Stellar jets

Thomas J. Maccarone
School of Physics and Astronomy, University of Southampton, Highfield, Southampton, SO16 4ES, United Kingdom

Abstract. With a goal of understanding the conditions under which jets might be produced in novae and related objects, I consider the conditions under which jets are produced from other classes of accreting compact objects. I give an overview of accretion disk spectral states, including a discussion of in which states these jets are seen. I highlight the differences between neutron stars and black holes, which may help give us insights about when and how the presence of a solid surface may help or inhibit jet production.

1. Introduction

Jets have been seen from a variety of classes of astrophysical objects. The first report of an astrophysical jet was a remark that a streak of light seemed to be emanating from the galaxy M87 (Curtis 1918), but studies of jets did not begin in earnest until the development of radio astronomy. It has long been appreciated that active galactic nuclei often power relativistic jets. In the past decade or so, a picture has been emerged in which it seems that a rotating magnetic field is sufficient to power a jet – jets have been seen from all sorts of accreting stars, like young stellar objects, supersoft sources, accreting stellar mass black holes, and accreting neutron stars in low mass X-ray binaries. Jets have also been seen from a few young rotation-powered pulsars, indicating that an accretion disk is not a necessary element for jet production. The only classes of objects from which jets have not been widely reported are accretion powered pulsars in high mass X-ray binaries (where the magnetic field truncates the accretion disk far from the surface of the accreting neutron star), and cataclysmic variables (where a few shallow non-detections of radio emission in the 1970’s led to a general disinterest in making deeper searches). In this paper, I will review the literature of jets from accreting stellar mass black holes and accreting low magnetic field neutron stars. I will then use these results to develop some intuition about when and why jets might be seen from accreting white dwarfs. For a more general review of astrophysical jets, I suggest Maccarone & Körding (2006) for readers looking for a gentle introduction to the topic, Livio (1999) for readers looking for a greater level of technical detail, and Fender (2006) for readers looking for a more detailed view of jets from stellar mass compact objects.
2. Spectral states of disks

For the purposes of establishing a connection between accretion and ejection, stellar mass black holes are the most useful objects. They vary in luminosity by factors of \( \sim 10^7 \) on timescales of years. As their emission comes out primarily in X-rays, they can be observed with all-sky monitors, so outbursts from new sources can be detected easily across most of the Galaxy.

In order to understand better the conditions in an accretion flow which allow jet production, it is necessary to understand some of the basics of accretion disk phenomenology. Black hole X-ray binaries exhibit a spectral state phenomenology, much of which has clear analogies to the spectral state phenomenology of neutron star X-ray binaries. These states are defined by qualitative patterns of behavior of both the spectral energy distribution and the Fourier power spectrum of the sources’ X-ray emission.

The simplest of the spectral states in accreting black holes is the high/soft state. In this state, a black hole’s X-ray spectral energy distribution is well described by a multi-temperature disk model – essentially the disk solution first proposed by Shakura & Sunyaev (1973) and Novikov & Thorne (1973). These disks appear to extend to the innermost stable circular orbits of the accreting black holes (e.g. Sobczak et al. 1999). In most cases a weak power law tail to the spectrum is detected, sometimes extending out to several MeV (McConnell et al. 2000), but never is it energetically important.

The next simplest state is the low/hard state, in which most accreting black holes spend most of the time. In this state, the X-ray spectral energy distribution is reasonably well modelled by an exponentially cutoff power law, with a photon index of 1.5-1.9, and the cutoff at about 100-200 keV. This type of spectrum is easily produced by thermal Comptonization (Thorne & Price 1975; Sunyaev & Trümper 1979) by a cloud of hot \((k_B T \approx 70\text{keV})\) with an optical depth close to unity.

