3. High Energy Emission in Binary Systems

Compact objects in X-ray binaries

Zel'dovich & Guseynov (1966, Soviet Astr.; 1966, ApJL) pointed out that X-rays emitted from single-line spectroscopic binaries would provide strong evidence for the presence of either a Neutron Star (NS) or a Black Hole (BH):

"Collapsed stars, whose existence is forecast by general relativity, should be observable solely by their gravitational field" (Zel'dovich & Guseynov 1966, ApJ)

Companion stars in X-ray Binaries

- High Mass X-ray Binaries (HMXBs): companion mass $M_* \geq 5 - 10 M_\odot$
  - Optical counterparts look like normal early type (OB) stars (spectra classified without difficulty)
  - $L_{*,optical} > L_X$
  - Companion is a supergiant (almost) filling its Roche-lobe or a main sequence Oe/Be star (with Balmer emission lines originating from circumstellar material)
  - *Mass transfer occurs mainly via stellar wind* (supergiants may also accrete through Roche-lobe overflow), rather anisotropic in the case of Oe/Be stars (high density, low velociy equatorial mass loss, probably related to rapid rotation)
- Low Mass X-ray Binaries (LMXBs): companions mass $M_* \leq 1 M_\odot$
  - Optical counterpart very blue: spectrum consists of emission lines superposed on a blue continuum (unlikely that of an ordinar star)
  - $L_{*,optical} \ll L_{X,repr}$
  - Companion is a giant filling its Roche-lobe
  - *Stable mass transfer through Roche-lobe overflow*
  - Observational evidence supports the idea that optical emission of LMXBs is generated by the absorption of X-rays by the accretion disk and the subsequent re-radiation in the optical (X-ray reprocessing) (e.g. Van Paradjis & McClintock 1995; Chakrabarty 1998):

* detection of quasi periodic oscillations in the range 0.001-10 Hz in both the optical and X-ray bands (e.g. GX 339-4, Motch et al. 1983)
* correlated X-ray and optical outbursts in X-ray bursters (Lewin, van Paradjis & Taam 1993)
* coherent optical pulsations (0.1-10 s) detected in some LMXB pulsars (Her X-1, 4U 1626-67, GX 1+4)

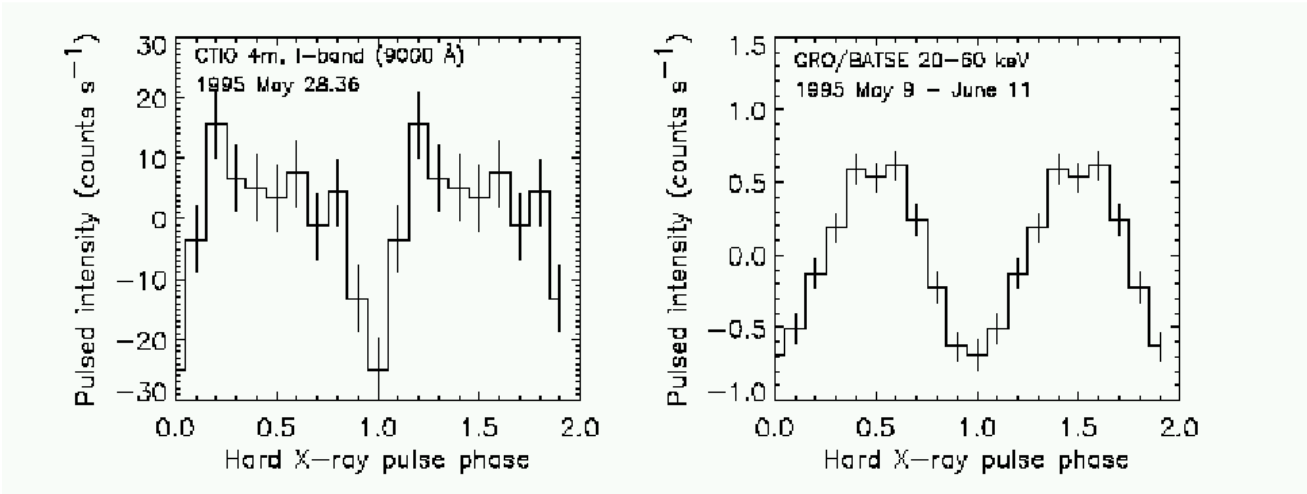


Figure 1: Intensity in the I and X-ray (20–60 keV) bands as a function of X-ray pulse phase for the LMXB pulsar 4U 1626-67 (from Chakrabarty 1998, ApJ). A coherent pulsation at 7.67s is detected in both bands, caused by rotation of the highly magnetized accreting neutron star. The optical pulsation can be understood as a reprocessing of the pulsed X-ray emission in the accretion disk.

➠ **Peristent** LMXBs: roughly steady sources (factors of a few variations in L_X; always detectable

in the X-ray band)

➠ **Transients** LMXBs (*Soft X-ray Transients* or *Novae*): X-ray (and > 5 mag optical) outbursts (often recurrent) during a few months/years, separated by long quiescent phases when the source is almost undetected in X-rays (up to 6-7 orders of magnitude fainter)

Almost all LMXBs containing BHs are transient, a fact still unexplained

For a review on the optical properties of XRBs see, e.g., van Paradijs & McClintock (1995), Charles & Coe (2006).

Black Hole Binaries

Some X-ray Binaries (XRBs) are believed to contain Black Holes (BHs) on the basis of dynamical measurements of the binary mass function:

$$F = \frac{M_c^3 \sin^3 i}{(M_c + M_*)^2} \qquad F = \frac{4\pi^2 a_c^3 \sin^3 i}{GP^2} \tag{1}$$

where i is the binary inclination with respect to the plan of the sky. If $M_* << M_c$: $F = M_c \sin^3 i$. Measuring F from the orbital period P and the projected semi-major axis $a_c \sin i$ (from the radial velocity shift of the companion spectral lines), it is possible to set a lower limit for M_c:

$$M_c \geq F \tag{2}$$

1) If $M_c > 3M_\odot$, the compact object is a BH, because modern models of nuclear interactions at supra-nuclear density show that the maximum mass for a stable Neutron Star (NS) is $M_{NS,max} = 1.8 - 2.2 M_\odot$ (Akmal et al. 1998, Phys. Rev. C).

2) Optical observations of the companion in quiescence yield a precise BH mass measurement (Orosz & Bailyn 1997, ApJ). In fact, in complete quiescence, the light curves are almost completely dominated by ellipsoidal modulations from the secondary star

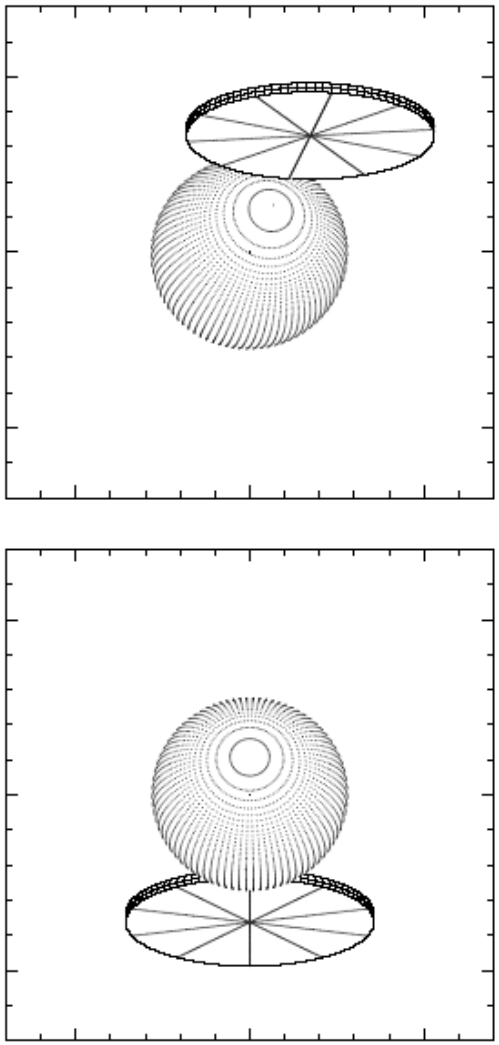


Figure 2: From Orosz & Bailyn (1997, ApJ)

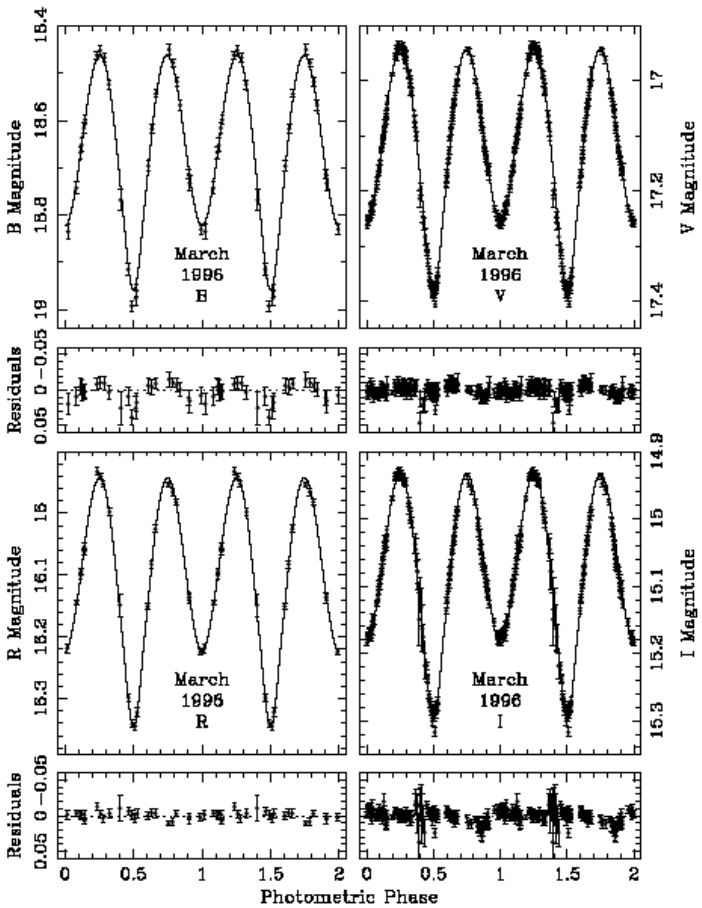


Figure 3: From Orosz & Bailyn (1997, ApJ)

