Progress on the knowledge of magnetic fields in neutron stars

28th Texas Symposium on Relativistic Astrophysics
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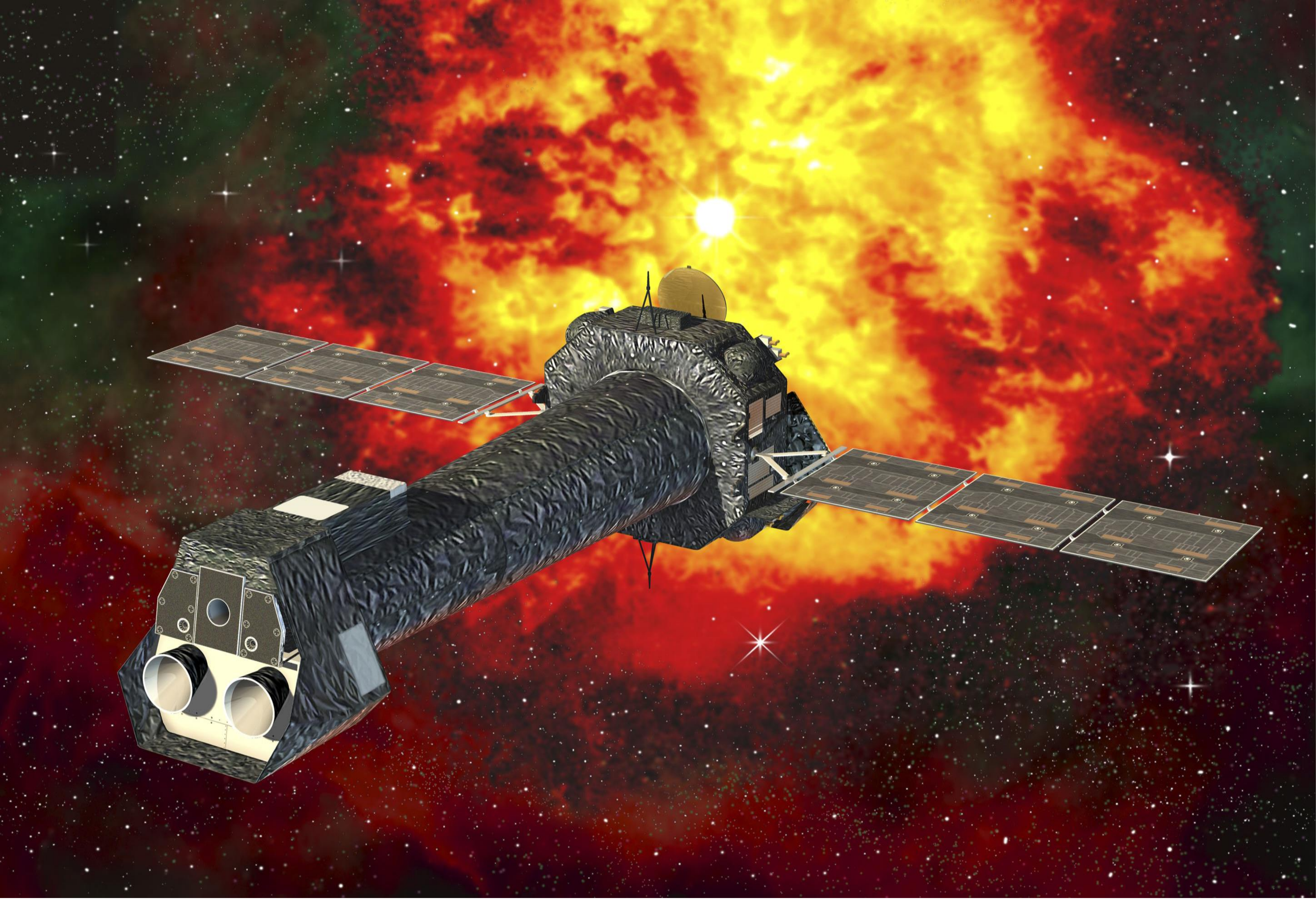
XMM-Newton

- XMM-Newton =
  X-ray Multi-mirror Mission
- Second cornerstone of ESA's Horizon 2000 Science Programme
- Launched by an Ariane 5 on 10 December 1999



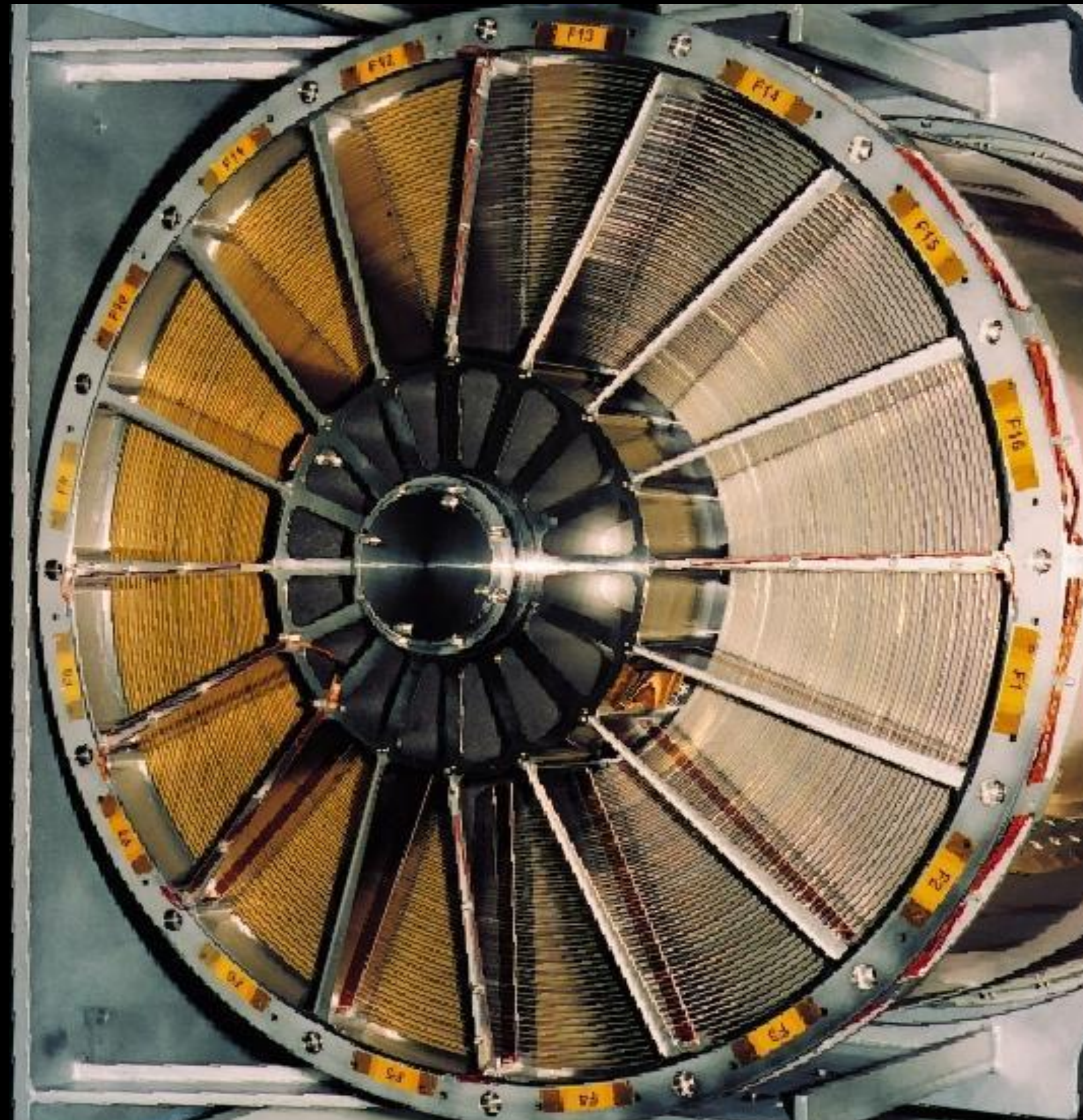
XMM-Newton preparation

Image courtesy of D. Parker

European Space Agency

Mirror Module:

- grazing-incidence Wolter 1 telescopes
- each mirror shell consists of a paraboloid and an associated hyperboloid
- 58 gold-coated nested mirrors