A third, hybrid state is seen at state transitions, and sometimes during extended period during which sources remain at luminosities very close to the Eddington limit. This state is called the very high state when it is seen at high luminosities, and the intermediate state when it is seen at lower luminosities. The X-ray spectra of these states show strong quasi-thermal components and strong power law components. The power law components in these states are steep (i.e. \( \Gamma = 2.5-3.0 \)), like the power law components in soft states. Generally, however, the properties of these two states, both in terms of X-ray spectra and variability, there are no clear differences apart from luminosity between what is generally called the very high state and what is generally called the intermediate state (see e.g. Homan et al. 2001).

2.1. Timing states of disks

Since the days of EXOSAT, when it became possible to make good power spectra of a large number of accreting sources at a variety of accretion rates, it has been clear that the timing properties of accreting black holes and neutron stars fit a set of patterns (e.g. van der Klis 2005 and references within). More recently, this picture has been extended to include, at least at some level, white dwarfs as well (Mauche 2002; Warner, Woudt & Pretorius 2003), indicating again that...
much of the physics of accretion is generic to disks, rather than being peculiar to objects where relativistic effects are important. There are some power spectral features which clearly are associated with only one class of source, such as the high frequency quasi-periodic oscillations seen with 2:3 frequency ratios in some black hole accretors and are seen at frequencies high enough to require relativistic effects (e.g. Strohmayer 2001; Abramowicz & Kluzniak 2001), but these are generally easily isolated from the global trends in the power spectra.

Low/hard state sources characteristically have higher amplitudes of variability than high/soft state sources, but lower characteristic frequencies of variability (e.g. van der Klis 1994). During the state transitions, and in the persistent very high states, strong quasi-periodic oscillations are often seen (van der Klis 1994). The geometrically thin accretion disks are stable against short timescale variability – this has been determined observationally through multiple techniques (Churazov, Gilfanov & Revnivtsev 2001; Maccarone & Coppi 2002). The small amplitude of variability in the high/soft state is driven by the component which produces the weak hard tail in the X-ray spectrum. Given this result, the relative variability properties of the hard and soft states agree with the picture – variability is produced in the hard X-ray emitting region, and the characteristic timescale of the variability is related to some characteristic spatial scale in the emission region. The strong quasi-periodic oscillations in the state transitions are less well understood.

2.2. When do the state transitions occur?

Transitions between spectral states do not appear at a fixed fraction of the Eddington luminosity as was predicted by the earliest theoretical work. Instead, a hysteresis behavior has been found from most X-ray binaries in their state transition luminosities (e.g. Miyamoto et al. 1995; Maccarone & Coppi 2003). Typically, state transitions from the hard state to the soft state occur at luminosities about five times higher than the luminosities on the return from the soft state to the hard state. Transitions from the soft state to the hard state happen typically at about 2% of the Eddington limit, with much less scatter than the transitions from the hard state to the soft state (Maccarone 2003), but there are cases of soft-to-hard state transitions at different luminosities in the same source (Xue, Wu & Cui 2006; Yu & Dolence 2006).

A particularly interesting recent result which has received remarkably little attention is that white dwarfs show spectral state transition phenomenology which is quite similar to that seen from accreting black holes and neutron stars – both harder emission at low luminosities than high luminosities (which had been known for some time), but also similar hysteresis loops in hardness versus intensity (McGowan, Priedhorsky, Trudolyubov 2004; Wheatley, Mauche & Mattei 2003). The models invoked for the hard spectral states in white dwarfs are generally not the same as those invoked in black hole and neutron star accretors (although possible similarities have been appreciated by some authors for about a decade – see for example Meyer & Meyer-Hofmeister 1994; Meyer-Hofmeister & Meyer 1999 which invoke essentially the same physics to describe the outburst properties and state transitions of dwarf novae and of soft X-ray transients with black hole accretors), but the similarities in the state transition properties, combined with the timing similarities between dwarf novae and X-
ray binaries together imply that much of what is seen is universal to accretion disks, rather than peculiar to accretion disks with a particular type of compact object.