Model fits to the light curves of GRO J1655-40, which take into account the temperature profile of the accretion disk and eclipse effects, yield i = 69.50±0.08 deg and $q = M_{BH}/M_* = 2.99 \pm 0.08$. This

allows for a measurement of the BH mass to an accuracy of $\approx$ 4% (Bailyn et al. 1998):

$$M_{BH} = F(1+q)^2/(q^2 \sin^3 i) \qquad \rightarrow \qquad M_{BH} = 7.02 \pm 0.22 M_\odot \tag{3}$$

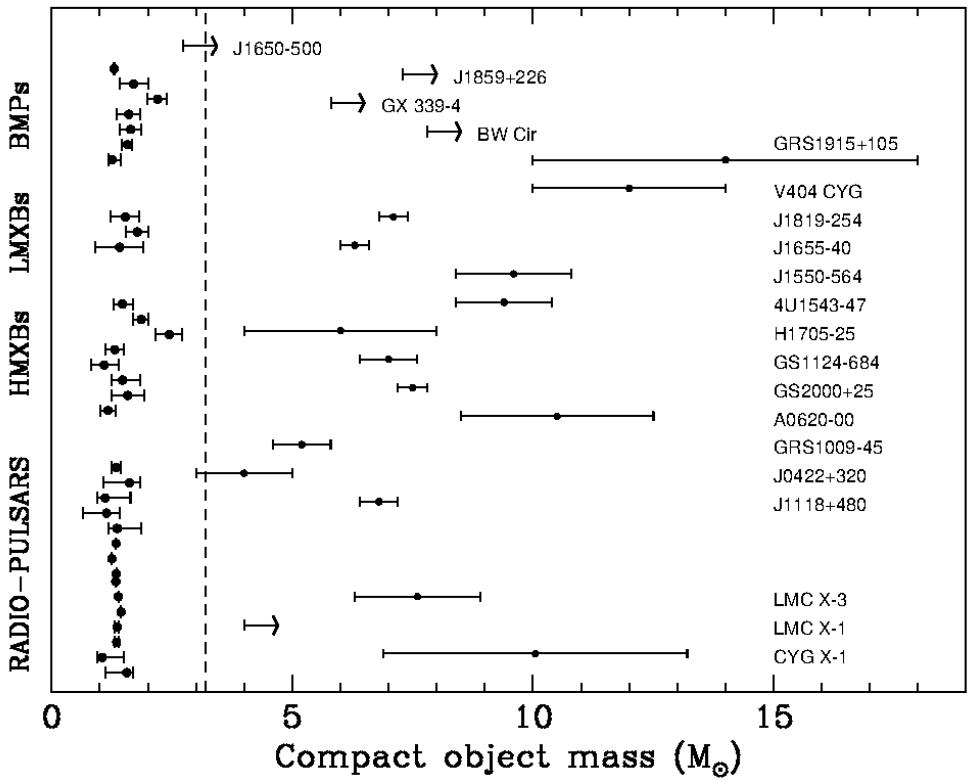


Figure 4: From Casares (2007, IAUS)

Black Hole Candidates (BHCs): XRBs for which there is a dynamical measurement of the compact object mass ($M_c > 3M_\odot$) + other $\sim$ 20 objects with *similar X-ray spectral and variability properties*.

BHCs: SPECTRAL STATES AND VARIABILITY

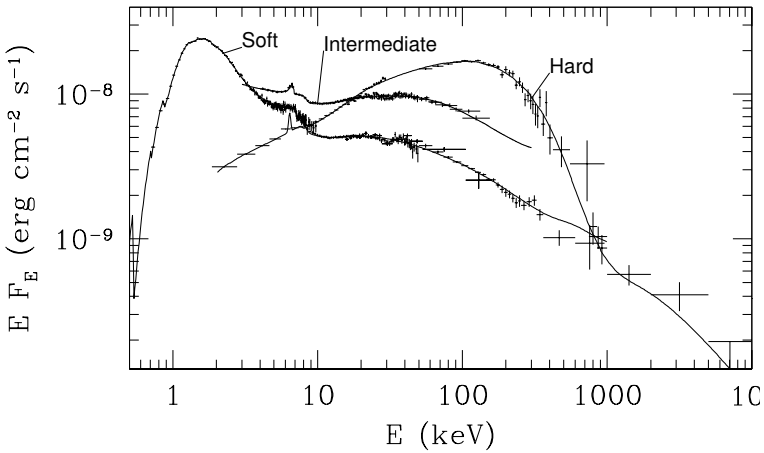


Figure 5: X-ray spectrum of Cyg X-1 (Zdziarski 2000, in IAU Symp. 195)

- HS (Soft State): $\rightarrow$ soft component with $T \sim 1$ keV, attributed to an accretion disk; weak power-law component with $\alpha \simeq$ 1.6–2.1 ($F_E \propto E^{-\alpha}$, $EF_E \propto E^{1-\alpha}$)
- LS (Hard State) $\rightarrow$ power-law component with E spec. index $\alpha \simeq$ 0.5–0.8 and cut-off at ~ 200 keV, produced by unsaturated comptonization by a hot, comptonizing medium (corona)
- IS/VHS (Interemediate/Very High State) $\rightarrow$ intermediate properties
- Spectral transitions are often observed in BHCs (e.g. Cygnus X–1, GS 1124–68). The sources GX 339–4 and Nova Muscae (transients) crossed all states (VHS/HS/IS/LS), indicating a clear dependence of the state on the average accretion rate. Analysis of large data sets allows for a clear categorization of the spectral transitions (Belloni et al. 2005; Dunn et al. 2008).

BHCs: SPECTRAL/TIMING EVOLUTION

The dense coverage and high-flexibility of *Rossi-XTE* has led to a more dynamic view of the time evolution of the spectral states of transient BH binaries. Spectral and timing evolution are strongly linked.

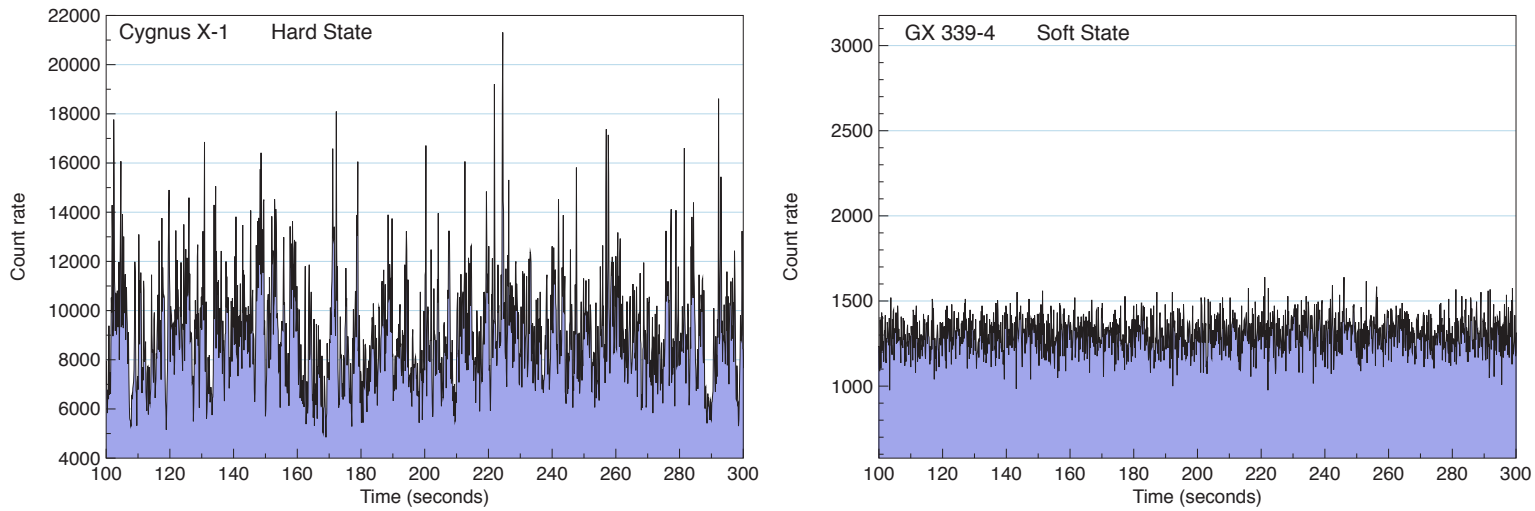


Figure 6: *Left panel*: a *RXTE*/PCA observation of Cygnus X-1 in the low-hard state. *Right panel*: a *RXTE*/PCA observation of GX 339-4 in the high-soft state (Belloni 2010).

The flux variability of a binned X-ray light curve C_i in count/s (with average $\bar{C} = \sum_i C_i/N$) is often measured in terms of the root mean square variability or rms (the same as standard deviation) and the fractional rms (f_{rms}):

$$rms = \sqrt{\frac{1}{N}\sum_i \left(C_i - \bar{C}\right)^2} \qquad f_{rms} = \frac{rms}{\bar{C}} \tag{4}$$

The X-ray spectrum is often characterized in terms of a spectral hardness (or hardness ratio), defined as the ratio of observed counts in two energy bands.

Two diagrams are particularly useful for characterizing the behavior of BHCs: the hardness-intensity diagram (HID), where the total count rate is plotted as a function of hardness, and the hardness-rms diagram (HRD), where the fractional rms (integrated over a broad range of frequencies) is plotted versus hardness.

