The Search for Cyclotron Resonant Scattering Harmonics in the Hard Spectra of Accreting Pulsars

Andrea Santangelo

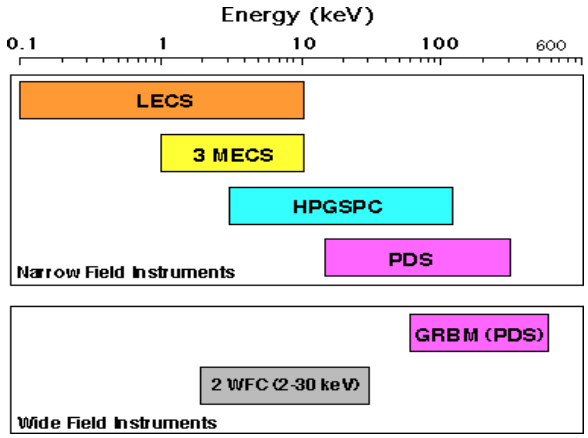
IASF-CNR Sez. Palermo

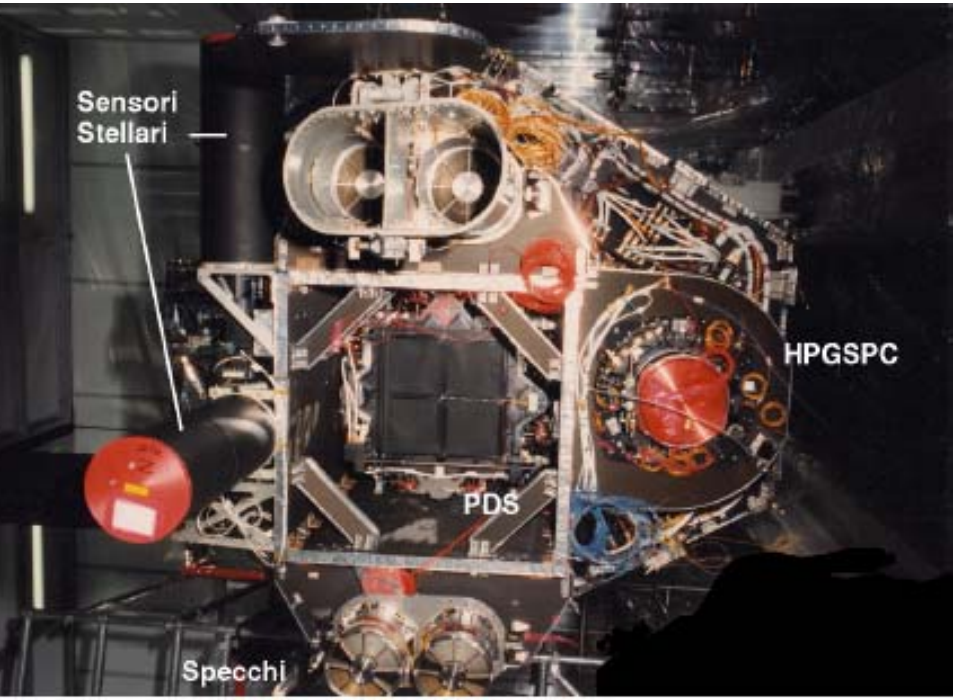
Contents

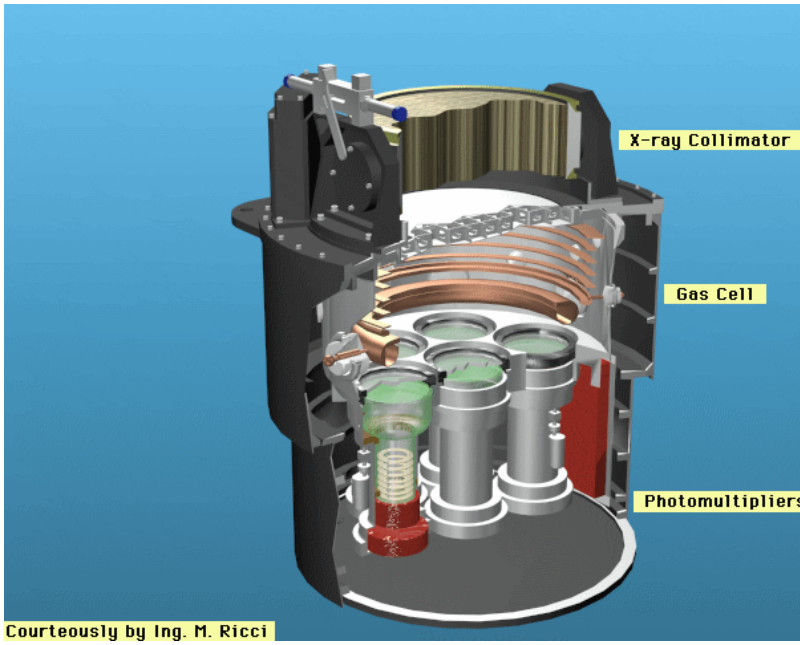
- **Introduction**
- **Review of the Observational Results**
  - ✓**AXRBPs with CRSF**
  - ✓**Multiple Harmonics**
- **Interpretations**
- **Conclusions**

The BeppoSAX Satellite

Four were the Narrow field Instruments onboard BeppoSAX → LECS, (3) 2 MECS, HPGSPC, PDS

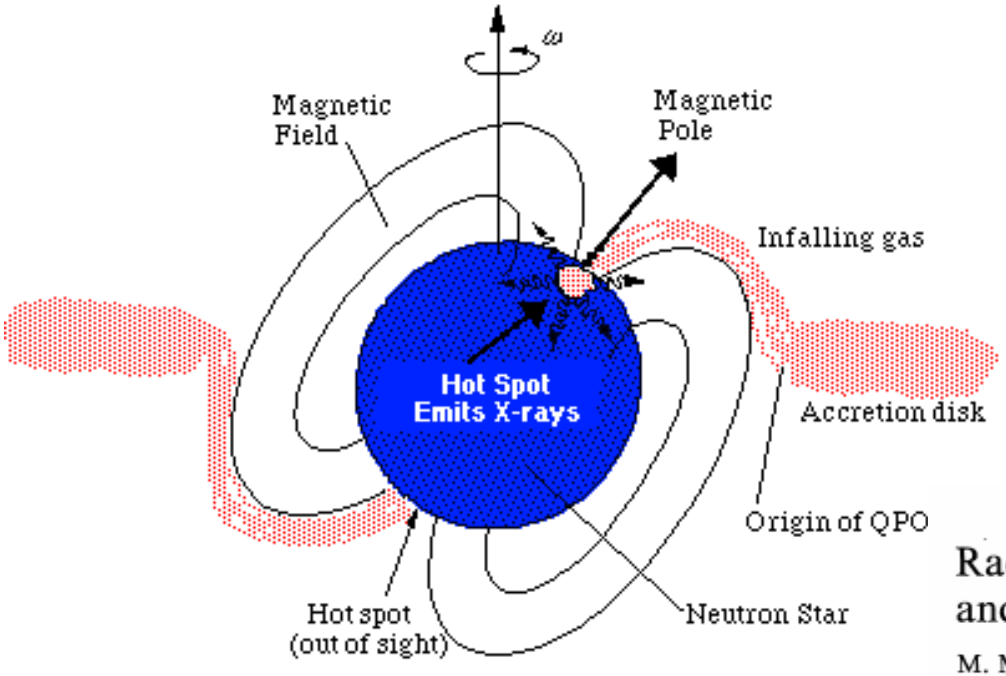






Basics

Woltjer, ApJ 140, 1309 (1964)
Pacini, Nature, 216, 567 (1967)



$B \sim 10^{12}$-10^{13} G

On grounds of magnetic flux conservation during the SN core collapse

Radiative Transfer in a Strong Magnetic Field and Accreting X-ray Pulsars

M. M. Basko and R. A. Sunyaev
Space Research Institute, Academy of Sciences of the USSR, Moscow

Received January 20, 1975

Signatures of electron cyclotron emission were to occur in the hard spectra of AXRBPs

Basco & Sunyaev, Astr. Ap., 42, 311 (1975); Gnedin & Sunyaev, Astr. Ap., 36, 379 (1974);

Cyclotron lines basic thoery

Fermions in the magnetosphere plasma will move helicodally along the B field lines with gyromagnetic Larmor frequency

The motion of the electron perpendicularly to the B field is quantized in the Landau levels

$$B_{cr} = \frac{m^2 c^3}{e\hbar} \cong 4.14 * 10^{13}\, G$$

$$\omega_c = \frac{eB}{\gamma mc}; \quad \hbar\omega_n = n\hbar\omega_c, \text{ Equispaced}$$

$$\hbar\omega_n = mc^2 \frac{\sqrt{mc^2 + 2n\hbar\omega_c \sin^2\theta} - 1}{\sin^2\theta}$$

If relativistic corrections are taken into account

$$E_{e,c} = 11.6 B_{12} \text{ (unit of } 10^{12} \text{ Gauss)}$$

$$B_{12} = (1+z) E_{e,c}^{obs} / 11.6$$

It it's a proton…or a Helium ion

$$E_{p,c} = 0.63 B_{14} (1+z)^{-1} \text{ (unit of } 10^{14} \text{ Gauss)}$$

$$E_{He} = 0.32 B_{14} (1+z)^{-1} \text{ (unit of } 10^{14} \text{ Gauss)}$$

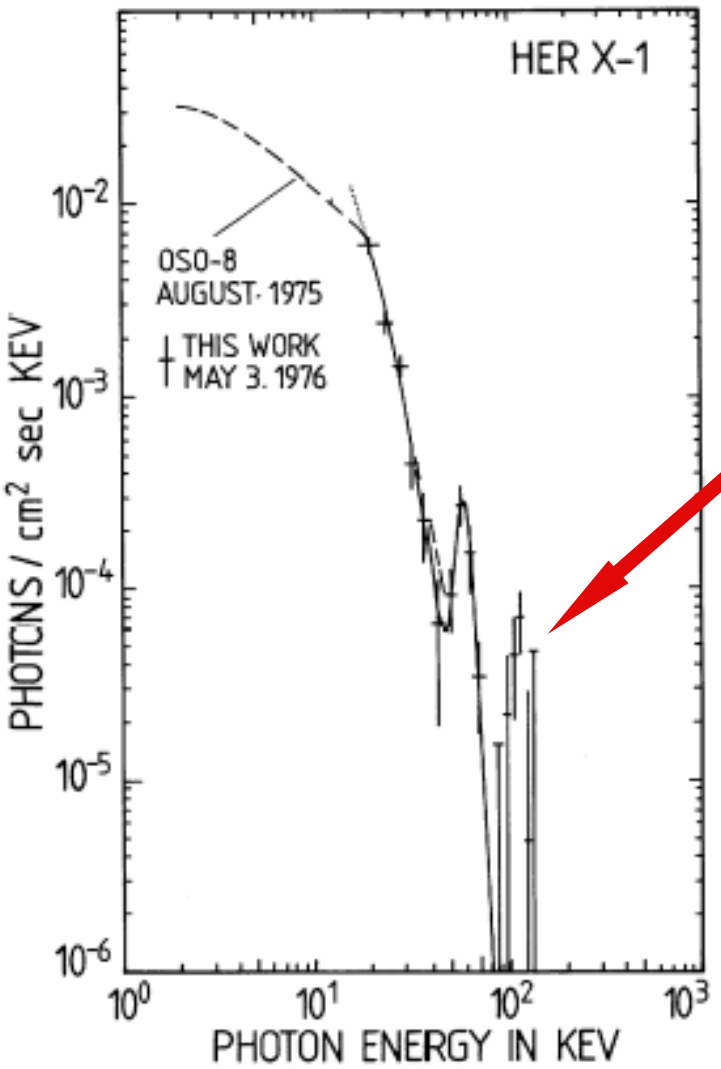
Early CRSFs Observations

In the Beginning…

J. Trümper, W. Pietsch, C. Reppin, B. Sacco*), Garching, **E. Kendziorra, R. Staubert,** Tübingen: Evidence for strong cyclotron emission in the hard X-ray spectrum of Her X-1**)

Abstract

We have measured the energy spectrum of the 1.24 second pulses of Her X-1 in the energy range 15–125 keV during a four hour balloon observation on May 3, 1976 from Palestine, Texas. The spectrum of the pulsed flux can be represented by an exponential with kT = 7.9 keV up to 50 keV. At about 53 keV a strong and rather narrow line feature occurs which we interpret as electron cyclotron emission from the polar cap plasma of the rotating neutron star. The corresponding magnetic field strength is 4.6×10^{12} Gauss.



