X-ray Emission as a Probe of the Wind-Driven Shock in WR 140

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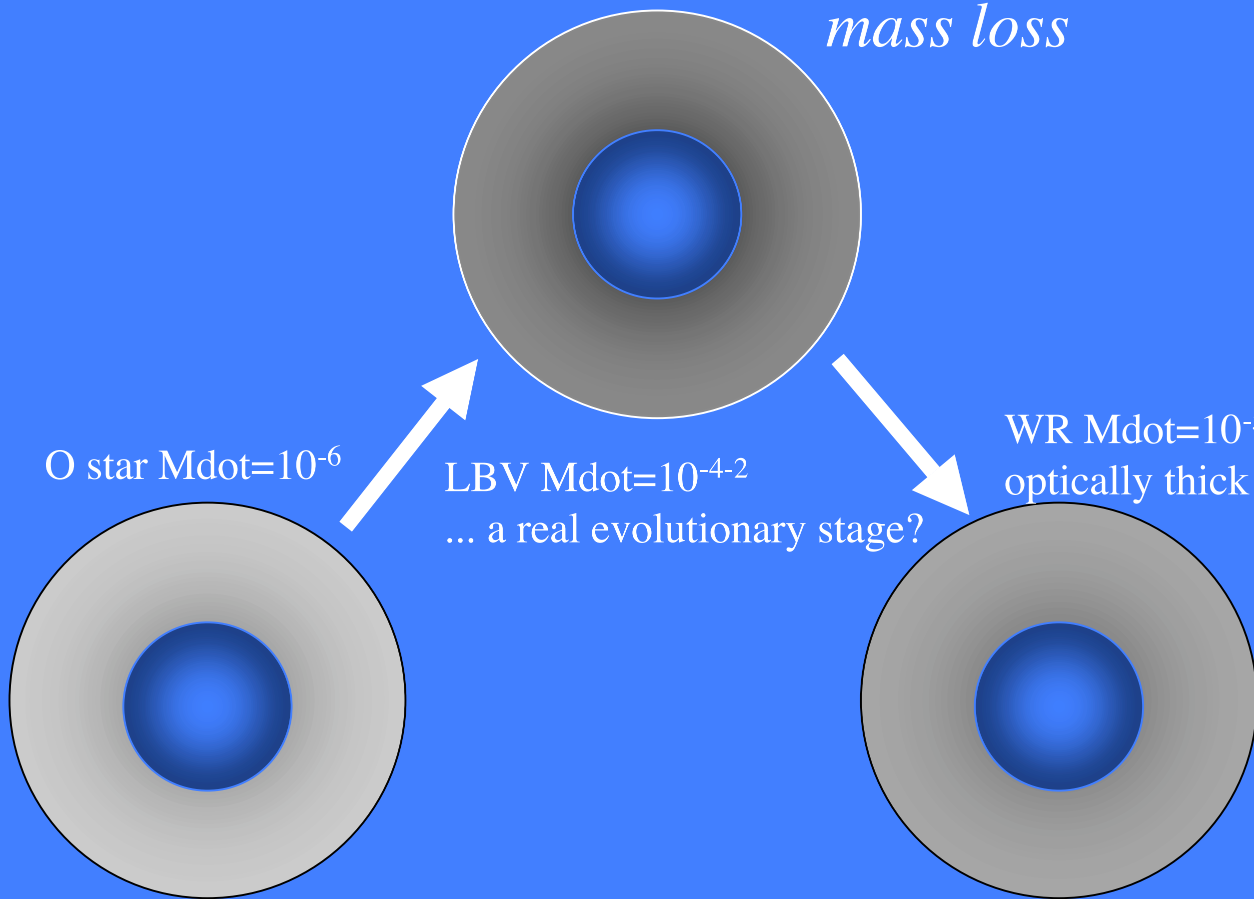
http://lheawww.gsfc.nasa.gov/users/corcoran/xmega/xmega.html

Massive Stars are rare (few thousand in the Galaxy) but significant beyond numbers:

- main sources of UV and ionizing radiation
- add mechanical energy to ISM via massive winds
- add mechanical, radiant energy to ISM by exploding
- chemical pollution and dust; nuclear lines

Evolution of High Mass Stars:

understanding the evolution of massive stars means understanding the history of mass loss



Additional consequences of evolution in massive binaries:

- wind–wind collisions
- particle acceleration
- mass transfer in close binaries
- HMXBs
- rejuvenation (SN 1987a)
- bipolar nebulae
- spin up and hypernovae

Binary fraction of massive stars *uncertain*

- ~35% (O stars); ~ 50% (WR stars)

? All ? (or just all WRs/LBVs...)

Binarity:

- offers opportunity to calibrate the HRD for massive stars in terms of mass, radius

... but evolution is necessarily more complicated by mass transfer

massive binary evolution much different from massive single star evolution

To understand the evolution of massive stars and their role in shaping the galaxy, understanding of the distribution of massive binaries is necessary (but not easy)

"*Progress in X-ray astronomy has opened up a fundamentally new opportunity for detecting binaries among WR stars*", A. M. Cherepashchuk, Sov. Astr. Letters, 2, 138, 1976

WR 140 (= HD 193793): “prototype” of evolved massive binary

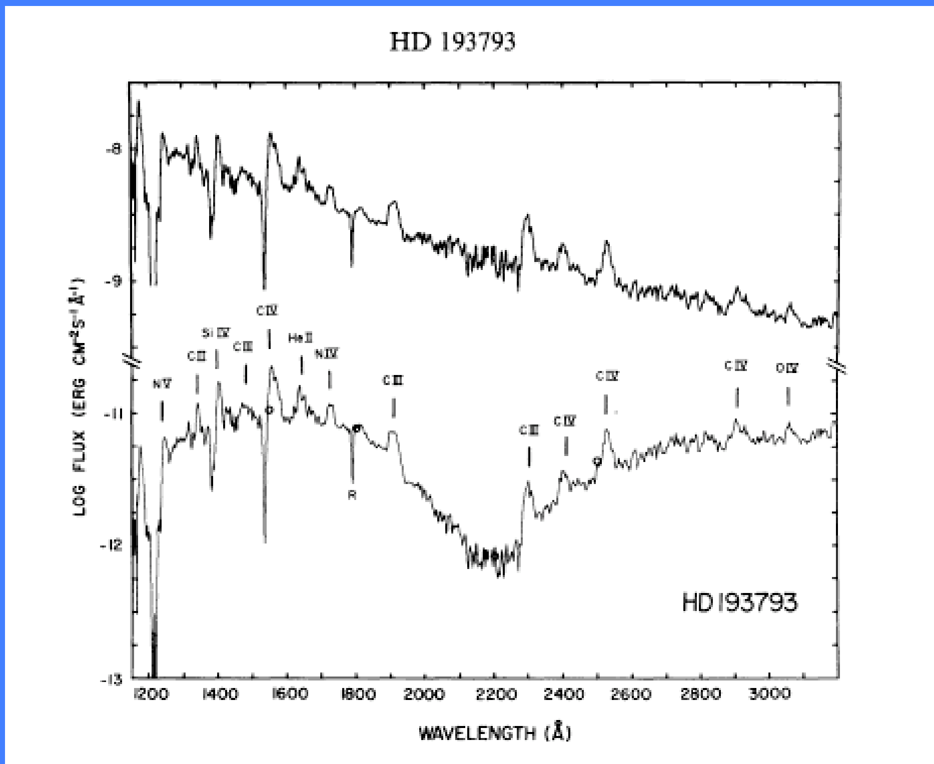
- WC7 (He burning) + O4-5 V (H burning)

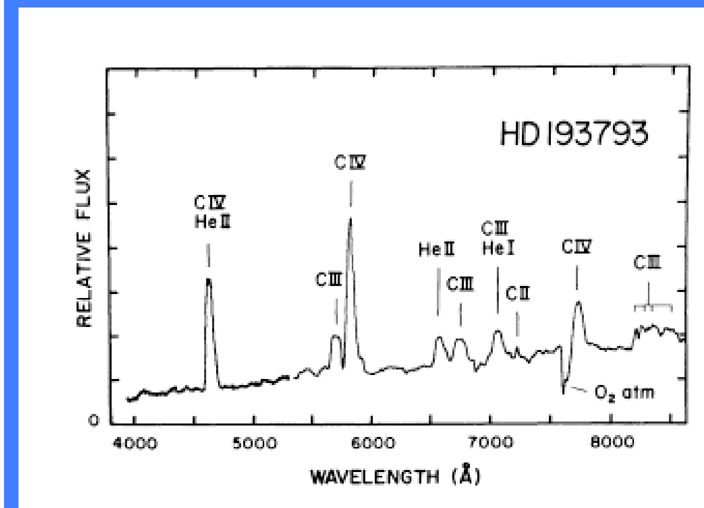
- absorption lines observed before binarity proven

- only small photometric variations (none seen in early monitoring dating to the 1960’s

- IR variations (Hackwell, Gehrz, Smith and Strecker 1978) suggest changes in density, mass loss rate, radii of stellar wind?