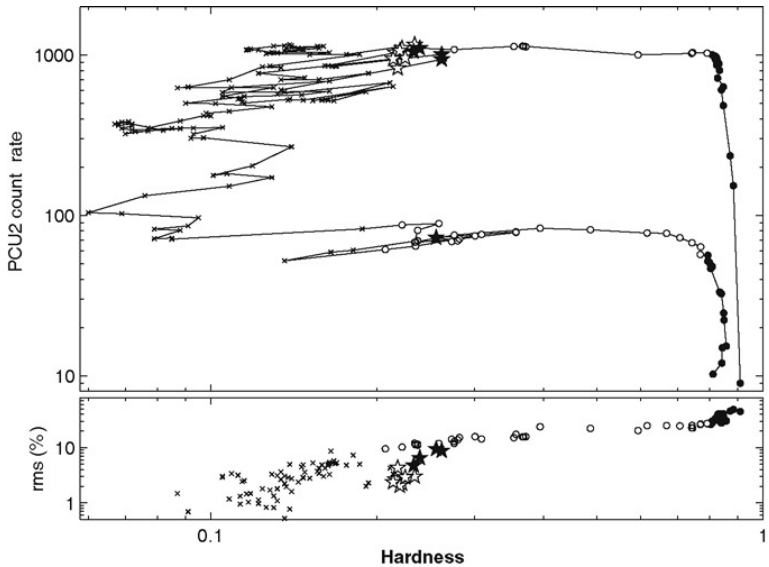


Figure 7: Hardness-intensity diagram (HID: top panel) and hardness-rms diagram (HRD: bottom panel) for the 2002-2003 outburst of GX 339-4 (Belloni 2010). RXTE/PCA count rate is in the energy range 3.8-21.2 keV. Hardness is defined as the ratio of counts in the energy bands 6.3-10.5 and 3.8-6.3 keV.

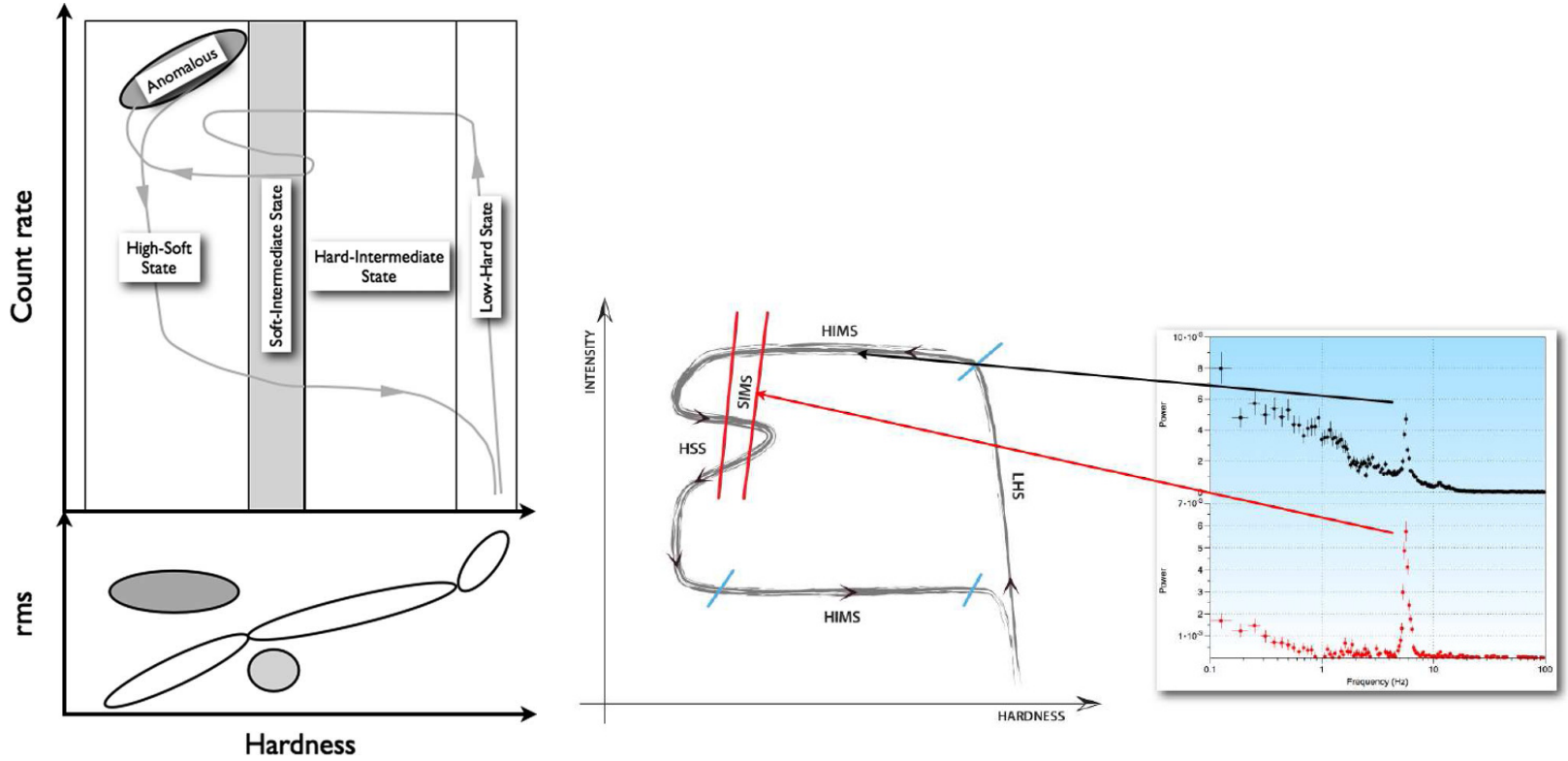


Figure 8: Sketch of a HID and a HRD of an outburst of an X-ray transient (Belloni 2010).

From the q-shaped HID (also referred to as ”turtle head”), four distinct branches can be identified, corresponding to the four sides of the q. These could be associated with the original pre-RXTE states.

Disk instabilities and transient sources

The majority of the BHCs (including the microquasars GRO J1655–40 and GRS 1915+105) are transient sources, i.e. they undergo sudden X-ray and optical luminosity outbursts followed by quiescent phases (when the X-ray flux is orders of magnitude lower) $\Longrightarrow$ belong to the class of *Soft X-ray transients (SXTs)* or *BH transients (BHTs)*.

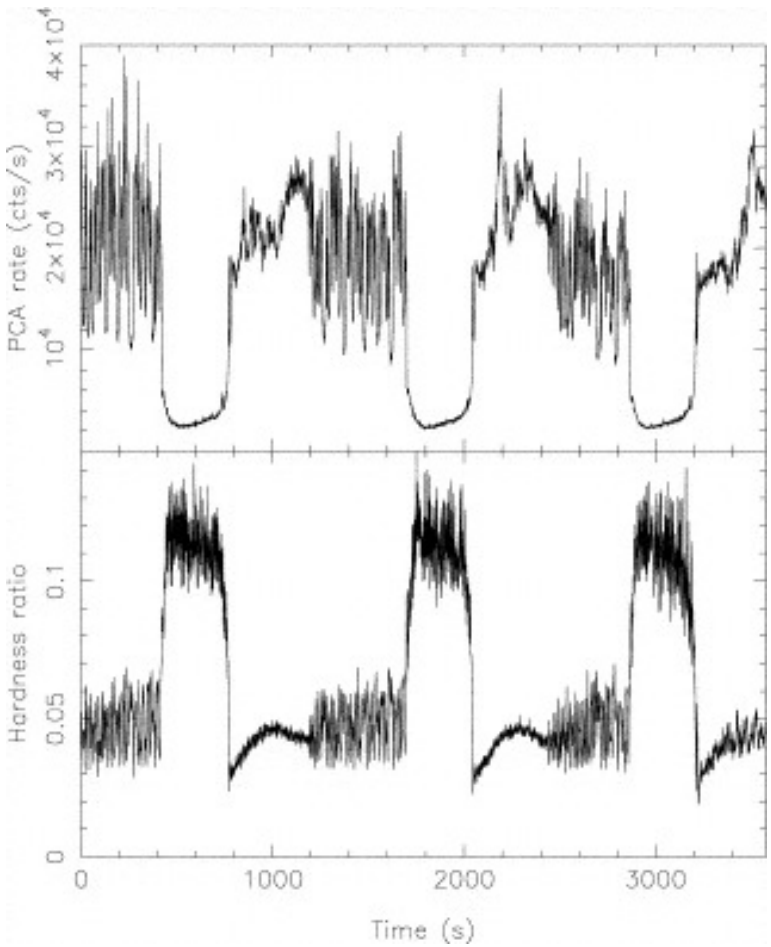
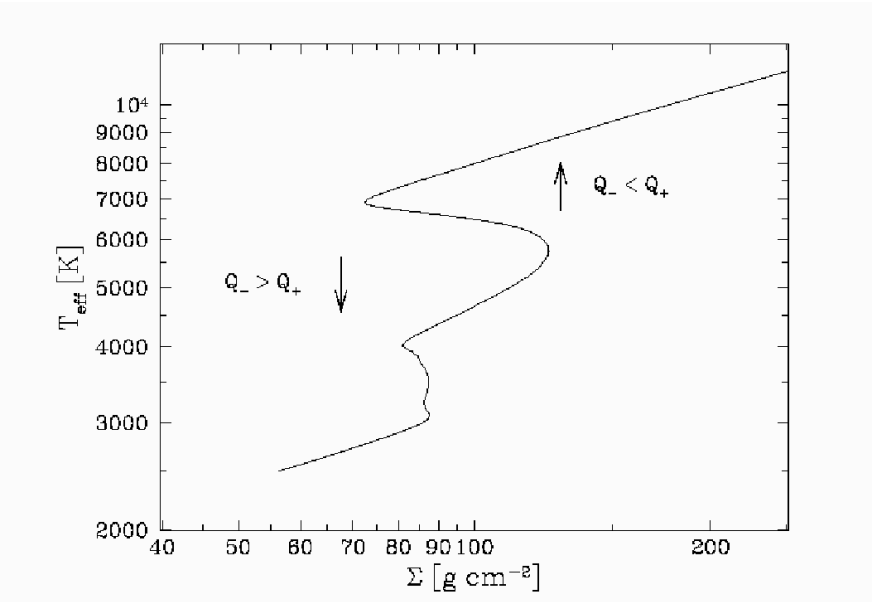


Figure 9: The 2.0–13.3 keV RXTE PCA light curve of GRS 1915+105 (Belloni et al. 1997, ApJL)

GRO J1655–40 and GRS 1915+105 are the first Galactic sources to show apparent superluminal motion in the radio band (caused by emission from matter ejected at relativistic velocities; Mirabel & Rodrìguez 1994, Nature).

