X-ray Emission from Massive Colliding Wind Binaries

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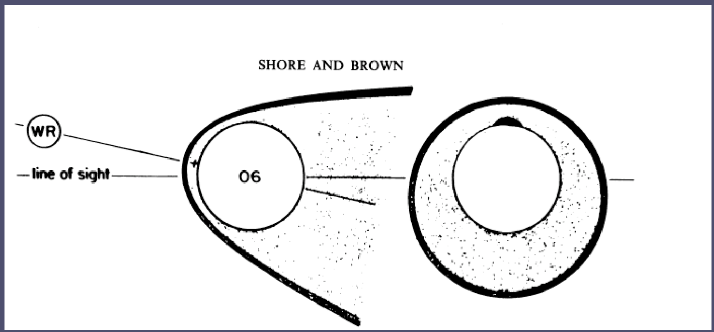
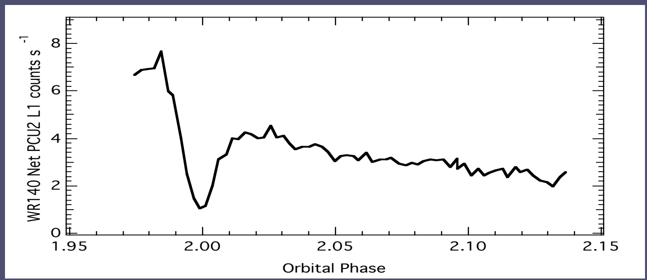
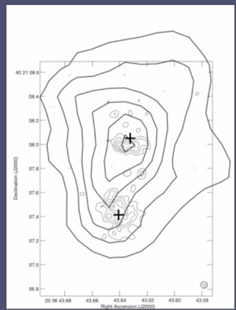
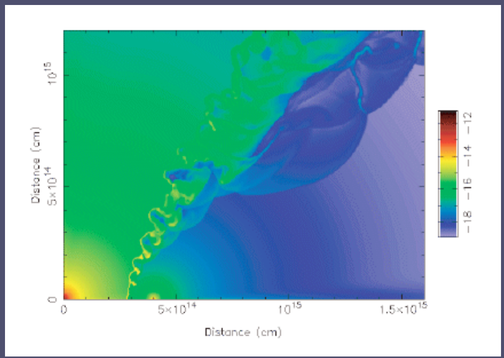
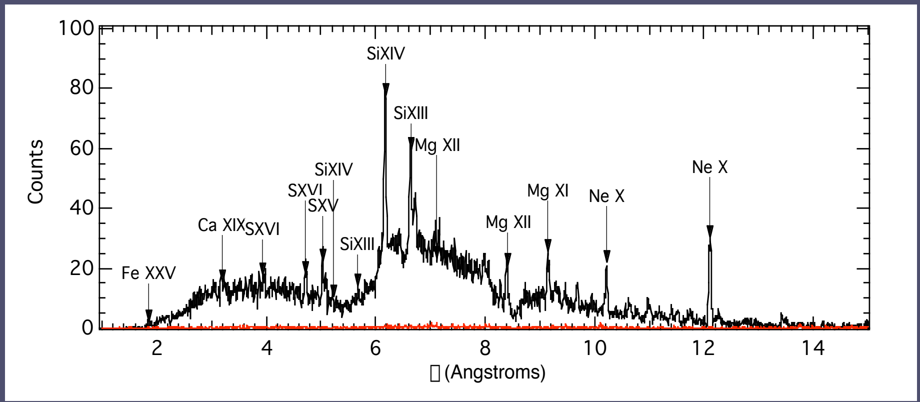










Significance of Wind-Wind Collisions in Massive Binaries

Massive stars are rare, yet have an impact on their host galaxies far beyond their numbers:

- they enrich the ISM via stellar winds with $Z > 2$ elements
- they explode as supernovae (hypernovae?)
- they form stellar-mass black holes

Yet, these stars are rather difficult to study:

- shrouded in winds and circumstellar ejecta (esp. in the later, most interesting evolutionary stages)
- exist in distant regions of high stellar densities
- don't last long

Binaries: Probes of Stellar Structure and Evolution

The theoretical understanding of the internal (nuclear) evolution of massive stars is very mature (and complex), as is the understanding of our understanding of external evolution (i.e. the evolution of the stellar wind & photosphere)

But testing these theories is rather difficult

One method: use binaries

- massive star binary fraction high (> 30%)
- in-situ probe allows direct determination of physical parameters
- but perhaps complications due to mass exchange, orbital evolution, etc. (esp. in close systems) [see Vanbeveren, de Loore & van Rensbergen, 1998, A&ARv, 9, 63]

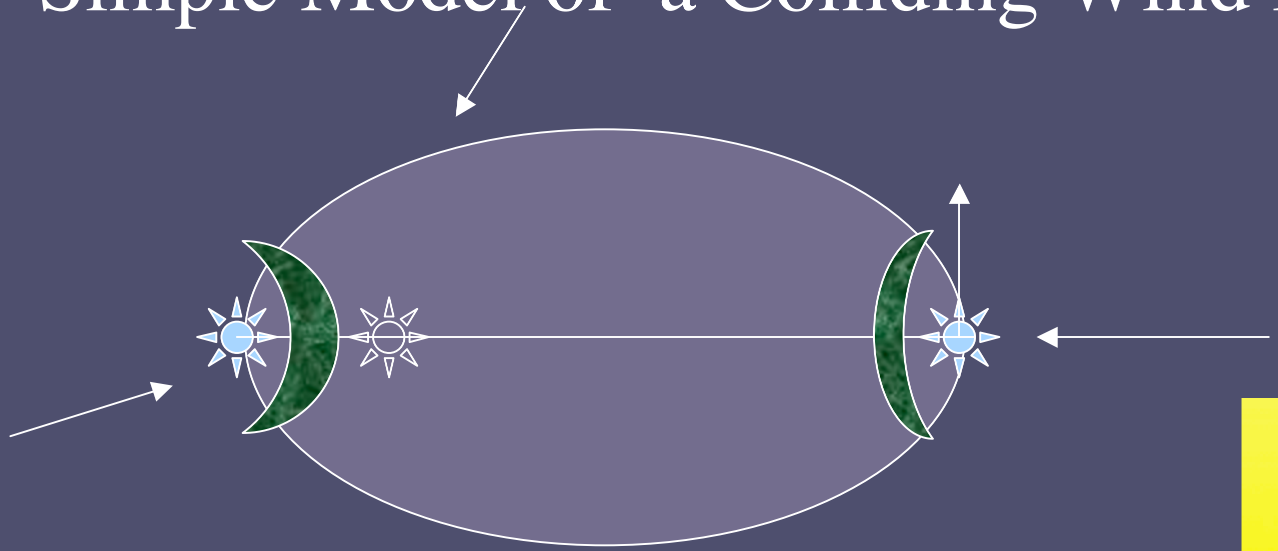
CWB X-ray Emission as a Stellar Probe

Classical methods of binary star analysis (photometric and spectrographic variability analyses) often biased by the presence of circumbinary gas (esp. true for later stages of evolution, where our understanding is poorest)

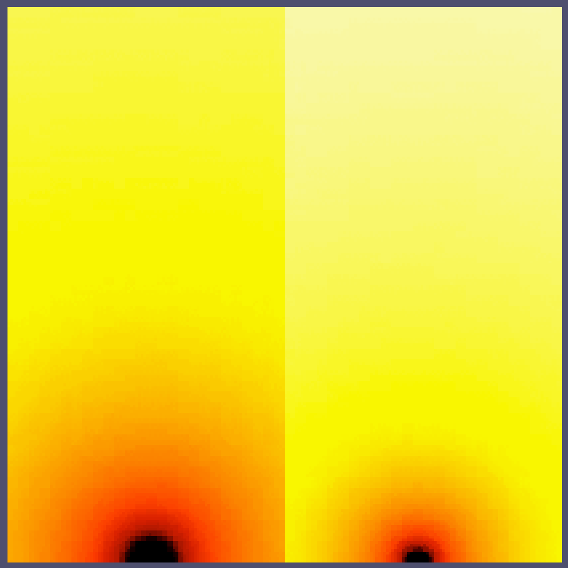
Colliding wind X-ray emission as a binary probe:

- binary detector: strong fast winds should produce observable high-energy (few keV) emission which should be detectable regardless of inclination, stellar separation, etc
- emission is observable independent of inclination
- emission depends on wind properties and orbital properties
- yields a measure of both the shocked and unshocked gas

Simple Model of a Colliding Wind Binary



Courtesy J. Pittard



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

$$\eta = \frac{\dot{M}_{OB} V^{\infty}_{OB}}{\dot{M}_{WR} V^{\infty}_{WR}}$$

From V. V. Usov 1992

$$L_{int} \simeq 1.3 \times 10^{35} \left(\frac{\dot{M}_{WR}}{10^{-5}\ M_{\odot}\ yr^{-1}} \right)^{1/2} \left(\frac{\dot{M}_{OB}}{10^{-6}\ M_{\odot}\ yr^{-1}} \right)^{3/2} \left(\frac{V^{\infty}_{WR}}{10^{3}\ km\ s^{-1}} \right)^{1/2} \left(\frac{V^{\infty}_{OB}}{10^{3}\ km\ s^{-1}} \right)^{-3/2} \left(\frac{D}{10^{13}\ cm} \right)^{-1} ergs\ s^{-1}$$

See also Prilutskii & Usov 1976; Cherepashchuk 1976; Luo, McCray & Mac Low 1990; Stevens, Blondin & Pollock 1992; Pittard & Stevens 1997; Folini & Walder 2000; Pittard & Stevens 2002

