Stellar wind accretion in high-mass X-ray binaries

I. Negueruela
DFISTS, EPSA, Universidad de Alicante, Apdo. 99, 03080 Alicante, Spain

Abstract.
Recent discoveries have confirmed the existence of a large population of X-ray sources fuelled by accretion from the stellar wind of an OB supergiant. Such systems are powerful laboratories to study many aspects of astrophysics. Over the last decades, the physics of accretion in these systems has been the subject of extensive research, mainly through numerical methods. In spite of this effort, large uncertainties remain in our understanding, reflecting the complexity of the physical situation. A crucial issue that remains open is the possible formation of accretion discs. Though the spin evolution of neutron stars in these systems suggests that angular momentum is, at least occasionally, accreted, and many observational facts seem to require the existence of discs, computational results do not favour this possibility. In this brief review, I will summarise some of the open questions in this area.

1. Introduction

High-Mass X-ray binaries (HMXBs) are X-ray sources composed of an early-type massive star and an accreting compact object (neutron star or black hole). The vast majority of HMXBs contain X-ray pulsars (magnetised neutron stars) and can be characterised by their pulse period, which corresponds to the spin period of the neutron star $P_s$. A few systems are considered good black hole candidates. The presence of an X-ray pulsar has allowed the determination of orbital parameters for a large number of systems via analysis of Doppler shifts in the pulse arrival times (e.g., Schreier et al. 1972; Rappaport et al. 1978).

Since so many parameters may be known, HMXBs represent important laboratories to study a large number of fundamental astrophysical questions. Among them, we can cite the masses of neutron stars and their equation of state (e.g., Kaper 1998; Quaintrell et al. 2003; van der Meer 2007). Also, because of their young age, they may act as tracers of star formation (e.g., Grimm et al. 2003; Lutovinov et al. 2005). When considered as a population, they can provide information on properties of galaxies (e.g., Gilfanov et al. 2004). Finally, they represent an important phase of massive binary evolution and, again considered as a whole, can provide strong constraints on binary evolution and the mechanisms for the formation of neutron stars and black holes (e.g., van Bever & Vanbeveren 2000; Brown et al. 2001). A recent list of known HMXBs is provided by Liu et al. (2007).

HMXBs can be divided in several subgroups, depending on their X-ray properties, which are found to depend fundamentally on the nature of the mas-
sive star donating mass. Corbet (1986) found that the position of an object in the orbital period vs. spin period ($P_{\text{orb}}/P_s$) diagram correlates well with other physical properties, allowing the definition of meaningful subgroups:

- A few objects with very close orbits and short $P_s$ are observed as very bright ($L_X \sim 10^{38}$ erg s$^{-1}$) persistent X-ray sources, with clear evidence for an accretion disc. Their neutron stars are spinning up most of the time, because angular momentum is transferred with the material accreted.

- Many systems with Be star counterparts are X-ray transients, showing very low X-ray fluxes in quiescence ($\lesssim 10^{33}$ erg s$^{-1}$; e.g., Campana et al. 2002) and luminosities close to the Eddington limit for a neutron star ($\sim 10^{38}$ erg s$^{-1}$) during bright outbursts. In spite of their short duty cycles, the majority of known HMXBs are Be/X-ray transients, suggesting that they represent the dominant population. Their X-ray characteristics are explained as a consequence of mass loss from the Be star in the form of a Keplerian disc (Okazaki & Negueruela 2001). Be/X-ray binaries populate a rather narrow region of the $P_{\text{orb}}/P_s$ diagram. The correlation between $P_{\text{orb}}$ and $P_s$ is believed to be connected to some physical equilibrium between the spin down of the neutron stars when they are not accreting and their spin up during outbursts, indicative of the formation of transitory accretion discs (Stella et al. 1986; Waters & van Kerkwijk 1989; Wilson et al. 2008).

