The Last Eclipse of Eta Carinae

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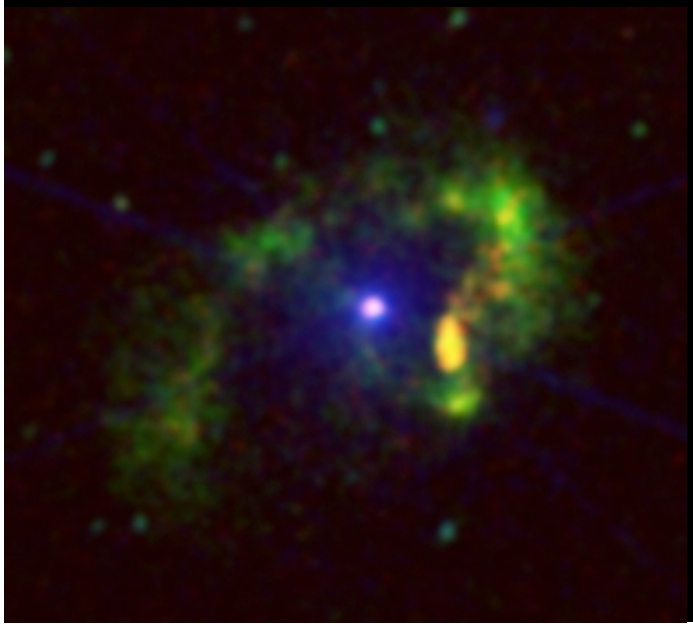
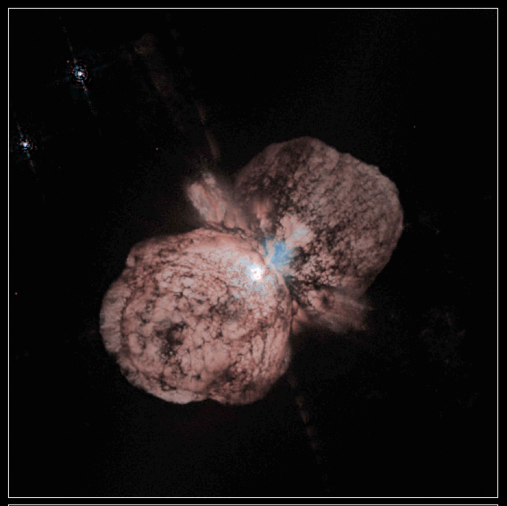
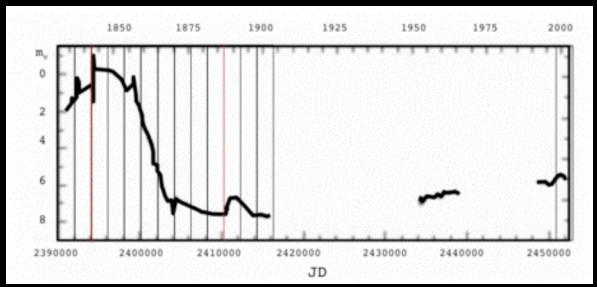




Eta Carinae

Hubble Space Telescope · WFPC2

PRC96-23a - ST ScI OPO - June 10, 1996 - J. Morse (U. CO), K. Davidson (U. MN) and NASA



Outline of the talk:

I. Overview of Extremely Massive stars

II. Eta Car: A typically unique example

III. Variability & Colliding Winds

IV. The Hunt for the Hidden Companion - Summer 2003

- X-ray evidence from RXTE, Chandra & XMM
- Other wavebands
- HST

V. Still to Do...

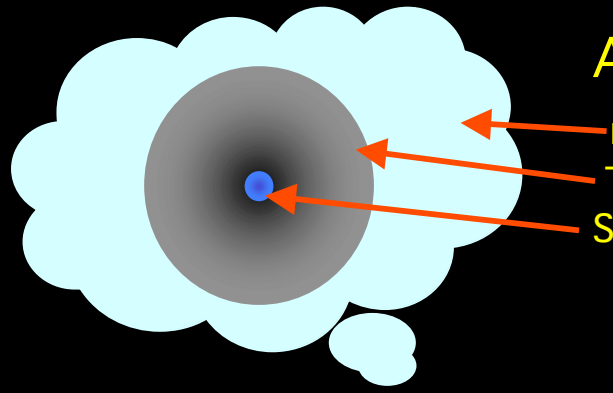
Extremely Massive stars (EMS)
(>50 times as massive as the Sun)

Properties

- are hot (surface temperatures ~ 20000-50000K)
- are large (radii ~ 15-30 solar radii or more)
- possess strong *stellar winds*:
  - ➡ wind speeds > 6 million miles per hour
  - ➡ winds expel matter into space (>100 earth masses per year)
- Are extremely variable
- LUMINOUS BLUE VARIABLES (LBVs): thought to be in a short-lived, transitional stage of the star's evolution

In the present epoch, most stars are less massive than the sun

- few dozen stars with M > 80 M_O
  - WR 20a - binary, dynamical masses > 80M_O, 3.7 day period
  - LBV 1806-20 (M>130 M_O; binary)
  - Pistol star M > 200 M_O (!)
  - Eta Car M > 90 M_O
- New candidates near the galactic center (Figer et al., Yusef-Zadeh et al.): Arches cluster, Quintuplet cluster..



An EMS consists of

messy stellar environment

Thick Stellar wind

Stellar surface (photosphere)

EMSs responsible for many interesting phenomena

- re-ionization in the early universe & chemical enrichment
- Heating of ISM
- end star formation &/or trigger new star formation
- Gamma-ray bursts (?)
- Collapsed objects: stellar (& intermediate-mass?) BHs
- Life

To understand these phenomena, we need to understand how these very massive stars form and evolve;

But these stars are rare and short lived, and so are difficult to study

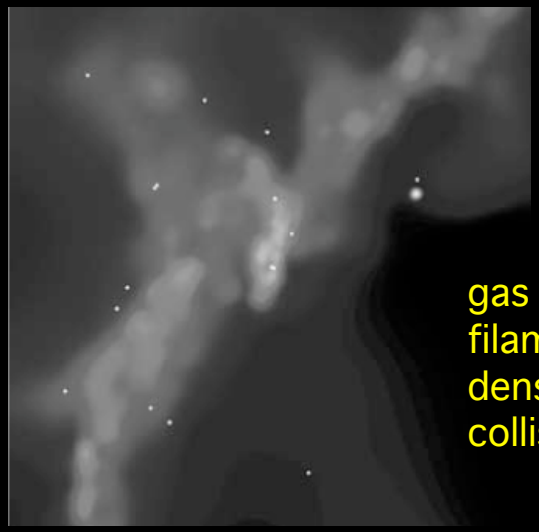
Only 3 problems remaining:

- Birth of EMS
- Life of EMS
- Death of EMS

Formation of EMS:

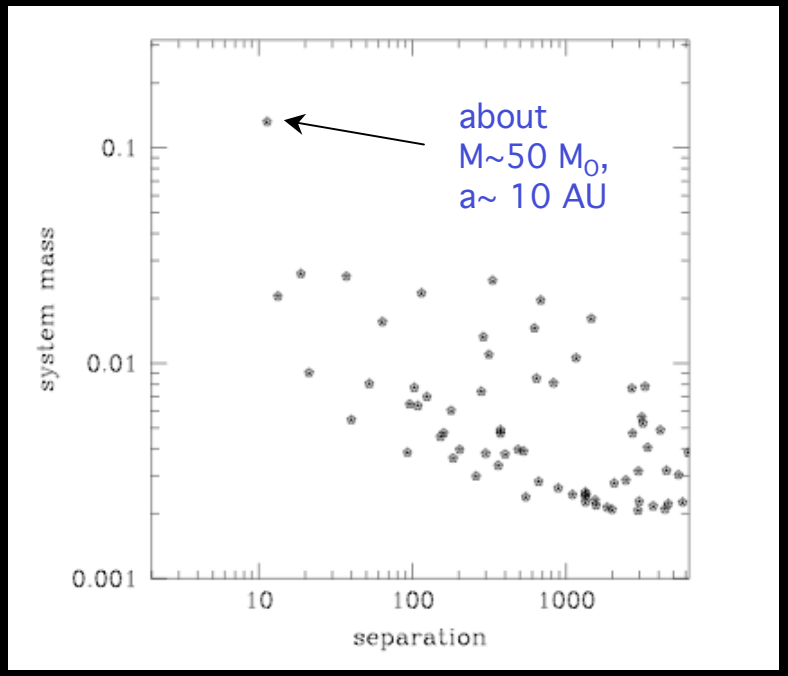
How to overcome radiation pressure, angular momentum barriers in non-Population III objects?

- Disk-like accretion? (but spin up by jets?)
- Collisional accretion? (but stellar densities too low?)



gas collapses into filaments, high stellar densities, frequent collisions

Bonnell & Bate 2002



Interior Evolution

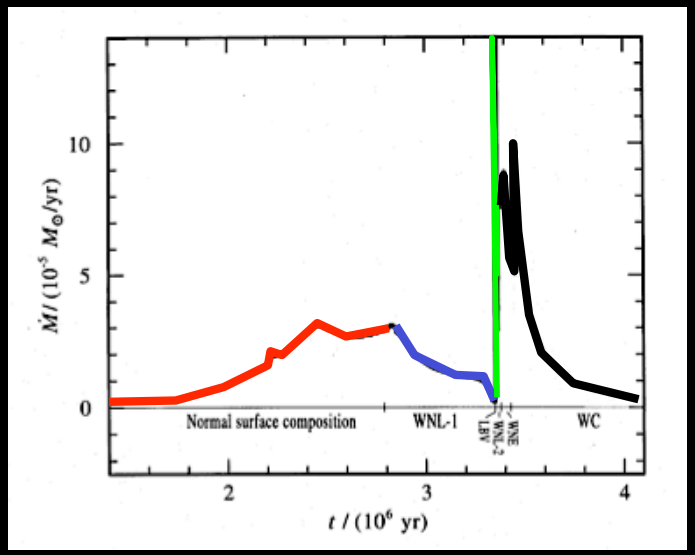
Nuclear burning stages: Log(duration/yr) for a 75 M_O star

Mass	H	He	C	Ne	O	Si
$75M_O$	6.5	5.7	3.0	-0.2	-0.1	-2.2

From Woosley & Heger 2002

2 days!

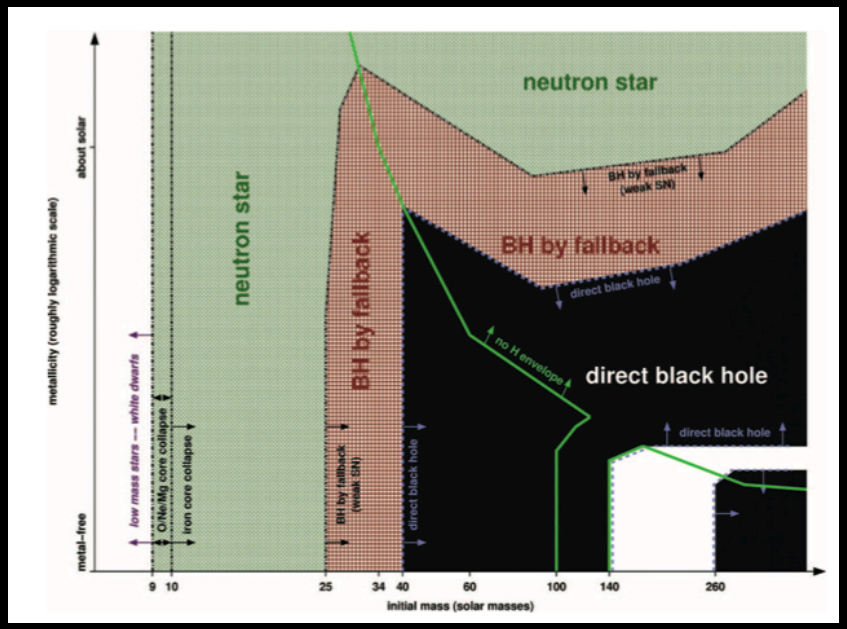
Surface evolution

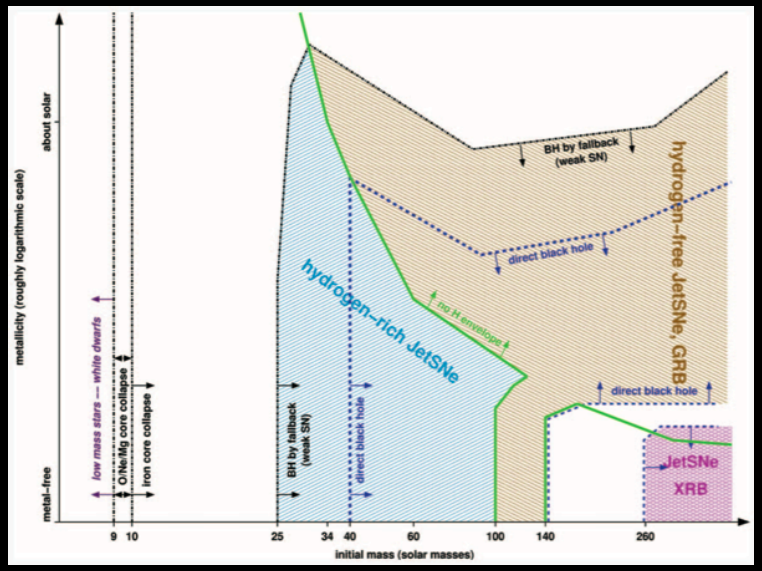


From Langer et al. 1994

	M	log(t/yr)	M_{lost}	M_{end}
MS	60.0	6.5	17.6	42.4
WN	42.4	5.8	21.7	20.7
LBV	20.7	4.9	5.4	15.3
WNE/WC	15.3	5.8	11.4	3.9

End states:

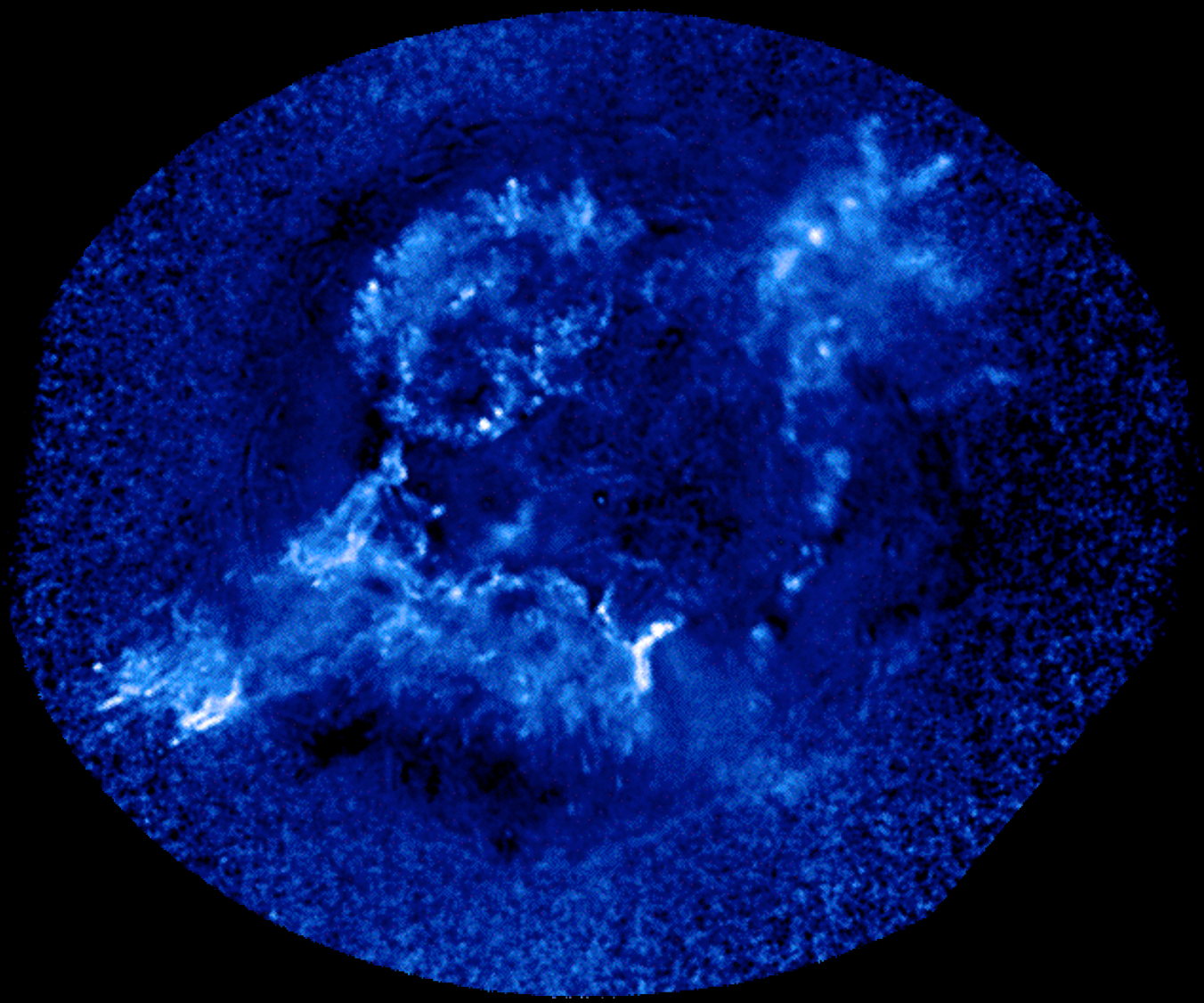




Fate of star depends on
amount of mass lost, which
depends on metallicity, angular momentum
evolution, magnetic fields...