WR 140 spectrum (Fitzpatrick, Savage & Sitko, 1982):





lines broad, blended and profiles variable (especially near periastron)

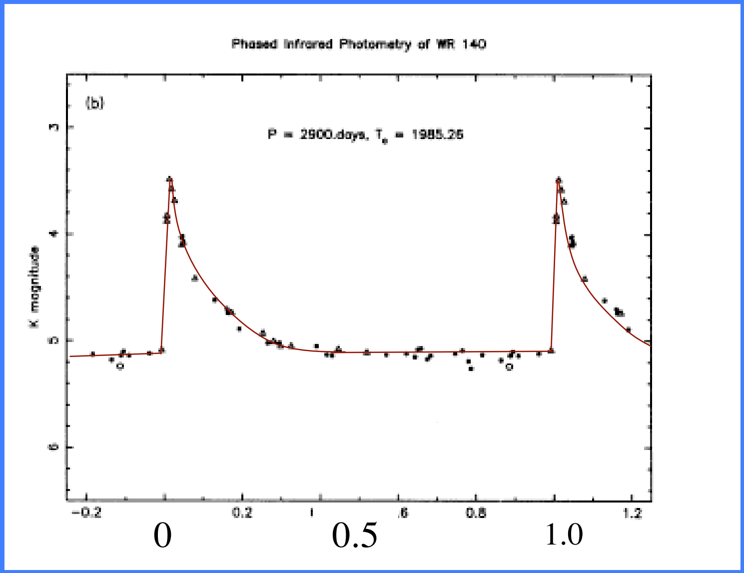
WR 140 observational history

• 1st suggested period - 2.97 years (LaMontagne, Moffat & Seggewiss 1984), but no correlation of derived periastron w/ IR outbursts

•1984 - Conti, Roussel-Dupre, Massey & Rensing found *no periodicity* in 16 years worth of spectra for WR140; “two stars are in the same line of sight”

• 1987 - episodic dust formation; P=7.9±0.1 year, consistent with available RV variations (Williams et al. 1990)

K mag

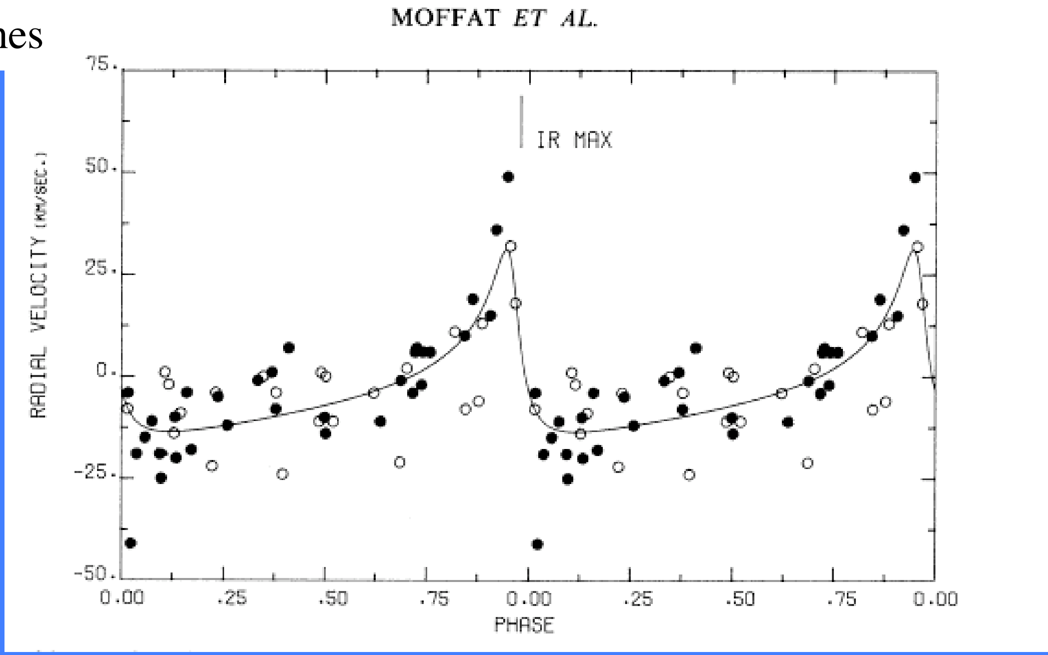


Phase

K-band lightcurve of WR 140 phased with *P*=7.9 years (Williams et al. 1990)

• 1987 - Moffat, LaMontagne, Williams, Horn & Seggewiss deduce a P=7.9 year binary period from 60 years of radial velocities; IR maximum (dust formation, m_{dust}=2 x 10^{-8} M_O) occurs near periastron; M_O=17, M_{WR}=9 Msuns; e=0.7

Absorption lines



RV curve (Moffat et al. 1987):