- A second large group is formed by systems with OB supergiant donors and long-$P_s$ neutron stars. These objects, known as Supergiant X-ray Binaries (SGXBs) are moderately bright ($L_X \sim 10^{36}$ erg s$^{-1}$) persistent X-ray sources with a large degree of short-term variability. Their characteristics are attributed to direct accretion from the wind of the supergiant on to the compact object. This mode of accretion is known as wind accretion, and, as we will discuss, it is believed to occur without the formation of a stable accretion disc.

Recent discoveries, however, are showing that the division of HMXBs into different groups, though physically meaningful, is not strict. Apparent exceptions have been found, which may perhaps be due to infrequent evolutionary stages (cf. Chaty, these proceedings).

2. The theory of wind accretion

Luminous OB stars produce powerful winds due to line scattering of the continuum radiation flux from the star (see Kudritzki & Puls 2000, for a review). Material is accelerated outwards from the stellar atmosphere to a final velocity $v_\infty$ according to a law that may be approximated as

$$v_w(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta,$$

where $R_*$ is the radius of the OB star and $\beta$ is a factor generally lying in the interval $\sim 0.8 - 1.2$. 

In these circumstances, high wind velocities are reached at a moderate height above the star’s surface (for example, for $\beta = 1.0$, $v_w(2R_*) = 0.5v_\infty$, i.e., $\sim 1000$ km s$^{-1}$). The wind is highly supersonic and the wind speed is much higher than the orbital velocity of the neutron star $v_{\text{orb}} \sim 200$ km s$^{-1}$ at $2R_*$. Under those conditions, the classical Bondi-Hoyle-Lyttleton formulation represents an approximation to the accretion process. A comprehensive review of Bondi-Hoyle-Lyttleton accretion is presented by Edgar (2004).

In this approximation, the accretion rate ($\dot{M}$) of a neutron star immersed in a fast wind is governed by its accretion radius, the maximum distance at which its gravitational potential well can deflect the stellar wind and focus the outflowing material towards the neutron star, given by

$$r_{\text{acc}} \sim \frac{2GM_X}{v_{\text{rel}}^2},$$

where the relative velocity of the accreted material with respect to the neutron star is $v_{\text{rel}}^2 = v_w^2 + v_{\text{orb}}^2$. For typical values of $v_w$, $r_{\text{acc}} \sim 10^8$ m, decreasing by a factor of a few from $r = 2R_*$ to $r = 10R_*$. The accretion rate is then

$$\dot{M} = 4\pi (GM_X)^2 v_w(r) \rho(r) \frac{v_w(r)}{v_{\text{rel}}^2},$$

where $\rho(r)$ is the wind density. If we assume a certain efficiency factor in the transformation of gravitational energy into X-ray luminosity, the X-ray luminosity will be proportional to

$$L_X \sim \dot{M} \sim \frac{\rho(r)v_w(r)}{v_{\text{rel}}^4}.$$  

This dependency means that, in this approximation, the X-ray luminosity of a neutron star in a circular orbit is constant. In an eccentric orbit, the luminosity varies with orbital phase. Different systems differ in their orbital parameters (semi-major axis, eccentricity) and wind properties (mass loss rate, velocity law and terminal velocity). Figure 1 is a simple diagram showing the dependence of the X-ray luminosity on these parameters. A transformation factor $L_X = \frac{1}{3}L_{\text{acc}}$ is assumed.

