Cyclotron absorption features in neutron star systems observed by INTEGRAL

Wei Wang

National Astronomical Observatories, Beijing, China

Cosmic magnetism, Kiama June 7 2010

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- Magnetic fields in neutron stars
- History of observing cyclotron line features
- Cyclotron absorption lines detected by INTEGRAL

  confirm previous known:

  Vela X-1; Her X-1; V0332+53; A0535+26

  new candidates:

  4U 2206+54; 2S 0114+65; IGR J01583+6713

Magnetic fields in Neutron stars

- Magnetic fields of pulsars

  indirect ways:

Assuming a magnetic dipole with measurements of spin period P and derivative of P, surface magnetic field given by

$$B_s = 3 \times 10^{19} (P\dot{P})^{\frac{1}{2}} \ G$$

then we find three classes of pulsars:

normal pulsars: P=30ms – 9 s , Bs = 10^{12} -10^{13} G ;

millisecond pulsars: P=1.3 – 20 ms, Bs=10^{8}-10^{9} G ;

magnetars : P=5-12 s, Bs =10^{14}-10^{15} G

- Magnetic flux conservation assumption

neutron star formation from massive star collapse

$R^2_{NS} B_{NS} = R^2_i B_i$

some magnetic stars with $B_{star} = 10^3$ G

then from flux conservation

$B_{NS} = 10^3 (600000/10)^2 = 3.6 \times 10^{12}$ G

many magnetic white dwarfs discovered, $B_{wd} = 10^{6\text{-}8}$ G

neutron stars may form from accretion induced collapse WD

$B_{NS} = 10^{6\text{-}8} (6000/10)^2 = 3.6 \times 10^{11\text{-}13}$ G

- A direct way:

cyclotron resonance scattering features (CRSF)

photons being resonantly scattered by electrons/protons out of the observers line of sight.

electron/proton energy are quantized into Landau levels, so energy of cyclotron line is a direct measure of magnetic field strength in the scattering region.

$$E_n = n\frac{\hbar eB}{m} = n \bullet 11.6\frac{B}{10^{12}\,G} keV\,(\,f\ or\ electron\,)$$

on surface of neutron star, observed energy has gravity redshift (1+z) =1.3

$$E_n^{obs} = n\frac{11.6}{1+z}\frac{B}{10^{12}\,G} keV$$

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Electron cyclotron line measurements:

If B =10^{12-13} G , observed E_1 = 8-80 keV

High energy space-based telescope required !

Proton line or electron line ?

10keV if electron case ⇨ B = 1.2×10^{12} G

if proton case ⇨ B = 2.4×10^{15} G

For finding Magnetars B = 10^{14-15} G

electron case E_1= 0.8 -8 MeV (difficult to detect)

proton case E_1 = 0.4 – 4 keV (contaminations with atomic lines)

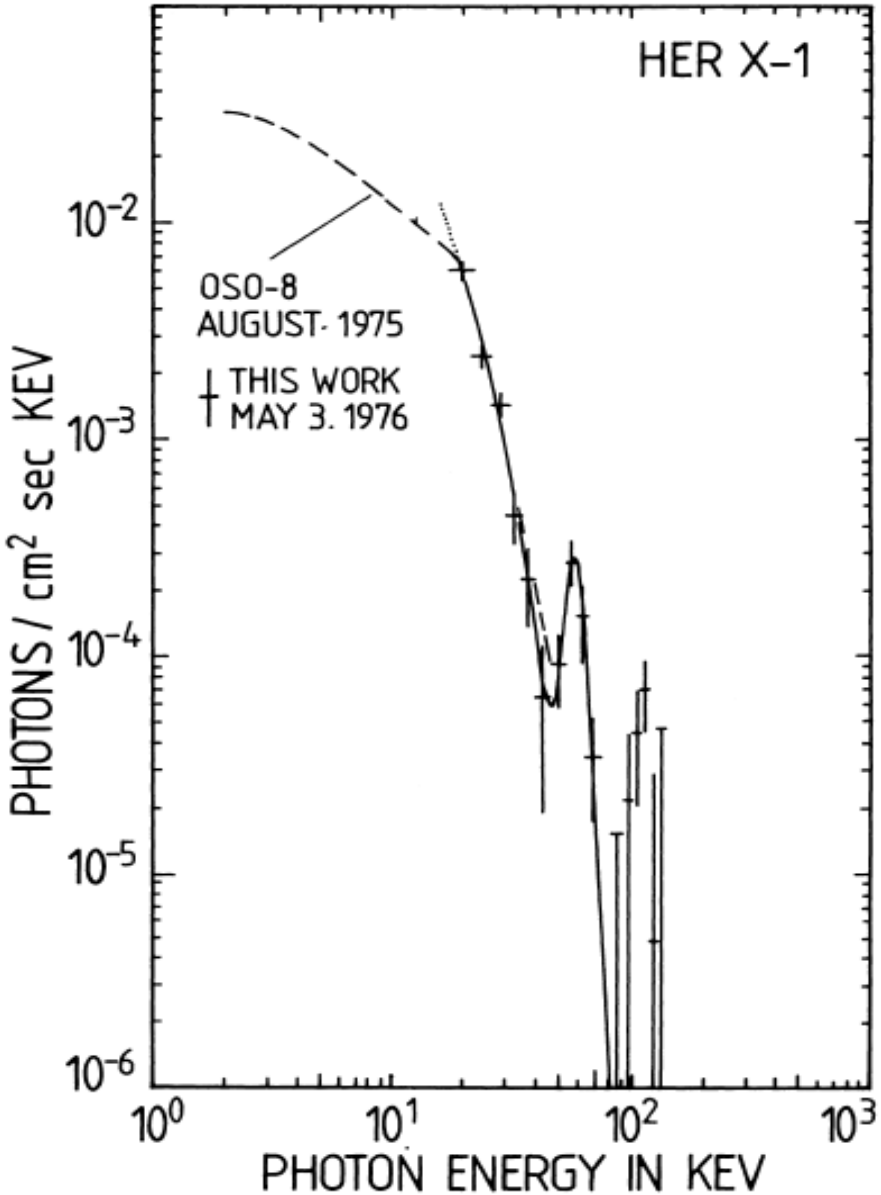
History

The first cyclotron line in neutron star system observed by a balloon flight (10 hours in 1976):

Her X-1
(Truemper et al. 1977; 1978)

Originally they thought lines were emission lines at 58 keV and 110 keV

Now the absorption line features at 42 keV and 80 keV were accepted.