From Heger et al. 2003

Death and Postmortem



Cas A Si-line image

Artist 's rendition of an EMS at the formation/collapse of the iron core to the eventual "hypernova" explosion

Eta Car: a Legendary Stellar Monster

Eta Car is one of the most enigmatic members of the class of LBVs

- it's relatively close (about 8000 light years)
- it's extremely luminous (and at one time extremely bright)
- It must have a mass near 100 Solar masses at present since otherwise it would blow itself apart due to the outward pressure of the light it generates
- due to mass loss it must have been even heavier when it formed
- it shows evidence of nuclear processing
- it erupted in 1843 in an event (called the Great Eruption) reported around the world

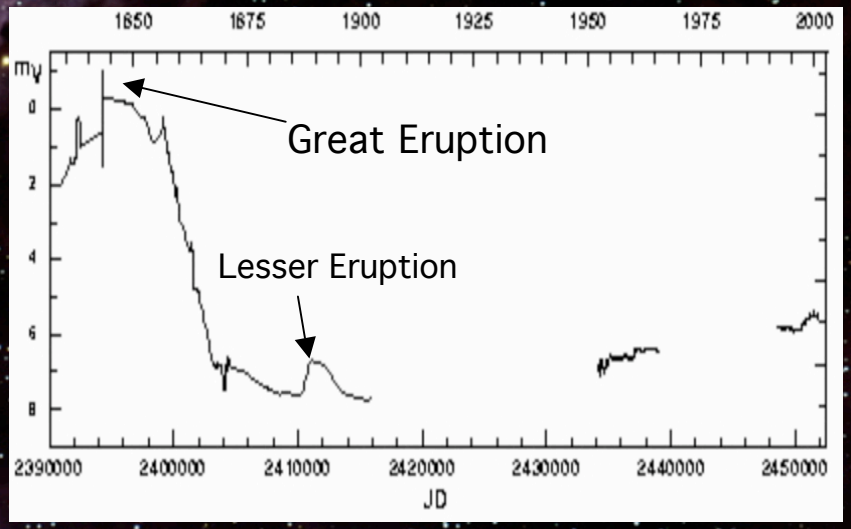
Eta Carinae's Neighborhood

Keyhole nebula

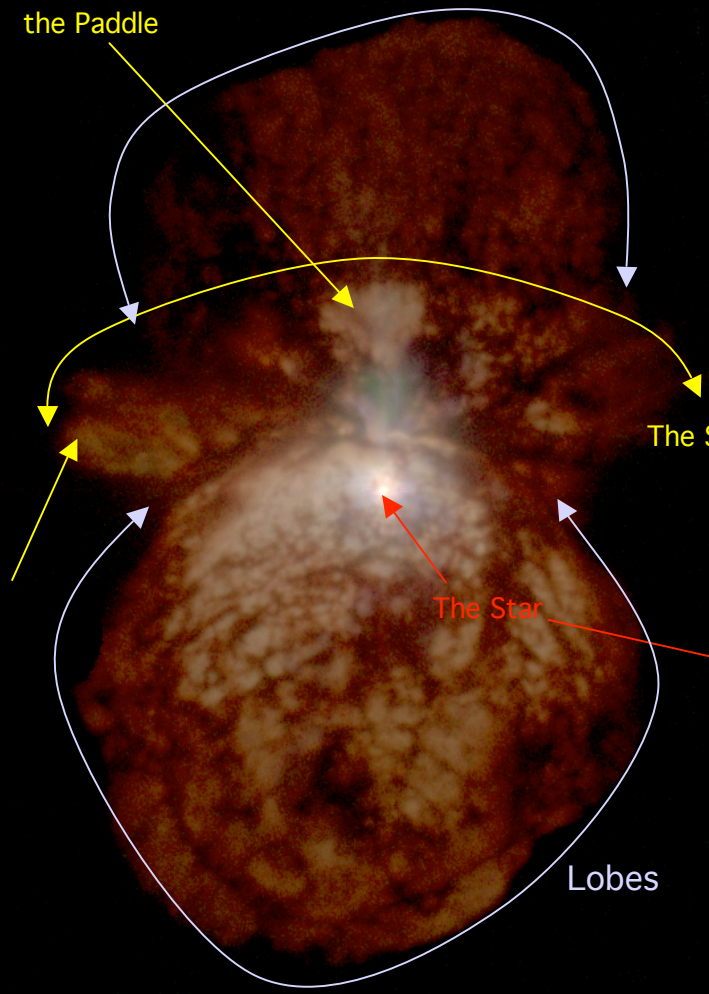
Trumpler 14

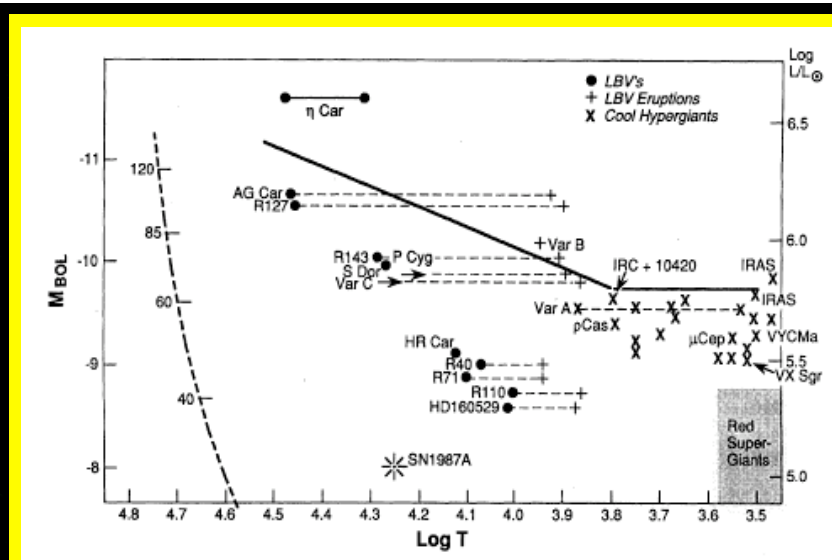
One of the Hottest stars known

Eta Car

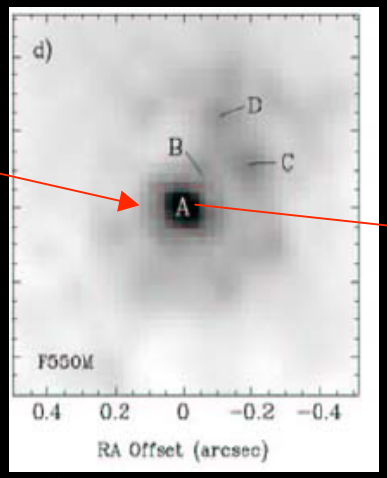


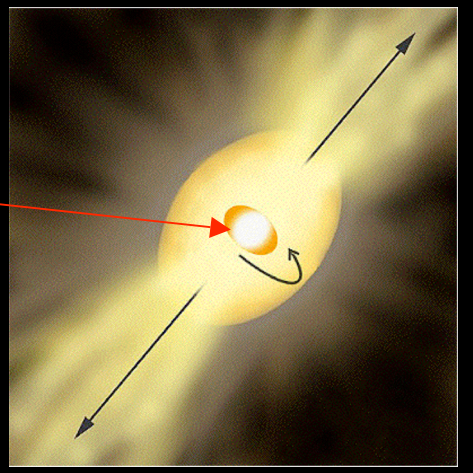
Eta Car and the Homunculus





Humphrey and Davidson 1994





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

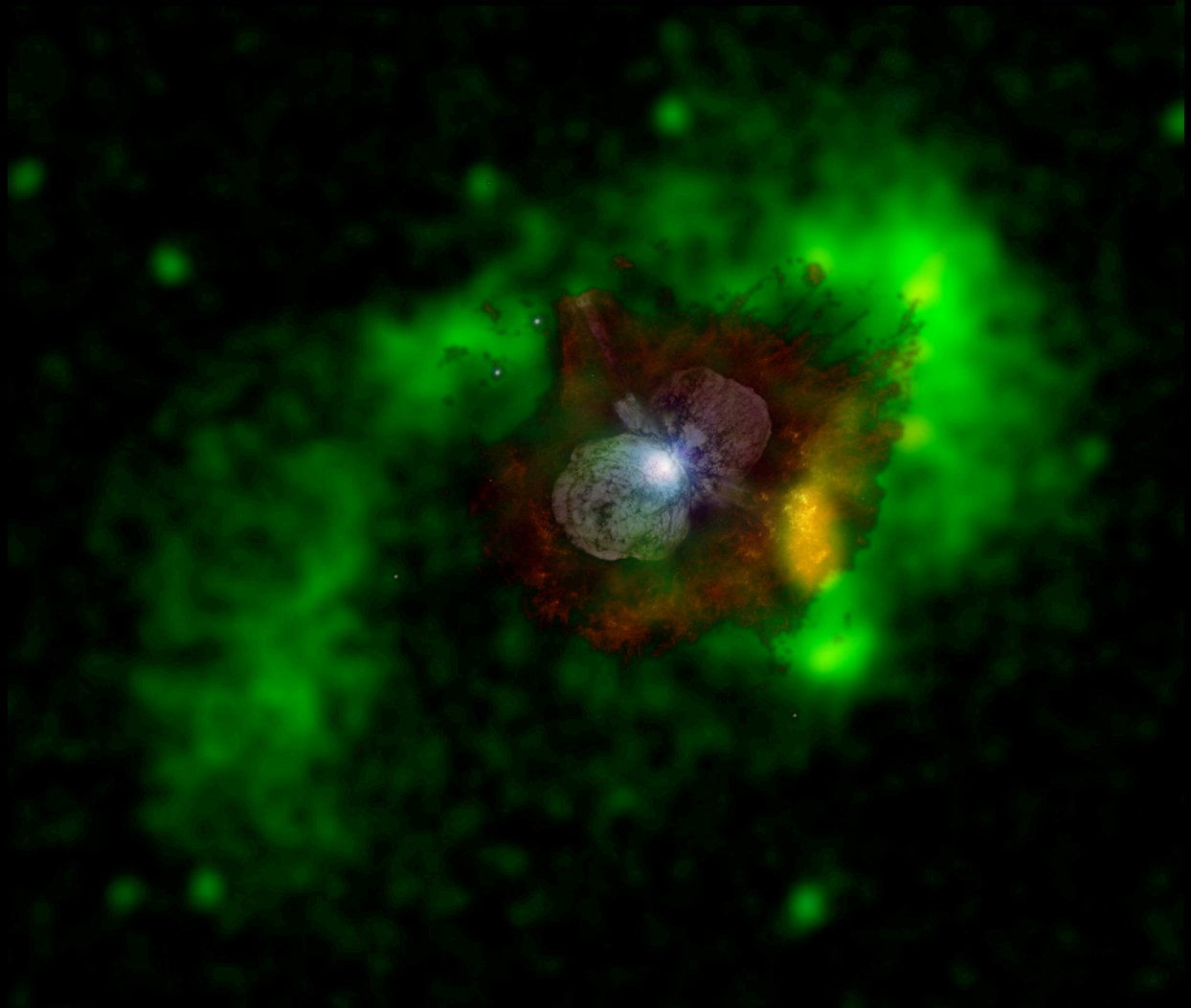
HST/ACS image of Eta Car (Courtesy the HST TREASURY PROJECT)

How can X-rays Help us Understand Eta Car?

X-rays can see through the homunculus and reveal the physical conditions near the star.

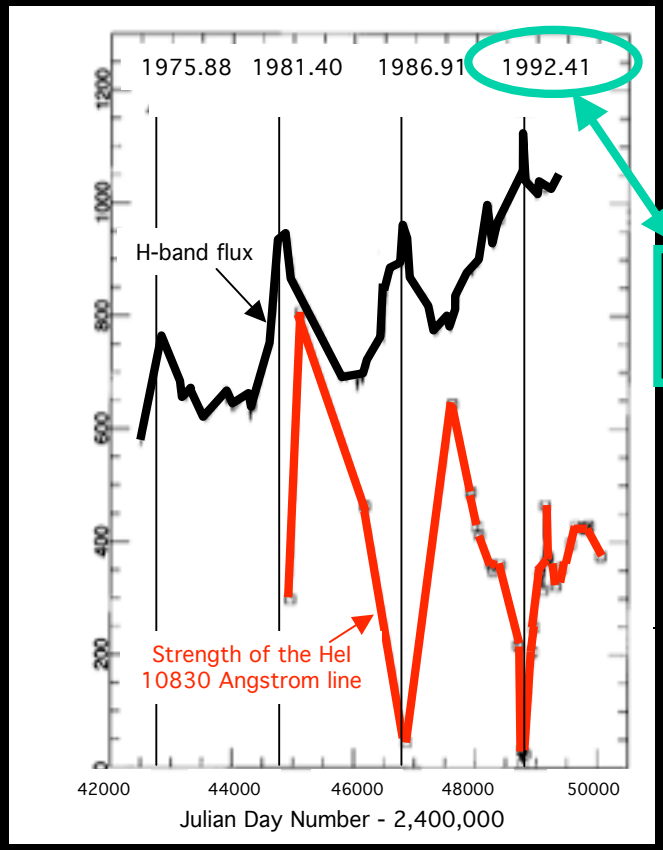
- Determine how much material is being lost from the star
- Probe conditions very near the star
- Help identify energetic processes near the star
- Reveal surprises

Eta Car: Optical vs. X-ray

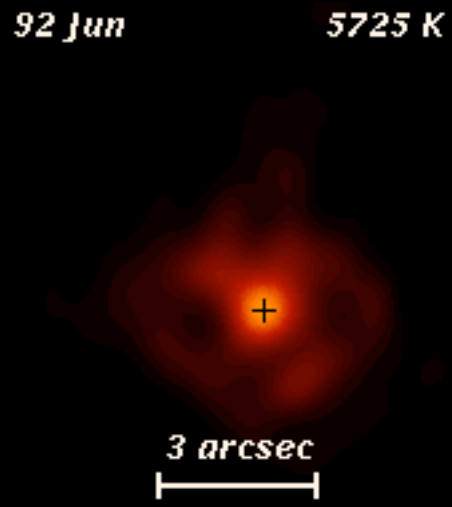


WFPC2 (courtesy of N. Smith, red/blue) and Chandra (500 ksec ACIS+HETG 0th order, yellow/green) composite of Eta Car

Detection of Periodic and Multiwavelength Variability from Eta Car



X-ray and Radio Observations

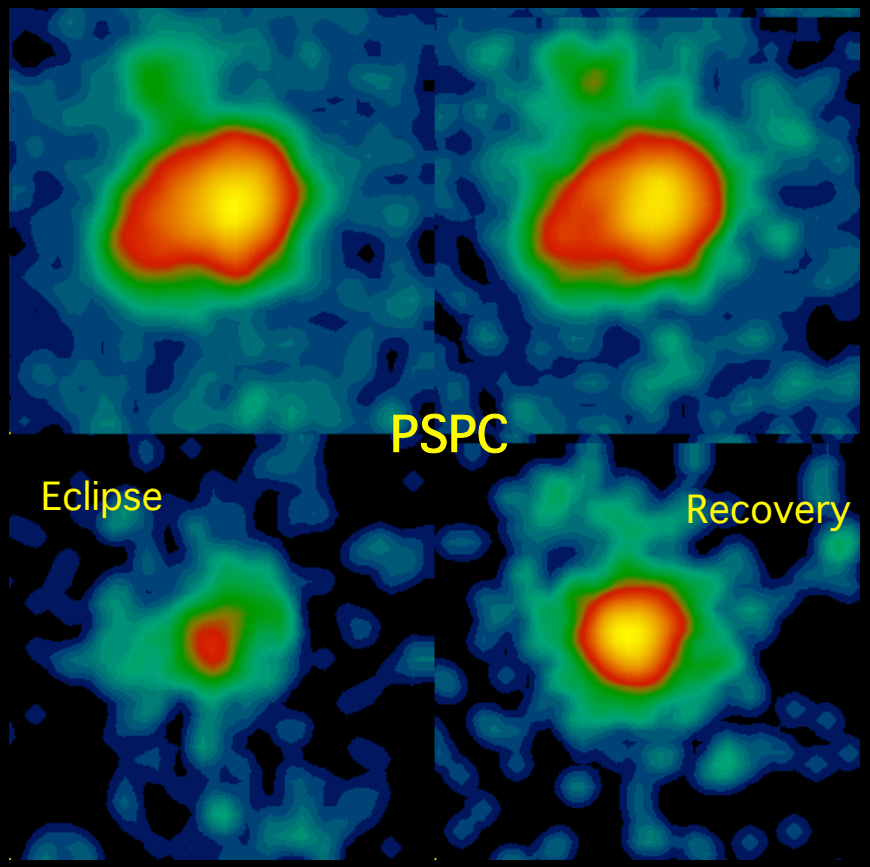


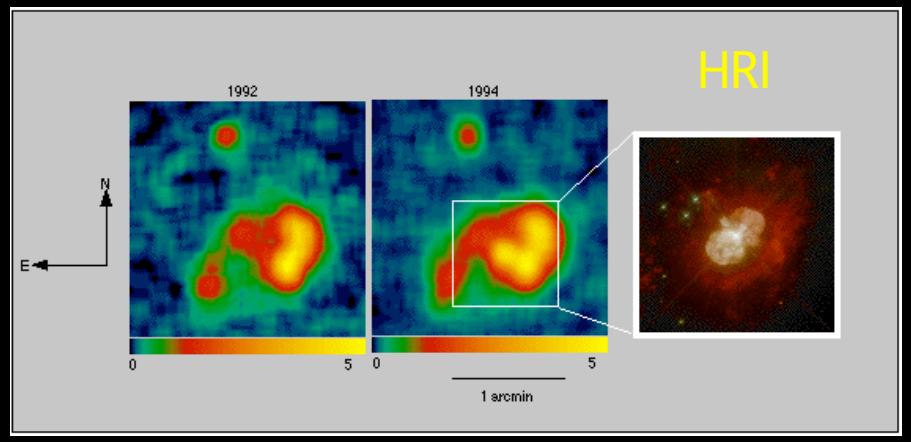
Radio variations of Eta Car by Bob Duncan (Australian Telescope National Facility) and Stephen White (UMd)

Ground-based Observations of Eta Car's Variability over 16 years by Augusto Damineli (IAGUSP, Brazil)

But confusion in optical, IR and radio due to emission from nebula...

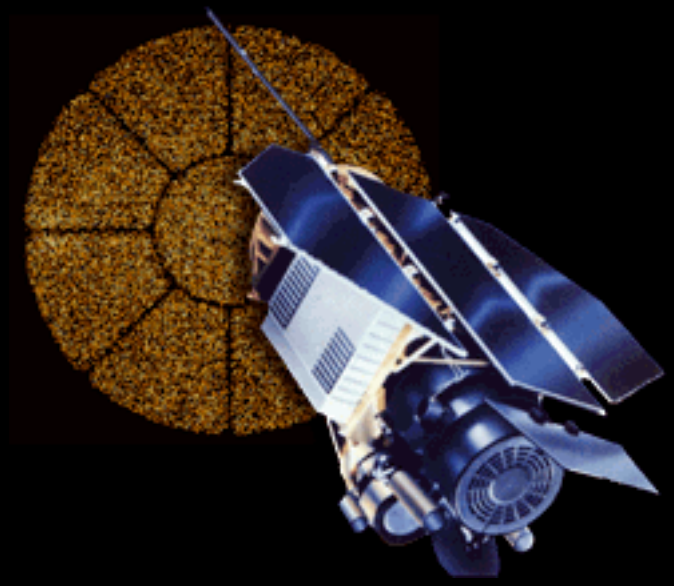
ROSAT saw X-ray variability from Eta Car in 1992 too:





Soft

Hard

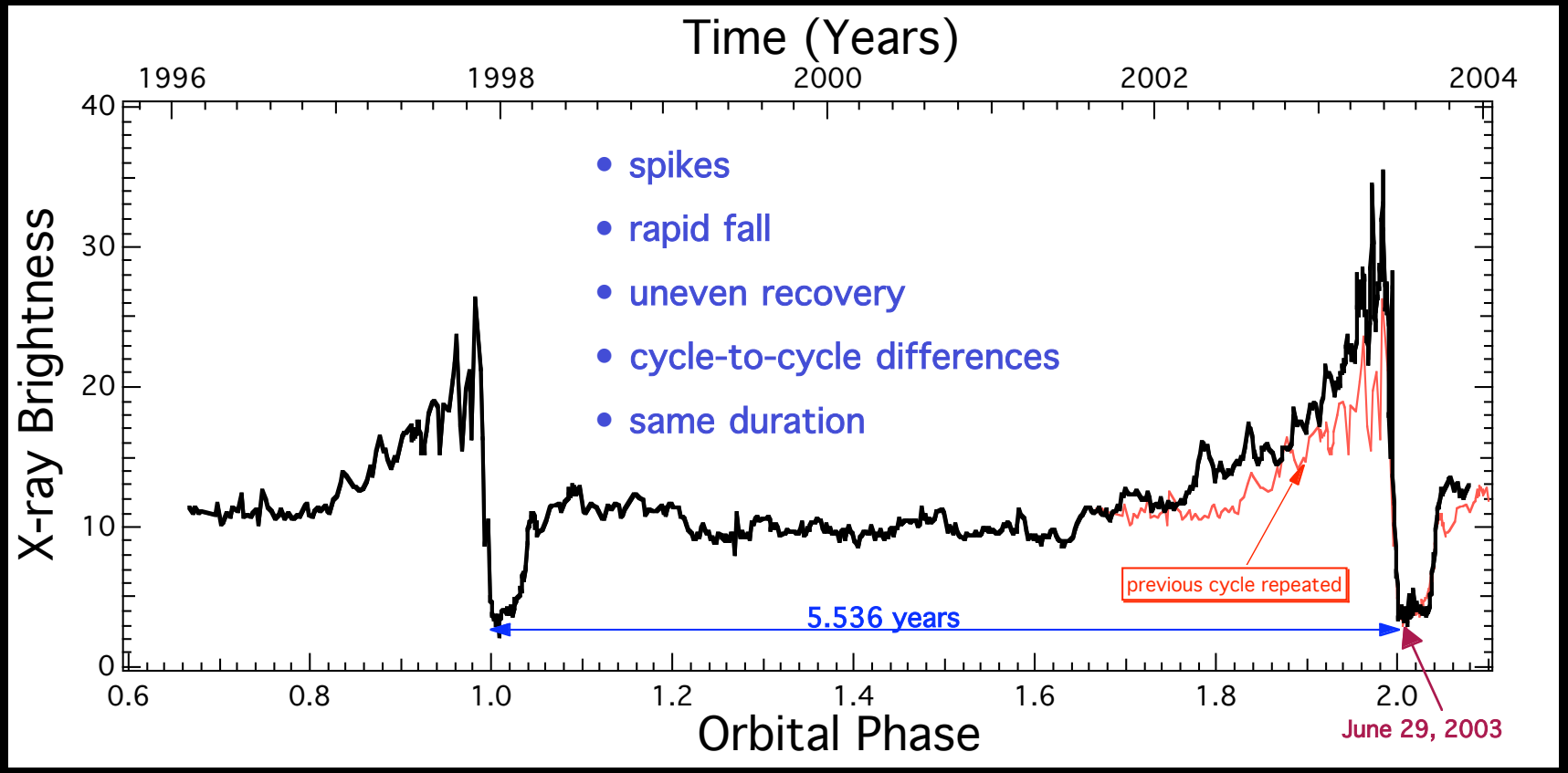


Corcoran et al. 1995

- *Is the X-ray variability periodic?*
- *how strongly tied to the optical/radio variability?*