Caveats:

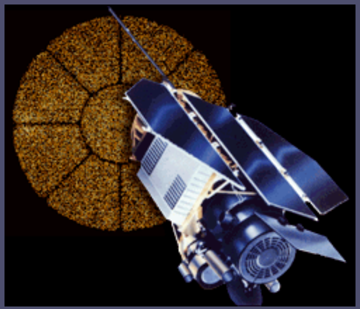
First attempts to find colliding wind emission met with disappointment:

- lack of instrumental sensitivity
- lack of instrumental resolution
- snapshot observations
- real physical effects (absorption, radiative braking...)
- contamination by “self-colliding wind” X-rays

Still some statistical evidence: WR binaries & OB binaries tended to be brighter than “single” stars (with wide scatter)

Recent Advances

New generation of X-ray observatories have led to breakthroughs in the detection of colliding wind X-ray emission and in understanding (or at least defining) the characteristics of the emission



ROSAT (1990-1999): Longevity, sensitivity. Discovered X-ray variability from a number of impt CWBs

ASCA (1993-2000): Longevity, bandpass. Monitored spectral variations for a number of CWBs

RXTE (1995-): timing, timing, timing

Chandra (1999-): Sensitivity, exquisite spatial resolution, bandpass, spectral resolution

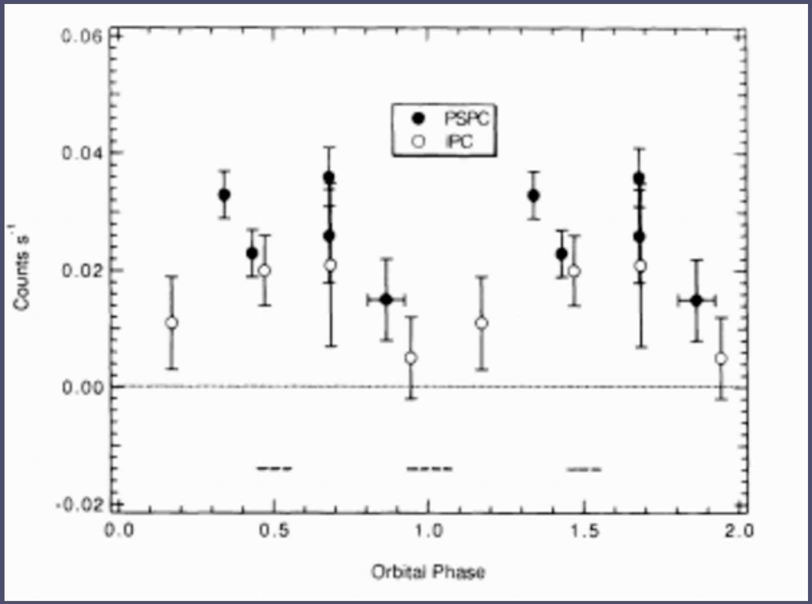
XMM-Newton (1999-): Sensitivity, spatial resolution, bandpass, spectral resolution

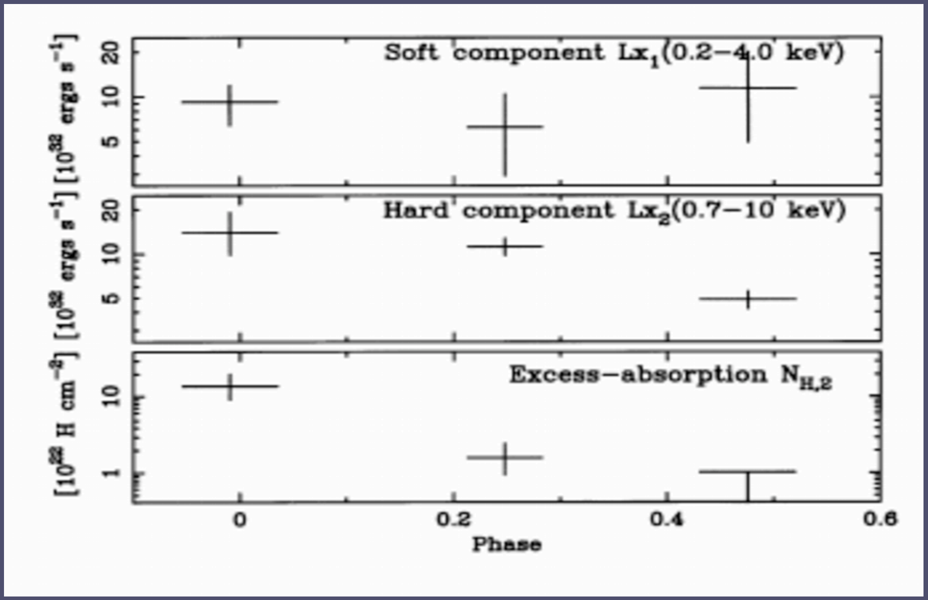
X-ray Colliding Wind Lightcurves

- Variations (>20%) of X-ray flux from single stars almost unknown
- In eclipsing binaries expect a factor of 2 variation (maximum at quadrature)
- Requires monitoring observations through one cycle
- Uses: lightcurve modeling to refine orbital & wind parameters, extent of interaction region & hot gas

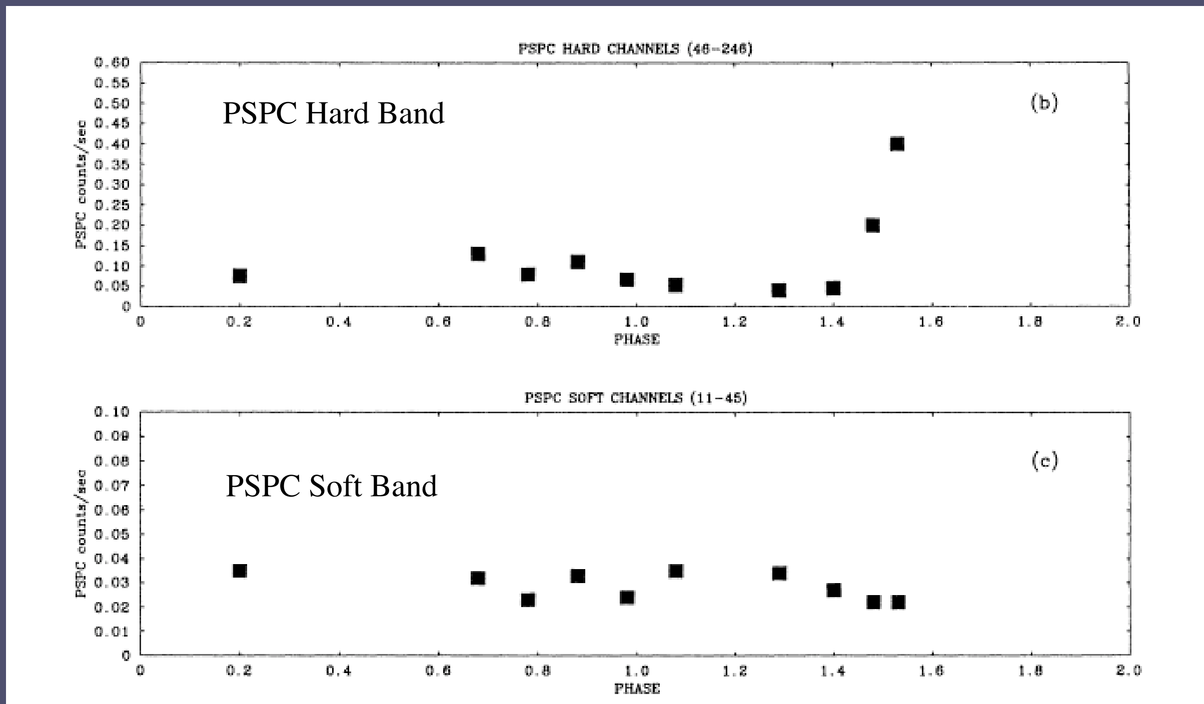
V444 Cyg (WN5+O6, P=4.2 days, eclipsing)

- disappointingly weak X-ray source (expect Lx~ 6 x 10^{32} from L_x/L_{bol})
- Observed Lx ~ 3-8 x 10^{32} (Moffat et al. 1982, Corcoran et al. 1996)
- However, ASCA shows soft+hard emission (Maeda et al. 1999) which varies in opposite ways



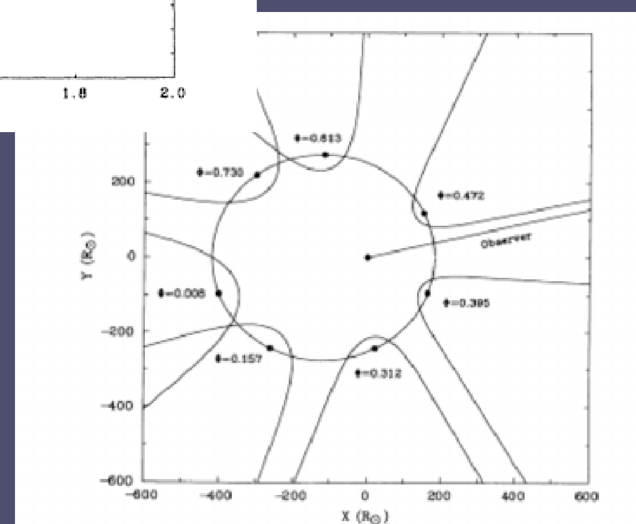


γ^2 Vel (WC8+O7.5III, $P=78^d$, $e=0.4$, $i<70^o$)



