Astrophysics of exotic stars: neutron stars in Be X-ray binaries

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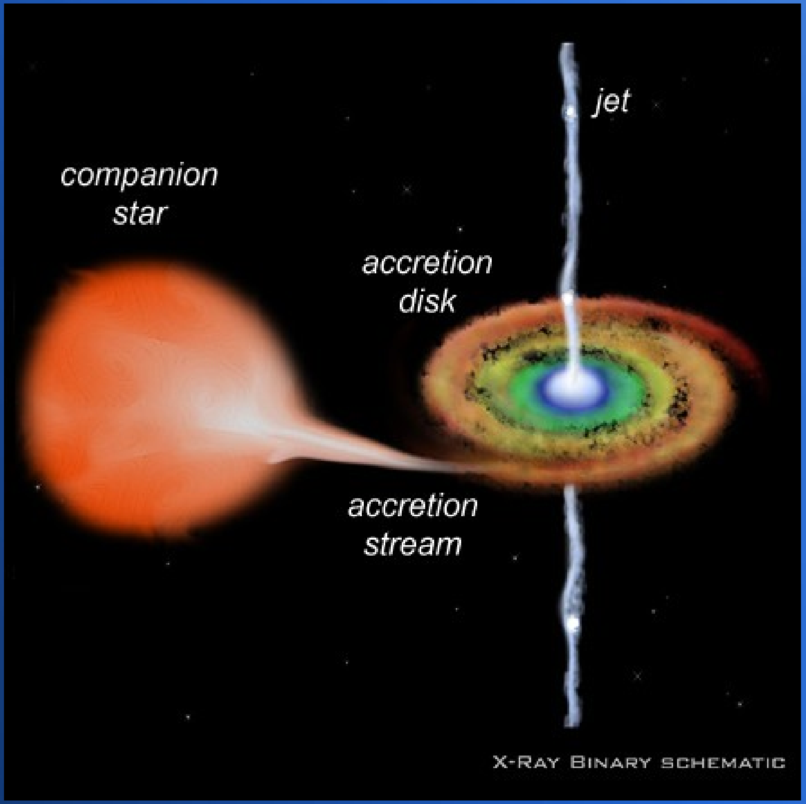
Variable sources in the sky

- Variable stars (erupting variable stars, novae, cataclysmic variables, etc.).
- Supernovae and Gamma-ray bursts.
- Active Galactic Nuclei (AGN) and quasars.
- Compact objects (neutron stars, black-holes).
- Anything else????



Model of a High-Mass X-ray binary

Exotic variable sources

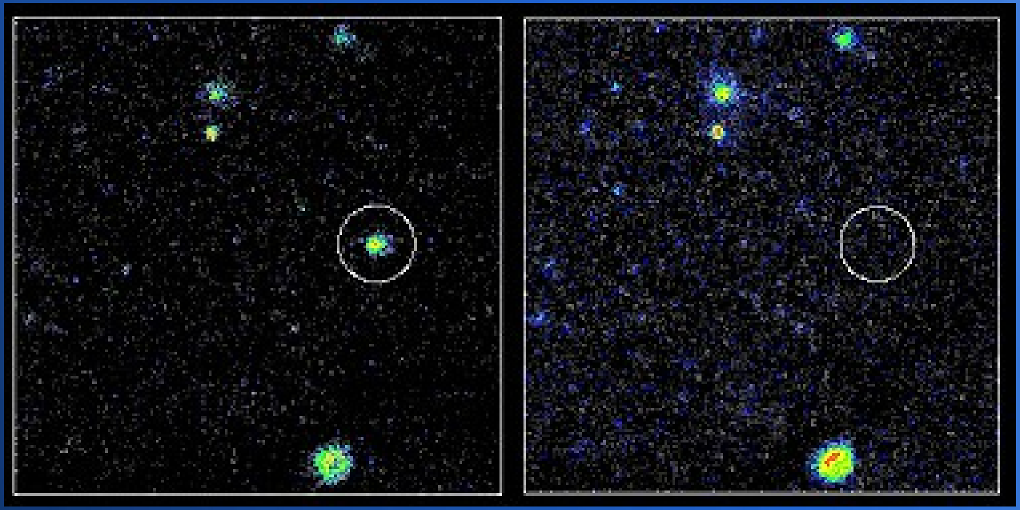
- Gravitational lensing.
- Binary mergers.
- Stellar tidal disruptions by black-holes.
- New classes of transients?

A tidal disruption occurs when a star wanders close to the central supermassive black-hole and is torn apart by tidal forces.

X-ray transients

Common for X-ray satellites. Because of:

- Continuous observations from space.
- *ROSAT* discovered many X-ray transients ($N \approx 10^5$).
- **But** currently, except *SWIFT* and *INTEGRAL*, little time is devoted to the observation of the whole sky.