Use the Rossi X-ray Timing Explorer (launched 1995) to monitor the 2-10 keV spectrum

The RXTE X-ray lightcurve, 2-10 keV:



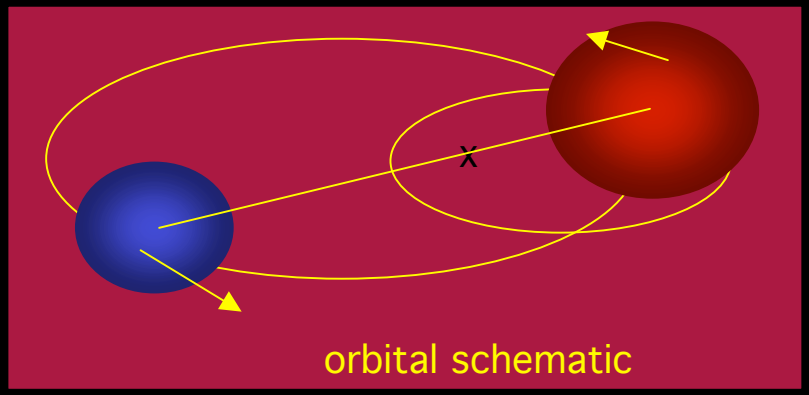
8 years of weekly-daily monitoring

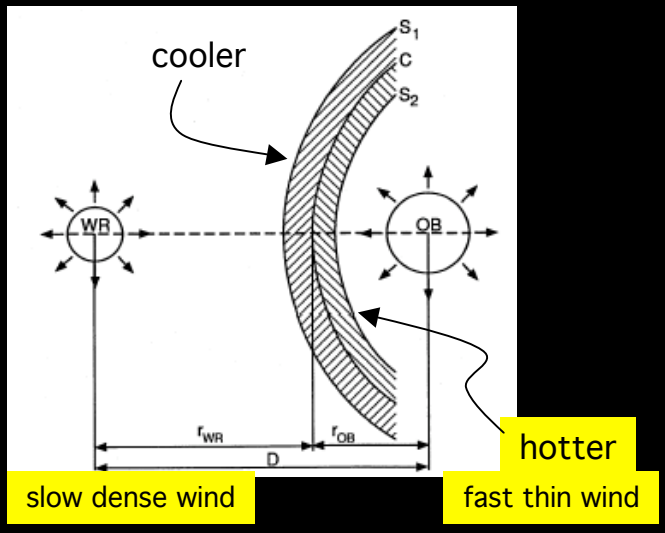
RXTE Monitoring results

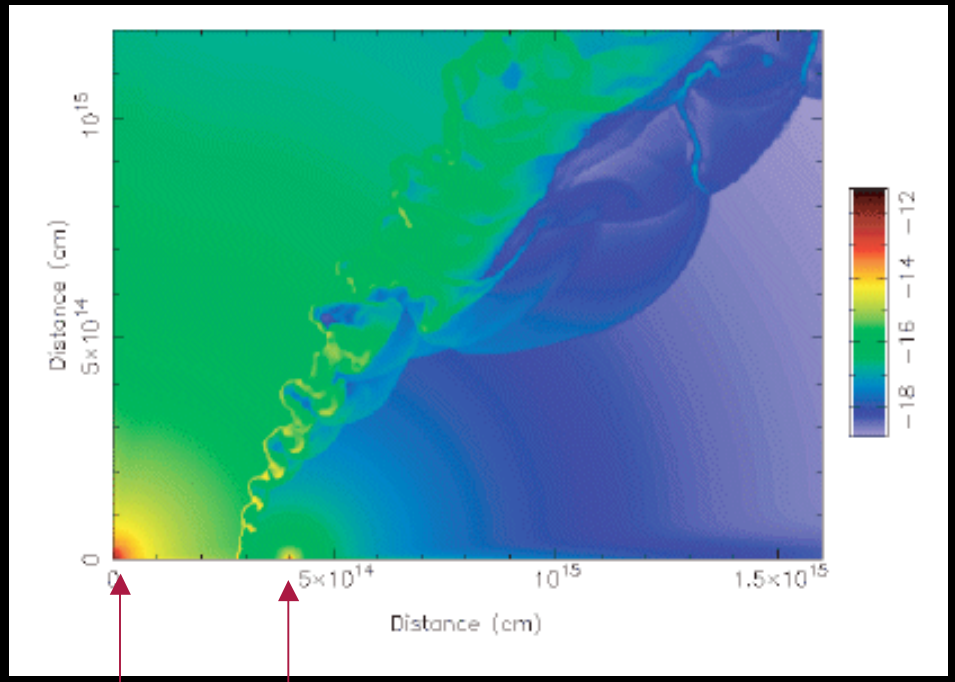
- RXTE saw an drop in the X-ray flux almost exactly 5.5 and 11 years after ROSAT discovery of X-ray variability: PERIODIC!
- Eta Car undergoes a brief “X-ray eclipse” period (only lasts about 3 months out of 5.5 years)
- Suggestion: Colliding wind X-ray emission (like WR 140)
- Orbital motion might also be responsible for changes seen in other parts of the EM spectrum
- If not gravity, how else to get an accurate clock? (periodic “starquakes”? Solar-type activity cycles, driven by magnetism?)

The multi-wavelength variability suggests a single origin:

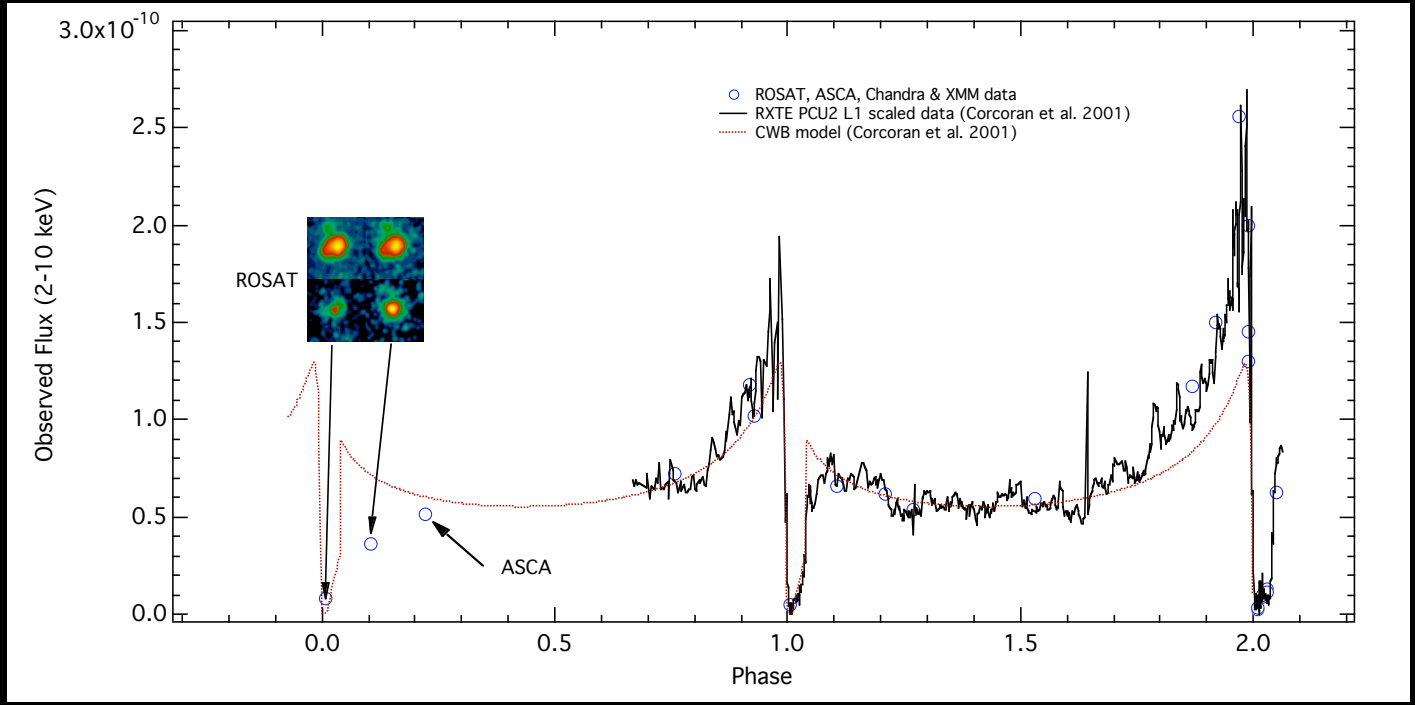
- That Eta Carinae is a binary star
- and the observed X-ray variations are produced by the collision of the wind from Eta Car with the companion star





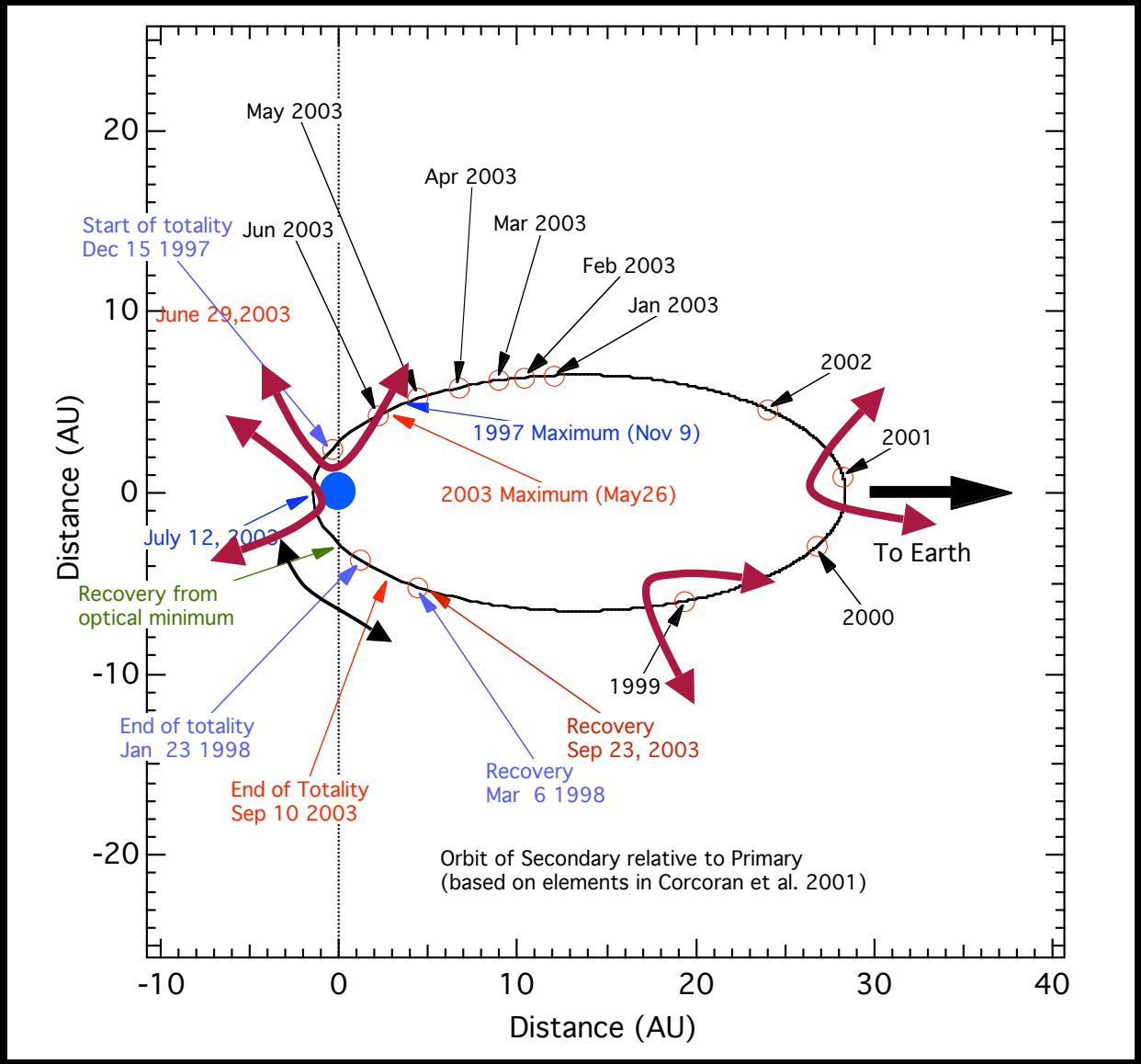


The red line is the predicted brightness based on a colliding wind binary model

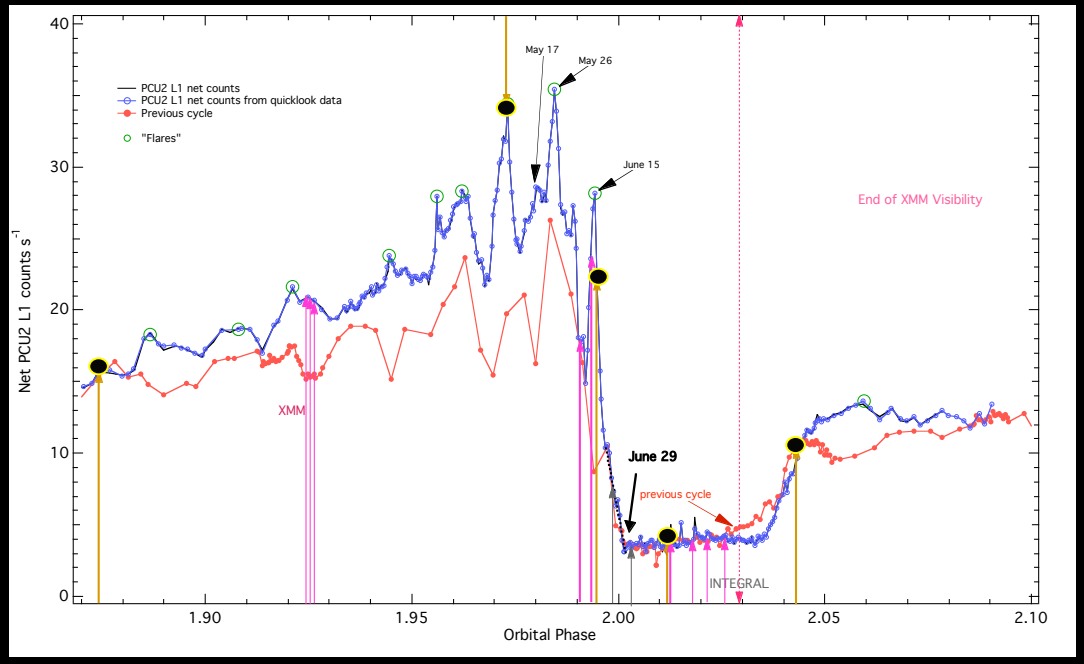


- Eta Car: M~80 M_O, Mdot~10^{-4} M_O/yr, V_{wind}=500 km/s
- Companion: M~30 M_O, Mdot~10^{-5} M_O/yr, V_{wind}=3000 km/s

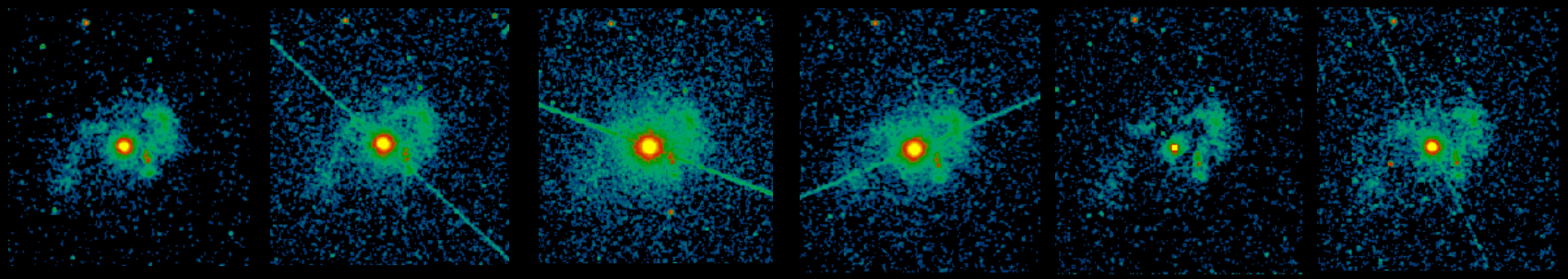
The Orbit of the companion around Eta Car:



Eta Car's Latest Eclipse: Caught in the Act

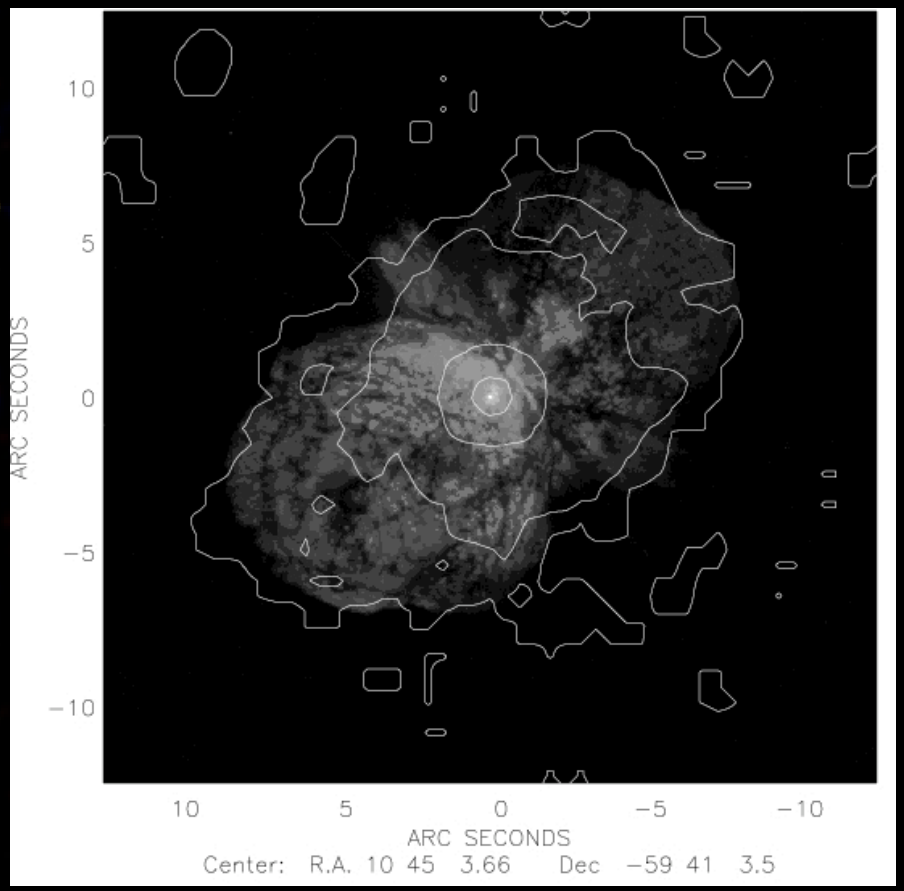


Around the time of the X-ray eclipse, snapshot monitoring of Eta Car's X-ray emission by Chandra and the XMM-Newton X-ray Observatories