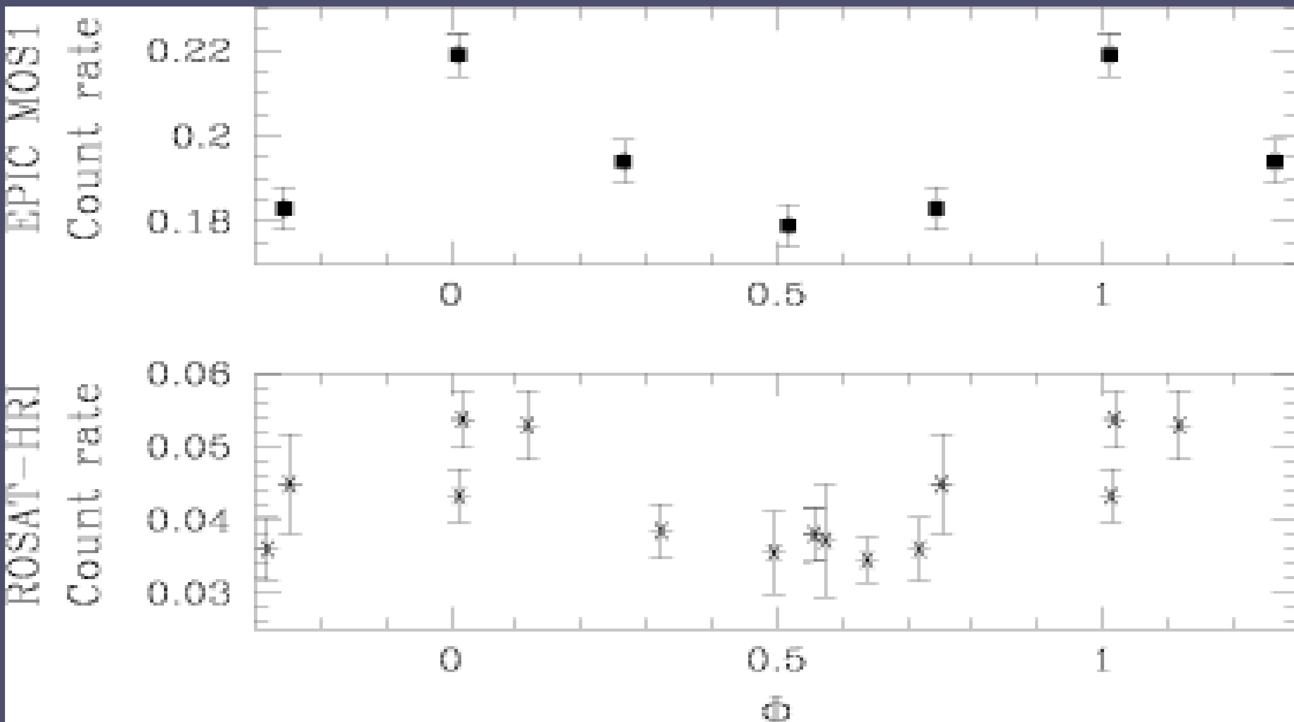
Willis, Schild & Stevens 1995, A&A, 298, 549

- hard emission variable, soft emission constant
- maximum near periastron (when O star in front)

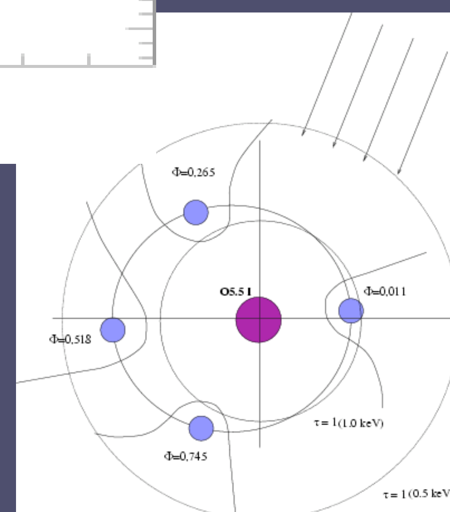


St. Louis, Willis & Stevens 1993, ApJ, 415, 298

HD 93403 (O5.5I+O7V, P=15.1^d, e=0.2 i=30^o)



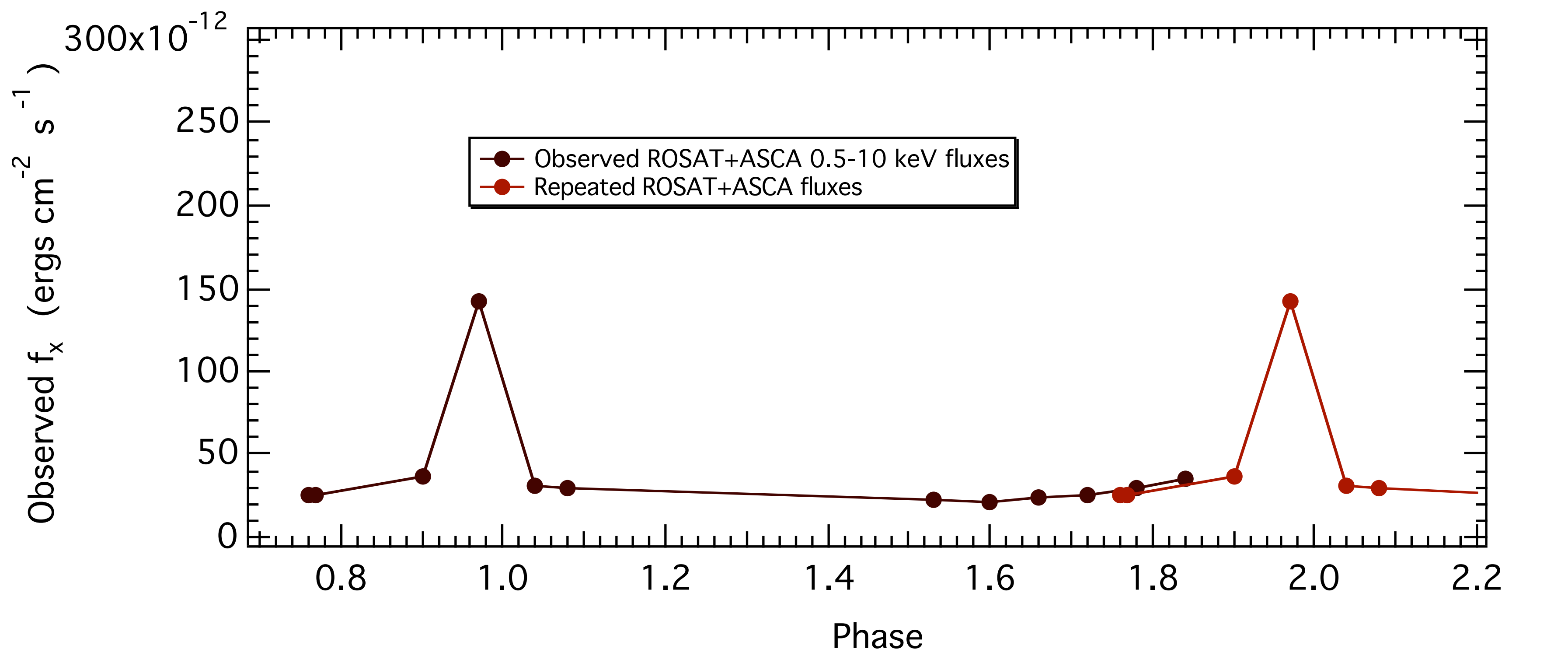
Rauw, G., et al., 2002, A&A, 388, 552



- Shows phase-locked variations, roughly follows expected 1/r dependence

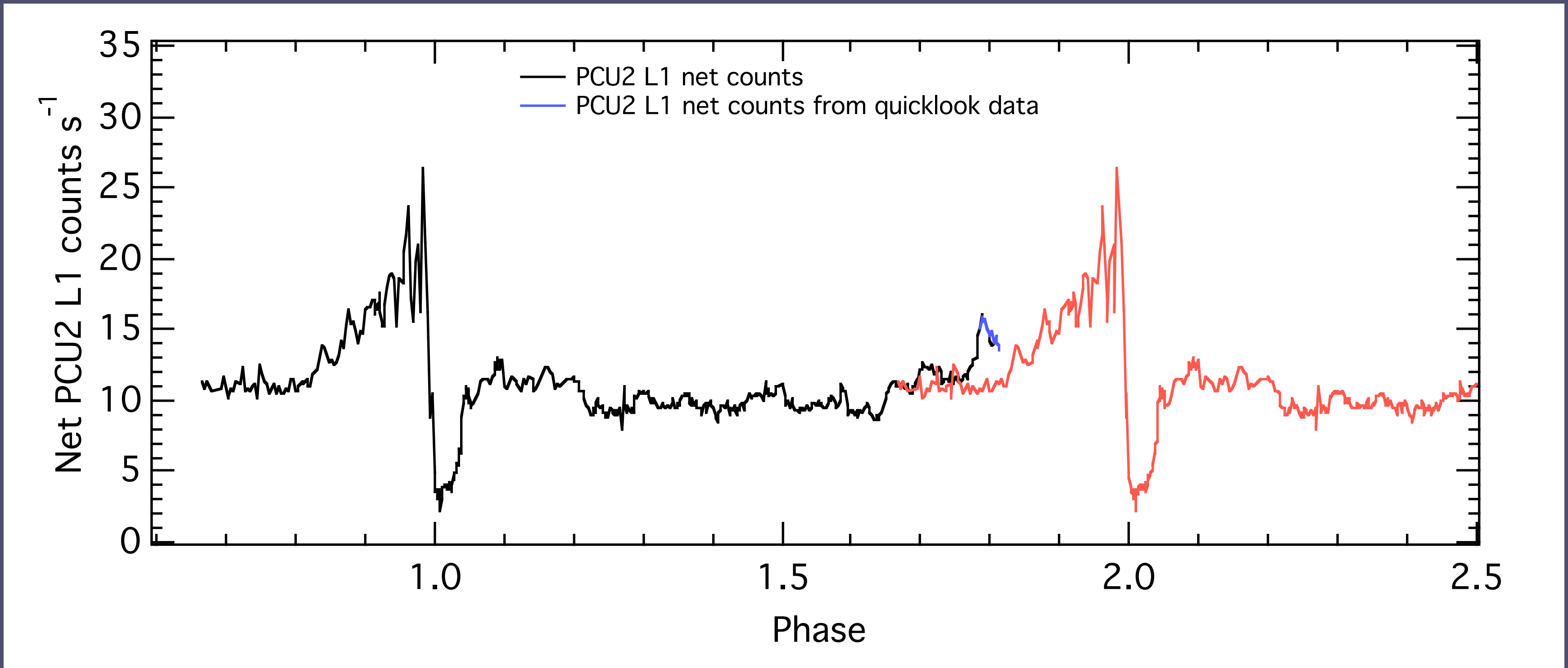
WR 140 (WC7+O4-5, P=2885^d, e=0.6)