3. Real winds and real accretion

Direct application of the simple model outlined above is able to crudely reproduce the average order of magnitude X-ray luminosity of real SGXBs (Ribó et al. 2006). However, their X-ray lightcurves provide strong evidence for a much more complex physical situation. The X-ray lightcurves of wind accreting systems are dominated by short-term (timescale of hundreds of seconds) variability, with flux changes by a factor of a few (e.g., Haberl et al. 1989, Kreykenbohm et al. 1999). The pulse periods of well-monitored SGXBs, such as Vela X-1, display random variations around an average value (Bildsten et al. 1997). These variations can
Figure 1. Minimum and maximum X-ray luminosities (within an orbit) predicted by a simple approximation (homogeneous wind + Bondi-Hoyle-Lyttleton accretion) for a range of system parameters ($P_{\text{orb}}, e$). The left panel shows luminosities for a slow wind ($v_{\infty} = 1000\ km\ s^{-1}$), typical of B-type supergiants. The right panel shows results for a fast wind ($v_{\infty} = 2000\ km\ s^{-1}$), more typical of O-type supergiants. The regions marked RLO are those where the donor undergoes Roche Lobe Overflow close to periastron. Courtesy of M. Ribó.

occur on short (days) timescales (Boynton et al. 1984), superimposed on longer-timescale trends (Nagase et al. 1984). The behaviour has been described as a random walk (e.g., Tsunemi 1989), and interpreted as short episodes of angular momentum accretion.

Some systems have shown very long term trends. For example, 4U 1907+09 showed persistent spin down, at an almost constant rate, during more than ten years. Afterwards, it changed to a lower spin-down rate and finally started spinning up (Fritz et al. 2006). These “torque reversals” have been taken as evidence for accretion discs that rotate in alternating senses (Nelson et al. 1997). Interestingly, these torque reversals are not only seen in wind-fed systems, but also in systems that always accrete from a disc, such as Cen X-3 (Nelson et al. 1997).

In order to explain this behaviour, the complex physics of SGXBs must be considered. In short, we may identify three main ways in which the actual physical process of accretion differs from the idealised formulation of the previous section:

1. The winds of massive stars are highly structured.

2. Accretion on to a very small object is an unstable process.

3. The magnetic field of the neutron star may affect the flow of material.

3.1. Complex radiative winds

From the early days of radiation driven wind theory (e.g., Owocki & Rybicki 1984), it was obvious that winds from hot stars should be highly unstable to
small-scale perturbations. This is a direct consequence of the driving mechanism and therefore an intrinsic property of the wind, which cannot be smooth, but must be highly structured. Observations of wind lines in OB stars have revealed the presence of large-scale (quasi)cyclical structures, which may be induced by instabilities generated by the star itself (see, e.g., Kaper & Fullerton 1998). In addition, theory predicts the existence of smaller-scale stochastic structure, caused by the appearance of shocks in the wind flow, directly related to its intrinsic instability. In simulations (e.g., Runacres & Owocki 2002), irregular variations in both density and velocity develop at a small height above the photosphere, leading to the appearance of structure already at a distance $r \lesssim 2 R_*$ from the centre of the star, where the wind has only reached about half its terminal velocity. The variations steepen into shocks that decelerate and compress rarefied gas, collecting most of the mass into a sequence of dense clumps bounded by shocks, which definitely dominate the wind structure beyond $r \gtrsim 3 R_*$ (Runacres & Owocki 2002) and perhaps much closer to the stellar surface (Puls et al. 2006).

The observational evidence for these clumps is, at present, indirect. Structured winds with numerous internal shocks are considered necessary to explain X-ray emission from isolated hot stars (Feldmeier et al. 1997). A clumpy structure was also invoked to explain the overall non-thermal radio emission from early-type stars, though this is now debated (van Loo et al. 2006). Recent model fits to optical and UV spectra of B-type supergiants seem to require a substantial amount of clumping (Prinja et al. 2005; Crowther et al. 2006). The observed stochastic variability on short timescales of Hα profiles in O-type stars is consistent with the predictions of wind models with clumping (Markova et al. 2005). In spite of all this, as we have no direct observations of wind clumps, even their most basic parameters (size, geometry, density) are unknown. Some authors find compelling reasons to argue for geometrically large, very massive clumps (Oskinova et al. 2007), but this is hotly debated. In any case, the approximation of a smooth wind of constant density must be considered unrealistic.

