Evolution of Binary and Multiple Star Systems
ASP Conference Series, Vol. 229, 2001
eds. Ph. Podsiadlowski, S. Rappaport, A. R. King, F. D'Antona, and L. Burderi

A Self-Regulating Braking Mechanism in Black-Hole X-Ray Binaries

Friedrich Meyer

Emmi Meyer-Hofmeister

Max-Planck-Institut für Astrophysik, Karl Schwarzschildstr. 1, D-85740 Garching, Germany

Abstract. The outbursts of black hole X-ray transients can be understood as caused by a limit cycle instability in the accretion disk, similar to dwarf nova outbursts. For adequately low mass overflow rates from the companion star long outburst recurrence times are expected. But the fact that we find predominantly long recurrence times or that only one X-ray nova outburst was detected at all poses a problem. The question arises whether any braking mechanism could act in a way that long recurrence times are favoured.

We suggest that a circumbinary disk exists and brakes the orbital motion of the binary stars by tidal interaction. The irradiation during an outburst leads to mass loss by winds from the circumbinary disk, relieving the braking force until the removed matter is refilled by diffusion from outer parts. We show that this reduction of braking will self-adjust the mass transfer to the marginal rate that gives long recurrence times.

1. Introduction

Soft X-ray transients (SXT) are binaries where a low-mass secondary star transfers mass by Roche lobe overflow to the compact primary via an accretion disk. The primary can either be a neutron star or a black hole. For black hole binaries the outbursts mostly occur after extremely long quiescence intervals. These so-called X-ray novae are usually detected in X-rays during the outburst. But for several systems only one outburst is known, that means the recurrence time is longer than at least 30, maybe 50 years. A recent review by Charles (1998) on black holes in our galaxy gives a comprehensive description of the observations.

The evolution of the accretion disk and the triggering of an outburst can be understood and modelled in the same way as dwarf nova outbursts. The first investigations were made by Huang & Wheeler (1989) and Mineshige % Wheeler (1989). Later detailed investigations by Cannizzo et al. (1995) and Cannizzo (1998, review 1999) including evaporation (in a simplified way) and the effects of irradiation focussed on modelling the exponential decline of the outburst. For the evolution of the disk during quiescence one feature, present also in dwarf nova disks but of minor role, is important in SXTs. It is necessary to have a truncated inner disk, otherwise the disk cannot be cool throughout. Such a geometrically thin cool disk results naturally from evaporation of the innermost disk region (Meyer & Meyer-Hofmeister 1994) into a corona/ADAF. Using the advection-dominated flow (ADAF), a number of quiescent black hole soft X-ray transients, A0620-00, V404 Cyg (Narayan et al. 1996, 1997), Nova Muscae (Esin et al. 1997) and GRO J1655-40 (Hameury et al. 1997) have been modelled successfully. The ADAF in the inner disk region together with the geometrically thin disk further out and the transition produced by evaporation provides a consistent picture for the accretion disk in SXTs and allows to understand the outburst cycles. We computed the disk evolution consistently (as will be described later) and found a minimum mass transfer rate to trigger the instability. An important ingredient is that matter flows through the disk into the corona continuously.

A problem is posed by the very long recurrence times observed. As the modelling of SXT disk evolution has shown (Meyer-Hofmeister & Meyer 2000) a spread in the rates of mass overflow from the companion will result in a spread of recurrence times. That means binaries with rare outbursts and systems with more frequent outbursts should both be found. But the observations indicate many more cases of extremely long recurrence time.

According to the standard theory of binary evolution, Roche lobe overflow from the companion star is caused by loss of angular momentum through gravitational radiation or magnetic braking or by expansion of the companion during nuclear evolution off the main sequence. The question which mass transfer rates are expected in black hole SXTs was already addressed earlier. King et al. (1996) considered the transient behaviour in low mass X-ray binaries based on magnetic braking and/or gravitational radiation and pointed out that irradiation of the disk by the central source is important for neutron star binaries but absent in black hole systems.

The present investigation concerns the long recurrence times. The theoretical modelling explains the long or even extremely long recurrence times, but it is not understood why we observe mainly systems with very rare outbursts. Could there be any mechanism which influences the mass overflow from the companion star in a way that rare outbursts are favoured? We make a suggestion for such a kind of "self-regulating braking". We suggest that a circumbinary disk irradiated in outbursts has such an effect.