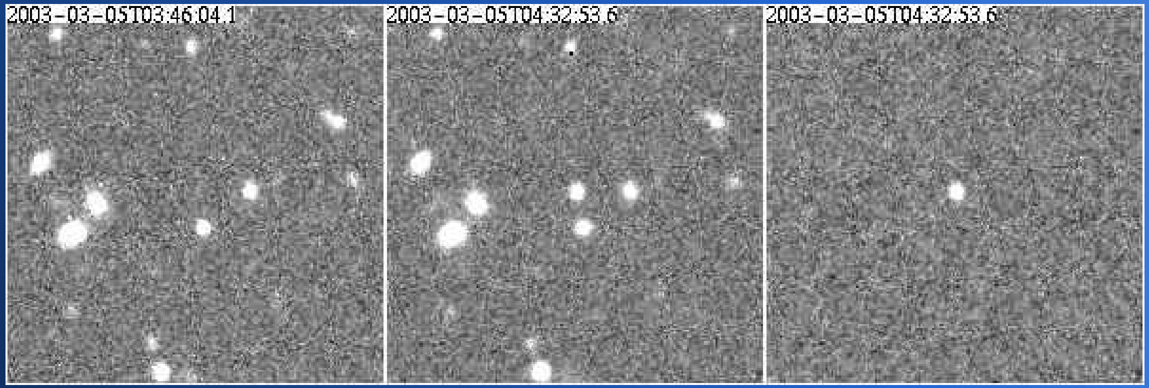


X-ray transient source RX J0045.4+4154

Optical transients

Not possible for large optical telescopes. But feasible for robotic optical telescopes on Earth. Because of:

- Large observation flexibility.
- Rapid slew times.
- “Cheap” and can be located everywhere → continuous observations.
- Additional observations can be triggered with large X-ray/Optical observatories.



Optical burst detected by difference imaging (right hand frame) in the Deep Lens Survey (DLS).

V0332+53

"Activity from the Be/X-ray binary system V 0332+53 during its intermediate-luminosity outburst on 2008"

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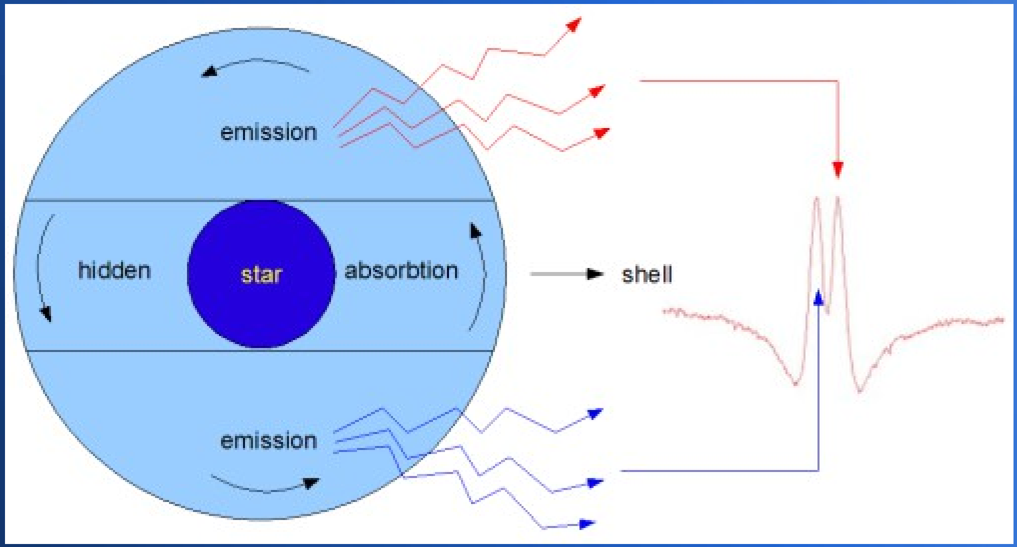
X-ray pulsars

HMXBs contain early-type (O or B) optical companions. Material from the giant is transferred to the NS which in turn may produce X-ray activity.

Be X-ray pulsars

The companion star is a *Be* star that rotates very rapidly and apparently sheds a disk of gas around its equator (Porter & Rivinius, 2003).

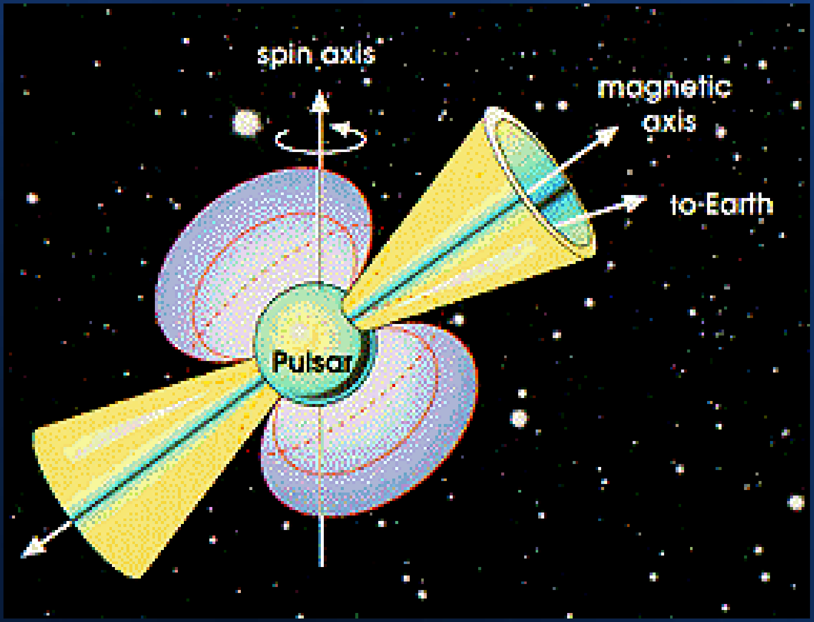
- The orbits of the neutron star with these companions are usually large and very elliptical in shape.
- When the neutron star passes nearby or through the *Be* circumstellar disk, it will capture material and temporarily becomes an X-ray pulsar.
- The circumstellar disk may (or not) be constant.