In addition, the overall geometry of the wind is the subject of debate. Radiation driven wind theory assumes a spherical geometry, but other physical effects, such as stellar rotation and magnetic fields, may cause important deviations. Some indirect evidence for the presence of equatorially enhanced mass loss, perhaps associated to magnetic fields, has been presented (Markova et al. 2005; Ud-Doula et al. 2008). On the other hand, the nebulae ejected by some massive stars are decidedly bipolar, suggesting enhanced mass loss at the poles (Smith & Townsend 2007).

3.2. Accretion on to a compact object

In the Bondi-Hoyle-Lyttleton approximation, particles follow ballistic trajectories and are accreted without any net transfer of angular momentum. However, from the very earliest numerical calculations, it was clear that accretion flows should be more complicated. Initial hydrodynamical simulations were carried out in two dimensions (e.g., Matsuda et al. 1987; Taam & Fryxell 1989) or considering an axisymmetric three-dimensional problem (e.g., Hunt 1971; Sawada et al. 1989), but many 3D schemes have been developed (e.g., Matsuda et al. 1991; Nagae et al. 2005). The details of the flow depend on the
thermodynamical properties of the gas accreted and the size of the accretor (cf., for instance, Ruffert 1994; Ruffert & Anzer 1995, and other papers in that series). The accretion rate predicted by the Bondi-Hoyle-Lyttleton scheme turns out to be a good approximation, but the accretion flow is much more complex than assumed, especially as more realistic physics are included (e.g., Theuns & Jorissen 1993). Bow shocks form and complex structure develops around the accretor. In the case when the mass donor fills an important fraction of its Roche lobe, as happens in most SGXBs, the accretion flow is especially complicated (Nagae et al. 2005).

When a density or velocity gradient is introduced in the accretion flow, it becomes possible to accrete angular momentum. High resolution 2D simulations by Matsuda et al. (1987) found that the accretion flow does not approach a steady state, but becomes unstable. The shock cone oscillates from one side of the accretor to the other, allowing the appearance of transient accretion discs. This instability, generally known as “flip-flop” oscillation, has been studied by a large number of authors, (e.g., Matsuda et al. 1991; Boffin & Anzer 1994). The instability produces fluctuations in the accretion rate and gives rise to stochastic accretion of positive and negative angular momentum, leading to the suggestion that it is the source of the variations seen in the pulse evolution of SGXBs (Benensohn et al. 1997; Shima et al. 1998). Anzer & Börner (1995) argued that the timescales and amplitudes of these fluctuations are too small to explain the spin variations, though larger amplitudes were found in 2D simulations by Shima et al. (1998). If the accretion flow is stable, the amount of angular momentum transferred to the neutron star is negligible. The more unstable the accretion flow, the higher the transfer rate of angular momentum (Matsuda et al. 1991).

Unfortunately, the results of simulations depend strongly on the procedure used. In general, the instability seems to appear when the physical size of the accretor is very small, but full 3D simulations are always much more stable than 2D simulations. Indeed, several 3D simulations showed stable flows, rising the possibility that the flip-flop instability could be just a numerical artifact (Ruffert 1999; Krivukov et al. 2005). A critical review of existing work is presented by Foglizzo et al. (2005), who suggest that the instability is most likely physical in origin, related to the coupling of advected perturbations to acoustic waves. Recent high-fidelity 2D numerical simulations (Blondin & Pope 2009) confirm that the flip-flop instability does not require any gradient in the upstream flow to develop, and that it is much stronger when the accretor is very small. If the accretor is sufficiently small, the secular evolution is described by sudden jumps between states with counter-rotating quasi-Keplerian accretion disks.

