X-ray Pulsars

Roland Walter & Carlo Ferrigno

Abstract X-ray pulsars shine thanks to the conversion of the gravitational energy of accreted material to X-ray radiation. The accretion rate is modulated by geometrical and hydrodynamical effects in the stellar wind of the pulsar companions and/or by instabilities in accretion discs. Wind driven flows are highly unstable close to neutron stars and responsible for X-ray variability by factors $\gtrsim 10^3$ on time scale of hours. Disk driven flows feature slower state transitions and quasi periodic oscillations related to orbital motion and precession or resonance. On shorter time scales, and closer to the surface of the neutron star, X-ray variability is dominated by the interactions of the accreting flow with the spinning magnetosphere. When the pulsar magnetic field is large, the flow is confined in a relatively narrow accretion column, whose geometrical properties drive the observed X-ray emission. In low magnetized systems, an increasing accretion rate allows the ignition of powerful explosive thermonuclear burning at the neutron star surface. Transitions from rotation-to accretion-powered activity has been observed in rare cases and proved the link between these classes of pulsars.

1 Introduction

Accreting binaries (Casares and Israeliian 2016) are among the brightest X-ray point sources of our Galaxy and the first ones to be detected in the early days of X-ray astronomy (Giacconi et al. 1964). Their X-ray emission originates from the dissipation of gravitational energy in material accreted from a companion star to a compact object. A large fraction of the brightest X-ray binaries harbour neutron stars, known as “accreting pulsars” or “X-ray pulsars”.

Neutron stars are the remnants of supernova explosion and are unique laboratories for the study of extreme densities, momentum, gravity and magnetic fields. Un-
Understanding them requires all fields of modern physics: plasma physics, electrodynamics, magneto-hydrodynamics, general relativity and quantum physics (Geppert, 2016; Weber, 2016; Wex, 2016). X-ray binaries are the result of complex evolutionary scenarios (van den Heuvel, 2016) established using the full arsenal of stellar evolution, supernova explosions, exchange and accretion processes.

The neutron star magnetic field (Zhang, 2016) and surface play key roles to determine how matter is accreted and where energy is dissipated. The pulsar magnetosphere dominates the flow of the accreted material within the Alfvén surface, where the bulk kinetic energy density of the gas is comparable to that of the magnetic field. This surface depends on the geometry of the magnetic field, of the accreting flow and of their interaction. Its characteristic size is a hundred times larger than the neutron star for a magnetic field of \(10^{12} \text{ G}\) and a luminosity reaching a fraction of the Eddington limit, and can reach the surface of the neutron star when the magnetic field is below \(10^{8} \text{ G}\). An offset between rotation and magnetic axes is required to obtain the flux modulation characterising bright X-ray pulsars.

High \((10^{11–14} \text{ G})\) surface magnetic fields are detected in young \((10^{6} \text{ y})\) high mass X-ray binaries (HMXB) with massive, O & B type, stellar companions (but see the peculiar Her X-1 with a magnetic field of \(10^{12} \text{ G}\) and a 2 \(M_{\odot}\) companion; Truemper et al., 1978). Low surface magnetic fields \((\lesssim 10^{10} \text{ G})\) are present in old binary systems with low mass \((\lesssim 1 M_{\odot})\) companions (LMXB). HMXBs are concentrated in the Galactic arms, close to their birthplace. LMXB populate the bulge of the Galaxy and globular clusters, where they can also form through stellar capture.

The Milky Way contains about 130 and 180 bright \((> 10^{35} \text{ erg/s})\) high and low mass X-ray binaries, respectively (Walter et al., 2015; Liu et al., 2007). The brightest sources dominate the X-ray emission of the Galaxy at a level of \(~ 10^{38}\) and \(~ 10^{39} \text{ erg s}^{-1}\) for the high and low mass systems. HMXBs and the hot interstellar gas dominate the X-ray luminosity of star forming galaxies, a tracer of their stellar formation rate (Grimm et al., 2003; Mineo et al., 2012).

In this chapter, we will concentrate on the accretion flows driving X-ray variability (section 2 & 3) and on the mechanisms driving X-ray emission in the direct vicinity of the pulsars (section 4 & 5).

## 2 Wind driven flows

In HMXBs, the pulsar attracts a small fraction of the stellar wind of its companion (Bondi and Hoyle, 1944; Davidson and Ostriker, 1973). In classical wind accreting systems, Bondi-Hoyle accretion takes place along the neutron star orbit and the accretion rate remains usually low. High accretion rates are expected in close systems, where the companion is practically filling its Roche lobe. The wind is then focussed through a tidal stream and, if its angular momentum is large enough, a transient accretion disk structure may form. Roche-lobe overflow from a high-mass companion is rarely observed, as the compact object is quickly enshrouded by the atmosphere of its companion.
Flares reaching the Eddington luminosity, occur when the compact object crosses a dense component of the stellar wind, usually expelled by a fast rotating main sequence star, featuring emission lines in the optical band. These systems are identified as “Be X-ray binaries”.

2.1 Classical systems

The instantaneous X-ray luminosity of an accreting pulsar with moderate magnetic field ($\sim 10^{12}$ G) in a HMXB system is mostly determined by the density and velocity of the stellar wind close to the compact object. The amplitude of the X-ray variability is determined by the pulsar orbital eccentricity, clumping and variability of the stellar wind, and by hydrodynamical effects induced by the gravity and photo-ionisation of the neutron star.