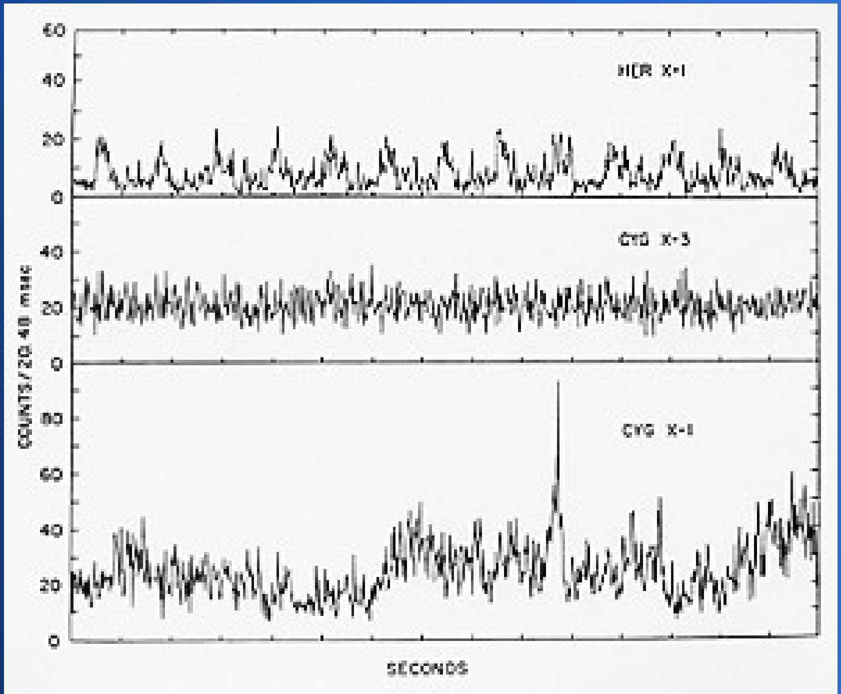
Model of a typical Be star (Kogure & Hirata. 1982)

X-ray pulses

- Due to the misalignment of the rotation and the magnetic field axes of the NS.
- They have as the period P_{spin}



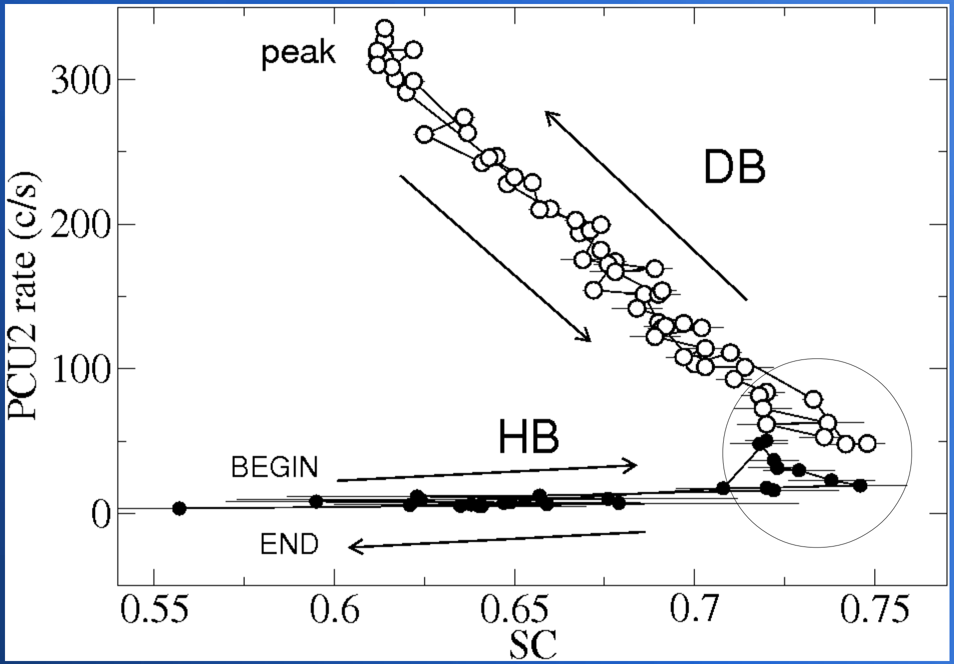
A diagram of a pulsar, showing its rotation and magnetic axes.