History

- Pair lines in 4U 0115+63 (12/24 keV) by HEAO-1 (White et al. 1983)
- Ginga era (1990s):

  more new cyclotron line discoveries

  Cep X-1 (30 keV), 4U 1538-52 (20 keV), 4U 1907+09 (21 keV), V0332+53 (27 keV), Vela X-1 (25/50 keV , GX 301-2 (35 keV)
- A 0535+26 (1995) : 50 keV by MIR/TMM and HEXE ; 110 keV by CGRO/OSSE

History

- 1996, both RXTE and BeppoSAX were launched.

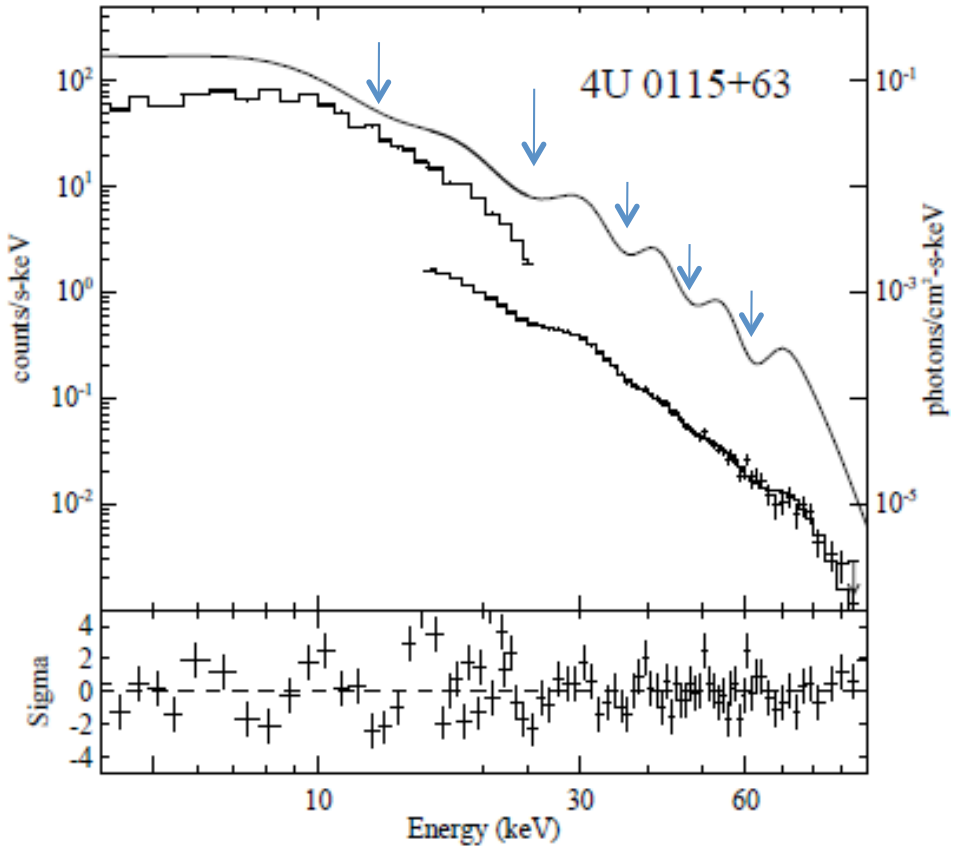
  new discoveries of cyclotron lines:
  4U 1626-67 (40 keV), Cen X-3 (30 keV),
  XTE J1946+274 (36 keV), X Per (30 keV),
  LMC X-4 (100 keV), OAO 1657-415 (36 keV),
  4U 1700-37 (37 keV), 1M 0656-072 (36 keV)

  higher harmonics in known sources:

  4U 0115+63 (5 harmonics), Her X-1,

  4U1907+09, 4U 1538-52,

  V 0332+53 (3 harmonics)



4U 0115+63

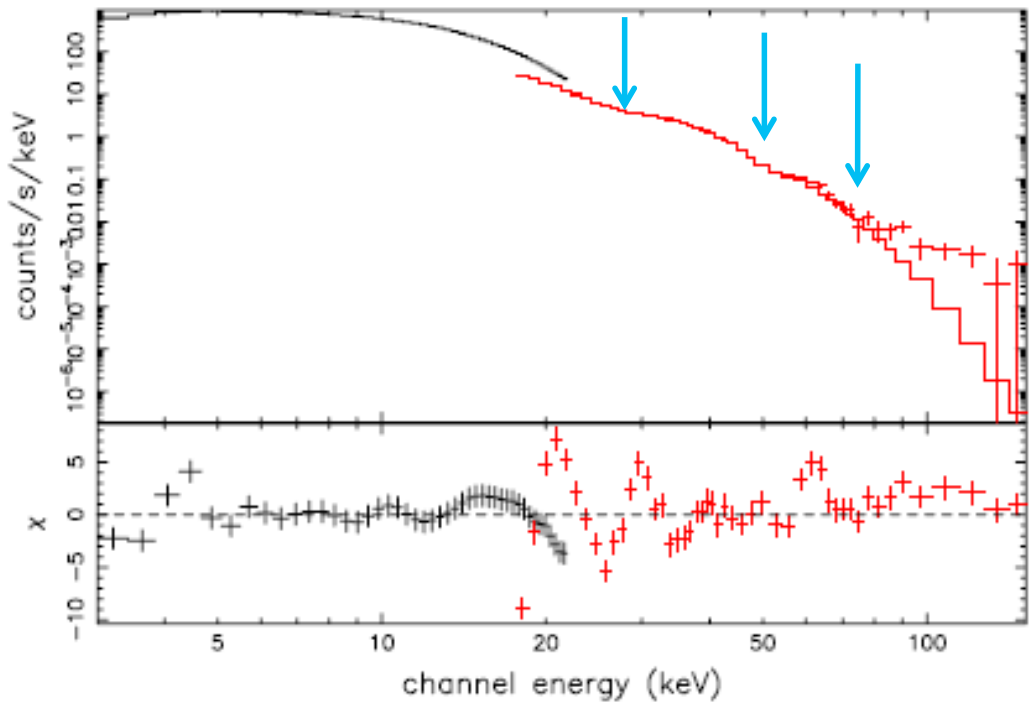
The spectrum in one pulse phase
(Heindl et al. 2000)