The variability of the accretion rate by a factor of 10-100 in wind-fed systems in circular orbits was successfully explained by hydrodynamical simulations (Blondin et al. 1990). Manousakis and Walter (2015a) have included the effect of photo-ionisation on the wind acceleration and could probe the dynamic of the region surrounding the neutron star and, in particular, the collision between the primary stellar wind, slowed down by photo-ionisation and a gas stream flowing back inwards from above the neutron star. As shown in Fig. 1, a shock front is generated, moving inwards and outwards regularly and creating low density bubbles, i.e., periods of very low X-ray luminosity. This generates instantaneous accretion rates varying by $10^3$, and transient modulations similar to those observed in Vela X-1 (Kreykenbohm et al. 2008). This back and forth shock motion occurs high above the magnetosphere and can be amplified further by an induced change of geometry of the accretion column.

Shakura et al. (2013) have shown that two regimes of subsonic accretion are possible at the boundary of the magnetosphere depending on whether or not the plasma is cooled by Compton processes (high vs low accretion rate). At lower luminosity, X-ray photons are emitted perpendicular to the neutron star surface, inverse Compton cooling is less efficient and a change of the X-ray spin modulation of the light curve is expected (Doroshenko et al. 2011).

Grebenev and Sunyaev (2007) suggested that high variability factors could be generated by Kelvin-Helmoltz instability at the magnetospheric boundary, leading to a magnetic gating of the accretion flow. This requires large magnetic fields ($> 10^{13}$ G) which are contrasting with the observations (Bhalerao et al. 2015). It is unclear if magnetic gating is at play in HMXBs.

The comparison of hydrodynamical simulations and X-ray observations allow to probe the stellar wind velocity and density fields (Manousakis and Walter 2015b). GX 301–2 and OAO 1657–415 feature peculiar variability patterns that could be related to the accretion of dense streams and large scale structures in the wind of their massive companions. Long term modulation of the accretion rate along the orbit because of eccentricity is observed in addition in several systems.
2.2 Systems close to Roche-lobe overflow

When the companion star in a HMXB gets closer to Roche-lobe overflow, a tidal stream develops, focuses the wind and increases the wind density close to the compact object and the X-ray luminosity [Blondin et al. 1991]. Enhanced obscuration by the stream trailing the neutron star is observed first at late orbital phases and covering more and more of the orbit when the neutron star gravity becomes dominant. Once the companion is close to overflowing its Roche lobe, deep spiral-in is unavoidable [van den Heuvel and De Loore 1973] and results in a common envelope phase [Taam and Sandquist 2000].

Five super-giant HMXBs feature persistently high obscuration ($N_H > 10^{23} \text{ cm}^{-2}$) and short orbital periods. They all reach X-ray high luminosities $> 10^{36}$ erg/s. Two obscured systems have longer orbital periods ($\approx 10$ days) and in these cases the obscuration is probably driven by unusually low wind velocity or by the environment. It is plausible therefore to assume that obscured sgHMXBs are classical systems in transition to Roche lobe overflow, or with relatively low velocity winds. As neutron
stars can cut-off wind acceleration via ionisation (Stevens and Kallman 1990), the wind of their companions can be slower on average than in isolated stars.  

Super-giant fast X-ray transients were identified as a new class of sources. These hard X-ray transients produce short and bright flares with typical durations of a few ksec. Further analysis indicates that many of them could be interpreted as classical or eccentric systems (Walter et al. 2015). Four of them are really peculiar: they have short orbital periods (3-6 days), so should be close to Roche lobe overflow, but feature anomalously low luminosities (< $10^{34}$ erg/s), excepting during episodic flares. Abnormally low mass-loss rates or high wind velocities could explain low accretion, but not high variability. Extreme wind clumping seems unlikely very close to the stellar surface. As none of these four sources show pulsation, it is possible that the magnetic and rotation axis are close together and that X-rays are beamed (Gnedin and Sunyaev 1973) in directions most of the time not favourable for the observer. Flares could be related to periods when the geometry of the accretion column changes significantly.

X-ray beaming has also been used to explain luminosities reaching $10^{40}$ erg/s (i.e. 100 times Eddington) observed in the ultra luminous X-ray source M82 X-2, an X-ray pulsar in a system close to Roche lobe overflow (Bachetti et al. 2014) or of Be nature. Magnetic gating is an alternate explanation both for M82 X-2 (Mushotkov et al. 2015a; Pan et al. 2016) and for the four SFXTs above (Bozzo et al. 2008) but would require high magnetic fields for which we have no evidence otherwise.

### 2.3 Be X-ray binaries

Besides the persistent accreting sources described above, transient systems with Be stars as secondaries constitute a substantial part of all HMXBs. Be stars are non super-giant B-type stars that have shown emission lines in their spectra, originating from a circumstellar disk expelled irregularly by a rapidly rotating star (Porter and Rivinius 2003). These equatorial mass ejection (which are independent of binarity) produce a dense ring of gas around the star and a shallow polar wind. The disk gives rise to a sudden appearance of hydrogen emission lines in their optical spectrum. Some Be system seems permanently active, others suddenly enter the Be phase for weeks to years (Slettebak and Snow 1987).