15-second X-ray samples. The 1.24 s pulsar period associated with Her X-1 is immediately evident from the data

X-ray (accretion) states

- Contrary to the case of BHs, timing-spectral studies of the accretion state in Be HMXBs have been barely performed.
- Only the **bright type II (i.e. giant) outbursts** have been "widely" studied (Reig+06, Reig+12). $L_X \approx 10^{38}$ erg/s
- There are two branches (i.e. accretion states) in the hardness-intensity diagram: **horizontal branch** (low-intensity state, with high variability) and **diagonal branch** (high-intensity state).
- BUT: what is the situation for outbursts with $10^{37} \leq L_X \leq 10^{38}$ erg/s, i.e intermediate-**outbursts** ???



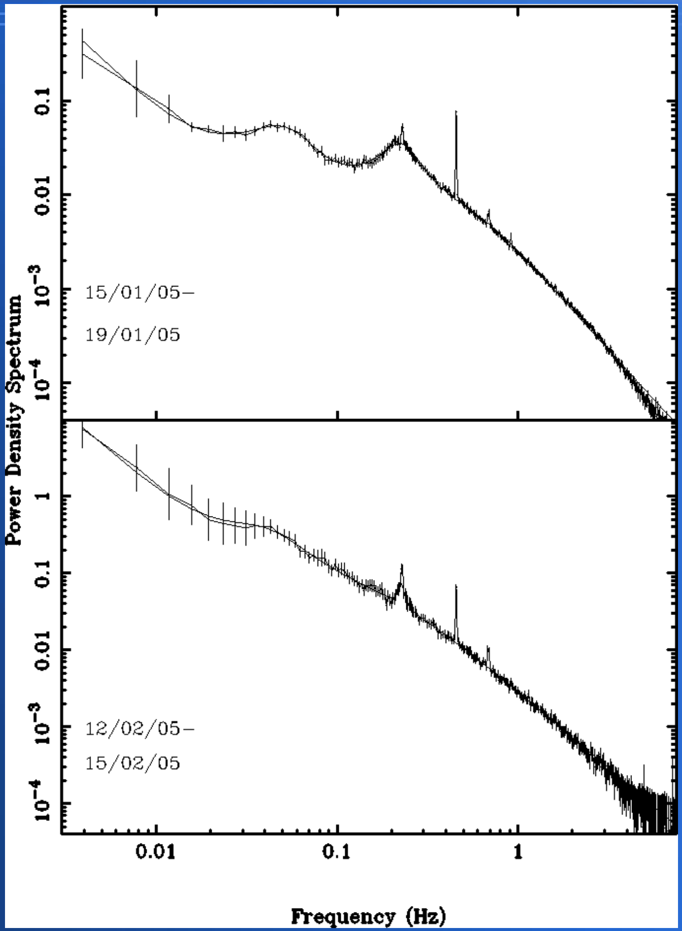
Hardness-intensity diagram of KS 1947+300 showing two spectral branches: a low-intensity (horizontal) branch and high-intensity (diagonal) branch.

V0332+53

- Be X-ray HMXB most of the time in the quiescent state. Interrupted by sudden increase of X-ray flux episodes (reaching the Eddington luminosity in type II outbursts).
- Discovered by the *Vela 5B* satellite (Terrell & Priedhorsky, 1984; Whitlock, 1989).
- Optical counterpart is a O8-9Ve star at D = 7 kpc (Negueruela+1999)
- Discovery of *pulsations* with X-ray period of $P_{spin} = 4.4$ s
- Orbital parameters: $P_{orb} = 34.2$ d ; e = 0.31 (Stella+1985)
- X-ray spectra show *QPOs* (0.05 Hz, 0.22 Hz; Qu+05) and *cyclotron lines* (25 keV, 50 keV, 70 keV,...; Kreykenbohm+05, Tsygankov+06).

Quasi-Periodic Oscillations (QPOs)

