Geometry and Beam Patterns of X-ray Pulsars Obtained from their Pulse Profiles

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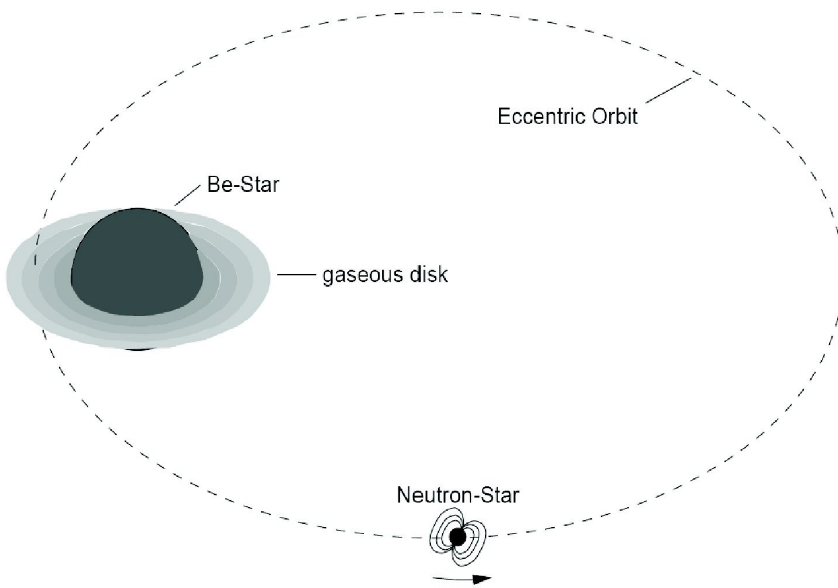
Outline

- Asymmetric Pulse Profiles of Be/X-Binaries
- Pulse Profile Decomposition Method
- Beam Patterns of EXO 2030+375, 4U 0115+63, A 0535+26, V 0332+53
- Models for Pulse Formation
- Conclusions

Be/X-ray Binaries

- X-ray pulsars: neutron stars in binary systems that accrete matter from the companion.
- We study binary systems consisting of neutron star and Be star.
- Transients:
  - Type I outburst during periastron passage of the neutron star.
  - Type II (giant) outburst with high spin-up rates. $L_X > 10^{37}$ erg/s. Related to the activities of the Be star.

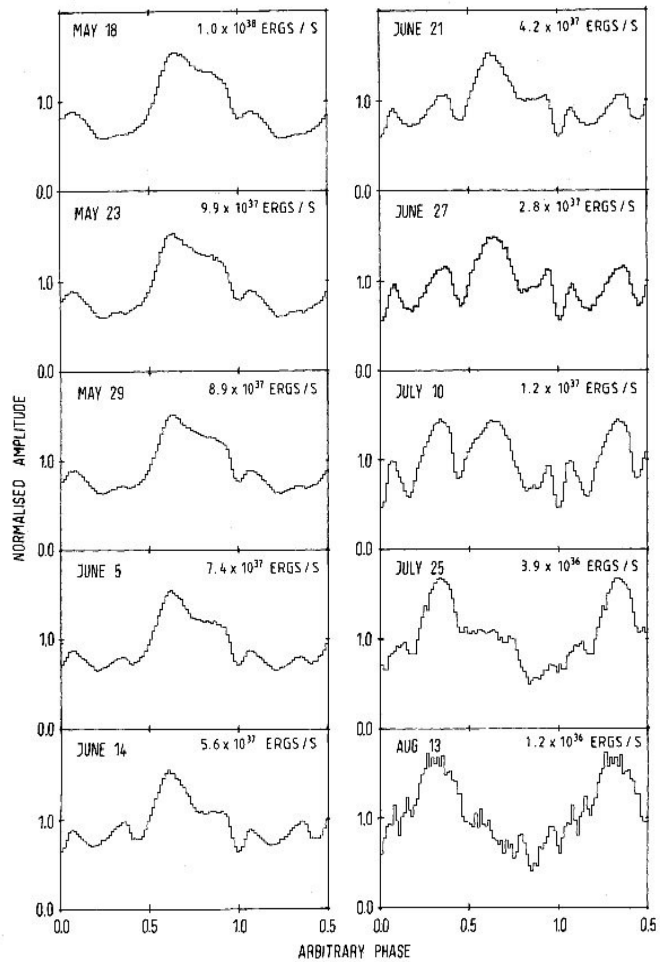


Kretschmar 1996

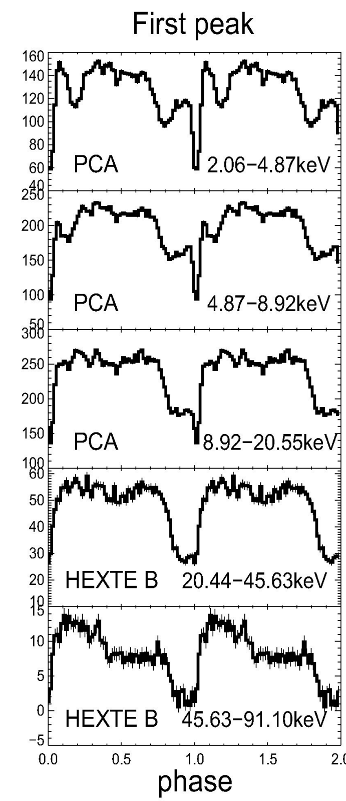
Pulse Profiles of Be/X-ray Binaries

	Orbital Period	Pulse Period
EXO 2030+375	46 d	42 s
4U 0115+63	24 d	3.6 s
A 0535+26	111 d	103 s
V 0332+53	34 d	4.4 s

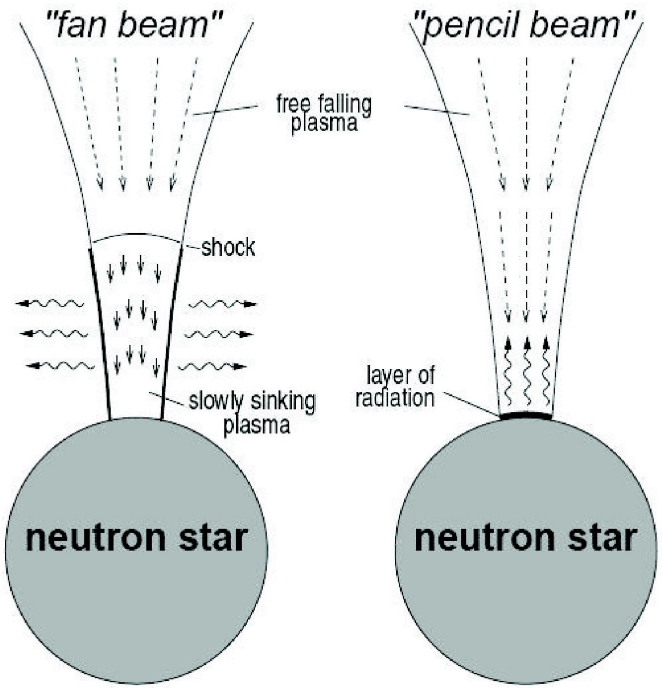
EXO 2030+375, type II outburst
Palmer et al. 1989



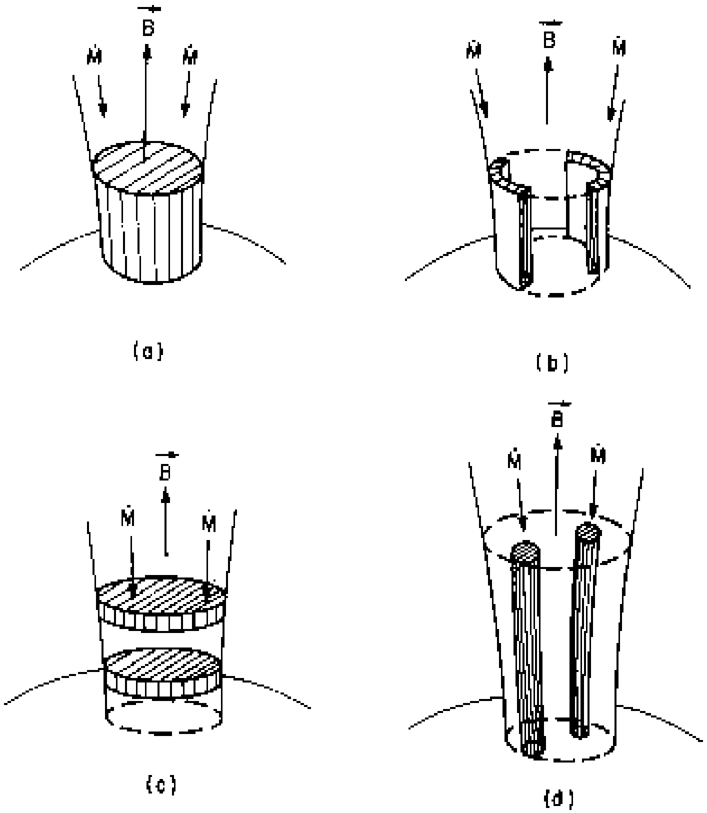
A 0535+26, type I outburst
Caballero et al. 2010



Accretion Geometries



Kretschmar 1996



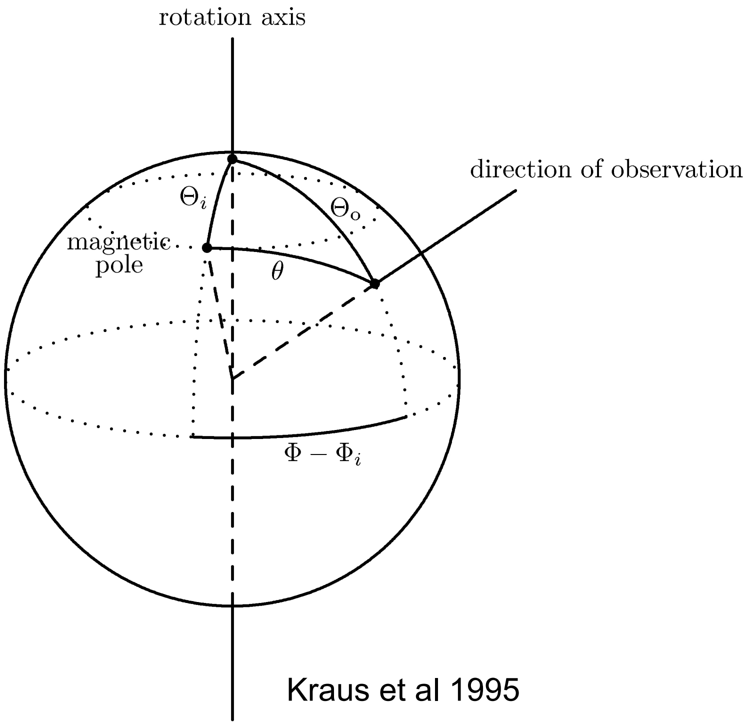
Meszaros 1984

Pulse Profile Decomposition Method

- Developed by Ute Kraus and applied to Her X-1 and Cen X-3 (Kraus et al. 1995, 1996; Blum & Kraus 2000).
- Possible explanation for asymmetric observed pulse profiles is a distorted magnetic dipole field in which the two magnetic poles are not located opposite to each other.
- Assumption: two symmetric and identical emission regions. Asymmetry in geometry results in asymmetric total pulse profile.
- Fit the pulse profiles with a sum of symmetric functions by Fourier analysis and get two symmetric functions that together describes the observed total pulse profiles.

