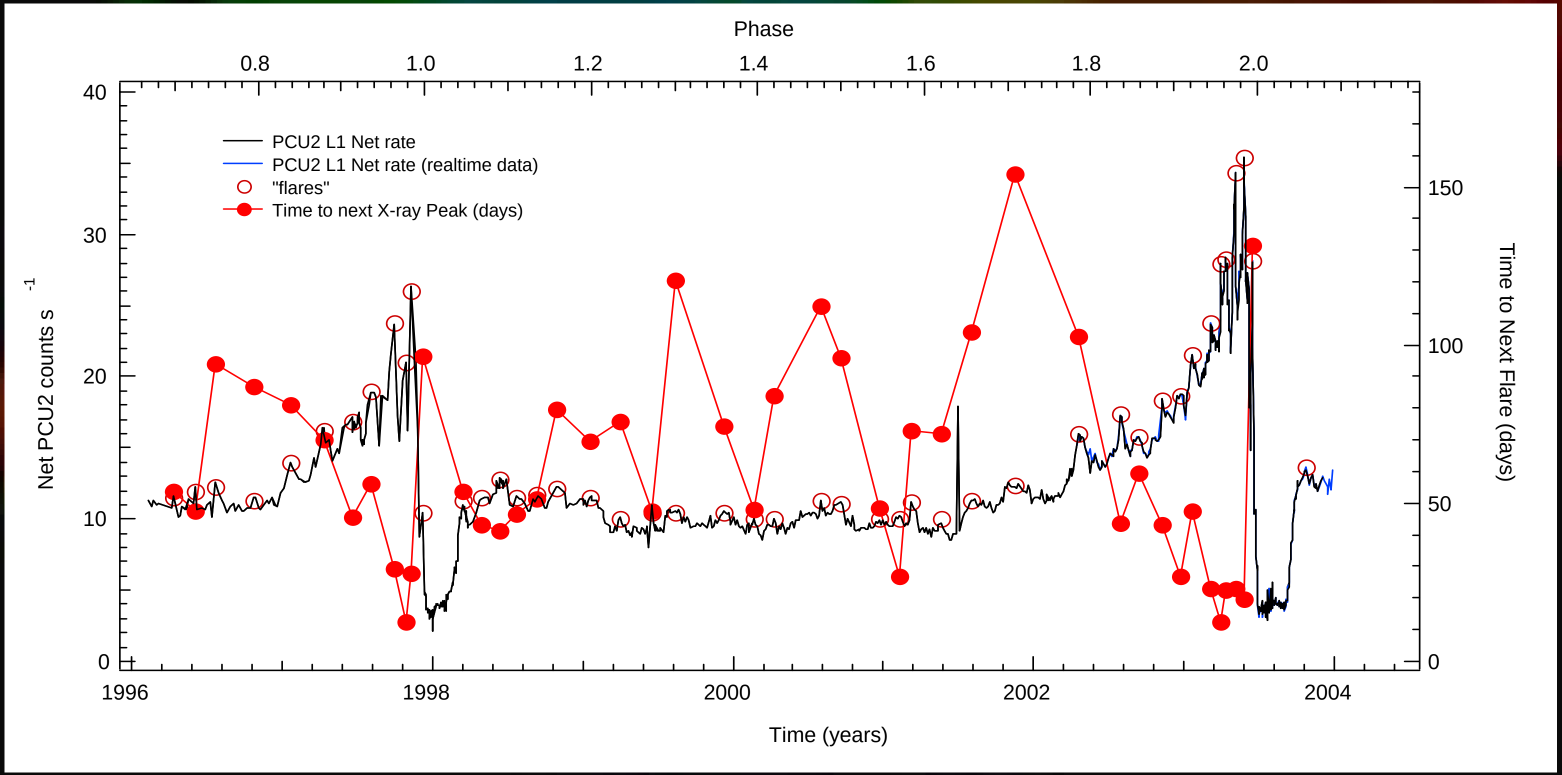
Variation of X-ray spectrum from XMM-Newton observations



Variation of observed X-ray flux and column density during 2003 X-ray minimum

X-ray "flares"

- Frequent monitoring of the X-ray flux of Eta Car with RXTE showed unexpected quasi-periodic spikes occurring ~every 3 months
- get stronger and more frequent on approach to X-ray minimum



Red points show the time between X-ray peaks.