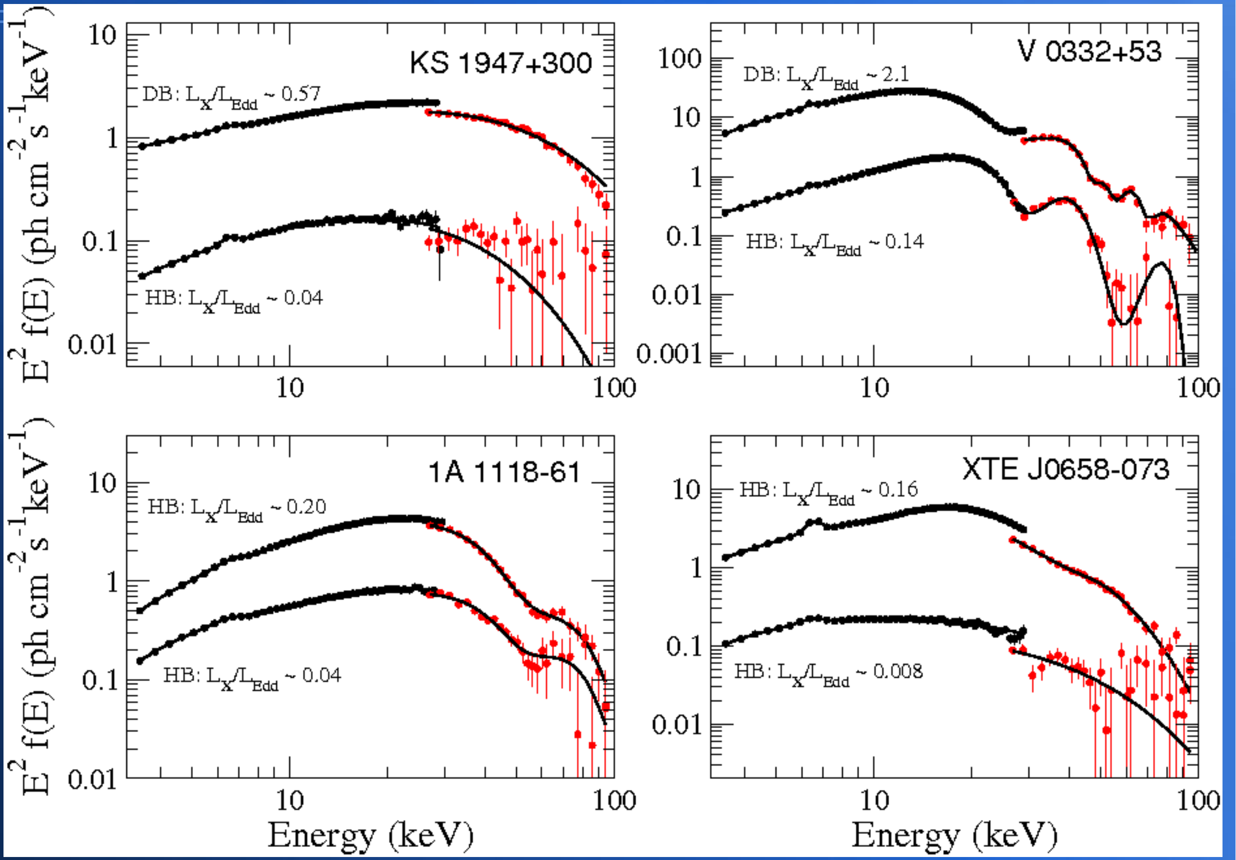
- They indicate the presence of an inner accretion disc.
- Sometimes present in the X-ray emission.
- Originated from the inner parts of the accretion disc around the NS (not necessary from the innermost regions).
- Frequencies commensurate with the spin of the NS (4.4 s).



Power spectra of V0332+53 obtained from two different datasets (Qu+2005).