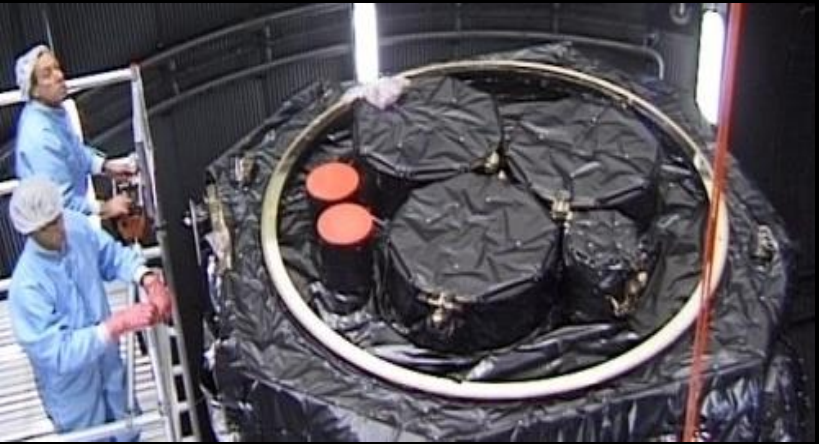


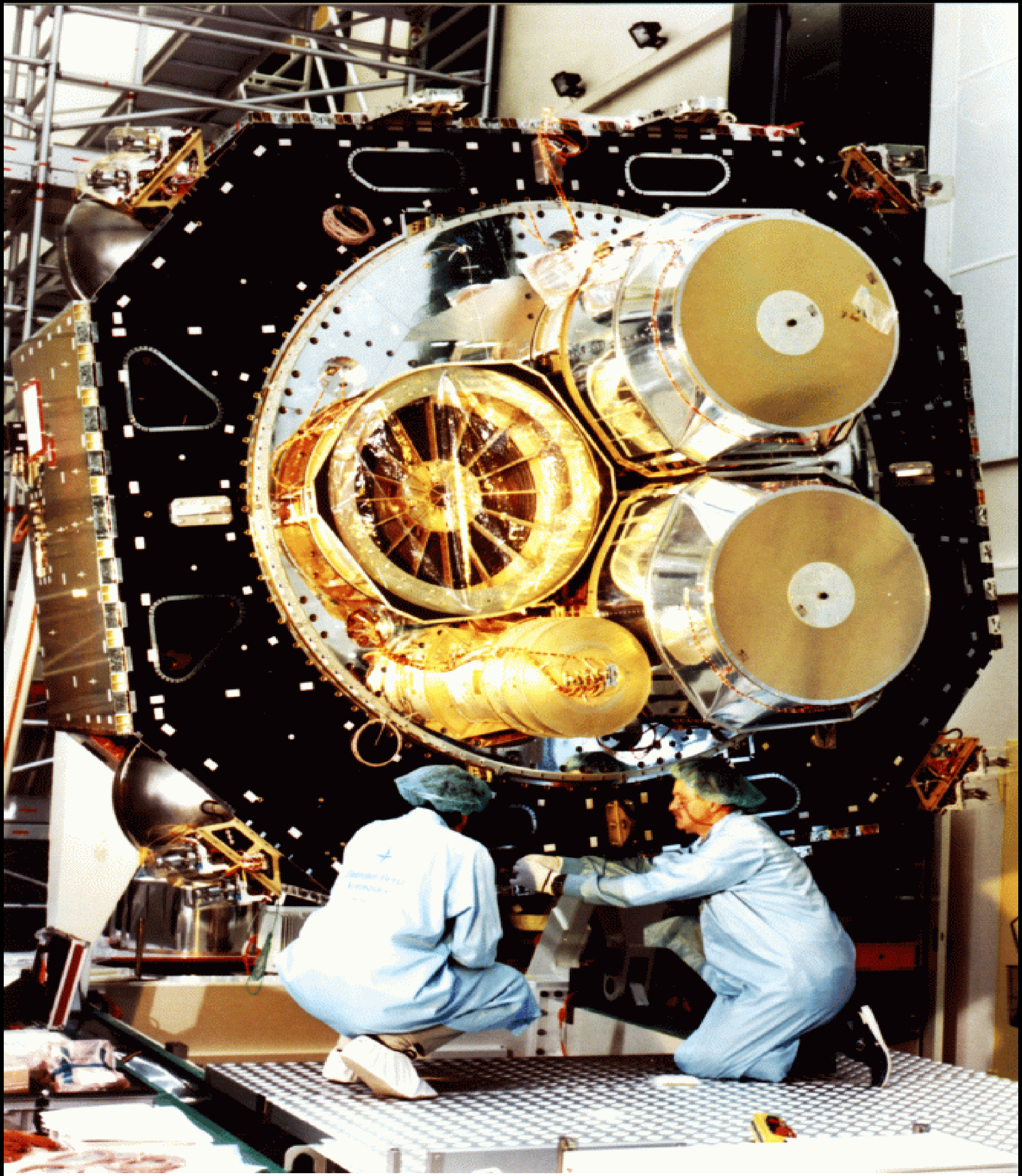
XMM-Newton mirrors during integration

Image courtesy of Dornier Satellitensysteme GmbH

European Space Agency

XMM-Newton has three mirror modules



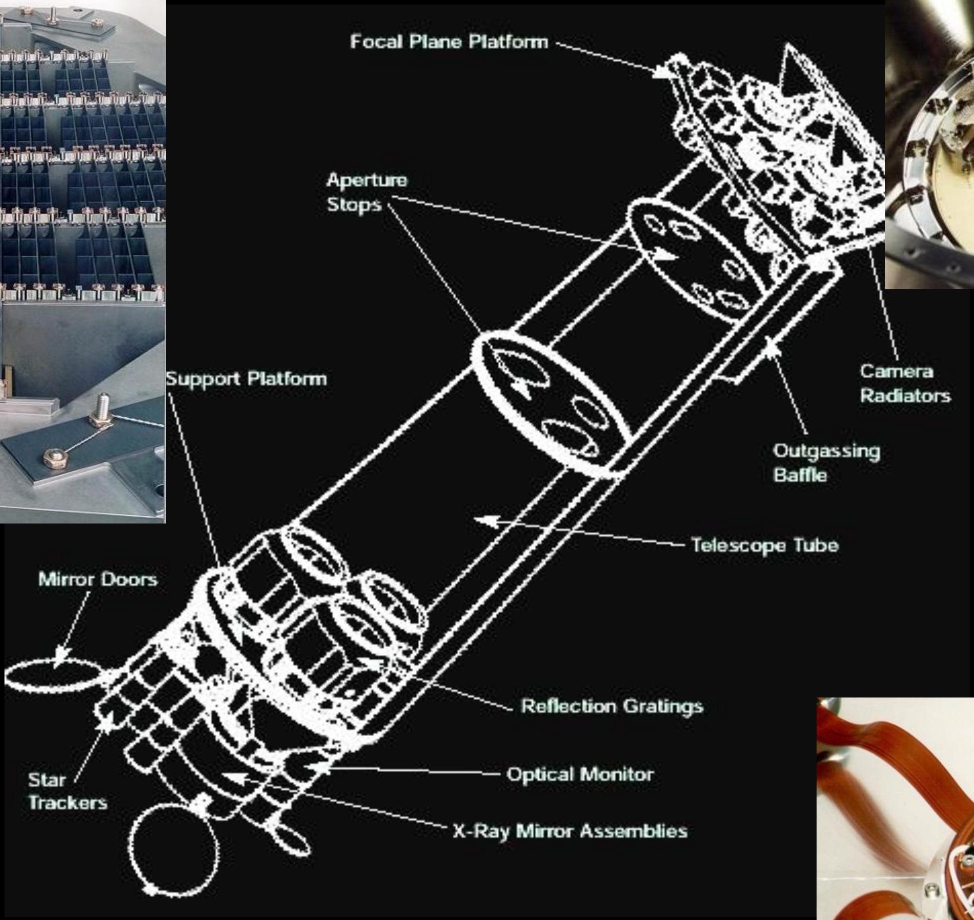


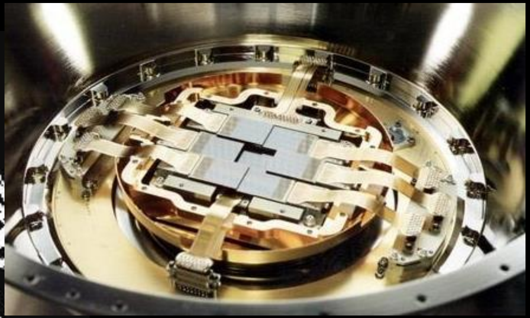
XMM-Newton mirrors during integration

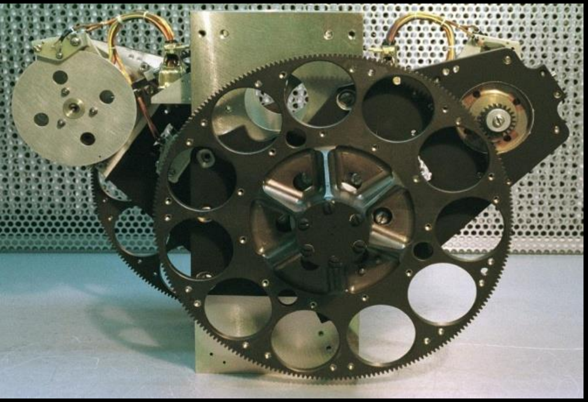
Image courtesy of Dornier Satellitensysteme GmbH

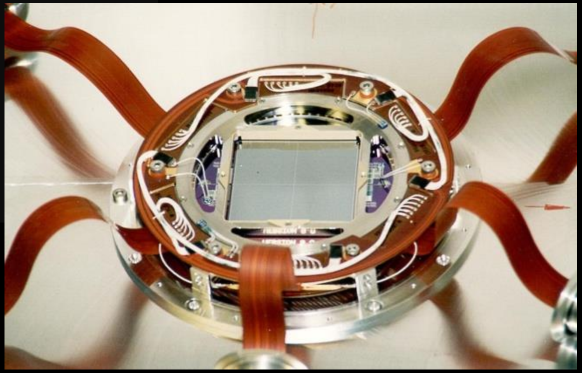
European Space Agency

Instruments



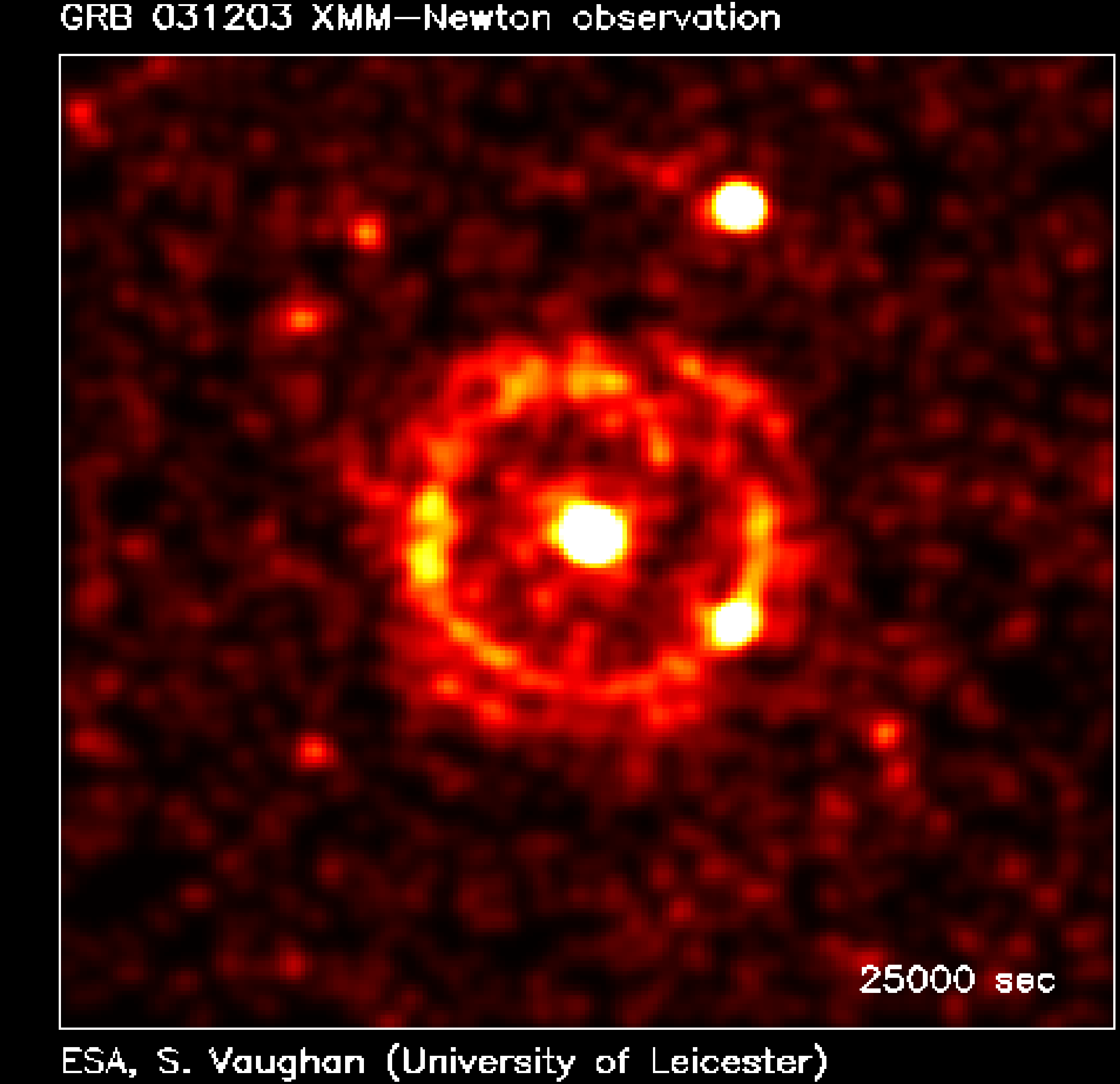






XMM-Newton

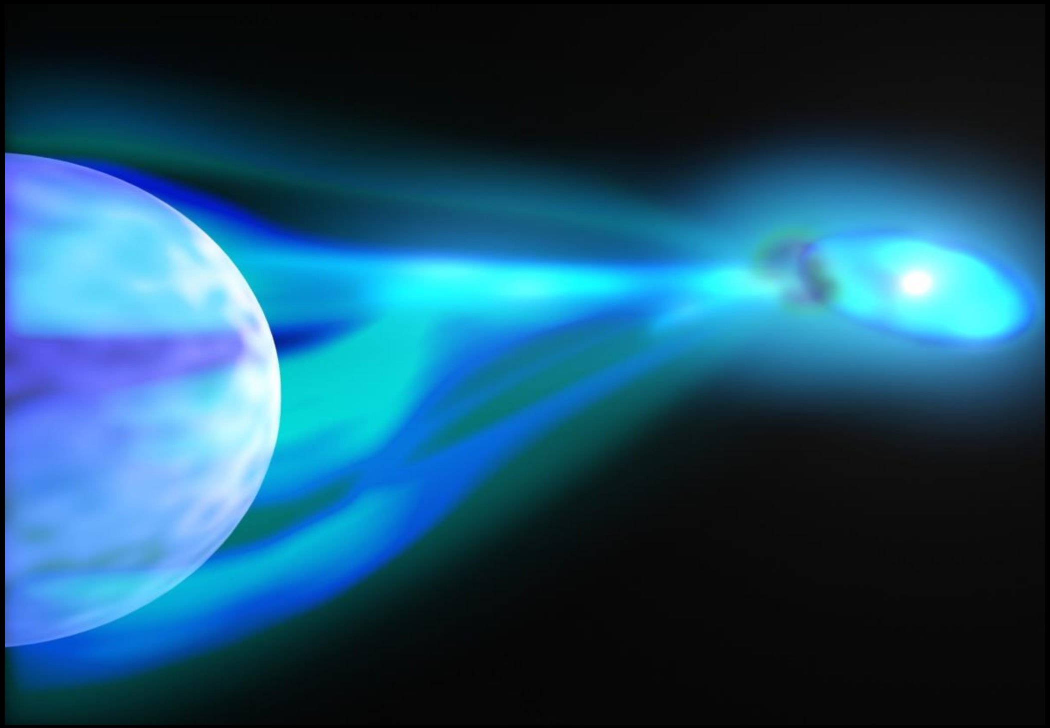
- 3 Mirror Modules / highest effective collecting area ever
- Six simultaneously observing instruments:
    - 3 CCD cameras (one pn and two MOSs)
    - 2 spectrometers (RGS)
    - 1 optical Monitor (OM)