When a neutron star orbits close enough to a Be companion, mass ejection could be accompanied by accretion and by an X-ray outburst. Two types of outbursts are observed: type I outbursts are caused by enhanced mass accretion rate close to periastron, last for 0.2-0.3 $P_{\text{orb}}$ and peak to $\approx 10^{37}$ erg s$^{-1}$; the rare type II outbursts, reaching the Eddington luminosity can last for several orbital periods. Low eccentricity Be systems are more efficient X-ray emitters. High eccentricity systems eventually circularise because of tidal effects.
3 Disk driven accretion flows

Accretion discs form when the stream of material flowing from the companion star intersects with itself before reaching the magnetosphere of the X-ray pulsar. This happens in LMXBs, and sometimes in HMXBs when a tidal stream develops and dominates Bondi-Hoyle accretion. Magneto-hydrodynamical simulations have investigated the transition of the flow from the disc to the central object, where the stream impinges the surface at the magnetic poles (see an example in Fig. 2).

![Diagram of disk-mediated accretion onto a neutron star with a low magnetic field (B ~ 10^8 G). The vectors Ω and μ represent the spin and the dipole magnetic field; magnetic field lines are represented in red, while a representative surface of equal density is plotted in green (the typical case of an accreting millisecond pulsar; from Kulkarni and Romanova, 2008).](image)

The angular momentum carried from the companion star through the accretion disk can be transferred to the neutron star at the magnetospheric boundary. The inner disk is forced to co-rotate with the neutron star before being channelled to the accretion column and gradually spins up or down the pulsar until an equilibrium period is reached. The interaction between the disk and the magnetosphere is not yet well understood. The differential rotation between the disk and the dipolar magnetosphere generates a toroidal magnetic field (Ghosh and Lamb, 1979) and the plasma leaves the disk towards the dipolar field lines. This model is roughly consistent with the accretion torque behaviour observed during Be/X-ray pulsar flares (Bildsten et al., 1997) when the accretion rate changes dramatically. If the combination of the magnetic field and neutron star rotation is too strong, as compared to the infalling plasma pressure, it can prevent accretion through propeller effects (Schwarzman, 1970).
This happens in the initial phases of pulsar evolution and when the accretion rate lowers, effectively quenching accretion.

The light curves of X-ray pulsars might be modulated periodically by quasi-periodic oscillations (QPOs): a variability pattern, which is normally transient and with a frequency slightly oscillating around a central value. The high-frequency (kHz) QPOs observed in LMXBs are consistent with orbital motions at the boundary of the magnetosphere (van der Klis 2000). In some cases, their frequency is so high that part of the accretion stream should extend further in the magnetosphere (Miller et al. 1998; Psaltis et al. 1999). The accretion flow undergoes a discontinuous change, when the QPO frequency exceeds or falls below the pulsar spin, the disc boundary extends inside or outside the radius at which the pulsar’s magnetic field co-rotates with the Keplerian flow, and when accretion is favoured or suppressed, respectively (Bult and van der Klis 2015). Twin kHz QPO can form and might indicate resonances in the disk (Lamb and Miller 2003). Low frequency QPO (0.1-100 Hz) are probably the signature of disk precession because of frame dragging (Stella and Vietri 1999) and of accretion instabilities.

Discs in HMXBs are unstable because of the hydrodynamical and 3D nature of the wind that feeds them. They are short lived and could rotate in alternate directions. Discs in LMXBs are more stable geometrically, but develop intrinsic instabilities which are likely related to temperature dependent viscosity. When the temperature increases, the mass accretion rate increases, the disc gets hotter, and material falls towards the compact object in a run-away reducing the surface density and returning back to a cooler state. Recurrent episodes of accretion outbursts may occur triggered by this mechanism, each one lasting from weeks to months, while quiescence can last many years. As X-ray pulsars are luminous objects, the irradiation and heating of the accretion disk by the central source launches thermally driven winds which could generate additional instabilities in the accretion disk (Díaz Trigo and Boirin 2016).

These cycles of variable accretion rates manifest themselves differently in the so-called “Atoll” and “Z” sources. “Z” sources show three X-ray spectral states, have higher accretion rates and tend to have longer orbital periods than “Atoll” systems. The latter are driven by lower accretion rates and characterised by X-ray thermonuclear flashes (see. Sect. 5).

4 Accretion Column In Highly Magnetized Systems

In highly magnetized systems, the plasma approaching the neutron star is stopped by the pressure of the dipolar pulsar magnetic field, independently of the way it flew from the companion star. The plasma is then forced to move along the field lines toward the magnetic poles, where it releases its gravitational energy in the form of high-energy radiation. This radiation is not emitted isotropically; misalignment of magnetic and rotational axes of the neutron stars ensure that periodic pulses of high-energy radiation could be detected.
Close to the neutron star surface, the plasma falls in a quasi-cylindrical accretion column, at a fraction of the speed of light (see a schematic representation in Fig. [3]). It then heats to $10^8$ K [Basko and Sunyaev 1976; Meszaros and Nagel 1985]. Bulk and thermal Comptonization of seed photons produced by modified bremsstrahlung in the high magnetic field and black body emission from the column’s base play a key role in the formation of the non thermal hard X-ray emission [Becker and Wolff 2007].