A Simple CWB Model

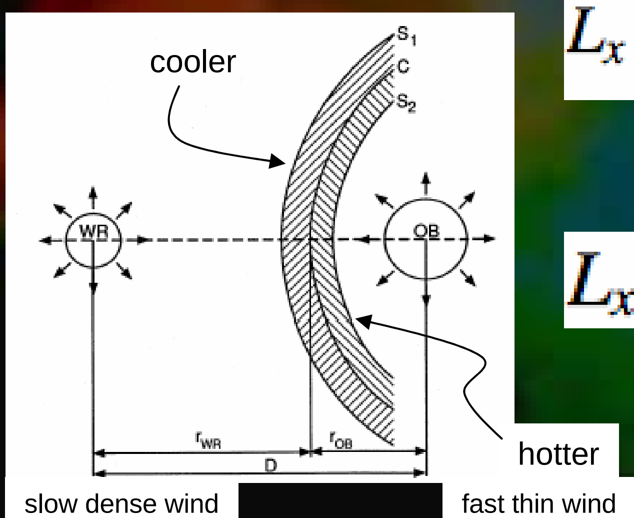
• X-rays are generated in the shock where the massive, slow wind from Eta Car smashes into and overcomes the thin, fast wind from the companion

$$\dot{p}_{wind,\eta}/\dot{p}_{wind,c} = \frac{\dot{M}_\eta V_{\infty,\eta}}{\dot{M}_c V_{\infty,c}}$$