S. Vaughan et al., 2004, ApJ 603, L5

- ➔ Discovery of an evolving dust-scattered X-ray halo
- ➔ Will allow highly accurate distance determina-tions to the dust

Dipping Low-Mass X-ray Binaries



- Dipping sources are normal LMXBs viewed from close to the orbital plane
- XMM-Newton observations of bright dipping LMXBs show changes in the X-ray continuum and the Fe absorption features during dip

➔ Increase in column density and decrease in the ionization state of a highly-ionized absorber

➔ Ionized plasma has a cylindrical geometry with a maximum column density close to the plane of the accretion disk

➔ Ionized plasmas are a common feature of LMXBs.

M. Díaz Trigo et al., 2006, A&A 445, 179

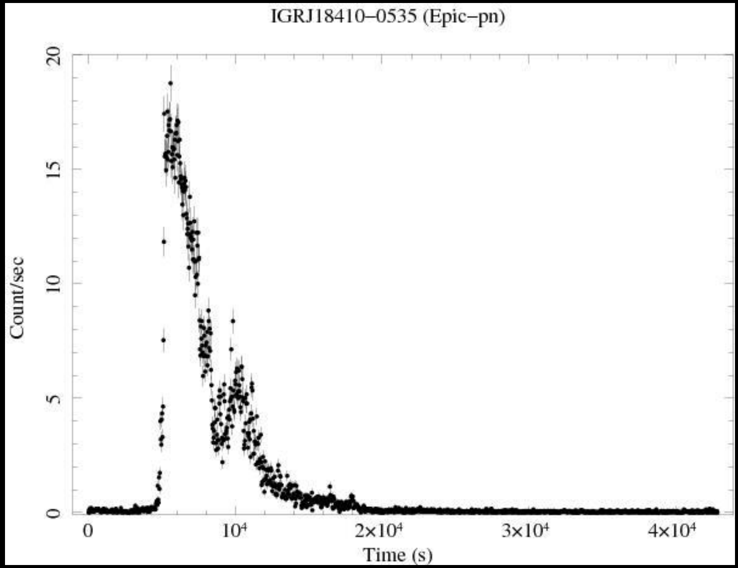
IGR J18410-0535: the accretion of a clump material by a supergiant fast X-ray transient

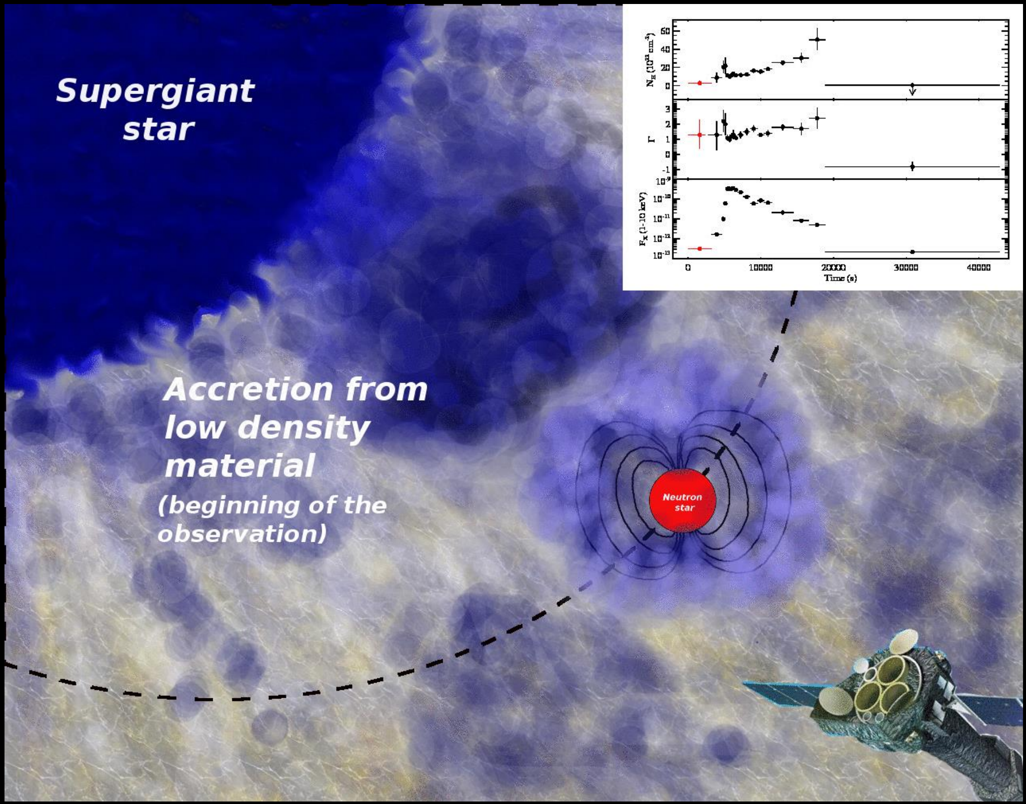
- subclass of supergiant X-ray binaries typically undergoes few-hour-long outbursts reaching luminosities of 10^{36}-10^{37} erg s^{-1} due to:

  1) combined effect of the intense magnetic field and rotation

  or

  2) the presence of dense structures ("clumps") in the wind of supergiant companion



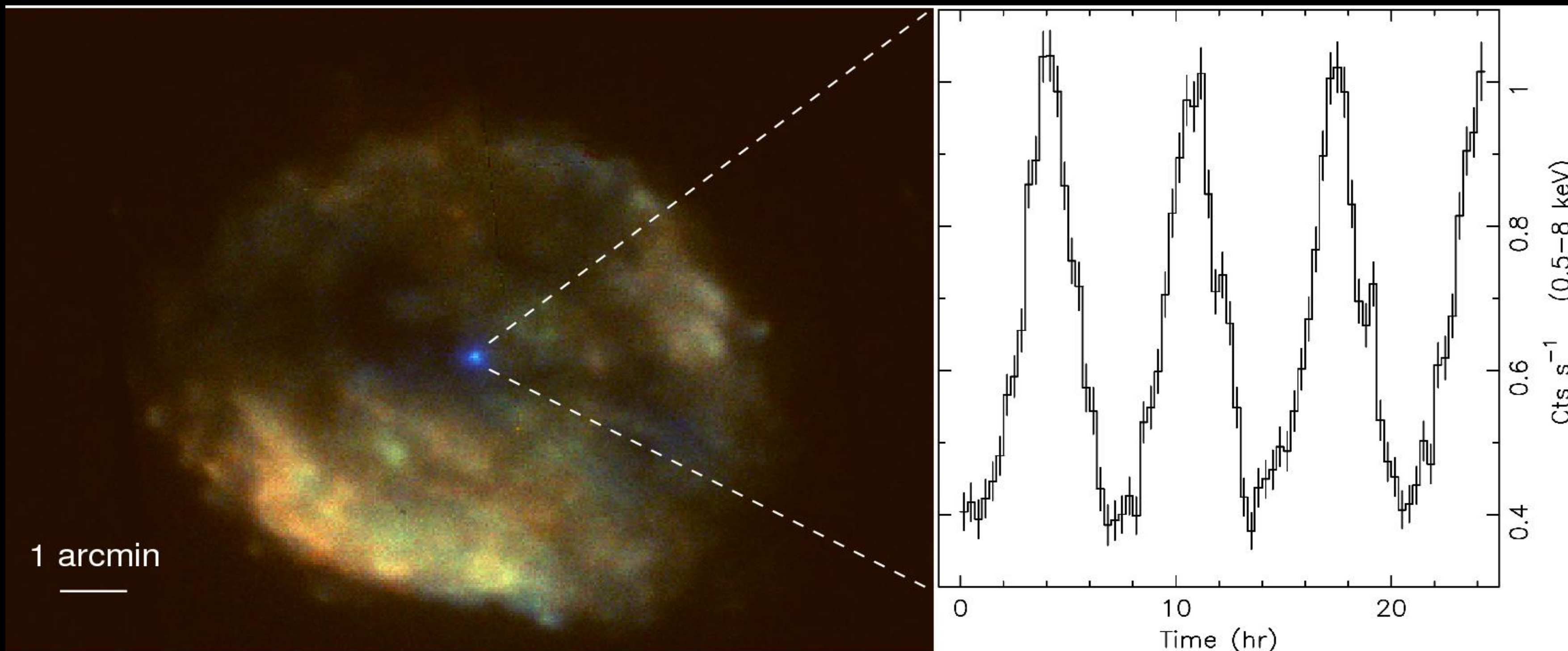


➔ XMM-Newton observation proved the second explanation

➔ estimate of $M \simeq 1.4 \times 10^{22}$ g and $R \simeq 8 \times 10^{11}$ cm assuming that the clump is spherical