The X-ray continuum of accreting pulsars is characterized by a power law $N_v \sim v^{-(1-2)}$ with a high-energy exponential cutoff (7-30 keV, White et al. 1983), sometimes modified by absorption and emission lines in the soft X-rays and by cyclotron resonance scattering features (CRSF) at higher energies (Truemper et al. 1978). CRSFs are caused by the scattering of hard X-ray photons on electrons whose energy is quantized by the magnetic field according to the Landau levels. Their energy separation can be measured from the source spectra and hence the magnetic field strength in the scattering region can be estimated. Variability of the CRSF with luminosity on long and spin period time scales indicate that the accretion flow is not uniform nor stationary (Mihara et al., 1998; Farinelli et al., 2016).

Observing transient X-ray pulsars in bright outburst (especially in Be systems) is essential to understand the physical processes at play close to the neutron star surface and in particular the response of the neutron star magnetosphere system to the variability of the mass accretion rate on different time scales.

Modelling the interaction of the radiation with the accreted matter in strong magnetic and gravitational fields is a complex problem. A number of authors attempted to simulate the shape of the continuum (Becker and Wolff 2007) and of the CRSFs (Araya-Góchez and Harding, 2000; Schönherr et al. 2007) as a function of the pulse phase, source luminosity, geometry of the emission regions, etc. The comparison of the model predictions with the observations still fails to provide strong constrains on the physical parameters of the accretion column because of the complexity of the models, the limitations of current hard X-ray telescopes, and the convolution of the signatures of many emitting and absorbing regions with different properties.

The discovery of an anti-correlation between the cyclotron line energy and the X-ray luminosity in transient X-ray pulsars (Mowlavi et al. 2006; Tsygankov et al. 2006) initiated a systematic study of the cyclotron line energy properties as a function of the source luminosity and was interpreted with a change of the geometry of the accretion column, rising above the neutron star surface at high luminosities (Becker et al. 2012). Nishimura (2014) modelled the cyclotron line by the sum of the contributions emerging from individual line-forming regions along the accretion column with different magnetic field strength, temperature, and density. An increase of the mass accretion rate causes the emergence of additional line-forming regions with lower magnetic fields that lead to a decrease of the cyclotron line energy. Another model (Poutanen et al. 2013) suggests that a significant part of the accretion column radiation is intercepted and reflected by the neutron star surface because of relativistic beaming. Variations of the accretion column height lead to a shift of the illuminated part of the neutron star surface toward the equator where the magnetic field is weaker. This naturally drives the observed anti-correlation of the cyclotron
line energy with luminosity. Moreover, this model is able to explain why the amplitude of the cyclotron energy variability remains limited, when the luminosity changes dramatically.

For lower-luminosity sources an opposite behaviour of the cyclotron energy with the luminosity has been observed (e.g. [Staubert et al. 2007], [Klochkov et al. 2012]). This has been explained as due to the redshift of the line centroid energy due to the motion of the in-falling plasma: at low luminosity, the plasma is in free-fall, while at higher luminosity the plasma slows down near the stellar surface, resulting in a reduced red-shift of the line centroid energy (Mushtukov et al. 2015b). Finally, no dependence of the cyclotron energy on luminosity has been detected for some transient pulsars (Caballero et al. 2013). Further observations of X-ray pulsars during bright outbursts are needed to discriminate between models.

5 Low Magnetized Systems And Accreting Millisecond Pulsars

There is a class of millisecond radio pulsars (MSPs) with about 300 members that have periods of rotation lower than ∼10 ms (Manchester et al. 2005[a]), while they slow down at an almost imperceptible rate. Since radiation is produced by emission of electromagnetic energy at the expense of their kinetic rotational energy, the product of period derivative and period is proportional to the pulsars’s magnetic field. This implies that these objects have a relatively low surface magnetic field (∼ 10^8 G)

[1] http://www.atnf.csiro.au/people/pulsar/psrcat/
decayed by the higher typical initial value. therefore, they are old (Gyrs), but they must be spun up during their existence. To explain their origin, it was suggested that they are recycled pulsars and that the spin-up occurred during a Gyr-long phase of accretion of mass transferred by a low-mass companion star through an accretion disk (e.g., Bisnovatyi-Kogan and Komberg [1974], Alpar et al. [1982], Radhakrishnan and Srinivasan [1982]). During the mass accretion phase these systems should be observed as bright LMXBs. In this phase, it has been argued that the magnetic field decays more rapidly than in an isolated neutron star, due to matter accumulated on the NS surface (see Zhang and Kojima [2006] and references therein). When mass transfer declines, a pulsar powered by the rotation of its magnetic field turns on and shines mostly in the radio band.

The very existence of millisecond pulsars powered by accretion was proven almost two decades after (Wijnands and van der Klis [1998]) and since then less than 20 objects have been ascribed to the class of accreting millisecond pulsars (AMSP). These show only sporadic, month-long outburst during which the companion star overfills its Roche lobe, initiating a months-long mass transfer phase. An accretion disc is formed, which truncates at several neutron star radii, where the pressure of the pulsar’s magnetic field equals the ram pressure of the infalling flow. In this phase, pulsars are detected with an X-ray luminosity of $\sim 10^{37}$ erg/s. For the rest of the time, they remain in quiescence, powered by rotation (Burderi et al. [2003]). However, no observational evidence of that transition was found, until the discovery of the first object transiting back and forth between the rotation- and accretion-powered phases (IGR J19245−2452; Papitto et al. [2013]). In addition to the radio and X-ray bright states, it has been evidenced that this object presents variability patterns, which are significantly different from the other LMXBs, while it also exhibits levels of activity at an intermediate level ($10^{35}$ erg/s) between the outburst and the X-ray quiescence ($10^{32}$ erg/s).