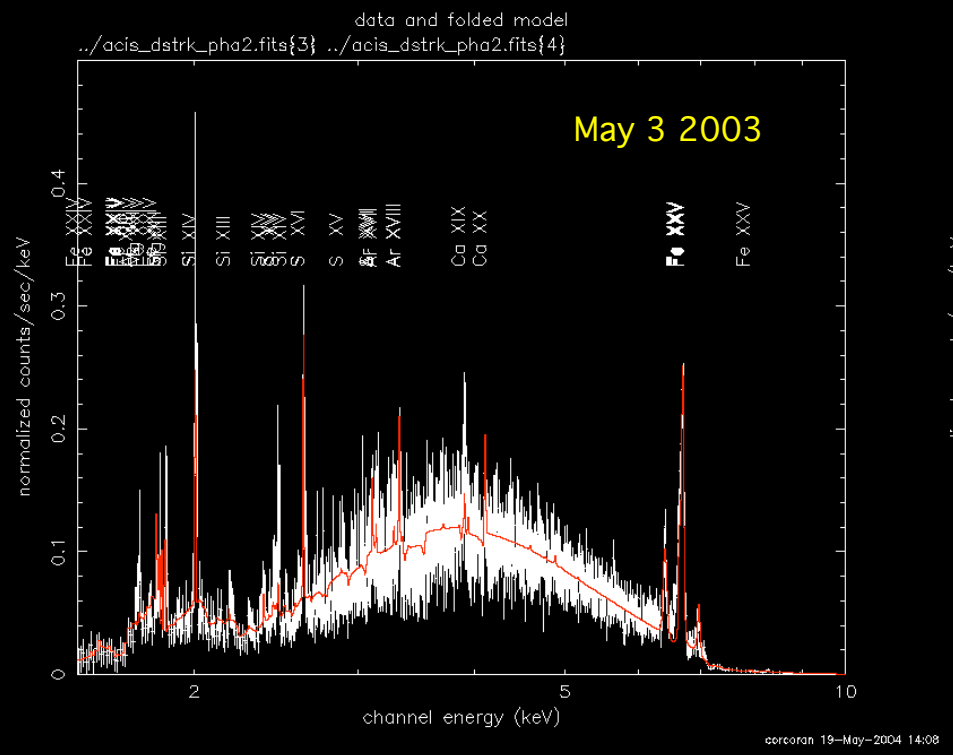
Nov 20 2000 | Oct 16 2002 | May 3 2003 | Jun 16 2003 | Jul 20 2003 | Sep 26 2003

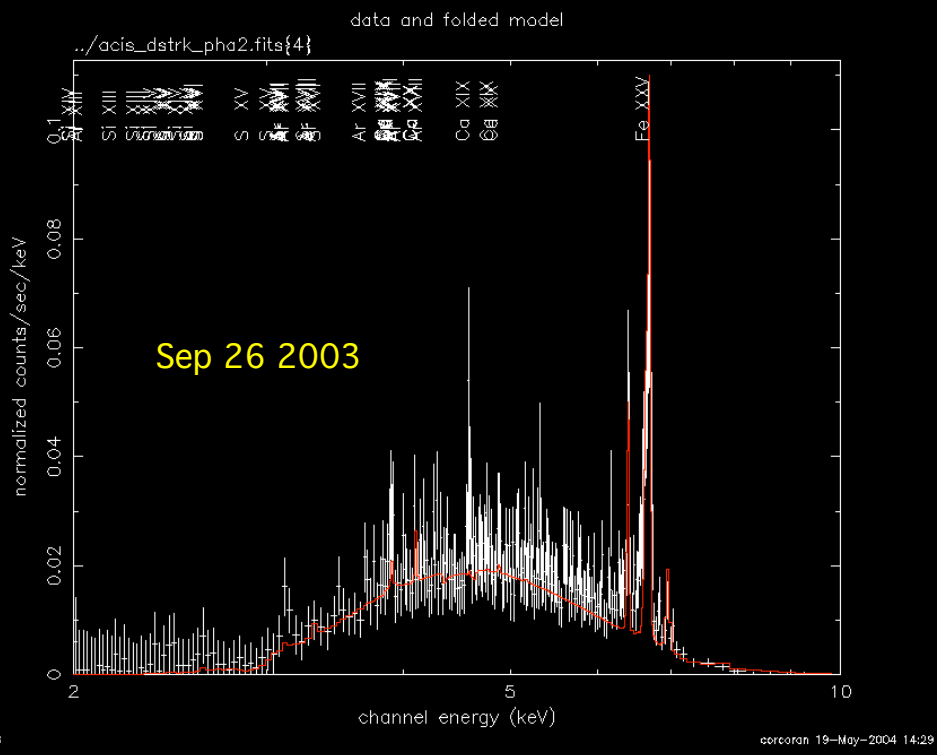
X-ray Reflection from the Homunculus

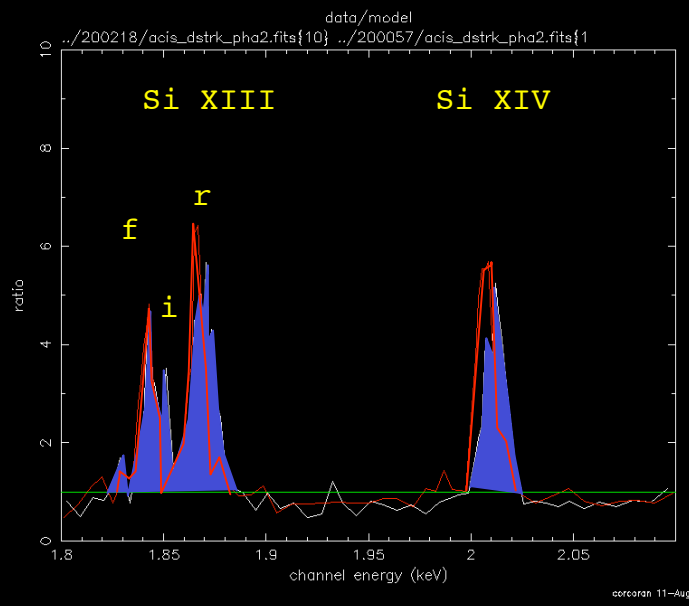


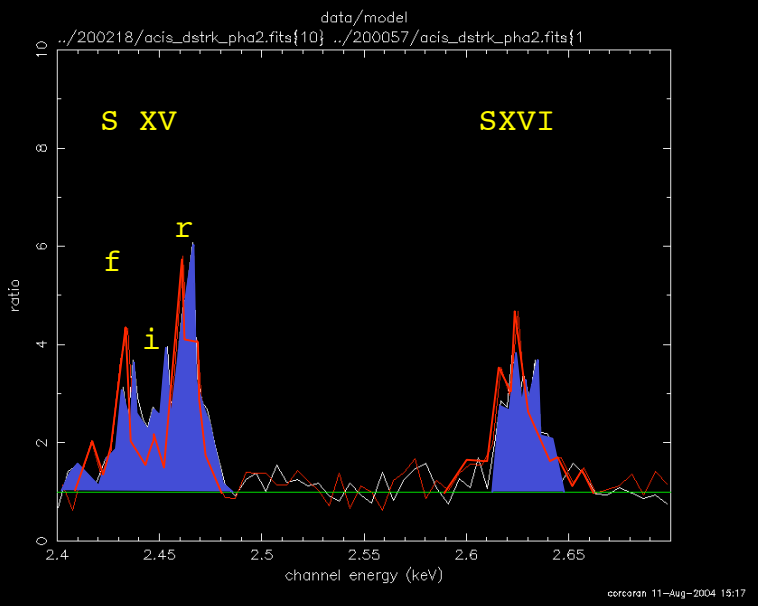
[NII] 6583 courtesy Nathan Smith

Chandra Grating Spectra

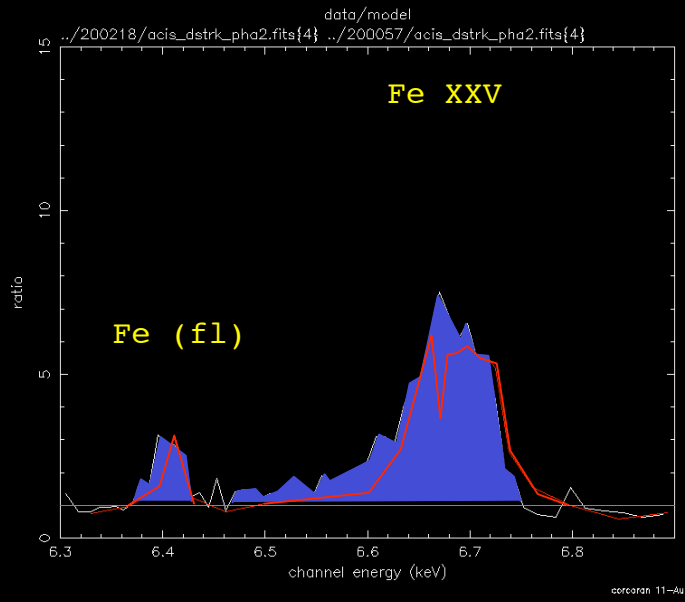








- periastron
- apastron



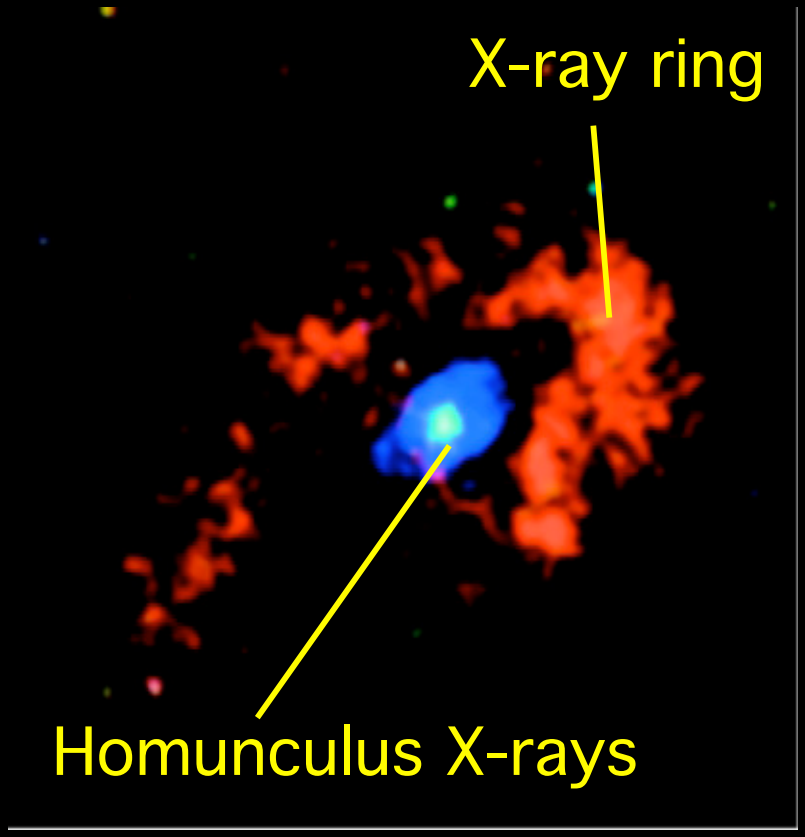
Si, S => blueshift from apastron to periastron?

Fe => redshift from apastron to periastron?

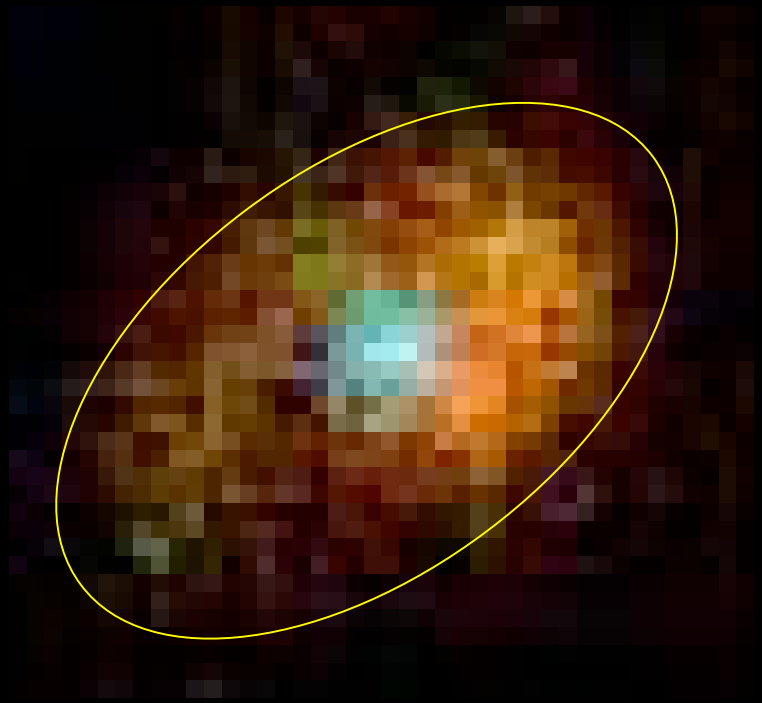
change in line shape?

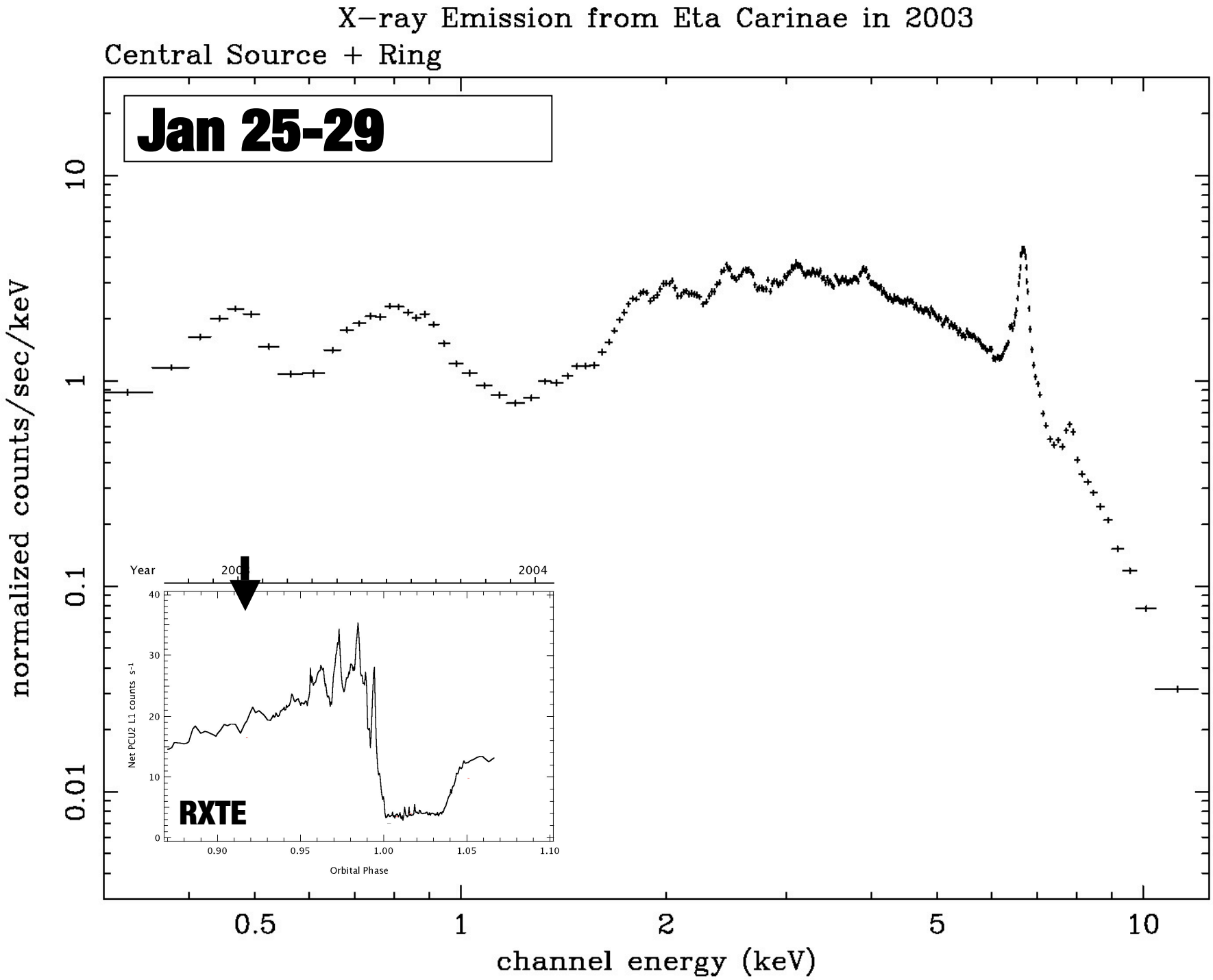
XMM/Chandra Imaging during the last minimum