2nd harmonic at
E^2_{cyc} ~ 110 keV
(3.3 σ)

Truemper et al., ApJL 219, L105 (1978)

EVIDENCE FOR STRONG CYCLOTRON LINE EMISSION IN THE HARD X-RAY SPECTRUM OF HERCULES X-1

J. Trümper, W. Pietsch, C. Reppin, and W. Voges
Max-Planck-Institut für Physik und Astrophysik, Institut für extraterrestrische Physik, Munich
AND
R. Staubert and E. Kendziorra
Astronomisches Institut der Universität Tübingen
Received 1977 August 19; accepted 1977 October 12

FIG. 2.—Deconvoluted X-ray spectrum of the Her X-1 *pulses*. *Solid line*, best-fitting exponential spectrum with a Gaussian line to the data points. The error bars are ±1 σ; the upper limits are at 2 σ. For comparison, a *total* X-ray spectrum of Her X-1 observed by OSO-8 during the 1975 August on-state is shown (Becker *et al.* 1977).

- The Milestone: discovery of a cyclotron line in the spectrum of Her X-1 (Truemper et al., ApJ 219, L105, 1978)
- Further advances:discovery of two lines in the spectrum of 4U0115+63 (Wheaton et al., 1979, White et al. 1983)
- The systematic study: Observations of lines with Ginga, showed that the presence of line is rather common and added an interpretative scheme (Mihara, thesis, 1995, Makishima et al., 1999)

Ginga firmly detected cyclotron features in 8 sources, showing that the presence of the cyclotron feature is rather common … but → Universal ?

CYCLOTRON RESONANCE EFFECTS IN TWO BINARY X-RAY PULSARS AND THE EVOLUTION OF NEUTRON STAR MAGNETIC FIELDS

K. MAKISHIMA
Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan 113-0033
T. MIHARA
Cosmic Ray Laboratory, The Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama, Japan 351-0198
F. NAGASE
Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa, Japan 229
AND
Y. TANAKA
Max-Planck-Institut für Extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany
Received 1998 August 21 ; accepted 1999 June 23

TABLE 1

SUMMARY OF THE CURRENTLY KNOWN CYCLOTRON RESONANCE FEATURES OF X-RAY PULSARS

Object	Period (s)	E_a [a] (keV)	E_t [b] (keV)	Status	B [c] (10^{12} G)	References
4U 0115+63 (1990).....	3.6	$11.3 \pm 0.6/22.1 \pm 0.4$	7.7 ± 1.3	Firm	1.0	1, 2*,**
4U 0115+63 (1991).....	3.6	15.6 ± 0.4/...	8.8 ± 0.9	Firm	1.3	3*, 4
4U 1907+09	439	$18.9 \pm 0.7/39.4 \pm 0.6$	14.2 ± 0.5	Firm	1.6	2*, 3–5, 6**
4U 1538−52	530	20.6 ± 0.2/...	14.2 ± 0.6	Firm	1.8	7, 2*
Vela X-1	283	$24.5 \pm 0.5/56 \pm 2$	18.8 ± 0.8	Firm	2.1	2*, 3, 5, 8, 9**
Cen X-3	4.82	25.8 ± 0.5/...	14.8 ± 0.4	Firm	2.2	10*
X0331+53	4.37	27.2 ± 0.3/...	13.9 ± 0.6	Firm	2.3	11, 2*
Cep X-4	66.3	28.8 ± 0.4/...	17.6 ± 0.4	Firm	2.5	12, 2*
Her X-1	1.24	33.1 ± 0.5/...	20.0 ± 0.5	Firm	2.9	13, 2*
4U 1626−67	7.66	38.1 ± 0.9/...	21.1 ± 0.4	Firm	3.3	14*
A0535+26.....	110	$\sim 50/110^{+2}_{-4}$	24 ± 2	Firm	4.3	8, 15*, 16**
GX 301−2	690	35.6 ± 1.6/...	19.6 ± 0.8	Probable	3.1	3*, 5
GS 1843+00	29.5	19.8 ± 2.1/...	19.8 ± 1.1	Possible	1.7	3*
LMC X-4	13.5	21.4 ± 1.2/...	16.1 ± 0.5	Possible	1.8	3*
X2259+586	7.0	4.20/...	...	Doubtful	0.6	1*, 17

Makishima et al., ApJ 525, 978 (1999)

BeppoSAX and RossiXTE

BeppoSAX and RXTE findings

X0115+63	20 Mar1999	**12.78±0.08**	**3.58±0.33**	Santangelo et al., ApJL **523**, L85 Heindl et al., ApJL **521**, L49
4U1538-52	29 Jul 1998	**21.5±0.4**	**6.7±1.2**	Robba et al., ApJ **562**, 950
Cen X-3	27 Feb 1997	**28.5±0.5**	**7.3±1.9**	Santangelo et al., A&A, **340**, L55
X Persei	Jul Dec 1998	**28.5±1.6**	**21±3**	Coburn et al., ApJ **552,** 738
XTE J1946+27	09 Oct 1998	**37±4**	**5±2**	Santangelo et al., submitted to ApjL, Heindl et al., ApJL, **563 L35**
OAO1657-415	04 Sep 1998	**36±2**	**10**	Orlandini et al. 1999, A&A **349**, L9
4U1626-67	06 Aug 1996	**38.0±0.9**	**11.8±1.7**	Orlandini et al. 1998, ApJL **500**, L165
4U1907+09	29 Sep 1997	**38.3±0.7**	**9.7±2.3**	Cusumano et al. 1998, A&A **338**, L79
Her X-1	27 Jul 1996	**42.1±0.3**	**14.7±1.1**	Dal Fiume et al. 1998, A&A **329**, L41
GX301-2	24 Jan 1998	**49.5±1.0**	**17.9±2.5**	Orlandini et al., proc. 32th Cospar
Vela X-1	14 Jul 1996	**54.8±0.9**	**25.0±2.1**	Orlandini et al. 1998, A&A **332**, 121
LMC X-4	20 Oct 1998	**100**	**45**	La Barbera et al., 2001ApJL **553** L375

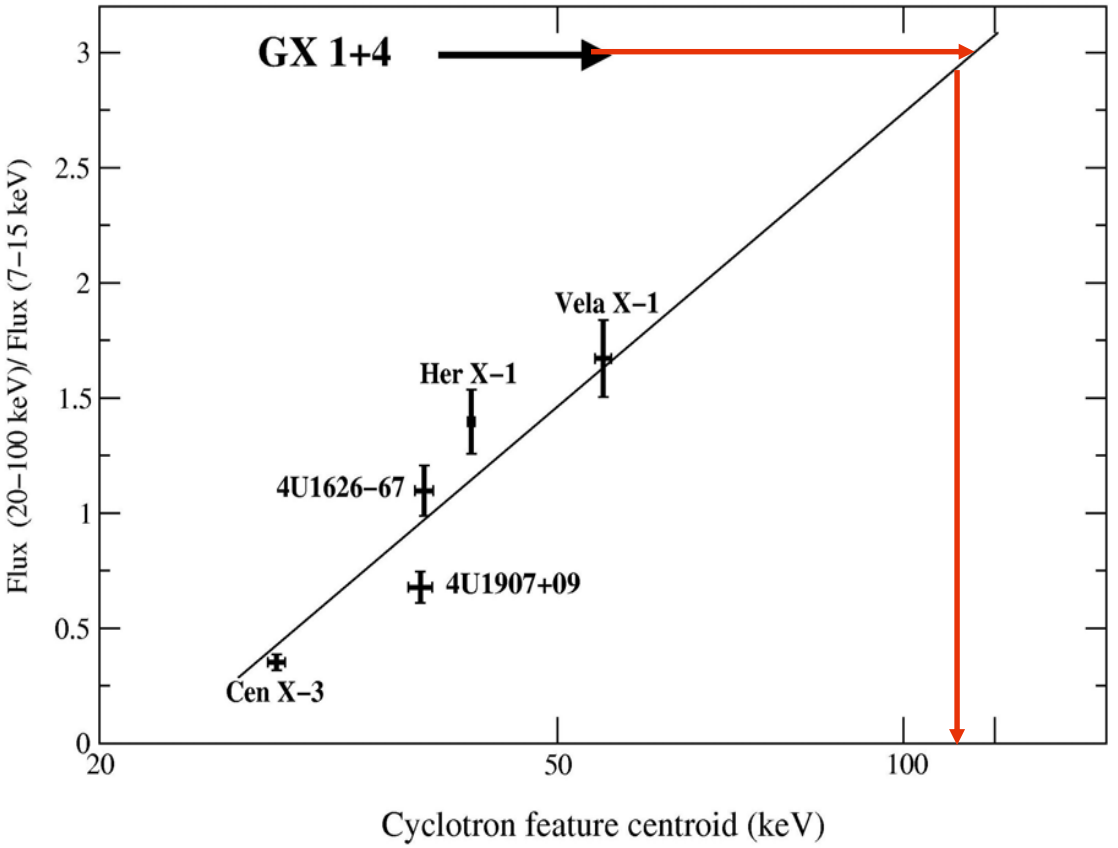
More recent findings

1 RXS J170849-400910	20 Mar 2003	**~8.1 ?**	**~0.4**	Rea et al., ApJL **586**, L65 (Based on BeppoSAX-MECS) Not confirmed by XMM
GX301-2	24 Jan 1998	**~29-39** **~30-45**		Kreykenbohm et al., La Barbera et al., in pre
Vela X-1	14 Jul 1996	**54.8±0.9**	**25.0±2.1**	Orlandini et al. 1998, A&A **332**, 121 Kreykenbhom et al., A&A, **395**, 129 La Barbera et al., A&A **400**, 900
SGR1806-20	20 Jul 2002	**~5 ?**	**~0.4**	Ibrahim et al., ApJ **574**, L51 Ibrahim et al., accepted ApJ

No Lines ?

GX 1+4	25 Mar 1997	**????**	**…**	Israel et al. 1998, Proc. "Active X-ray Sky" Conf., Roma, 1998
GS 1843+00	04 Apr 1997		**…**	Piraino et al. 2000, A&A **357, 501**

The Source shows the hardest spectrum among AXRBPs



Mony et al. (A&A, 247,405) and Dotani et al., (PASJ,41,427)

$B \sim (2\text{-}3)\times 10^{13}$ G

Ecyc ~ 200-300 keV

Correlation between the spectral hardness indicator and line energy → Dal Fiume et al., 2000

Ecyc ≥ 100 keV

Multiple Harmonics

Second Harmonic ?

If the mechanism of cyclotron resonance scattering is at work multiple harmonics are expected.