Assumed Geometry of the Neutron Star

- Angle between the rotation axis of the neutron star and the line of sight is Θ_0.
- Polar angles of the magnetic poles: Θ_1, Θ_2.
- Symmetry points Φ_1, Φ_2 in the pulse profile corresponds to the rotation angles of the two poles.
- Angle θ between the first magnetic pole and the line of sight also changes with Φ.

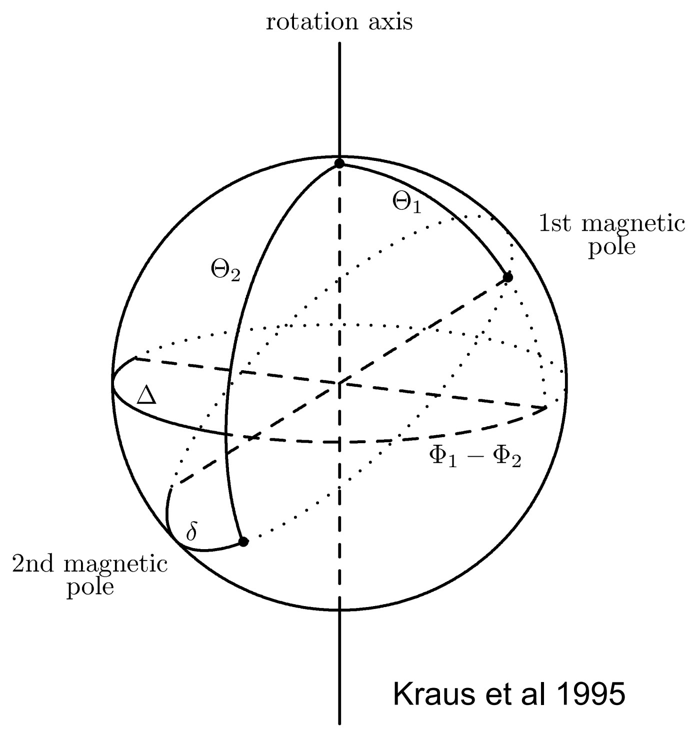


Kraus et al 1995

Assumed Geometry of the Neutron Star

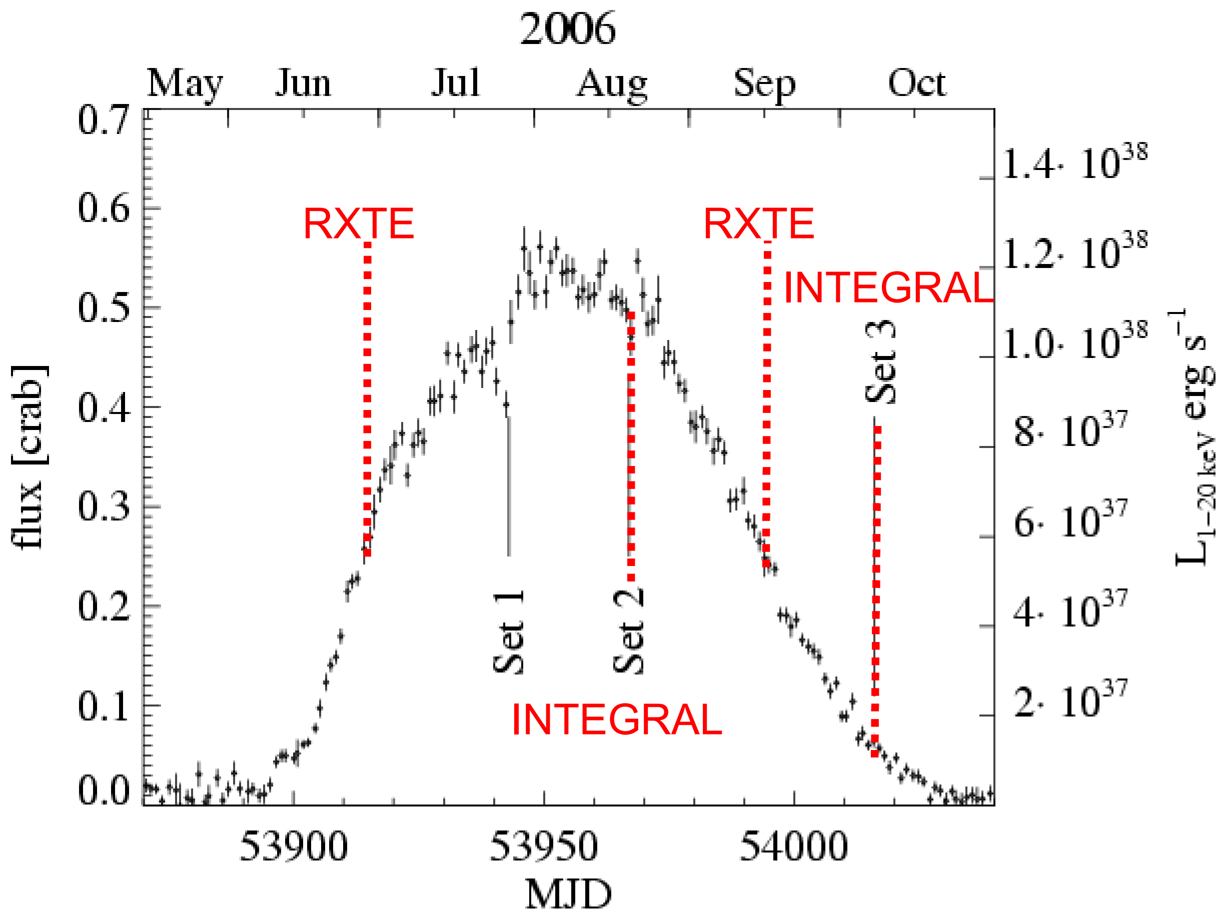
- The second magnetic pole is not located on the axis through the first magnetic pole and the center of the neutron star. Instead, it has an offset of δ.
- For the phase it causes a shift Δ between the symmetry points of the emission:

  $\Delta = \pi - (\Phi_1 - \Phi_2)$.



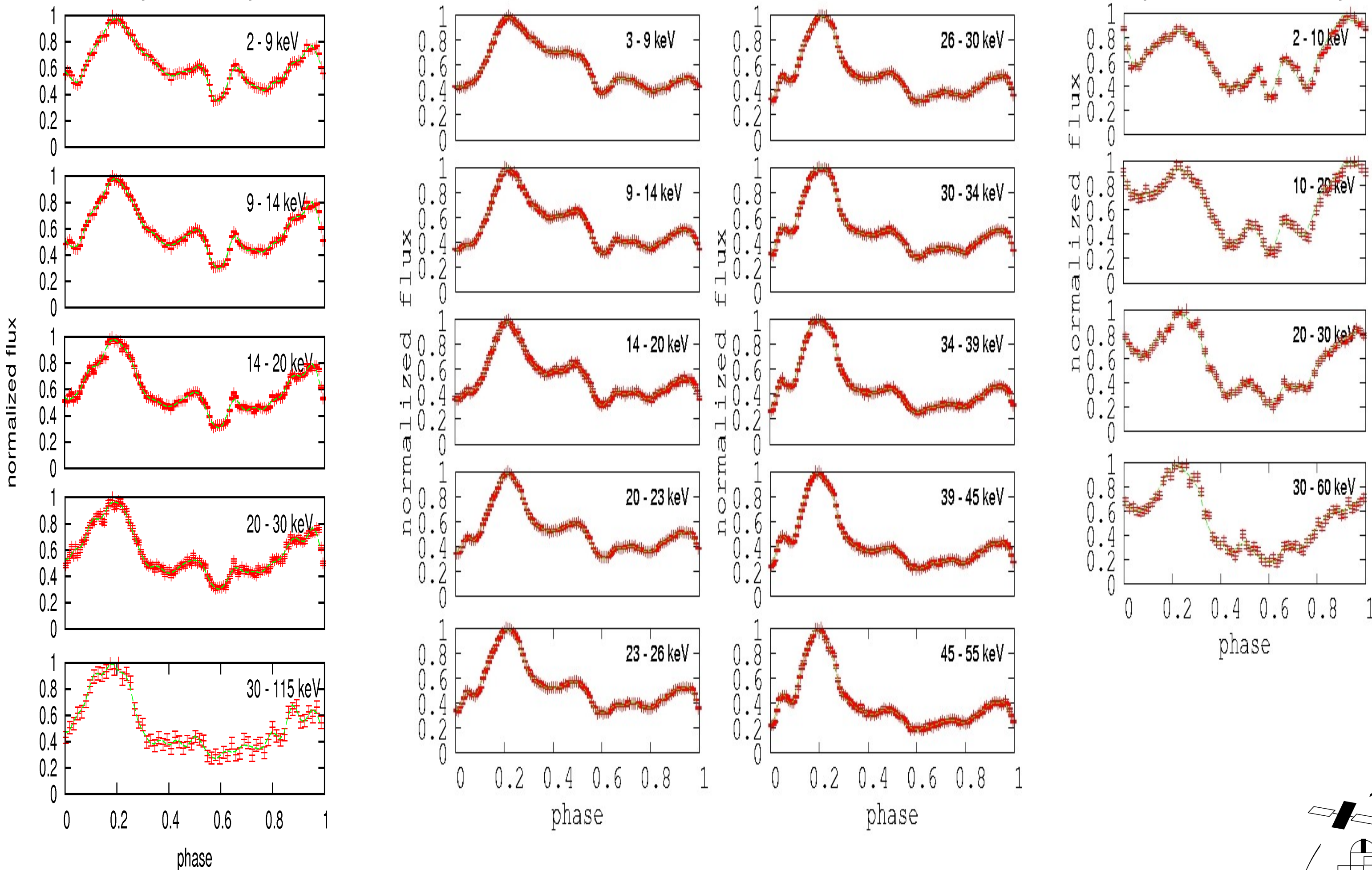
Kraus et al 1995

Giant Outburst of **EXO 2030+375** in 2006



Observed Total Pulse Profiles of **EXO 2030+375**

Before maximum (RXTE) | Maximum (INTEGRAL) | End of decay (INTEGRAL)