Bozzo, E. et al., 2011, A&A 531, 130

RCW 103 Supernovae Remnant



- Strong periodic modulation at 6.67+/-0.03 hours

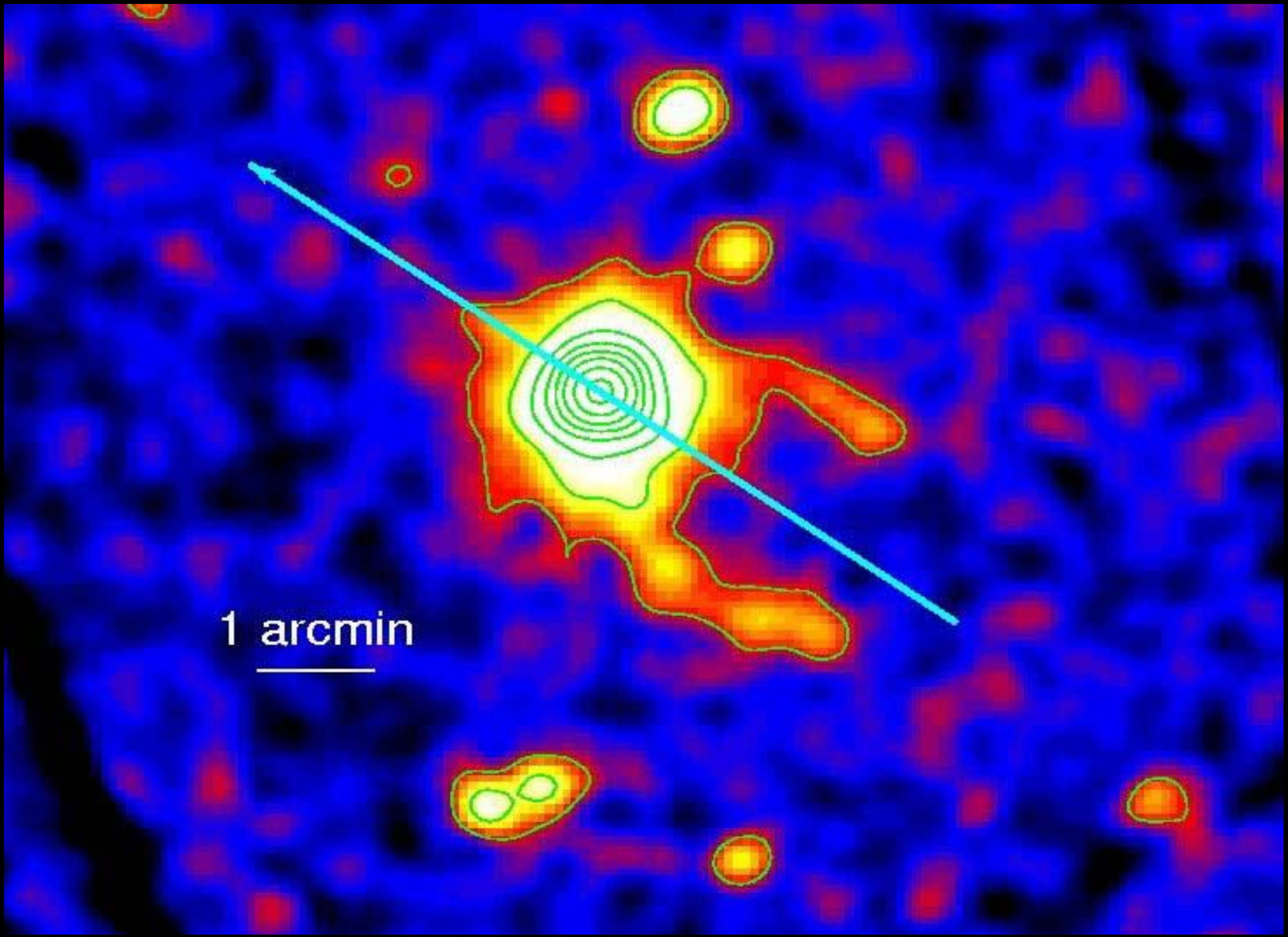
De Luca et al., 2006, Science 313, 814

- 2000-year-old supernova remnant RCW 103

→X-ray binary or peculiar magnetar

→ Both scenarios require nonstandard assumptions

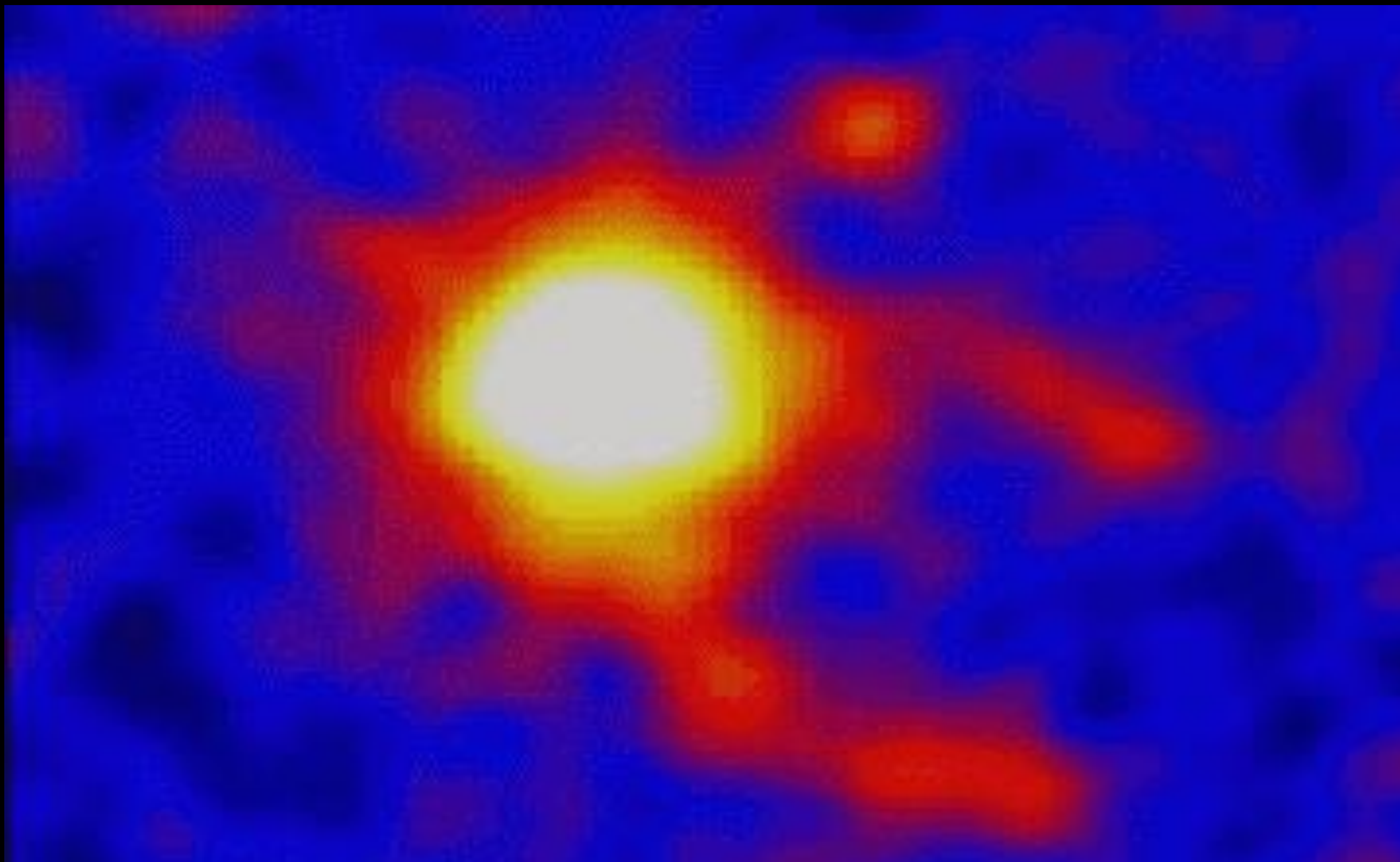
Geminga's Tails: A Pulsar Bow Shock Probing the Interstellar Medium



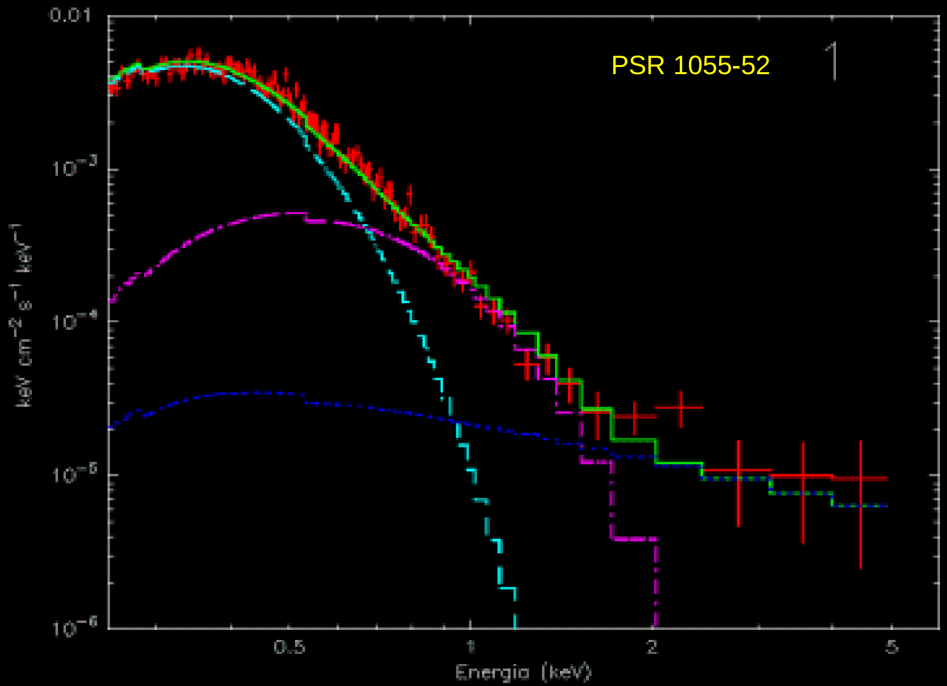
- P. A. Caraveo et al., 2003, Science 301, 1345
- Tails aligned with the object's super-sonic motion
- Electron-synchrotron emission in the bow shock between the pulsar wind and the surrounding medium

➔ Gauge the pulsar electron injection energy and the shock magnetic field

Phase-Resolved Spectroscopy of Geminga Shows Rotating Hot Spots



Polar Caps of the Three Musketeers



- Three isolated neutron stars: Geminga, PSR B0656+14, and PSR B1055-52
- Phase-resolved spectros-copy: two blackbody components + power-law
- Hotter bb coming from a smaller portion of the star surface (a ``hot spot'')

➔ Complex models of neutron star magnetic field configuration and surface temperature distribution are required

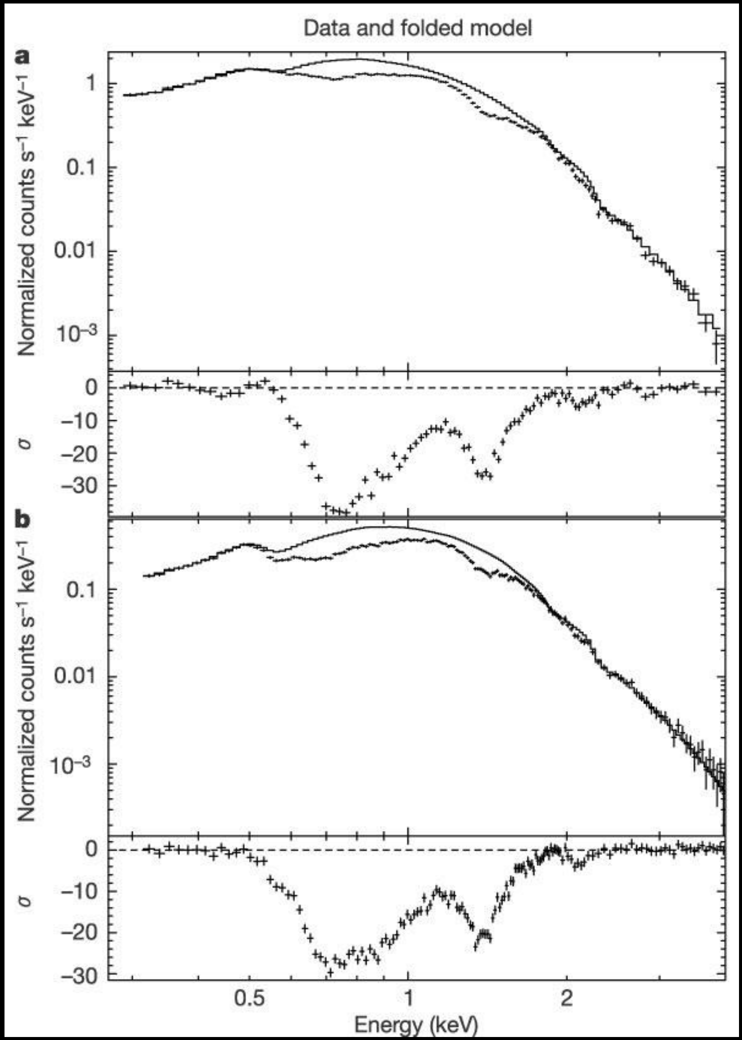
P. A. Caraveo, et al., 2004, Science 305, 376
A. De Luca, 2005, 2005, ApJ 623, 1051

The magnetic field of an isolated neutron star from X-ray cyclotron absorption lines

- Features in their X-ray spectra of isolated neutron stars could reveal the presence of atmospheres, or estimation of the strength of their magnetic fields (cyclotron process)
- but almost all isolated neutron star spectra observed so far appear as featureless thermal continua
- the only exception is 1E1207.4-5209, where two deep absorption features have been detected, but with insufficient definition to permit unambiguous interpretation
- EPIC spectra of a long XMM-Newton observation shows three distinct features, regularly spaced at 0.7, 1.4 and 2.1keV, plus a fourth feature of lower significance, at 2.8keV, which vary in phase with the star's rotation.