Limit cycle behavior



(from Schreiber 2001, PhD Thesis, University of Göttingen)

For BHTs (and Dwarf Novae), this limit cycle behavior (local instability) occurs in regions of partial ionization and turns rapidly into a global instability

For microquasars, the limit cycle behavior appears in regions of the disk that are radiation-pressure dominated and where the opacity is dominated by electron scattering ($T \propto \Sigma^{-1/4}$; full relativistic hydrodynamics calculation in Szuszkiewicz & Miller 1998, MNRAS)

Neutron Star Binaries

Persistent Neutron Star LMXBs

- Average luminosity $L_X \sim 10^{35} - 10^{38}$ erg s^{-1}

  Distance estimates from: X-ray column density of the intervening ISM, flux emitted during Type I X-ray bursts, companion optical luminosity

- X-ray spectra of NS LMXBs

  Spectral components and their interpretation not as clear-cut as for BHCs

  – Above ~ 2 keV: power-law with an exponential cut-off at $\sim$ 10 keV (for high magnetic field NSs, it represents emission from a magnetic accretion-column)

  – In bright sources ($L_X \sim 10^{37} - 10^{38}$ erg s^{-1}), a second component may be present, typically fitted with a Planckian distribution (emission from the inner edge of the disc at the magnetospheric boundary)

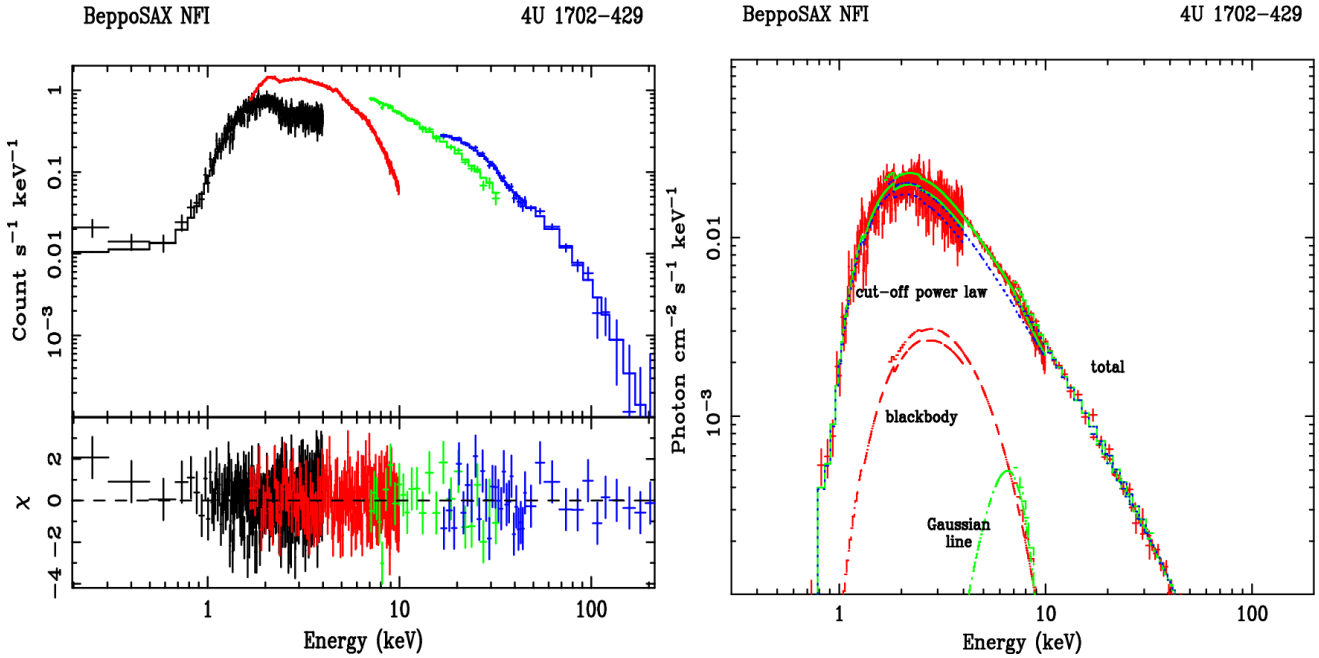


Figure 10: From Church et al. (2014).

- Persistent NS LMXBs usually show small variations of the X-ray flux and spectrum on timescales of hours/days (Hasinger & van der Klis 1989, A&A)

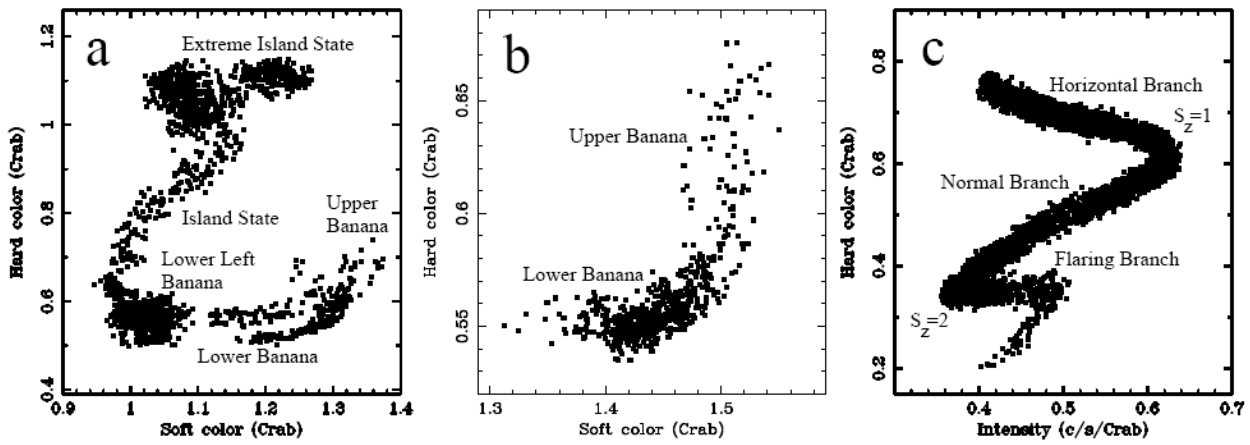


Figure 11: (a) Color-color plot of the atoll source 4U1608-52, (b) color-color plot of the GX atoll source GX9+1, and (c) intensity-color plot of the Z source GX340+0. RXTE/PCA data; soft colour 3.5–6/2–3.5 keV, hard colour 9.7–16/6–9.7 keV, intensity: 2–16 keV, normalized to Crab. Conventional branch names are indicated. Compare van Straaten et al. (2003), Reerink et al. (2004), Jonker et al. (2000a). From van der Klis (2004).

Continuum motion along the track and probable correlation position-$\dot{M} \Longrightarrow$ variations in the average $\dot{M}$ induce the observed changes

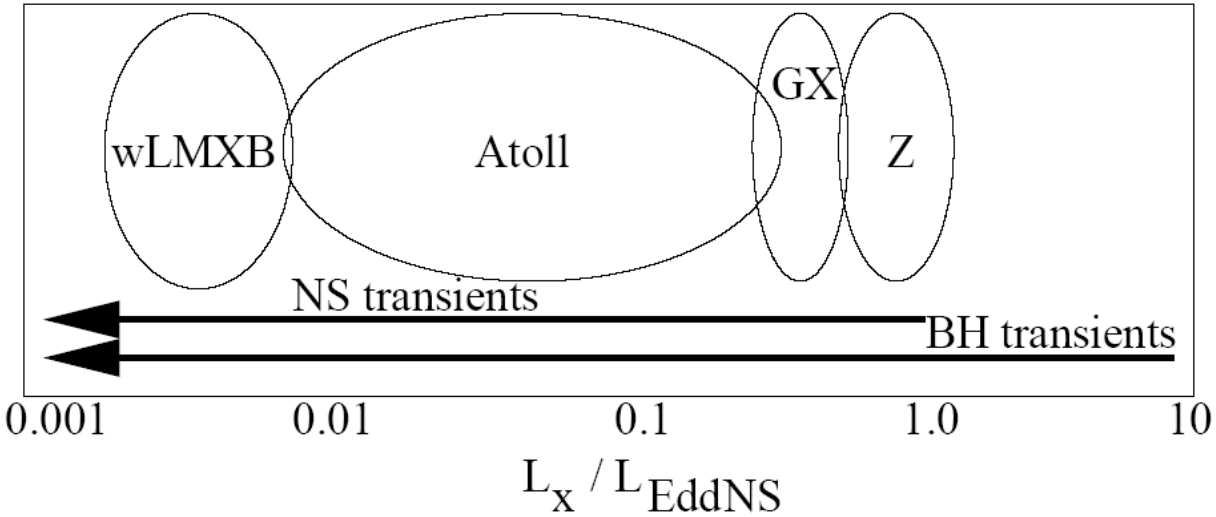


Figure 12: Luminosities attained by Z sources, GX atoll sources, ordinary atoll sources and weak LMXBs, respectively, as well as by neutron-star and black-hole transients. The extent of the L_X overlaps between these source types is undecided in detail, but those shown here are likely. From van der Klis (2004).