force balance determines which wind dominates

$$L_x \propto n^2 v \propto \frac{\dot{M}^2}{D}$$

Intrinsic X-ray luminosity varies the square of the density x volume

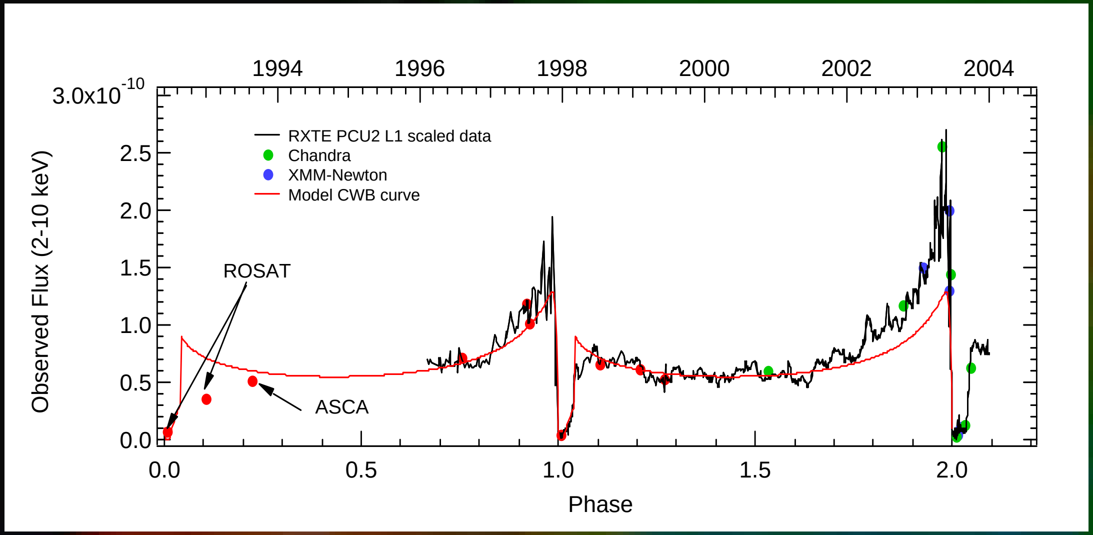


$$L_{x,obs} \propto L_x e^{-\sigma N_H}$$

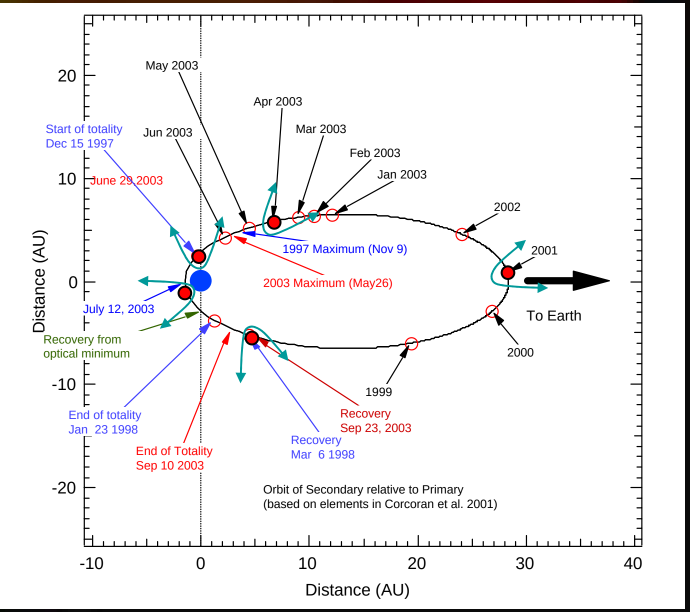
Observed flux is proportional to intrinsic flux modified by absorption

In eccentric orbit, intrinsic L_x a maximum at periastron

Comparisons to the Simple Model



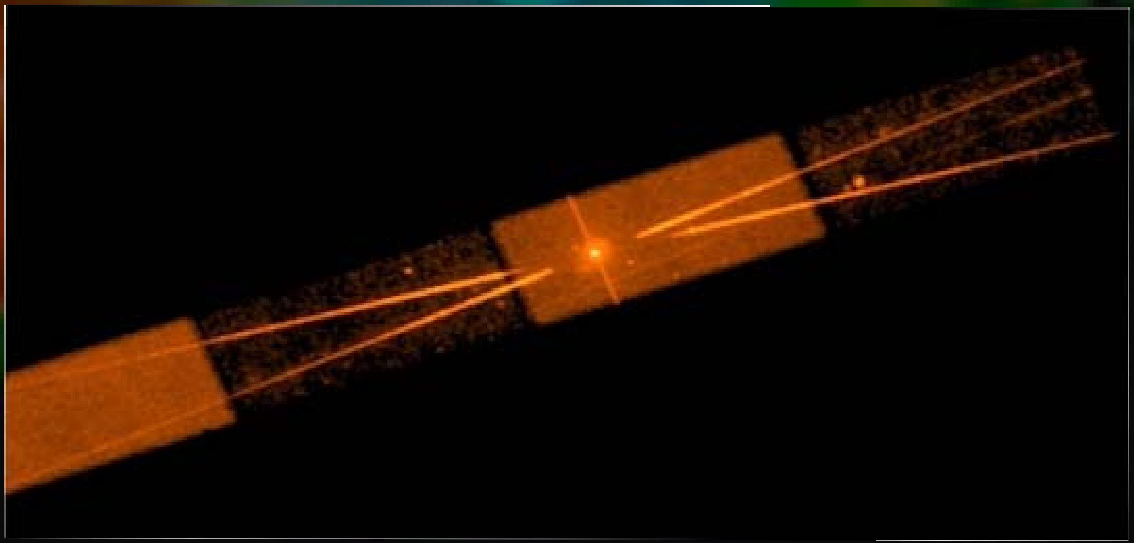
- General trends are reproduced; details (secular increases in L_x, short-period variability) not
- requires extra absorption to match width of minimum