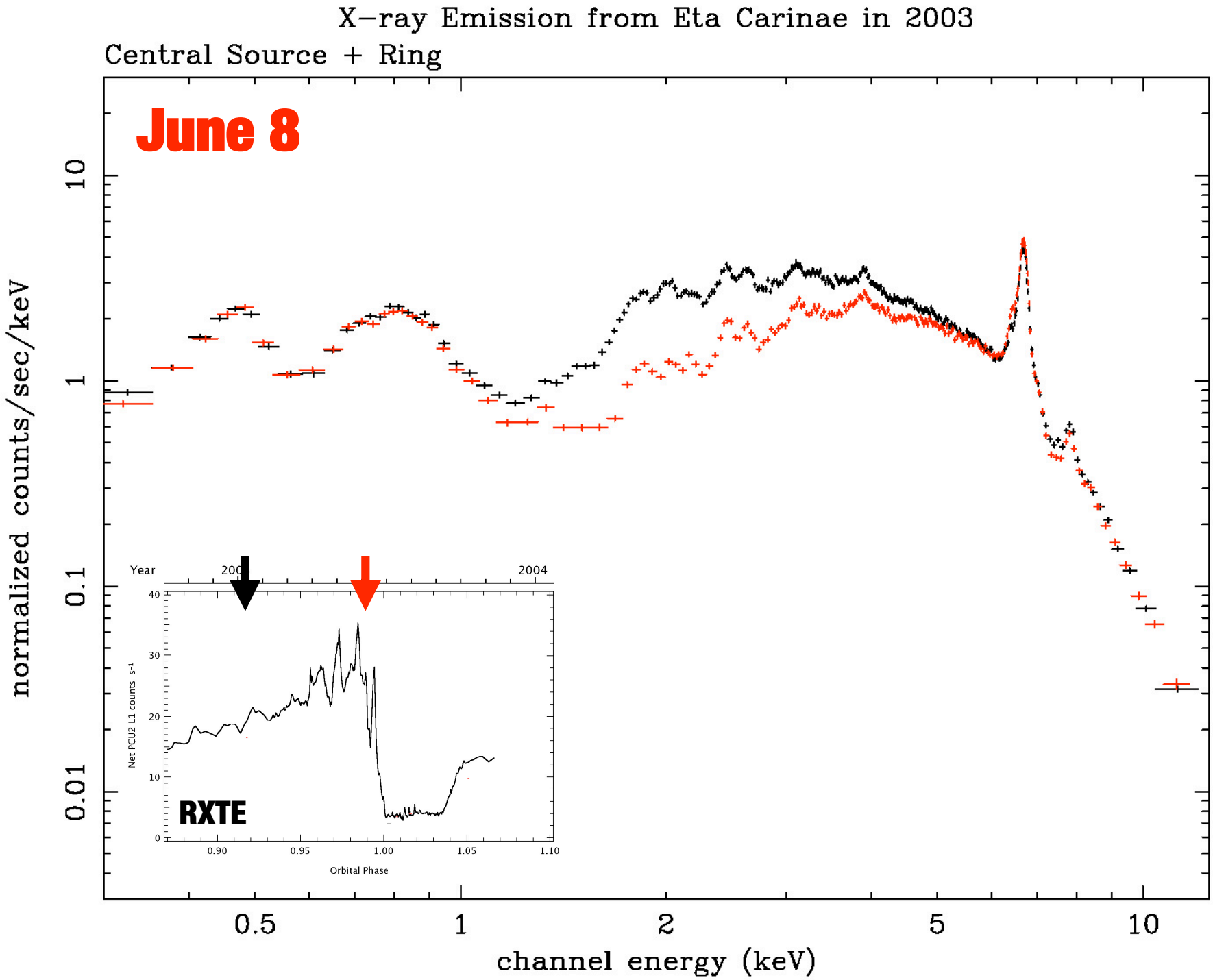
Chandra (2003/7/20)

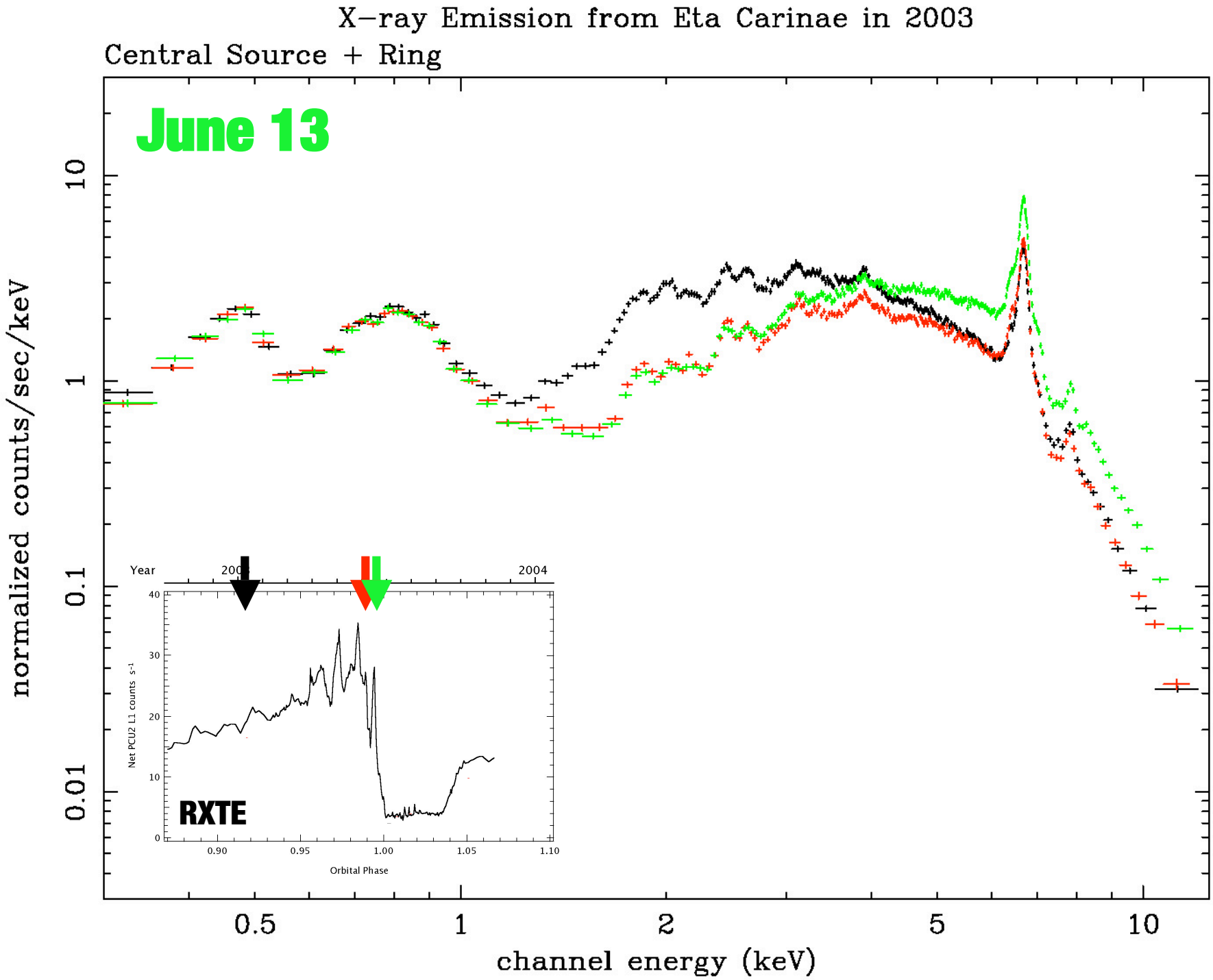


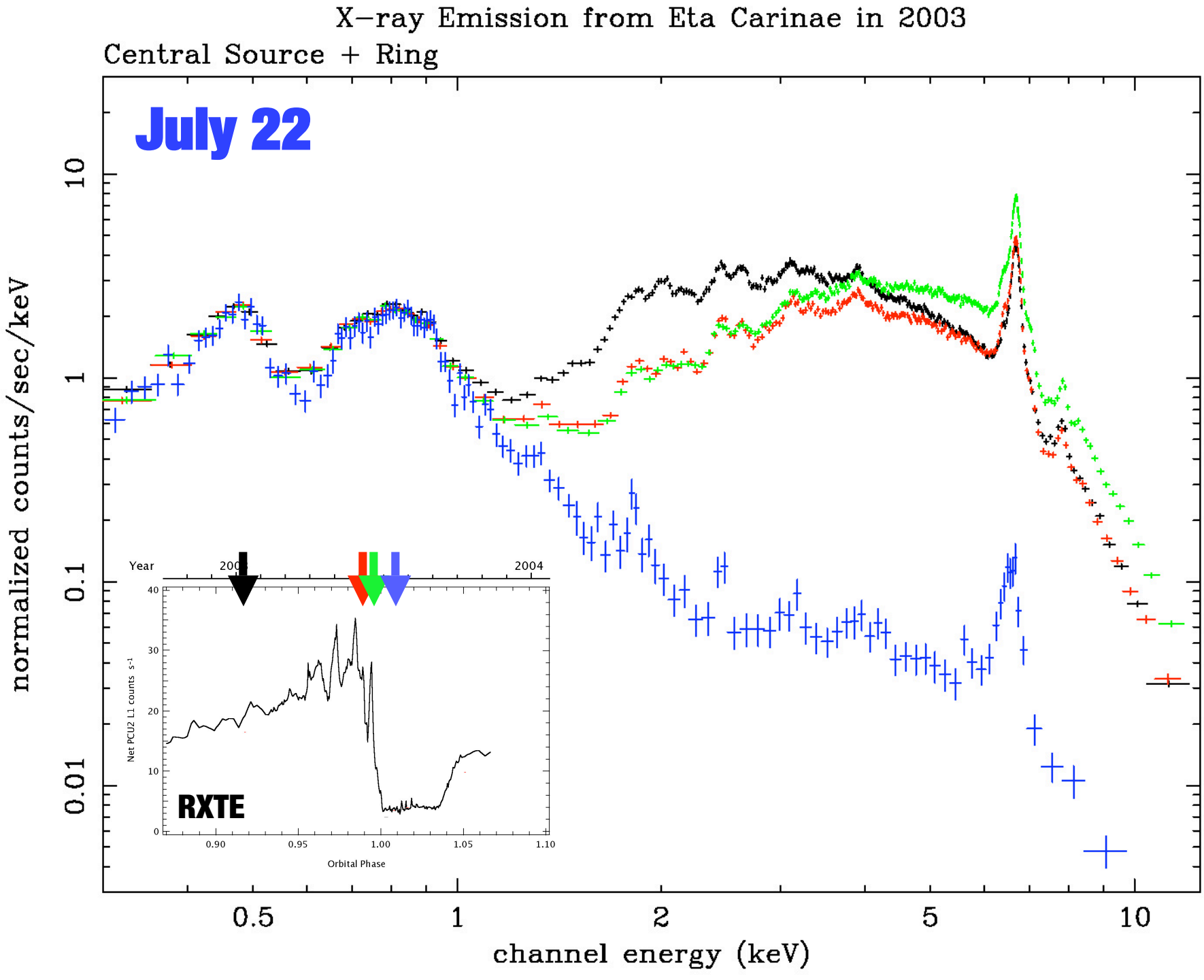
XMM-Newton (2003/7/22)

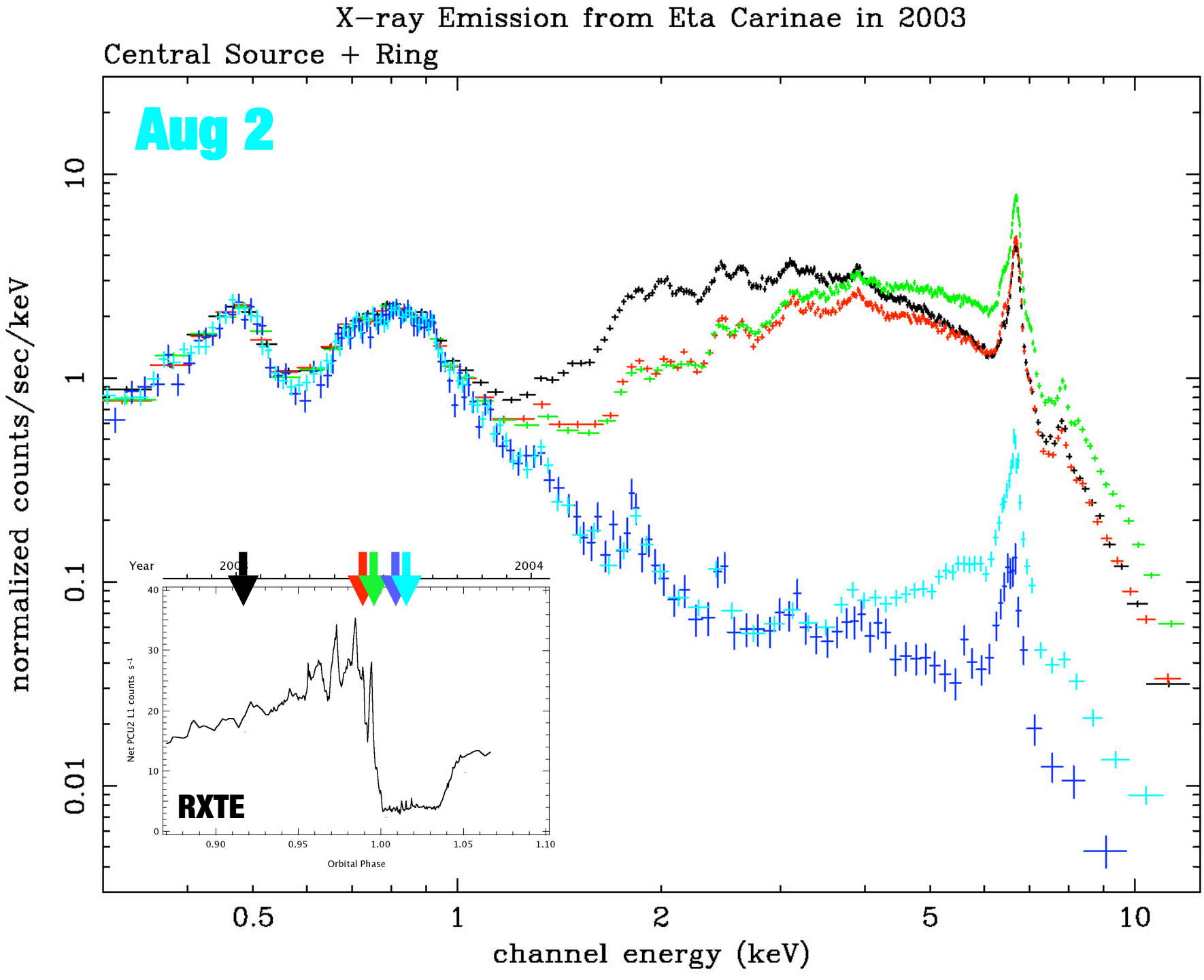


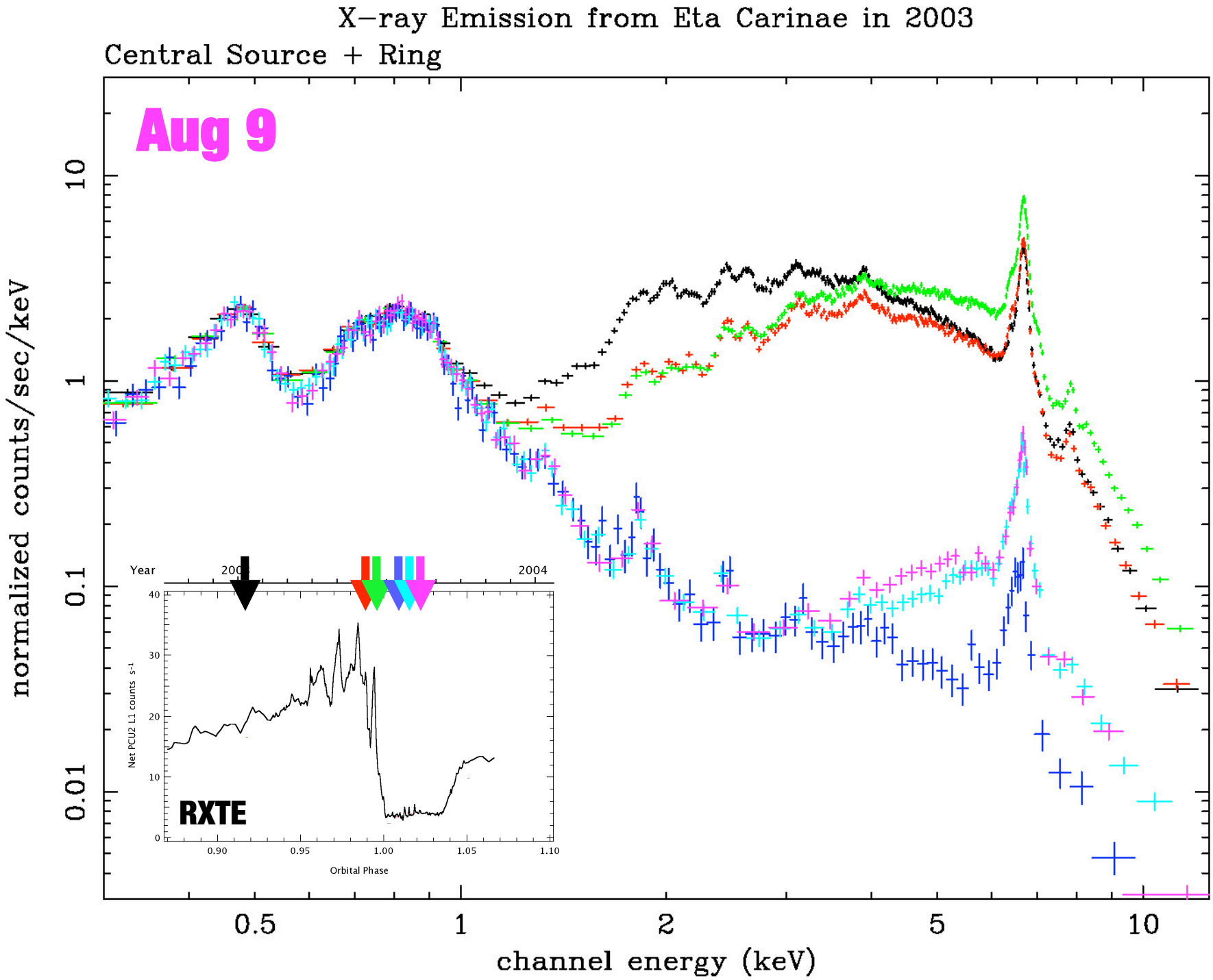

X−ray Emission from Eta Carinae in 2003
Central Source + Ring
Jan 25-29
normalized counts/sec/keV
10
1
0.1
0.01
0.5
1
2
5
10
channel energy (keV)
Year
2004
Net PCU2 L1 counts s⁻¹
40
30
20
10
0
0.90
0.95
1.00
1.05
1.10
Orbital Phase
RXTE

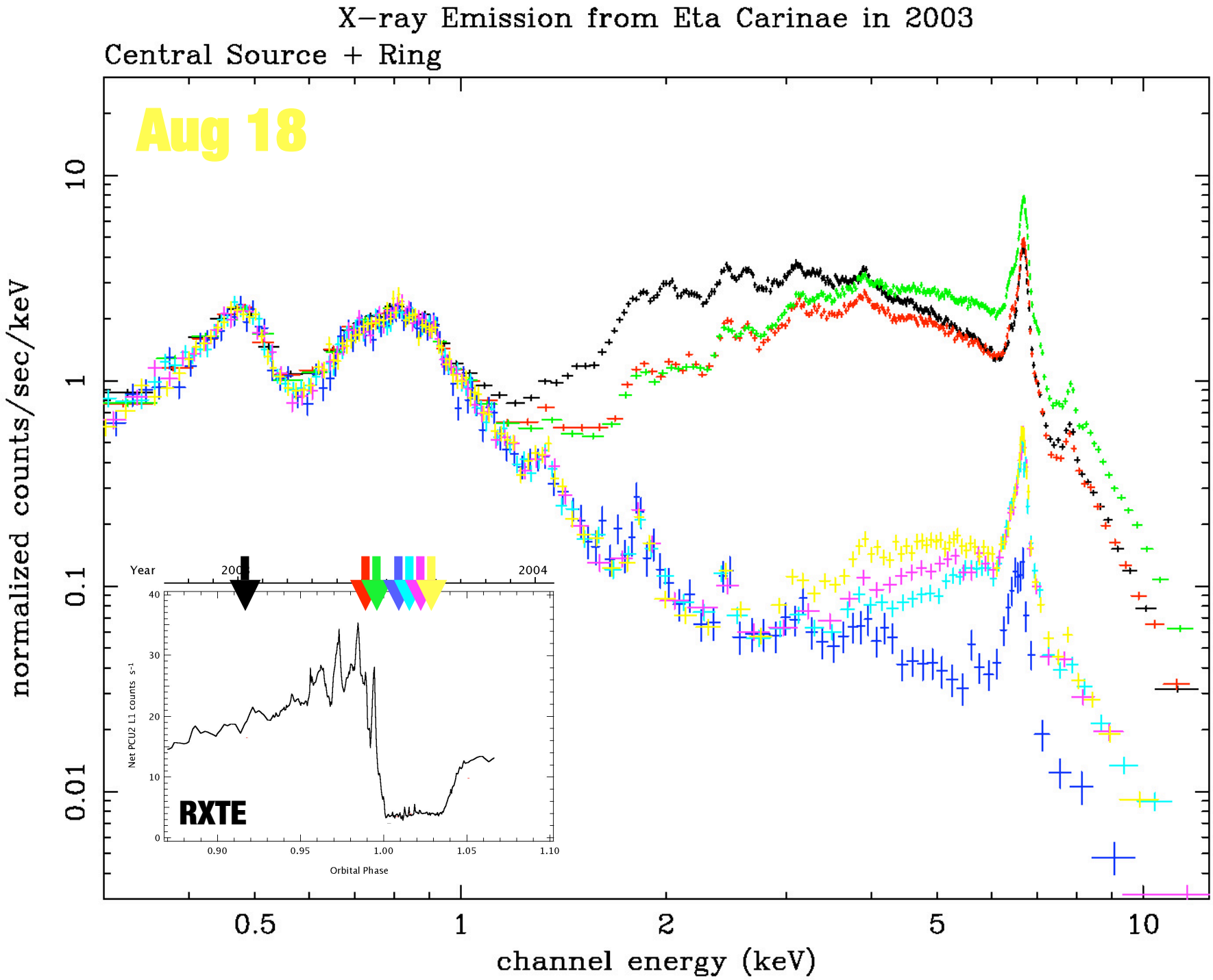

X−ray Emission from Eta Carinae in 2003
Central Source + Ring
June 8
normalized counts/sec/keV
channel energy (keV)
0.01
0.1
1
10
0.5
1
2
5
10
Year
2004
Net PCU2 L1 counts s⁻¹
Orbital Phase
RXTE