At the time of writing, only two other objects have been found to switch between rotation-powered phase and this intermediate level of activity: PSR J1023+0038 (Archibald et al. [2009]) and XSS J1227.0−4859 (Stappers et al. [2014]). Pulsations for these objects have been detected in the radio band when their X-ray luminosity is at the quiescent level and they were not surrounded by an accretion disk. The spin period modulations show that they are in a binary system with a low-mass companion and that there are frequent disappearances of the signal due to the shielding by a thick intra-binary medium, produced by the companion’s evaporation due to the pulsar’s wind. These systems can quickly (on a time scale of months) change their status when some mechanism triggers the formation of an accretion disc around the neutron star. In such phase, they shine in $\gamma$-rays (0.03–300 GeV) and increase their X-ray luminosity to an average value of $\sim 10^{34}$ erg/s (see also Tanaka, 2016). X-ray pulsations have been found while the radio pulsed signal is absent (Archibald et al. [2015]). This has been interpreted as accretion in a strong propeller regime with most of the matter ejected by the centrifugal motion of the pulsars magnetic field and some still reaching the surface to produce periodically modulated X-rays (Papitto and Torres [2015]).
X-ray pulsations from most of the other bright low mass X-ray binaries have eluded any detection with the exception of a handful of sources showing a coherent oscillation at the onset of their thermonuclear bursts (see references in Papitto et al, 2014). On the contrary, when the source is powered by accretion, the pressure of the accreting material is so strong that the accretion disk likely extends down to the surface, inhibiting pulsations for symmetry reasons.

Thermonuclear bursts originate in weakly magnetised pulsars because plasma deposit at the surface of the pulsar over a relatively large area without reaching the temperature necessary to ignite thermonuclear reactions. When enough material is accumulated, it can ignite explosive burning (like in the core of normal stars), generating a powerful outburst with a duration of some tens or hundreds of seconds \( L_X \gtrsim 10^{38} \text{ erg/s} \). It is believed that the flames propagate through the atmosphere of the neutron star and, in the initial seconds, not all the surface is covered. Oscillations at the onset and tail of X-ray flashes allow us to detect the rotation of the star and to study the accretion and spreading of the plasma over the neutron star surface. On the contrary, for higher magnetic fields, the geometrical area over which the plasma is accreted is smaller, leading to conditions in which stable burning occurs.

To summarize, rotating neutron stars in close binary systems are believed to possess four main states with respect to accretion. They do not accrete and some of them shine as radio pulsars while the X-ray luminosity is \( L_X \sim 10^{32} \text{ erg/s} \); they accrete at a level in which the pressure of the accretion disk is almost entirely balanced by the magnetic pressure and produce strong outflows \( L_X \sim 10^{34} \text{ erg/s} \); the accretion disc is truncated at several neutron star radii and coherent pulsations are observed during weeks-long outbursts \( L_X \sim 10^{37} \text{ erg/s} \); some other systems possess very high accretion rates, however coherent pulsations are not observed excepting during some thermonuclear bursts.

Observing pulse profile of accretion-powered msec pulsars and of thermonuclear bursts with a high throughput X-ray instrument will allow to constrain the neutron star mass and radius with an accuracy of a few % and to determine the dense matter equation of state (Haensel and Zdunik, 2016; Lo et al, 2013).
Cross-References

- X-ray Binaries (Casares and Israeli, 2016)
- Thermal Evolution of Neutron Stars (Geppert, 2016)
- Nuclear Matter in Neutron Stars (Haensel and Zdunik, 2016)
- Gamma Ray Pulsars; from Radio to Gamma Ray (Tanaka, 2016)
- Supernovae and the Evolution of Close Binary Systems (Van den Heuvel, 2016)
- Strange Quark Matter Inside Neutron Stars (Weber, 2016)
- Neutron Stars as Probes for General Relativity and Gravitational Waves (Wex, 2016)
- Magnetic Field Evolution of Neutron Stars (Zhang, 2016)