➔ the logical interpretation is that they are features from resonant cyclotron absorption, which allows to calculate a magnetic field strength of 8×10^{10}G, assuming the absorption arises from electrons.

Bignami, G. F., et al., 2003, Nature 423, 725



Synchronous X-ray and Radio Mode Switches: A Rapid Global Transformation of the Pulsar Magnetosphere

Simultaneous observations of PSR B0943+10 with XMM-Newton and GMRT and LOFAR:

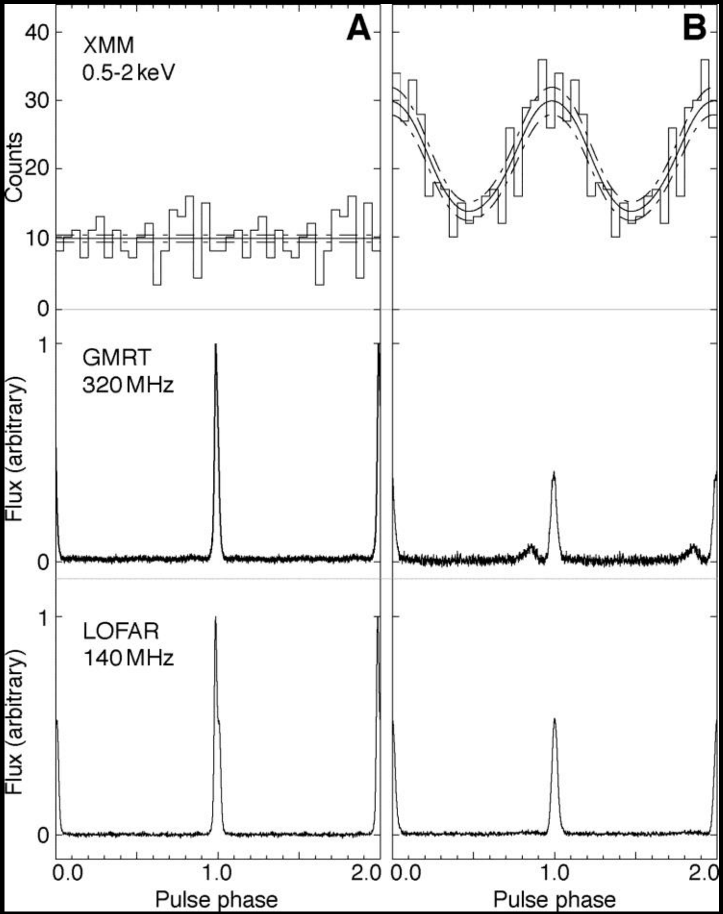
➔ Detection of synchronous switching in the radio and x-ray emission properties

➔ When the pulsar is in a sustained radio-"bright" mode, the x-rays show only an unpulsed, nonthermal component

➔ When the pulsar is in a radio-"quiet" mode, the x-ray luminosity more than doubles and a 100% pulsed thermal component is observed along with the nonthermal component.

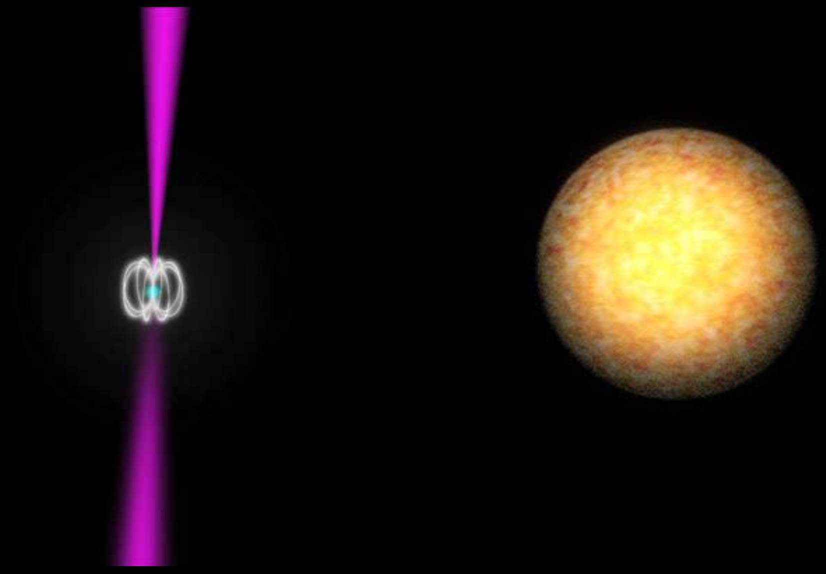
➔ Indicates rapid, global changes to the conditions in the magnetosphere, which challenge all proposed pulsar emission theories.

Hermsen, W., et al., 2013 Science 339, 436



Aligned x-ray and radio pulse profiles of PSR B0943+10 in its B and Q modes. (A) B mode: There is no evidence for a pulsed signal in the B-mode x-ray data, the flat distribution showing constant emission from the pulsar. (B)Q mode: The x-ray profile in the Q mode represents a 6.6s detection on top of a flat constant level

Swings between rotation and accretion power in a binary millisecond pulsar



- XMM-Newton, radio and other X-ray satellites observations of X-ray transient IGR J18245–2452, which was first detected by INTEGRAL

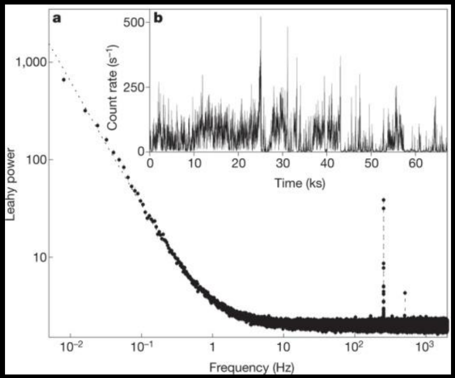
- First observations of accretion-powered, millisecond X-ray pulsations from a neutron star previously seen as a rotation-powered radio pulsar.

- Within a few days after a month-long X-ray outburst, radio pulses were again detected.

➔ evolutionary link between accretion and rotation-powered millisecond pulsars

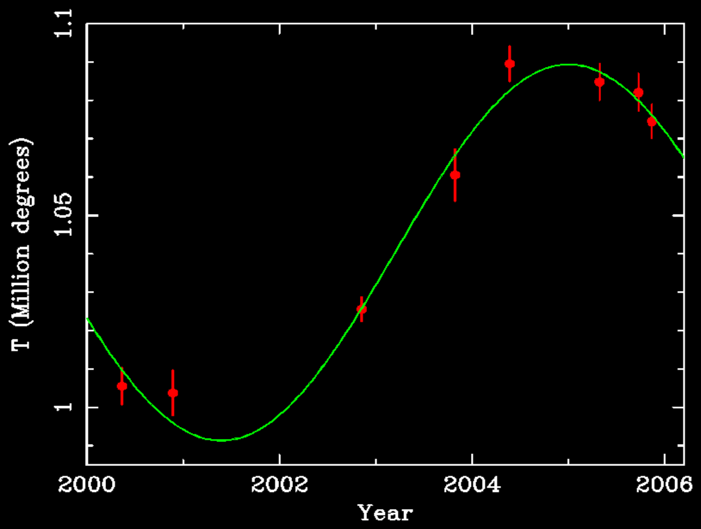
➔ some systems can swing between the two states on very short timescales

Fourier power spectral density of the 0.5–10-keV X-ray photons obser ved by the EPIC pn camera. The peaks at 254.3 and 508.6 Hz represent the first and second harmonics of the coherent modulation of the X-ray emission of IGR J18245–2452.



Papitto et al., 2013,
Nature 501, 517

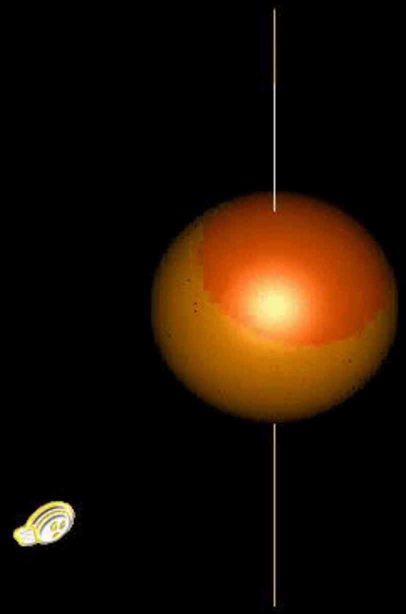
Isolated Neutron Star RX J0720.4-3125



- XMM-Newton spectra over 4.5 years
- Sinusoidal variations in:
  - inferred blackbody temperature
  - size of the emitting area
  - depth of the absorption line
  - period of 7.1 +/- 0.5 years

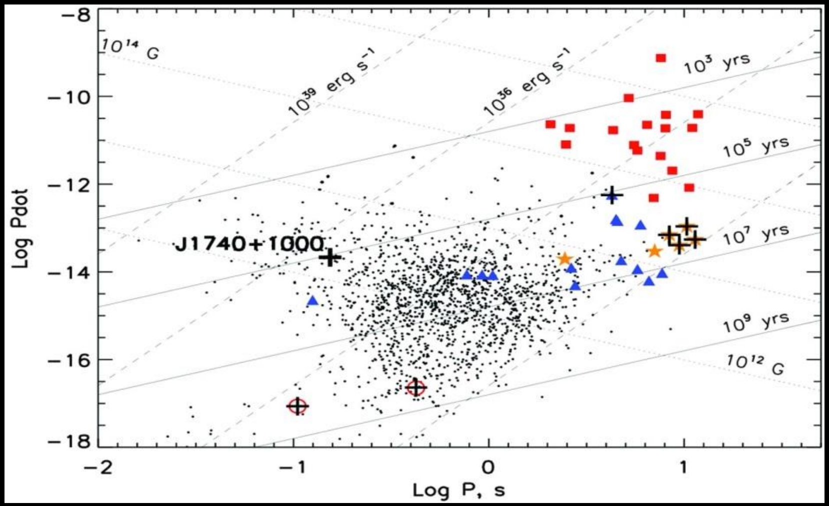
➔ Precession of the neutron star

➔ Two hot spots of different temperature and size, probably not located exactly in antipodal positions



F. Haberl et al., 2006 A&A 451, L17

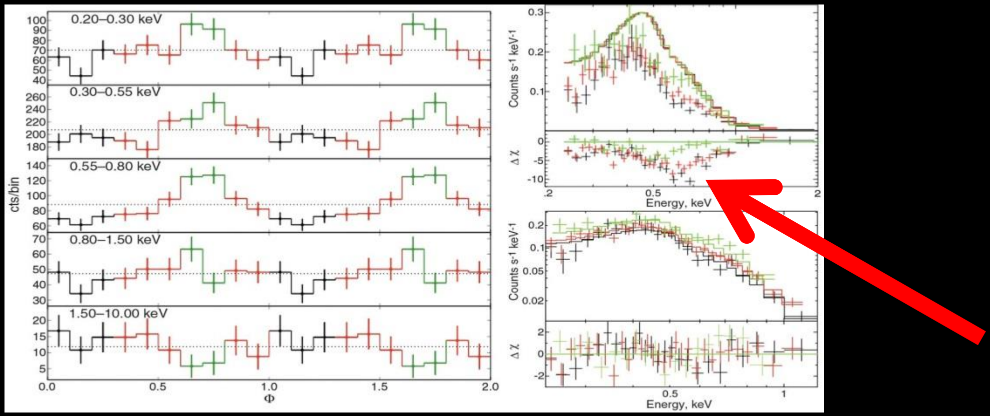
Absorption Features in the X-ray Spectrum of an Ordinary Radio Pulsar



- Vast majority of known non-accreting neutron stars (NS) are rotation-powered radio and/or γ-ray pulsars

- Their spectra have all been described satisfactorily continuum models, with no spectral lines.