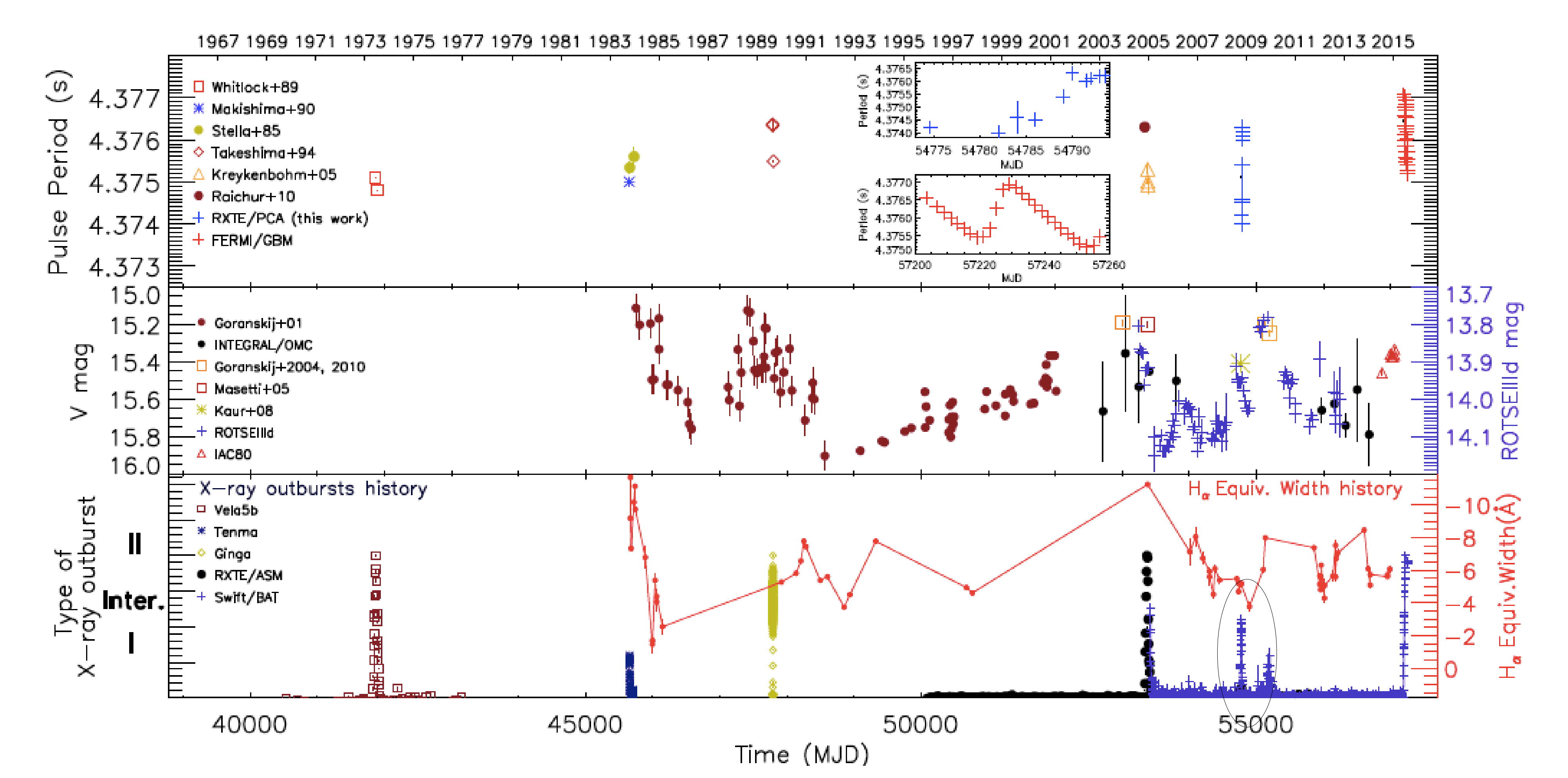
Spectral analysis

- *RXTE* spectra fitted well with a model consisting of a power-law with a high-energy exponential cut-off (@ 10-20 keV).
- Spectra distorted by the presence of cyclotron resonant scattering features → strong B (∝ 2.7×10^{12} G)
- <u>Unknown physical components.</u>
- Phenom. model: Model used:**phabs*constant*gabs*gabs(cutoffpl + gaussian)** for the 1-60 keV *SWIFT* + *RXTE* spectra.



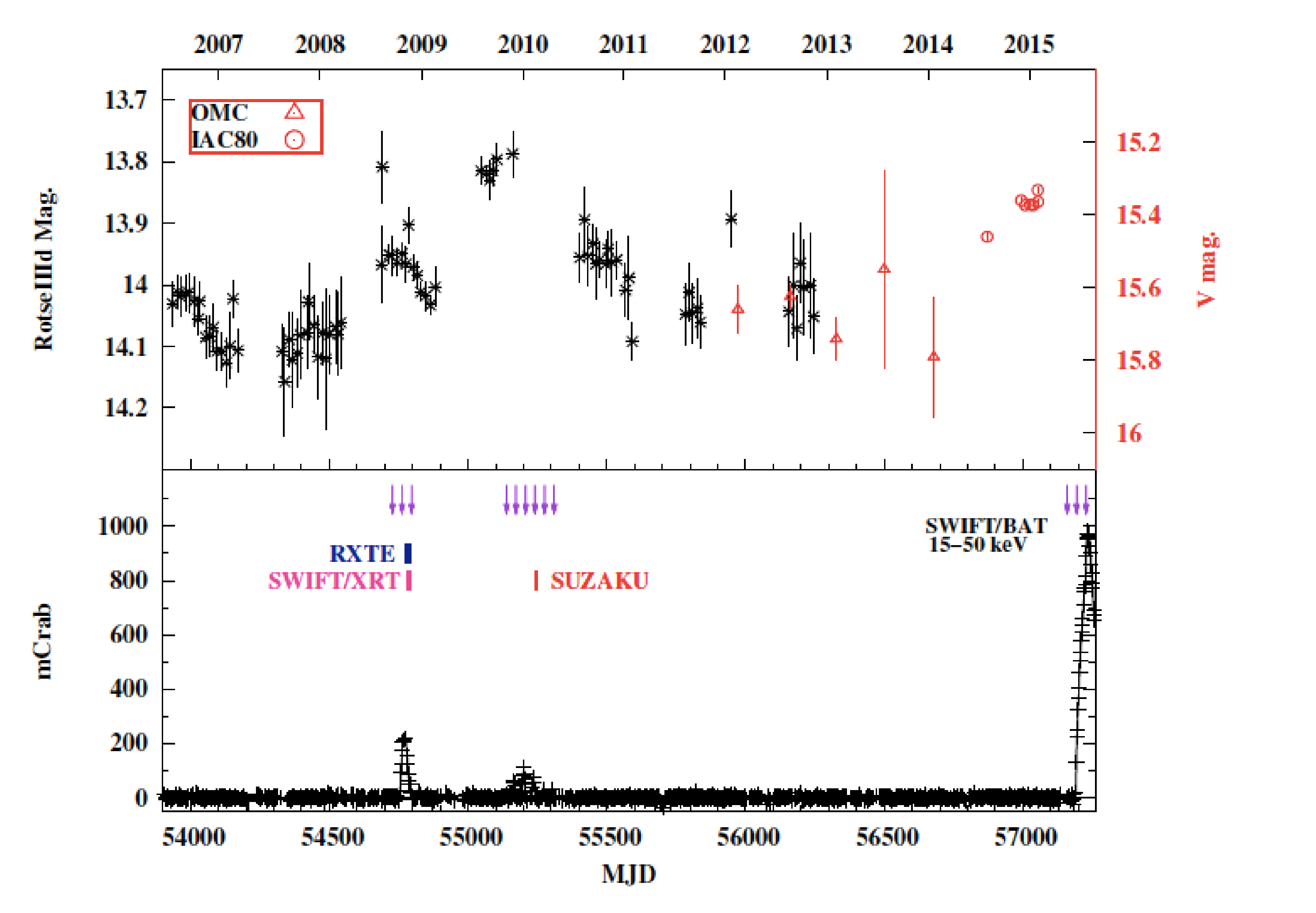
Average 2-100 keV energy spectra in the low and high intensity states (from Reig+12).