Before BeppoSAX and RossiXTE very little was known on higher cyclotron harmonics…

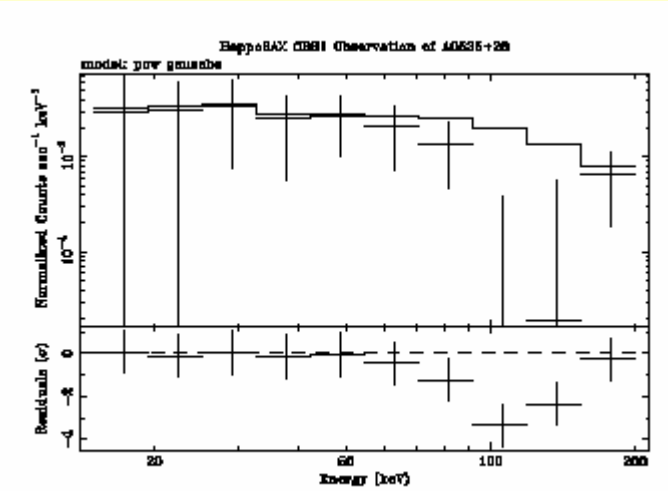
- *4U 0115+63* — White, Swank & Holt (1983, HEAO1)
- *Vela X-1* — Kendziorra et al. (1992, Kvant)
- *A0535+26 (?)* — Kendziorra et al. (1994, Kvant); Grove et al., (1995, OSSE-CGRO)

Second Harmonics

BeppoSAX and RossiXTE discovered or had evidence of multiple harmonics in some of the sources, therefore establishing the presence of second harmonic as a possible common feature (to be observed provided the adequate sensitivity)!

A0535+26

4σ, 118 keV



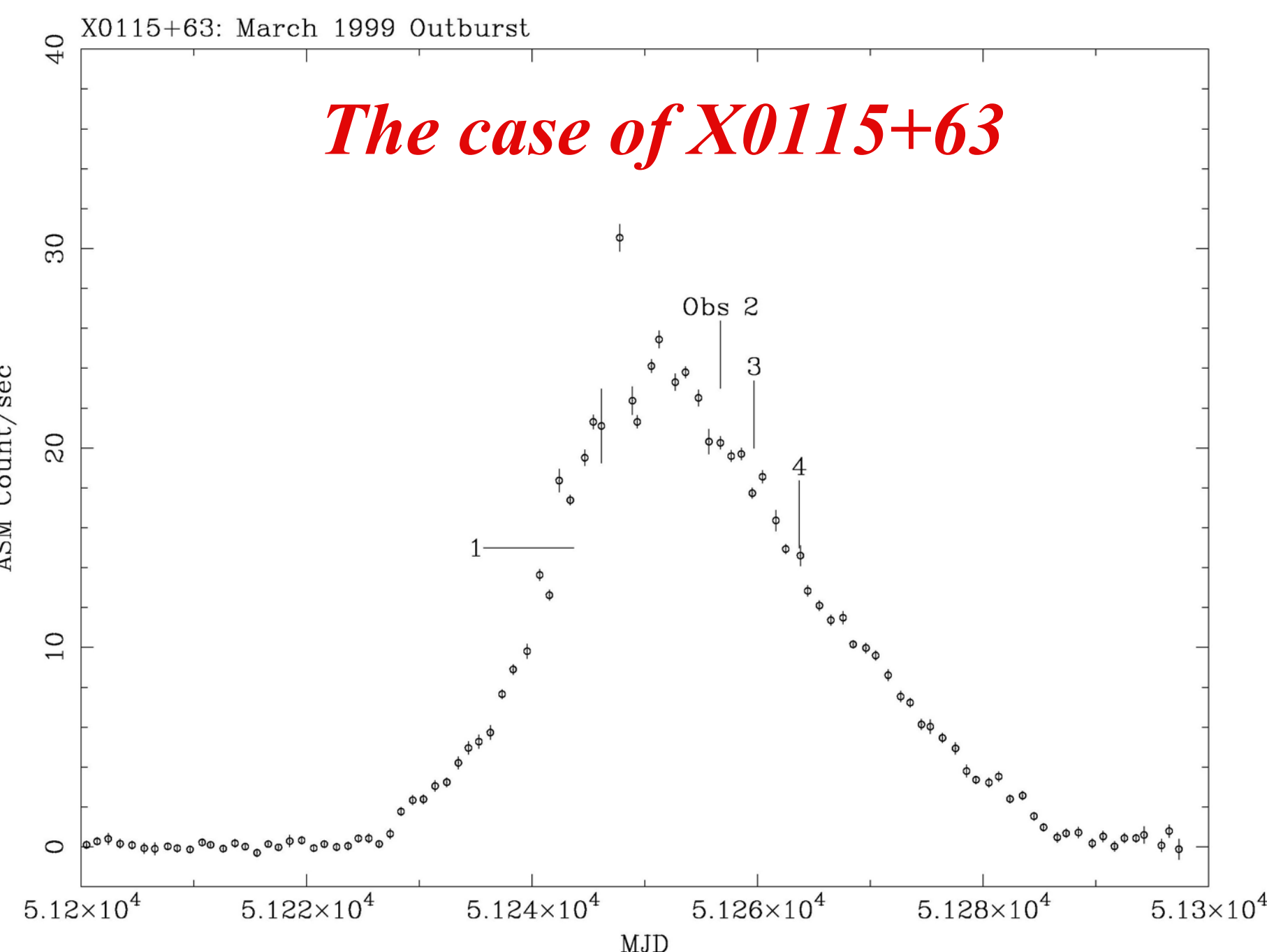
Orlandini et al., 2004

Cen X-3

4U1907+09

4U1626-67 (?)

VELA X-1 (!?)


X0115+63: March 1999 Outburst
The case of X0115+63
ASM Count/sec
0
10
20
30
40
Obs 2
3
4
1
5.12×10^4
5.122×10^4
5.124×10^4
5.126×10^4
5.128×10^4
5.13×10^4
MJD

DISCOVERY OF A THIRD HARMONIC CYCLOTRON RESONANCE SCATTERING FEATURE IN THE X-RAY SPECTRUM OF 4U 0115+63

W. A. HEINDL, W. COBURN, D. E. GRUBER, M. R. PELLING, AND R. E. ROTHSCHILD
er for Astrophysics and Space Sciences, Code 0424, University of California, San Diego, La Jolla, CA 92093; wheindl@ucsd.edu
AND
J. WILMS, K. POTTSCHMIDT, AND R. STAUBERT
itut für Astronomie und Astrophysik–Astronomie, University of Tübingen, Waldhäuser Strasse 64, D-72076 Tübingen, Germany
Received 1999 April 14; accepted 1999 June 8; published 1999 July 6

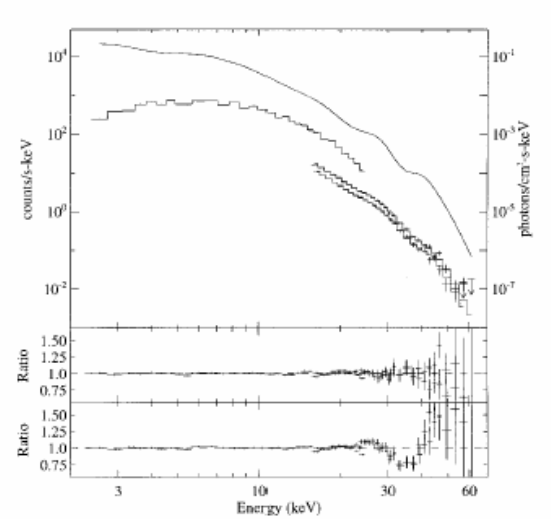
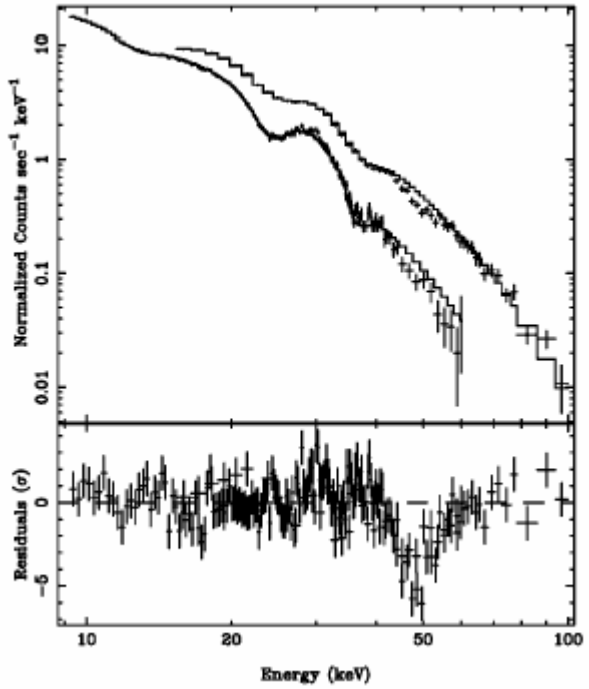


FIG. 3.—*Top:* PCA and HEXTE count spectra (*plus signs*) for pulse phase 0.70–0.76. Also shown are the best-fit model (*histograms*) with three CRSFs and the inferred incident spectrum (*smooth curve*). *Middle:* Ratio of the data to the best-fit model. *Bottom:* Ratio of the data to a model fit with only two CRSFs. The residuals between 30–40 keV and the underprediction of the continuum above 40 keV emphasize the presence of the third line.

THE ASTROPHYSICAL JOURNAL, 521:L49–L53, 1999 August 10

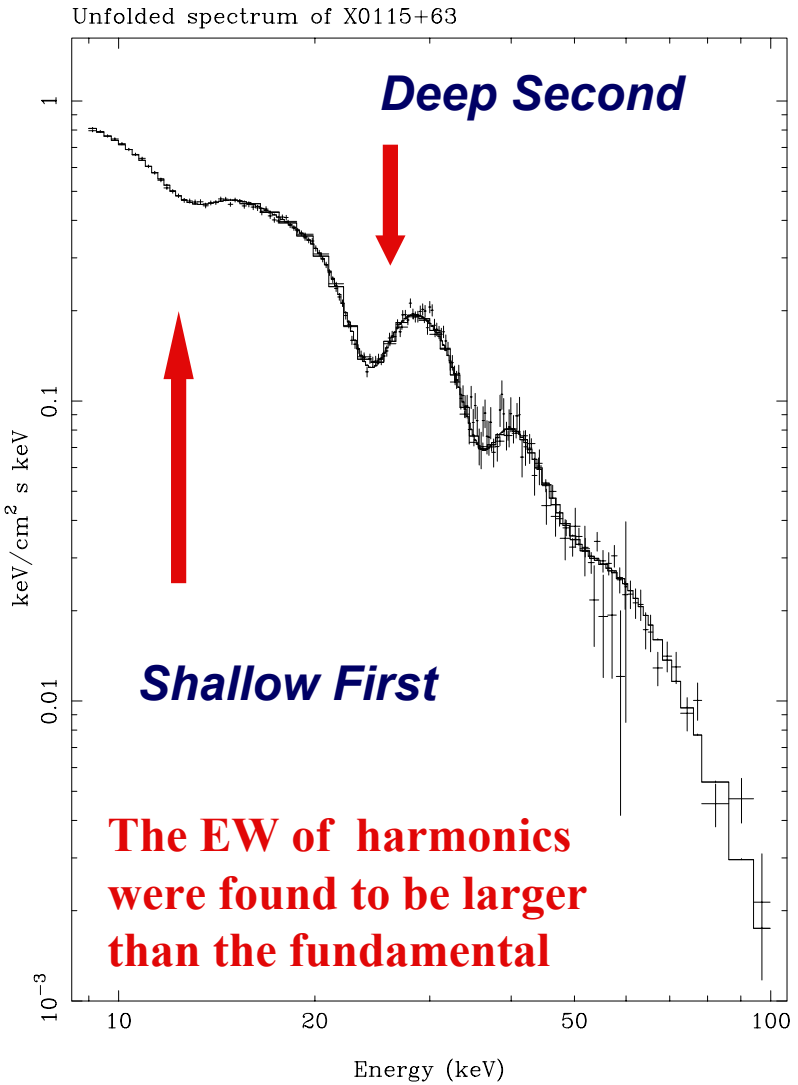
A *BEPPOSAX* STUDY OF THE PULSATING TRANSIENT X0115+63: THE FIRST X-RAY SPECTRUM WITH FOUR CYCLOTRON HARMONIC FEATURES