Kargaltsev et al., 2012, Science 337, 946



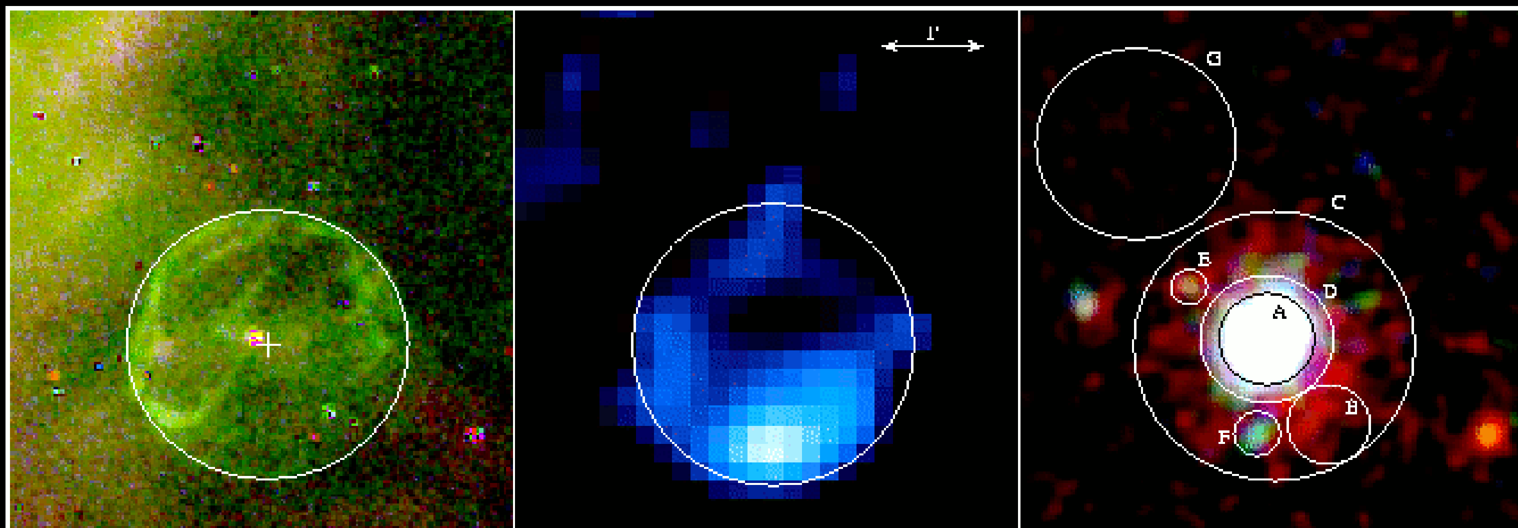
- Spectral features in a handful of exotic NSs were thought to be a manifestation of their unique traits.

➔ Absorption features in the spectrum of an ordinary rotation-powered radio pulsar, J1740+1000

➔ Bridges the gap between pulsars and more exotic neutron stars

➔ Features are more common in the NS?

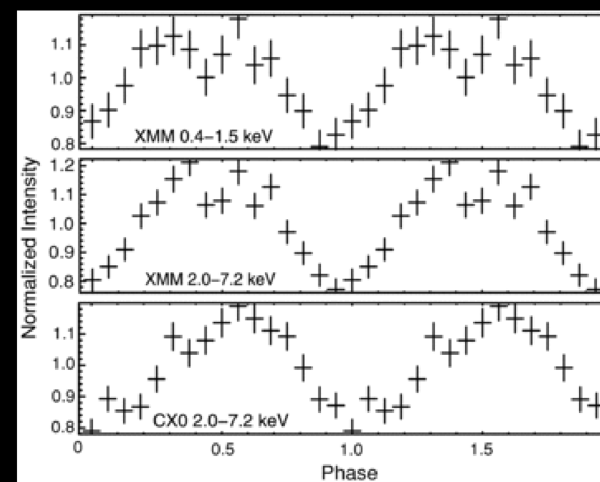
SXP 1062: On the age of neutron stars



- Hénault-Brunet, V. et al., 2011, MNRAS, tmpL.372H
- F. Haberl, et al., 2012, A&A 537, L1

- Discovery of a new supernova remnant (SNR) around Be/X-ray binary pulsar SXP 1062 in radio, optical and X-ray images.
- The Be/X-ray binary system is found near the centre of the SNR
- The neutron has a spin period of 1062 s (the second longest known in the SMC) and shows a very high spin-down rate of 0.26 s/day
- The age of SNR is estimated to be 10 000−25 000 years

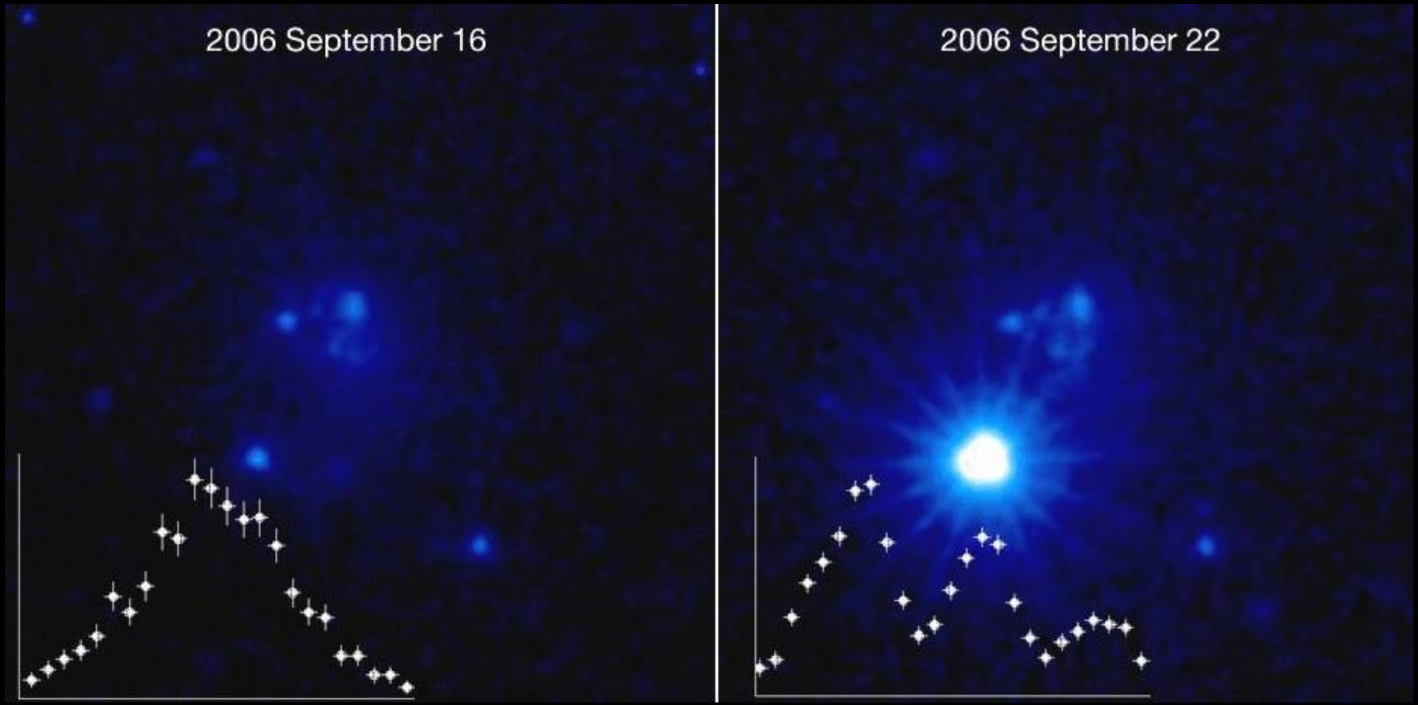
➔ Neutron stars in Be/X-ray binaries with long spin periods can be much younger than currently anticipated



Exciting the Magnetosphere of the Magnetar in Westerlund 1

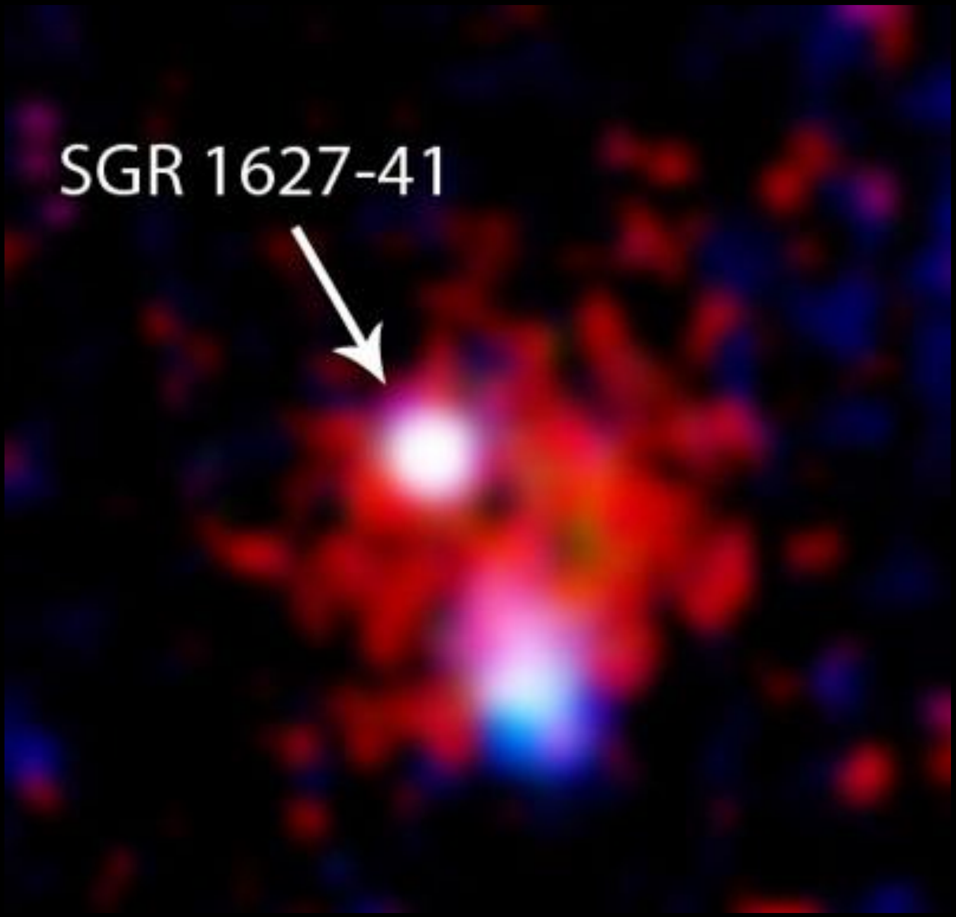
- XMM-Newton observations taken 4.3 day prior to and 1.5 day subsequent to
  - (i) a 20-ms burst with an energy of 10^{37} erg (15-150 keV)
  - (ii) a rapid spin-down (glitch) with $\Delta P/P \sim -10^{-4}$

P. M. Muno et al., 2007, MNRAS tem L40



➔ **Plastic deformation of the neutron star crust induced a very slight twist in the external magnetic field, which in turn generated currents in the magnetosphere that were the direct cause of the X-ray outburst**

Discovery of 2.6 s pulsations in SGR 1627-41



- The Soft Gamma-ray Repeater SGR 1627-41 reactivated on 2008 May 28 after nearly a decade of quiescence.