5 lines fitted:
13, 24, 36, 48, 62 keV

V 0332+53

The spectrum in an outburst
during 2004 Nov
3 lines:
27 keV, 54 keV, 80 keV

(Coburn et al. 2006)



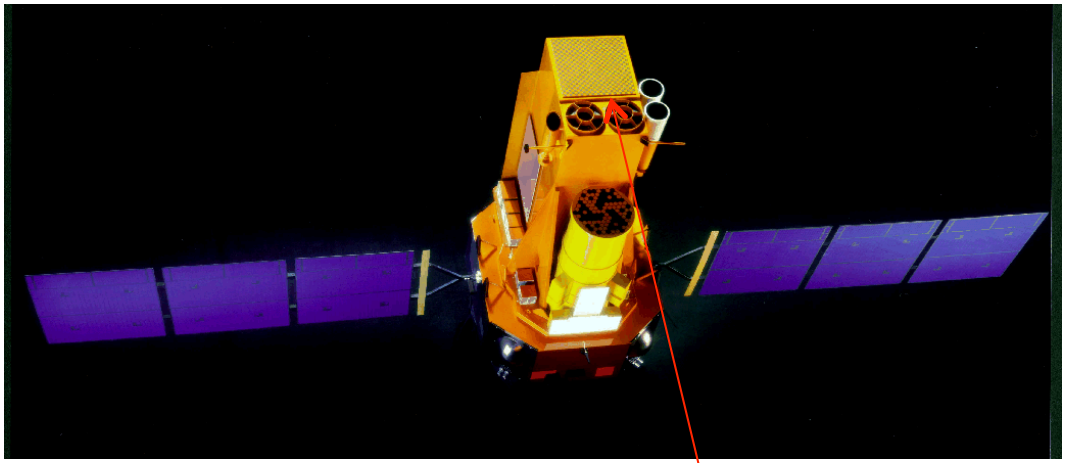
INTEGRAL observations

- The INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) is an European (ESA) Gamma-Ray Observatory Satellite Mission for the study of cosmic gamma-ray sources in the keV to MeV energy range.

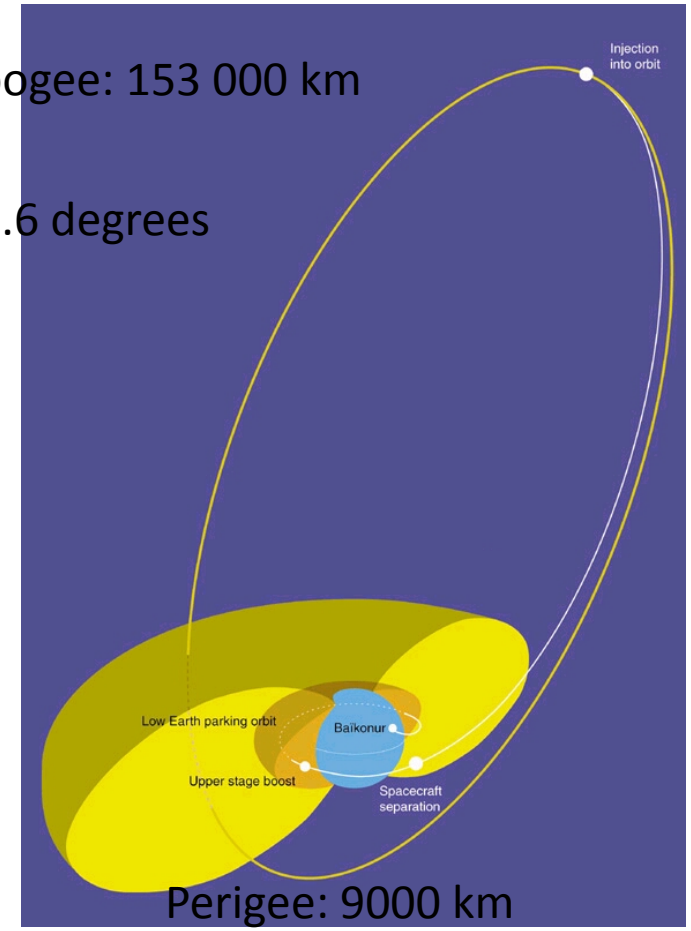
Launch Date: October 17th 2002
Launch Mass: 4000 kg
Orbit Period: 72 hours

