The Astrophysical Journal, 576:L45–L48, 2002 September 1


# ON THE EJECTION MECHANISM OF BULLETS IN SS 433

Sandip K. Chakrabarti,[1,2] P. Goldoni,[3] Paul J. Wiita,[4] A. Nandi,[1] and S. Das[1]

*Received 2002 July 4; accepted 2002 July 24; published 2002 August 2*

## ABSTRACT

We discuss plausible mechanisms to produce bulletlike ejecta from the precessing disk in the SS 433 system. We show that nonsteady shocks in the sub-Keplerian accretion flow can provide the basic timescale of the ejection interval while the magnetic rubber-band effect of the toroidal flux tubes in this disk can yield flaring events.

*Subject headings:* accretion, accretion disks — hydrodynamics — instabilities — shock waves — stars: individual (SS 433) — stars: mass loss

## 1. INTRODUCTION

SS 433 remains one of the most enigmatic objects in the sky. Even 25 years after its first appearance in the catalog of Stephanson & Sanduleak (1977), it is not clear whether the compact object is a black hole or a neutron star. However, there is ample evidence that the companion is an OB-type star with an orbital period of 13.1 days, which is losing mass at the rate of about $10^{-4}$ $M_\odot$ yr$^{-1}$ (van den Heuvel 1981), corresponding to extremely super-Eddington accretion regardless of the mass of the compact object.

One of the most curious properties of the jets of SS 433, which first made their presence distinctly felt through the emission of variable H$\alpha$ lines, is that they are apparently ejected as bullets (e.g., Borisov & Fabrika 1987; Vermeulen et al. 1993; Paragi et al. 1999, 2002; Gies et al. 2002), with a surprisingly nearly constant radial velocity of about 0.26*c*. The absence of a significant intrinsic rotational velocity (i.e., $v_\phi$) component is clear from the fact that the kinematic model (e.g., Abell & Margon 1979), which assumes only radial injection, quite accurately explains the time variation of the red- and blueshifts of the H$\alpha$ emission from the jets with a period of 162 days, which is attributed to the precession of the accretion disk about the compact object. The radial velocity is less than the maximum allowed sound speed of $c/\sqrt{3}$, and thus hydrodynamic acceleration could, in principle, explain it. Therefore one may not require a magnetic or electrodynamic acceleration process (e.g., Belcher & MacGregor 1976; Lovelace 1976). However, the rather good collimation (Margon 1984; Paragi et al. 1999) supports the hypothesis that a substantial degree of confinement produced by toroidal flux tubes may be present. Gies et al. (2002) showed that the ratios of the H$\alpha$ emission equivalent widths from the approaching and receding jets as a function of precessional phase could be fitted nicely only if these emission components are bulletlike. Indeed, the recent *Chandra X-Ray Observatory* discovery of X-rays at a distance of about $10^{17}$ cm from the center may result from the collision of such bullets (S. Migliari, R. P. Fender, & M. R. Mendez 2002, in preparation).

SS 433 poses another interesting problem: it was pointed out by Chakrabarti (1999) and Das & Chakrabarti (1999) that significant outflows are produced only when the accretion rate is such that the X-ray source is in a low/hard state, and all the observational indications in other microquasars also suggest that the jets are indeed produced in low/hard states (Corbel et al. 2001; Klein-Wolt et al. 2001). However, it is difficult to imagine how SS 433 manages to remain in the low/hard state with $10^{-4}$ $M_\odot$ yr$^{-1}$ of wind matter ejected from its companion. The answer to this quandary probably lies in the recent results of Paragi et al. (1999) and Blundell et al. (2000), whose high-resolution radio maps show that there is a large region of roughly 50 AU in radius that is filled with enough gas and dust to obscure the accretion disk and the base of the jets. They also found an equatorial outflow. Gies et al. (2002) present additional evidence from observations of the "stationary" H$\alpha$ and He I lines for an extended "disk wind." So it is distinctly possible that most of the matter from the donor is rejected either by centrifugal force (Chakrabarti 2002) or by radiation force far outside the central accretion disk, and thus the compact object receives only a few times the Eddington rate ($\dot{M}_{\rm Edd}$) of its companion's wind matter to accrete. This consideration finds further support from the fact that the kinematic luminosity of the jet itself is around $10^{39}$ ergs s$^{-1}$ (Margon 1984), which corresponds to about 1 Eddington rate for a 10 $M_\odot$ compact object.