- ROSAT, ASCA covered the periastron passage in 1993
- XMEGA started 6 month monitoring campaign with ASCA from phase 1.6 (after apastron)
- Periastron pass in 2001 covered in detail by RXTE (Pollock et al. 2002, in preparation)

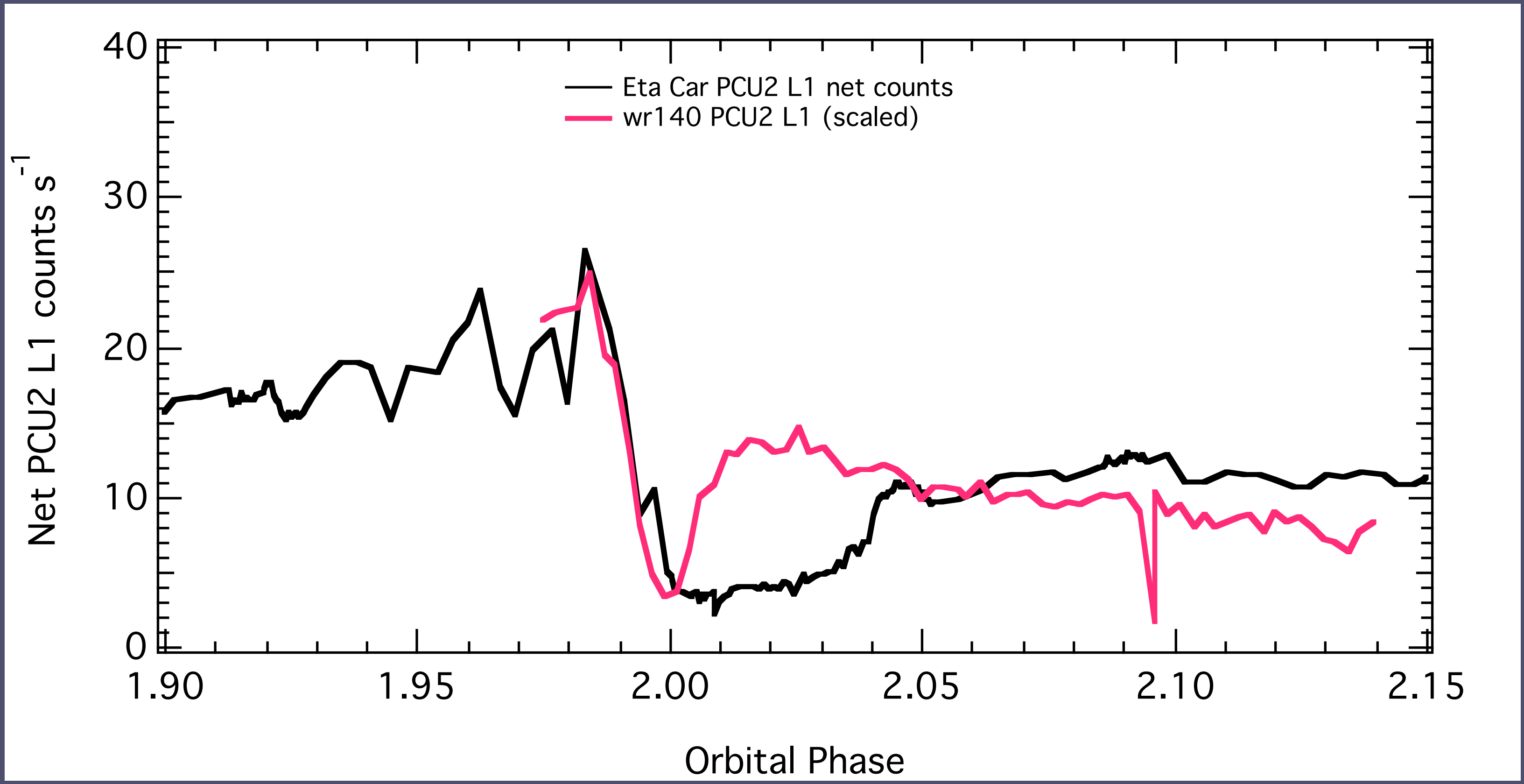


Eta Car (pec. + ?, P=2010d, e=0.9)

- IR and near IR periodicity of 5.52 year
- X-ray “eclipse” discovered with ROSAT; apparently periodic
- has been monitored with RXTE from 1996



Comparison of Eta Car and WR 140



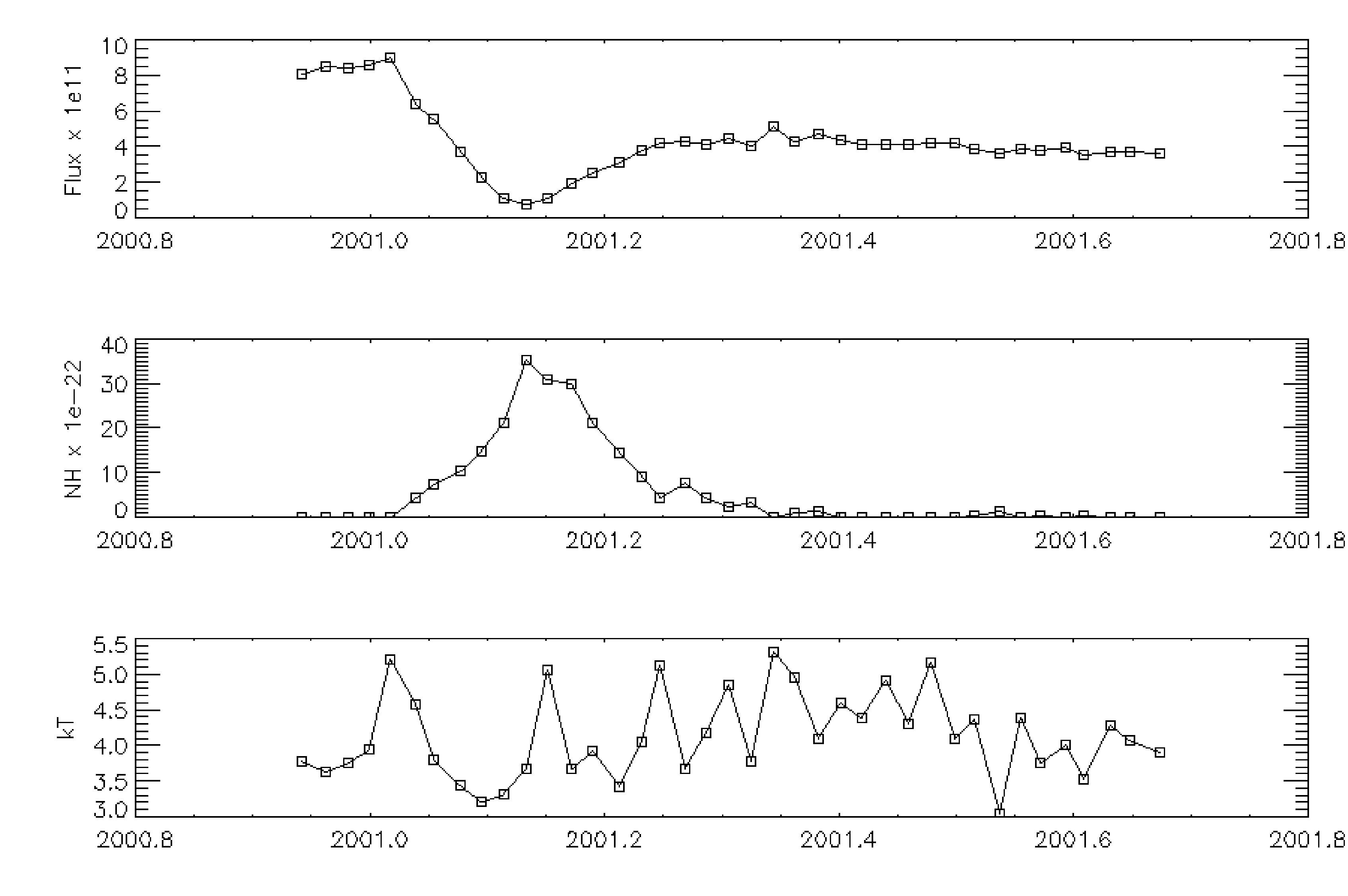
- Eta Car has longer minimum
- show similar ingress/egress asymmetries