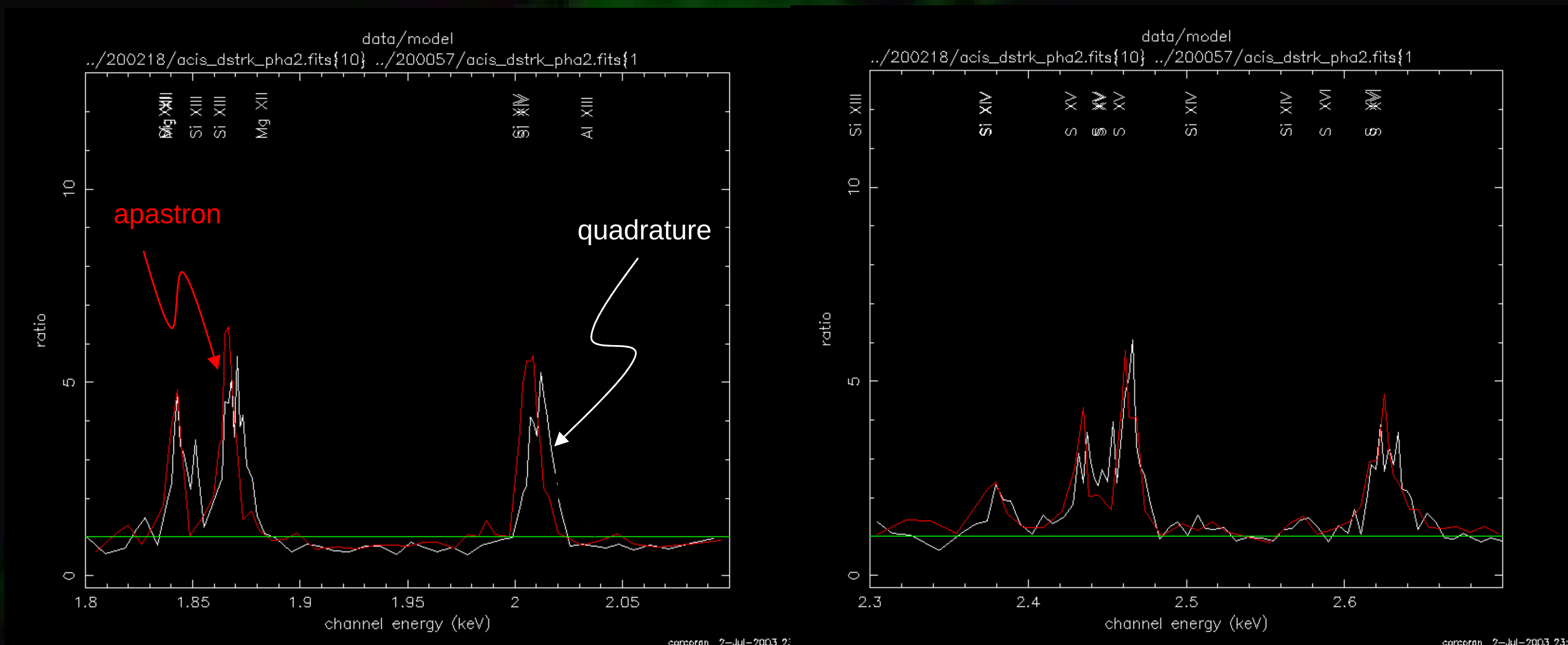
Derived orbit of companion around Eta Car, based on the model lightcurve