2. Modelling the Outburst Cycles of X-Ray Transients

The observations for X-ray novae in outburst and quiescence provide constraints for the theoretical modelling such as an estimate of the amount of matter accreted during the outburst, values of the accretion rate in quiescence from the ADAF model based spectral fits, the radius of the transition from the thin disk to the ADAF from the maximum velocity width of the accretion disk Hα line (Kepler velocity) (for a review see Narayan et al. 1998).

The only free parameters for the disk evolution during quiescence are the mass overflow rate $\dot{M}$ and the viscosity parameter for the cool state α_{cool}. A further ingredient is the amount of matter and its distribution in the disk right after the outburst. King & Ritter (1998) showed that irradiation can explain the long-lasting exponential outburst decline observed for X-ray transients. This results in a practically empty disk after the outburst. Therefore we assume that

Table 1. Black–hole transient sources

Source name	X-ray Nova	BH mass ($M_\odot$)	comp. star	$P_{\rm orb}$ (hr)	outburst year	Δt (yr)
J0422+32	Per	>3.2	M 2 V	5.1	'92	>30
A0620-00	Mon	>7.3	K 5 V	7.8	'17,'75	58
GS2000-25	Vul	6-7.5	K 5 V	8.3	'92	>30
GS1124-68	Mus	$\sim$ 6	K 0-4 V	10.4	'91	>30
H1705-25	Oph	$\sim$ 6	K	12.5	'77	>30
4U1543-47	Lup	2.7-7.5	A 2 V	27.0	'71,'83,'92	$\approx$ 10
J1655-40	Sco	7.02$\pm$0.22	F 3-6 IV	62.7	'94	>30
GS2023-338	Cyg	8-15.5	K 0 IV	155.3	'38,'56,'79,'89	10-20

Note: Systems established as black hole transients, data for black hole mass, spectral type of companion star, orbital period and outburst year from Charles (1998).

only little mass is left in the disk at the beginning of the new quiescence. In this case the disk evolution in quiescence and outburst can be studied separately. The accumulation of mass in the disk during the long quiescence and the question when a new outburst is triggered does not depend on the foregoing outburst. Our computer code for the evolution of the disk in quiescence (Meyer-Hofmeister & Meyer 1999) includes a variable inner and outer disk edge (the inner edge is determined by evaporation, the outer edge by conservation of angular momentum and the 3:1 resonance appropriate for systems with a low mass ratio; Whitehurst 1988; Lubow 1991).

For the modelling of A0620-00 we took the standard viscosity value $\alpha_{cool}=$ 0.05, used also for dwarf nova outburst modelling. (We point out that despite similarities in the outburst cycles of SXTs and WZ Sge stars a very small value of α_{cool} used for the modelling of the latter (Meyer-Hofmeister et al. 1998) cannot be adequate here, otherwise the total amount of matter in the SXT disk would be much too high.) That the modelling of A620-00 fits the observational constraints makes these results a promising description of SXT disk evolution. Following the method used there, we also studied the evolution of the disks for binaries with different black hole mass and different mass overflow rates. Orbital periods of 4, 8 and 16 hours were considered. The period determines the size of the accretion disk. The computations for this range of parameters describe the variety of outburst behaviour in the observed black hole X-ray binaries. One of the results of theoretical modelling is that about one half of the mass transferred from the companion star is accreted on to the black hole during quiescence and one half during the outburst (wind loss neglected). The fraction of accumulated mass to transferred mass decreases with increasing outburst recurrence time, but is surprisingly similar for different black hole masses. This fact is related to the