➔ XMM-Newton observations on 2008 September 27-28 allowed the detection of pulsations with P = 2.594578(6) s (>6σ confidence, fundamental and the second harmonic)

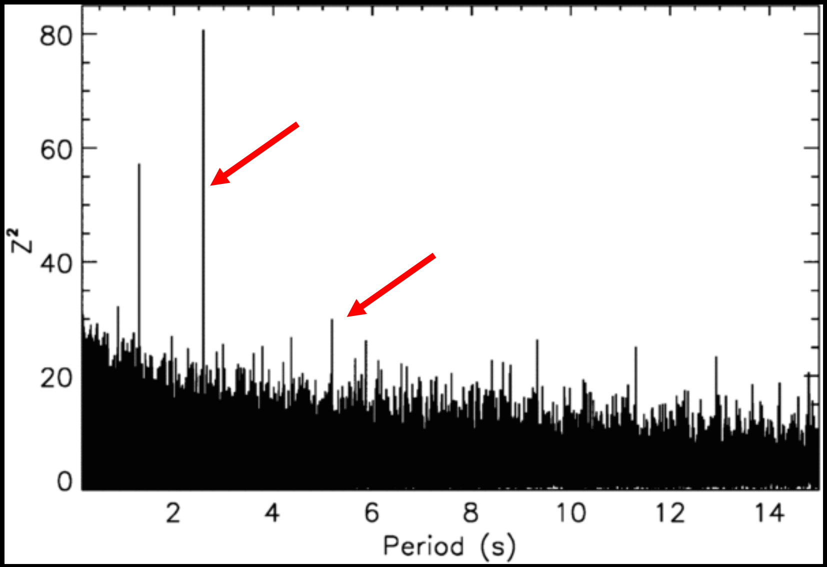
➔ In combination with Chandra data from 2008 June:l

  ➔ long-term spin-down rate of (1.9+/ 0.4) × 10-11ss^{-1}.

  ➔ characteristic age of ~2.2 kyr

  ➔ surface dipole magnetic field strength of ~2 × 10^{14} G.

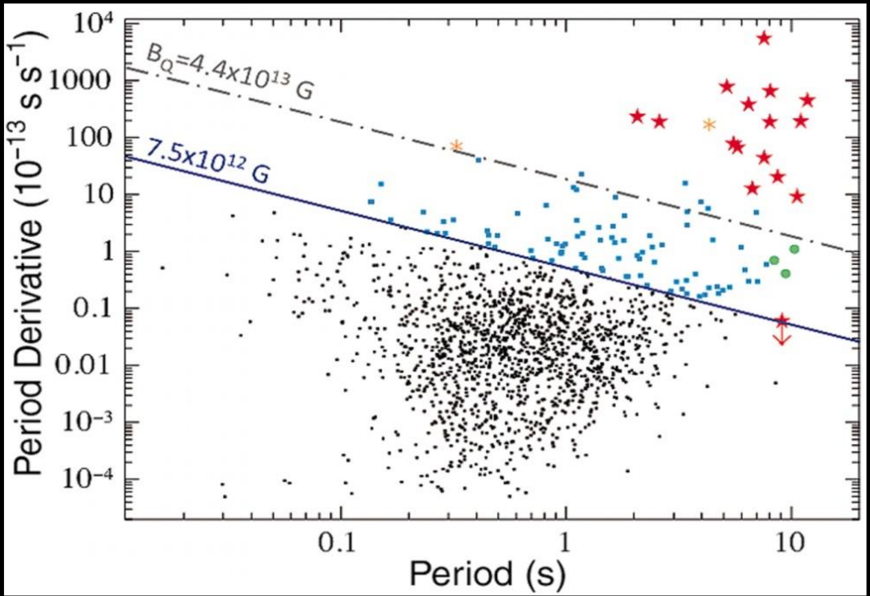
➔ These properties confirm magnetar nature of SGR1627-41

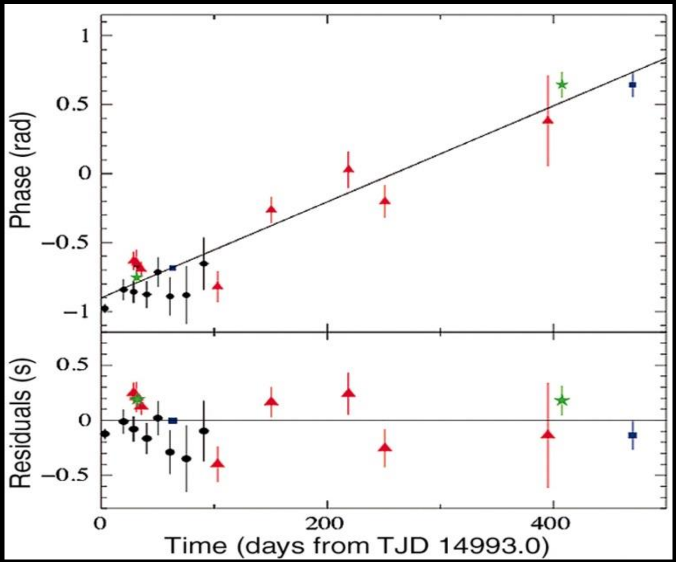


P. Esposito, et al., 2009 ApJ 690, L105 & 2009, MNRAS 399, L44

A Low-Magnetic-Field Soft Gamma Repeater

- Magnetars: neutron stars with extreme magnetic fields, B ~ 10^{14} to 10^{15} gauss, i.e. the binding energy of an electron exceeds its rest mass
- It was generally assumed that Gamma Ray Burst are a characteristics of Magnetars, which consequently were identified with: Anomalous X-Ray Pulsars and Soft Gamma Repeaters (SGR)



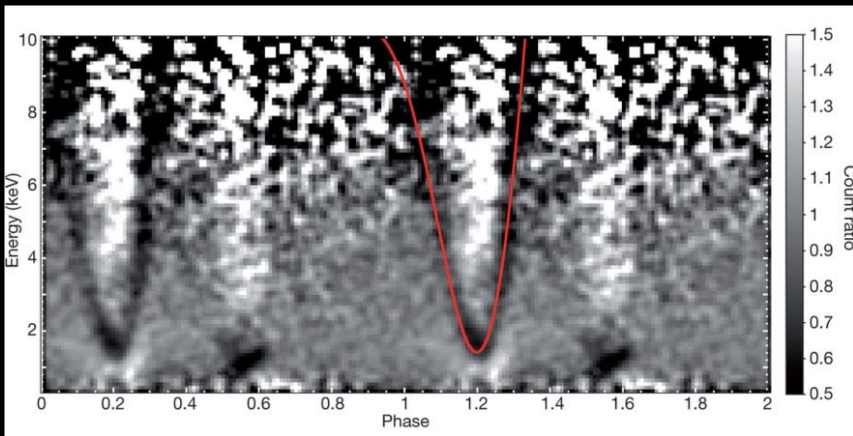


➔ XMM-Newton (& other X-ray observatories) found that SGR 0418+5729 has a magnetic field of < 7.5 × 10^{12} gauss

➔ The emission of a Gamma Ray Burst does not prove a high magnetic field

N. Rea et al., 2010, Science 330, 944

Magnetic multipole field in SGR 0418+5729

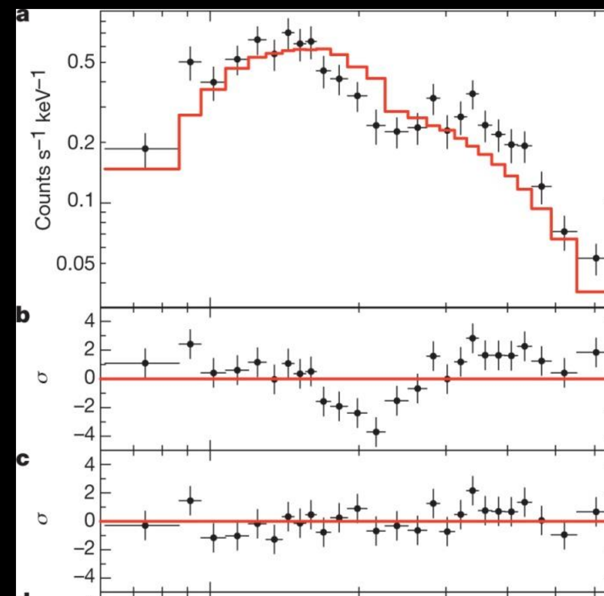


Phase-dependent spectral feature in the EPIC data of SGR 0418+5729.

- Soft-γ-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are neutron stars that sporadically undergo X-ray/γ outbursts
- sources are mainly powered by their own magnetic energy.
- magnetic fields inferred from several observed properties of SGRs and AXPs are greater than those of radio pulsars

- SGR 0418+5729 has a weak dipole magnetic moment of B = 6 × 10 10^{12} G (derived from timing parameters)
- A strong field has been proposed in the stellar interior and in multipole components on the surface
- **X-ray absorption line**
- **which depend strongly on the star's rotational phase**

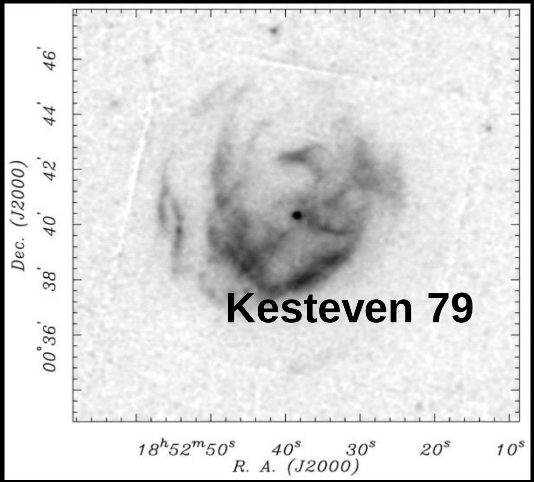
→proton cyclotron
→magnetic field from 2 × 10^{14} G to > 10^{15} G

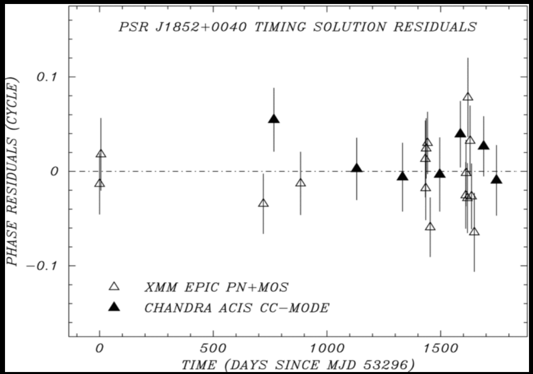


a: spectrum from phase interval 0.15–0.17 and phase-averaged spectrum in red
b: residuals; c: residuals after adding an absorption line

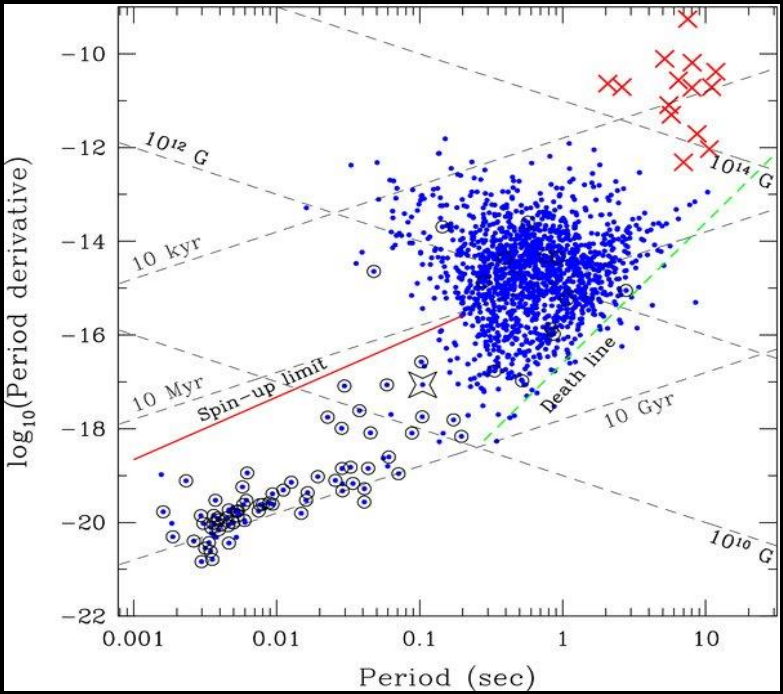
Tiengo et al., 2013, Nature 500, 312

Spin-Down Measurement of PSR J1852+0040





Halpern & Gotthelf, 2010, ApJ 709, 436



PSR J1852+0040 is Central Compact Object (CCO)