In addition to the intrinsic instability of the accretion flow, in a real SGXB, the presence of the neutron star has an impact on the wind dynamics (Stevens 1988). It may dynamically induce an enhancement of the mass loss (leading to the formation of an accretion stream; cf. Blondin et al. 1991) and it may even induce the supergiant to pulsate (Quaintrell et al. 2003). Also, if the neutron star is actively emitting X-rays, it can impact on the wind by photo-ionising the heavy elements that drive the outflow. In this way, it may slow down the wind, effectively increasing the accretion radius (Blondin et al. 1991). Indeed, the photo-ionisation effect of the X-ray source is readily visible in the ultraviolet
spectra of SGXBs. Wind lines show pronounced orbital variability (Kaper et al. 1993). Far ultraviolet spectra of the counterpart to 4U 1700–37 show important changes in the ionisation structure of the wind with the binary phase, suggesting that the X-ray source ionises much of the wind (Iping et al. 2007). In the optical counterpart to Vela X-1, optical spectra reveal additional absorption components on the wings of photospheric lines at inferior conjunction of the neutron star (Kaper et al. 1994). These features are attributed to the presence of a photo-ionisation wake trailing the neutron star.

The complexity of the accretion environment can provide an explanation to the short-term variability of the X-ray lightcurves of SGXBs. Simulations by Blondin et al. (1990) showed that the accretion wake trailing the neutron star contains dense filaments (up to 100 times denser than the undisturbed wind). Their accretion may produce abrupt changes in X-ray luminosity.

3.3. Magnetic field

The neutron stars in SGXBs are young, and possess strong ($\sim 10^{12}$ G) magnetic fields. As material approaches the neutron star, it is captured by the magnetic field and deflected along the magnetic field lines. Many situations are possible, depending on the relative strengths of the magnetic field and the ram pressure of the incoming material (Stella et al. 1986; Bozzo et al. 2008). If the ram pressure is low, the incoming material may be stopped at the magnetosphere, and the neutron star may then be in the propeller regime (Iliarinov & Sunyaev 1975). Accretion is then told to be centrifugally inhibited. If the magnetic field is strong enough to affect the flow beyond the accretion radius, there will be magnetic inhibition of the accretion (Stella et al. 1986).

Though changes in the accretion state have been invoked to explain the behaviour of Be/X-ray transients (e.g., Campana et al. 2002), magnetic effects have not been traditionally considered while explaining the long-term evolution of SGXBs. However, the spin fluctuations (which are also seen in systems with an accretion disc; e.g., Bildsten 1997) are highly suggestive of magnetic interaction between the accretion disk and the stellar magnetosphere. Anzer & Börner (1995) argued that a disc or torus could form around the magnetosphere and interact with it, acting as a reservoir of mass and angular momentum. This interaction represents a possible way to provide the neutron star with enough angular momentum to explain random variations in pulse period, though Anzer & Börner (1995) estimate that magnetic fields too high by an order of magnitude are needed for the torque to be effective.

4. Case study: GX 301−2

Though Vela X-1 is probably the best studied SGXB, an important effort has also been dedicated to understanding a very special system, GX 301−2. This wind accreting X-ray pulsar differs from other SGXBs in two very important aspects: first, its orbit is wider ($P_{\text{orb}} = 41.5$ d) and more eccentric ($e = 0.46$) than those of other systems; second, the mass donor is a B1 Ia$^+$ hypergiant, implying that it is larger than the donors in other systems and has a denser, slower wind. Because of these characteristics, the X-ray luminosity is strongly modulated at the orbital period, The flux close to periastron is $\sim 4$ times higher
than at other phases, peaking 1–2 d before periastron (e.g., [Watson et al. 1982; Koh et al. 1997]). The varying conditions along the orbit make GX 301–2 a very good test of different accretion models.

GX 301–2 occasionally undergoes rapid spin-up episodes, lasting a few weeks, which have been attributed to the formation of transient accretion discs (Koh et al. 1997). In order to explain the existence of strong periastron and weak apastron flares, Pravdo & Ghosh (2001) postulated the presence of circumstellar disc around the hypergiant, perhaps in the form of a collimated, denser equatorial wind. Optical observations of the mass donor, however, do not show any evidence for such a disc (Kaper et al. 2006).