References

Alpar MA, Cheng AF, Ruderman MA, Shaham J (1982) A new class of radio pulsars. Nature 300:728–730
Araya-Góchez RA, Harding AK (2000) Cyclotron-Line Features from Near-critical Fields. II. On the Effect of Anisotropic Radiation Fields. ApJ 544:1067–1080, DOI 10.1086/317224, astro-ph/0007191
Archibald AM, Stairs IH, Ransom SM, Kaspi VM, Kondratiev VI, Lorimer DR, McLaughlin MA, Boyles J, Hessels JWT, Lynch R, van Leeuwen J, Roberts MSE, Jenet F, Champion DJ, Rosen R, Barlow BN, Dunlap BH, Remillard RA (2009) A Radio Pulsar/X-ray Binary Link. Science 324(5):1411
Archibald AM, Bogdanov S, Patruno A, Hessels JWT, Deller AT, Bassa C, Janssen GH, Kaspi VM, Lyne AG, Stappers BW, Tendulkar SP, D’Angelo CR, Wijnands R (2015) Accretion-powered Pulsations in an Apparently Quiescent Neutron Star Binary. ApJ 807(1):62
Bachetti M, Harrison FA, Walton DJ, Grefenstette BW, Chakrabarty D, Fürst F, Barret D, Beloborodov A, Boggs SE, Christensen FE, Craig WW, Fabian AC, Hailey CJ, Hornschemeier A, Kaspi V, Kulkarni SR, Maccarone T, Miller JM, Rana V, Stern D, Tendulkar SP, Tomlick J, Webb NA, Zhang WW (2014) An ultraluminous X-ray source powered by an accreting neutron star. Nature 514:202–204, DOI 10.1038/nature13791, 1410.3590
Basko MM, Sunyaev RA (1976) The limiting luminosity of accreting neutron stars with magnetic fields. MNRAS 175:395–417, DOI 10.1093/mnras/175.2.395
Becker PA, Wolff MT (2007) Thermal and Bulk Comptonization in Accretion-powered X-Ray Pulsars. ApJ 654:435–457, DOI 10.1086/509108, astro-ph/0609035
Becker PA, Klucochov D, Schönherr G, Nishimura O, Ferrigno C, Caballero I, Kretschmar P, Wolff MT, Wilms J, Staubert R (2012) Spectral formation in accreting X-ray pulsars: bimodal variation of the cyclotron energy with luminosity. A&A 544:123
Bhalerao V, Romano P, Tomsick J, Natalucci L, Smith DM, Bellm E, Boggs SE, Chakrabarty D, Christensen FE, Craig WW, Fuerst F, Hailey CJ, Harrison FA, Krivonos RA, Lu TN, Madsen K, Stern D, Younes G, Zhang W (2015) NuSTAR detection of a cyclotron line in the supergiant fast X-ray transient IGR J17544-2619. MNRAS 447:2274–2281, DOI 10.1093/mnras/stu2495.

Bildsten L, Chakrabarty D, Chiu J, Finger MH, Koh DT, Nelson RW, Prince TA, Rubin BC, Scott DM, Stollberg M, Vaughan BA, Wilson CA, Wilson RB (1997) Observations of Accreting Pulsars. ApJS 113:367–408, DOI 10.1086/313060.

Bisnovatyi-Kogan GS, Komberg BV (1974) Pulsars and close binary systems. AZh51:373

Blondin JM, Kallman TR, Fryxell BA, Taam RE (1990) Hydrodynamic simulations of stellar wind disruption by a compact X-ray source. ApJ 356:591–608, DOI 10.1086/168865

Blondin JM, Stevens IR, Kallman TR (1991) Enhanced winds and tidal streams in massive X-ray binaries. ApJ 371:684–695, DOI 10.1086/169934

Bondi H, Hoyle F (1944) On the mechanism of accretion by stars. MNRAS 104:273, DOI 10.1093/mnras/104.5.273

Bozzo E, Falanga M, Stella L (2008) Are There Magnetars in High-Mass X-Ray Binaries? The Case of Supergiant Fast X-Ray Transients. ApJ 683:1031-1044, DOI 10.1086/589990.

Bult P, van der Klis M (2015) PULSE AMPLITUDE DEPENDS ON kHz QPO FREQUENCY IN THE ACCRETING MILLISECOND PULSAR SAX J1808.4-3658. ApJ 798(2):L29

Burderi L, di Salvo T, D’Antona F, Robba NR, Testa V (2003) The optical counterpart to SAX J1808.4-3658 in quiescence: Evidence of an active radio pulsar? A&A 404(3):L43–L46

Caballero I, Pottschmidt K, Marcu DM, Barragan L, Ferrigno C, Klochkov D, Zurita Heras JA, Suchy S, Wilms J, Kretschmar P, Santangelo A, Kreykenbohm I, Fürst F, Rothschild R, Staubert R, Finger MH, Camero-Arranz A, Makishima K, Enoto T, Iwakiri W, Terada Y (2013) A Double-peaked Outburst of A 0535+26 Observed with INTEGRAL, RXTE, and Suzaku. ApJ 764:L23, DOI 10.1088/2041-8205/764/2/L23.

Davideon K, Ostriker JP (1973) Neutron-Star Accretion in a Stellar Wind: Model for a Pulsed X-Ray Source. ApJ 179:585–598, DOI 10.1086/151897

Díaz Trigo M, Boirin L (2016) Accretion disc atmospheres and winds in low-mass X-ray binaries. Astronomische Nachrichten 337:368, DOI 10.1002/asna.201612315.

Doroshenko V, Santangelo A, Suleimanov V (2011) Witnessing the magnetospheric boundary at work in Vela X-1. A&A 529:A52, DOI 10.1051/0004-6361/201116482.