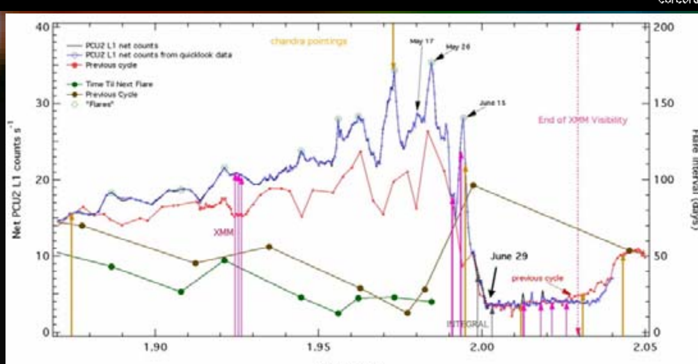
X-ray Grating Spectroscopy: Measuring the Flow Geometry

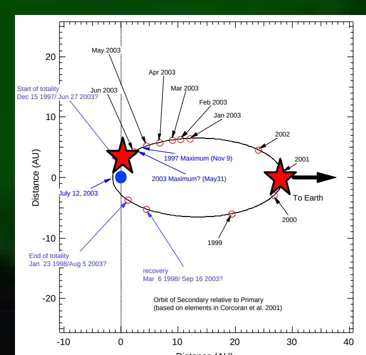
- Nearby CWB systems are bright enough for X-ray grating spectroscopy
- line diagnostics (width, centroids, ratios) measure characteristics of the material flow in the shock, the location of the shock between the stars, the orientation of the shock cone