Apogee: 153 000 km

Inclination: 52.6 degrees

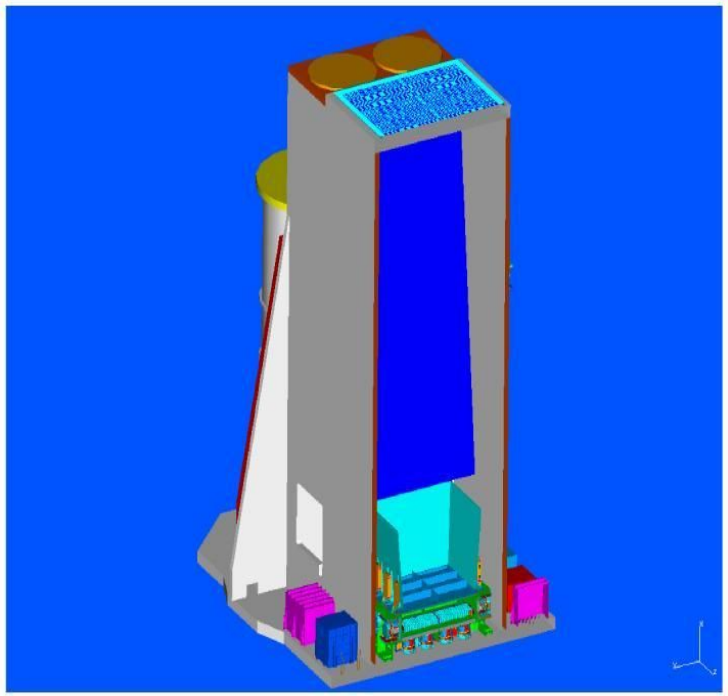


Soft gamma-ray imager IBIS



Perigee: 9000 km

The imager on-board INTEGRAL (IBIS) : Coded-mask imaging



Performance

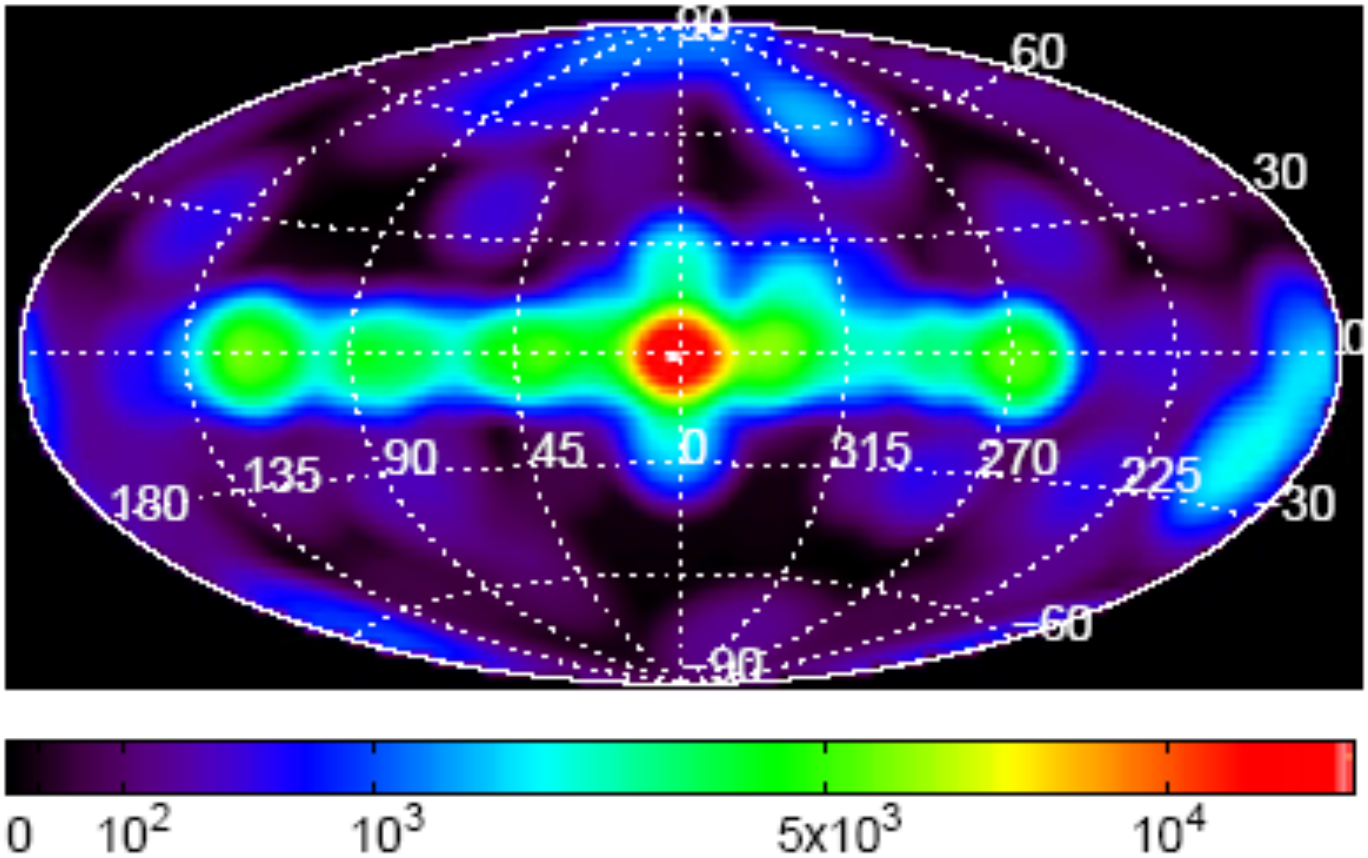
Energy range: 15 keV - 10 MeV
Detector area: 3000 cm^2
Spectral resolution: 9% @ 100 keV
Field of view: 9 x 9 deg
Angular resolution: 12 arcmin
Source Location: < 1 arcmin
Narrow-line sensitivity (10^6 s): 2.0 x 10^{-5} ph s^{-1} cm^{-2}
Continuum sensitivity (10^6s): 5 x 10^{-7} ph s^{-1} cm^{-2} keV^{-1}
Timing accuracy: 0.92 ms
Mass: 677 kg

Good angular resolution, high sensitivity, spectral resolution in 16 – 100 keV

→ **ability to search for cyclotron line features**

Present exposure map of INTEGRAL all-sky surveys (early 2010)

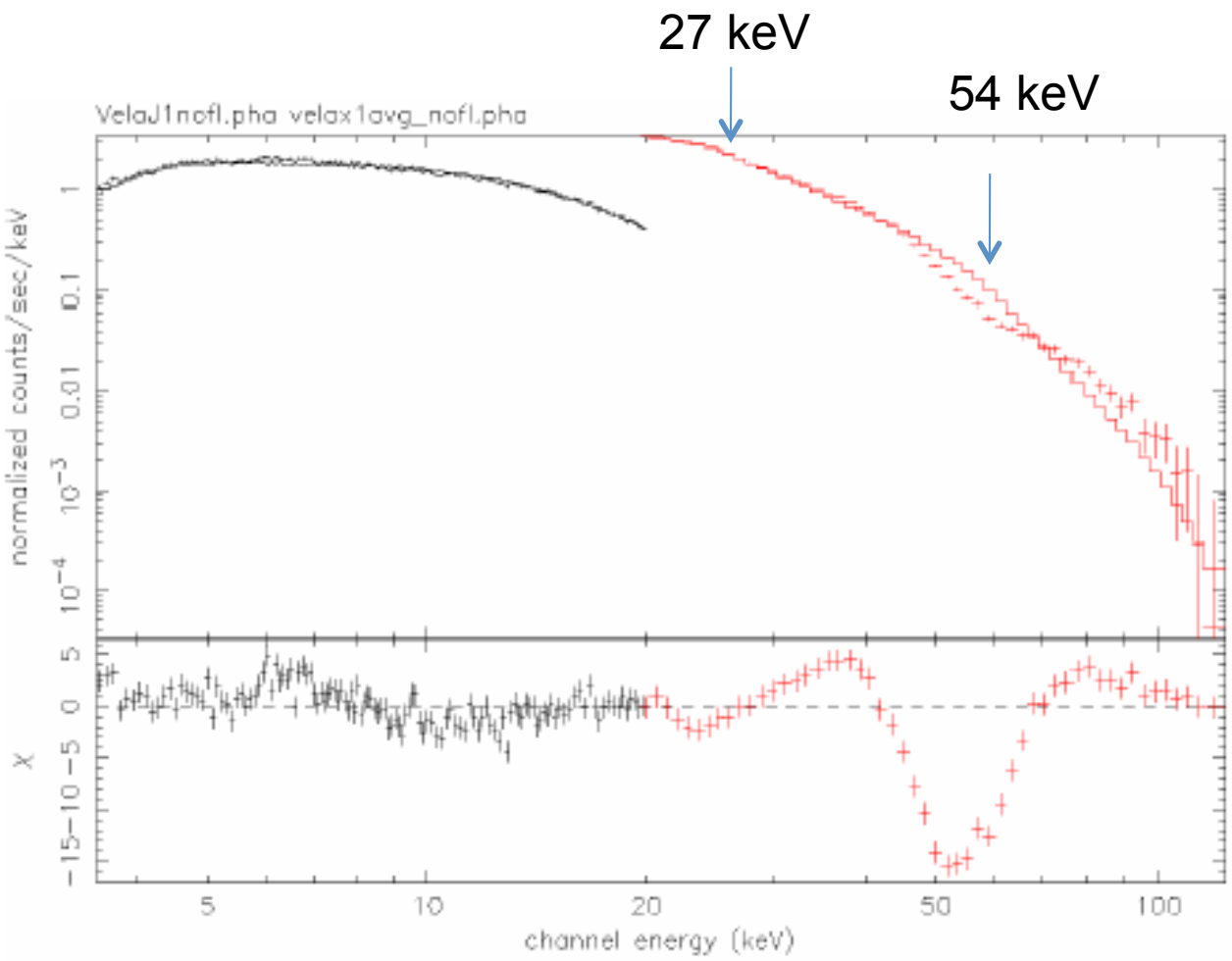
Deep surveys along the Galactic plane in soft gamma-rays
Good news for us to study neutron star systems