3. Jets from black hole X-ray binaries

Three classes of jets have been seen from X-ray binaries with likely black hole accretors. The first class consists of the spatially extended, highly variable but quasi-persistent jet emission from the systems which have been studied the longest – SS 433 and Cygnus X-3. Both these systems suffer from high obscuration of the X-ray emission from the source, likely due to a strong stellar wind in Cygnus X-3 and to an edge-on geometrically thick accretion disk in SS 433. Furthermore, both these source may be accreting more material than is needed for them to reach the Eddington limit, and neither has a reliable mass estimate, leaving open the possibility that one or both actually has a neutron star accretor. Thus while these two objects are quite interesting, they seem unlikely to be the keys for understanding the behavior of the broader class of X-ray binaries.

The two other classes of jets are seen from more normal soft X-ray transients, as well as from the canonical black hole X-ray binary Cygnus X-1. These are steady jets in the low/hard state and the more rapid jet ejections seen at state transitions. It should be noted that these rapid ejections are not seen in every outburst of every soft X-ray transient. Some outbursts do not reach a high enough luminosity to undergo a state transition (e.g. Brocksopp, Bandyopadhyay & Fender 2004), with the typical peak outburst luminosity in X-ray binaries, like in CVs, related roughly monotonically to the orbital period of the system (Warner 1987; Shahbaz, Charles & King 1998; Portegies Zwart, Dewi & Maccarone 2004).

Radio emission in low/hard state X-ray binaries is ubiquitous. These objects have flat-to-slightly inverted radio spectra (i.e. \( \alpha = 0.0 - 0.3 \), where \( f_\nu \propto \nu^\alpha \), with \( f_\nu \) the flux density, and \( \nu \) the frequency) typical of compact conical jets (Blandford & Königl 1979; Hjellming & Johnston 1988), with a break typically in the infrared or optical (Russell et al. 2006 and references within). It is worth noting that flat radio spectra do not generically imply jets (such radio spectra are also seen, for example, from HII regions and planetary nebulae, indicating that flat spectrum sources need be neither due to synchrotron emission nor from collimated regions), so additional evidence is required to prove that this radio emission is from synchrotron emission in compact conical, relativistic jets.

In Cygnus X-1 such jets have actually been imaged (Stirling et al. 2001), and the data quality has generally not been good enough to do so for other low/hard state black holes. The brightness temperatures implied by the fluxes of radio emission implied require that the emission comes from a region much larger than the orbital separation of the binary. Furthermore, where good data exist, the radio emission is seen to show weak, but significant linear polarization with a steady polarization angle (Corbel et al. 2000), also indicative of a jet. The best (or at least most interesting, in this writer’s opinion) evidence that these jets are at least mildly relativistic comes from time series analysis of XTE J1118+480, where the lag between the X-ray emission and the optical emission gives a rough estimate of the time it takes for changes in the accretion disk
where the X-rays are produced to propagate up the jet to the region where the optical emission is produced (e.g. Malzac, Merloni & Fabian 2003).

In low/hard states, the radio luminosity, $L_R$ from the jet scales with the X-ray luminosity from the accretion flow $L_X$ such that $L_R \propto L_X^{0.7}$ (Corbel et al. 2000; Gallo, Fender & Pooley 2003). Considerable scatter is seen about this relation. Much of the scatter likely derives from a variety of sources which may not reveal much about the physics of jet production – non-simultaneity of the X-ray and radio data, uncertainties in the distances to sources, and uncertainties in source masses. However, there is clearly some scatter due to reasons which are based in physics, and not in observational difficulties. Recently, it has been suggested that GX 339-4 shows parallel tracks in radio versus X-ray emission (Nowak et al. 2005), and shown clearly that parallel tracks exist in the infrared versus X-ray emission in XTE J1550-564 (Russell et al. 2007). Additional parallel tracks were reported during “failed state transitions” in Cygnus X-1 (Nowak et al. 2005).