Emission lines

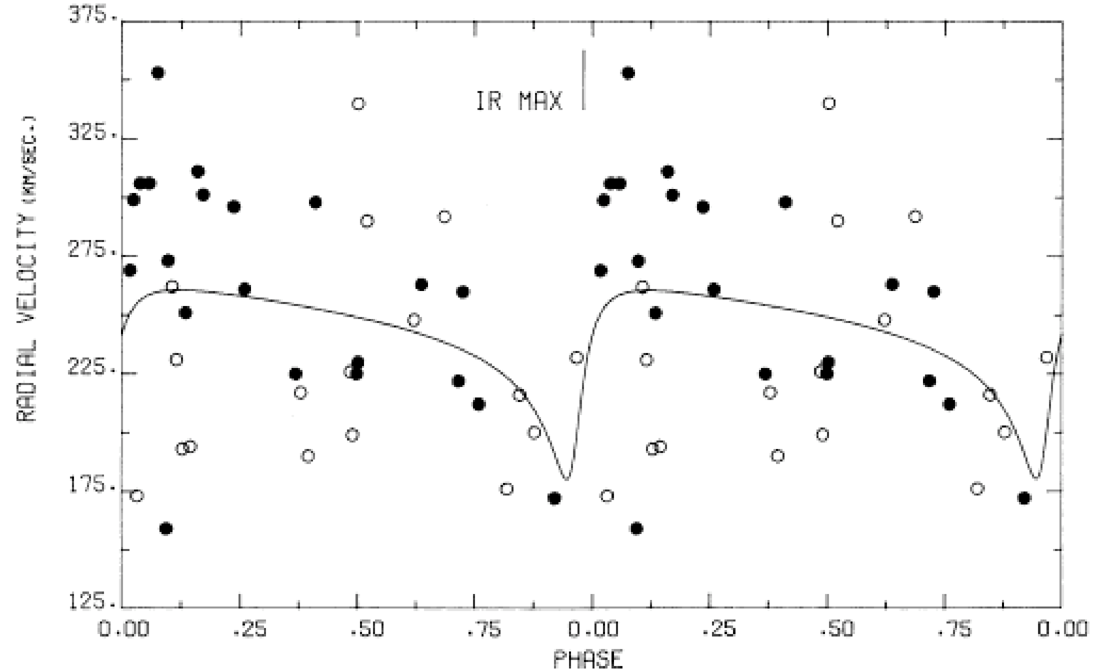


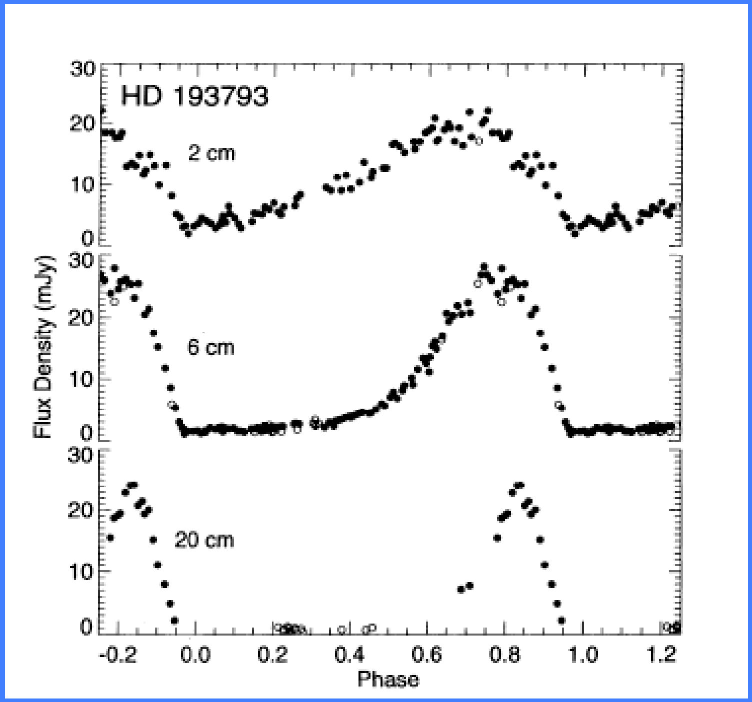
FIG. 4.—Phased plot of the C IV emission-line RVs with the calculated orbit as in Table 3. Symbols and phase as in Fig. 3.

• WR 140 known as a radio source since the 70’s (Florkowski & Gottesman 1977)

• radio spectrum non-thermal

• *1986 - referring to a report of non-thermal radio emission in WR 140 by Abbott, Pollock suggests non-thermal X-ray emission*

• Becker & White obtained the first radio lightcurve of WR 140 over a full cycle:



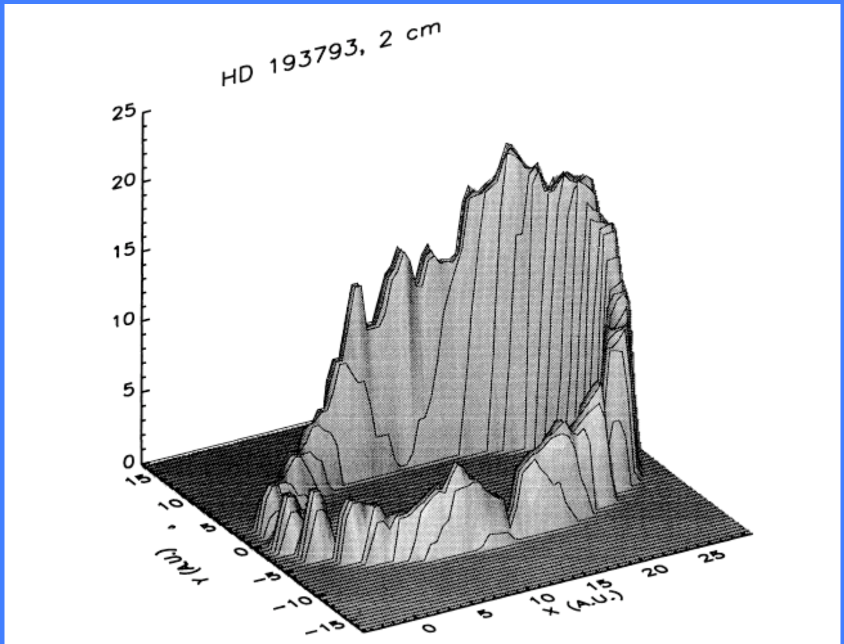
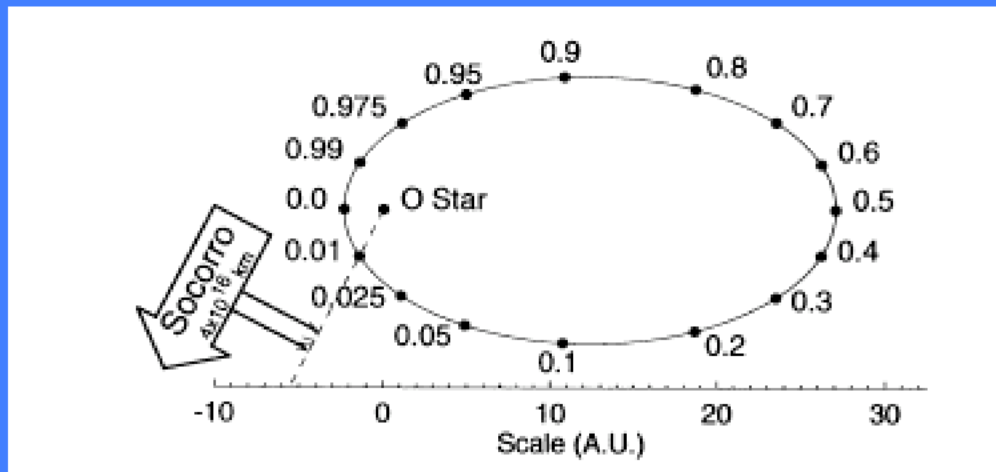


FIG. 4a

• large hole in WR atmosphere produced by the O star
• or disk around WR star?

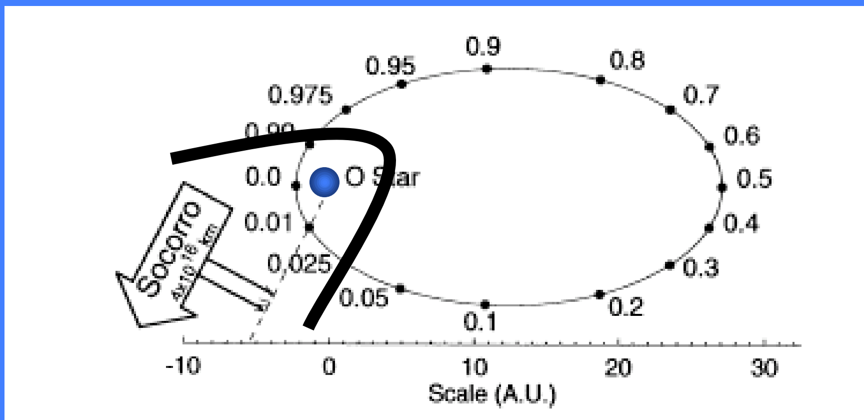
Orbit of WR 140 wrt the O star:



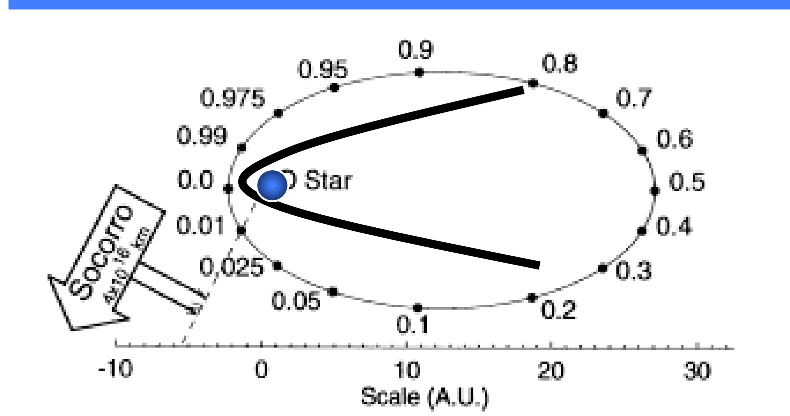
from Becker & White 1995

□	d (□=1, WR)	d (□=1, O)
2 cm	30 AU	2 AU
6 cm	60 AU	5 AU
20 cm	100 AU	10 AU

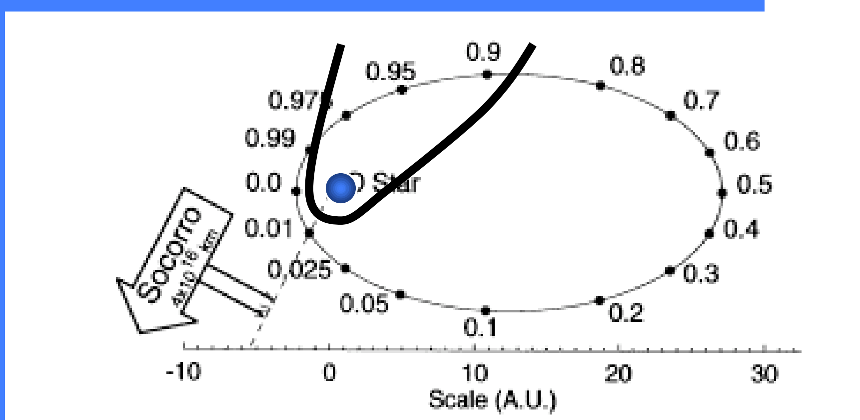
The Wind-Wind Collision in WR140



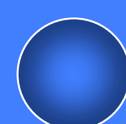
Near Radio Maximum



Near Periastron



Near Minimum

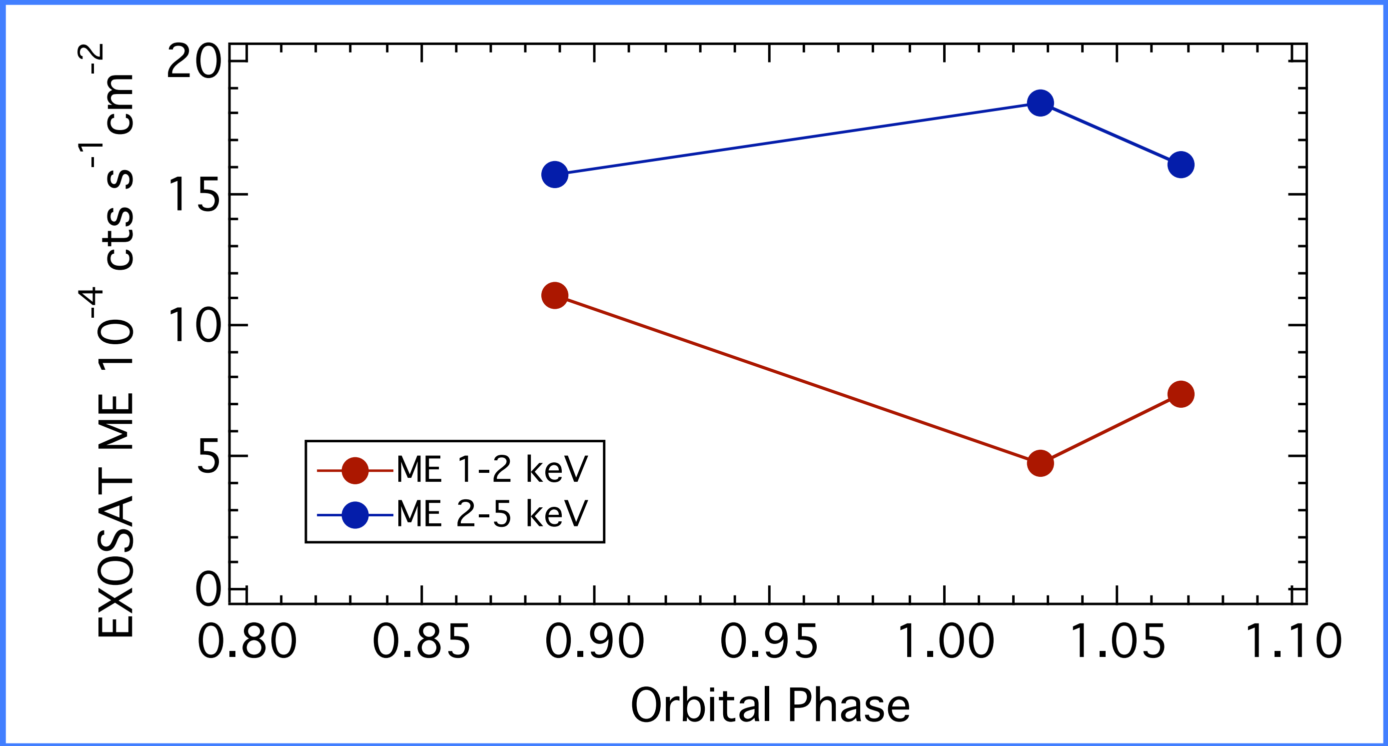


O star

X-ray Emission from WR 140

EXOSAT: 3 observations with ME (1984.4, 1985.5, 1985.8, Pollock 1987, Williams et al. 1990) show

- WR 140 atypically bright ($L_x/L_{bol} \sim 10^{-5}$ vs. 10^{-7} for O stars)
- WR 140 atypically hard
- WR 140 atypically variable



X-ray Emission from WR 140

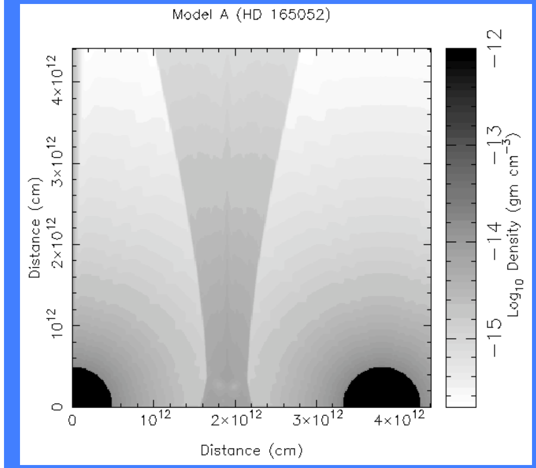
Ginga: 2 Observations with the LAC (Aug 1987, Aug 1988, Koyama et al 1990) show

- Fe K line emission
- No significant variability following the 1985.26 periastron
- Lx (2-6 keV) ~ 1.5 x 10^{-11} ergs s^{-1}

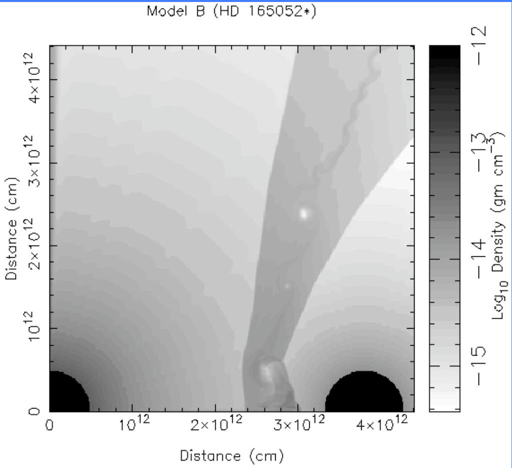
EXOSAT: consistent with standard picture of colliding wind X-ray emission