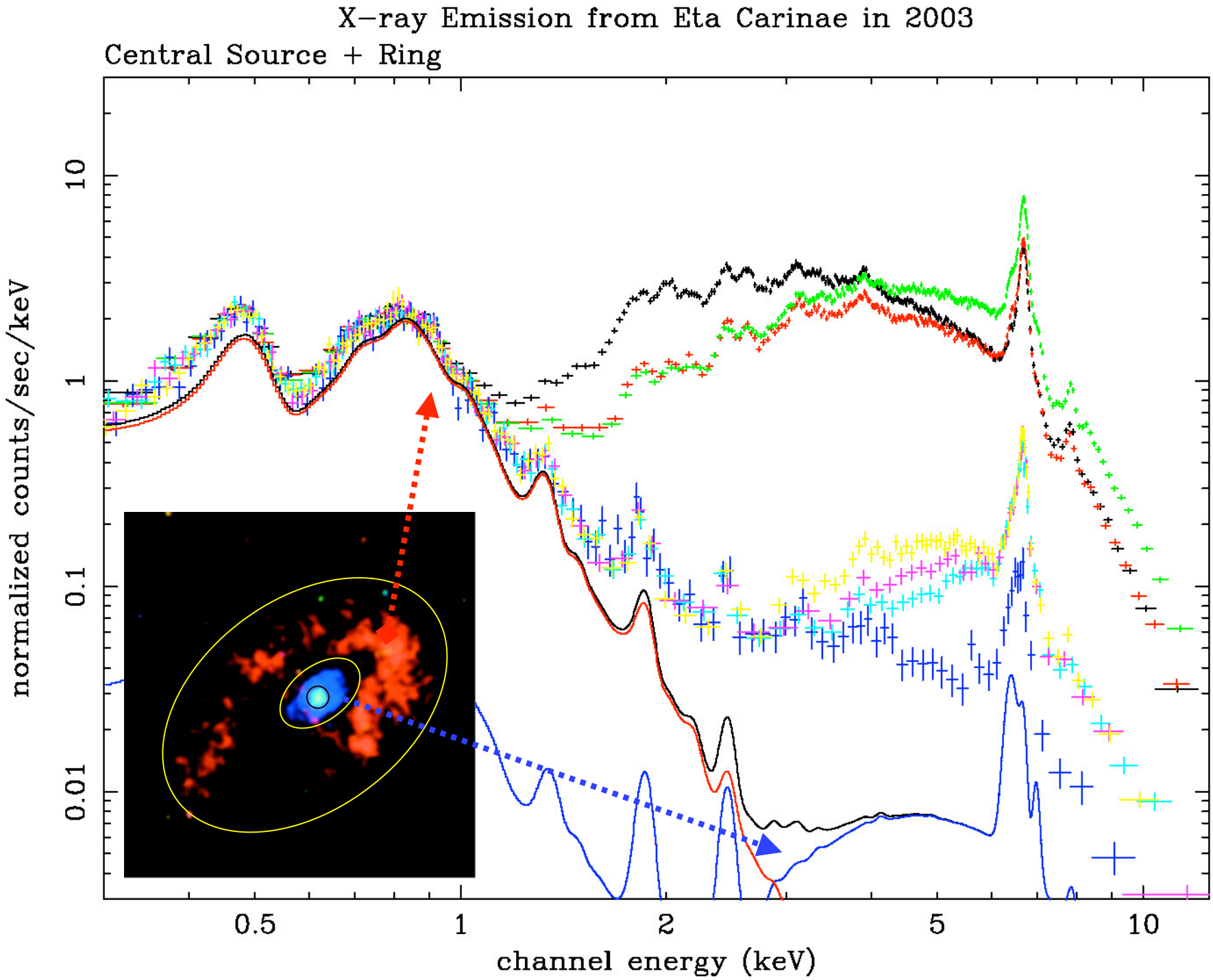

X−ray Emission from Eta Carinae in 2003
Central Source + Ring
June 13
normalized counts/sec/keV
10
1
0.1
0.01
0.5
1
2
5
10
channel energy (keV)
Year
2004
Net PCU2 L1 counts s⁻¹
40
30
20
10
0
0.90
0.95
1.00
1.05
1.10
Orbital Phase
RXTE

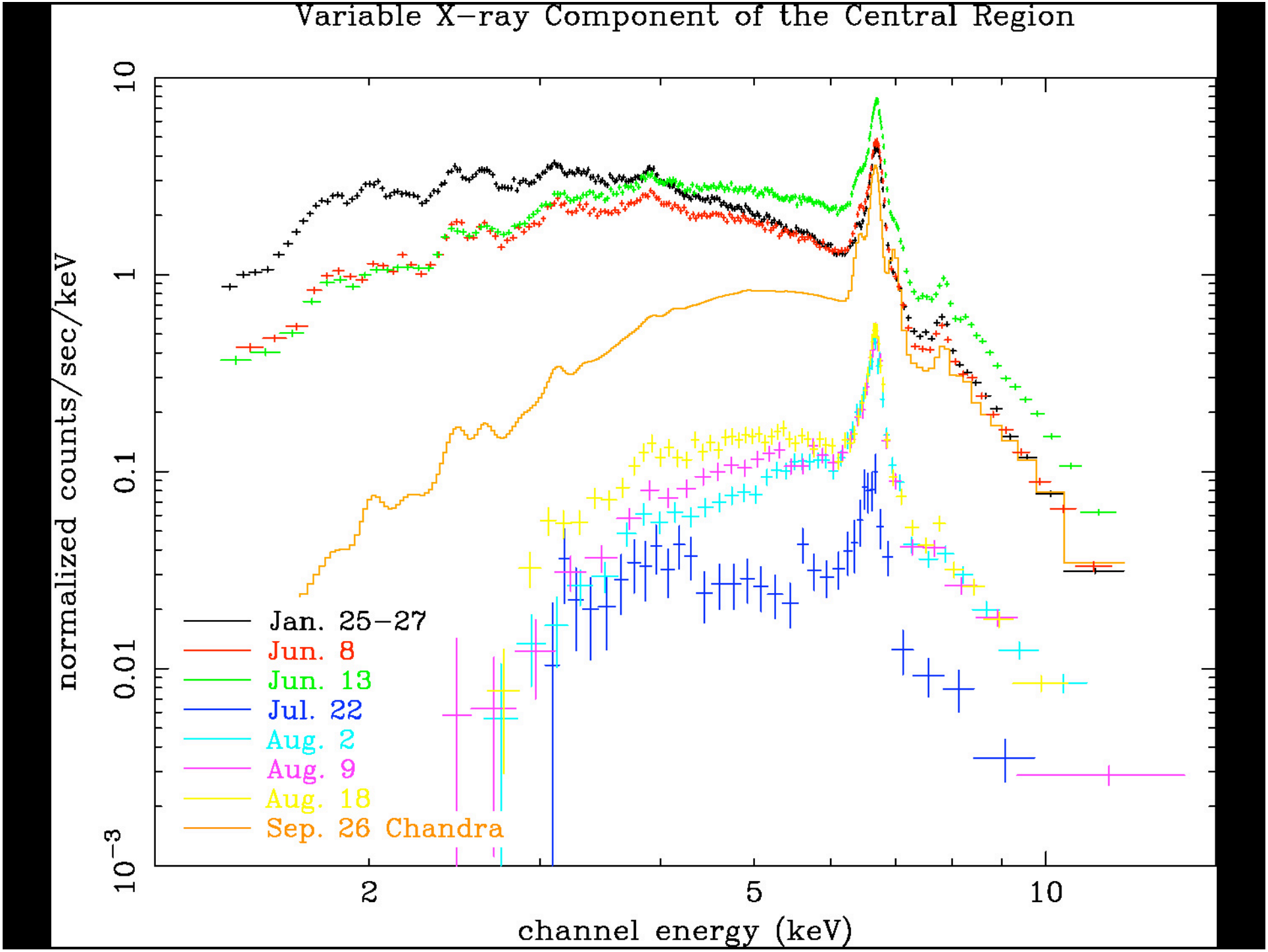

X−ray Emission from Eta Carinae in 2003
Central Source + Ring
July 22
normalized counts/sec/keV
channel energy (keV)
0.5
1
2
5
10
0.01
0.1
1
10
Year
2004
Net PCU2 L1 counts s⁻¹
Orbital Phase
0.90
0.95
1.00
1.05
1.10
RXTE

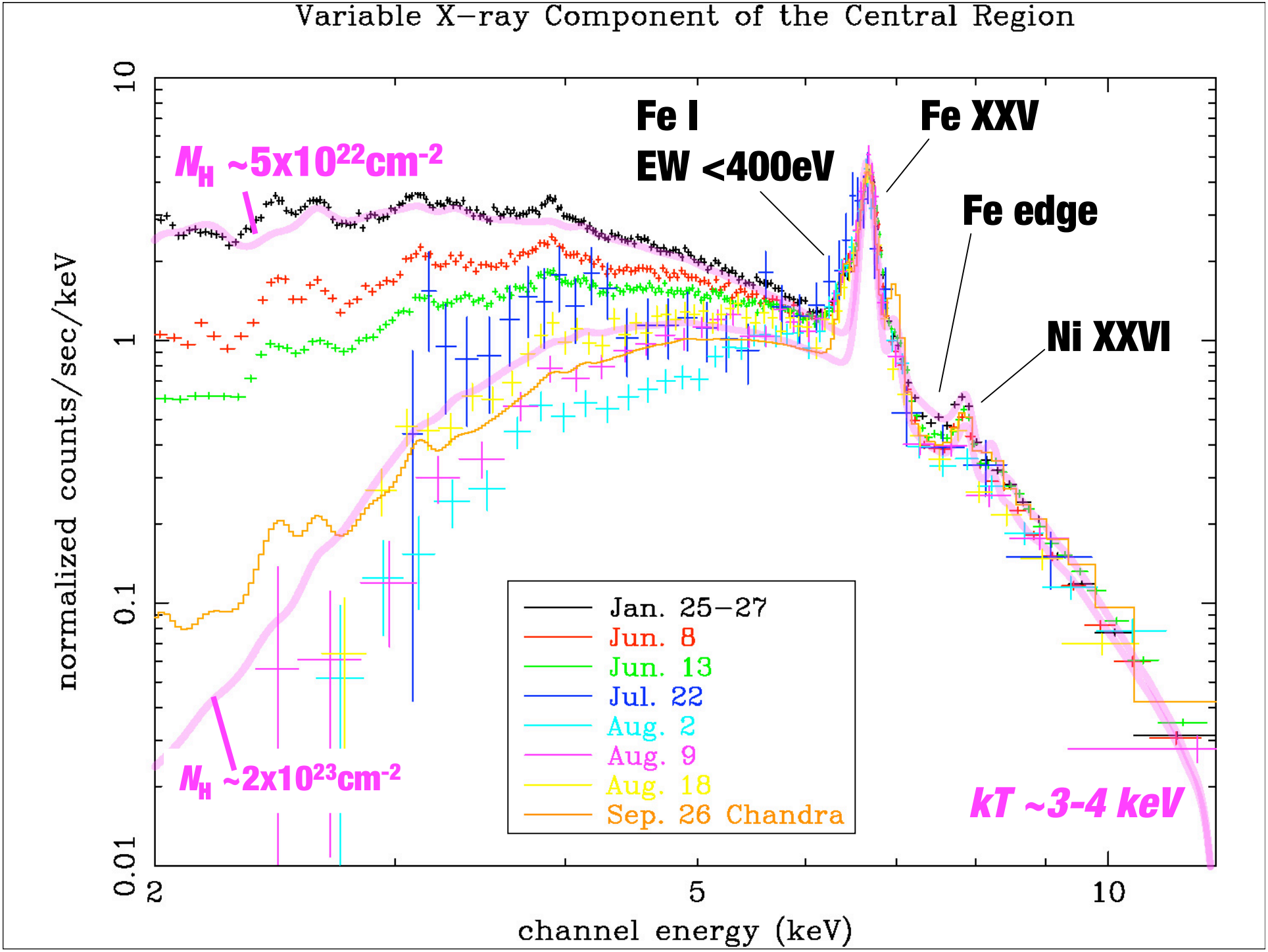

X−ray Emission from Eta Carinae in 2003
Central Source + Ring
Aug 2
normalized counts/sec/keV
10
1
0.1
0.01
0.5
1
2
5
10
channel energy (keV)
Year
2004
Net PCU2 L1 counts s⁻¹
40
30
20
10
0
0.90
0.95
1.00
1.05
1.10
Orbital Phase
RXTE


X−ray Emission from Eta Carinae in 2003
Central Source + Ring
Aug 9
normalized counts/sec/keV
10
1
0.1
0.01
0.5
1
2
5
10
channel energy (keV)
Year
2004
Net PCU2 L1 counts s⁻¹
40
30
20
10
0
0.90
0.95
1.00
1.05
1.10
Orbital Phase
RXTE

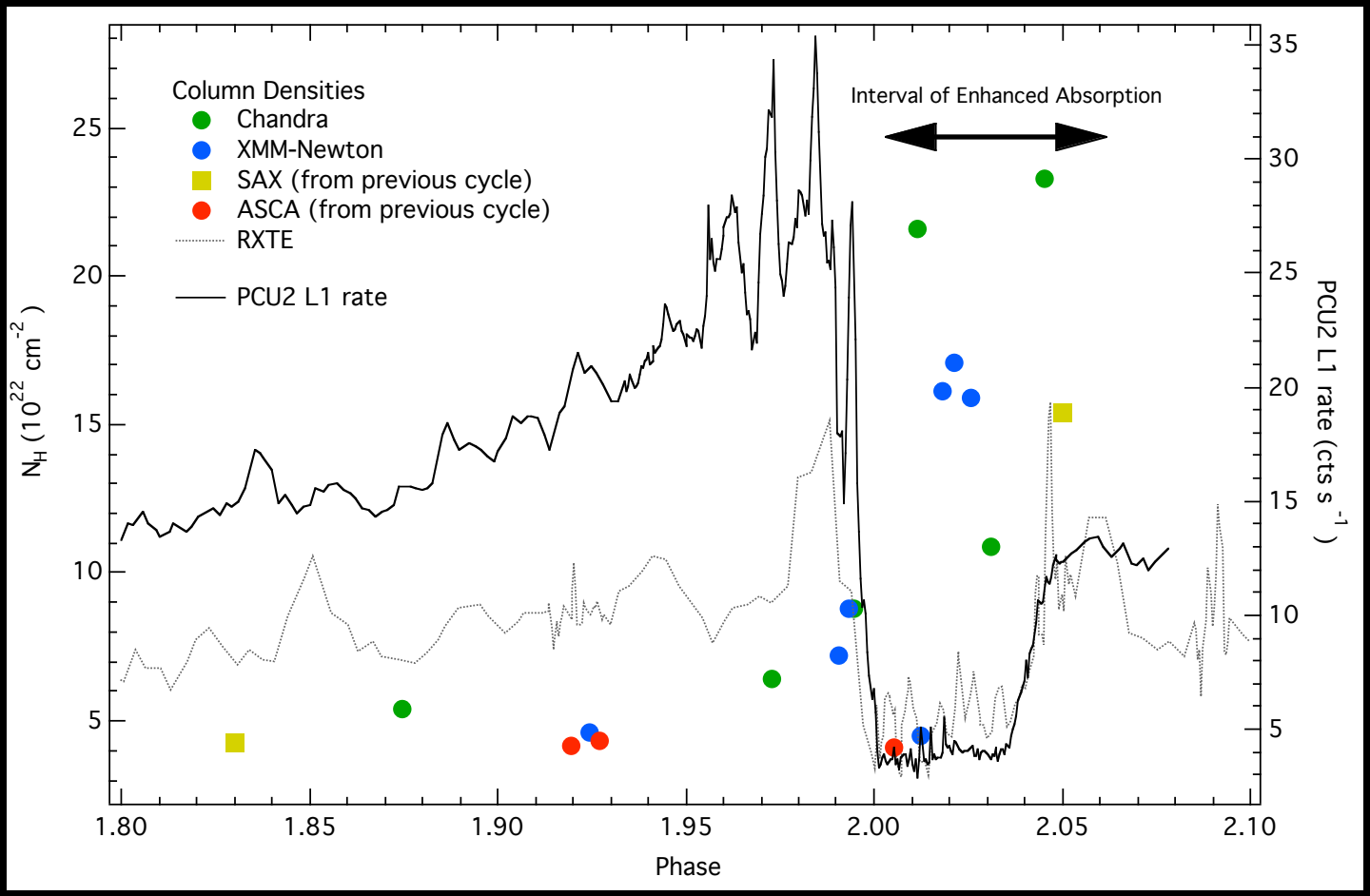

X−ray Emission from Eta Carinae in 2003
Central Source + Ring
Aug 18
normalized counts/sec/keV
channel energy (keV)
0.01
0.1
1
10
0.5
1
2
5
10
Year
2004
Net PCU2 L1 counts s⁻¹
Orbital Phase
0.90
0.95
1.00
1.05
1.10
RXTE


X−ray Emission from Eta Carinae in 2003
Central Source + Ring
normalized counts/sec/keV
10
1
0.1
0.01
0.5
1
2
5
10
channel energy (keV)