In the high/soft states of black holes, radio emission has been detected only once, and this appears to have been decaying emission from a transient event that had taken place shortly before the observation (Corbel et al. 2004). The best searches for radio emission from soft state black holes indicate that the jet power is suppressed by a factor of at least 30-50 in the high/soft state (Corbel et al. 2001). In fact, that radio emission is well correlated with hard X-rays and anti-correlated with soft X-rays was first discovered about 35 years ago (Tananbaum et al. 1972), but has only become well-appreciated in the last decade or so (Harmon et al 1995; Fender et al. 1999). In the early 1970’s, this result was considered exciting because the association of a state transition in the X-rays with a dramatic change in the radio properties of a source in the X-ray error box allowed the use of a radio position for searches for the optical counterpart of Cygnus X-1. Attempts to establish a dynamically confirmed black hole were, not surprisingly, considered more important than attempts to understand the radio emission from stellar mass black holes. It took the confluence of the discovery of the “microquasar phenomenon” generating new interest in X-ray binaries, along with the launches of CGRO and RXTE, which could provide intensive flux monitoring of X-ray binaries, to go beyond Tananbaum's original discovery to promote an understanding of jet production based on X-ray/radio connections in X-ray binaries.

At the transitions from hard to soft states, there have very often been high luminosity, high velocity jet ejections observed (e.g. Mirabel & Rodriguez 1994; Hjellming & Rupen 1995). An intriguing possibility is that these events occur because the jet velocity is tied to the escape speed at the inner “edge” of the accretion disk, and, as the state transitions proceed, the inner edge of the accretion disk moves inwards, raising the velocity of the jet, and leading to external shocks of the newer high velocity jet material against the old slow jet material ejecting during the long low/hard states (Vadawale et al. 2003; Fender, Belloni & Gallo 2003).

Some recent work (e.g. Rykoff et al. 2007 and references within) has been suggested to indicate that the inner edge of the accretion disk stays fixed at the innermost stable circular orbit even across state transitions into the low hard state. It is more likely that there are not sudden and dramatic changes in the inner disk radius at the time of the state transition, but rather smooth changes
in the inner disk radius as a function of luminosity throughout the low/hard state, with the brightest low/hard states having inner disk radii quite close to the innermost stable circular orbits. Gradual transitions would better explain the timing data – the characteristic timescales change smoothly throughout the low/hard state, especially in the rising low/hard states (e.g. Pottschmidt et al. 2003; Körding et al. 2007) – and would even better explain the spectral data presented in Rykoff et al. (2007): the best fitting inner disk radii are larger for the low/hard states where there are sufficient counts to make constraining spectral fits than they are in the high/soft state observations. This picture would also allow for the clear evidence of large inner disk radii for quiescent black hole X-ray binaries without requiring the disk to begin receding at some arbitrary luminosity below the state transition luminosity.

4. Thick disks and the theory of jet production

The phenomenological association of radio emission with hard X-ray emission is likely associated with a more direct, physically motivated connection between geometrically thick accretion flows and jet production. It has been suggested that large scale height magnetic fields are necessary for extracting rotational energy from accretion disks and/or extracting the spin energy from a black hole (Livio, Ogilvie & Pringle 1999; Meier 2001), and these are the two most prominent means for providing the energy needed to power jets with accretion disks (e.g. Blandford & Znajek 1977; Blandford & Payne 1982).

5. Jets from neutron star X-ray binaries

Until very recently, the radio emission from neutron star X-ray binaries has been considerably less well studied than that from black hole X-ray binaries. A number of factors have contributed to this discrepancy. The most important is that the relative faintness of the neutron stars as radio sources, coupled with the locations of most of the brightest neutron stars in the Southern Hemisphere where they are unaccessible or barely accessible to the Very Large Array, has made such studies technically challenging. Despite these technical challenges, some major advances have been made in the past few years in understanding the radio emission from neutron stars.