GINGA: probably consistent too

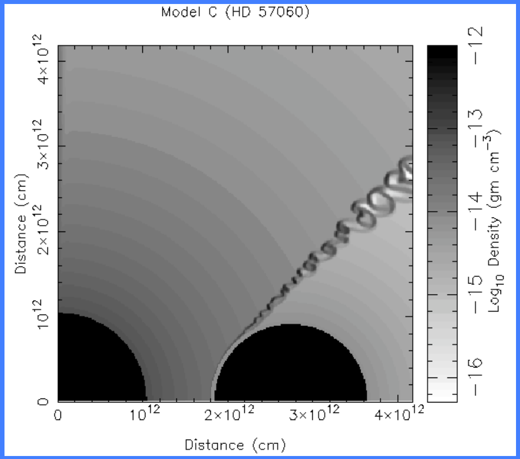
Standard Colliding Wind Picture



$p_{wind,1} = p_{wind,2}$



$p_{wind,1} > p_{wind,2}$



$p_{wind,1} >> p_{wind,2}$

Courtesy Julian Pittard

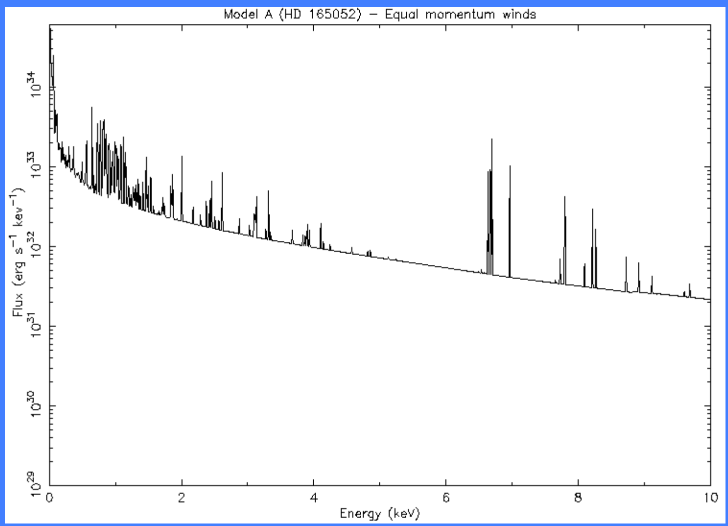
http://ast.leeds.ac.uk/~jmp/

X-rays from Colliding Winds

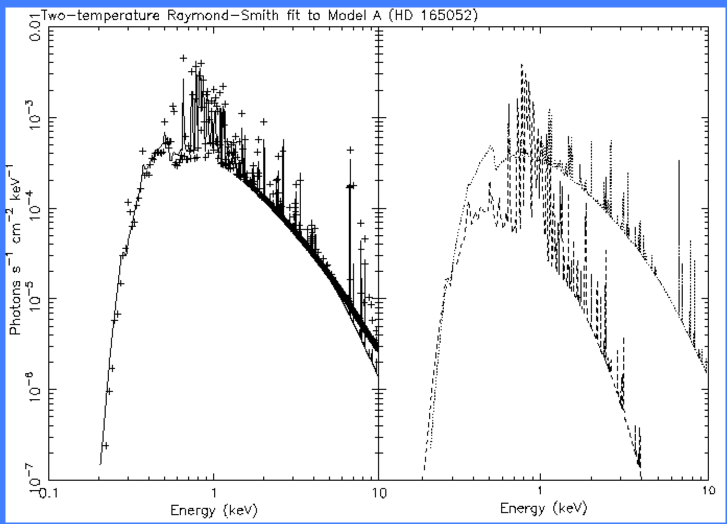
Since the wind velocities are typically > 1000 km/s, and the sound speed in the wind is typically 10 km/s, the wind-wind collision generates a strong shock and high temperatures

Soft X-rays absorbed by the wind from the frontmost star

X-rays measure both the SHOCKED and COOL material



Intrinsic



Intrinsic + absorption

courtesy JMP

X-ray Variability Models:

- Emission measure of shock changes if orbit is eccentric, since wind densities r^{-2} (L_x $1/D$)
- absorption changes since line of sight to the shock changes

Total intrinsic X-ray luminosity

Total emitted luminosity

Lx 0.5-4.0 keV

Lx 4-30 keV

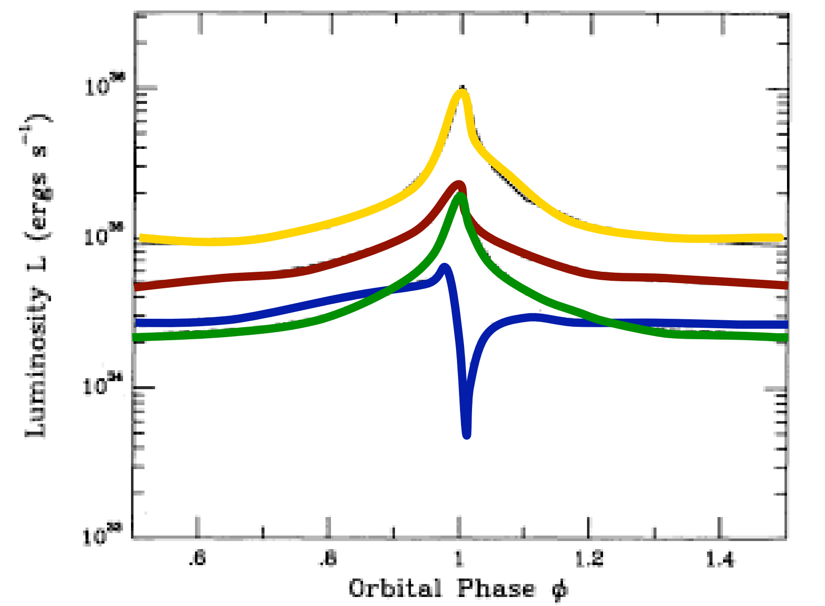


FIG. 21.—Orbital variation of the luminosity in different wave bands for HD 193793, plotted as a function of orbital phase ϕ. Periastron is assumed to occur at $\phi = 1$ and apastron at $\phi = 0.5$, 1.5. The wave bands shown are as follows: (*a*) total intrinsic luminosity (*solid line*); (*b*) total emitted luminosity (*long-dashed line*); (*c*) luminosity in the 0.5–4 keV wave band (*dot-dash line*); (*d*) luminosity in the 4–30 keV wave band (*short-dashed line*).

from Stevens, Blondin & Pollock (1992)

X-ray emission is a good (the best?) probe of the system:

- X-ray emission is localized (only wavelength range where the location of the emission is known)
- X-ray emission & absorption depend on the mass loss properties
- X-ray emission & absorption depend on the orbital properties
- X-ray emission depends on the wind abundances

Monitoring the X-ray Variability of WR 140

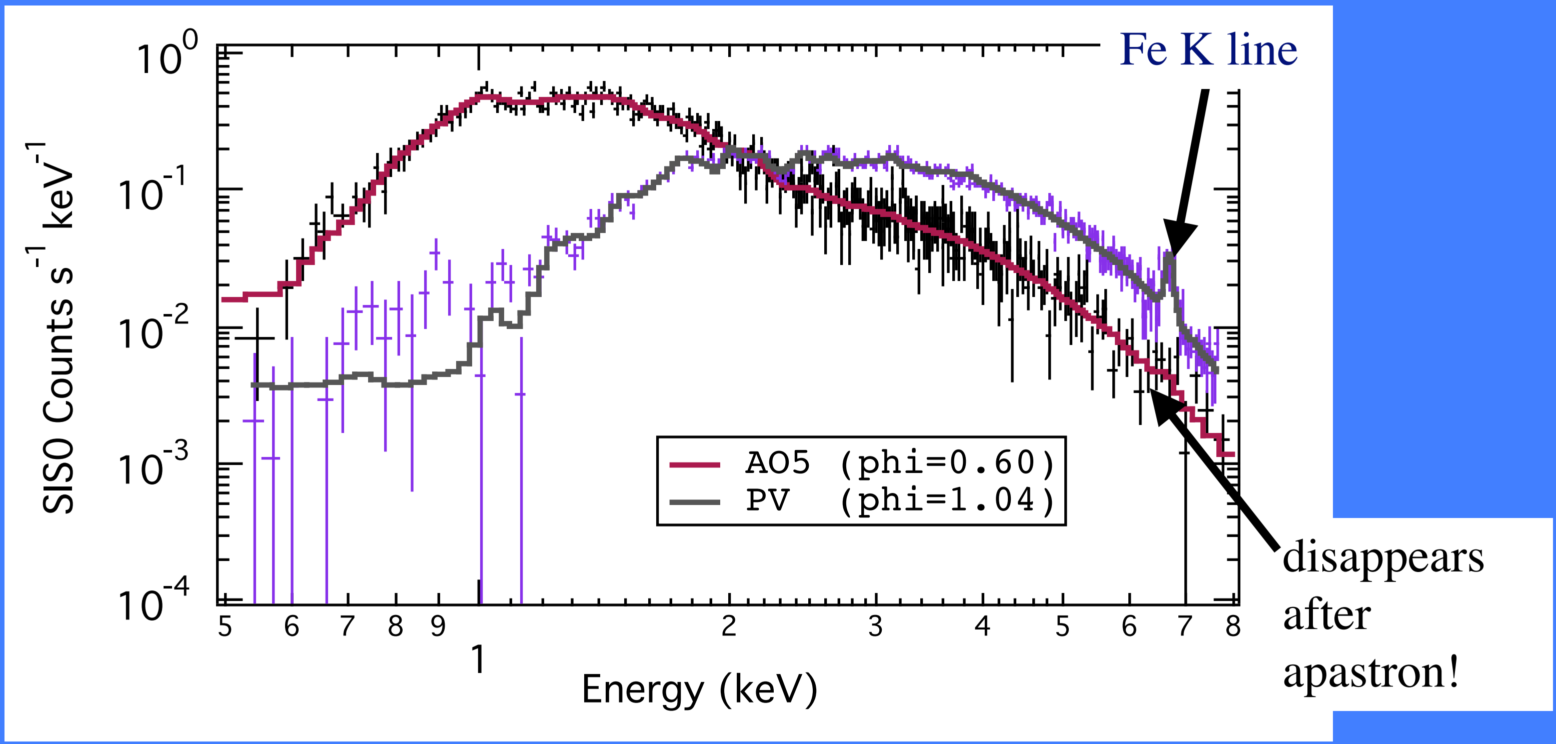
Recent Periastron Passages:

- 1985.26 (EXOSAT, GINGA)
- 1993.16
  - ROSAT monitoring up to periastron
  - ASCA PV observation just after periastron
  - ASCA monitoring from apastron
- 2001.06 (RXTE, CHANDRA, XMM)
  - RXTE detailed monitoring just prior to periastron/through periastron & after
  - Chandra grating spectrum
  - XMM (maybe?)