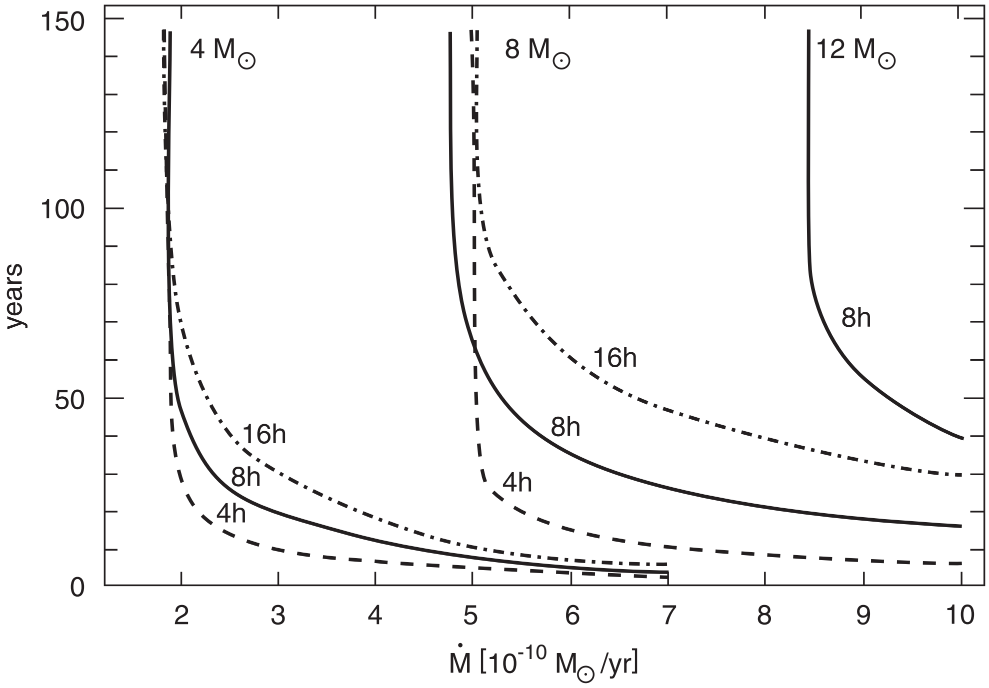

Figure 1. Computed outburst recurrence time for different black hole masses and orbital periods of the binary as a function of the mass transfer rate $\dot{M}_T$ from the companion star. Note that the recurrence time increases steeply with decreasing $\dot{M}_T$ as the situation of only marginal triggering of the disk instability is approached. For even lower rates the disk is stable.

evaporation efficiency which increases with black hole mass (Meyer-Hofmeister & Meyer 2000).

In Figure 1 we show the computed recurrence times. Given a black hole mass and orbital period (which determines the disk size, larger for longer periods) the outburst recurrence time decreases with increasing mass transfer rate. This behaviour is expected because the critical surface density at which an outburst is triggered (for details see Meyer-Hofmeister & Meyer 1999) is reached later for a lower transfer rate. For very low rates the matter accumulation never reaches the critical surface density value and no outburst occurs. The difficulty to trigger an outburst for relatively low transfer rates is reflected in the steep increase of recurrence time.

The dependence of the evaporation on the black hole mass influences the location of the transition from disk to ADAF and therefore the mass flow and accumulation of matter. A larger black hole mass results in more evaporation and a higher mass transfer rate is needed to trigger an outburst after a given time interval, for example higher by a factor 2.5 for a disk around a $8M_\odot$ than for a disk around a $4M_\odot$ black hole, as can be seen from Figure 1. But from Figure 1 we see also that for a spread of $\dot{M}$ we would expect only very few systems with extremely long and many with shorter recurrence times. The same is true for a sample of SXTs with different black hole masses.

In Table 1 we give data for systems established as black hole transient sources. Charles (1998) discusses in detail all constraints and procedures for the derivation of the black hole masses and gives ranges of uncertainty. In other compilations for some systems narrower ranges are given (see also Tanaka & Shibazaki 1996; Chen et al. 1997; Ritter & Kolb 1998). For three further candidates for black holes V4641 Sgr, J1858+2239 and MN Vel only few data are available.

For a remarkable number of black hole SXTs only one outburst was observed. Chen et al. (1997) discussed the properties of X-ray novae, the event distribution over 30 years, sky coverage and detection probability. A detection of an optical nova outburst prior to 1975 on archival plates as for A0620-00 (Nova Mon 1975) and GS2023+338 (Nova Cyg 1989) is difficult because of the low apparent luminosity (see discussion in Romani 1998). But even if an outbursts would have been missed, the question arises why we find such long recurrence times. In our theoretical picture this means the mass transfer rates would have to be the marginal ones, and different for different black hole masses. This seems implausible if not these rates were adjusted in some way to cause the long recurrence times.

3. Magnetic Braking, Mass Overflow Rates and Resulting Recurrence Times

The problem posed by the observed extremely long recurrence times brings us to an interesting question: what causes the mass transfer rates? In Figure 2 we show the mass transfer rates resulting from different angular momentum loss mechanisms. If the secondary would be a main sequence star, the rates from magnetic braking would clearly be higher than the estimates from observation for SXTs (compare Tanaka & Shabazaki 1996). But King et al. (1996) had already argued that the radius of the secondary star in black hole binaries must be larger than its main sequence radius if it is to fill its Roche lobe. We therefore give here the transfer rates for half of the main sequence star mass (following King et al. 1996). The comparison of rates shows that the magnetic braking (reduced mass) could just give the rates necessary to produce outbursts. But if this mechanism determines the transfer rate we should also find many systems with shorter recurrence time.