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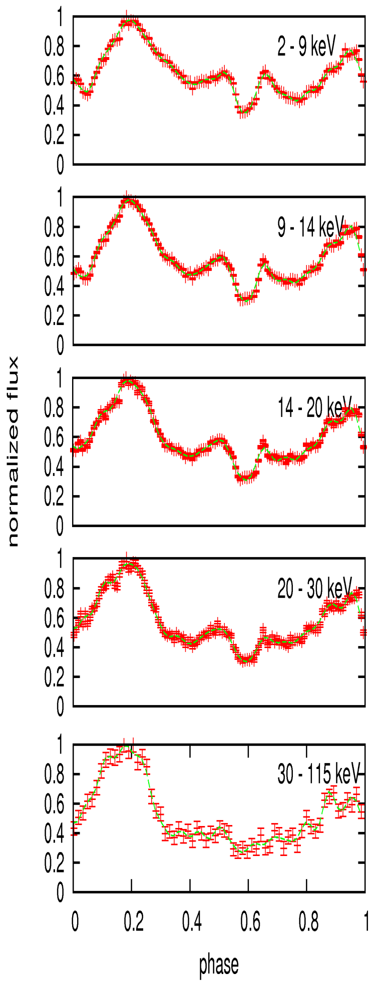
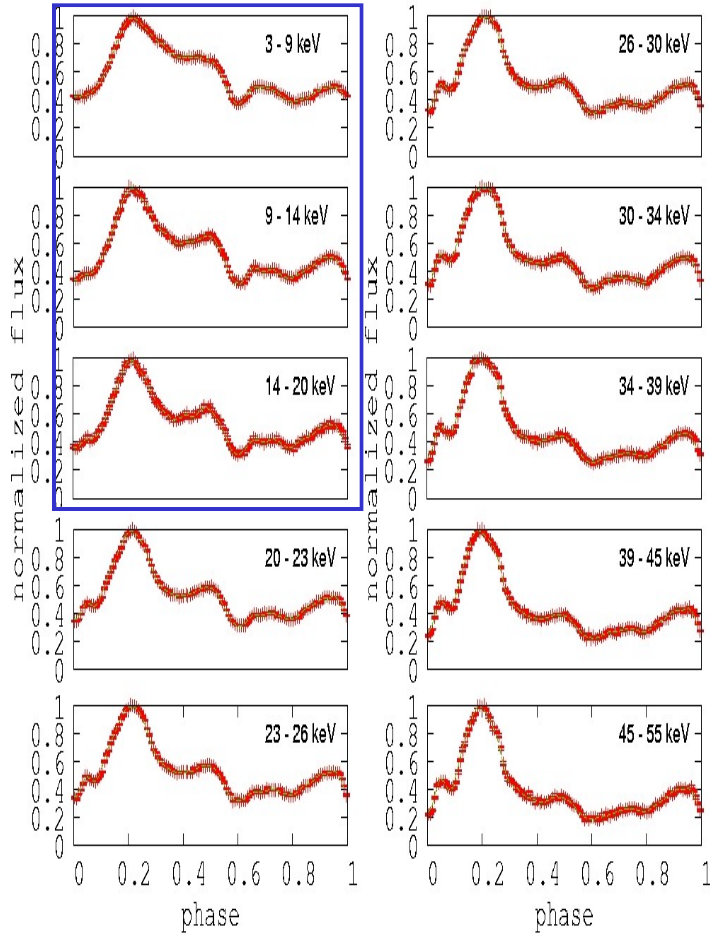
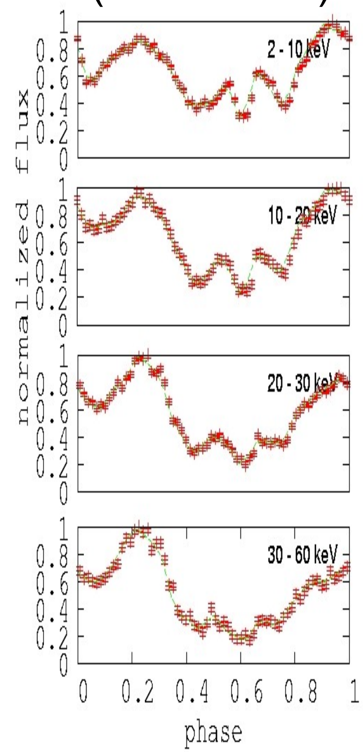


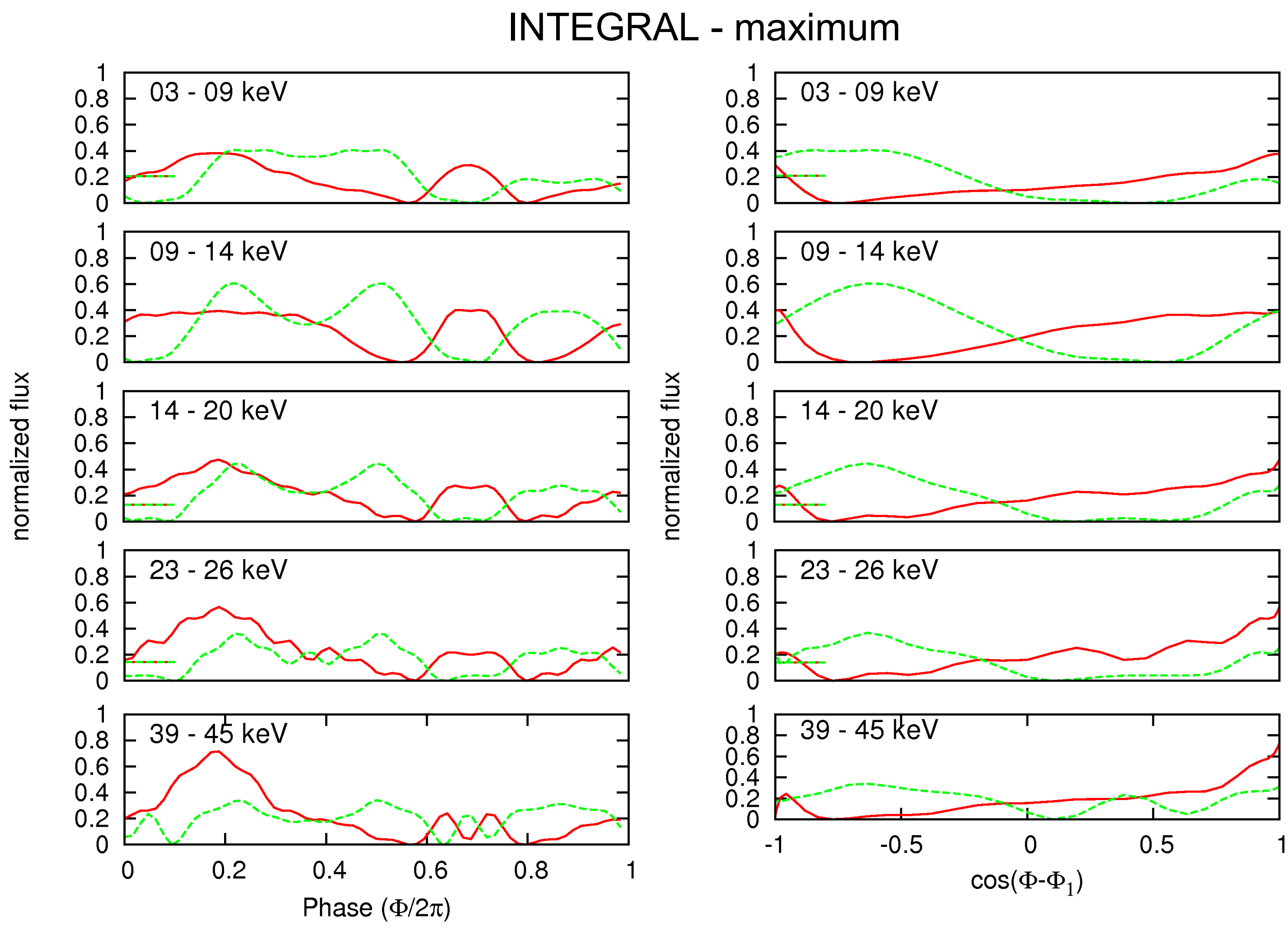
Maximum (INTEGRAL)



End of decay (INTEGRAL)

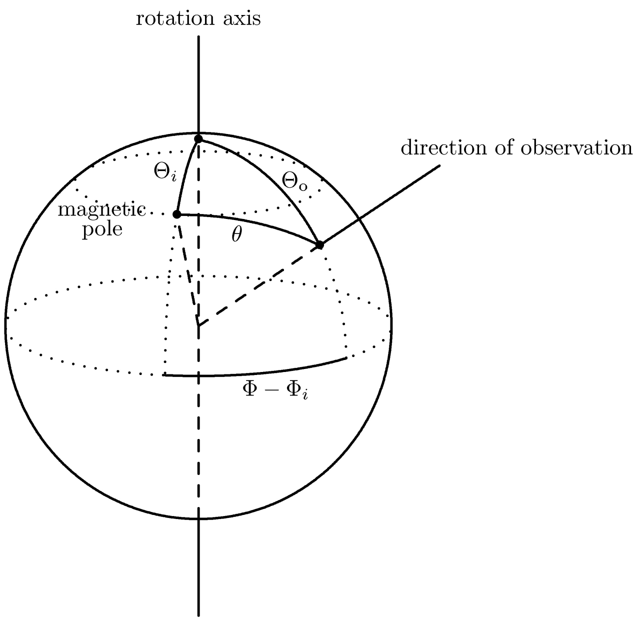


Decompositions



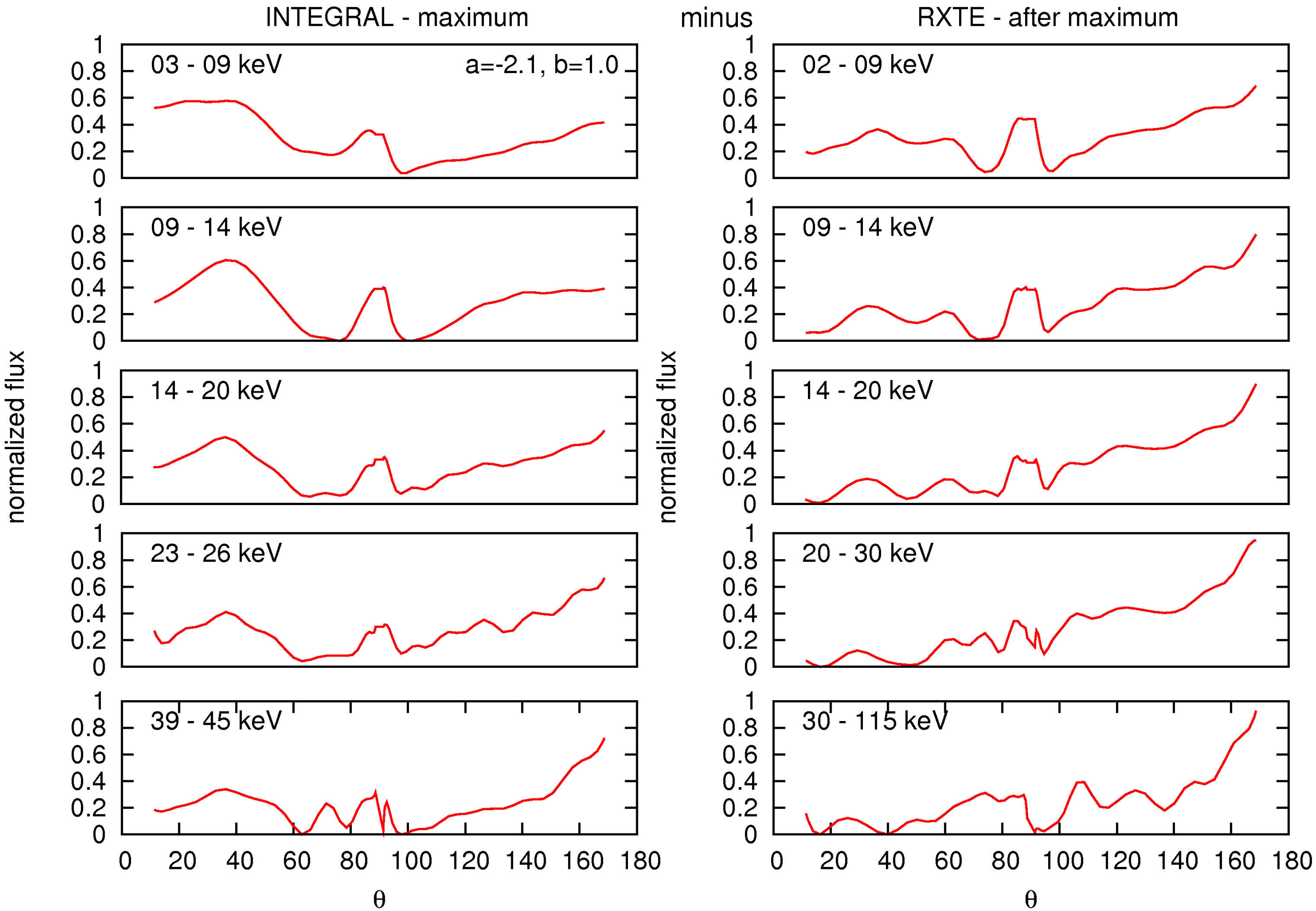
Reconstruction of Beam Patterns

- Two beam patterns are obtained from the decomposition for each pulse profile.
- If the two emission regions have the same beam pattern, the emission that one sees at θ from one pole might be the same emission as what one sees at θ' from the other pole.
- During one revolution of the neutron star, there may be a range of the viewing angle θ in which the observer sees emission from both emission regions.