Vela X-1

Presence of two cyclotron lines is debated for a long time, specially for the 27 keV line (Kreykenbohm et al. 2002; La Barbera et al. 2003).

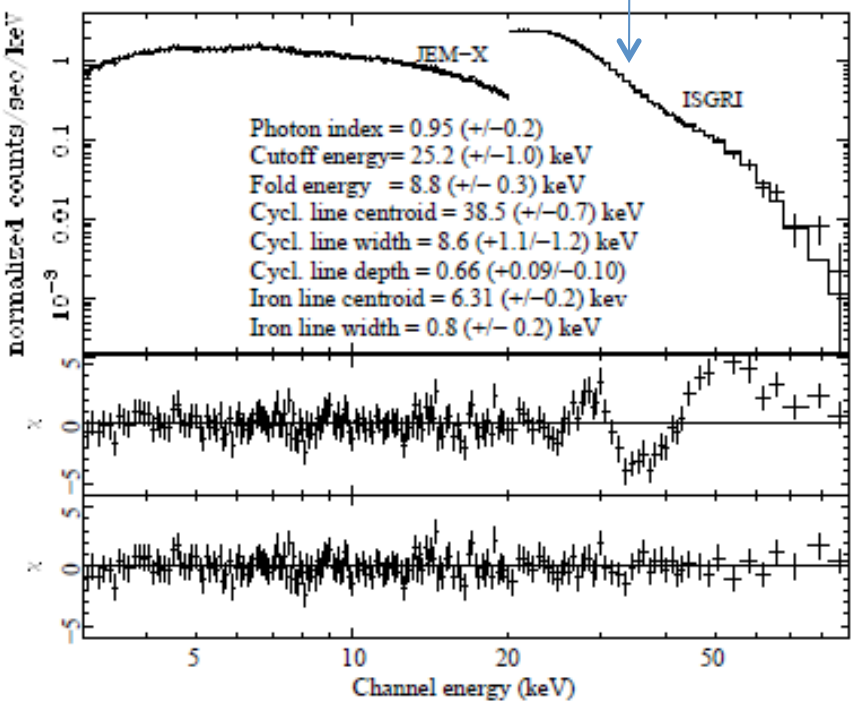
INTEGRAL/IBIS observations confirmed the two lines (Schanne et al. 2007).



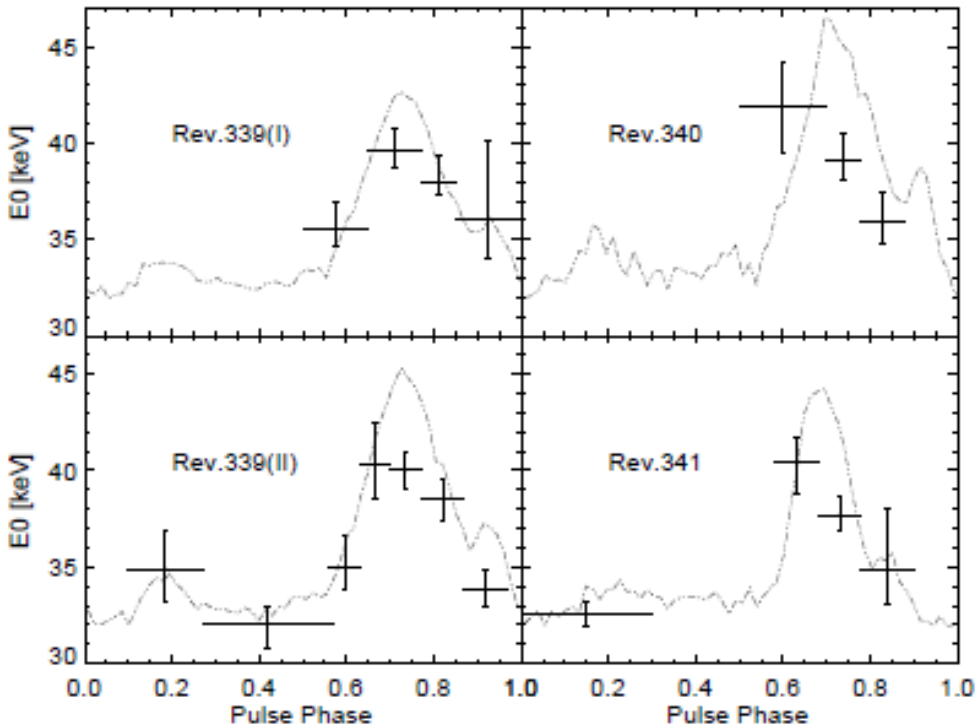
Her X-1

The first cyclotron line (Truemper et al. 1978)