4. A Mechanism of Self-Adjusted Braking

4.1. General Properties of a Self-Adjusting Braking Mechanism

We search for a braking mechanism which establishes the mass transfer rates so that long recurrence times result, a kind of "adaptive braking procedure". (We then assume that magnetic braking is not the dominant mechanism). If the outburst should occur every 30 or 50 years, or even more rarely, such a mechanism must work in the way that the recurrence time increases if the outbursts

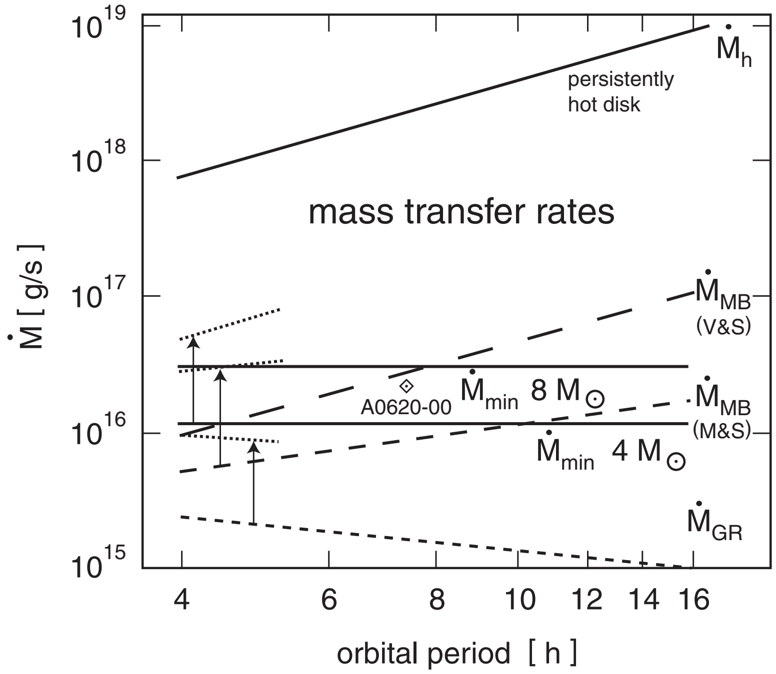

Figure 2. Mass transfer rates $\dot{M}$ from the companion star due to different mechanisms. Long and short dashed lines: magnetic braking as suggested by Verbunt & Zwaan (1981) and Mestel & Spruit (1987), very-short-dashed line: braking by gravitational radiation. (Assumptions in all cases: the black hole mass is $6M_\odot$, the companion star mass is half of that of a main sequence star for the given orbital period (i.e., a slightly evolved star); for a main sequence star mass the lines would lie higher in the diagram as indicated by the dotted lines.) Upper solid line: limiting mass transfer rate above which the disk is persistently hot. The two horizontal solid lines $\dot{M}_{\rm min}$ are the minimal mass transfer rates necessary to get outbursts for 4 and 8 $M_\odot$, practically independent of orbital period (compare Fig. 1). The position of A620-00 in the diagram is indicated.

tend to appear more often and vice versa. We here discuss the braking by a circumbinary disk and the effect of irradiation during the outburst on this disk.

4.2. The Circumbinary Disk

Matter in a circumbinary disk might have remained from an earlier common envelope phase when binary stars with an extreme mass ratio evolve into a helium star and a low mass companion, or during the expected subsequent collapse of the helium star into a black hole (for recent work on black hole formation see e.g. Kalogera 1999). Fossil disks formed by fallback matter in supernova explosions have been discussed in connection with accretion on to anomalous X-ray pulsars (Perna et al. 2000) and are indicated by the observation of planets around a neutron star (Wolszczan 1994).

In the evolution of such disks mass is settling inward while angular momentum is transported outward. At the inner edge mass flow is halted by the tidal transfer of angular momentum from the interior binary which thereby is braked. The more mass piles up at the inner edge of the circumbinary disk, the stronger is the braking of the binary orbit and the stronger is the induced mass transfer from secondary to primary.

There are now two effects that work in such a system in a way that lets us see more soft X-ray transients in a phase of marginal mass transfer than in phases of higher transfer rates. One is the natural aging of the circumbinary disk. As it receives angular momentum from the inner binary it spreads viscously to larger and larger distances and its mass distribution flattens. This relieves the braking torque at its inner edge and leads to gradually decreasing inner binary transfer rates. The diffusive "aging" of such disks typically is a power law decay with time (e.g. Meyer & Meyer-Hofmeister 1989) such that the duration of each phase is proportional to the age of the system at this phase. Therefore one finds ten times more systems with about marginal mass transfer rates than with ten times higher transfer rates.