- This means that, assuming that the two magnetic poles have the same emission characteristics, we can combine the visible beam patterns of the two poles to obtain the total beam pattern of one pole.

Asymptotic Beam Patterns of EXO 2030+375



07/14/2010 Manami Sasaki

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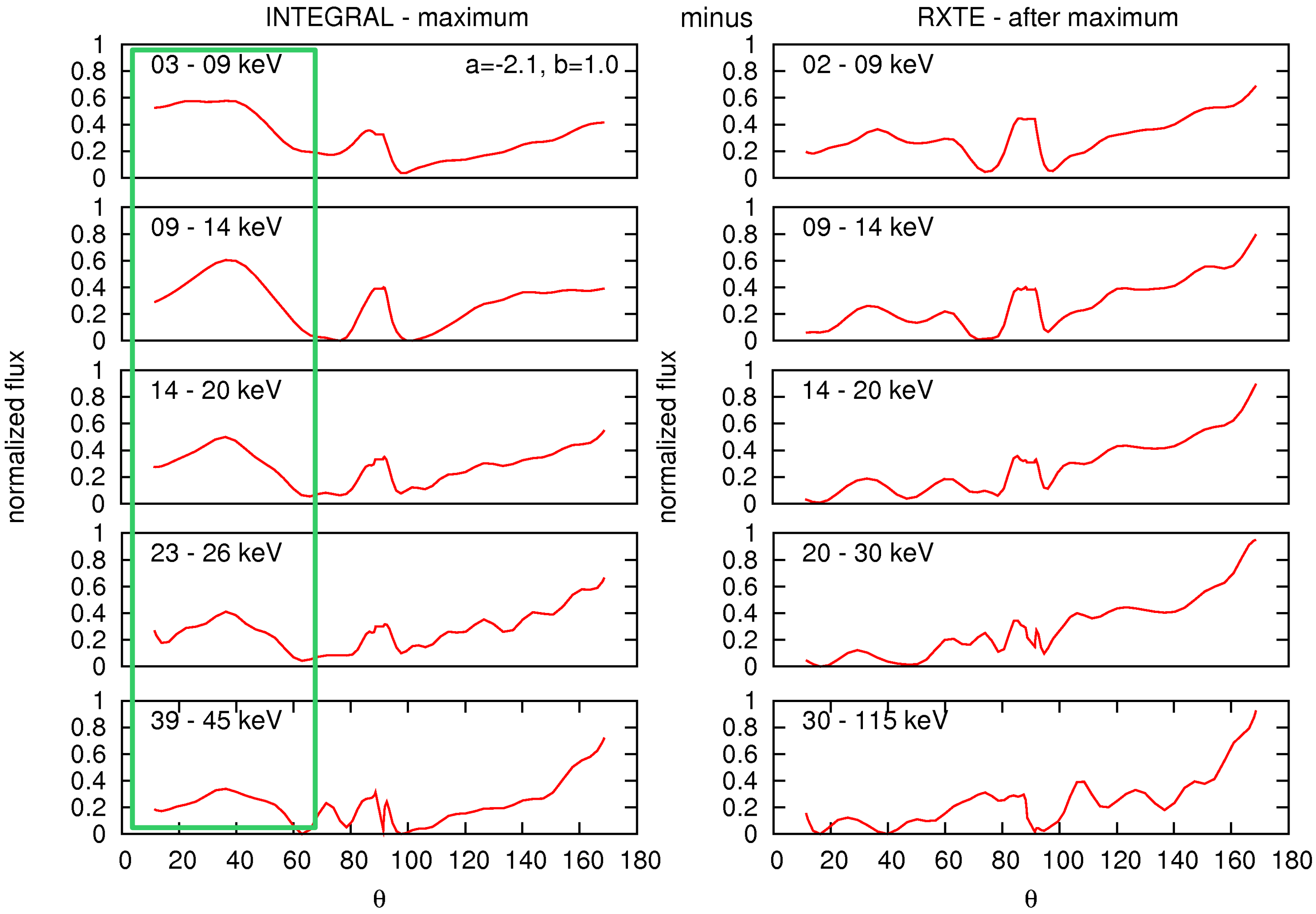
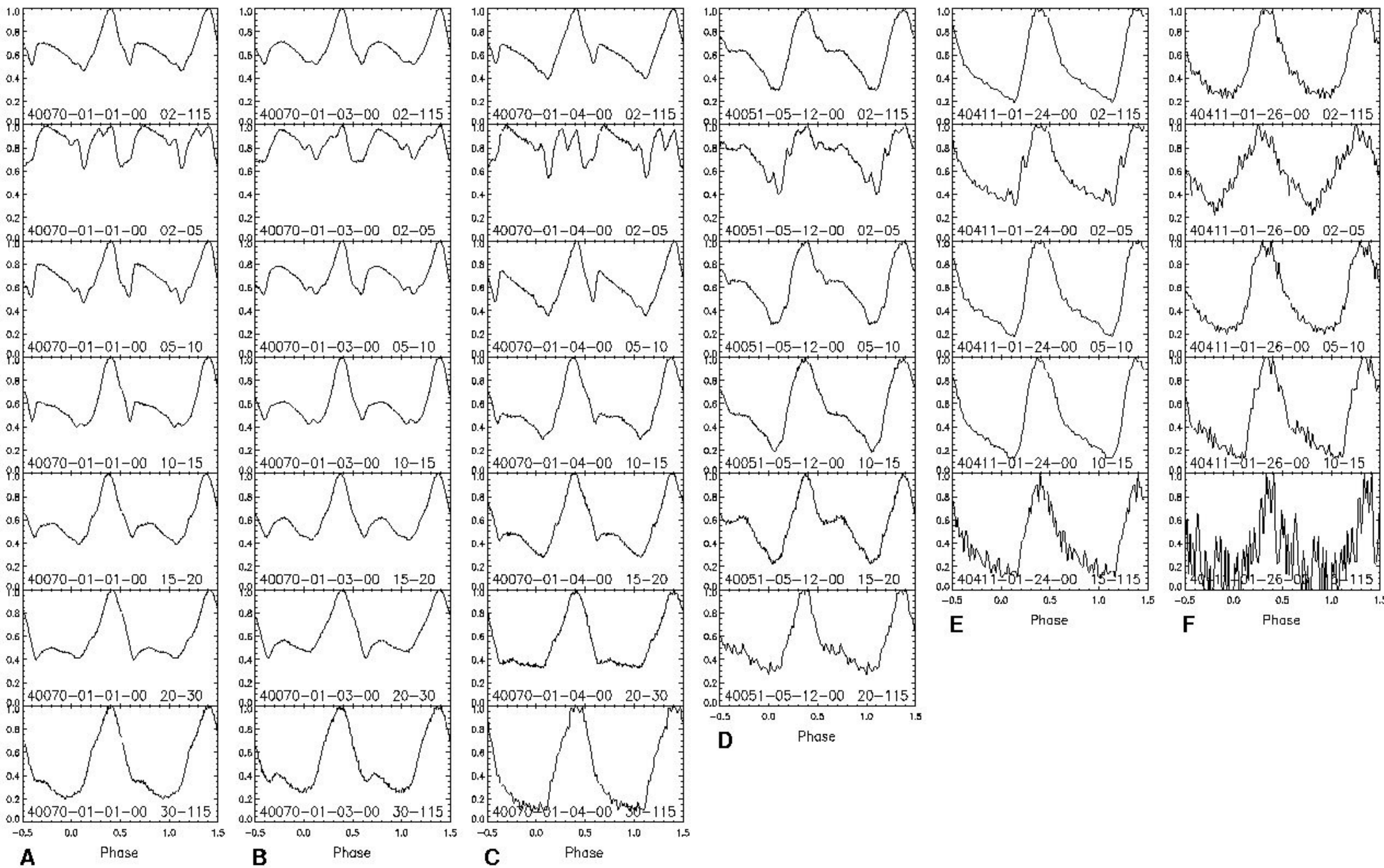


Pulse Profiles of **4U 0115+63**



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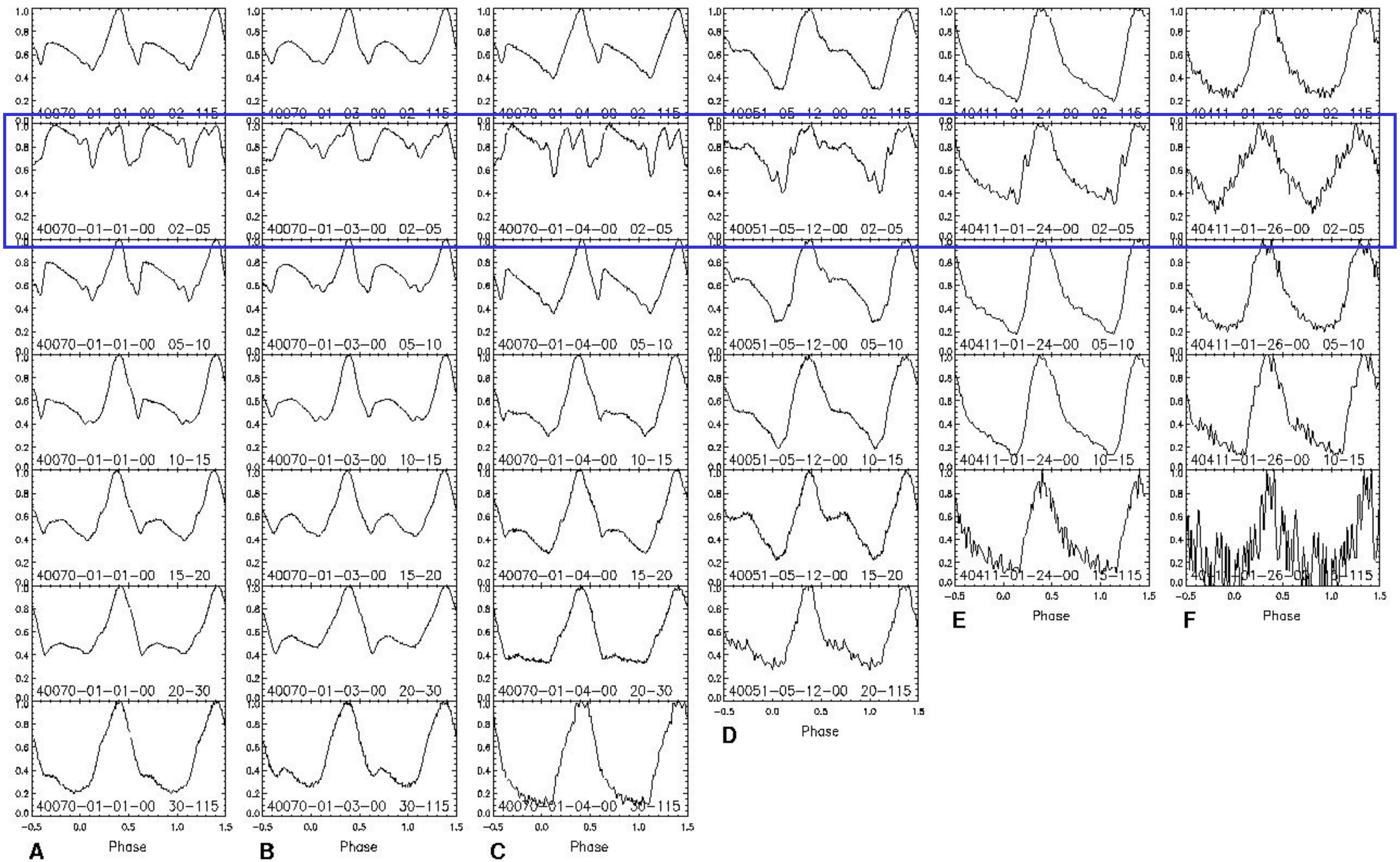