Comparison: Apastron vs. Quadrature



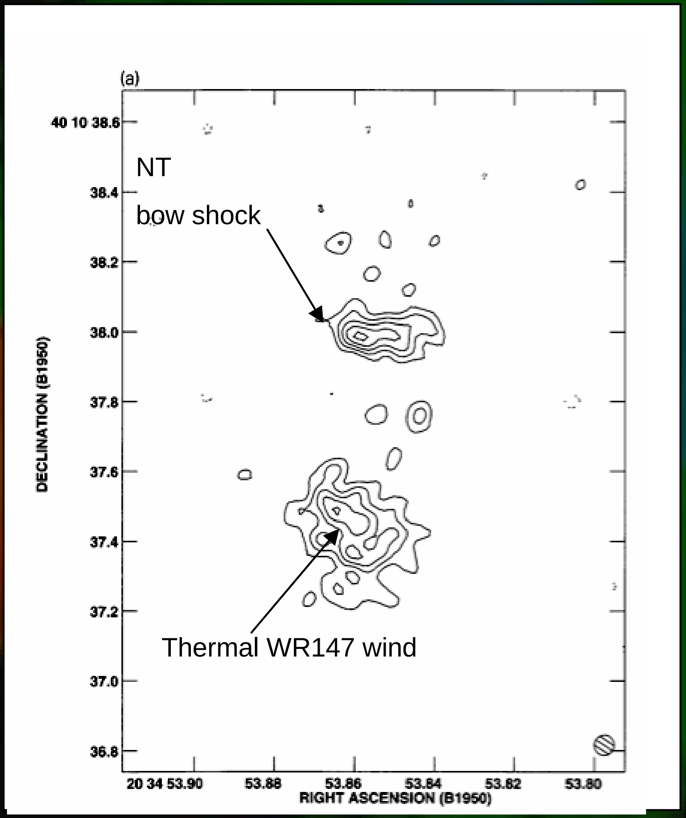




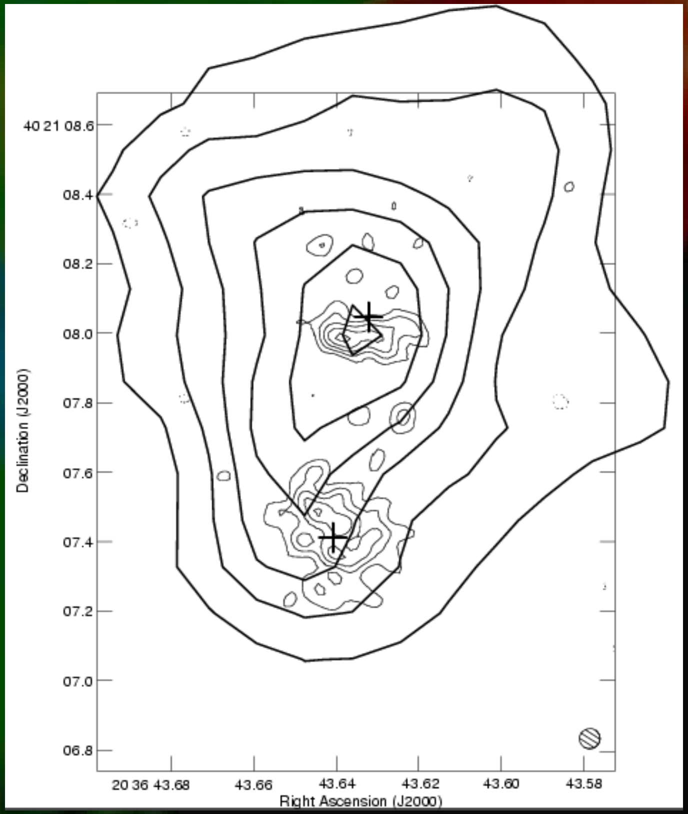
- Decrease in f/i ratio
- broader, double-peaked lines
- Doppler shifts?

Spatial Morphology (1): Resolving the shock structure

WR 146, WR 147: composite radio spectra, have been resolved in the radio, NT emission from a bow shock

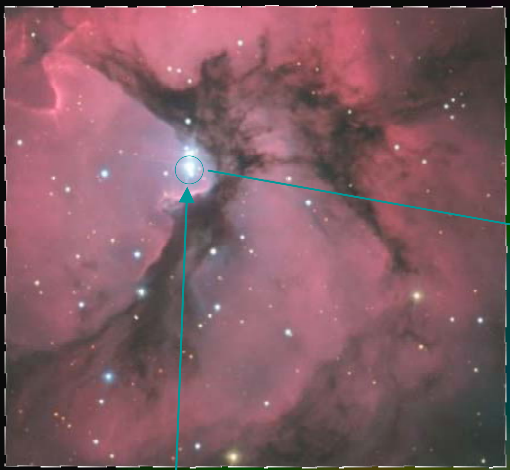


WR 147: Williams et al (1997)

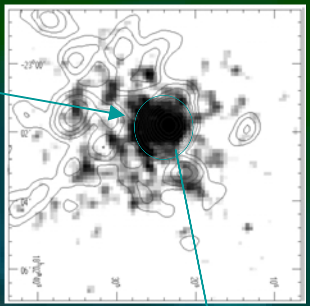


Pittard et al. (2002)

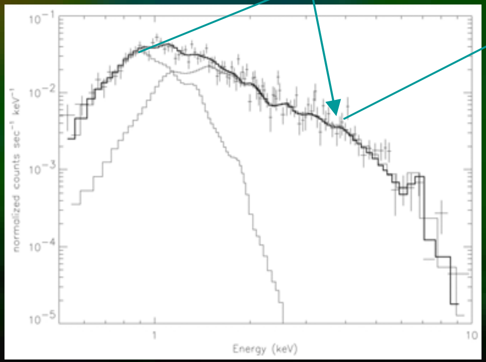
Resolving Confusion in The Trifid Nebula