Spectra & Spectral Variations

- changes in gross spectrum due to changes in emission measure, absorption (and possibly temperature?)
- information concerning both the shocked and unshocked winds
- 3-d extent of interaction region

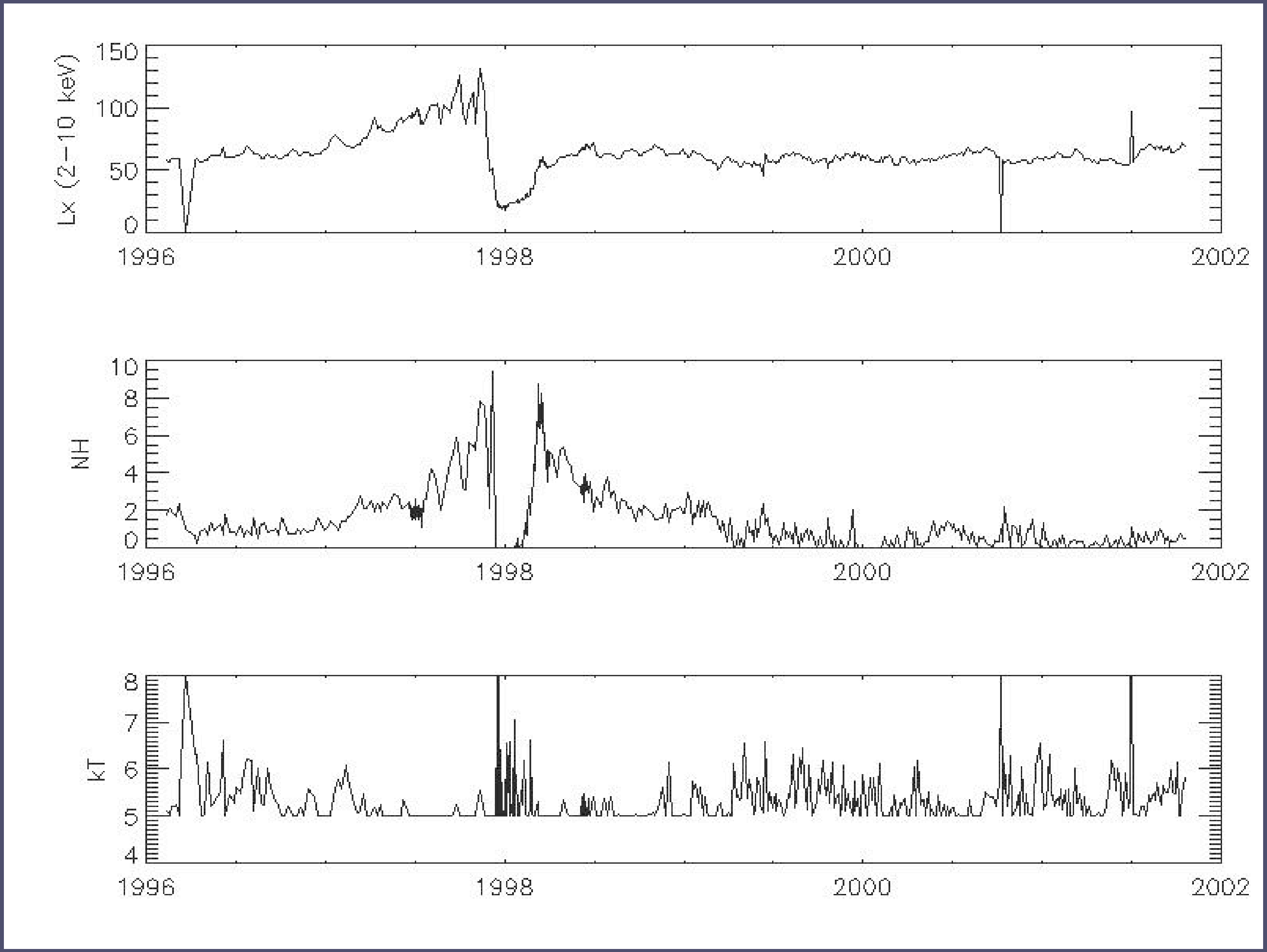
WR140

- 2-10 keV spectral variation from RXTE (1-T thermal brems)



Eta Car

- 2-10 keV RXTE spectral variability (2-T model)

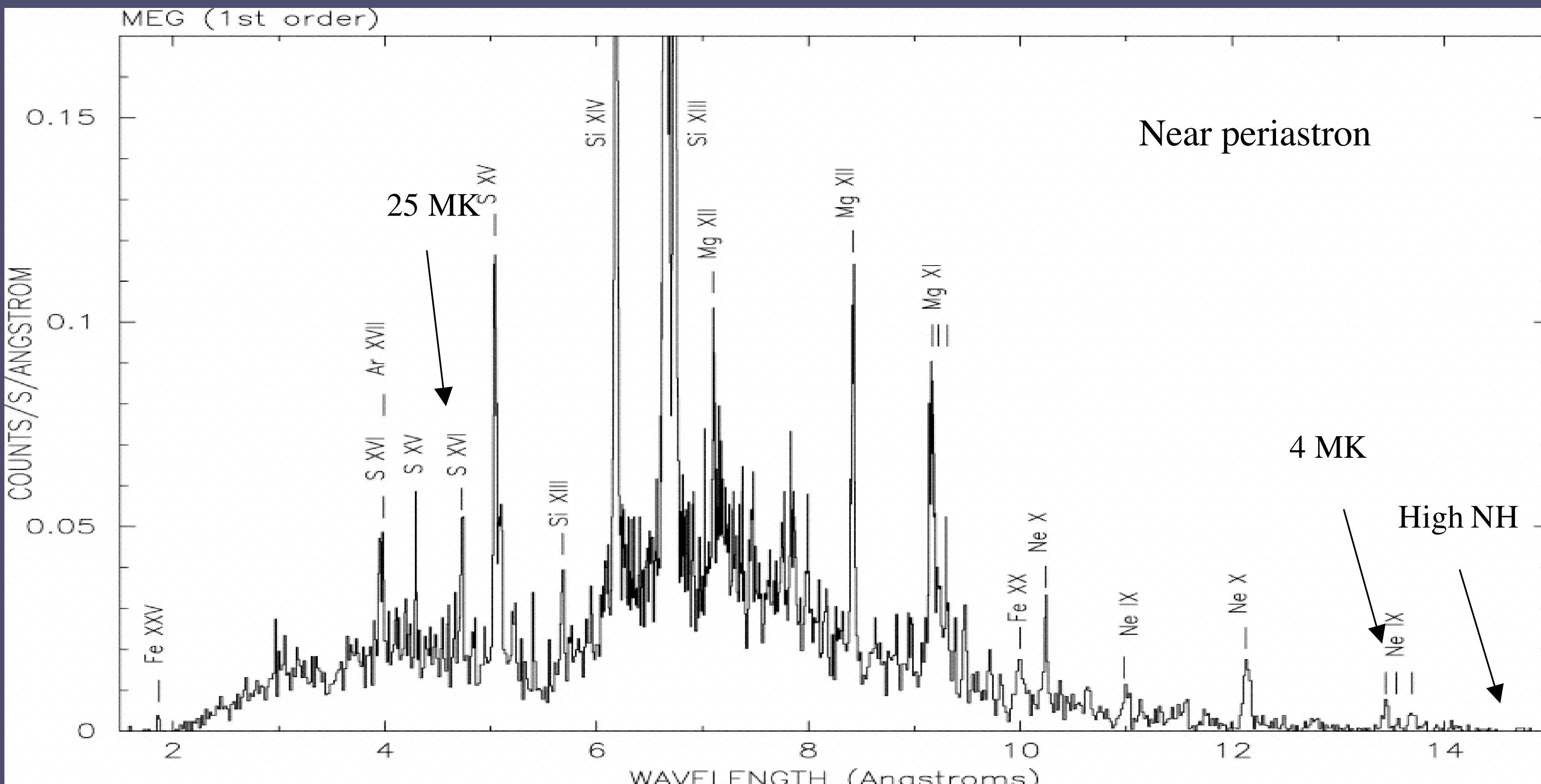


Grating Spectroscopy

- Detailed look at emission measure distribution vs. temperature
- LINES!
  - abundances
  - bulk flow dynamics