Long-term evolution



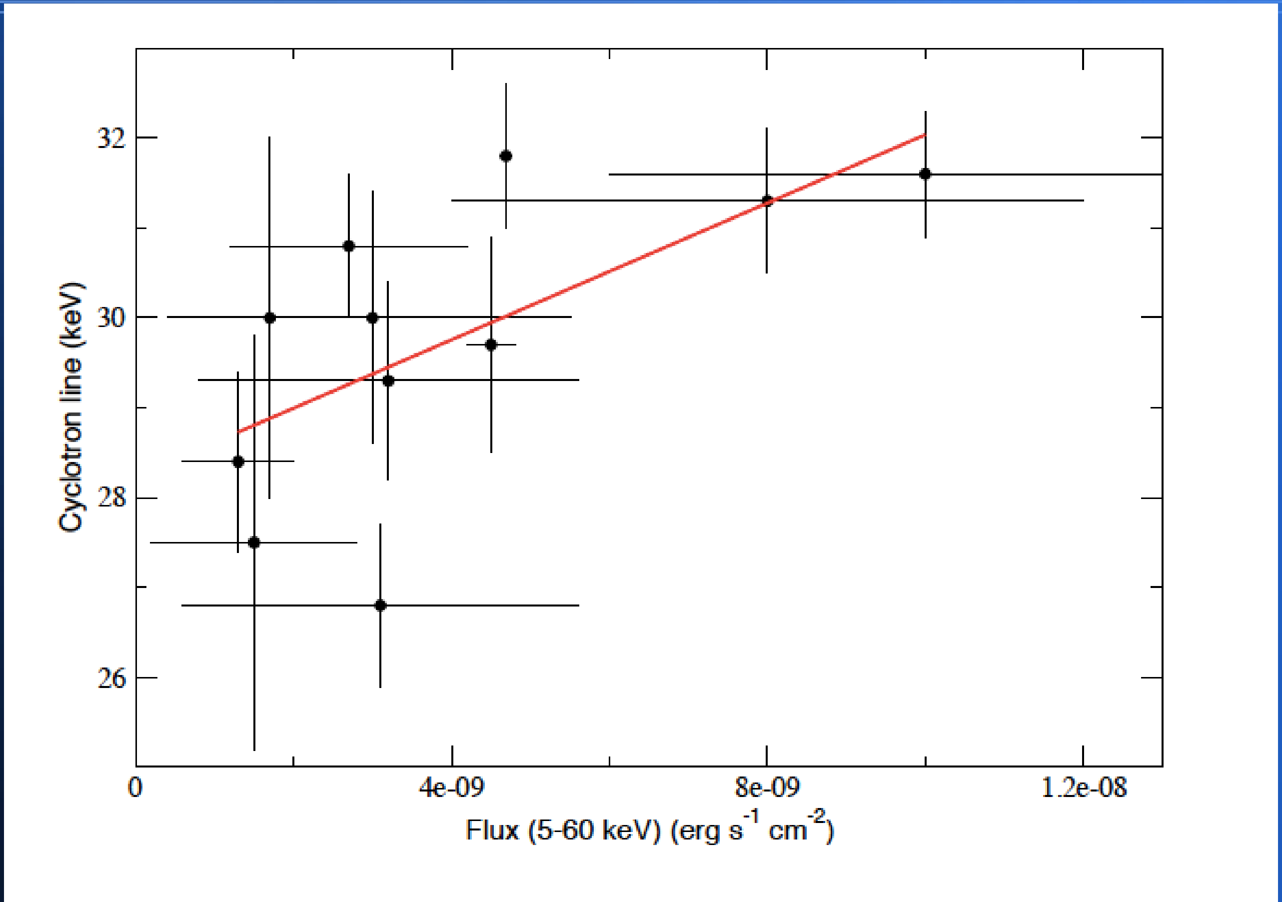
Long-term evolution of V0332+53 since its discovery in 1973.

The outburst on 2008



X-ray and optical light curve since 2008

Spectral results



Cyclotron line energy vs. flux in X-rays. <u>Important relationship for constraining theoretical models on the physics of Neutron Stars. Previously found in very few other sources.</u>