Persistent Neutron Star LMXBs: bursting sources

Many *atoll* sources show X-ray bursts (almost always recurrent on timescales of hours/days): sudden, rapid (1 to 10 seconds) increase in X-ray flux, reaching 5 to 20 times quiescent values, followed by a longest duration decay (10 seconds to several minutes)

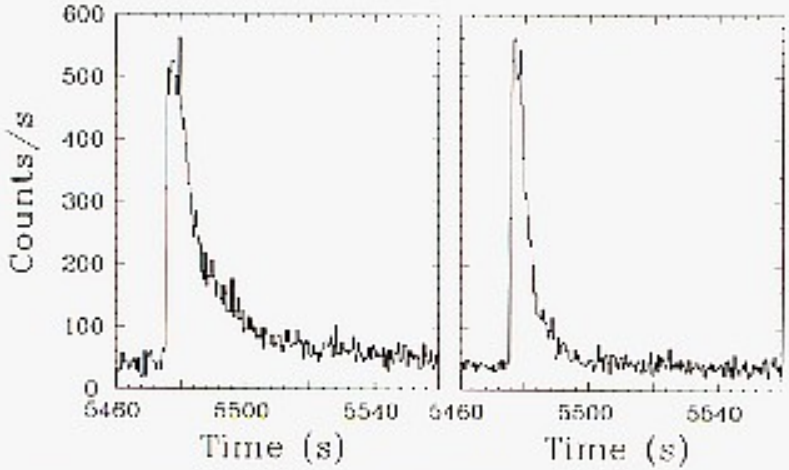


Fig. 4.3. One X-ray burst from 1702−429 observed with EXOSAT in the 1.2–5.3 keV band (left), and the 5.3–19.0 keV band (right). Time is in seconds since April 8, 1986, UT 03:31:31. The softening of the X-ray burst spectrum during decay is apparent as a relatively long tail in the low-energy burst profile. (Courtesy T. Oosterbroek.)

Figure 13: From Lewin, van Paradijs & Taam (1993)

First discovered in 1975 $\Longrightarrow$ solid surface of a neutron star

For comprehensive reviews on X-ray bursting sources see Lewin, van Paradijs & Taam (1995) and Strohmayer & Bildsten (2005).

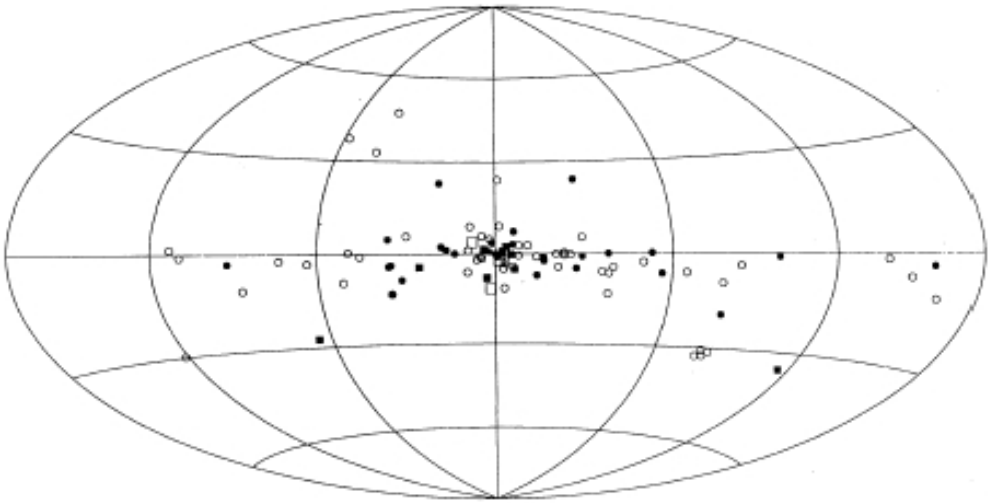


Figure 14: Plot (in Galactic coordinates) of the $\sim$ 100 known LMXBs. *Squares*: LMXBs in globular clusters; *circles*: LMXBs outside of globular clusters; *filled symbols*: X-ray bursters; *open symbols*: non-bursting sources (from Lewin, van Paradijs & Taam 1993).

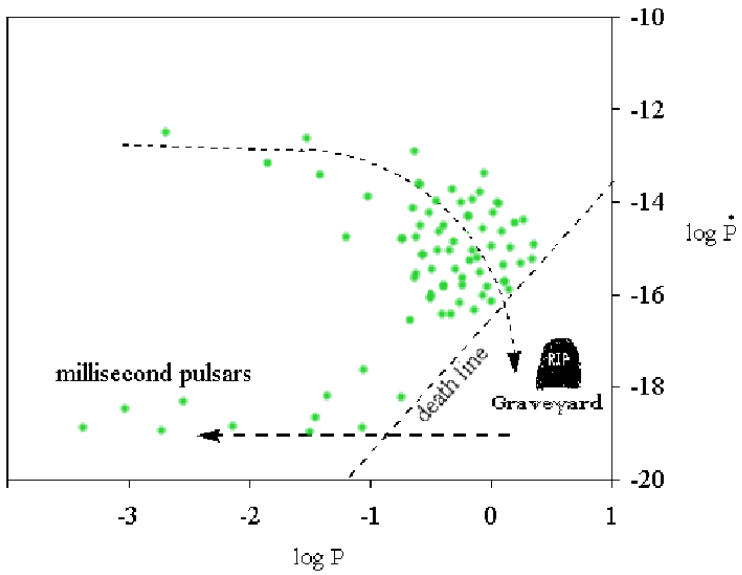
- 1) Type I X-ray bursts (from a subset of ~ 40 LMXBs): Thermonuclear explosions occurring on the surface of an accreting NSs (thermonuclear flash model; Woosley & Taam 1976; Maraschi & Cavaliere 1977)
- 2) Type II X-ray bursts: Observed essentially in two sources (the *Rapid Burster* MXB 1730-335 and the *Bursting Pulsar* GRO 1744-28) and attributed to a sudden release of energy associated with accretion of matter onto the NS surface

  $\longrightarrow$ **nature of the accretion instability not yet established**

Type I X-ray bursts

- Models of Type I X-ray bursts involve complex nuclear reactions (see, e.g., Strohmayer & Bildsten 2005)
- Millisecond (300-600 Hz) oscillations, so called burst oscillations have been discovered during bursts (see Section on timing properties of XRBs)

Persistent NS LMXBs: millisecond pulsars



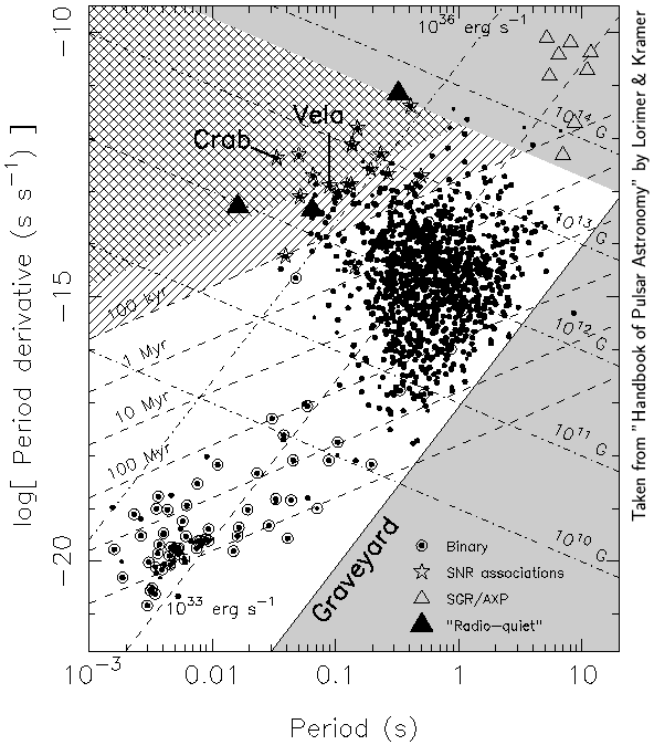
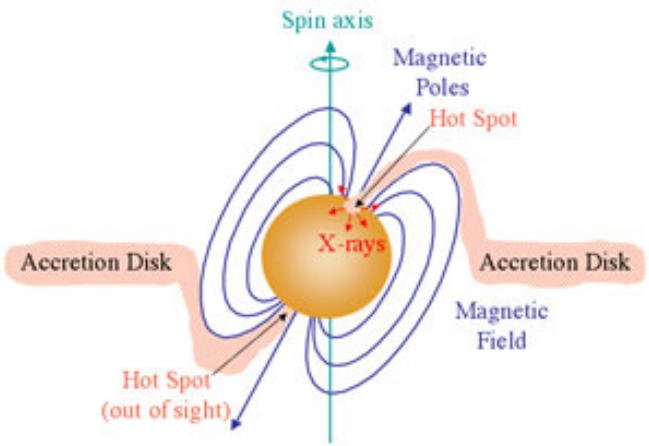


Figure 15: From http://astrosun2.astro.cornell.edu/academics/courses//astro201/pulsar_graph.htm

Figure 16: From "Handbook of Pulsar Astronomy", Lorimer & Kramer (also http://www.cv.nrao.edu/course/astr534/Pulsars.html)

- *millisecond pulsars* ($P < 10$ ms) enter the "graveyard"[a] as members of binary systems. As the companion evolves, mass and angular momentum are transfered from the companion to the pulsar