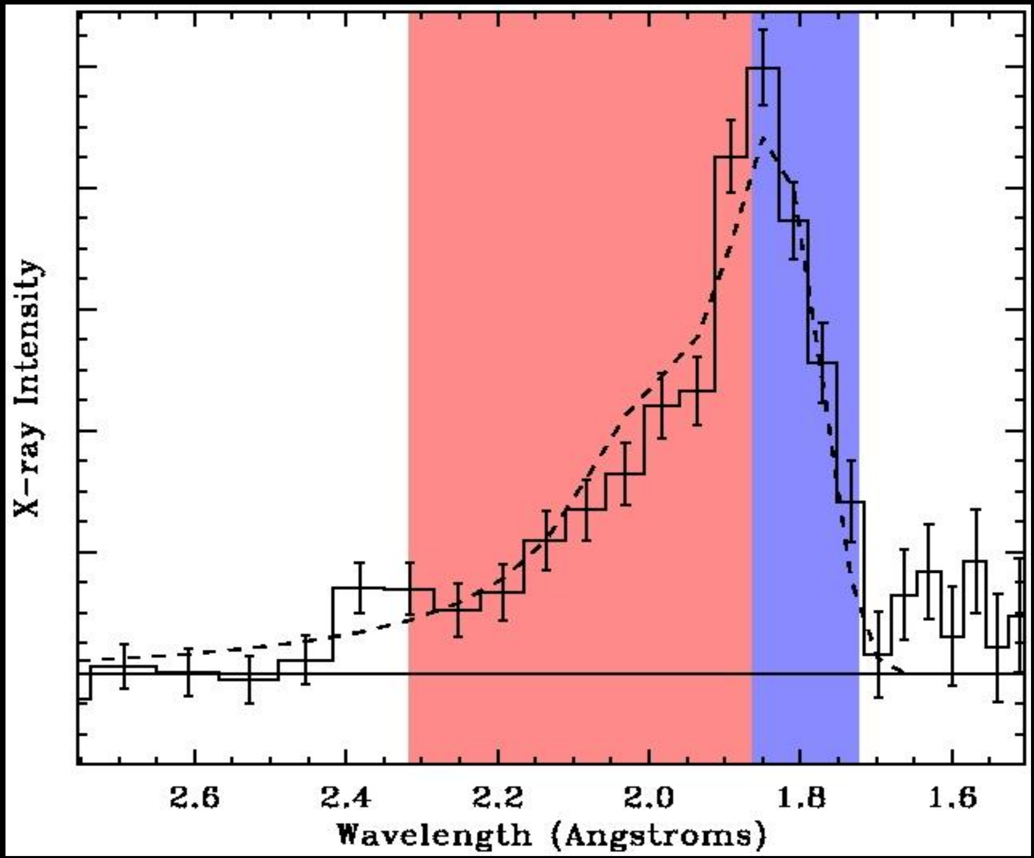
First measurement of the spin-down rate of a CCO:

- ➔ dP / dt = $(8.68 \pm 0.09) \times 10^{-18}$
- ➔ $B_s = 3.1 \times 10^{10}$ G, the smallest ever of a young neutron star and consistent with being a fossil field
- ➔ Strong support for "anti-magnetar"
- ➔ Consistent with low luminosity and lack of magnetospheric activity or synchrotron nebulae

Broad Relativistic Iron Line From Serpens X-1

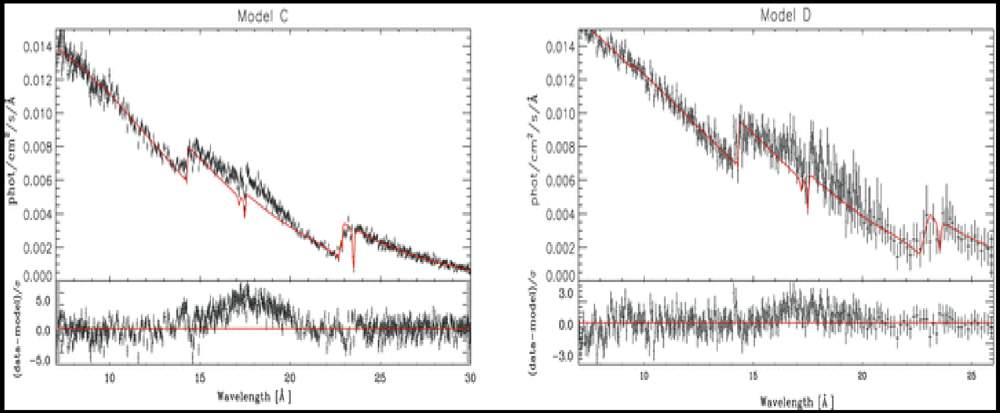
- Neutron star low-mass X-ray binary (LMXB) Serpens X-1
- Previously known broad iron Kα emission line
- Asymmetric shape of the line supports an inner accretion disk origin

➔ First strong evidence of a relativistic line in a neutron star LMX



Bhattacharyya & Strohmayer, 2007, ApJ 664, L103

Broad O VIII Lyα line in the ultracompact X-ray binary 4U 1543-624

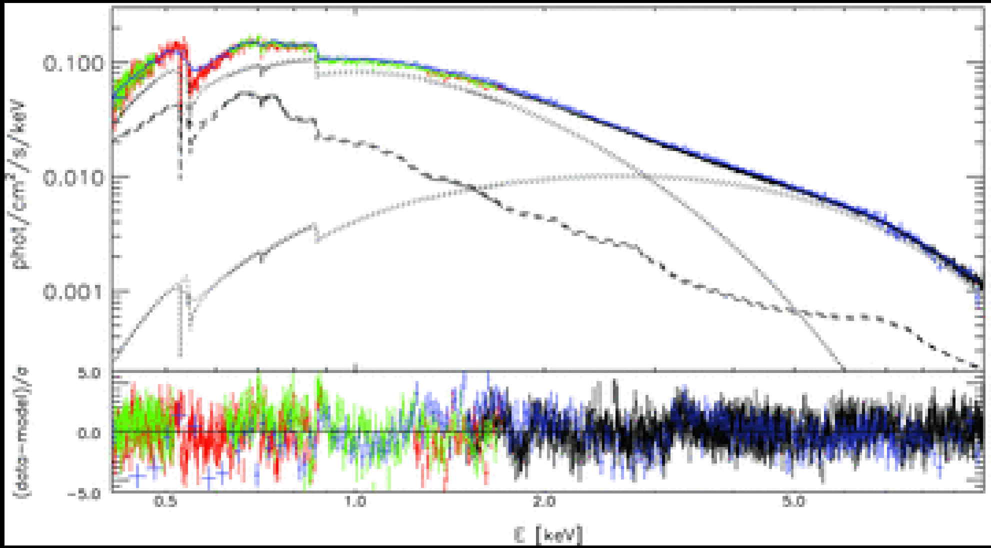


- Discovery of a broad emission feature at ~0.7 keV with the high-resolution spectrographs of the XMM-Newton and Chandra satellites.
- Confirmation of the presence of a weak emission feature at ~6.6 keV

➔ O VIII Lyα and Fe Kα emission caused by X-rays reflected off the accretion disc in the strong gravitational field close to the neutron star

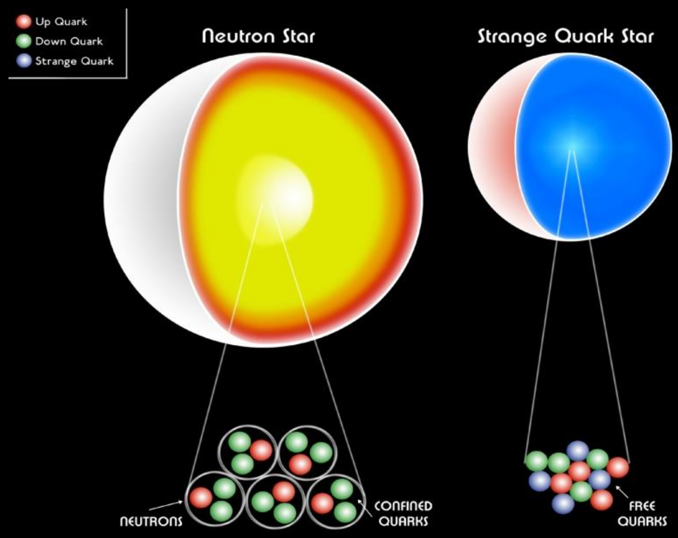
- Ultracompact X-ray binary 4U 1543-624:
  - donor star is a CO or ONe white dwarf
  - transfers oxygen-rich material to the accretor, conceivably a neutron star.

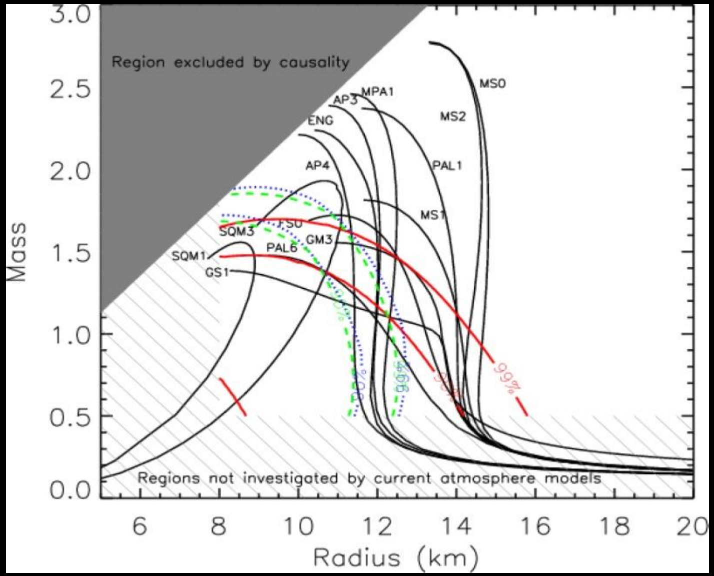
➔ The X-rays reprocessed in the oxygen-rich accretion disc could give a reflection spectrum with O VIII Lyα as the most prominent emission line.



O.K. Madej & P.G. Jonker, 2011, MNRAS 412, L11

Constraining the Equation of State of Supra-nuclear Dense Matter





- Quiescent X-ray binaries in globular clusters: ω Cen, M13, NGC 2808

N. Webb & D. Barret, 2007, ApJ 671, 727

- Distance to globular clusters is well known

- X-ray spectra are from a hydrogen atmosphere.:

➔ Radii to be from 8 km and masses up to 2.4 M_{sol}

➔Equations of state: normal nucleonic matter and one possible strange quark matter mode

Neutron Stars

-- Most important results:

- Blackbody & now spectral features
- Low-magnetic field magnetars
- CCO
- Relativistically broadened lines
- Structure of surface of neutron stars
- Connection between X-ray and Gamma-ray emission
- Equation of state of nuclear matter

XMM-Newton

- How to get observing time:
  - -- Can wait for a year:
    - --- AOs (deadline beginning to mid October)
    - --- http://xmm.esac.esa.int/
  - -- Can not wait:
    - ---TOOs
    - --http://xmm2.esac.esa.int/external/xmm_sched/too/too_alert.shtml

What’s past is prologue; what to come,
In yours and my discharge[1]

[1] W. Shakespeare, 1623, The Tempest, Act 2, Scene 1

XMM-NEWTON- THE NEXT DECADE

9-11 May 2015

ESAC, Madrid, Spain