In fact, the size of the hypergiant is such that it may be very close to filling its Roche lobe when the neutron star is at periastron (Koh et al. 1997), allowing the formation of an accretion stream. Some indications of the existence of such a stream are seen in optical spectra of the companion (Kaper et al. 2006). The average X-ray lightcurve of GX 301–2 can be successfully fit by a model that considers accretion from a spherical wind and an accretion stream (Leahy & Kostka 2008). As a matter of fact, in this model, most of the X-ray luminosity is due to accretion of dense material from the stream, rather than direct wind accretion.

5. An unexpected test on the model: supergiant fast X-ray transients

Over the last few years, there has been a huge increase in the number of HMXBs known. Many of these systems are believed to be wind accretors (e.g., Walter et al. 2006). Several new SGXBs have been found, most of them heavily obscured. Many other sources, however, have been found to display very brief outbursts, with a rise timescale of tens of minutes and lasting only a few hours (Sguera et al. 2005). They have been identified with OB supergiants: (e.g., the prototype XTE J1739−302; Smith et al. 2006; Negueruela et al. 2006a), leading to the definition of a class of Supergiant Fast X-ray Transients (SFXTs; Negueruela et al. 2006b; Smith et al. 2006). The distances to their counterparts imply typical $L_X \sim 10^{36}$ erg s$^{-1}$ at the peak of the outbursts. Outside outburst, they display rather lower luminosities (between $\sim 10^{33}$ and $\sim 10^{35}$ erg s$^{-1}$, depending on the particular system; Sidoli et al. 2008).

As the number of these new systems increases, it is becoming clear that the separation between SFXTs and SGXBs is not well defined (Walter & Zurita Heras 2007; Negueruela et al. 2008). Some systems behave as SGXBs during part of their orbits (e.g., SAX J1818.6−1703, Zurita Heras & Chaty 2008; IGR J18483−0311, Rahoui & Chaty 2008), and all show spectra and lightcurves typical of wind accretion.

Explaining the behaviour of these sources has become a major challenge for our models of wind accretion. In some systems, variability is obviously related to orbital motion. The orbital period of SAX J1818.6−1703, for example, is 30 d, and so its orbit is wider than those of SGXBs, meaning that the neutron star is most of the time further away from the donor than in the persistent systems. However, geometry alone does not seem able to explain all the differences. The idea that the flares are related to accretion of wind clumps was
Wind accreting HMXBs

advanced by In’t Zand (2005) and developed by Walter & Zurita Heras (2007). Negueruela et al. (2008) speculated with the possibility that the development of clumps made accretion less efficient when the neutron star was relatively distant from the mass donor. Alternatively, Sidoli et al. (2007) proposed that the outbursts were associated with the crossing of a thin circumstellar disc surrounding the supergiant. Other authors have suggested that the reason of the outbursts must be sought in the interaction of the wind with the magnetosphere (Grebenyev & Sunyaev 2007), though Bozzo et al. (2008) calculated that this was only plausible if the neutron stars in SFXTs had magnetic fields two or three orders of magnitude stronger than those in SGXBs.

Walter & Zurita Heras (2007) suggested that the X-ray lightcurves of SGXBs could be tracing directly the matter density met by the neutron star. In this way, the neutron star could be used as a probe of the stellar wind. Unfortunately, detailed observations of outbursts from SFXTs do not support the idea that each outburst can be identified with the accretion of a wind clump. The outbursts last many hours (or even days) and are generally multi-peaked. Many of them are also very asymmetric, with fast rises and slow decays, casting doubt on the possibility that they may be caused by direct accretion during passage through a disc.