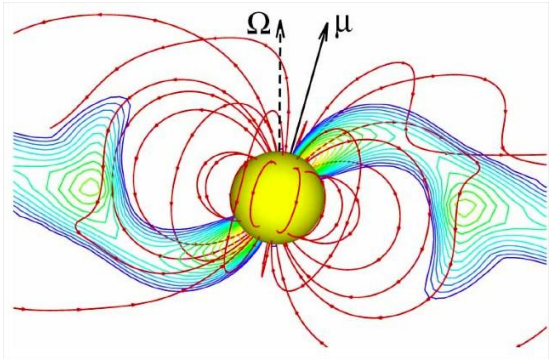


Figure 17: From http://astronomy.swin.edu.au/cosmos/X/X-ray+Pulsar

Figure 18: From http://astrophysics.fi/index.php?p=amp_descr

- Once the accretion phase finishes, the pulsar is "spun-up" and "born again" as a millisecond pulsar
- Equilibrium state reached when the rotation speed of the NS Ω_{NS} equals the local Keplerian speed Ω_K of accreting matter at the magnetospheric boundary r_{mag} (sse e.g. Bhattacharya 1995):

$$\Omega_{NS} = \Omega_K(r_{mag}) \tag{5}$$

[a]The death line corresponds to neutron stars with sufficiently low B and high P that the curvature radiation near the polar surface is no longer capable of generating particle cascades.

$$P_{NS,eq} = \frac{2\pi}{\Omega_K(r_{mag})} = 2\pi \left(\frac{r_{mag}^3}{GM}\right)^{1/2} \tag{6}$$

Taking $r_{mag} = r_A$ (Alfén radius, where $p_{mag} = p_{ram}$) as an order of magnitude estimate

$$r_A = \left(\frac{B_c^2 r_c^2}{\dot{M}\sqrt{2GM}}\right)^{2/7} \tag{7}$$

$$P_{NS,eq} = 1.9 B_9^{6/7} M_{c,1.4}^{-5/7} r_{c,6}^{16/7} (\dot{M}/\dot{M_{Edd}})^{-3/7}\,\mathrm{ms} \tag{8}$$

- In 1998 discovery of a highly significant pulsation at 401 Hz (2.5 ms) in the accreting ms pulsar SAX J1808.4-3658 (Wijnands & van der Klis 1998) $\Longrightarrow$ spectacular confirmation of the long sought link between LMXBs and ms pulsars!

- Accretion-powered, millisecond X-ray pulsations from a neutron star previously seen as a rotation-powered radio pulsar have been discovered in IGR J18245-2452. Within a few days after a month-long X-ray outburst, radio pulses were again detected. Some systems can swing between between accretion and rotation-powered millisecond pulsars on very short timescales (Papitto et al. 2013).

  Old, low magnetic field ms pulsars are "recycled" in LMXBs

- The problem with this picture is that it would predict that all millisecond pulsars are members of binary systems. But not all of them are ($\sim 90\%$ in the Galactic disk, $\sim 50\%$ in globular clusters). They may evaporate their companions away (PSR 1957+20; Fruchter et al. 1988)

Transitional millisecond pulsars

We nowadays know three systems that swing between a rotation-powered millisecond pulsar phase and an accretion phase (PSR J1824-2452, Papitto et al. 2013; PSR J1023+0038, Archibald et al. 2009; PSR J1227-4853, de Martino et al. 2010). They are called transitional Millisecond Pulsars (tMPs).

Their study is a topic of much current research interest, because understanding these systems is instrumental to understanding the formation of millisecond pulsars and the accretion physics in low magnetic field neutron stars.

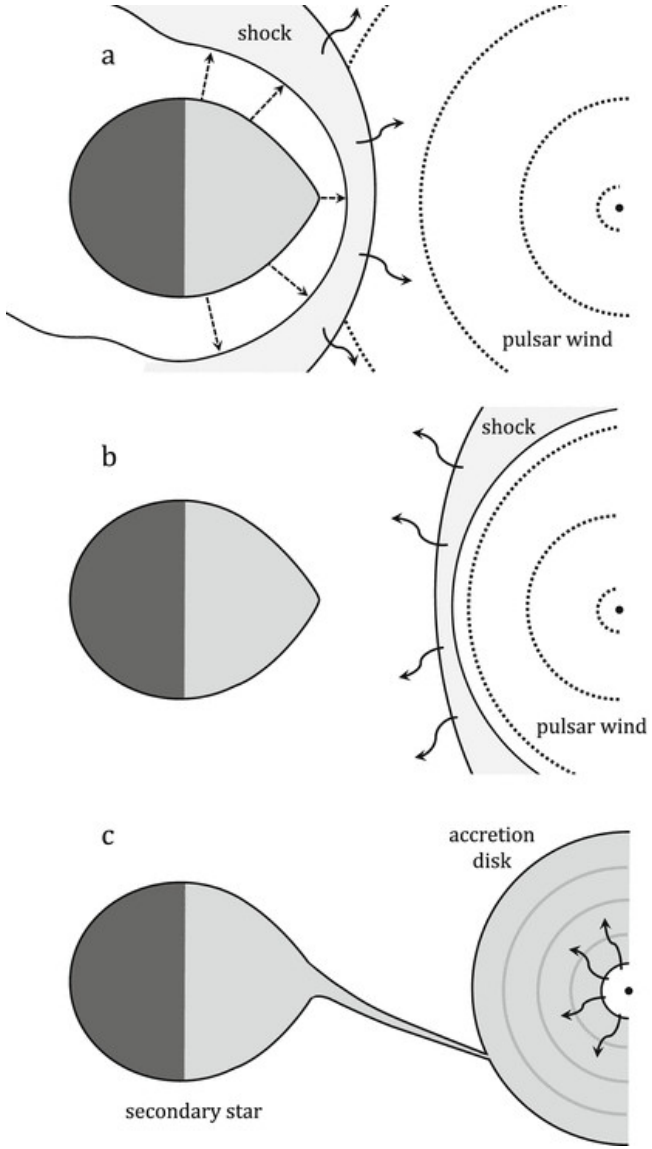


Figure 19: From Bogdanov (2017).

PSR J1023+0038

- accreting until 2000-2001 (Bond et al. 2002)
- in the millisecond radio pulsar phase until June 2013 (Archibald et al. 2009)
- accreting again at present (Halpern et al. 2013; Patruno et al. 2014; Stappers et al. 2014)

During the accretion phase:

* the infrared, optical and X-ray fluxes are larger and very variable

* *the radio pulsar activity quences and X-ray pulsations are observed* (e.g. Jaodand et el. 2016)

* millisecond optical pulsations appear (Ambrosino et al. 2017; Zampieri et al. 2019)

Gamma-ray emission (in the GeV band) is always present, with the flux increasing by a factor 3-5 during the accretion phase (Torres et al. 2017).

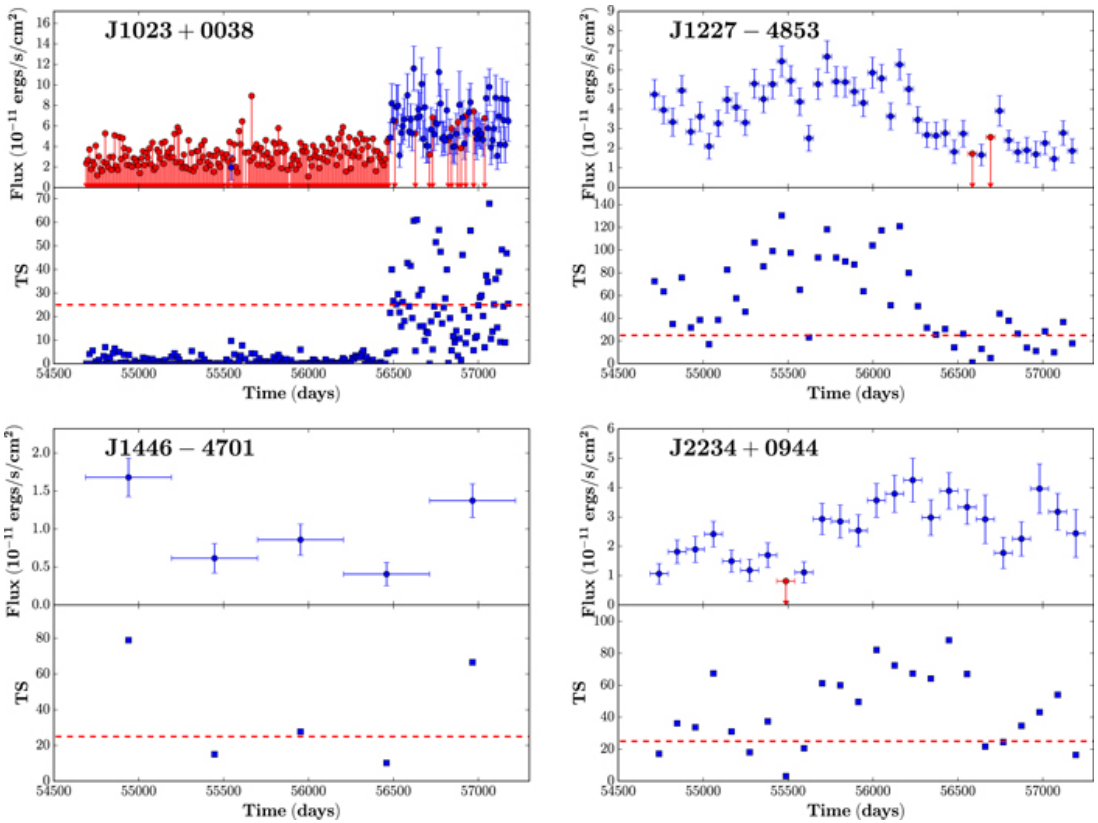


Figure 20: From Torres et al. (2017).

Persistent NS HMXBs: X-ray pulsars

About 20 persistent HMXRBs show slower oscillations of the X-ray flux on timescales of 1–10 s (first discovered in 1971–1972).