39 keV



The variations of the centroid line energy with the luminosity of the source



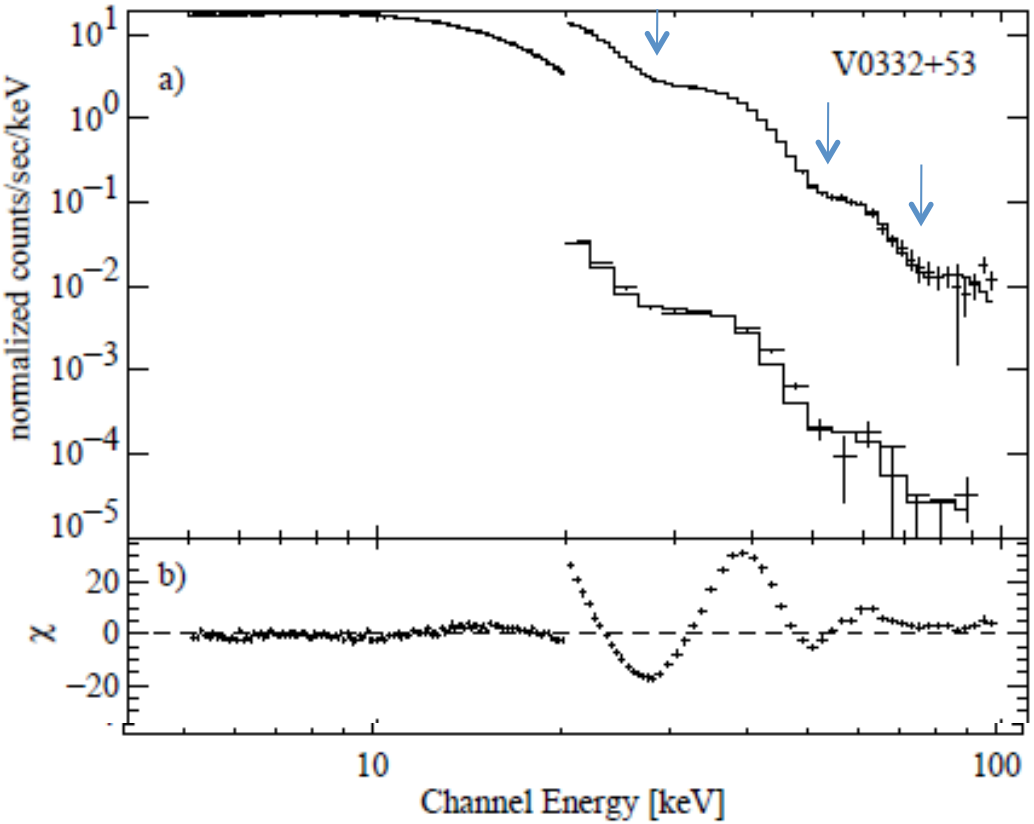
Klochkov et al. 2007

V0332+53

V 0333+53 is also a Be transient X-ray pulsar
P=4.375 s

The spectrum of the outburst during 2004 November

3 cyclotron lines:
26 keV
49 keV
74 keV

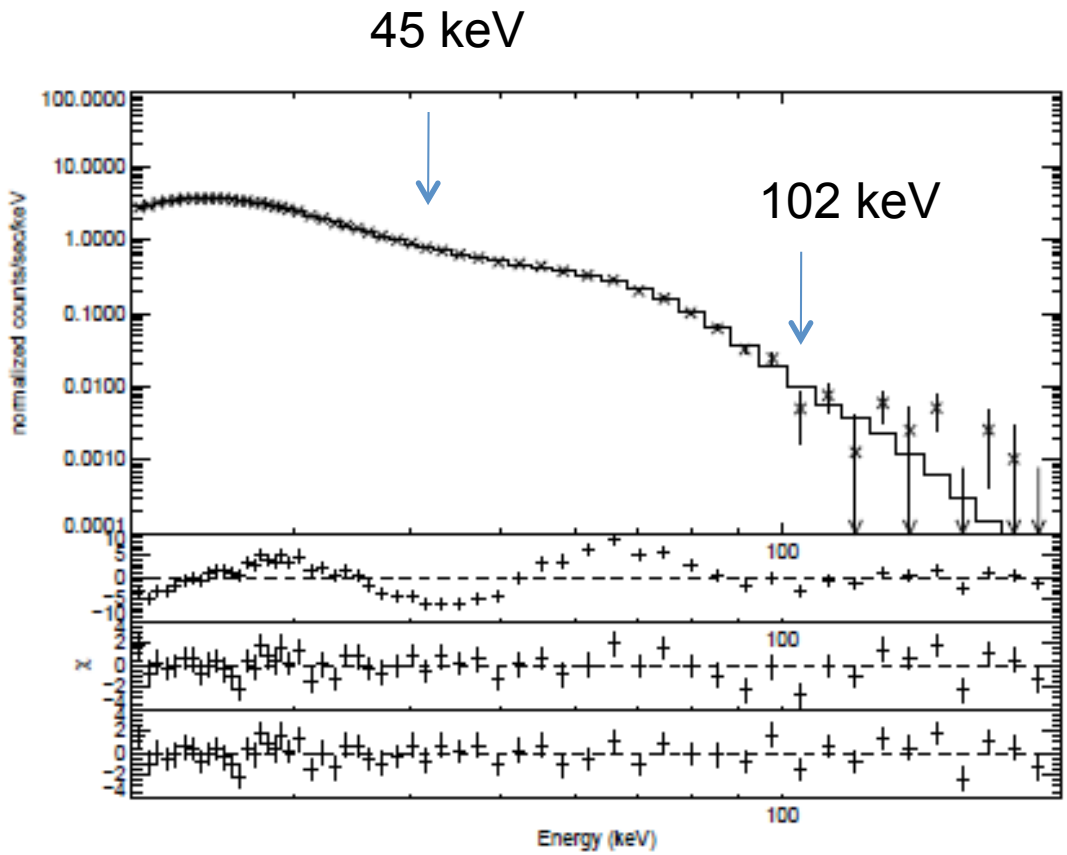


A0535+26

A Be transient X-ray pulsar, detected in the recurrent outburst states

The spectrum of the outburst in 2009 August (Caballero et al. 2010)