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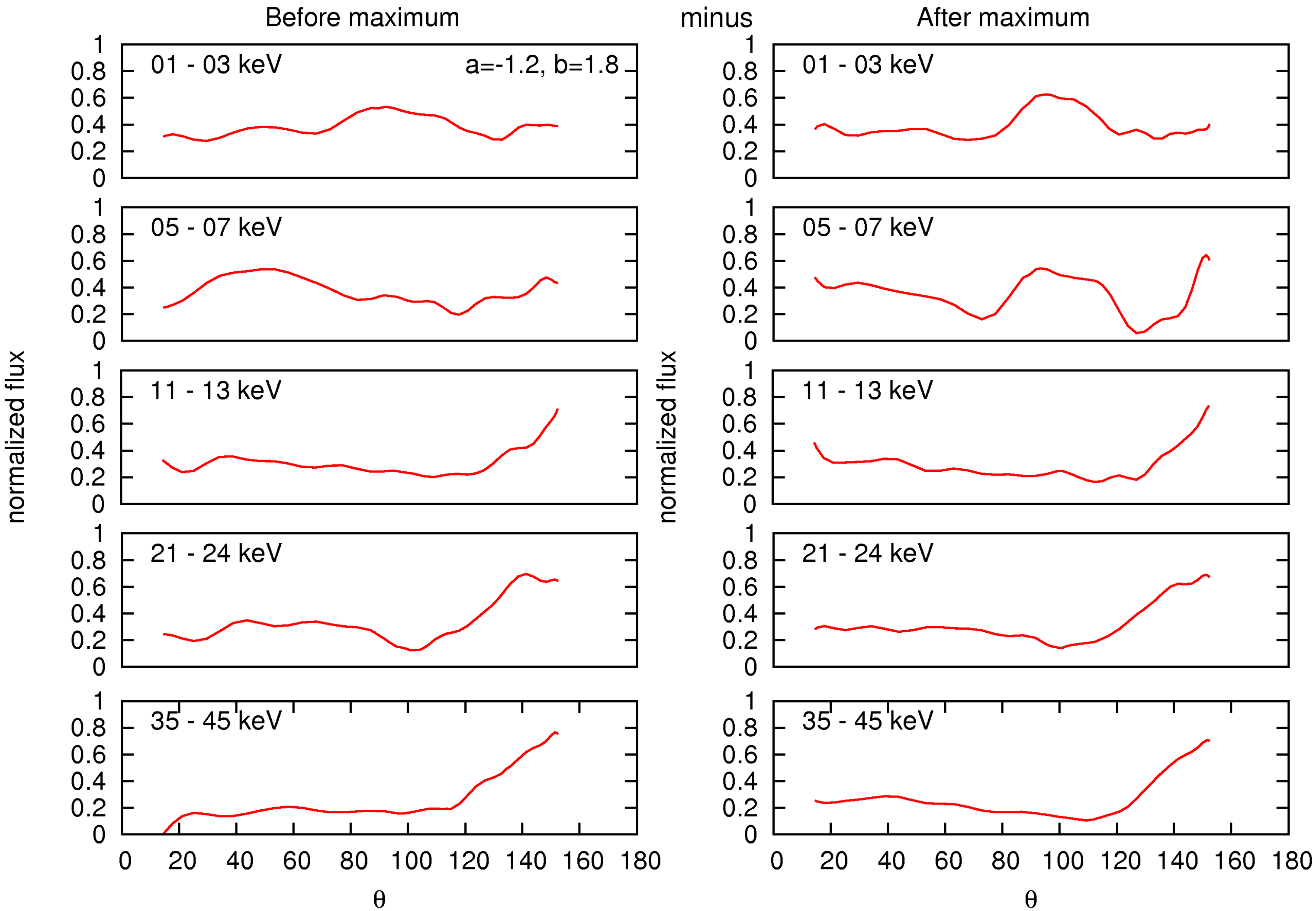

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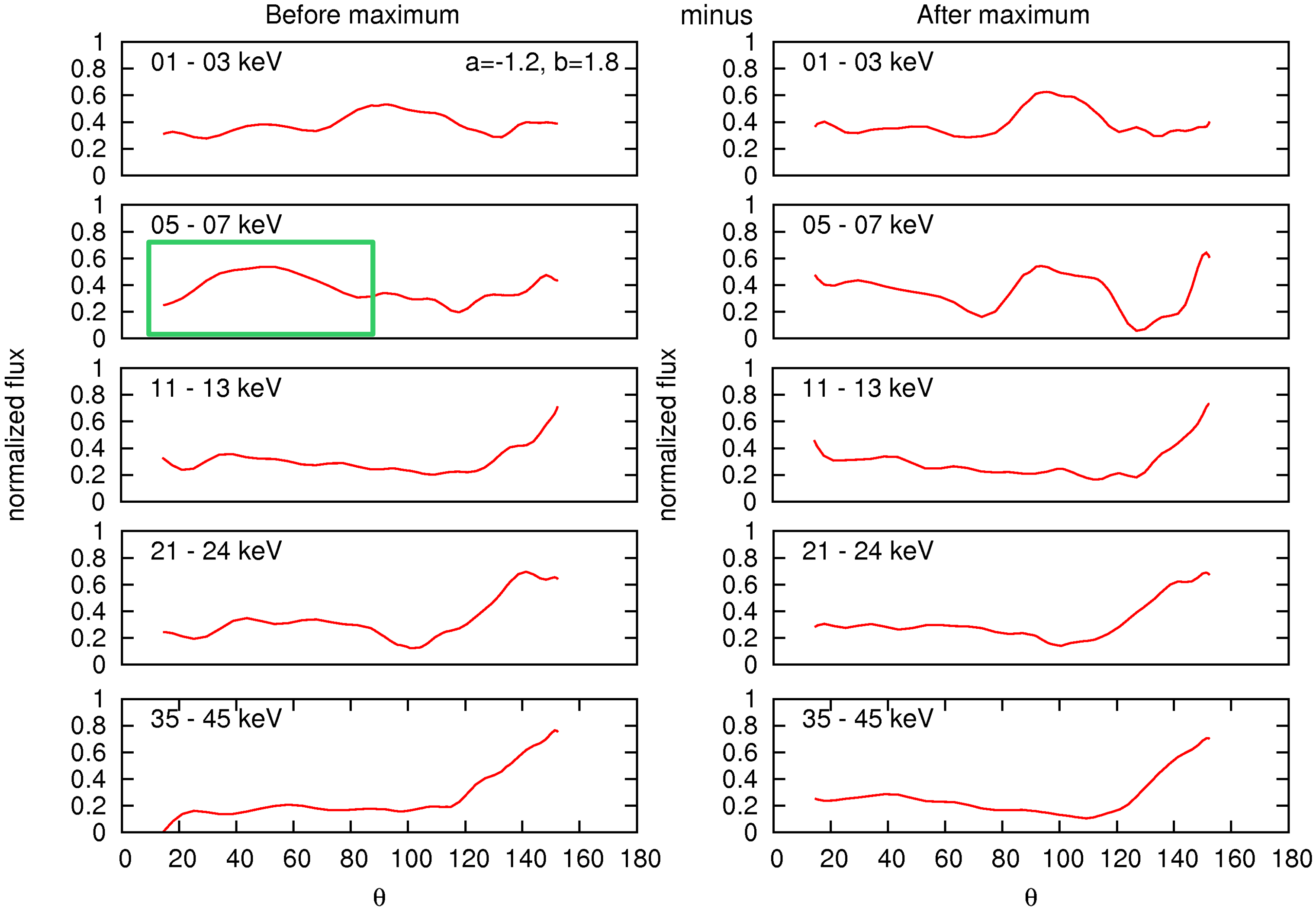
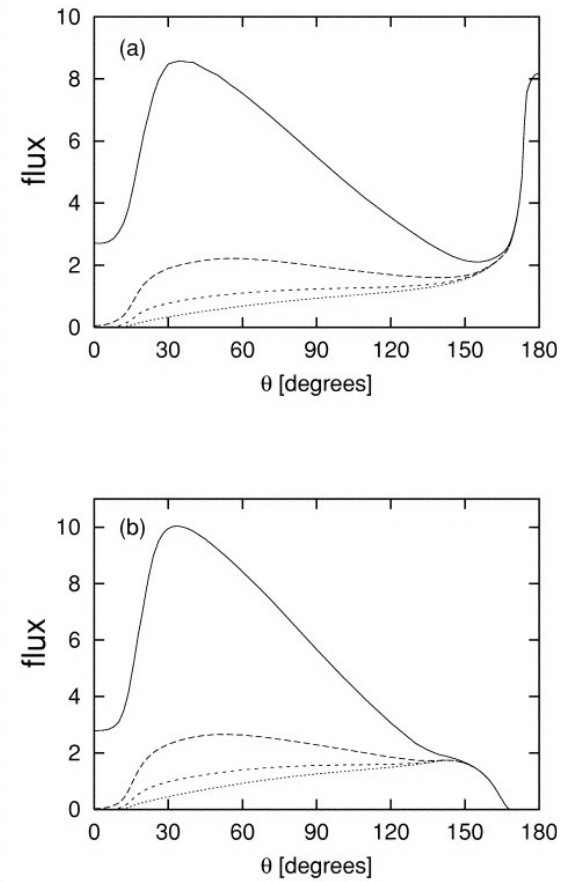


Accretion Column + Halo

- Kraus et al. 2003: assuming isotropic emission from the column; halo at the bottom of the column.
- Top: compact neutron star $r_n/r_S = 2$.
- Bottom: less compact $r_n/r_S = 2.4$
- Photon energies = 1, 5, 10, and 20 keV.
- Halo emission dominates for lower energies.