Radio observations of accreting neutron stars yield both key similarities and differences. For the low/hard state neutron stars there is still a clear correlation between radio and X-ray luminosity, as seen in the low/hard state black holes, but with a much stronger dependence of radio power on X-ray power. The best fitting power law index for the radio/X-ray relation in accreting neutron stars is \( L_R \propto L_X^{1.4} \) (Migliari & Fender 2006), twice as steep as the relation for black holes. This has been interpreted as evidence that the black hole systems advect energy across their event horizons, while the neutron star systems release this energy in their boundary layers; the difference is naturally and exactly accounted for by a radiative efficiency which is constant for neutron star accretors, and which scales with \( \dot{m} \) for black hole accretors, as predicted for example, in advection dominated accretion flow models (e.g. Narayan & Yi 1994).
Figure 1. A schematic diagram showing the similarities and differences between neutron stars (grey regions) and black holes (black regions) in their jet production properties. The similarities are increasing $L_R$ with increasing $L_X$ in low luminosity states, a deficit compared to the extrapolation of the low/hard state trend (the left hand portion of the diagram) in the high/soft states (enclosed within the vertical lines), and a higher, but more scattered radio luminosity in the “very high” states. The most important difference is that the soft state radio emission is not nearly as strongly suppressed in neutron star systems as it is in black hole systems.

At higher luminosities, a key difference between neutron stars and black holes presents itself. In their equivalents of the high soft state, neutron stars are detectable radio emitters. Their radio fluxes are well below the extrapolation of what might be expected based on their X-ray fluxes and the relation in the hard state, so jet production is, in some sense, suppressed in neutron stars in soft states, but it is not suppressed by nearly as much as the black hole systems are. Figure 1 presents a schematic view of the similarities and differences between jet properties in neutron stars and black holes.

While much less is known about jets from white dwarf systems and their connections with the properties of the underlying accretion flow, there is some reason to believe that that qualitative behavior is analogous to that from neutron stars. The symbiotic star CH Cyg showed a correlation between a jet ejection event and a dramatic reduction in the amount of high frequency flickering (Sokoloski & Kenyon 2003), suggesting some agreement with this picture.

6. Are boundary layers important for jet production?

The radio emission in low luminosity neutron stars and black holes are largely the same, with the differences being accounted for by the fact that neutron stars cannot advect energy across their nonexistent event horizons. In these states,
then, it seems most likely that a geometrically thick accretion disk is providing the bulk of the energy that goes into the jet. In the higher luminosity states, where the accretion disk is geometrically thin, the downturn in radio luminosity is much stronger in the black hole systems than in the neutron star systems.

It is most natural, then, to associate the jets seen from soft state neutron stars with some means of launching jets that makes use of the solid surface of the neutron star. We had previously suggested that this might be due to the magnetic field of the neutron star providing a “seed” field (Maccarone & Körding 2006). However, what is needed is a magnetic field with a scale height of order the radius of the neutron star, and the $1/r^3$ dependence of dipole fields may present a problem here, as might magnetic screening (Cumming, Zweibel & Bildsten 2001) which can dramatically reduce the effective magnetic fields of high accretion rate neutron stars.

More likely then, is that the boundary layers of the surface of the neutron star, which have strong differential rotation (a key ingredient for dynamos) and have large scale heights (typically of order the neutron star radius in the neutron star case – Popham & Sunyaev 2001), can generate magnetic fields which can be used to power jets. Indeed, this suggestion has been raised in the past, as a candidate for being the extra “energy source” suggested to be necessary for jet production, apart from normal disk accretion (Livio 1999). By its very nature, a boundary layer is a region with differential rotation, implying that it would be reasonable for dynamos to work effectively in a boundary layer. When the accretion flow is geometrically thin, the amount of rotational energy which can be extracted from the boundary layer exceeds the amount which can be extracted from the thin disk.