HD 164492A (O7.5III) ionizes the nebula

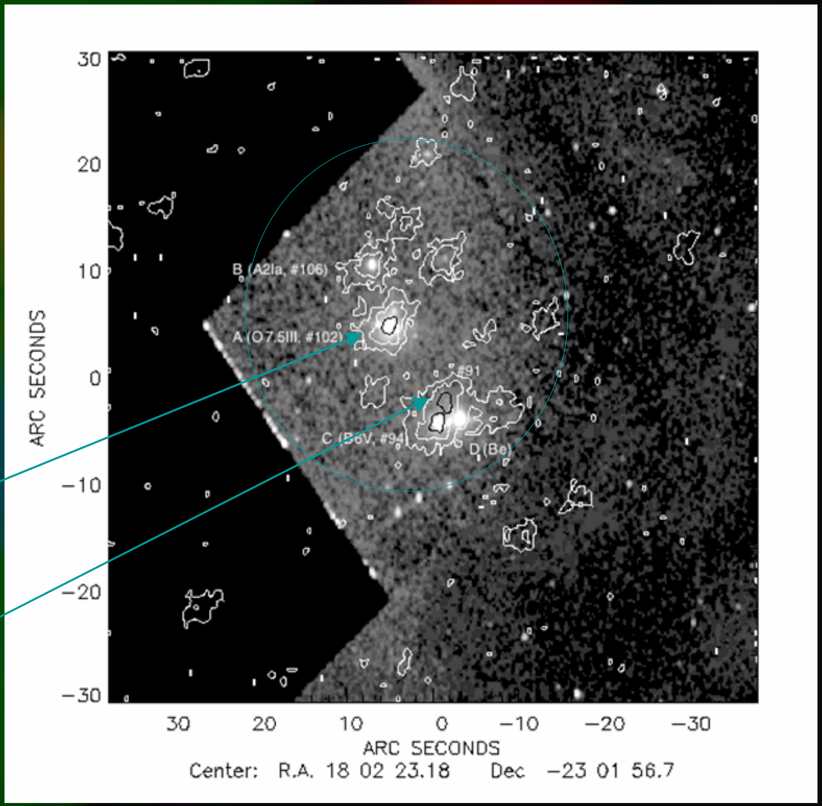


ROSAT & ASCA found a bright hard source coincident with the star



Rho et al. 2001

Rho et al. 2004



…but Chandra resolved the O star as a soft source; hard source is an optically faint object to the south

Self-Colliding Winds

- Radiatively driven winds intrinsically unstable to doppler perturbations (Lucy & Solomon 1970; Feldmeier 1998). Shocks can form and produce observable emission
  - X-rays: soft, non-variable
  - NT radio?