□^{2} Vel: Chandra

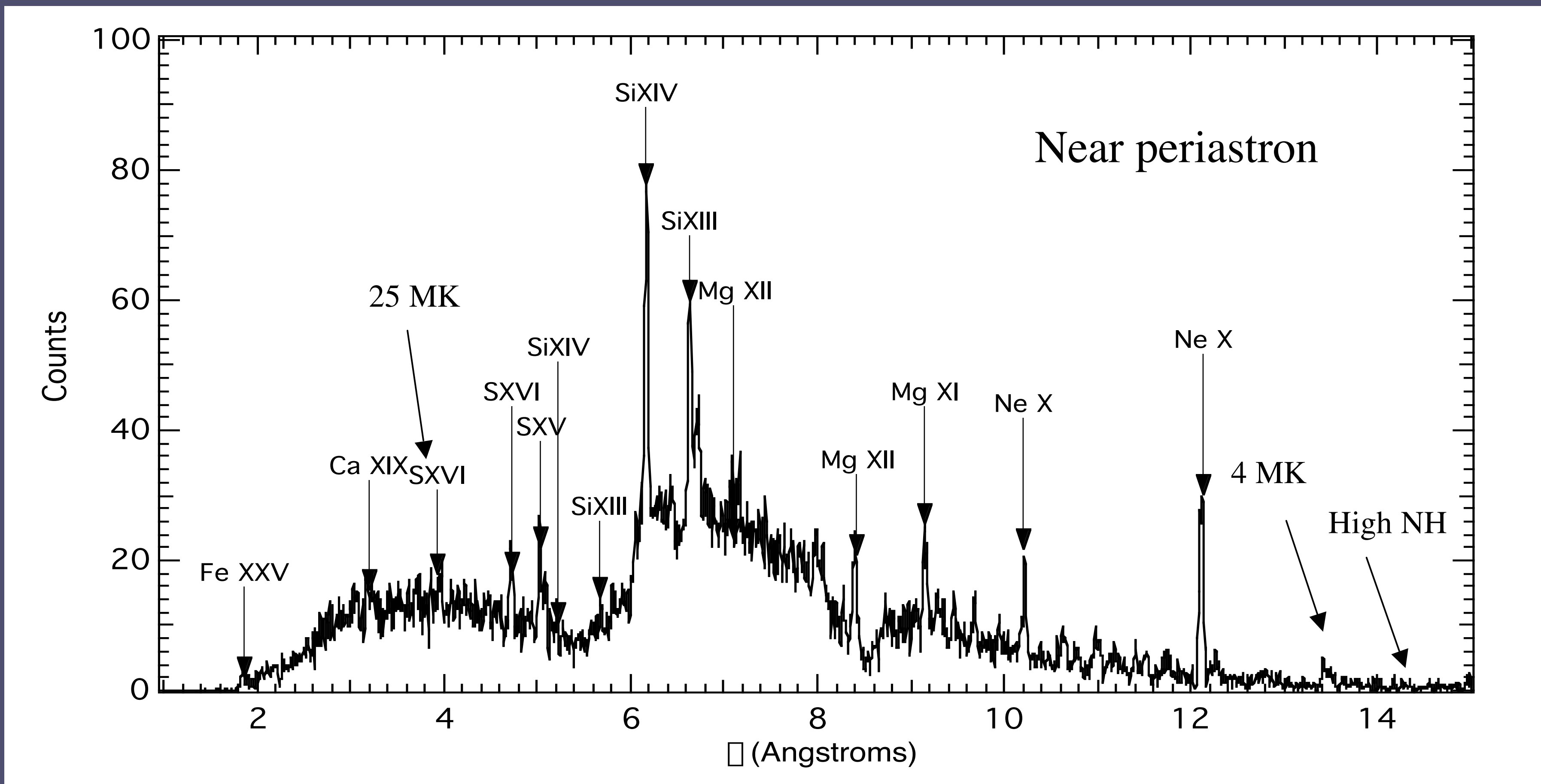
- Skinner et al. (2001) used the HETGS to obtain a spectrum of □^{2} Vel near periastron
- Multi-temperature emission, lines broad, unshifted, large f/i ratio



Skinner et al. 2001 ApJ 558, L113

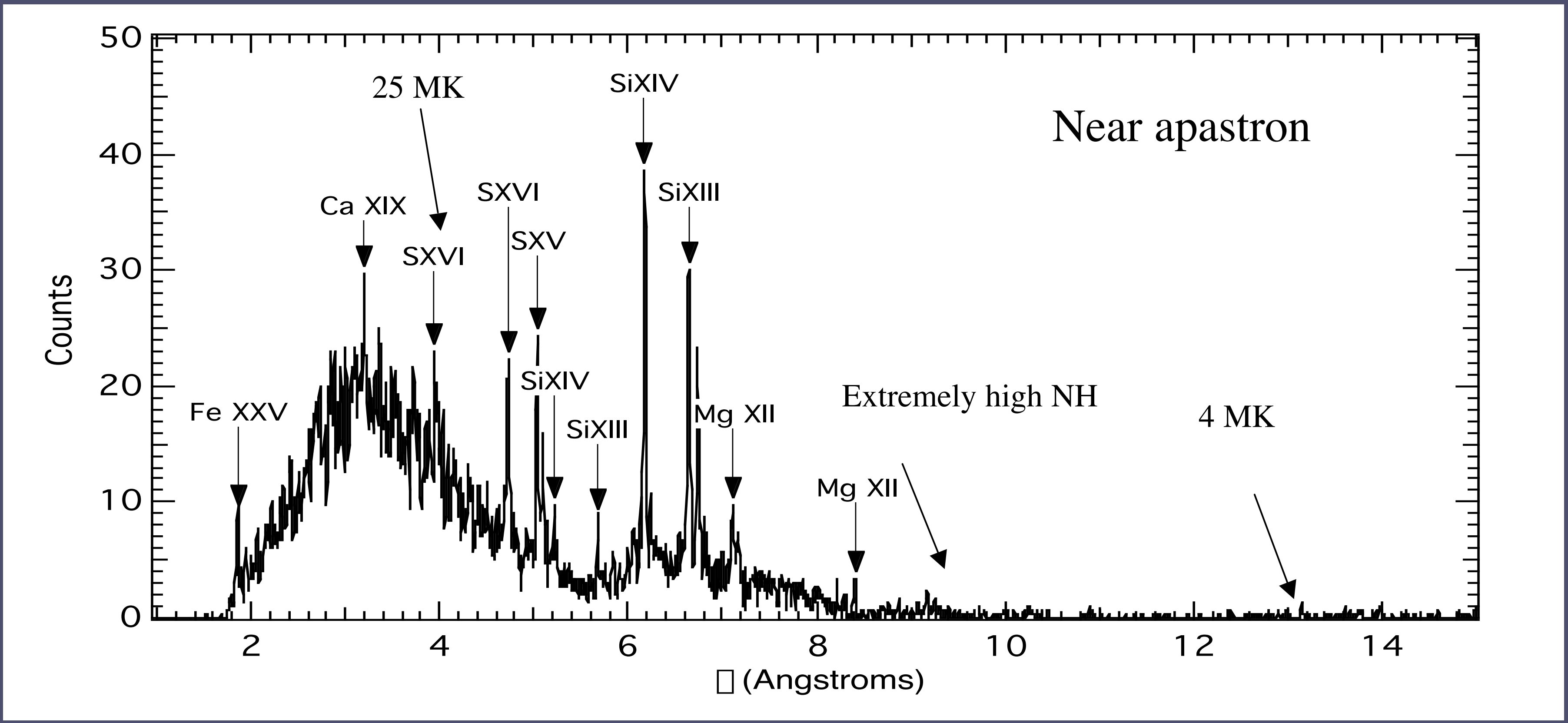
WR 140: Chandra

- Pollock et al. (2002, in prep.) observed WR140 near periastron with HETG
- multi-temperature emission, lines broad and shifted, f/i ratio not so large



Eta Car: Chandra

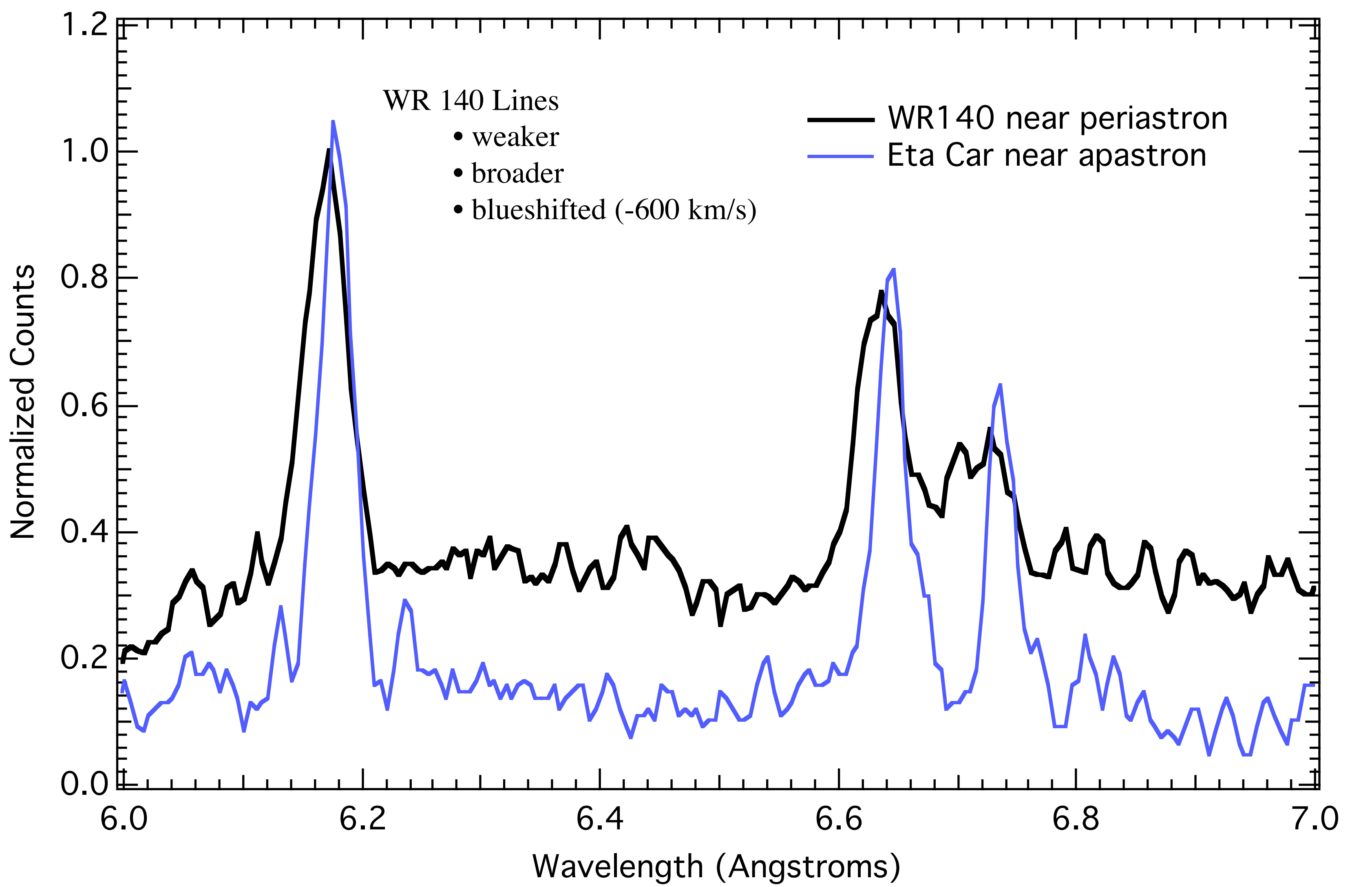
- Corcoran et al. (2001) observed Eta Car near apastron with HETG
- multi-T gas (up to 100 MK), lines narrow, unshifted, f/i large