4.3. Irradiation

The other effect is the irradiation of the circumbinary disk by X-rays during the outbursts of the inner binary (Fig. 3). This results in the formation of a hot corona with X-ray temperatures. At that distance from a primary black hole where the inner circumbinary disk finds itself, of the order of the binary separation, these temperatures are high enough to drive a wind with considerable mass loss. If outbursts occur sufficiently frequently, such mass loss is enough to remove all matter from the inner circumbinary disk which is continuously settling inward.

Whether this mechanism constitutes an efficient self-regulating machine to bring soft X-ray transients always close to marginal mass transfer rates and long quiescent intervals depends on the strength of the mass loss rates during the outbursts. If a large amount of mass is lost during each outburst, infrequent outbursts suffice to keep the braking rate low. We have performed estimates of the rate of mass loss by wind using a detailed analysis performed for Her X-1 (Schandl & Meyer 1994) as a guide line.

Irradiation is reduced by the foreshortened appearance of the flat X-ray radiating inner accretion disk and by possible shadowing through a scattering

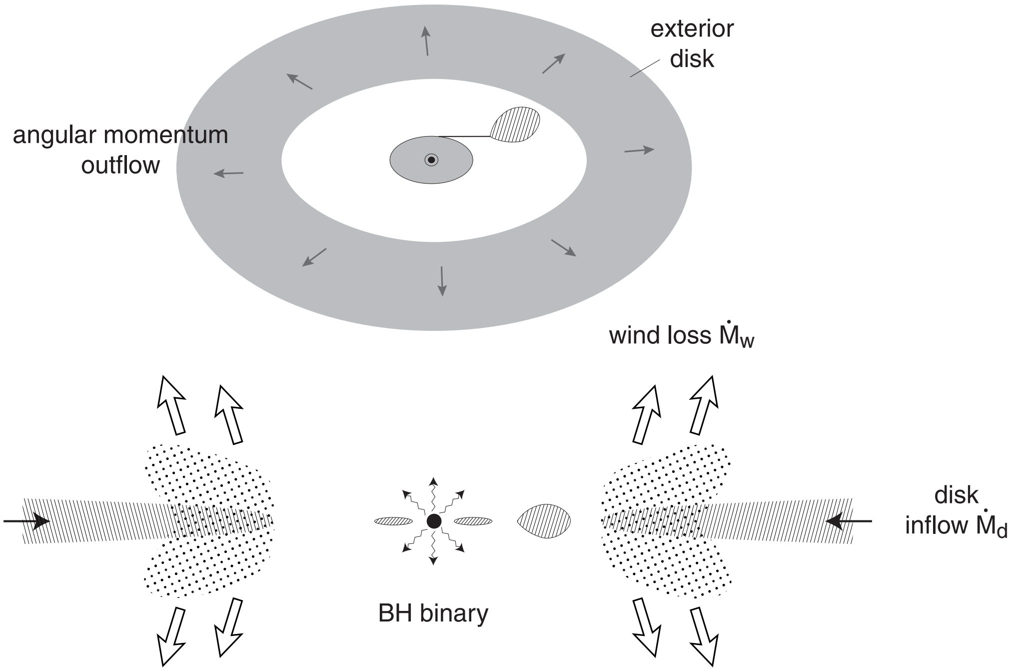

Figure 3. Schematic drawing of a circumbinary disk around the black hole binary (upper drawing). Irradiation caused corona during the outburst and wind loss are indicated below.

optically deep coronal layer in the inner region. The softer X-rays (1 keV) of the SXTs, on the other hand, are more effectively photo-absorbed by metals than the harder ones (10 keV) of Her X-1 giving more efficient heating and higher pressure in the corona in comparison.

We have estimated the effects and calculated the wind loss from such an irradiation caused corona above the inner region of a circumbinary disk, at a characteristic distance of $10^{11.6}$cm from the inner black hole system, appropriate e.g. for A0620-00. Integrating over the X-ray light curve with an initial luminosity of 10^{38} erg/s exponentially decreasing on a timescale of 80 days, we obtain a mass loss $\Delta M_{\rm w}$ by wind from the circumbinary disk of

$$\Delta M_{\rm w} = 10^{25.7}{\rm g}$$

per outburst. If outbursts occur every 50 years this constitutes a mean mass removal rate of

$$\dot{M}_{\rm w} = 10^{16.5}{\rm g/s}$$

and correspondingly higher or lower for more or less frequent outbursts.