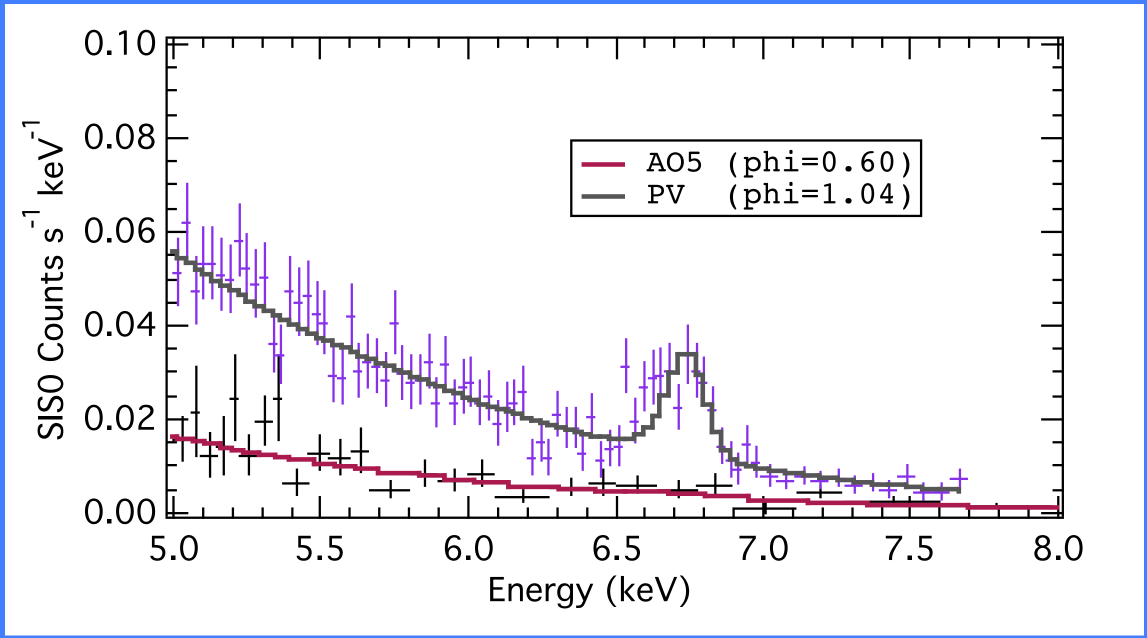
X-ray spectrum complex:

- 2 components + variable iron K line

ASCA apastron/periastron spectra key!



All ASCA and ROSAT spectra can be fit by soft thermal component plus hard power law (with hot Fe K line)



What's going on?