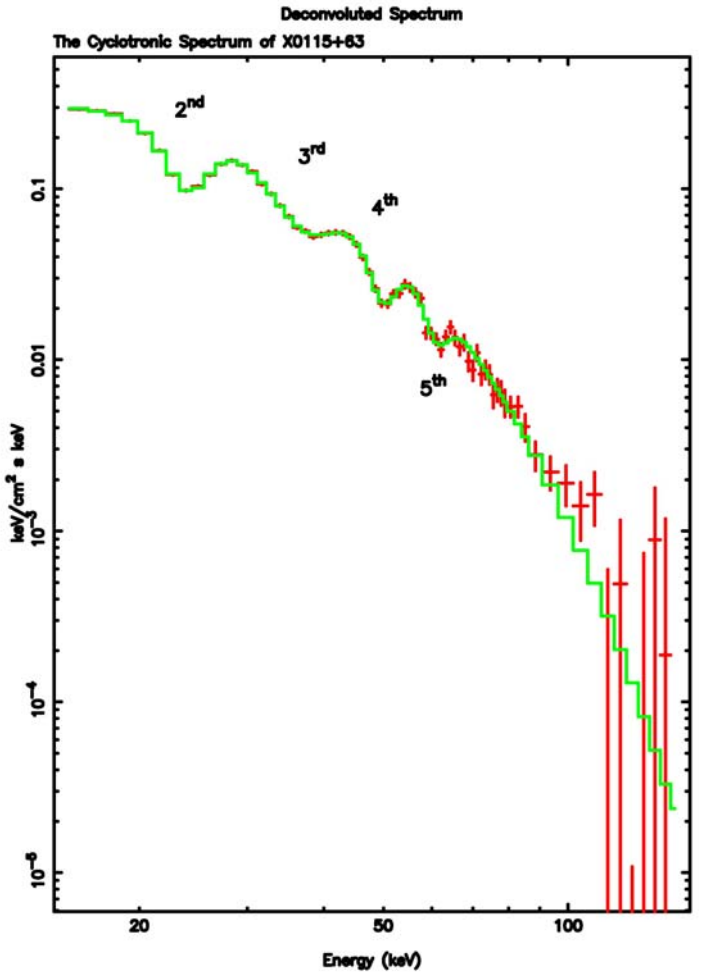
A. SANTANGELO,[1] A. SEGRETO,[1] S. GIARRUSSO,[1] D. DAL FIUME,[2] M. ORLANDINI,[2] A. N. PARMAR,[3] T. OOSTERBROEK,[3] T. BULIK,[4] T. MIHARA,[5] S. CAMPANA,[6] G. L. ISRAEL,[7] AND L. STELLA[7]
Received 1999 April 27; accepted 1999 July 12; published 1999 August 17



THE ASTROPHYSICAL JOURNAL, 523:L85–L88, 1999 September 2

Harmonic ratios 1:(1.9±0.05):(2.8±0.05):(3.9±0.1)





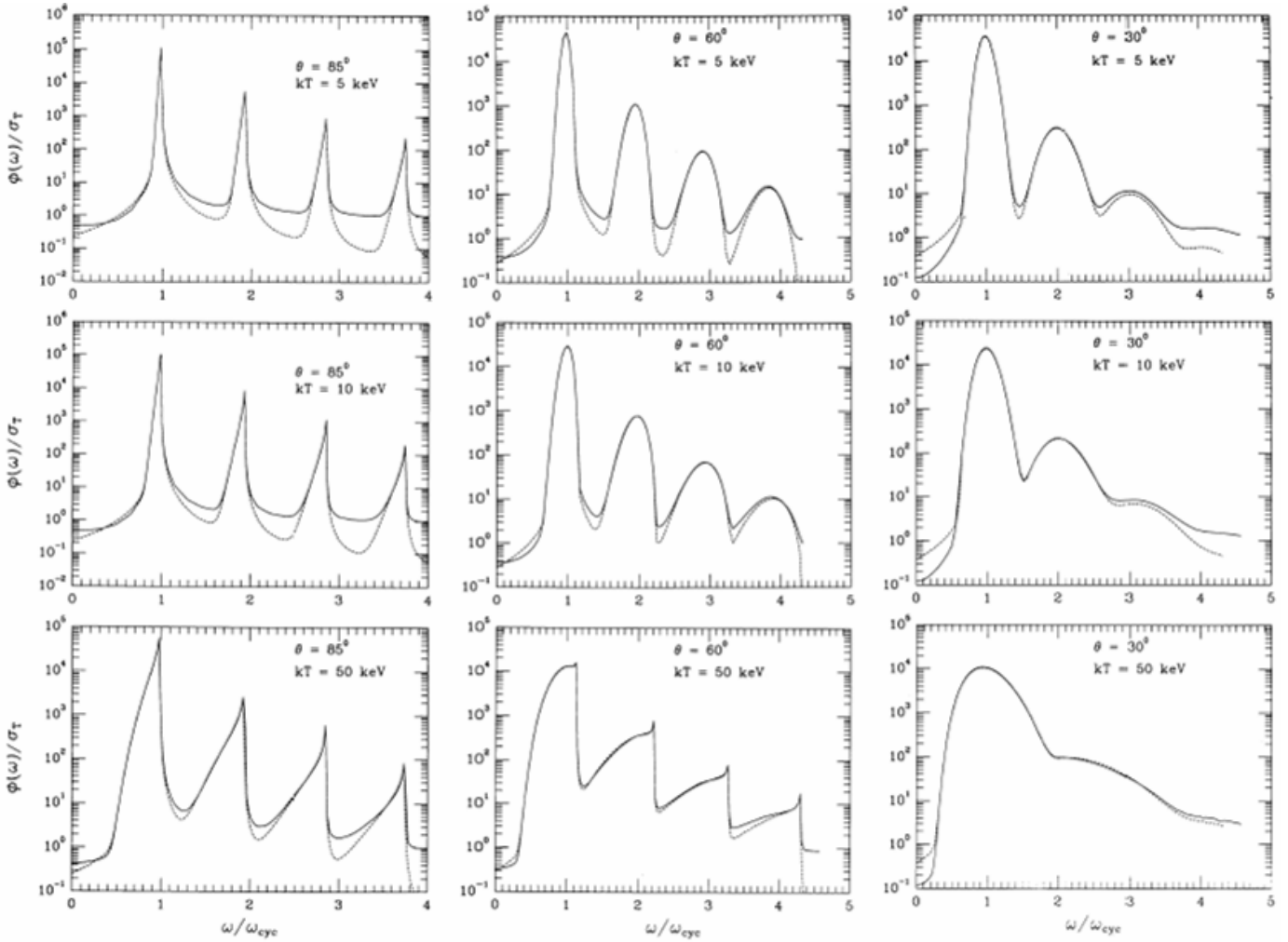
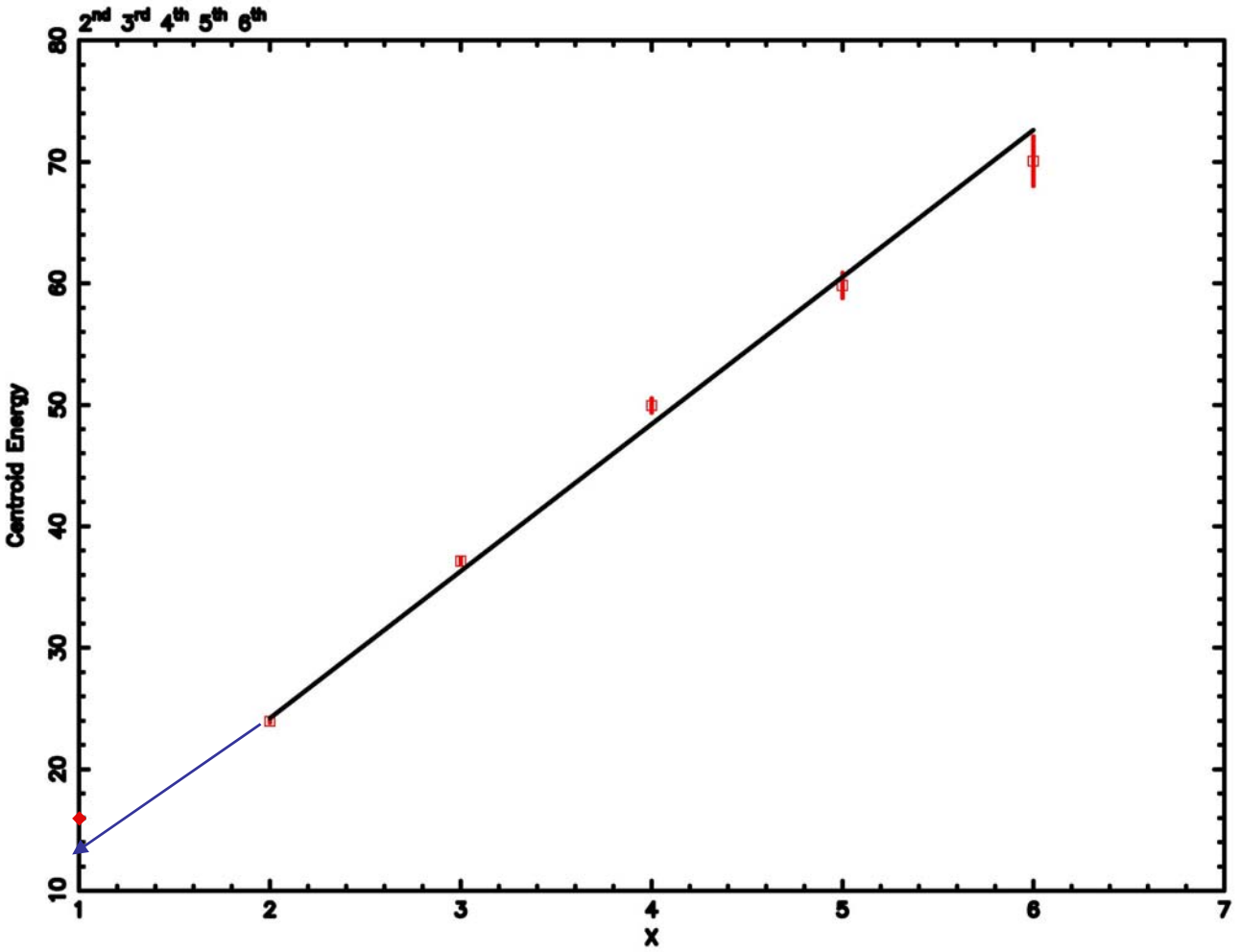