One line at 45 keV
Second at 102 keV



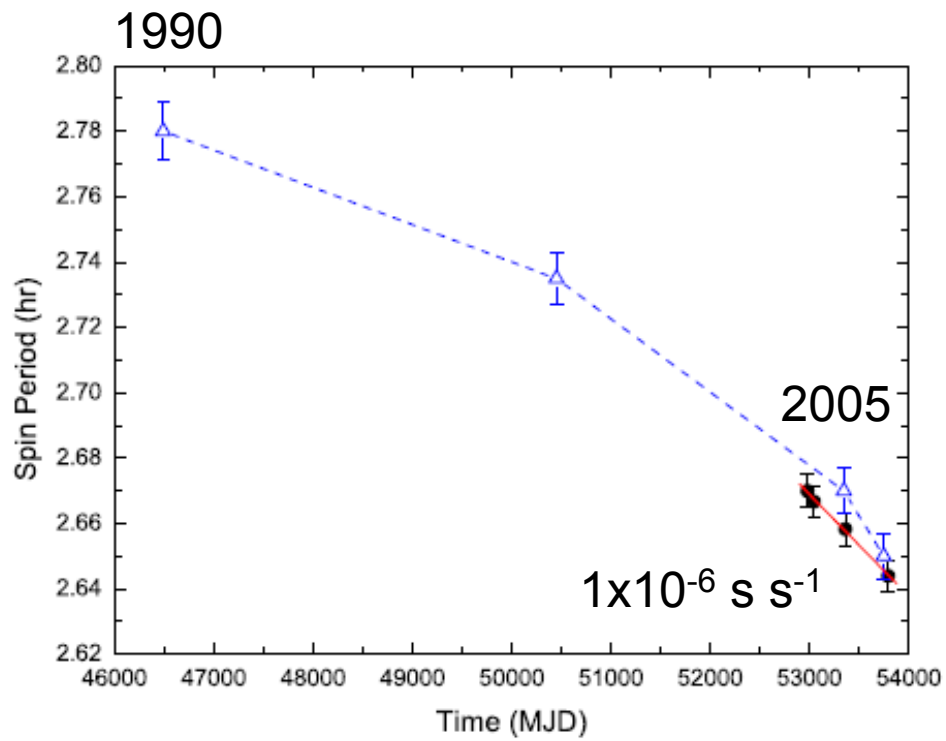
New Candidates

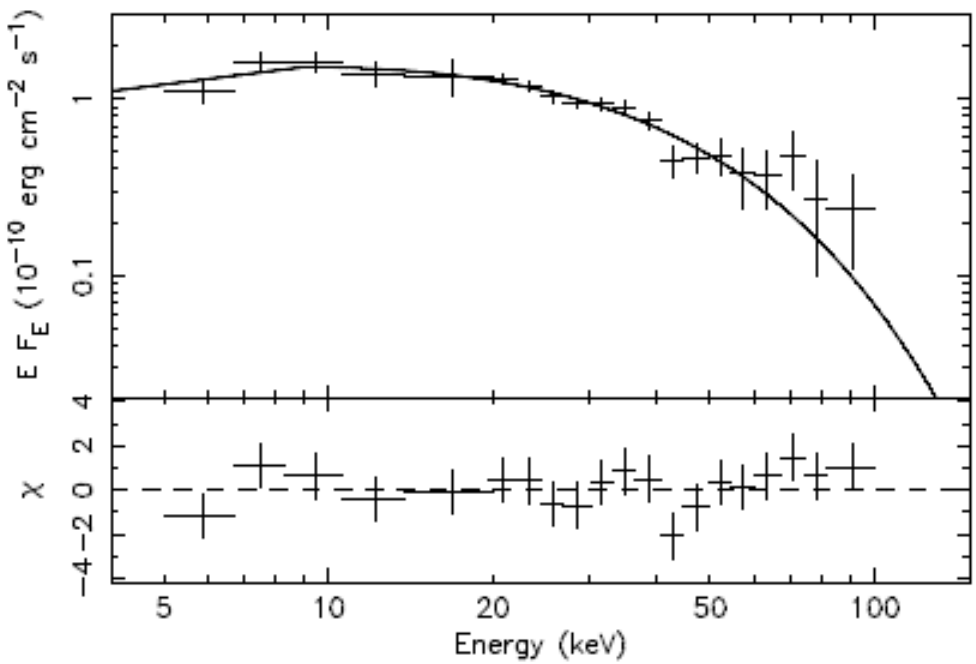
2S 0114+65

One of the slowest pulsation neutron star P=2.7 hr (Hall et al. 2000; Farrell et al. 2008)
And the pulsar is spinning up! (Wang 2010)

Bonning & Falanga (2005) found a feature around 40 -50 keV in the residuals.
Two-harmonic cyclotron line fit found lines at 22 keV and 44 keV.

Need further check!





4U 2206+54

A slow-pulsation pulsar

P=1.54 hr

(Reig et al. 2009, Wang 2009)