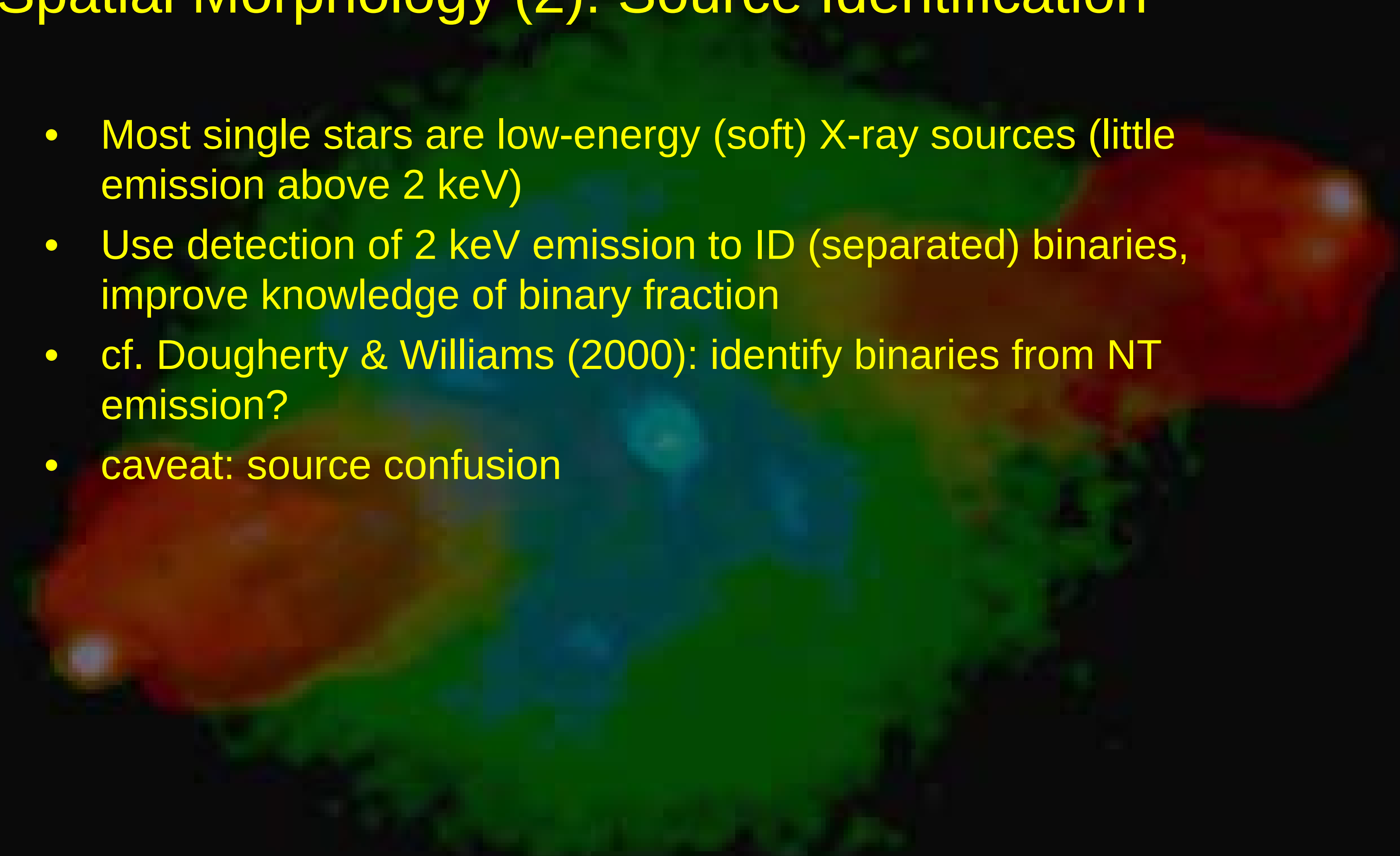
- Dipolar magnetic field (few hundred G at surface) embedded in a wind can produce magnetically confined wind shock (Babel & Montmerle 1997)
  - rotationally modulated
  - hard emission
  - explains θ^1 Ori C?

Conclusions

- Colliding wind binary stars provide good laboratories for testing models of shock-generated radio & X-ray emission
- Studies of CW emission provide unique information about the densities, temperature ranges and structure of the interaction region
- Detailed timing, spectral and imaging studies suggest shocks and winds are not smooth and homogeneous
- shape, stability and aberration of the shock cone important
- X-ray line profile variability can reveal details about the geometry and dynamics of the outflow
- Presence of hard X-ray emission and/or NT radio emission from unconfused sources may be a good indicator of a companion (and hence a good probe of the binary fraction for long-period systems)

Spatial Morphology (2): Source Identification

- Most single stars are low-energy (soft) X-ray sources (little emission above 2 keV)
- Use detection of 2 keV emission to ID (separated) binaries, improve knowledge of binary fraction
- cf. Dougherty & Williams (2000): identify binaries from NT emission?
- caveat: source confusion



Characteristics of Stellar Colliding Wind X-ray and Radio emission

	X-ray	Radio
SED	collisionally ionized plasma	synchrotron emission (composite spectrum?)
e^- Acceleration	shock heating	Fermi acceleration
Variability	emission measure, luminosity, and absorbing column, not kT	luminosity & absorption
ν_{char}	1GGHz (5keV)	5 GHz (0.02 neV)
WR star $\tau(\nu_{char})$=1 radius	few Rstar	few 100 Rstar