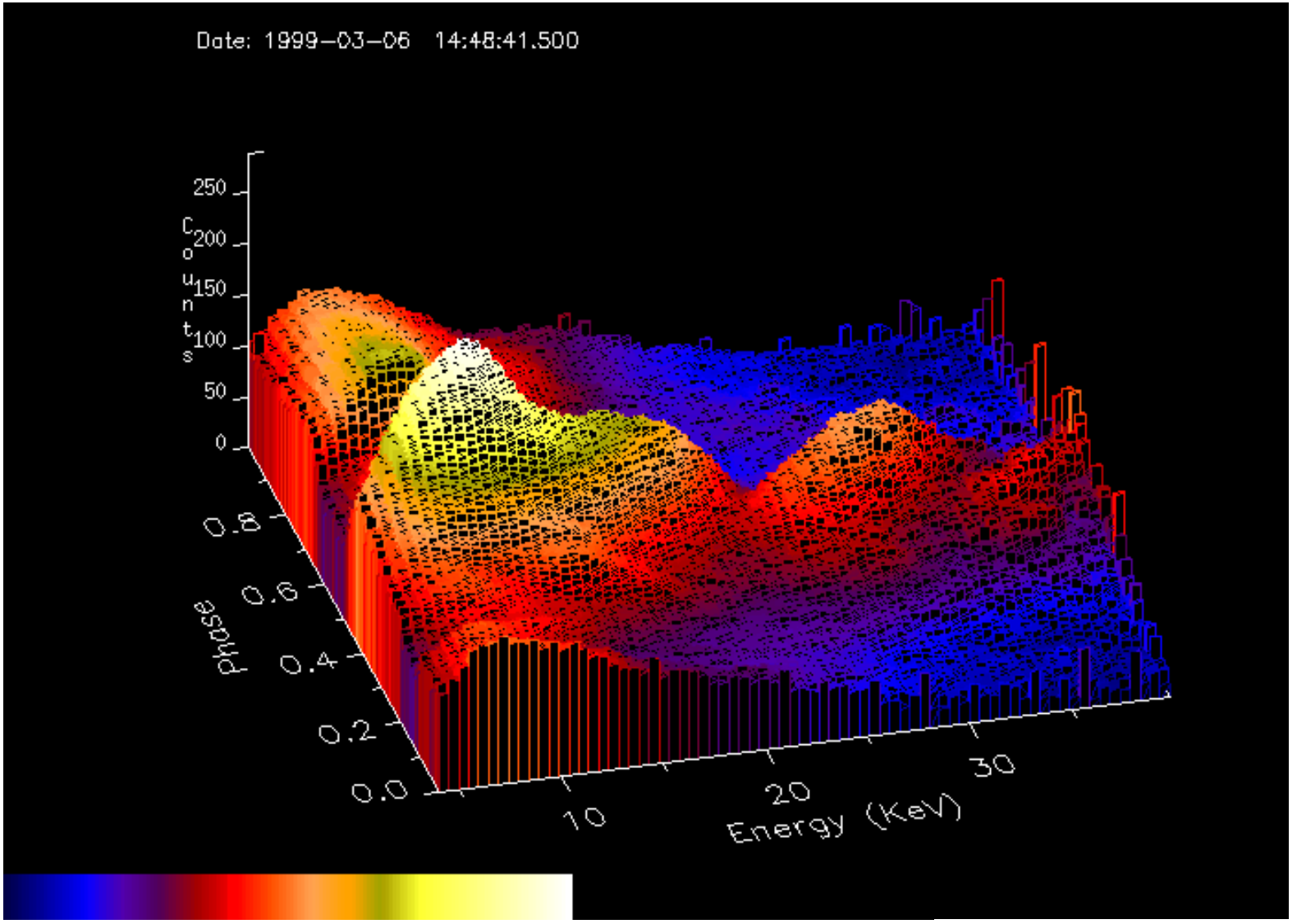
FIG. 5.—Scattering (*solid line*) and absorption (*dashed line*) profiles, $\phi(\omega, \mu)$, in units of the Thomson cross section at various photon angles, θ, and electron parallel temperatures, kT, for a magnetic field strength $B = 1.7 \times 10^{12}$ G.

Harding & Daugherty et al., ApJ 374, 687 (1991)

The issue of linearity



Phase Resolved spectroscopy X0115+063



(Isenberg et al., 1998 Araya & Harding, 1996, 1999)

Alxander & Mészáros, ApJ 372, 565 (1991)

Araya & Harding, ApJ 517, 334 (1999)

Araya & Harding, ApJ 544, 1067 (2000)

Relativistic cyclotron spectra from internally irradiated atmospheres assuming magnetic Compton (one and multiple photon) scattering.

Raman-Landau Photon spawning

TABLE 2

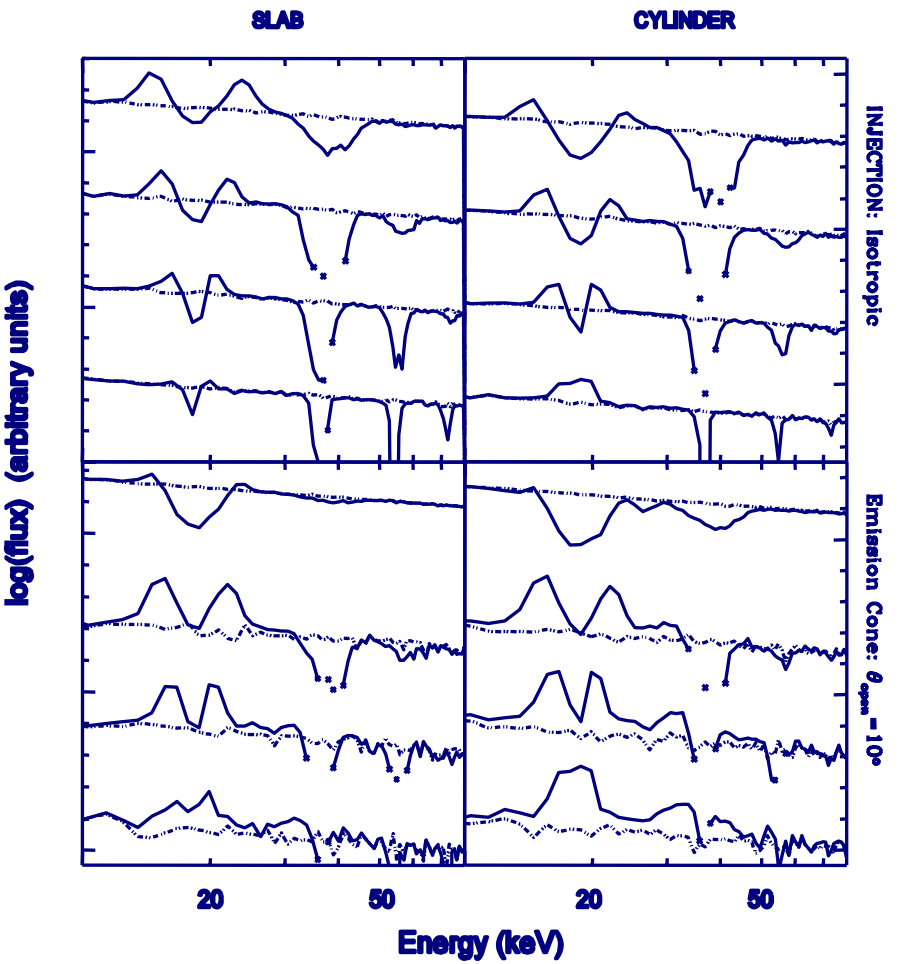
RELATIVE NUMBER OF SPAWNED FUNDAMENTAL PHOTONS[a]

$\tau_c[\times 10^{-3}]$	0.1	0.3	1.0	3.0
$N_{sp}^{sl}/\{N_{inj}+N_{sp}\}$	10%	16%	23%	32%
$N_{sp}^{cy}/\{N_{inj}+N_{sp}\}$	7%	12%	19%	28%

[a] As a function of optical depth and geometry for a field $B' = 0.04$. The superscript refers to slab and cylindrical geometries.

Relativistic angular distribution

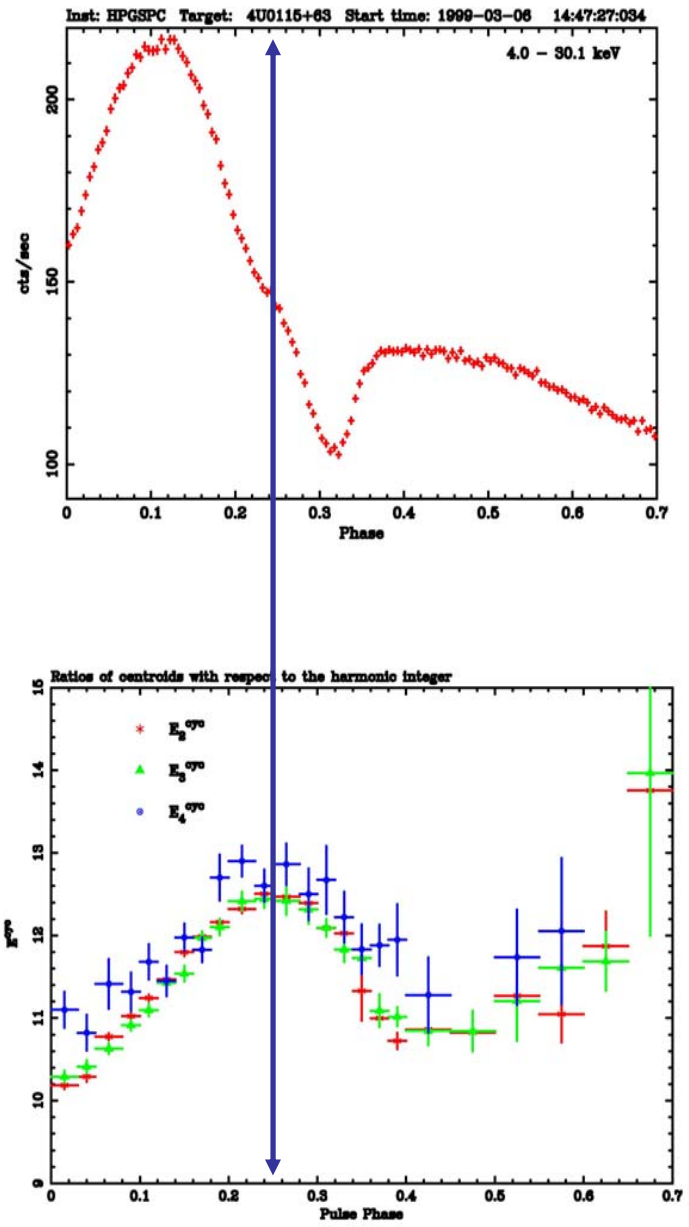
$$\omega_{nn'} = \frac{2(n-n')\,\omega_c\, mc^2}{E_\pi(1+\sqrt{1-2x})} \quad \text{with} \quad x = \frac{(n-n')(\hbar\omega_c)\sin^2\theta}{E_\pi^2/mc^2}.$$



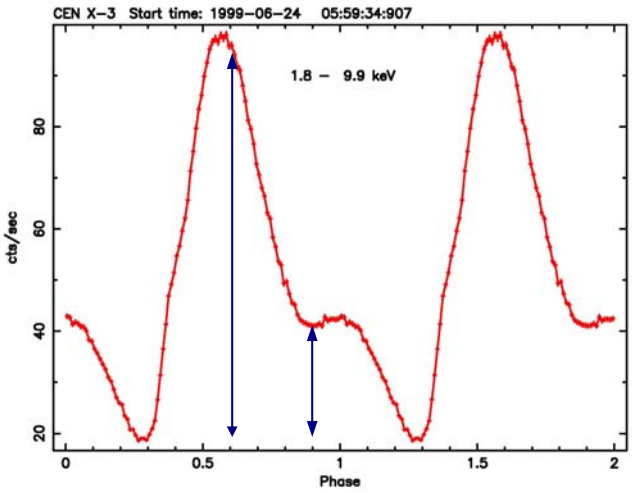
The “peak” of field phase-distribution is phase shifted with respect to the flux peak

Evidence of the complex non-dipole structure of the magnetic field:

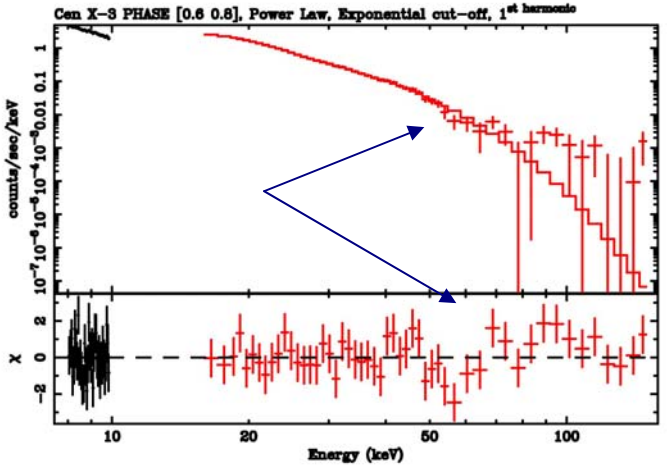
Magnetic field non axisymmetric



Is X0115+63 a unique case ?