only permanent wind-fed HMXB

with a main-sequence donor

Low X-ray luminosity

The spectra when it became brighter

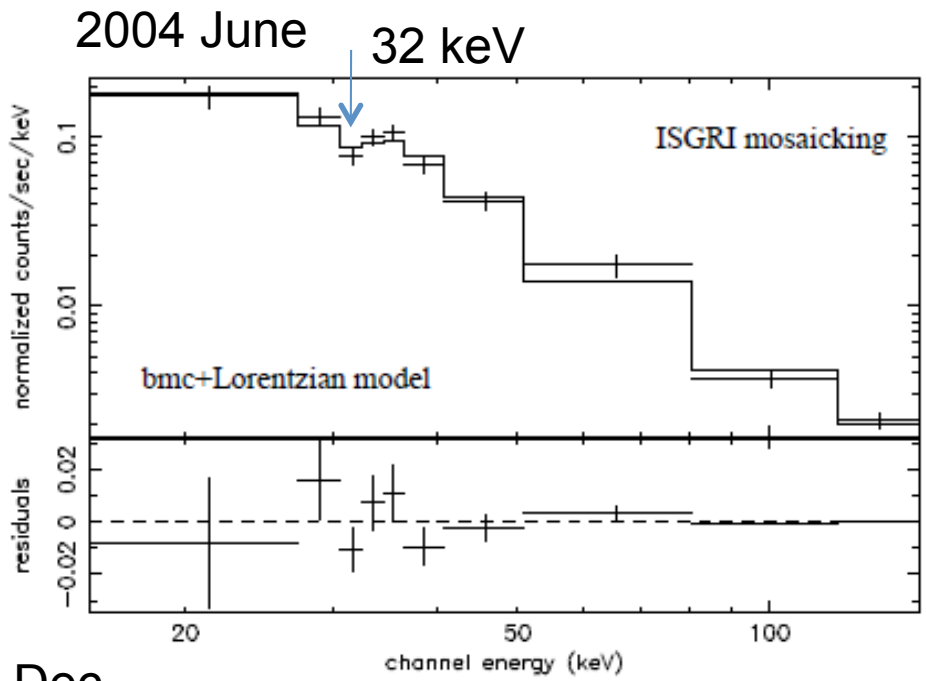
2 lines were found

29.6±2.8 keV

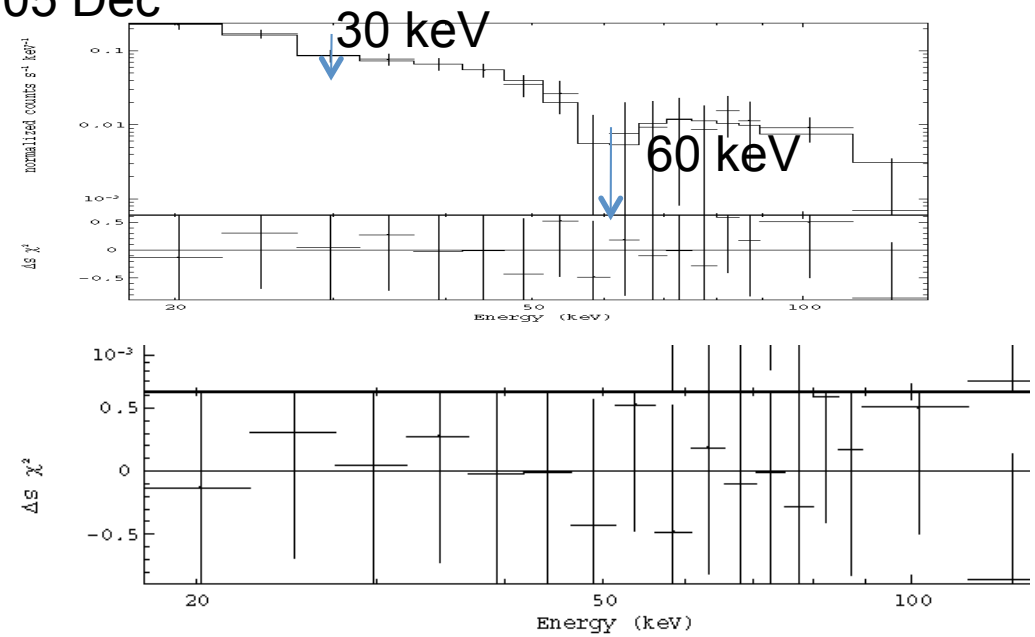
59.5 ±2.1 keV

(Blay et al. 2005, Wang 2009)

2004 June



2005 Dec



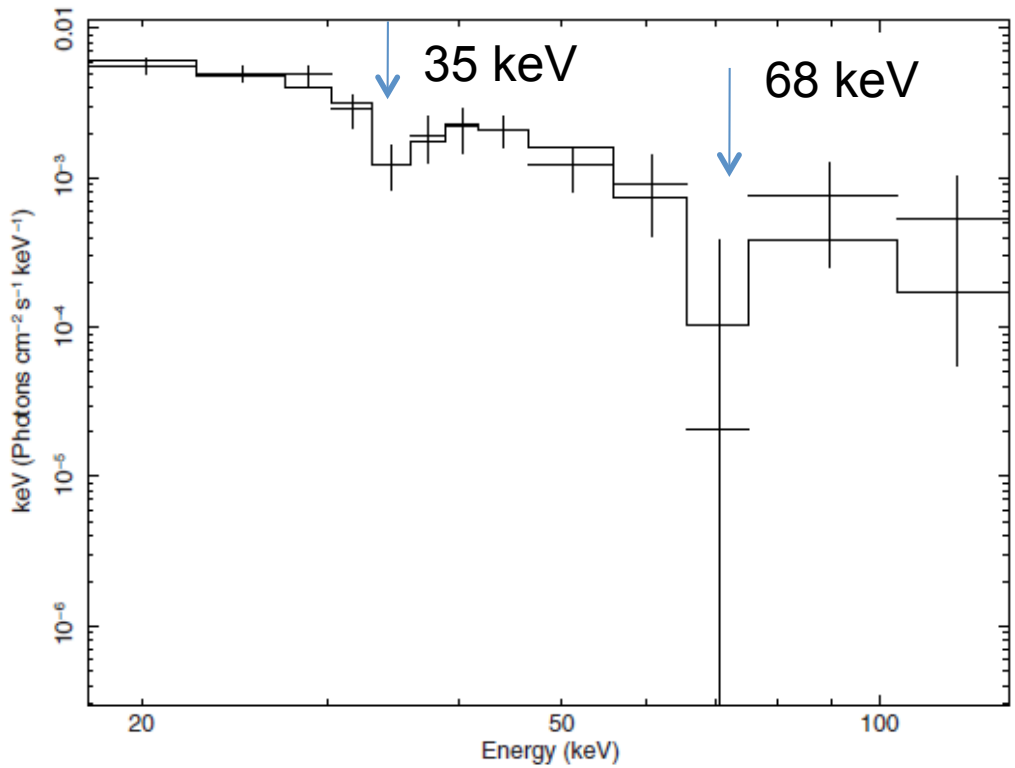
IGR J01583+6713

A hard X-ray transient source discovered by INTEGRAL/IBIS (Steiner et al. 2005).
On Dec 6 2005, IBIS detected the new source.
The flux decayed; never detected after 2005 Dec 13 (Wang 2010).
Optical observations suggested it may be a Be/X-ray star (Halpern et al. 2005).

The spectrum of the transient source during the outburst

Two cyclotron lines :
35.3 ±1.6 keV
67.9 ±4.8 keV

Possible nature:
Magnetic neutron star in a Be transient binary?
Search for the period in next outburst if possible



Summary

- At present in about 20 neutron star systems (HMXBs), cyclotron lines are detected;
- INTEGRAL discovered 3 new ones; expected to find more (2003-2012);
- With each generation of new satellites we are getting a wealth of observations on line features in neutron stars, especially with the large number of higher harmonics, now no doubt that these features are cyclotron lines, which are used to measure the magnetic field of neutron stars.
- Theoretical work on cyclotron line is still currently lagging behind observations.

Magnetic field strengths of neutron stars determined by cyclotron line observations

$$B \sim (1 - 6) \times 10^{12}\ G$$