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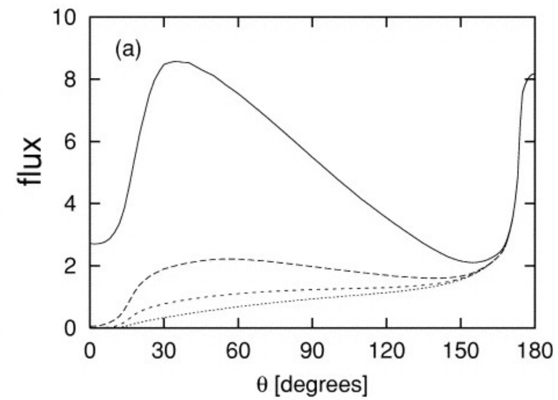
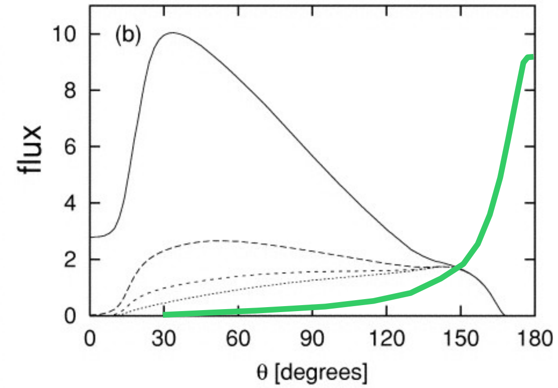
- Photon energies = 1, 5, 10, and 20 keV.
- Halo emission dominates for lower energies.
- Kraus et al. 2010: if scattering in the upper accretion stream is included, accretion column emission is significant only up to ~160°, steep increase of flux from the upper stream for > 160° for > 20 or 30 keV.