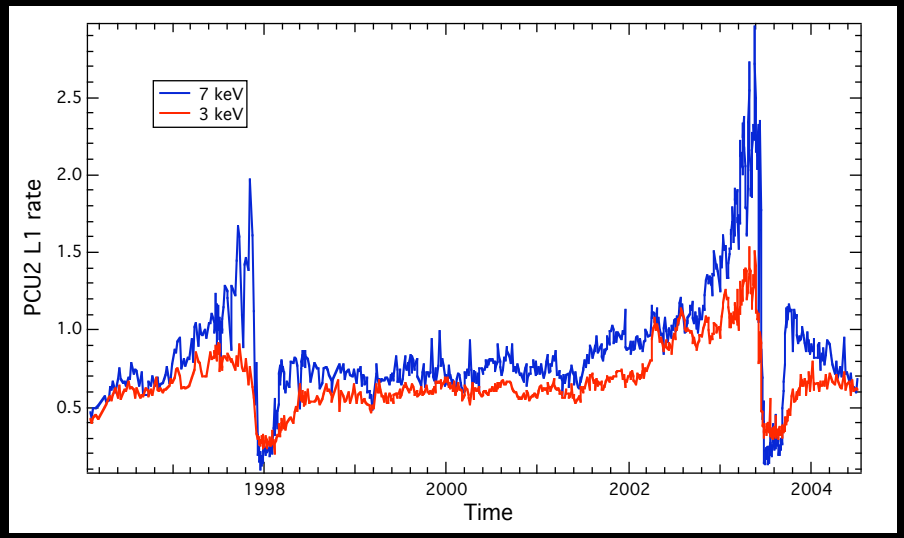

Variable X-ray Component of the Central Region
normalized counts/sec/keV
10
1
0.1
0.01
10^{-3}
2
5
10
channel energy (keV)
Jan. 25-27
Jun. 8
Jun. 13
Jul. 22
Aug. 2
Aug. 9
Aug. 18
Sep. 26 Chandra

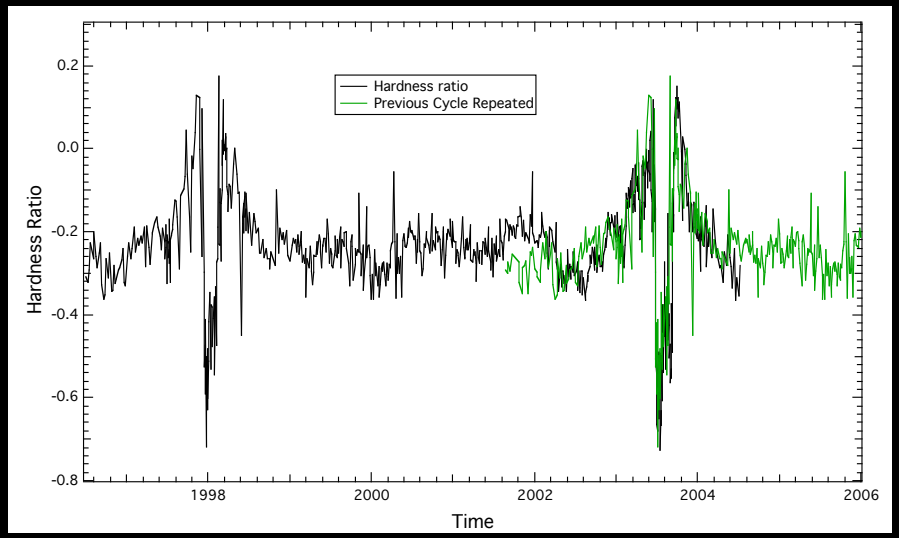

Variable X-ray Component of the Central Region
Fe I
EW <400eV
Fe XXV
Fe edge
Ni XXVI
N_H ~5x10^{22}cm^{-2}
N_H ~2x10^{23}cm^{-2}
kT ~3-4 keV
Jan. 25-27
Jun. 8
Jun. 13
Jul. 22
Aug. 2
Aug. 9
Aug. 18
Sep. 26 Chandra
normalized counts/sec/keV
channel energy (keV)
0.01
0.1
1
10
2
5
10

Absorption Increases:



RXTE hardness variations:



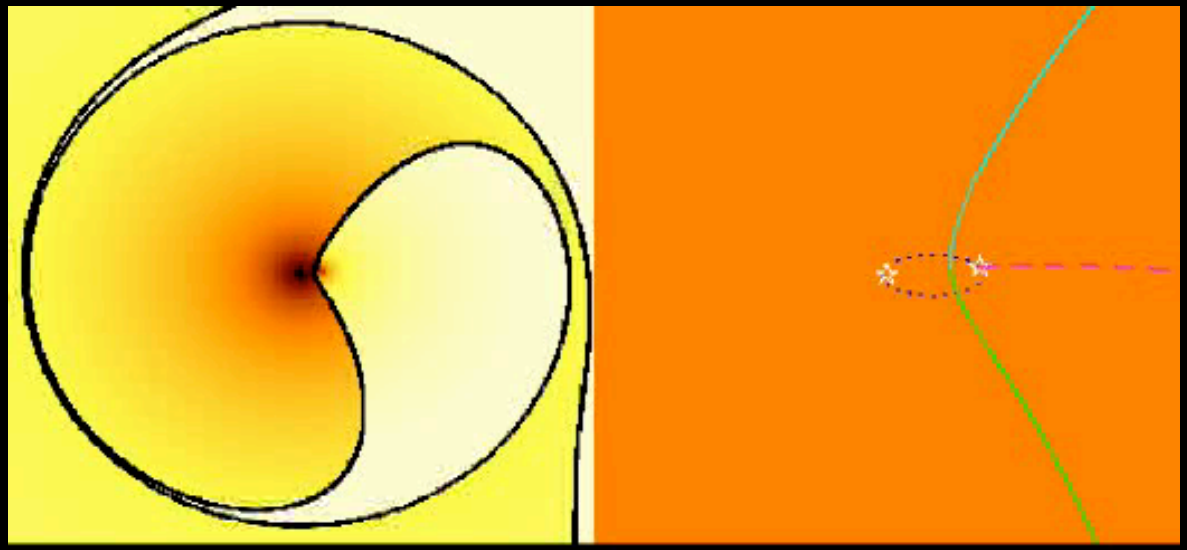


3 keV flux doesn't rise as much, recovers later than 7 keV flux.

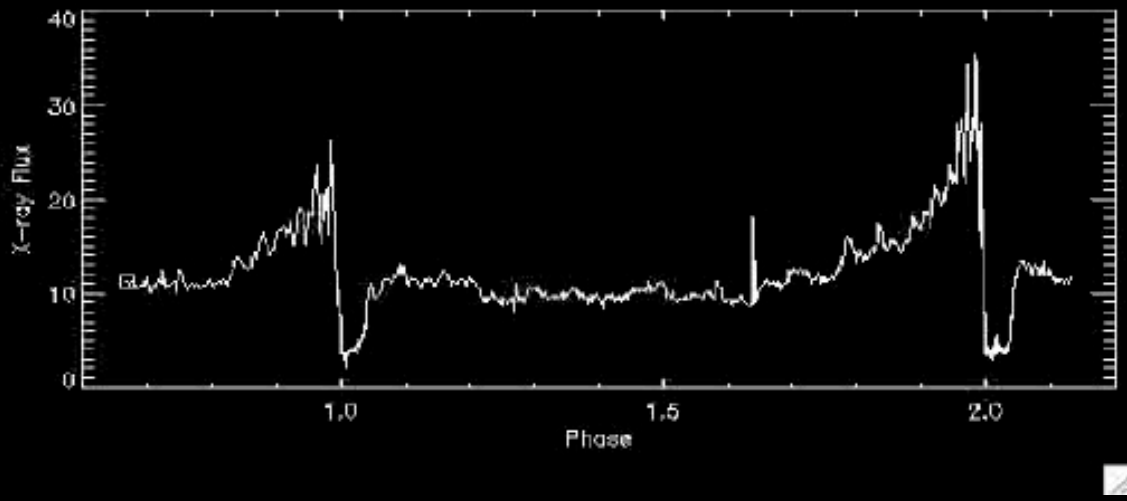
Hardness ratio doesn't vary much from cycle-to-cycle

Orbital Dynamics (in reference frame of Eta Car):

View of circumbinary wind density

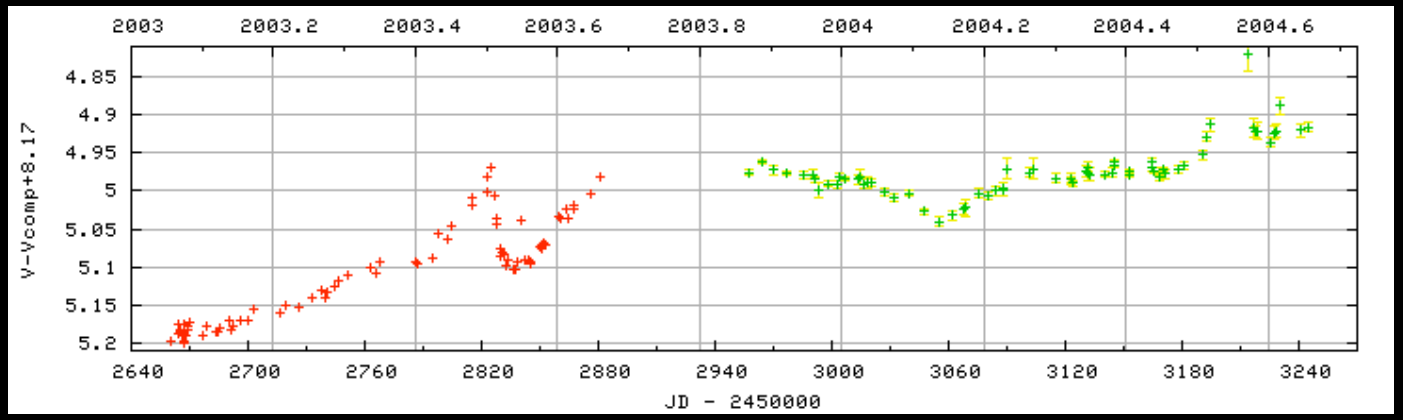


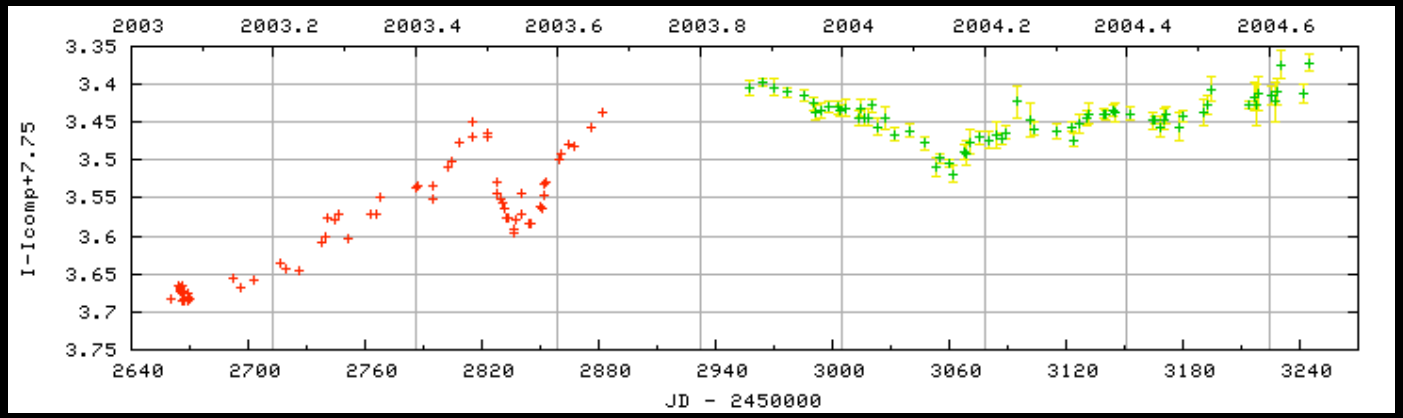
zoomed in view of the shape of the interaction region



Model Courtesy Perry Williams, Julian Pittard

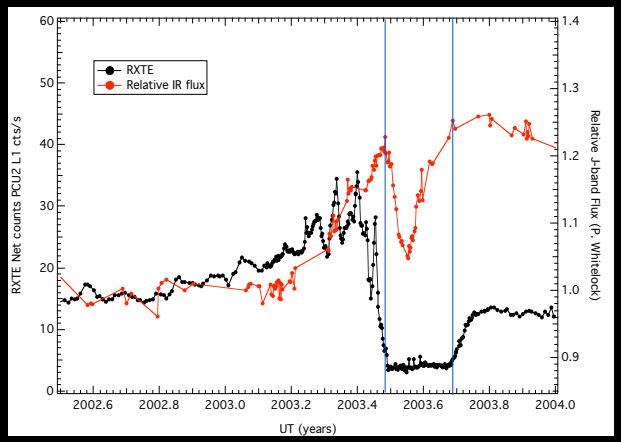
Recent Optical Monitoring from La Plata Observatory

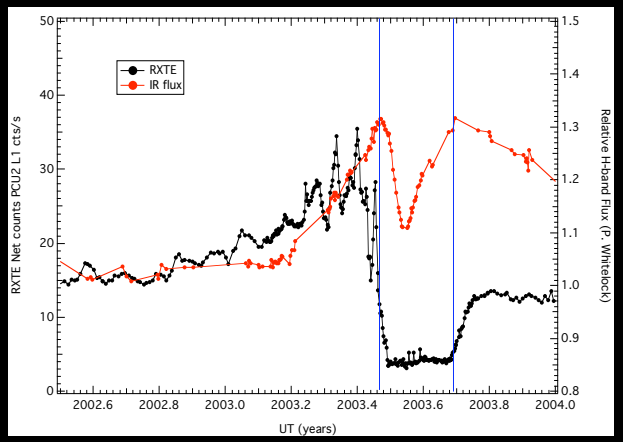


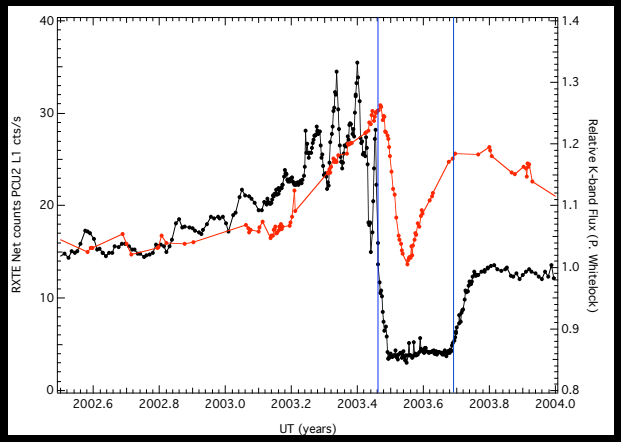


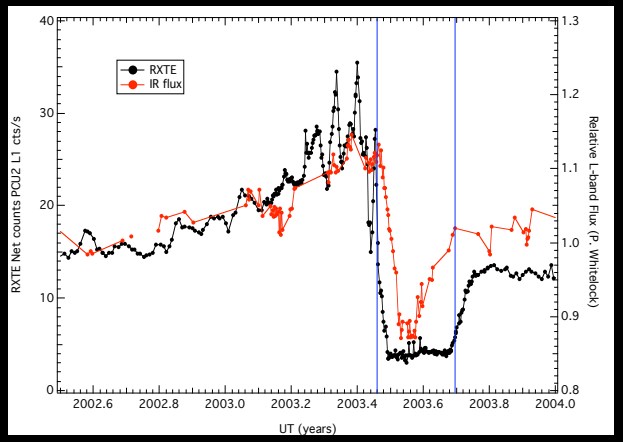
http://lilen.fcaglp.unlp.edu.ar/EtaCar/

Comparison of X-ray and IR photometry (courtesy Patricia Whitelock)



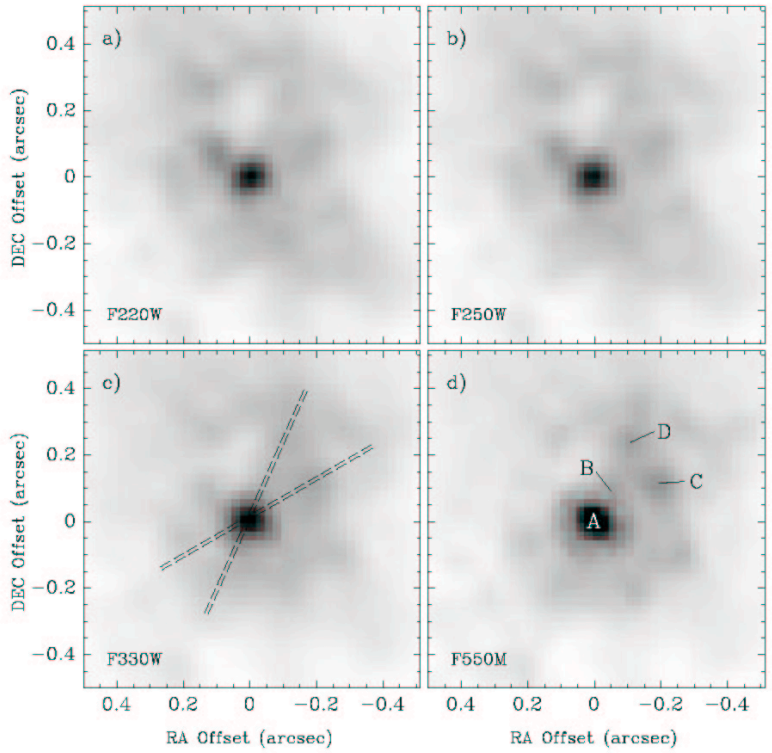




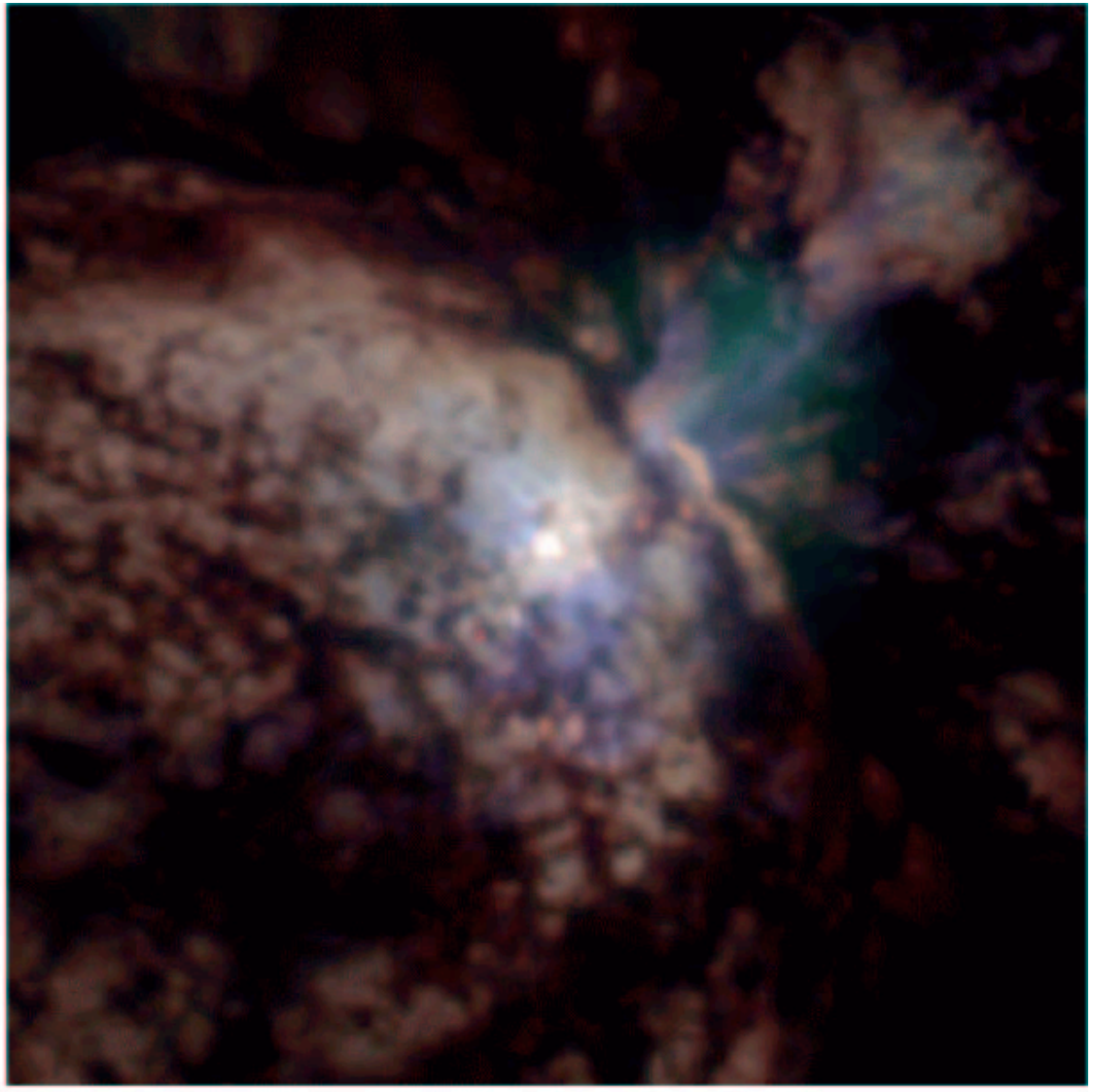


The HST Treasury Project

Kris Davidson (PI)