This scenario, where the boundary layer provides the seed of the magnetic field, thus implies that white dwarf accretion disks with high accretion rates and relatively thick boundary layers should be capable of powering jets; similarly, even supersoft sources and symbiotic stars, where there need not be an accretion disk, should be able to power jets though extracting some of their boundary layers’ rotational energy.

7. Conclusions

The jet properties of compact objects are set primarily by the class of compact object, the state of the accretion disk, and the mass accretion rate – a good estimate of the jet spectrum and luminosity can be made based on these parameters. At the same time, the observed hysteresis effects indicate that clearly some other information is important for understanding the jet-disk connection. Spectral state phenomenology seems remarkably similar in accretion disks around black holes and neutron stars, and perhaps even in disks around white dwarfs. While geometrically thick accretion disks seem to be the most efficient way to power radio jets, the detection of reasonably strong radio emission from some soft state neutron star systems indicates that thick disks are not the only way to power such jets. The boundary layer seems the most likely source of jets in such systems, and since powerful accretion onto boundary layers in white dwarf systems is also seen, this is a possible explanation for jets seen from high accretion rate white dwarfs.
Acknowledgments. I am especially grateful to Elmar Körding for discussions which went into our 2006 Astronomy & Geophysics article, which helped form the basis for many of the thoughts presented here, as well as for numerous other useful discussions. I am also grateful for discussions with numerous colleagues and collaborators over the years – especially Rob Fender, Elena Gallo, Simone Migliari, Mike Nowak and Dave Russell, and for enlightening discussions during this workshop, especially with Michael Rupen and Jeno Sokoloski.