They enable the NS mass to be determined directly with ordinary astronomical techniques for binary systems (double-lined spectroscopic binaries). Six systems (including Her X-1, Cen X-3 and Vela X-1) are, in fact, also eclipsing $\rightarrow$ inclination angle constrained

- X-rays: pulsar spin period modulated by orbital motion $\rightarrow$ radial velocity of the NS
- Optical: Doppler shift of the absoption lines of the companion (typically a massive, early type star) $\rightarrow$ radial velocity of the companion

Table 1: NS masses of eclisping X-ray pulsars (from Charles & Seward 1995).

Source	Companion mass ($M_\odot$)	NS mass ($M_\odot$)
Her X-1	1.99	1.0$\pm$0.6
SMC X-1	16.8	1.1$\pm$0.3
Cen X-3	19.8	1.1$\pm$0.5
LMC X-4	14.7	1.4$\pm$0.5
Vela X-1	23.0	1.8$\pm$0.2

Most accurate NS mass measurements after those of binary radio pulsars

X-ray pulsars: basic model (Davidson & Ostriker 1973)

- Wind accretion from an early type star sufficient to power X-ray pulsars (but there debated cases, such as Her X-1 and Cen X-3)

$$f = 2.1 \times 10^{-3} M_{c,1}^{4/3} v_{W,1000}^{-4} P_{day}^{-4/3} \quad (9)$$

$$\dot{M}_W = f \dot{M}_* = 10^{-8} f_{-3} \dot{M}_{*,-5}\, M_\odot/\mathrm{yr} \quad (10)$$

$$L_{acc,W} = 10^{38} \eta_{0.1} \dot{M}_{W,-8}\, \mathrm{erg/s} \quad (11)$$

- Flow channeled at the magnetospheric radius by the NS magnetic field lines and accreted along the polar caps
- Strong, hot shock formed when gas hits the NS surface

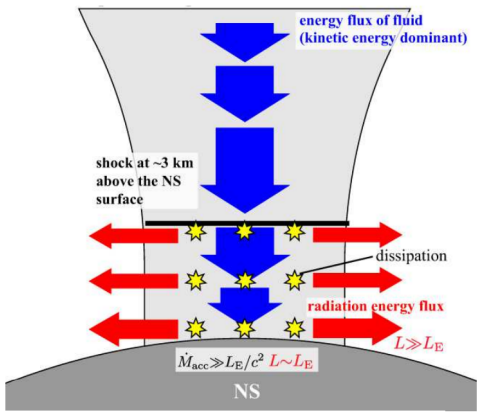


Figure 21: From Kawashima et al. (2016).

- Because of the column material above it, X-ray emission is not uniform in all directions $\longrightarrow$ if polar caps are displaced from the rotation axis, *emission is pulsed at the NS spin frequency*

X-ray (and accreting ms) pulsars: spin-up and spin-down

- As in LMXB millisecond pulsars, during the accretion phase mass and angular momentum are transfered from the companion to the pulsar $\Longrightarrow$ **spin-up**
- During periods of inactivity/low activity, spind-down caused by the usual (radio) pulsar activity is expected to dominate $\Longrightarrow$ **spin-down**

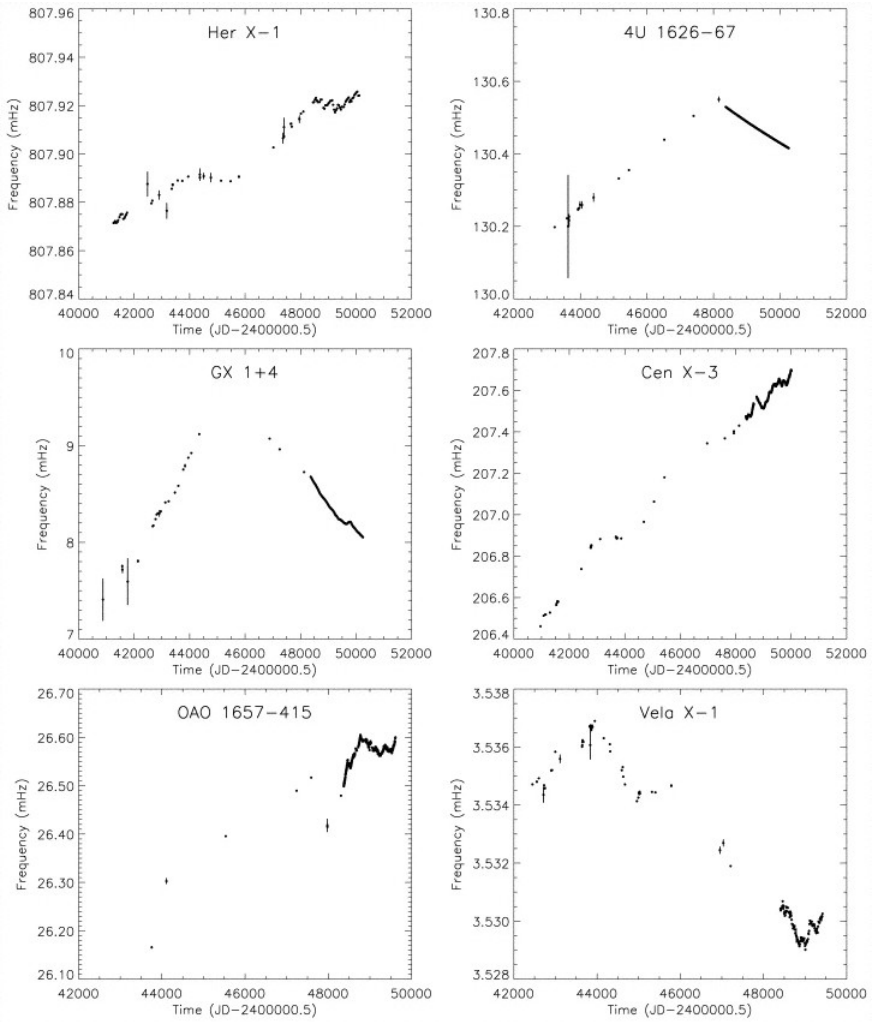
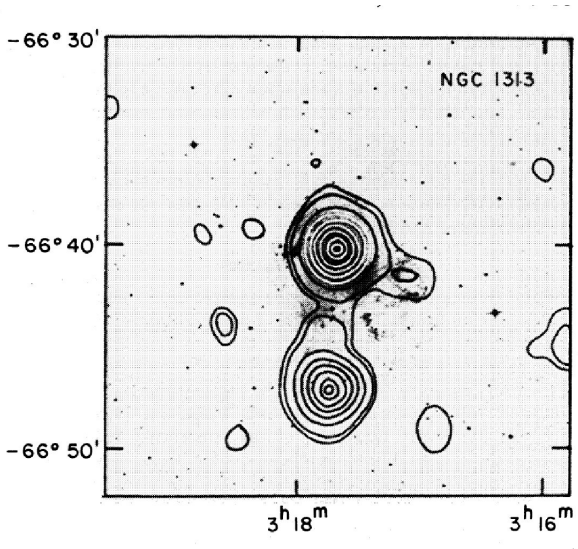


Figure 22: From Bildsten et al. (1997).

XRBs and Ultraluminous X-ray Sources in Nearby Galaxies

- X-ray binaries are an important component of the X-ray emission of galaxies (Fabbiano 1995; 2005). Point-like X-ray sources in nearby galaxies were first detected with the Einstein Observatory (e.g., Fabbiano 1989; 2006).
- Very luminous X-ray sources in nearby galaxies first noticed in the '80 in Einstein/IPC data (Long Van Speybroeck 1983; Helfand 1984; Fabbiano 1989), originally called Super-Eddington sources and later Intermediate-luminosity X-ray Objects (IXOs; Colbert Ptak 2002)



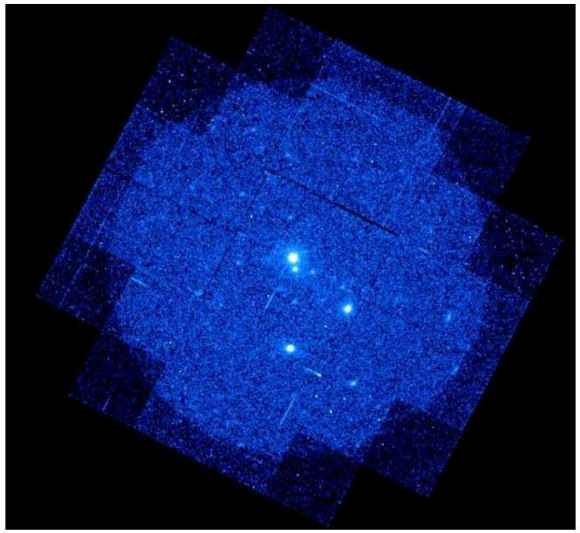


Figure 23: ULXs in the SBc galaxy NGC 1313. Left: Einstein/IPC image (Fabbiano Trinchieri 1987; Fabbiano et al. 1992). Right: XMM-Newton image

Nowadays, we call them Ultraluminous X-ray Sources ULXs and observationally define them as **point-like, off-nuclear X-ray sources in nearby galaxies with $L_X > 10^{39}$ erg s^{-1}**.

Several hundreds ULXs (or ULX candidates) are known nowadays (Liu & Bregman 2005, ROSAT catalogue; Swartz et al. 2004, Chandra archive; Walton et al. 2011, XMM-Newton catalogue).