ACS/HRC Images (10/2002)

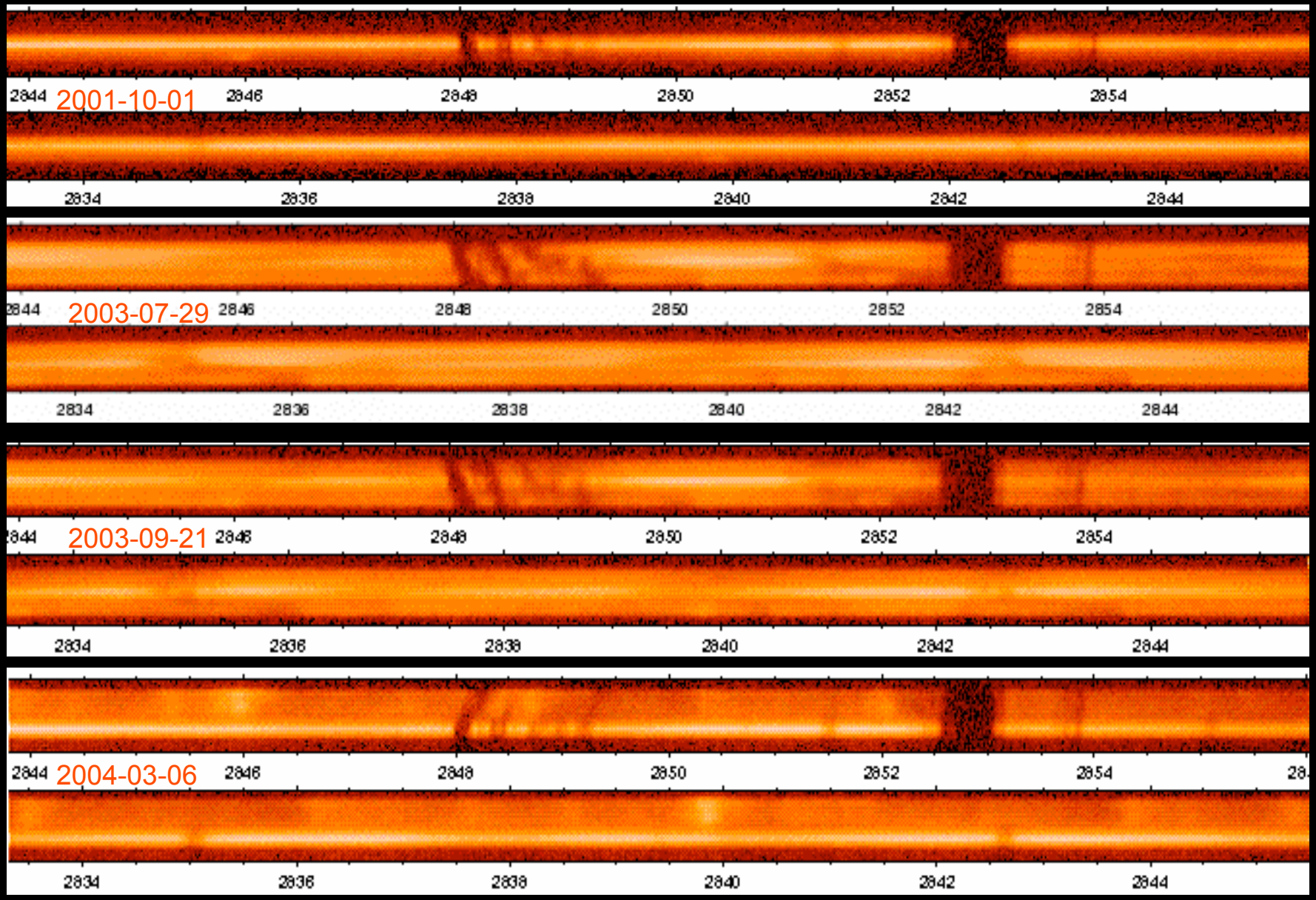


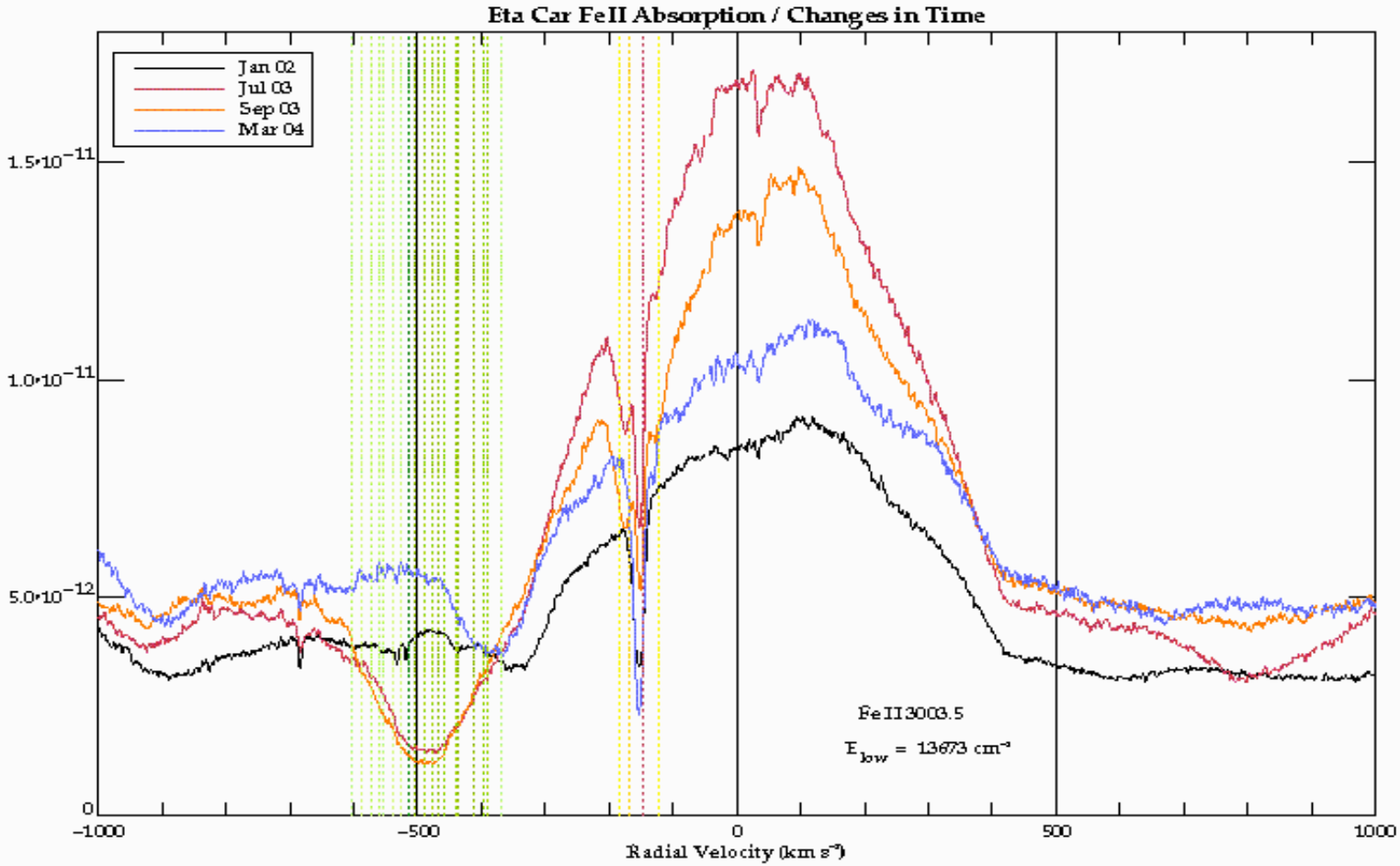
6”

Courtesy J. Morse, Kris Davidson, T. Gull

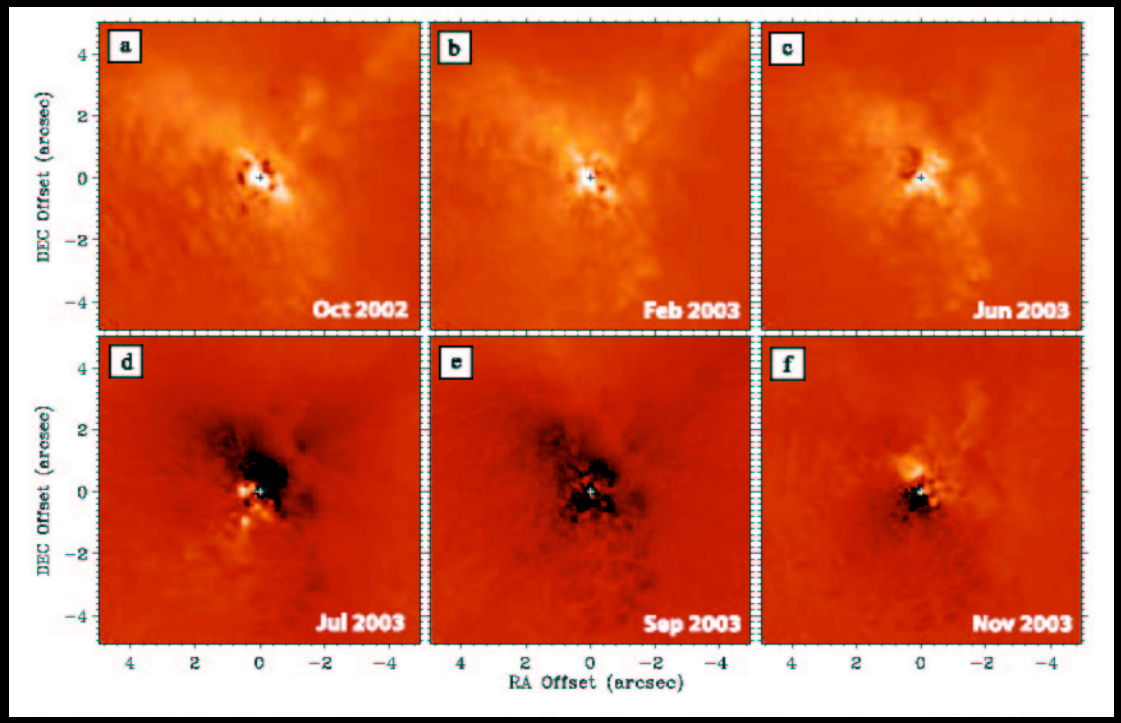
Courtesy T. Gull

NOTE: Different Position Angles

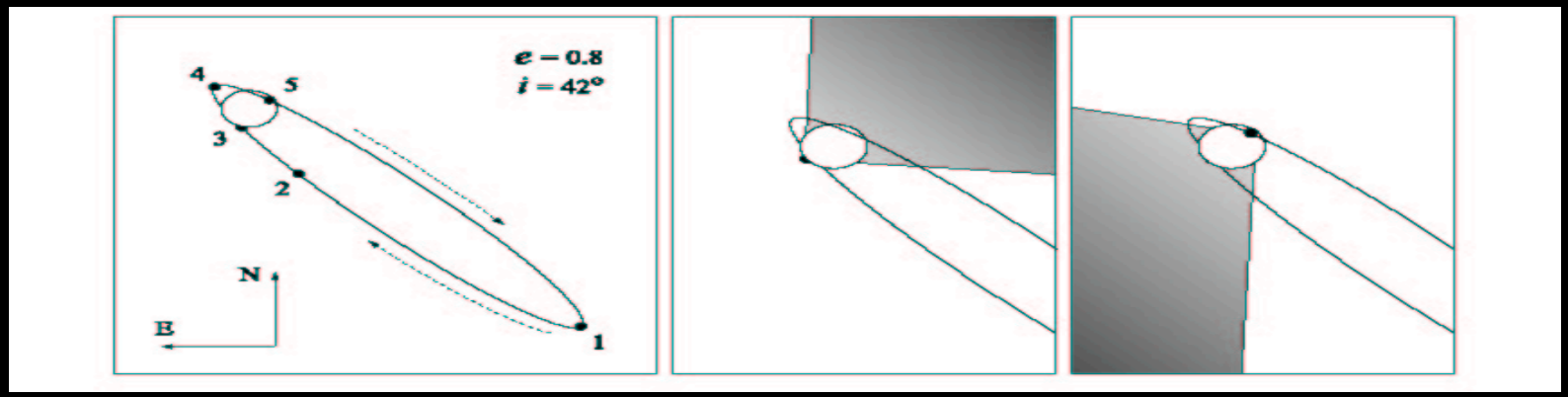




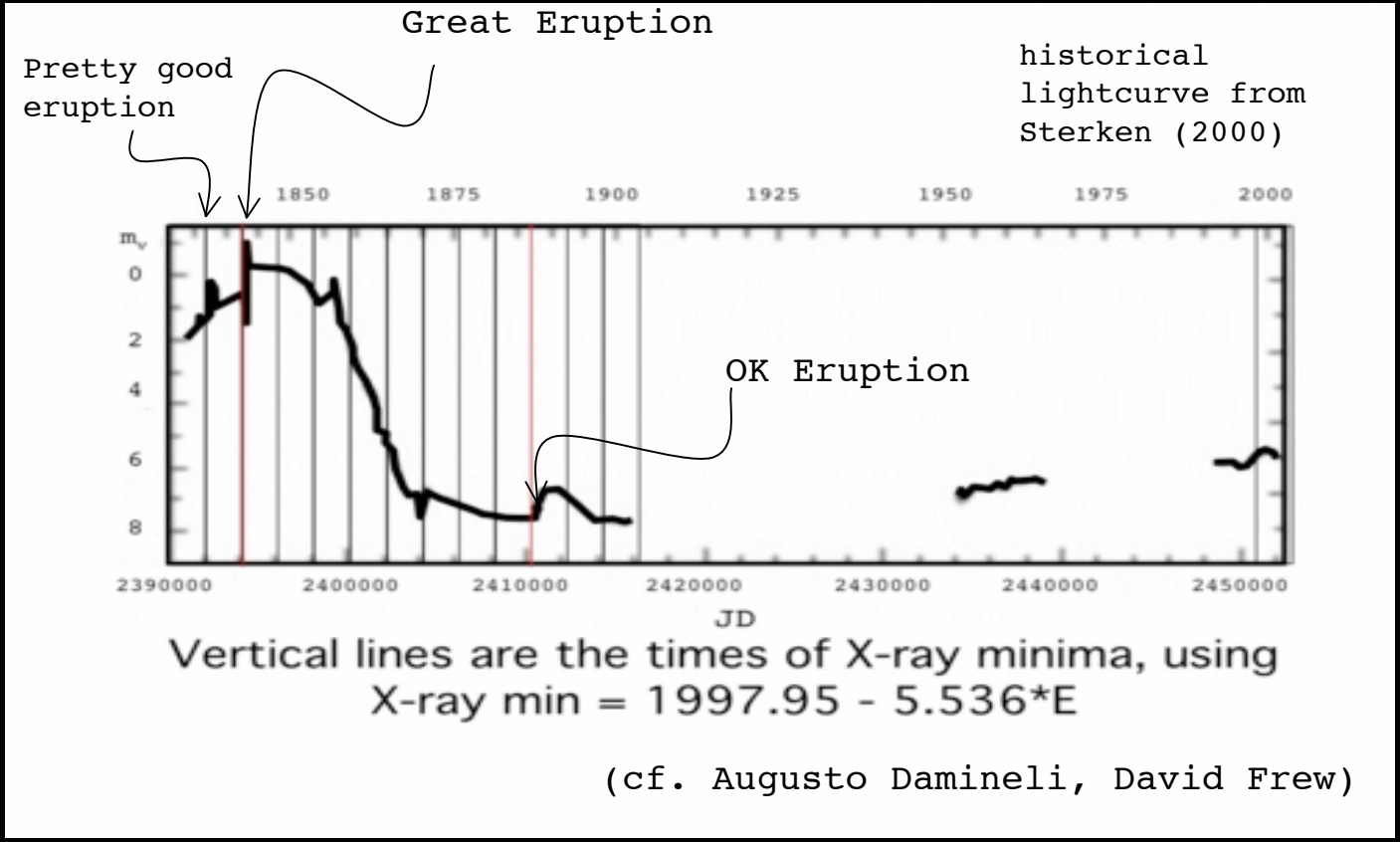
Courtesy T. Gull



HST/ACS imaging sees shadowing of the UV flux during the minimum (Smith et al. 2004)

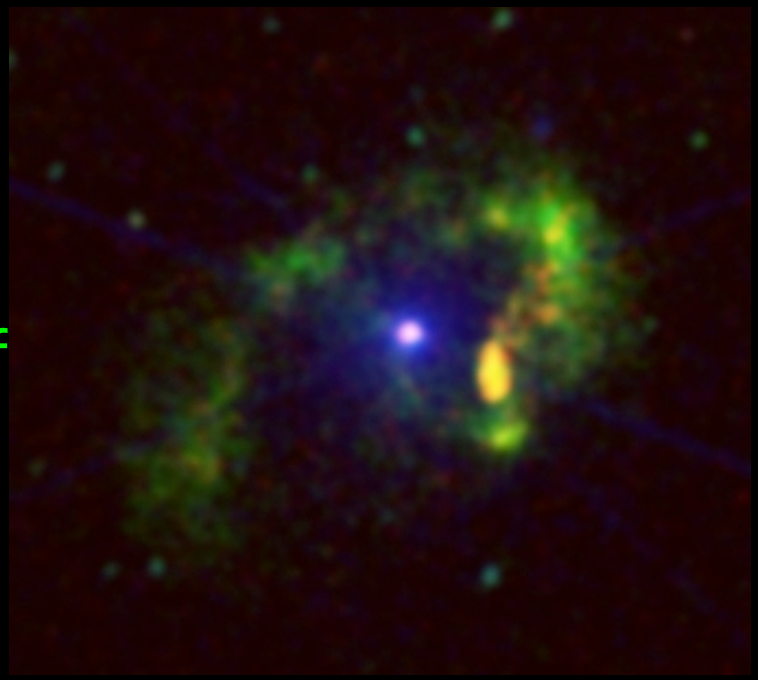


Relation to Giant Eruptions?



At least some of the “giant eruptions” seem to have begun (been triggered?) by periastron passages
Period stable through the eruptions?

Work in Progress:



- Refining the orbit: shape, orientation & mass & identity of companion: O star, WR star...(black hole?)
- Understanding the cycle-to-cycle variations in X-ray brightness (fundamental change in Eta Car?)
- The big picture: X-ray variations in context of changes in visible, UV, IR, radio (example: can we find evidence of doppler shifts to confirm orbital motion?)

Remaining Issues:

- Is it really a binary? (Almost) all signs point to yes...
- Can we understand the influence of the companion on the evolution of the star (and the Great Eruption)?
- Can we determine the abundances/evolutionary state?

SN 1987A

- Which star erupted? Why? How often?
- How close to SN/hypernova?