Farinelli R, Ferrigno C, Bozzo E, Becker PA (2016) A new model for the X-ray continuum of the magnetized accreting pulsars. A&A 591:A29, DOI 10.1051/0004-6361/201527257.
Ghosh P, Lamb FK (1979) Accretion by rotating magnetic neutron stars. III - Accretion torques and period changes in pulsating X-ray sources. ApJ 234:296–316, DOI 10.1086/157498

Giacconi R, Gursky H, Waters JR (1964) Two Sources of Cosmic X-rays in Scorpius and Sagittarius. Nature 204:981–982, DOI 10.1038/204981a0

Gnedin YN, Sunyaev RA (1973) The Beaming of Radiation from an Accreting Magnetic Neutron Star and the X-ray Pulsars. A&A 25:233

Grebenev SA, Sunyaev RA (2007) The first observation of AX J1749.1-2733 in a bright X-ray state - Another fast transient revealed by INTEGRAL. Astronomy Letters 33:149–158, DOI 10.1134/S1063773707030024

Grimm HJ, Gilfanov M, Sunyaev R (2003) High-mass X-ray binaries as a star formation rate indicator in distant galaxies. MNRAS 339:793–809, DOI 10.1046/j.1365-8711.2003.06224.x,[astro-ph/0205371]

Illarionov AF, Sunyaev RA (1975) Why the Number of Galactic X-ray Stars Is so Small? A&A 39:185

Klochkov D, Doroshenko V, Santangelo A, Staubert R, Ferrigno C, Kretschmar P, Caballero I, Wilms J, Kreykenbohm I, Potschmidt K, Rothschild RE, Wilson-Hodge CA, Pühlhofer G (2012) Outburst of GX 304-1 monitored with INTEGRAL: positive correlation between the cyclotron line energy and flux. A&A 542:L28, DOI 10.1051/0004-6361/201219385,[1205.5475]

Kreykenbohm I, Wilms J, Kretschmar P, Torrejón JM, Potschmidt K, Hanke M, Santangelo A, Ferrigno C, Staubert R (2008) High variability in Vela X-1: giant flares and off states. A&A 492:511–525, DOI 10.1051/0004-6361:200809956, [0810.2981]

Kulkarni AK, Romanova MM (2008) Accretion to magnetized stars through the Rayleigh-Taylor instability: global 3D simulations. MNRAS 386(2):673–687

Lamb FK, Miller MC (2003) Sonic-Point and Spin-Resonance Model of the Kilo-hertz QPO Pairs. ArXiv Astrophysics e-prints [astro-ph/0308179]

Liu QZ, van Paradijs J, van den Heuvel EPJ (2007) A catalogue of low-mass X-ray binaries in the Galaxy, LMC, and SMC (Fourth edition). A&A 469:807–810, DOI 10.1051/0004-6361:20077303,[0707.0544]

Lo KH, Miller MC, Bhattacharyya S, Lamb FK (2013) Determining Neutron Star Masses and Radii Using Energy-resolved Waveforms of X-Ray Burst Oscillations. ApJ 776:19, DOI 10.1088/0004-637X/776/1/19,[1304.2330]

Manchester RN, Hobbs GB, Teoh A, Hobbs M (2005) The Australia Telescope National Facility Pulsar Catalogue. AJ 129:1993–2006, DOI 10.1086/428488,[astro-ph/0412641]

Manousakis A, Walter R (2015a) Origin of the X-ray off-states in Vela X-1. A&A 575:A58, DOI 10.1051/0004-6361/201321414,[1412.5419]

Manousakis A, Walter R (2015b) The stellar wind velocity field of HD 77581. A&A 584:A25, DOI 10.1051/0004-6361/201526893,[1507.01016]

Meszaros P, Nagel W (1985) X-ray pulsar models. II - Comptonized spectra and pulse shapes. ApJ 299:138–153, DOI 10.1086/163687
Mihara T, Makishima K, Nagase F (1998) Cyclotron line variability. Advances in Space Research 22:987–996, DOI 10.1016/S0273-1177(98)00128-8, [1401.5138]

Miller MC, Lamb FK, Psaltis D (1998) Sonic-Point Model of Kilohertz Quasi-periodic Brightness Oscillations in Low-Mass X-Ray Binaries. ApJ 508:791–830, DOI 10.1086/306408, astro-ph/9609157

Mineo S, Gilfanov M, Sunyaev R (2012) X-ray emission from star-forming galaxies - I. High-mass X-ray binaries. MNRAS 419:2095–2115, DOI 10.1111/j.1365-2966.2011.19862.x, [1105.4610]

Mowlavi N, Kreykenbohm I, Shaw SE, Pottschmidt K, Wilms J, Rodriguez J, Prodi N, Soldi S, Larsson S, Dubath P (2006) INTEGRAL observation of the high-mass X-ray transient V 0332+53 during the 2005 outburst decline. A&A 451:187

Mushtukov AA, Suleimanov VF, Tsygankov SS, Poutanen J (2015a) On the maximum accretion luminosity of magnetized neutron stars: connecting X-ray pulsars and ultraluminous X-ray sources. MNRAS 454:2539–2548, DOI 10.1093/mnras/stv2087, [1506.03600]

Mushtukov AA, Suleimanov VF, Tsygankov SS, Poutanen J (2015b) The critical accretion luminosity for magnetized neutron stars. MNRAS 447:1847–1856, DOI 10.1093/mnras/stu2484, [1409.6457]

Nishimura O (2014) Variations of Cyclotron Line Energy with Luminosity in Accreting X-Ray Pulsars. ApJ 781:30, DOI 10.1088/0004-637X/781/1/30

Pan YY, Song LM, Zhang CM, Tong H (2016) The magnetic field evolution of ULX NuSTAR J095551+6940.8 in M82 - a legacy of accreting magnetar. MNRAS 461:2–5, DOI 10.1093/mnras/stw1041, [1510.08597]

Papitto A, Torres DF (2015) A Propeller Model for the Sub-luminous State of the Transitional Millisecond Pulsar PSR J1023+0038. ApJ 807(1):33