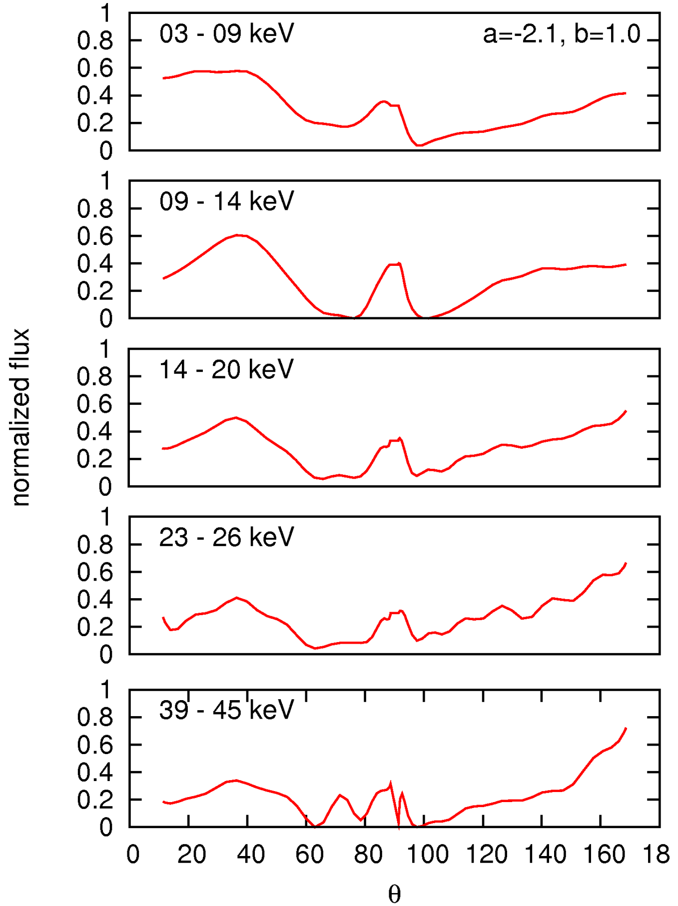




Halo + Column + Upper Stream

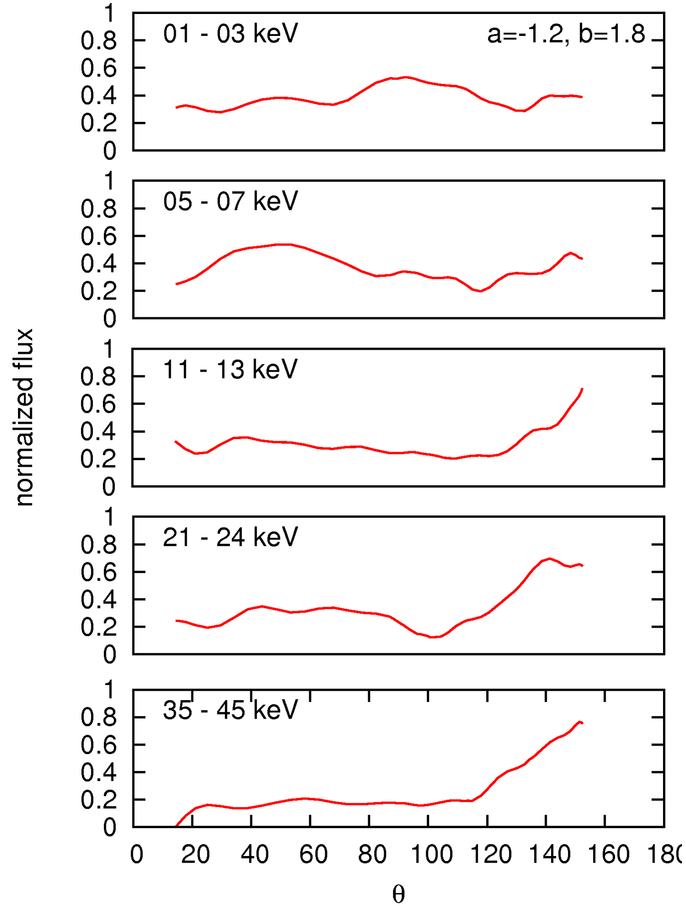
EXO 2030+375

INTEGRAL - maximum



4U 0115+63

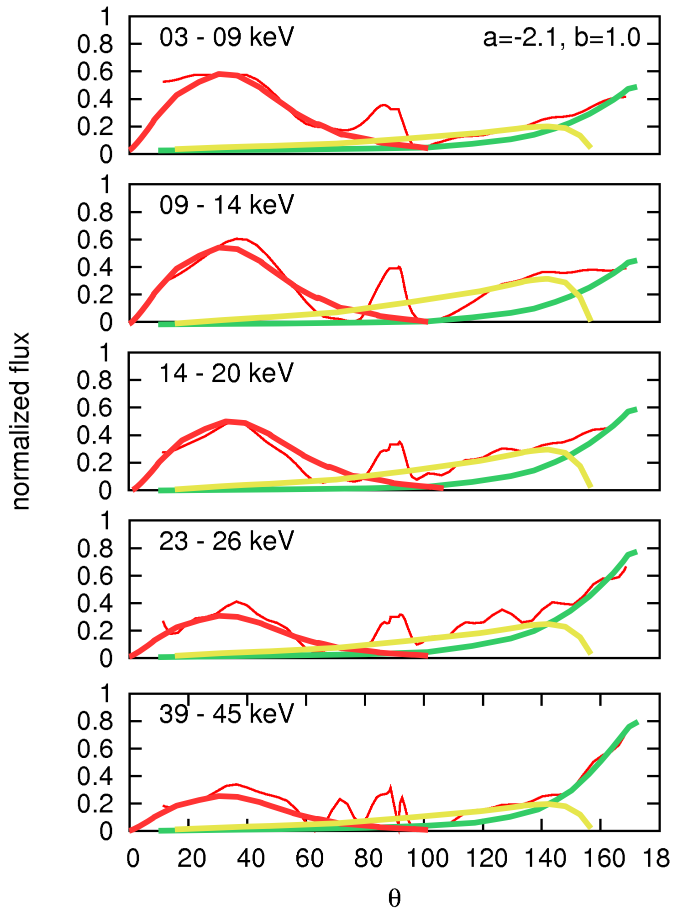
Before maximum



Halo + Column + Upper Stream

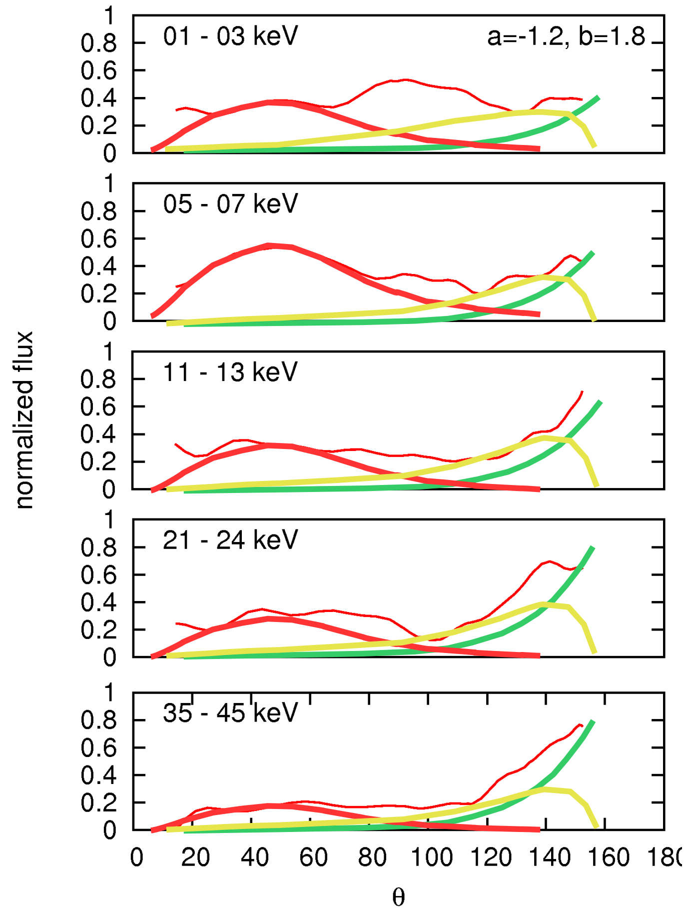
EXO 2030+375

INTEGRAL - maximum



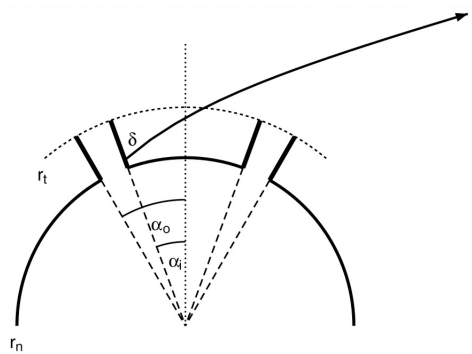
4U 0115+63

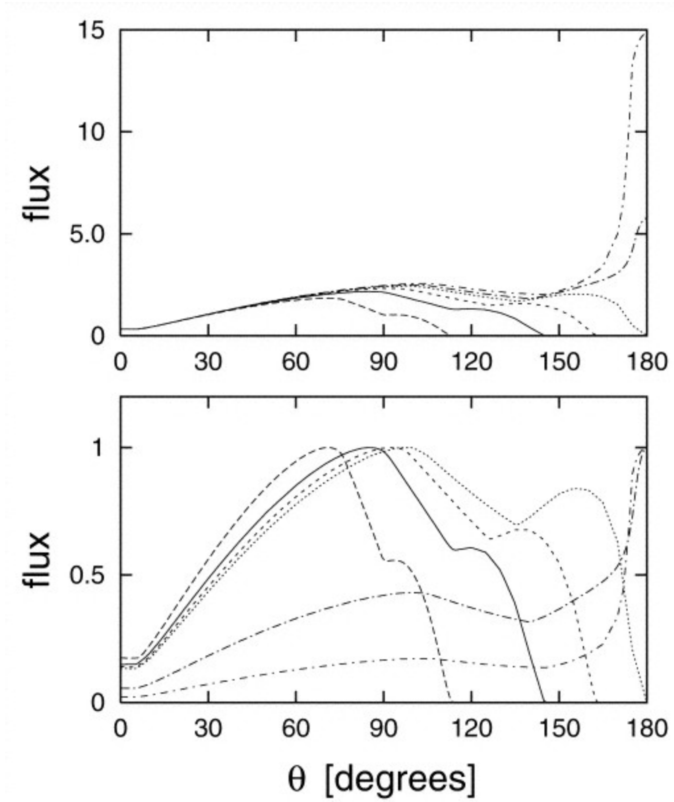
Before maximum



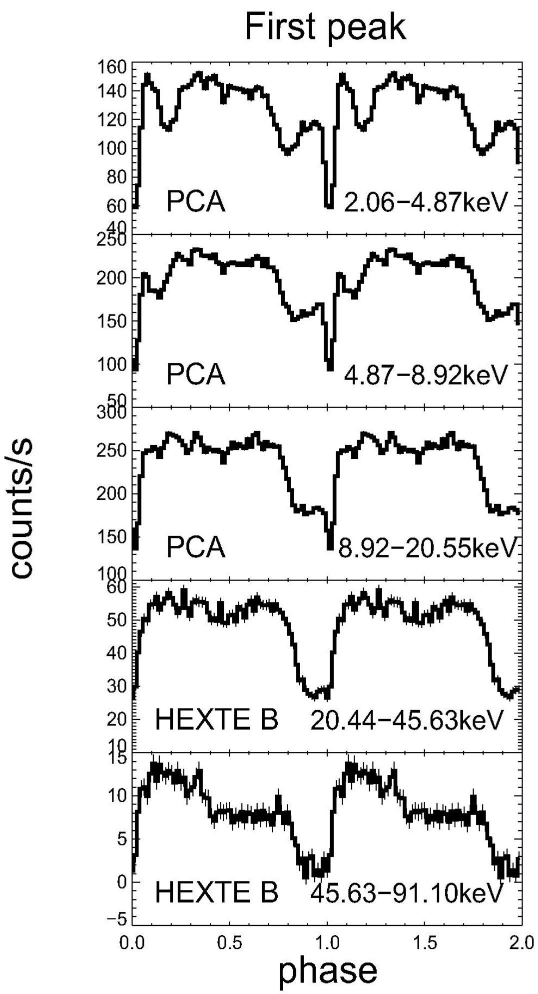
Kraus 2001: Thin Hollow Column

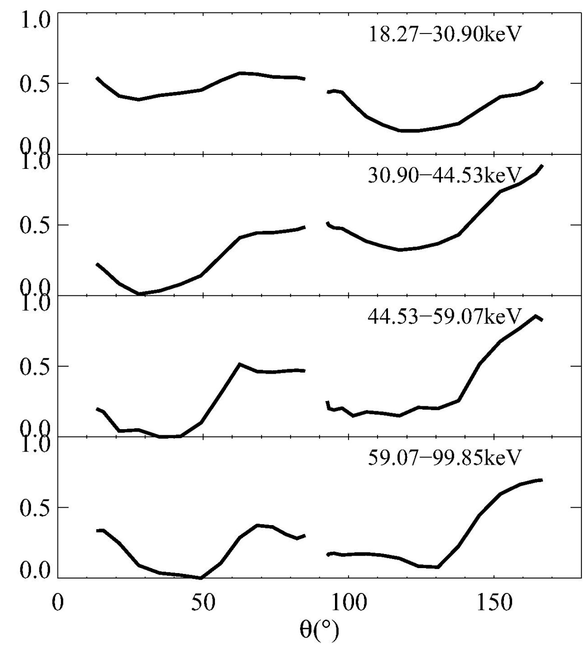
- Beam patterns for thin hollow column, assumed $\alpha_0 = \alpha_i = 0.1$.
- $r_n/r_S = \infty$, 3.3, 2.5, 2.2, 2.1, and 2.
- Upper panel: absolute values.
- Lower panel: normalized to show the shape more clearly.
- Combined emission from the inner and the outer column wall causes two maxima.



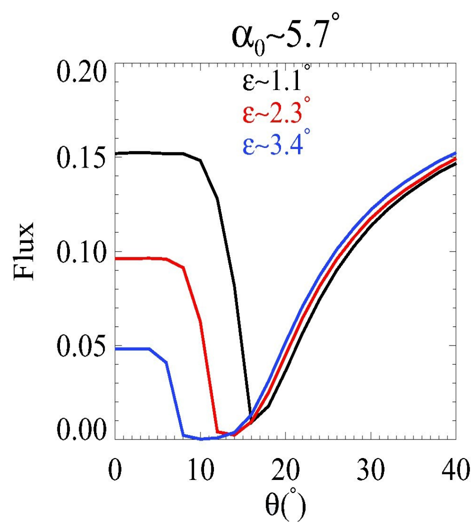


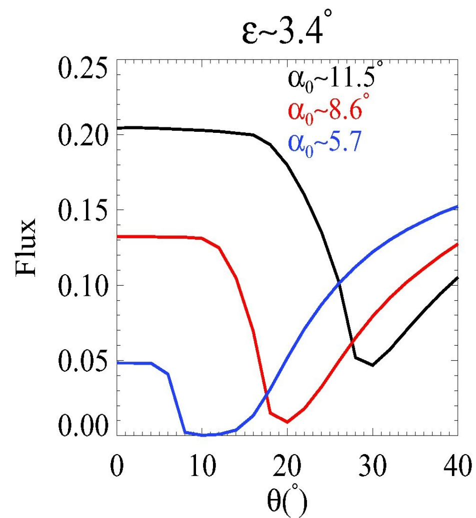
Pulse Profiles and Beam Patterns of **A 0535+26**





Caballero et al. 2010





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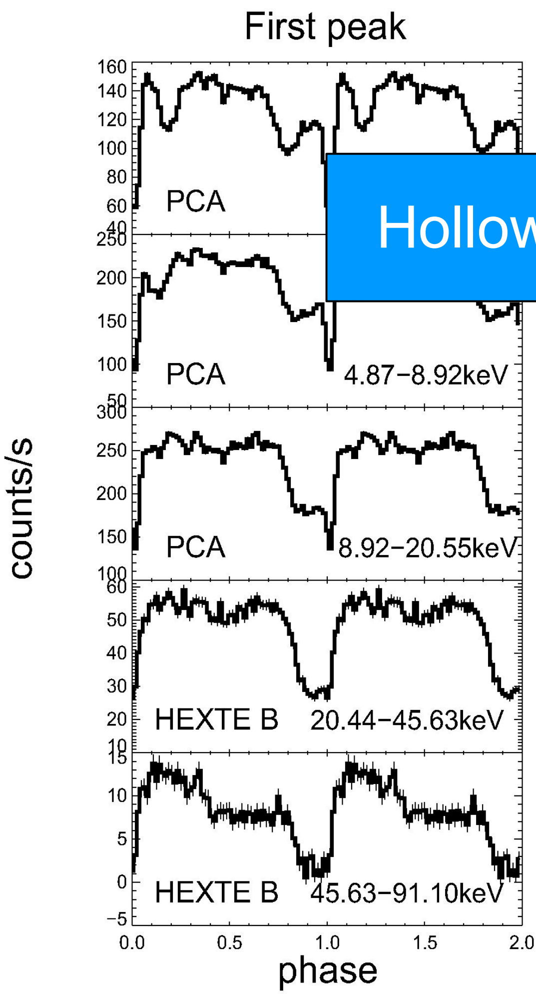
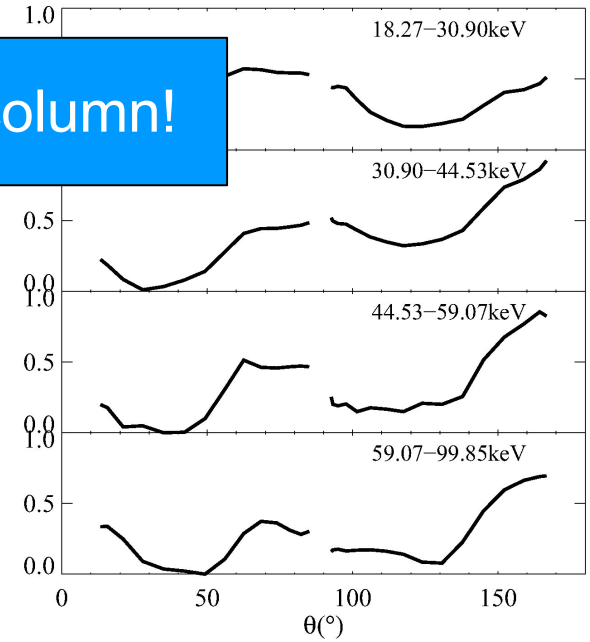


Hollow column!