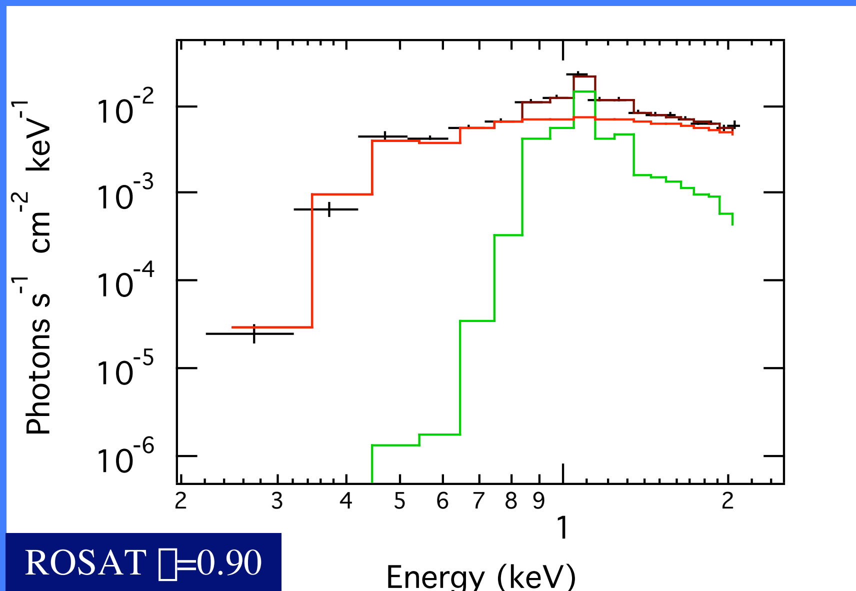
? Shock emission thermal at kT ~ 1keV

? shock accelerates e^-'s via Fermi process to relativistic energies

? electrons produce NT emission via inverse Compton

? when WR in front, NT emission fluoresces warm Fe in WR wind or in dense shock

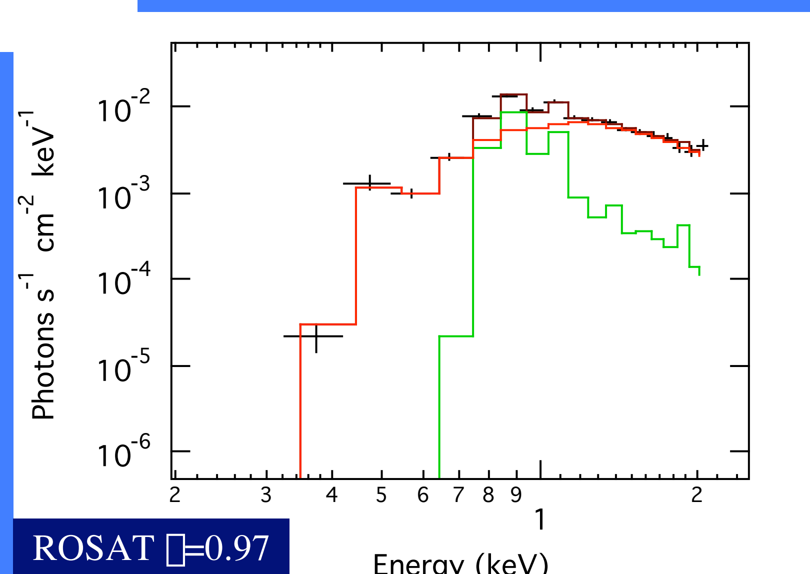
ROSAT PSPC observations



ROSAT □=0.90

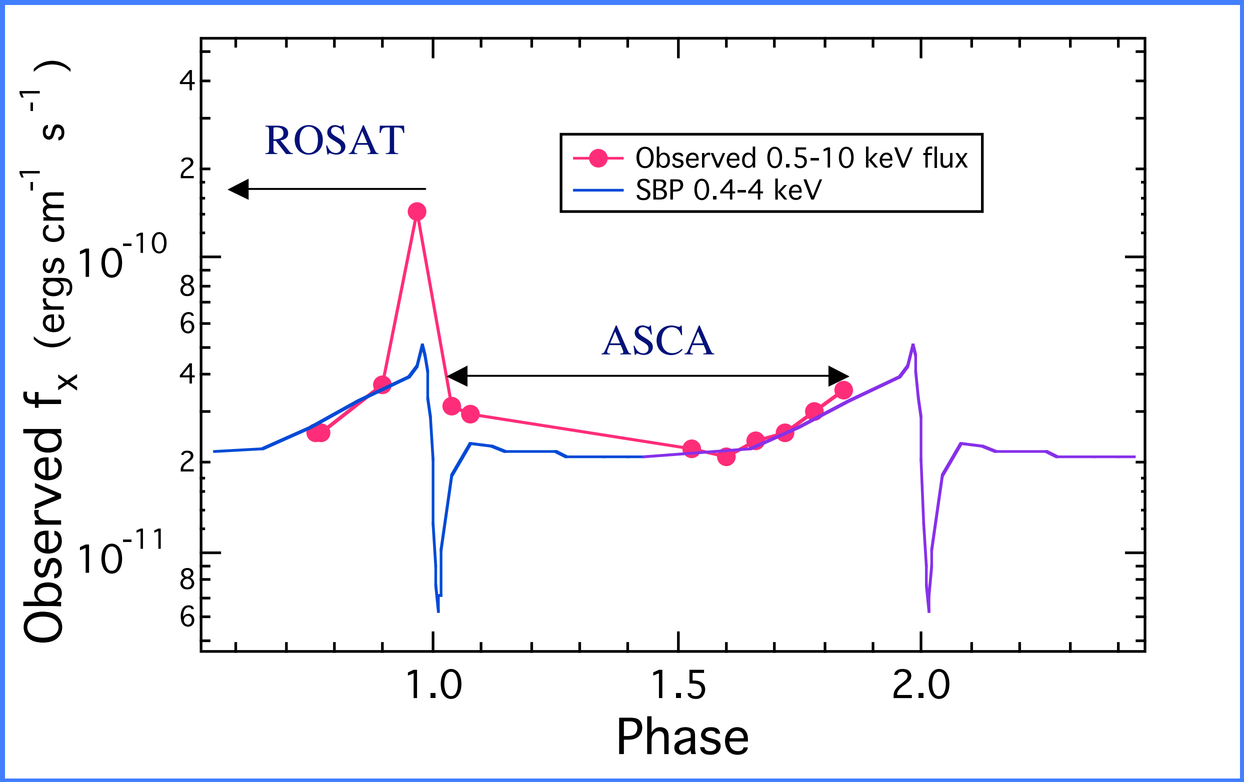
SEQ_ID	EXPO	START	PI
RP200079N00	1403.00	1991.106	BECKER
RP200080N00	3584.00	1991.128	BECKER
RP200544N00	1780.00	1992.141	BECKER
RP201027N00	3372.00	1992.326	BECKER

3 PSPC spectra up to 0.90 show little variation; large change at □=0.97



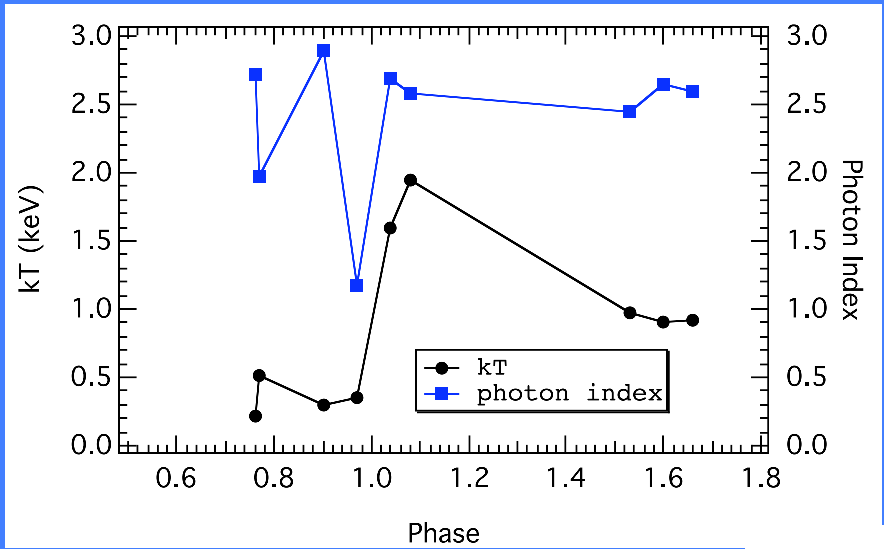
ROSAT □=0.97

X-ray Flux Variability since the last periastron passage:



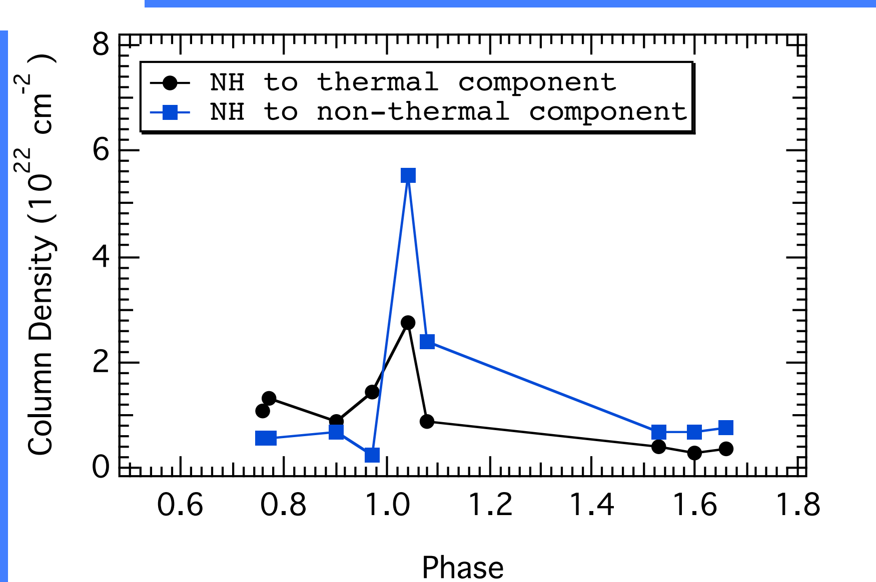
observed flux variation similar to CWB models

Variations in the X-ray spectrum

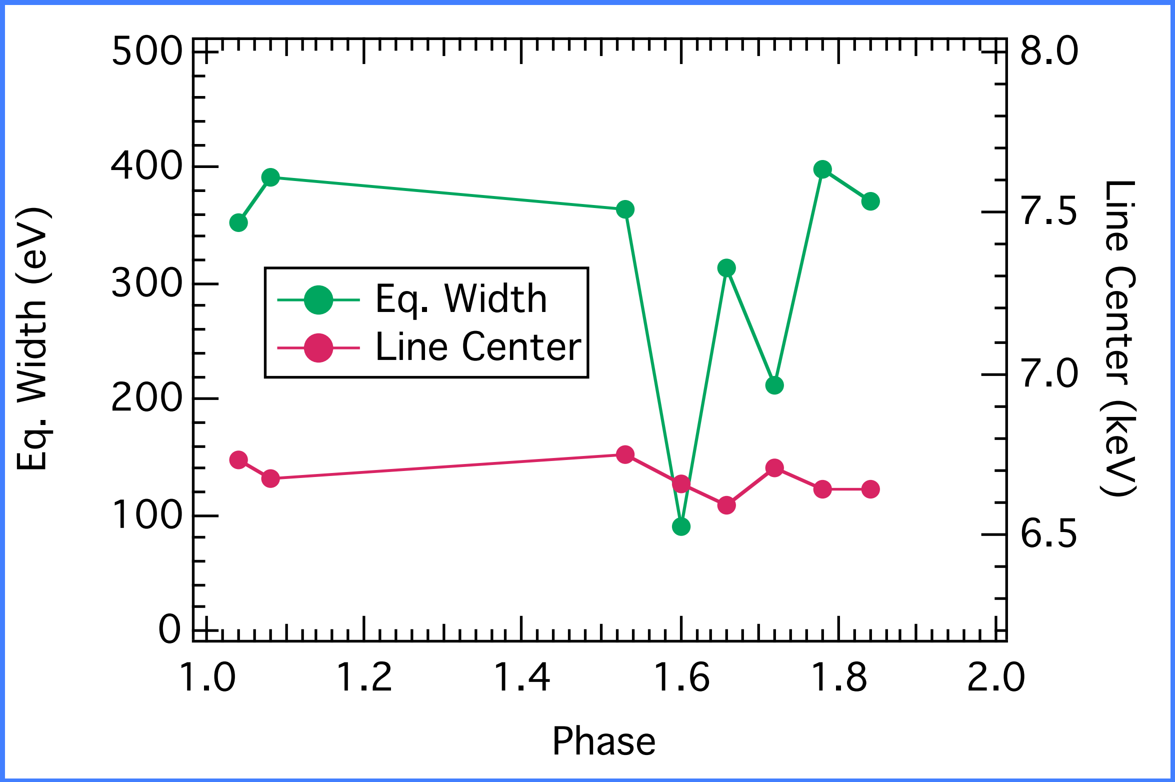


- Highest temperature seen when WR passes from in front of O star;
- away from periastron, temperature when stars far apart higher than when stars nearby