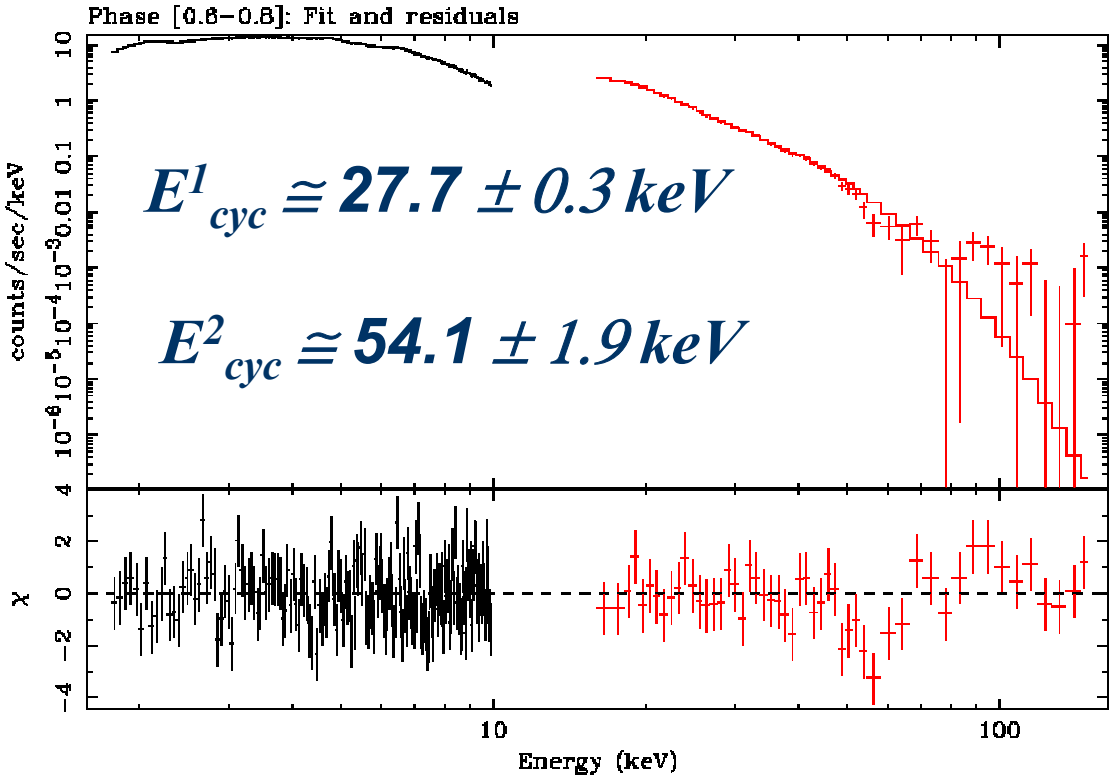
Cyclotron Scattering Second Harmonic in Cen X-3



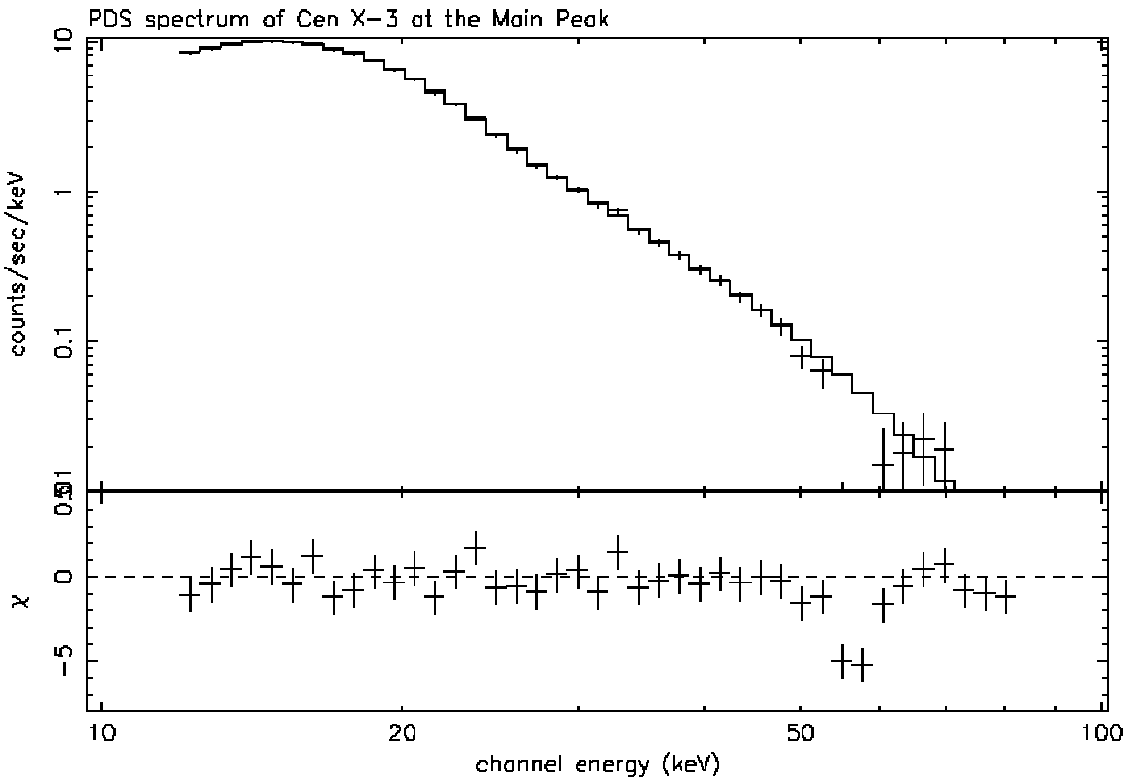
$E^1_{cyc} \cong 27.7 \pm 0.3\,keV$

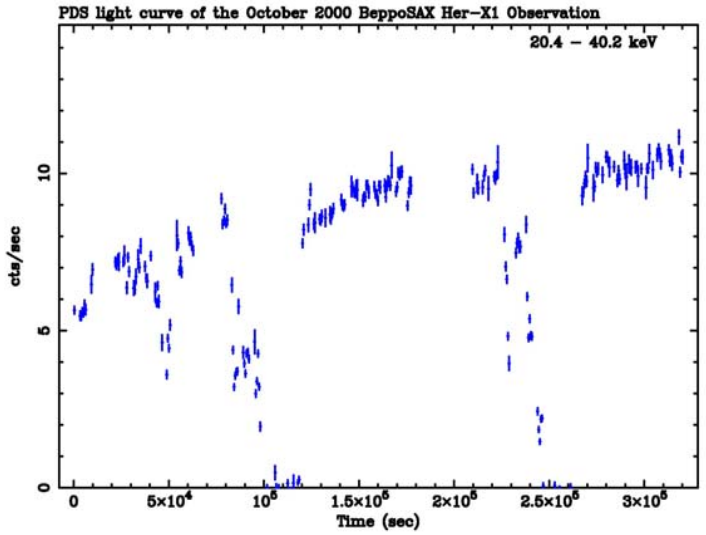
$E^2_{cyc} \cong 54.1 \pm 1.9\,keV$

Cen X-3: 1999 Observation



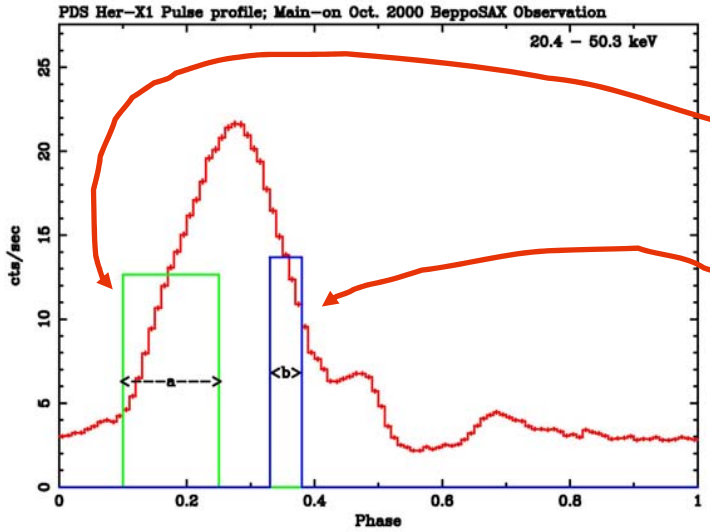
'97 Observation





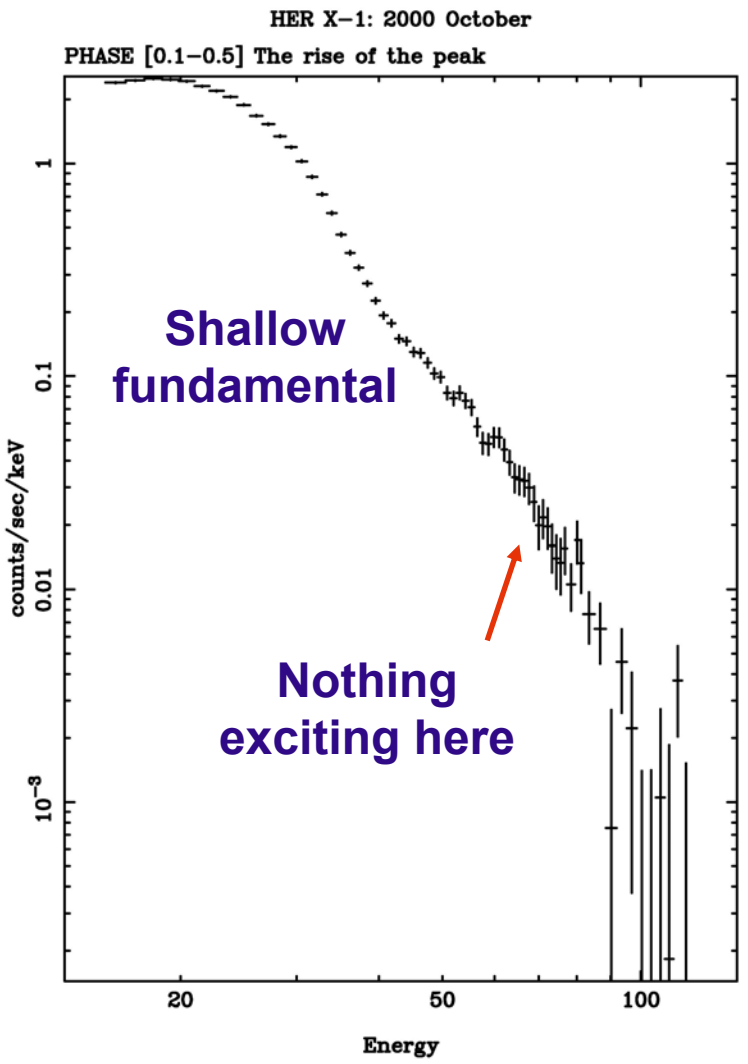
Her X-1 was observed by BeppoSAX on October 2000