Corcoran et al., 2001, ApJ, 562, 1031; Pittard & Corcoran 2002, A&A, 383, 636 (see poster I.49 by Pittard)

WR 140 and Eta Car Emission Lines

- Si lines from Eta Car (blue) and WR 140 (black)

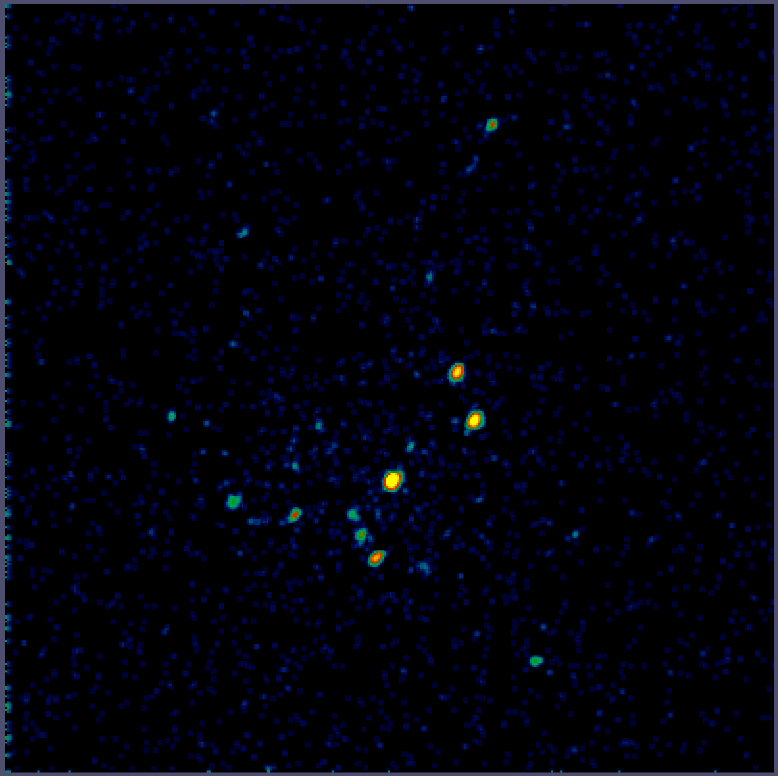


Imaging

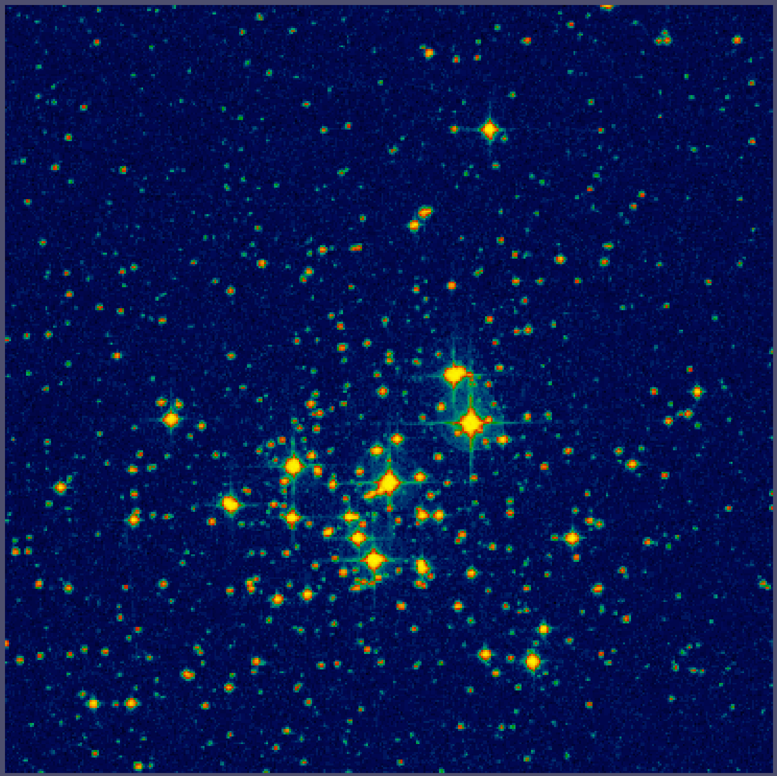
- High spatial resolution to reveal X-ray bright stars in clusters
- Can we spatially resolve the colliding wind shock in X-rays?

Sco OB1

- HD 152248 (O7I+O7I, P~6^{d}) strong X-ray source
- WR 79 (WC7+O, P~9^{d}) not detected