References

Abramowicz, M.A. & Kluzniak, W., 2001, A&A, 374L, 19
Blandford, R.D. & Konigl, A., 1979 ApJ, 232, 34
Blandford, R.D. & Znajek, R.L., 1977, MNRAS, 179, 433
Blandford, R.D. & Payne, D.G., 1982, MNRAS, 199, 883
Brocksopp, C., Bandyopadhyay, R.M. & Fender, R.P., 2004, New Astronomy, 9, 249
Churazov, E., Gilfanov, M.,& Revnivtsev, M., 2001, MNRAS, 321, 759
Corbel, S., Fender, R.P., Tzioumis, A.K., Nowak, M., McIntyre, V., Durouchoux, P. & Sood, R., 2000, A&A, 359, 251
Corbel, S., Fender, R.P., Tomisiek, J., Tzioumis, A.K. & Tingay, S., 2004, ApJ, 617, 1272
Corbel, S., et al., 2001, ApJ, 554, 43
Cumming, A., Zweibel, E. & Bildsten, L., 2001, ApJ, 557, 958
Curtis H.D., 1918, Publications of Lick Observatory, 13, 55
Fender, R.P., Belloni T. & Gallo E., 2004, MNRAS, 355, 1105
Fender, R.P., et al. 1999, ApJL, 519, 165
Fender, R.P., in Compact Stellar X-ray Sources
Gallo, E., Fender, R.P. & Pooley, G.G., 2003, MNRAS, 344, 60
Harmon, B.A., et al., 1995, Nature, 374, 703
Hjellming, R.M. & Johnston, K.J., 1988, ApJ, 328, 600
Hjellming, R.M. & Rupen, M.P., 1995, Nature, 375, 464
Homan, J., Wijnands, R., van der Klis, M., Belloni, T., van Paradijs, J., Fender, R.P., Klein-Wolt, M. & Mendez, M., 2001, ApJS, 132, 377
Körding, E.G., Migliari, S., Fender, R., Belloni, T., Knigge, C. & McHardy, I., 2007, astro-ph/0706.2959
Livio, M., 1999, Physics Reports, 311, 225
Livio, M., Ogilvie, G.I., & Pringle J.E., 1999, ApJ, 512, 100
Maccarone, T.J., 2003, A&A, 409, 697
Maccarone, T.J. & Coppi, P.S., 2002, MNRAS, 335, 465
Maccarone, T.J. & Coppi, P.S., 2003, MNRAS, 338, 189
Maccarone, T.J. & Koerding, E., 2006, A&G, 47, 29
Malzac, J., Merloni, A., & Fabian, A.C., 2004, MNRAS, 351, 253
Mauche, C.W., 2002, ApJ, 580, 423
Meier, D.L., 2001, ApJL, 548, 9
Meyer, F. & Meyer-Hofmeister, E., 1994, A&A, 288, 175
Meyer-Hofmeister, E. & Meyer, F., 1999, A&A, 348, 154
McConnell M., et al., 2000, ApJ, 543, 928
McGowan, K.E., Friedhorsky, W.C. & Trudolyubov, S.P., 2004, ApJ, 601, 1100
Migliari, S., Fender, R.P., Rupen, M., Wachter, S., Jonker, P.G., Homan, J. & van der Klis M., 2004, MNRAS, 351, 186
Migliari, S. & Fender, R.P., 2006, MNRAS, 366, 79
Mirabel, I.F. & Rodriguez, L.F., 1994, Nature, 371, 46
Miyamoto, S., Kitamoto, S., Hayashida, K. & Egoshi, W., 1996, ApJL, 442, 13
Narayan, R. & Yi, I., 1994, ApJL, 428, 13
Nowak, M.A., Wilms, J., Heinz, S., Pooley, G.G., Pottschmidt, K. & Corbel, S., 2005, ApJ, 626, 1006
Popham, R. & Sunyaev, R., 2001, ApJ, 547, 355
Portegies Zwart, S.F., Dewi, J. & Maccarone, T., 2004, MNRAS, 355, 413
Pottschmidt, K., et al., 2003, A&A, 409, 1039
Russell, D.M., Fender, R.P., Hynes, R.I., Brocksopp, C., Homan, J., Jonker, P.G. & Buxton, M.M., 2006, MNRAS, 371, 1334
Russell, D.M., Maccarone, T.J., Koerding, E.G. & Homan, J., 2007, astro-ph/0705.3594
Rykov, E.S., Miller, J.M., Steeghs, D. & Torres, M.A.P., 2007, astro-ph/0703497
Shahbaz, T., Charles, P.A. & King, A.R., 1998, MNRAS, 301, 382
Shakura, N.I. & Sunyaev, R.A., 1973, A&A, 24, 337
Sobczak, G.J., McClintock, J.E., Remillard, R.A., Cui, W., Levine, A.M., Morgan, E.H., Orosz, J.A. & Bailyn, C.D., 2000, ApJ, 544, 993
Sokoloski, J.L. & Kenyon, S.J., 2003, ApJ, 584, 1021
Stirling, A.M., Spencer, R.E., de la Force, C.J., Garrett, M.A., Fender, R.P. & Ogley, R.N., 2001, MNRAS, 327, 1273
Strohmayer, T., 2001, ApJL, 552, 49
Sunyaev, R.A. & Trümper, J., 1979, Nature, 279, 506
Tananbaum, H., Gursky, H., Kellogg, E., Giacconi, R. & Jones, C., 1972, ApJL, 177, 5
Thorne, K.S. & Price, R.H., 1975, ApJL, 195, 101
Vadawale, S.V., Rao, A.R., Naik, S., Yadav, J.S., Ishwara-Chandra, C.H., Pramesh Rao, A. & Pooley, G.G., 2003, ApJ, 597, 1093
van der Klis, M., 1994, ApJS, 92, 511
van der Klis, M., 2005, Ap&SS, 300, 149
Warner B., 1987, MNRAS, 227, 23
Warner, B.D., Woudt, P.A. & Pretorius, M.L., 2003, MNRAS, 344, 1193
Wheatley, P.J., Mauche, C.W. & Mattei, J.A., 2003, MNRAS, 345, 49
Xue, Y., Wu, X.-B. & Cui, W., 2006, astro-ph/0606194
Yu, W. & Dolence, J., 2006, astro-ph/0608601