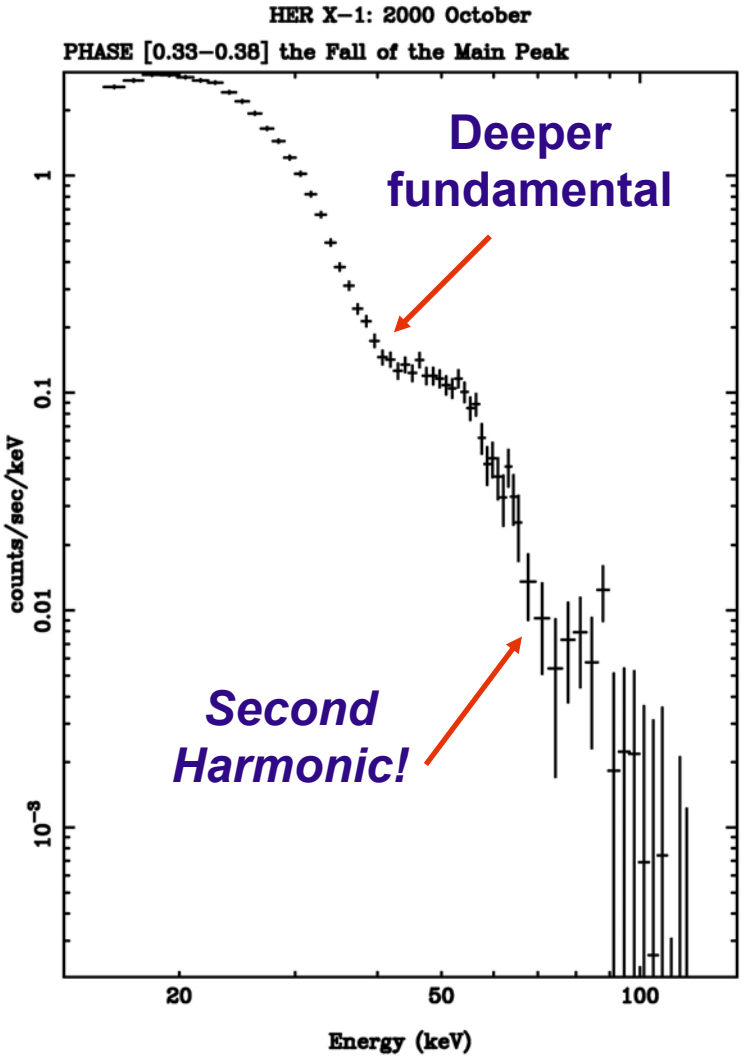
BeppoSAX observed the first "main on" state after an extended low state that last almost two years

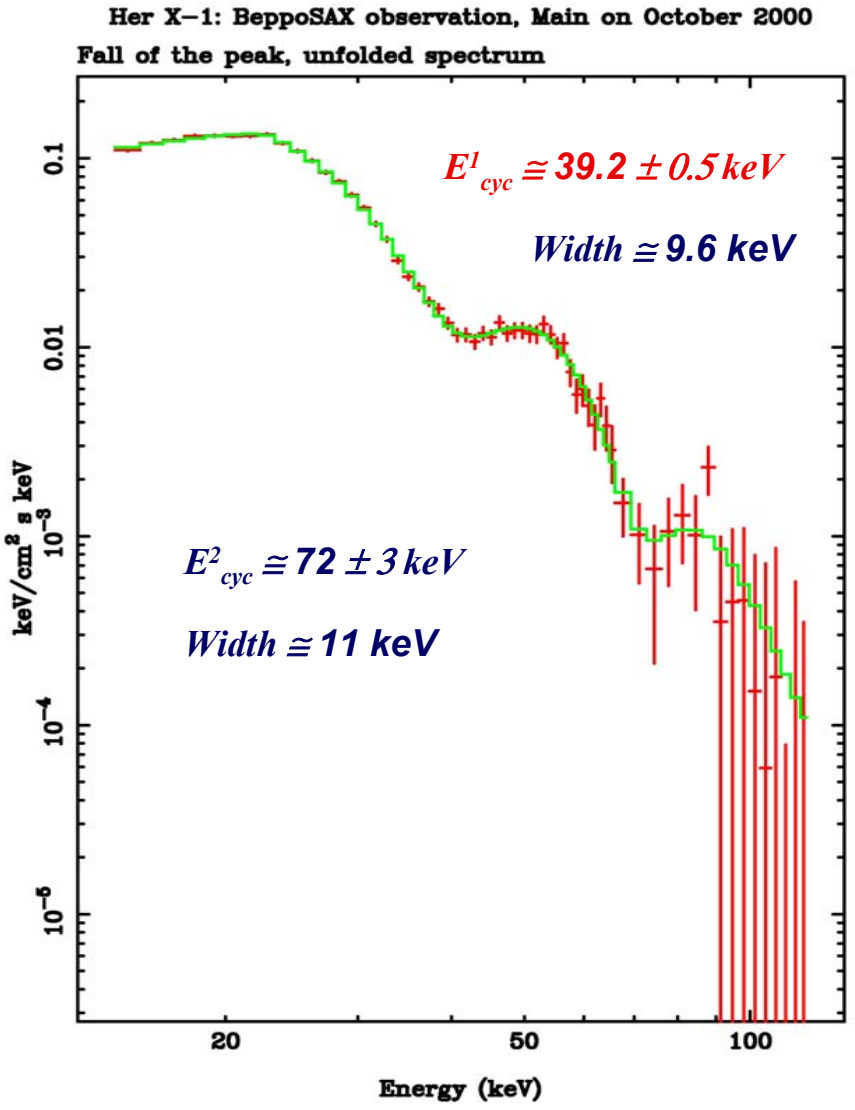


Pulse profile were apparently not very different from other observations. Evidence for spin down.

The source was bright → We searched for features in the rising and falling edge of the main peak pulse…

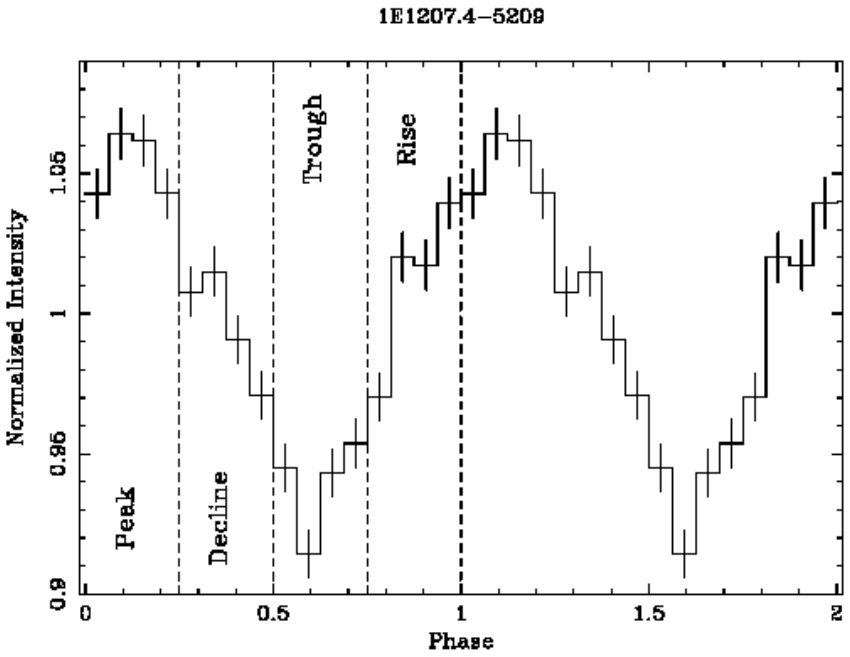

HER X−1: 2000 October
PHASE [0.1−0.5] The rise of the peak
Shallow fundamental
Nothing exciting here
counts/sec/keV
1
0.1
0.01
10^{-3}
20
50
100
Energy


HER X−1: 2000 October
PHASE [0.33−0.38] the Fall of the Main Peak
Deeper fundamental
Second Harmonic!
counts/sec/keV
1
0.1
0.01
10^{-3}
20
50
100
Energy (keV)


Her X−1: BeppoSAX observation, Main on October 2000
Fall of the peak, unfolded spectrum
$E^1_{cyc} \cong 39.2 \pm 0.5$ keV
Width ≅ 9.6 keV
$E^2_{cyc} \cong 72 \pm 3$ keV
Width ≅ 11 keV
keV/cm² s keV
Energy (keV)
0.1
0.01
10⁻³
10⁻⁴
10⁻⁵
20
50
100