Moreover, intensive monitoring of SGXBs has also revealed new phenomenology, which increases the similarity to SFXTs. Vela X-1 has been observed to display “giant” flares, which resemble very closely the outbursts of SFXTs, with flux increases of ~10 and a timescale of a few hours (Kreykenbohm et al. 2008). Conversely, it has also been found to display “off states”, during which the flux decreases orders of magnitude and the pulse period is not detectable. Kreykenbohm et al. (2008) discuss the differences and similarities of SGXBs and SFXTs in the context of a scenario in which wind clumping, the highly structured accretion flow and the magnetic field all play a role.

More recently, the discovery that the SFXT IGR J16479−4514 has an orbital period of only 3.3 d (Jain et al. 2009), and that its outbursts appear to be locked in phase (Bozzo et al. 2009), has posed a strong challenge to all the models developed. Once more, the physics of wind accretion reveals its complexity.

6. Wind accretion in very high energy sources

A handful of HMXBs produce γ-rays. To this day, two very different models have been proposed to explain their behaviour (see these proceedings). In both, the stellar winds play an important role, but accretion is an important element in only one of them.

Of the γ-ray binaries, LS 2883/PSR B1259−63 is the only one for which a model is universally accepted. PSR B1259−63 is a radio pulsar in a very wide an eccentric orbit ($P_{\text{orb}} = 3.4$ yr, $e = 0.87$) around the Be star LS 2883. Timing of the radio pulses provides an accurate orbital solution (Wex et al. 1998). As the neutron star approaches periastron, it interacts with the disc around the Be star and radio pulses are quenched. The interaction between the pulsar wind and the Be star outflow produces shocked material, where particles are efficiently accelerated to relativistic velocities. Tavani & Arons (1997) proposed a number of feasible mechanisms to explain the production of high-energy photons.
However, it must be noted that they used a radial outflow model for the mass loss of Be stars (Waters et al. 1988). This model has subsequently been ruled out by observations, which strongly support a Keplerian disc around Be stars (Porter & Rivinius 2003). New modelling is necessary for this system (cf. Naito, these proceedings).

The γ-ray binary LS I +61°303 is similar to LS 2883/PSR B1259−63 in the sense that the mass donor is an early Be star and the orbit is highly eccentric (Casares et al. 2005). The orbital period is, however, much shorter (26 d). In the third γ-ray binary, LS 5039, the situation is very different, as the mass donor is an O6.5 V star in a close orbit (Clark et al. 2001). The wind structure is expected to be extremely different from those in the Be systems. However, it is worth noting that our knowledge of the winds of these systems is completely indirect. Only LS I +61°303 was observed on a few occasions by IUE, but the spectra are of low quality (Howarth 1983).

Moreover, with the small sample known, we have been unable to identify the key ingredients necessary to have a γ-ray binary. For example, the system SAX J0635+0533, which shows remarkable similarities to PSR B1259−63 and LS I +61°303 (a young fast-spinning pulsar in an eccentric orbit around an early Be star; Cusumano et al. 2000) is not a source of γ rays (Aharonian et al. 2006).

An interesting possibility is opened by the proposed association of the SFXT IGR J11215−5952 and the high-energy source EGR J1122−5946 (Sguera 2009), though the error circle for the the EGRET source is too large to consider this identification certain.

7. Conclusions

Supergiant X-ray binaries represent powerful laboratories to study the physics of accretion from a wind. As our observations become more extensive and sensitive, new phenomena are revealed, reflecting the complexity of the physical situation. Increased computational resources have provided very detailed models of wind accretion. These models have shown that the accretion process is likely intrinsically unstable, and perhaps dominated by stochastic processes. The most important question that we need to understand is whether accretion discs may form and angular momentum can be effectively transferred to the accreting neutron star. Several observational facts strongly point to a positive answer, but models still suggest that the effective accretion of angular momentum is very difficult. New observations are being taken and more powerful models being developed. The next few years are likely to see important developments in this field.

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