Timing results

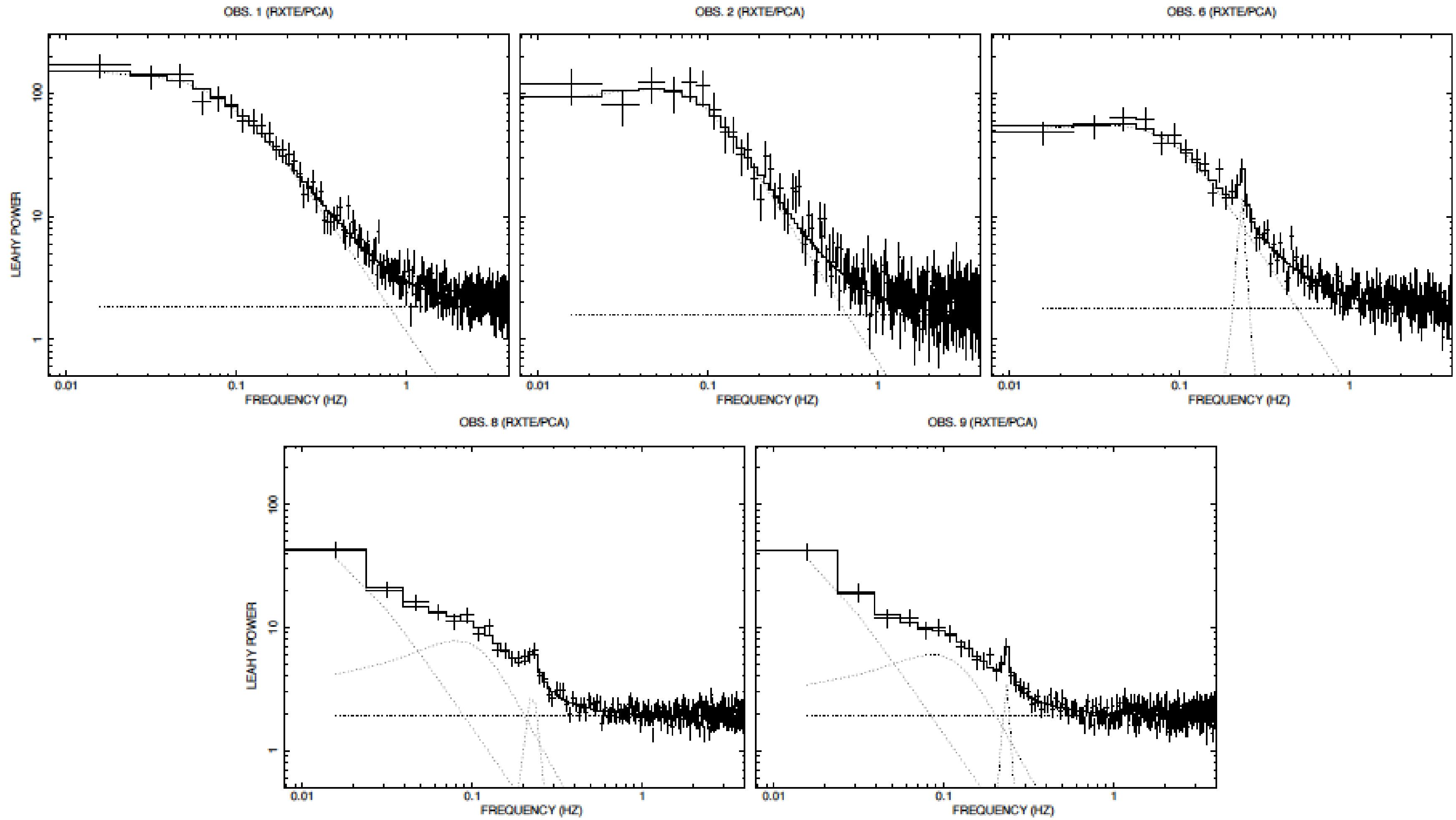


Fig. 5. Power density spectra of the *RXTE* PCA data in the energy and frequency range (2-60 keV) and 0.008-4 Hz, respectively, during observations 1, 2, 6, 8 and 9 (top-left to bottom-right) with the best fit model (solid line) and the model components (dotted line). The results of the fitting are shown in Tab. 2 and discussed in the text.

Conclusions (II)

- *Spectral-timing studies of source states* have been very useful to understand the physics of accretion for Black Hole binaries. *Very scarce* yet for Be X-ray HMXBs with NS.
- We seek to use the same tools for Be X-ray HMXBs with NS.
- Previous works (Reig+6,12,13) have shown *interesting* results for very bright accretion states (type II outbursts).
- We have presented here an introduction of our work (accepted *in A&A*) on the spectral-timing variability of the Be HMXB V0332+53 during its 2008 (intermediate) outburst (*SWIFT, RXTE, Suzaku* and optical data).
- An additional goal is to investigate the Be-disc/NS interaction thanks to our long-term multiwavelength monitoring from different ground-based telescopes: TUBITAK National Observatory in Antalya (Turkey), Observatorio del Teide (Canary islands) and Sierra Nevada Observatory (Granada) in Spain.
- Our observations cover an unexplored intensity state (intermediate). The goal is: **to give further insights into the accretion mechanisms around these (still enigmatic) compact objects and to "see" the *closest inner regions* around the NS.**

(Final) conclusions

- The era of research on <u>optical transients</u> is about to start.
- Optical observations in small, cheap and worldwide-distributed optical telescopes constitutes an advantage with respect big telescopes.
- Flexibility of observations, good strategy and quick responses are mandatory.
- Both photometric and spectroscopic studies in optical (and IR) are mandatory for reaching the goals.
- **Let us discover our non-static Universe !!!!**

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