It can be shown that the removal of mass at such a rate reduces the braking efficiency of the circumbinary disk by very closely the amount whose braking effect would have induced a mass transfer rate from the secondary to the primary of the same amount. One can now see in Figure 2 that this is of the right order of magnitude to efficiently affect the rate of occurrence of outbursts in these soft X-ray transients.

5. Conclusions

Our estimates for the rates of mass transfer from the companion star caused by braking by a circumbinary disk need confirmation by more accurate calculations. But they indicate that a circumbinary disk could explain why most of the observed soft X-ray transients appear to operate at marginal mass transfer rates. With a circumbinary disk providing most of the orbital braking these systems, as long as they are visible, will spend most of their time in phases where their braking without irradiation would produce mass transfer above but not an order of magnitude above the marginal rate. In these extended phases however, the irradiation produced wind loss will shift the actual braking rate very close to the marginal one, as observed.

This contribution is dedicated to Peter Eggleton on the occasion of his 60^{th} *birthday in respect and gratitude for his so fundamental, rich, and fruitful work.*

References

Cannizzo, J. K., Chen, W., & Livio, M. 1995, ApJ, 454, 880

Cannizzo, J. K. 1998, ApJ, 494, 366

Cannizzo, J. K. 1999, In: Proc. of Disk Instabilities in Close Binary Systems, eds. S. Mineshige & J. C. Wheeler (Universal Academic Press: Kyoto), p.177

Charles, P. A., 1998, In: Theory of Black Hole Accretion Disks, eds. M. A. Abramowicz, G. Bjornsson & J. E. Pringle (CUP: Cambridge), p. 1

Chen, W., Shrader, C. R., & Livio, M. 1997, ApJ, 491, 312

Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865 505, 854

Hameury, J.-M., Lasota, J.-P., McClintock, J. E. et al. 1997, ApJ, 489, 234

Huang, M., & Wheeler, J. C. 1989, ApJ, 343, 229

Kalogera, V. 1999, ApJ, 521, 723

King, A. R., Kolb, U., & Burderi, L. 1996, ApJ, 464, L127

King, A. R., Kolb, U., & Szuszkiewicz, E. 1997, ApJ, 488, 89

King, A. R., & Ritter, H. 1998, MNRAS, 293,L42

Kuulkers, E. 1999, In: Proc. of Disk Instabilities in Close Binary Systems, eds. S. Mineshige & J. C. Wheeler (Universal Academic Press: Kyoto), p.169

Lubow, S. H., 1991, ApJ, 381, 268

Mestel, L., & Spruit, H. 1987, MNRAS, 226, 57

Meyer, F., Meyer-Hofmeister, E. 1989 In: Theory of Accretion Disks, eds. R. Meyer et al. (Nato ASI Series), Vol 290, p. 307

Meyer, F., & Meyer-Hofmeister, E. 1994, A&A, 288, 175

Meyer-Hofmeister, E., & Meyer, F. 1999, A&A, 348, 154

Meyer-Hofmeister, E., & Meyer, F. 2000, A&A, 355, 1053

Mineshige, S., & Wheeler, J. C. 1989, ApJ, 343, 241

Narayan, R., McClintock, J. E., & Yi, I. 1996, ApJ, 457, 82

Narayan, R., Barret, D., & McClintock, J. E. 1997, ApJ, 482, 448

Narayan, R., Mahadevan, R., & Quataert, E. 1998, In: The Theory of Black Hole Accretion Discs, eds. M. A. Abramowicz et al. (Cambridge University Press), p.148

Perna, R., Hernquist, L., & Narayan, R. 2000, ApJ, 541, 344

Ritter, H., & Kolb, U., 1998, A&AS, 129, 83

Romani, R. W. 1998, A&A, 333, 583

Schandl, S., & Meyer, F. 1994, A&A, 289, 149

Spitzer, L., 1962, Physics of Fully Ionized Gases, 2nd edition (Interscience Publ.: New York)

Tanaka, Y., & Shibazaki, N. 1996, ARA&A, 34, 607

Verbunt, F., & Zwaan, C. 1981, A&A, 100, L7

Whitehurst, R. 1988, MNRAS, 232, 35

Wolszczan, A. 1994, Science, 264, 538