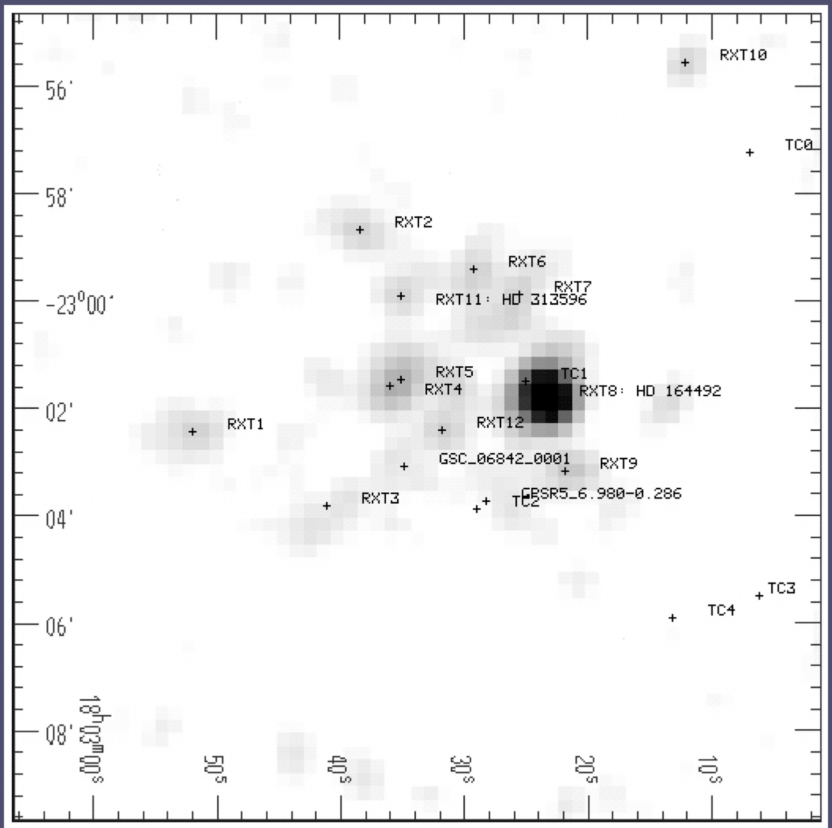


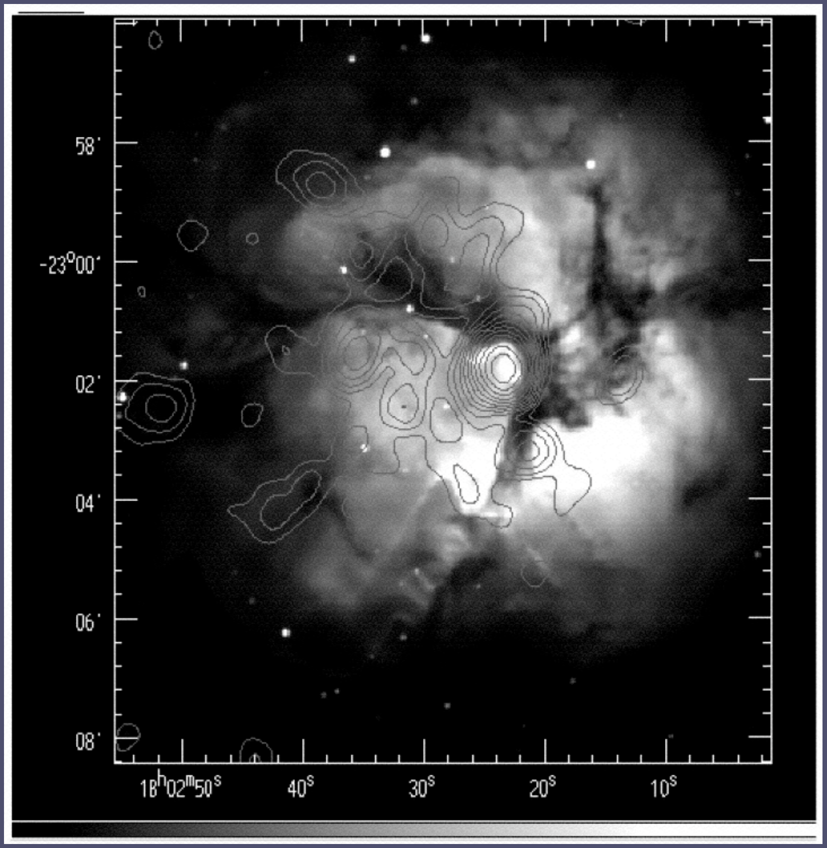
ROSAT HRI



Digitized Sky Survey

The Trifid and HD 164492

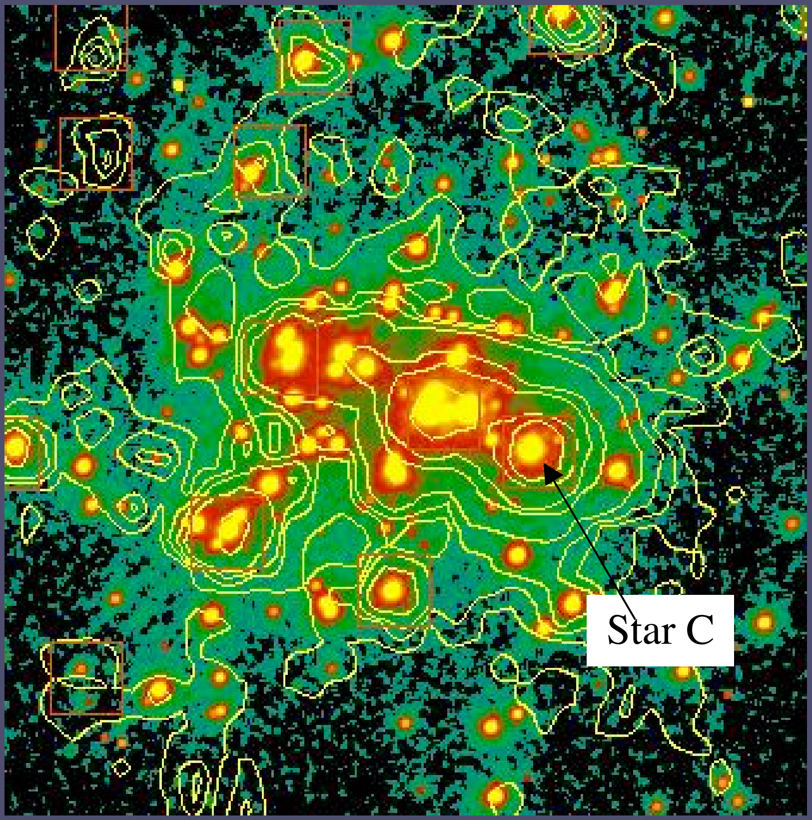




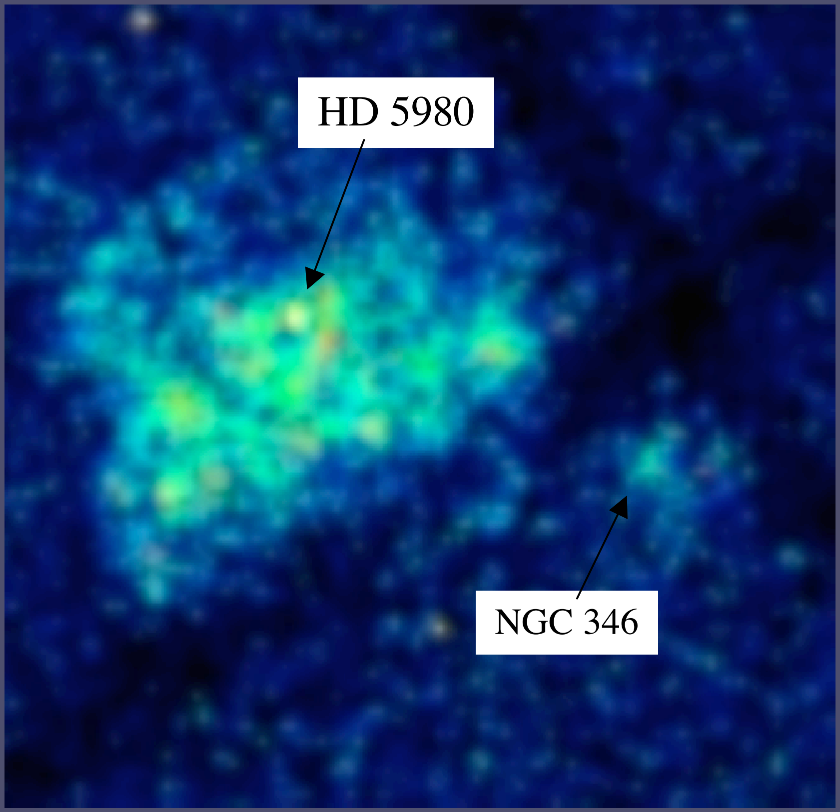
Rho et al. 2001, ApJ 562:446

• HD 164492 (O7) shows $L_x/L_{bol} > 10^{-5}$ and very hard emission (Rho et al. 2001); is it a CWB? (or are there unresolved PMS stars?)

Supergiant HII regions: NGC 3603 & NGC 346/HD 5980

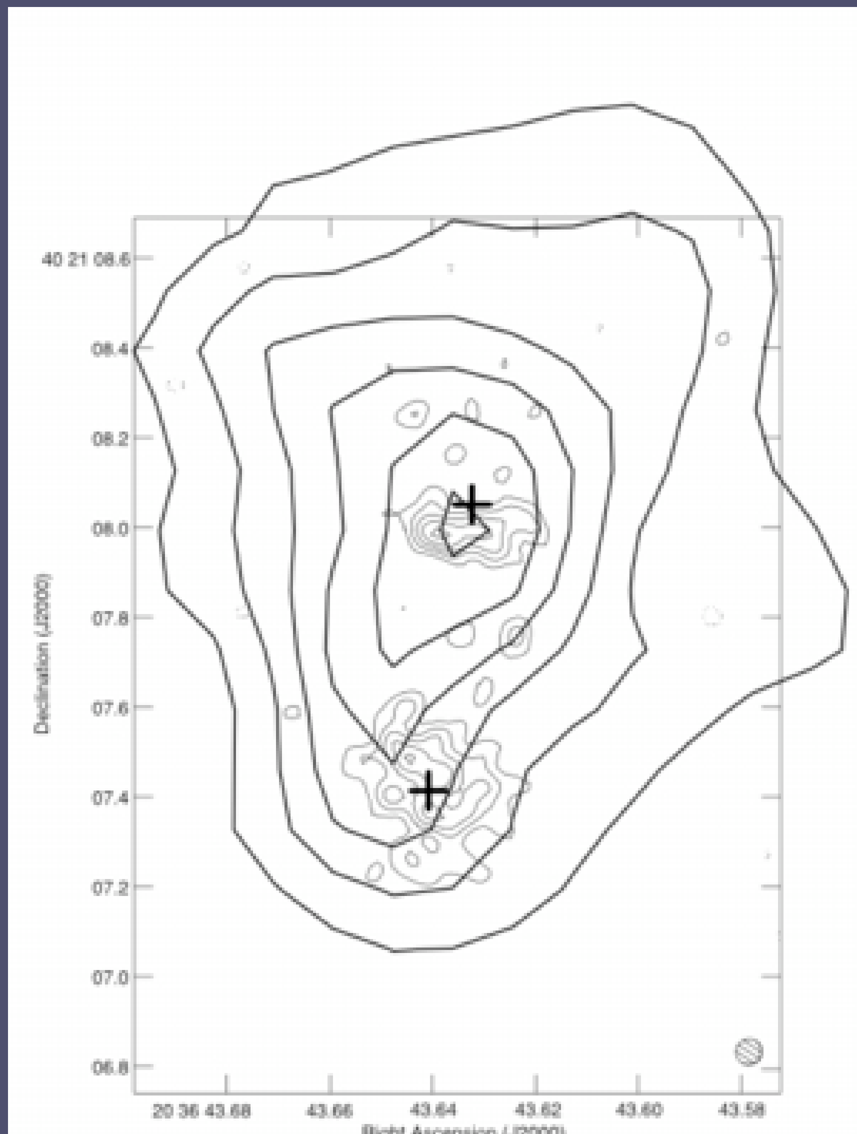


NGC 3603: WFPC2 image + ACIS X-ray contours. Star C is a bright X-ray source and probably WR+O binary. (see AFJ Moffat, session IIId)



NGC 346 rather weak X-ray emission; HD 5980 ("LBV"+WR, $P=19.3^d$) strong variable X-ray source. (Naze et al, 2002, submitted; Flores et al., 2002, in prep.)

WR 147 (WR+O, P=unknown)



- Colliding wind shock NT emission resolved in radio (Williams et al. 1997, Niemela et al. 1998)
- HRC-I observation shows extended X-ray source near the radio bow shock (Pittard et al. 2002)

Conclusions

- X-ray emission valuable probe of wind and orbital parameters of massive binaries:
  - unexpectedly large emitting region in γ^2 Vel (Ne IX $> 2a$)
  - X-ray minimum due to absorption in WR 140
  - Unexpectedly low mass loss rate in Eta Car
  - Need detailed models!
- High spatial and spectral resolution provided by Chandra & XMM-Newton provide great deal of heretofore unavailable information
  - broad lines in γ^2 Vel and WR 140
  - velocity shifts in WR 140, not in γ^2 Vel or Eta Car
- Wide range of observed properties, dependencies still unclear:
  - geometry? stellar? radiative?