- ~ 20% Background AGNs
- ~ 5% Supernovae interacting with the circumstellar medium
- $\sim 60 - 70$% Accreting binaries

XRB nature supported by several observational evidences:

- Stellar optical counteparts (Tao et al. 2011; Gladstone et al. 2013)
- Modulations in the X-ray and optical light curves, interpreted as orbital or super-orbital periods of the system (Kaaret et al. 2006; Liu et al. 2009, 2013; Motch et al. 2014; Kong et al. 2016; Walton et al. 2016)
- Significant short-term (1-100 s) variability in some ULXs (Heil et al. 2009)

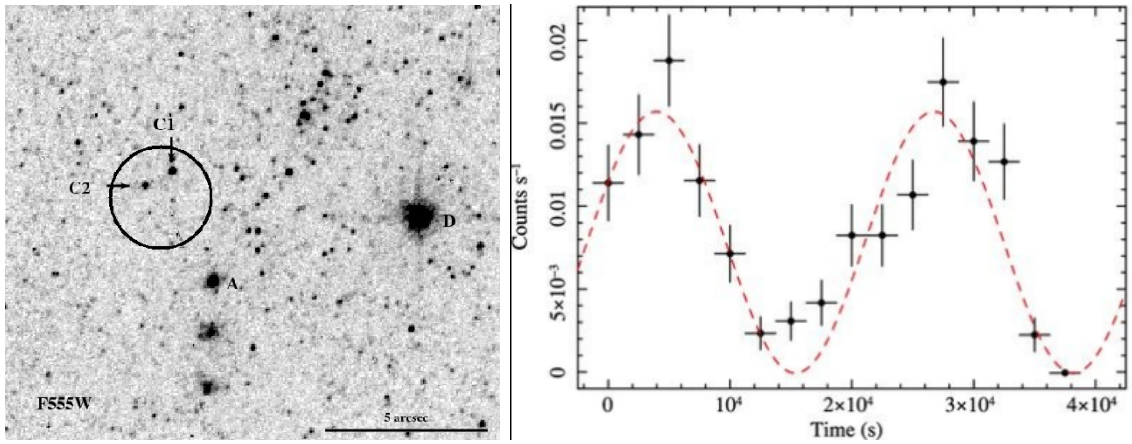


Figure 24: *Left*: Optical counterpart(s) of NGC 1313 X-2 (Mucciarelli et al. 2007). *Right*: Light curve of NGC 4490 ULX-1 (Esposito et al. 2013).

But what type of XRBs are they? What is their accreting compact object? What is the origin of their exceptionally high (isotropic) luminosity? What is the character of their accretion flow?

Accreting compact objects in ULXs

- After several year of attempts, *first sucessful measurements of the mass function* F in two ULXs. In one case the value of F is sufficiently high to be consistent only with a BH

  M 101 ULX-1 (Liu et al. 2013): $P_{orb} = 8.2$ d, $M_* = 19 M_\odot$ (Wolf-Rayet star), $M_c > 5 M_\odot$
  $\rightarrow$ **ULX with a BH**

  Caveat: only a few radial velocity measurements performed with a He emission line

  NGC 7793 P13 (Motch et al. 2014): $P_{orb} = 64$ d, $M_* = 18 - 23 M_\odot$ (B9Ia), $M_c < 15 M_\odot$

- *Recent discovery of periodic oscillations* in the XMM-Newton and/or NuSTAR data of four ULXs $\rightarrow$ **ULXs with a NS** ($L/L_{Edd} > 100$)
  - **M 82 X-2** (Bachetti et al. 2014): $P_{spin} = 1.37$ s, $\dot{P} = -2 \times 10^{-10}$ s/s
  - **NGC 5907 ULX-1** (Israel et al. 2017a): $P_{spin} = 1.14$ s, $\dot{P} = -8.1 \times 10^{-10}$ s/s
  - **NGC 7793 P13** (Fuerst et al. 2016; Israel et al. 2017b): $P_{spin} = 0.42$ s, $\dot{P} = -4 \times 10^{-11}$ s/s
  - **NGC 300 ULX-1** (Carpano et al. 2018): $P_{spin} = 31.6$ s, $\dot{P} = -5.56 \times 10^{-7}$ s/s

X-ray spectral 'states' and non-standard accretion

Many ULXs show either curved X-ray spectra or a turnover at $\sim$3-5 keV, sometimes with a soft excess below 1 keV (**ultraluminous state**, Gladstone et al. 2009).

Hard/high to soft/low transitions sometimes occurr (Pintore Zampieri 2012).

Spectral properties and variability not alike those of Galactic BH binaries (Pintore et al. 2014).

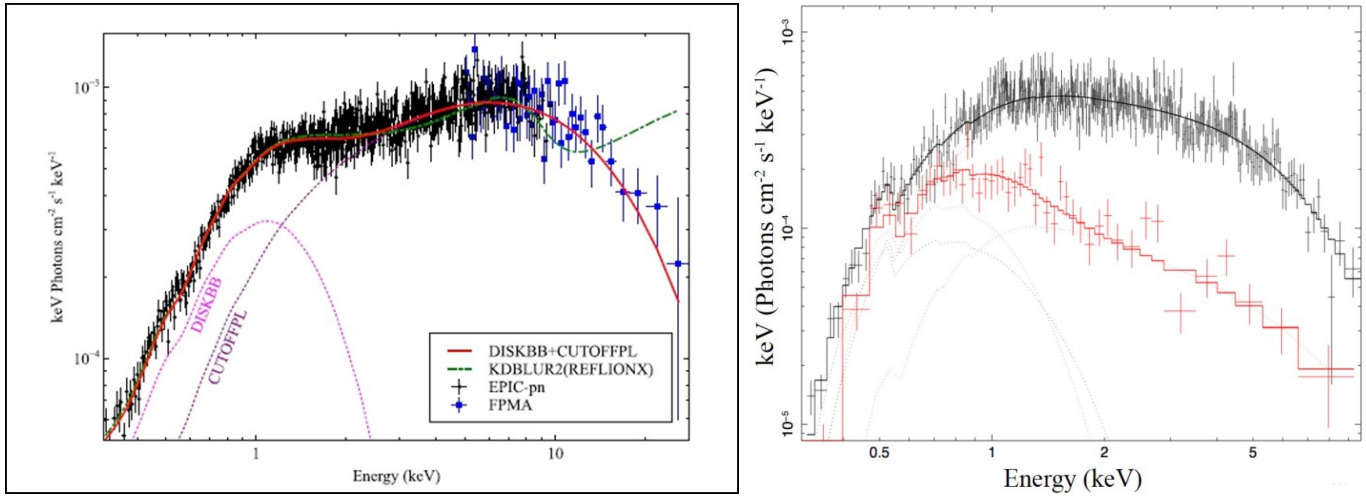


Figure 25: *Left*: XMM-Newton+NuSTAR spectrum of NGC 1313 X-2 (Bachetti et al. 2013), a characteristic ultraluminous state spectrum. *Right*: XMM-Newton spectrum of NGC 1313 X-2 in different observations (Pintore & Zampieri 2012), showing a peculiar hard/high to soft/low transition.

XMM-Newton+NuSTAR spectra are well fit with two-thermal components spectral models that assume non-standard accretion onto a BH. Interpreted in terms of emission from a comptonized, advection dominated disc and an outflow that establish during non-standard accretion onto a BH (e.g. Sutton et al. 2013, Pintore et al. 2014).

But spectra of pulsar ULXs and other ULXs can be well fit with a model for Galactic accreting magnetic NSs (Pintore et al. 2017).

Supercritical accretion onto BHs and magnetized NSs

For both BHs and NSs, a very high mass transfer rate is needed to explain maximum (isotropic) luminosities in excess of 10^{40} erg/s:

$$\dot{M} = L_{max}/\eta c^2 = 1.6 \times 10^{-6}\, b\, \eta_{0.1}^{-1}\, M_\odot/\mathrm{yr} \tag{12}$$

where $b < 1$ accounts for the possibility of (geometry-dependent) partially beamed emission.

High inferred mass transfer rates require that the donor is filling its Roche lobe.

For NSs and BHs with a mass $< 20 M_\odot$ (similar to Galactic stellar-mass BHs), the system is accreting above Eddington: *advection dominated disc with an outflow for a BH, accretion column with extreme properties for a NS*.

ULXs may be laboratory for extreme accretion environments (where photon trapping becomes important), possibly relevant for first Quasars at very high z.

Other types of BHs in ULXs?

INTERMEDIATE-MASS BHs

HLX-1 in ESO 243-49 has a maximum luminosity of 10^{42} erg/s (Farrell et al. 2009, Wiersema et al. 2010) and shows variable radio emission during BH-like X-ray spectral states. Assuming it is a BH binary, **the estimated mass of the BH is 10000-100000** $M_\odot$ (Webb et al. 2012).

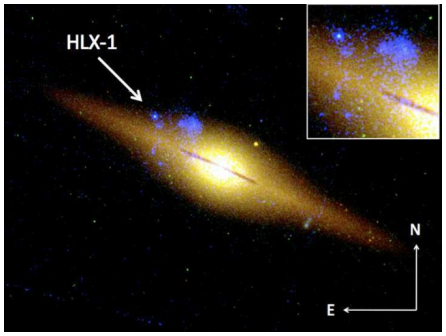


Figure 26: HST composite image of HLX-1 in ESO 243-49 (Mapelli et al. 2013).

The optical counterpart shows an H-α emission line with redshift consistent with that of the host galaxy. HLX-1 may be the nucleus of a satellite galaxy undergoing a minor merger with ESO 243-49 (Mapelli et al. 2013)

But how may an IMBH form?

- In globular clusters, through repeated mergers of stellar mass BHs (Miller & Hamilton 2002)
- In young, dense stellar super clusters, from the dynamical collapse of supermassive stars in their centres (e.g. Portegies Zwart et al. 2004)

MASSIVE-STELLAR BHs

Bright ULXs may contain BHs with masses above $\sim 30 - 40 M_\odot$ and up to $\sim 80 - 90 M_\odot$, formed from ordinary stellar evolution of massive ($\sim 30 - 120 M_\odot$) stars in a low-metallicity natal environment (Zampieri & Roberts 2009; Mapelli et al. 2009; Belczynski et al. 2010).