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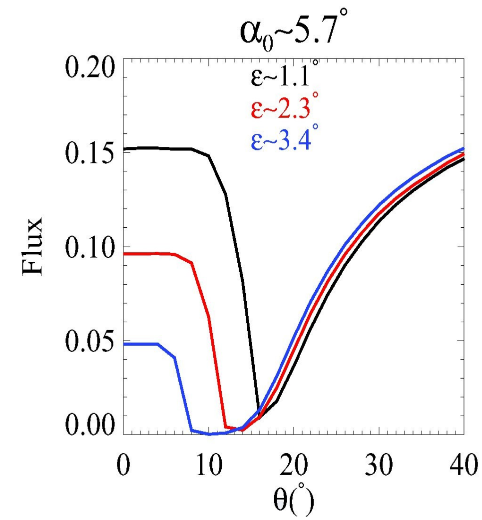
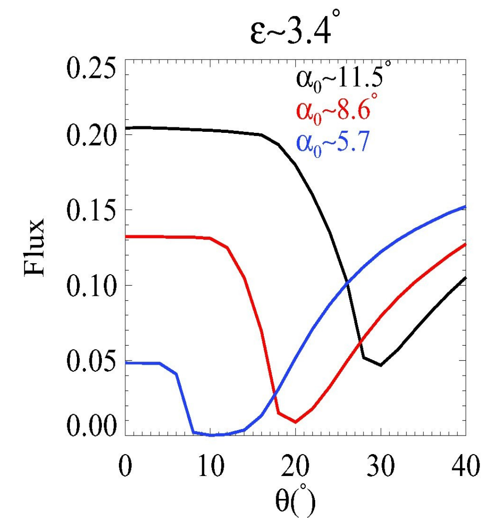
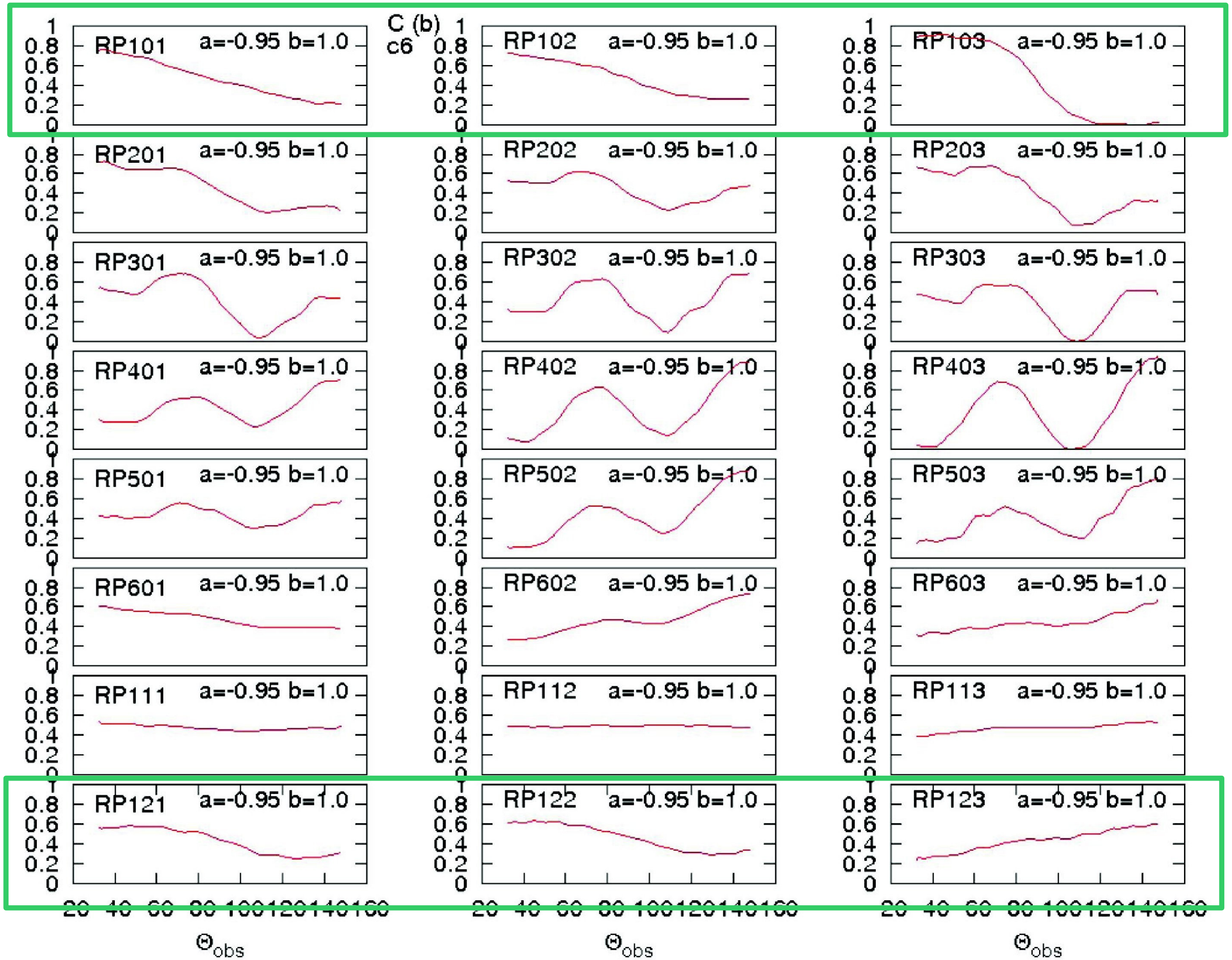




Asymptotic Beam Patterns of **V 0332+53**



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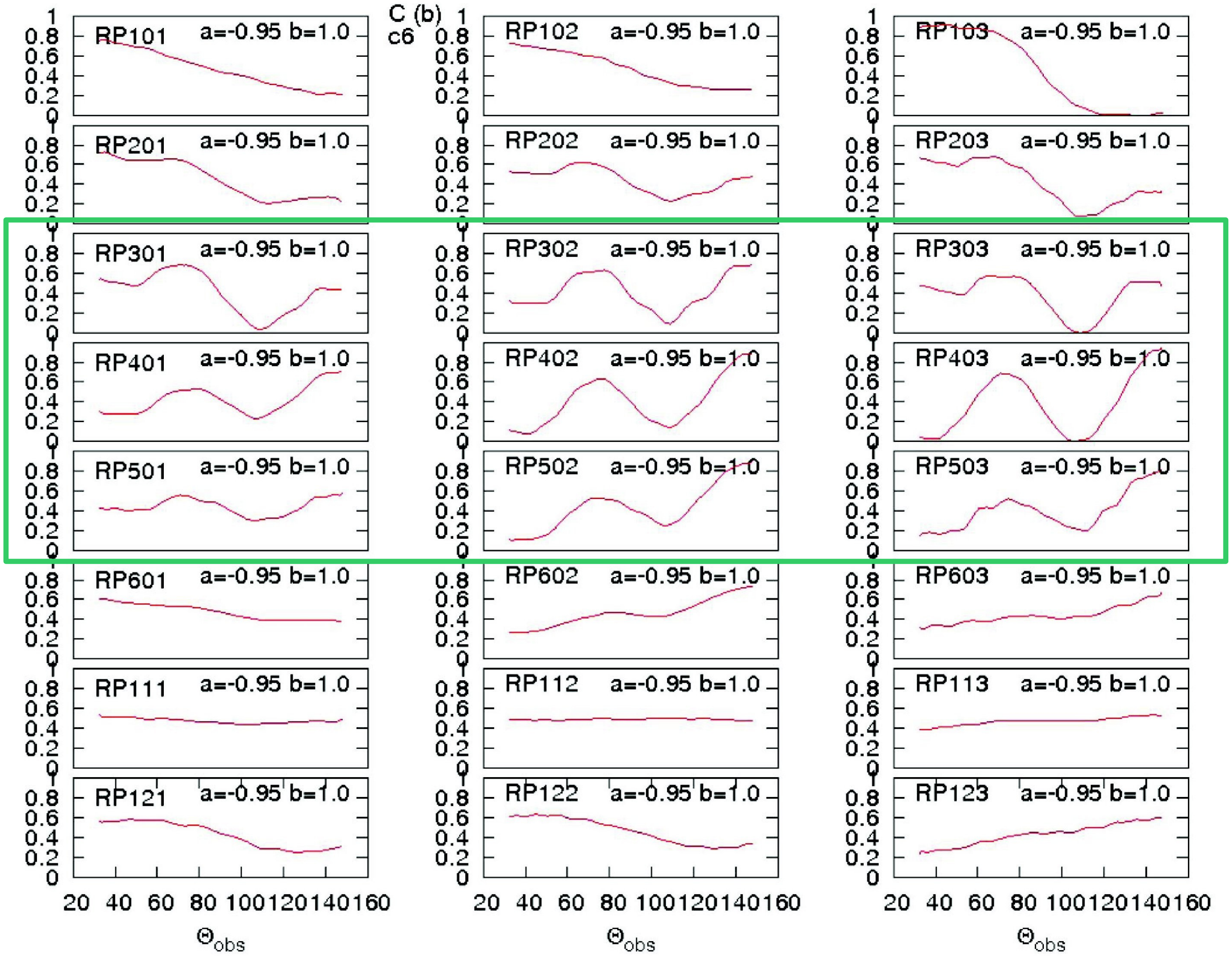

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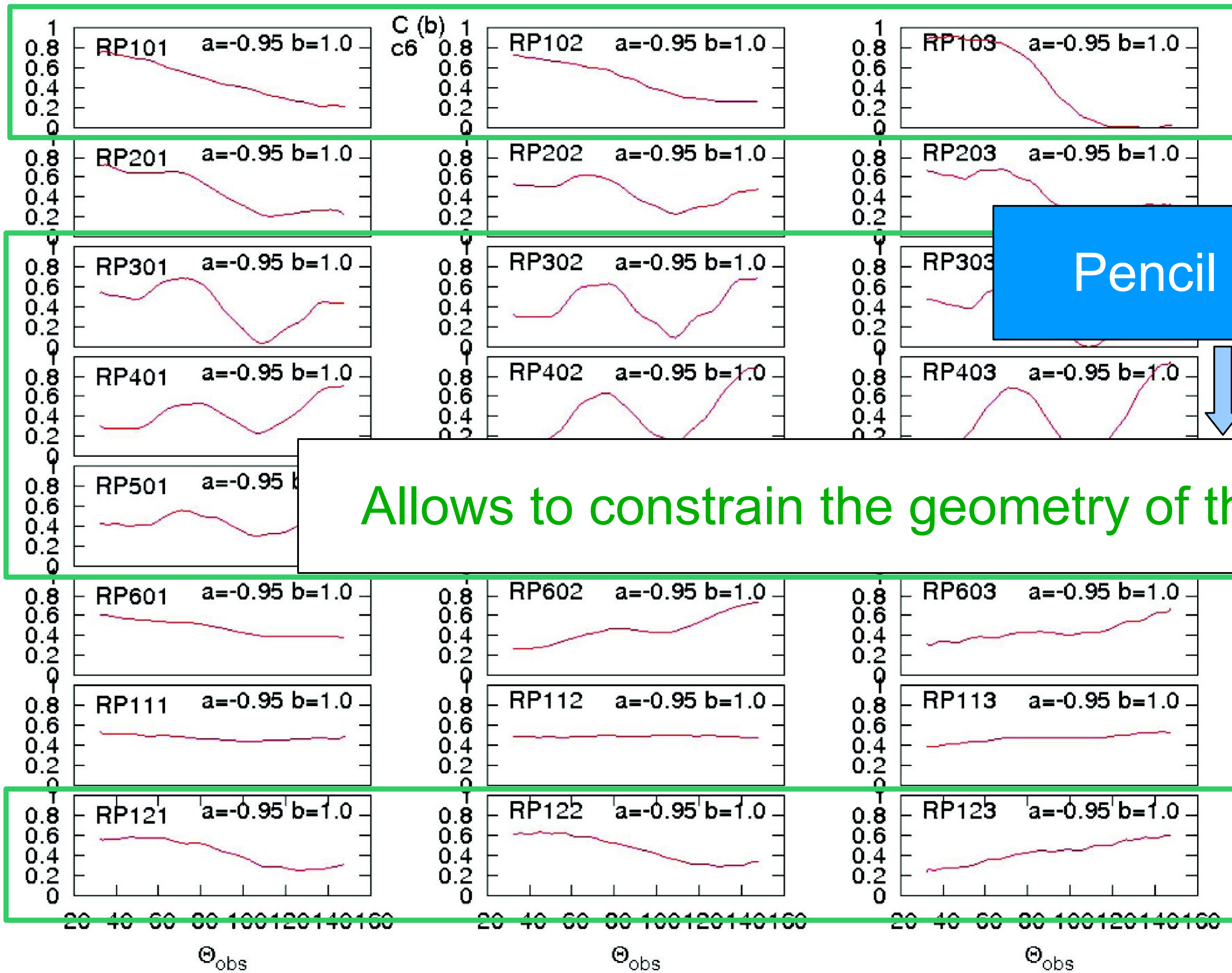

Pencil beam

Allows to constrain the geometry of the NS!

Conclusions

- Slightly distorted magnetic fields.
- EXO 2030+375 and 4U 0115+63: strong evidences for halo emission (< 10 keV) and scattering in the upper accretion stream (> 30 keV).
- Indications for a hollow column (A 0535+26) or other complicated geometries.
- V 0332+53: pencil beam emission for lower Lx, emission from hot spots; a column forms during the maximum.
- More detailed analysis of < 10 keV band might be interesting!
- To pin down the values for the polar angles of the magnetic poles Θ_1, Θ_2, and thus the exact geometry, an independent measurement of the angle between the rotation axis of the neutron star and the line of sight is still necessary.