Papitto A, Ferrigno C, Bozzo E, Rea N, Pavan L, Burderi L, Burgay M, Campana S, di Salvo T, Falanga M, Filipovic MD, Freire PCC, Hessels JWT, Possenti A, Ransom SM, Riggio A, Romano P, Sarkissian JM, Stairs IH, Stella L, Torres DF, Wieringa MH, Wong GF (2013) Swings between rotation and accretion power in a binary millisecond pulsar. Nature 501(7):517–520

Papitto A, Torres DF, Rea N, Tauris TM (2014) Spin frequency distributions of binary millisecond pulsars. A&A 566:A64

Porter JM, Rivinius T (2003) Classical Be Stars. PASP115:1153–1170, DOI 10.1086/378307

Poutanen J, Mushtukov AA, Suleimanov VF, Tsygankov SS, Nagariner DI, Doroshenko V, Lutovinov AA (2013) A Reflection Model for the Cyclotron Lines in the Spectra of X-Ray Pulsars. ApJ 777:115, DOI 10.1088/0004-637X/777/2/115, [1304.2633]

Psaltis D, Wijnands R, Homan J, Jonker PG, van der Klis M, Miller MC, Lamb FK, Kuulkers E, van Paradijs J, Lewin WHG (1999) On the Magnetospheric Beat-Frequency and Lense-Thirring Interpretations of the Horizontal-Branch Oscillation in the Z Sources. ApJ 520:763–775, DOI 10.1086/307460, astro-ph/9903105
Radhakrishnan V, Srinivasan G (1982) On the origin of the recently discovered ultra-rapid pulsar. Current Science 51:1096–1099
Schönherr G, Wilms J, Kretschmar P, Kreykenbohm I, Santangelo A, Rothschild RE, Coburn W, Staubert R (2007) A model for cyclotron resonance scattering features. A&A 472:353–365, DOI 10.1051/0004-6361:20077218,[0707.2105]
Schwarzman VF (1970) Izv Vyssh Uchebn Zaved Radiofiz 13:1852
Shakura N, Postnov K, Hjalmarsdotter L (2013) On the nature of ‘off’ states in slowly rotating low-luminosity X-ray pulsars. MNRAS 428:670–677, DOI 10.1093/mnras/sts062,[1209.4962]
Slettebak A, Snow TP (1987) Physics of Be stars. Proceedings of the 92nd Colloquium of the International Astronomical Union, held at Boulder, CO, USA, 18 - 22 August 1986.
Stappers BW, Archibald AM, Hessels JWT, Bassa CG, Bogdanov S, Janssen GH, Kaspi VM, Lyne AG, Patruno A, Tendulkar S, Hill AB, Glanzman T (2014) A State Change in the Missing Link Binary Pulsar System PSR J1023+0038. ApJ 790(1):39
Staubert R, Shakura NI, Postnov K, Wilms J, Rothschild RE, Coburn W, Rodina L, Klochkov D (2007) Discovery of a flux-related change of the cyclotron line energy in Hercules X-1. A&A 465(2):L25–L28
Stella L, Vietri M (1999) Lense-Thirring precession and QPOs in low mass X-ray binaries. Nuclear Physics B Proceedings Supplements 69:135–140, DOI 10.1016/S0920-5632(98)00196-0
Stevens IR, Kallman TR (1990) X-ray illuminated stellar winds - Ionization effects in the radiative driving of stellar winds in massive X-ray binary systems. ApJ 365:321–331, DOI 10.1086/169486
Taam RE, Sandquist EL (2000) Common Envelope Evolution of Massive Binary Stars. ARA&A 38:113–141, DOI 10.1146/annurev.astro.38.1.113
Truemper J, Pietsch W, Reppin C, Voges W, Staubert R, Kendziorra E (1978) Evidence for strong cyclotron line emission in the hard X-ray spectrum of Hercules X-1. ApJ 219:L105–L110, DOI 10.1086/182617
Tsygankov SS, Lutovinov AA, Churazov EM, Sunyaev RA (2006) V0332+53 in the outburst of 2004-2005: luminosity dependence of the cyclotron line and pulse profile. MNRAS 371:19–28, DOI 10.1111/j.1365-2966.2006.10610.x, astro-ph/0511237
van den Heuvel EPJ, De Loore C (1973) The nature of X-ray binaries III. Evolution of massive close binaries with one collapsed component - with a possible application to Cygnus X-3. A&A 25:387–395
van der Klis M (2000) Millisecond Oscillations in X-ray Binaries. ARA&A 38:717–760, DOI 10.1146/annurev.astro.38.1.717,[astro-ph/0001167]
Walter R, Lutovinov AA, Bozzo E, Tsygankov SS (2015) High-mass X-ray binaries in the Milky Way. A closer look with INTEGRAL. A&A Rev. 23:2, DOI 10.1007/s00159-015-0082-6,[1505.03651]
White NE, Swank JH, Holt SS (1983) Accretion powered X-ray pulsars. ApJ 270:711–734, DOI 10.1086/161162
Wijnands R, van der Klis M (1998) A millisecond pulsar in an X-ray binary system. Nature 394(6):344–346
Zhang CM, Kojima Y (2006) The bottom magnetic field and magnetosphere evolution of neutron star in low-mass X-ray binary. MNRAS 366(1):137–143