DISCOVERY OF X-RAY CYCLOTRON ABSORPTION LINES MEASURES THE MAGNETIC FIELD OF AN ISOLATED NEUTRON STAR

Bignami et al, 2003

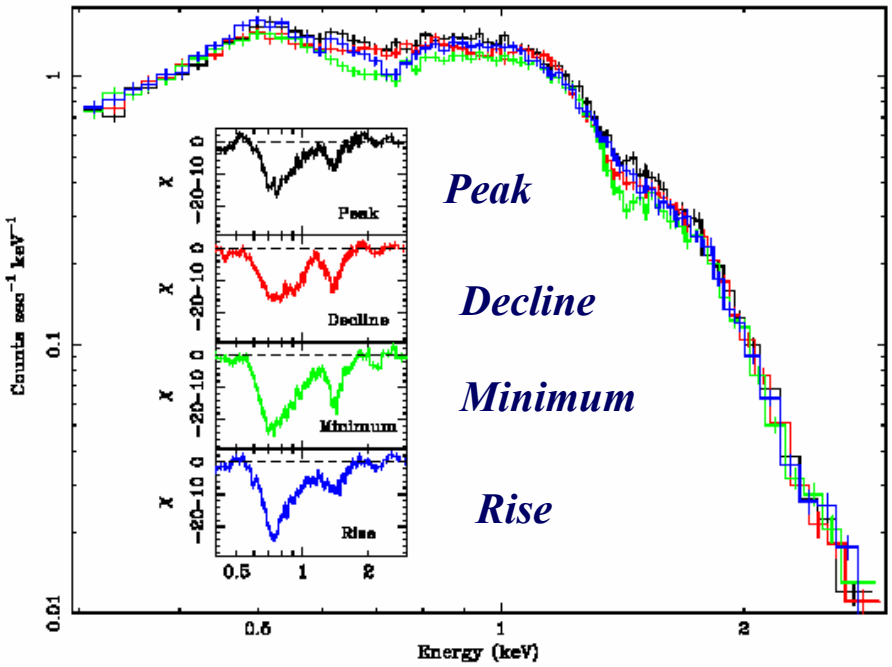


If due to electron CRSF →

$B \sim 8\times10^{10}$ G

Not in agreement with →

$B \sim 2\text{-}3\times10^{12}$ G rotating dipole hypothesis

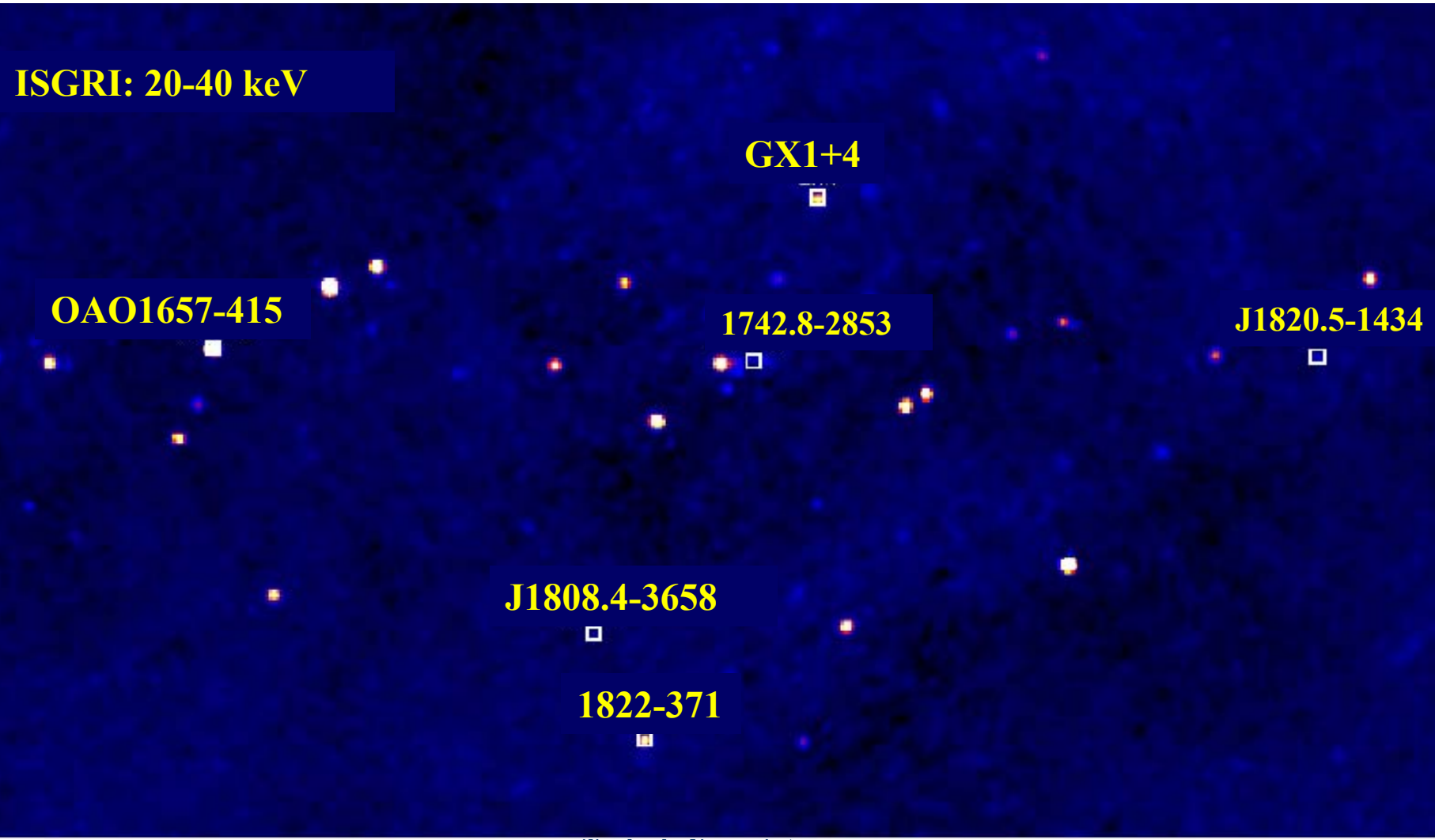


275 ks observaton of XMM

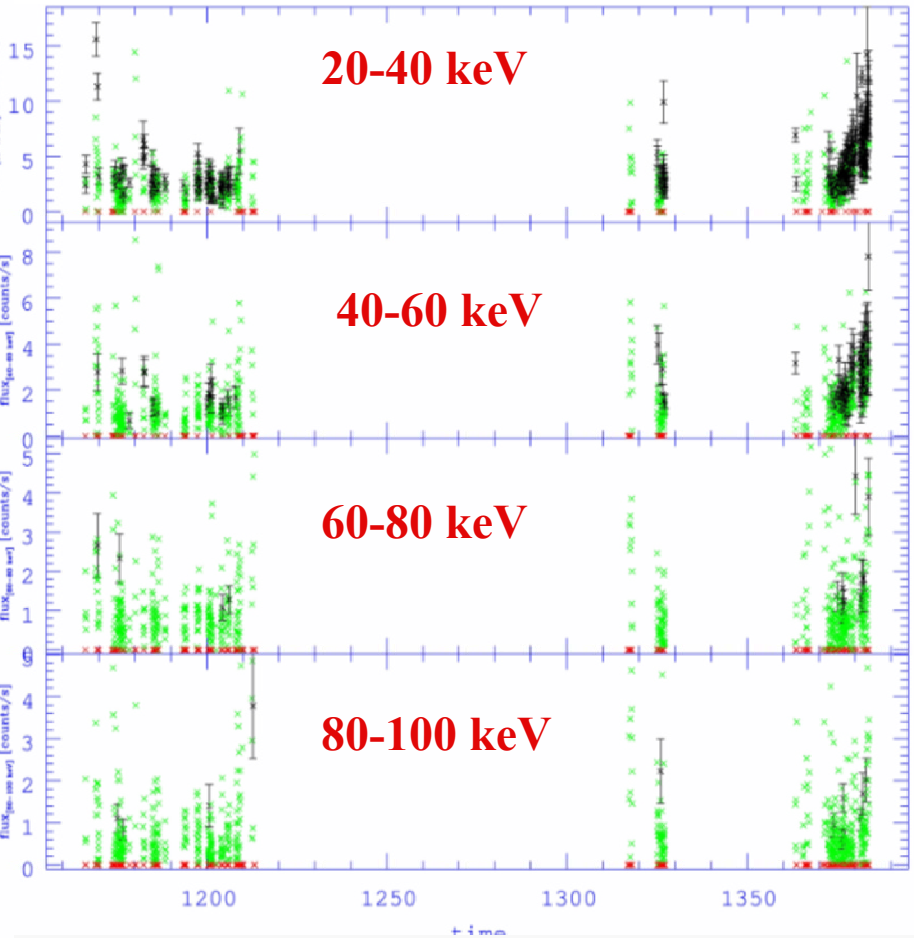
Evidence for three phase dependent regularly spaced absorption-like features →

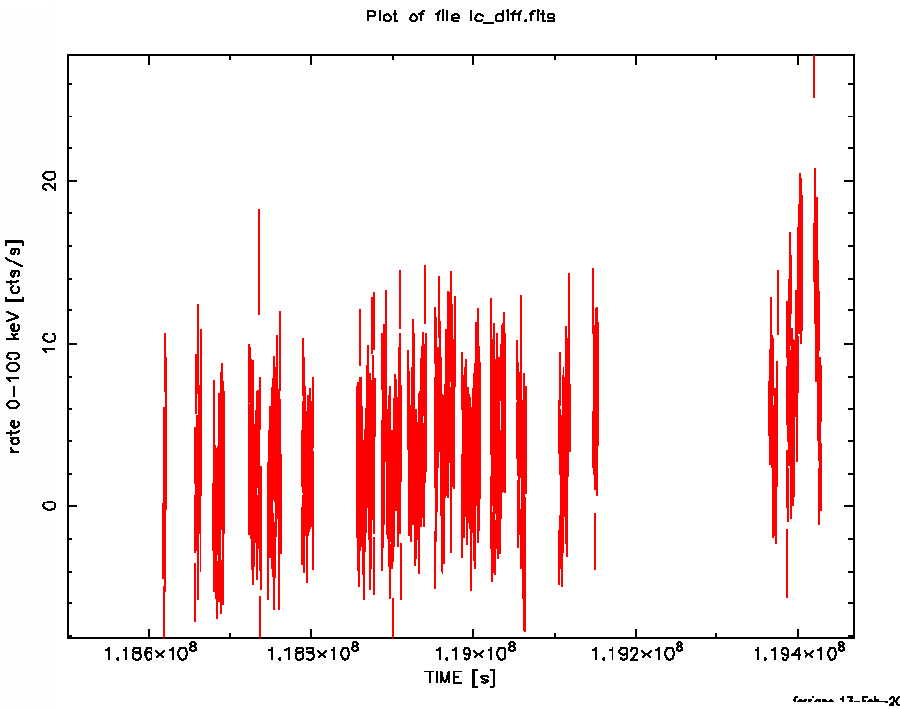
~0.7, 1.4, 2.1 keV

AXRPs in the Galactic Center



Light Curve of GX 1+4





600 ks observation during GCDE

$Flux_{2\text{-}100\ keV} \sim 10$mCrab

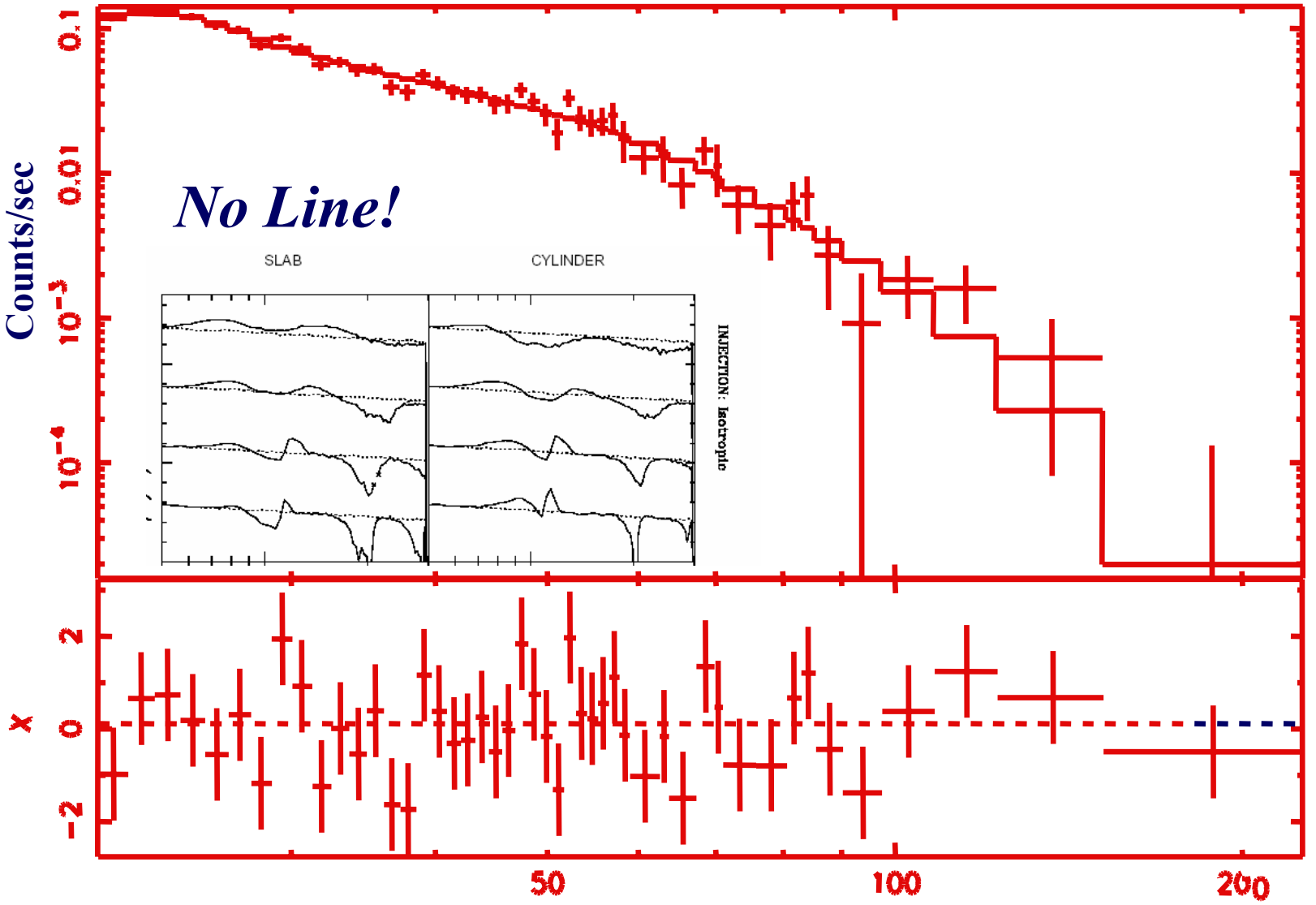
Flare ⇓

$Flux_{2\text{-}100\ keV} \geq 100$ mCrab

C. Ferrigno et al., 2004, in prep.

Galloway et al., MNRS 311, 755 (2000)

The ISGRI 20-200 keV Spectrum of GX1+4



The flourishing of X-ray Astronomy continue…

- ASTRO E II (…to be launched in 2005, high res. Spectroscopy and high sensitivity at hard X-ray)
- MIRAX (Hard X-ray imaging, monitoring of the GC Region)
- DUO (All sky survey)
- Rosita (Wolter-I optics, CCD, All sky imaging survey)
- NeXT (New X-ray Telescope, Multy layer, CdTe Arrays)
- SIMBOL X (0.5-70 keV, fomation flight)
- HEXIT Sat new-generation (20-70 keV) telescopes based on focusing multilayer optics and high Z solid-state detectors.

XEUS

Summary

- BeppoSAX and RXTE have revealed multiple harmonics in a number of AXRBPs, thus suggesting the presence of higher harmonic(s) as a possible common feature
- The discovery of the "cyclotronic" spectrum of 4U0115+63 is providing the observational base to check theorethical models of AXRBPs emission and line production
  - Role of multiple photon scattering
  - Emission geometry (slab vs. cylinder)
  - Relativistic kinematics
- Though Integral will contribute to the field, the next generation of X-ray observatories is expected to produce a real breakthrough