Maximum N_H occurs when WR star in front of shock

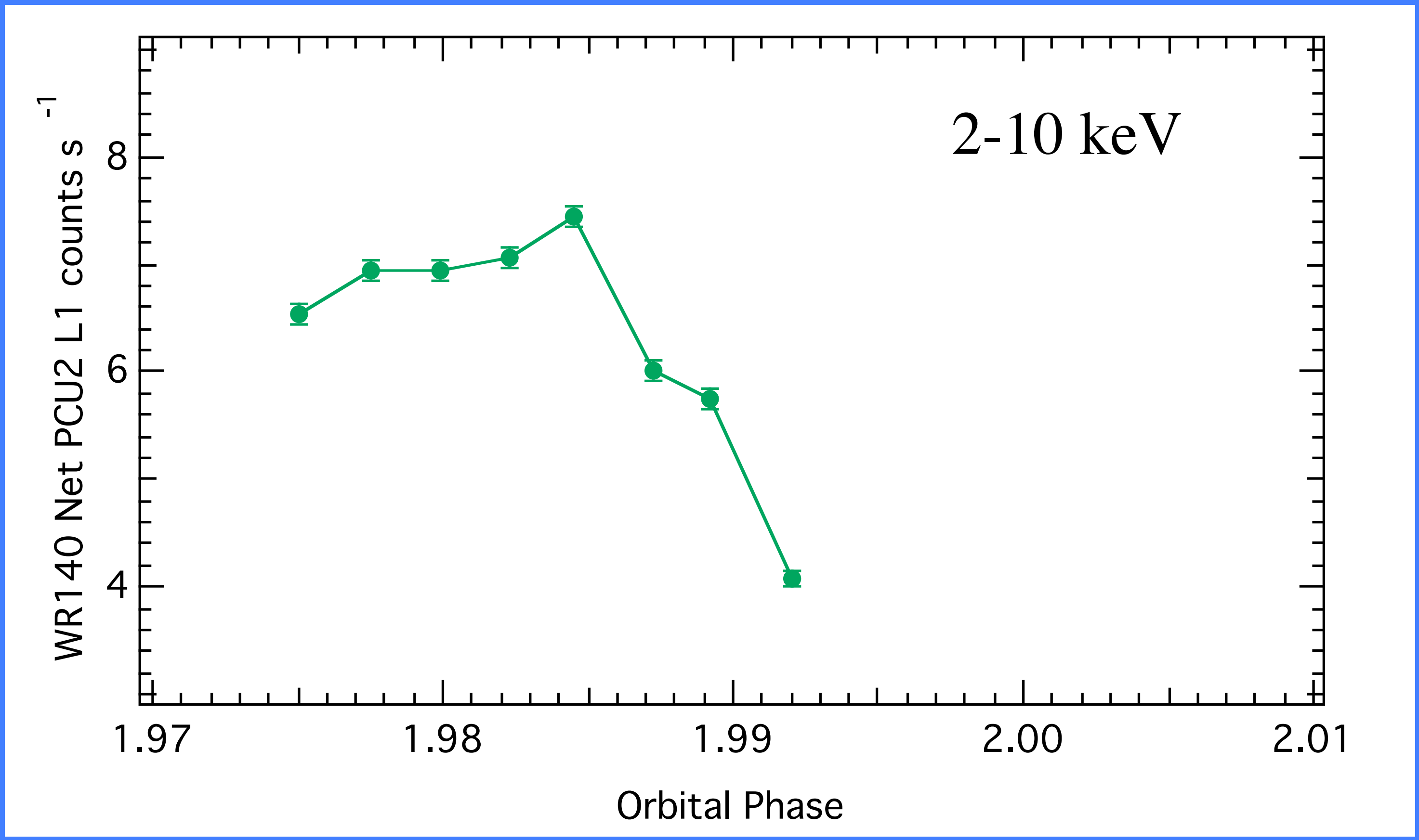


Fe line variability seen by ASCA

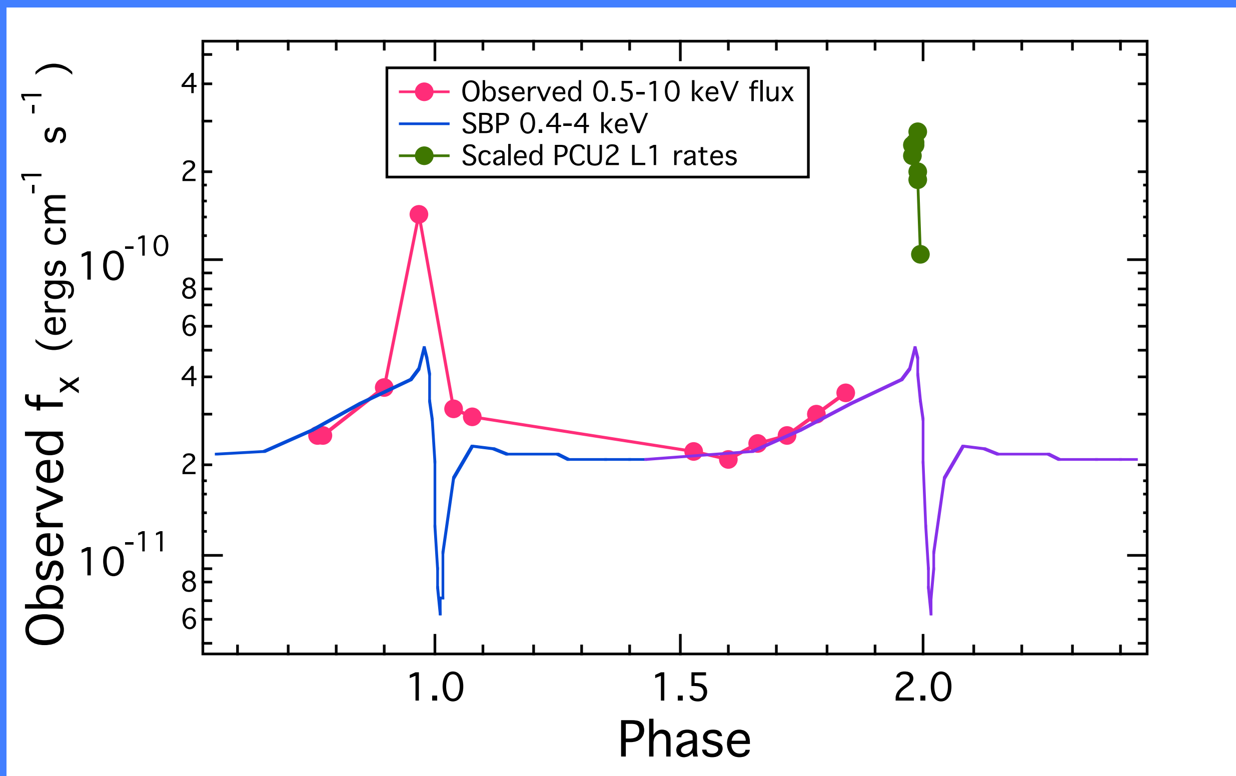


significant variations near apastron, though no significant change in line energy

RXTE Monitoring



ROSAT, ASCA and RXTE lightcurve



Conclusions:

- X-ray flux variations and N_H changes agree well with simple colliding wind models, with spherically symmetric winds
- temperature change near periastron probably selection effect?
- Emission mechanism, if really non-thermal, go beyond simple CWB models
  - Fe K line produced by fluorescence in the WR wind?
  - perhaps change in spectral index of emission?
  - source of B field?
  - or does NEI contribute? (Zhekov & Skinner 2000)
  - Suggests particle acceleration may be important - but upper limit to particle energy not well defined

Chandra Grating spectra: coming soon!