In numerical simulations of supercritical winds by Eggum, Coroniti, & Katz (1985) designed to model SS 433, it was shown that only a fraction of a percent of the infalling matter is ejected from a radiation pressure–supported Keplerian disk, which indicates that the accretion rate must be at least $100\dot{M}_{\rm Edd}$ if the accretion takes place through a Keplerian disk. On the other hand, numerical simulations of a sub-Keplerian disk by Molteni, Lanzafame, & Chakrabarti (1994) suggest that about 15%–20% of matter is ejected as an outflow, indicating that the accretion rate onto the compact object in SS 433 need be at most a few $\dot{M}_{\rm Edd}$. Similar simulations with different parameters yield situations where no steady shocks can form, even though two saddle-type sonic points are present (Ryu, Chakrabarti, & Molteni 1997, hereafter RCM); under these conditions, large-scale shock oscillations produce intermittent outflows instead of continuous outflows. Since the compact object is a wind accretor, a low angular momentum, sub-Keplerian flow is the most likely description of the accretion flow. Indeed, the presence of sub-Keplerian flows in several other high-mass X-ray binaries has now been verified (Smith, Heindl, & Swank 2002).

In this Letter, we present a few scenarios leading to ejection of matter as bullets in SS 433. We discuss four possible ways

[1] S. N. Bose National Center for Basic Sciences, JD-Block, Salt Lake, Kolkata 700098, India; chakraba@bose.res.in, anuj@boson.bose.res.in, sbdas@bose.res.in.

[2] Also at Centre for Space Physics, P-61 Southend Gardens, Kolkata 700084, India.

[3] Service d'Astrophysique, CEA/Saclay, 91191 Gif-sur-Yvette Cedex, France; paolo@discovery.saclay.cea.fr.

[4] Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303; wiita@chara.gsu.edu.

to create blobs of matter emerging from the disk and conclude that periodic ejection of the blobs by the large-scale oscillation of an accretion shock (something like a piston) may be the fundamental production mechanism of the "normal" bullets. The irregularly observed rapid flaring (Vermeulen et al. 1993) could be understood in terms of the catastrophic collapse of toroidal magnetic flux tubes, very similar to what has been argued to be occurring in GRS 1915+105 (Vadawale et al. 2001; Nandi et al. 2001). In the next section, we discuss these processes and their suitability or unsuitability for SS 433. In § 3, we present concluding remarks.

## 2. MECHANISMS TO PRODUCE BULLET-LIKE EJECTA FROM ACCRETION FLOWS

In both the works of Eggum et al. (1985) and Molteni et al. (1994), continuous ejection was reported when a radiation pressure–dominated Keplerian disk, or a sub-Keplerian disk capable of producing a steady shock, was considered. However, in SS 433 the basic ejection is bulletlike, and since the size of the X-ray–emitting region is smaller than $l_X \sim 10^{12}$ cm within which the material in the jets is already accelerated to $v_{jet} \sim 0.26c$ (Watson et al. 1986; Stewart et al. 1987), the bullets are not expected to be delayed by more than $l_X/v_{jet} \sim 100$ s. Indeed, recent *Rossi X-Ray Timing Experiment* (*RXTE*) observations of hard X-rays from SS 433 indicated variability on timescales of 50–1000 s (Safi-Harb & Kotani 2002), roughly corroborating this picture. In fact, a simultaneous measurement of a flare at 2 GHz in the radio (Kotani & Trushkin 2001) and in hard X-rays (Safi-Harb & Kotani 2002) indicated a strong anticorrelation of radio and X-ray fluxes, similar to what is observed in GRS 1915+105 (Mirabel & Rodriguez 1994). Moreover, the X-ray luminosity is very low ($\sim 10^{36}$ ergs s$^{-1}$) and is believed to come from the base of the jets (Watson et al. 1986). It is believed to have a thermal origin, and *EXOSAT* (Watson et al. 1986) and *Ginga* (Yuan et al. 1995) observations were adequately fitted with a thermal bremsstrahlung model with $kT \gtrsim 30$ keV. The overall spectral shape suggests that the source has always been in a standard low/hard state, and so far no quasi-thermal emission expected from a "Keplerian disk" has been detected. From the interaction of the jet with the supernovae remnant W50, the lower limit of kinematic luminosity is found to be at least $10^{39}$ ergs s$^{-1}$ (Biretta et al. 1983; Davidson & McCray 1980). This means that the mean mass outflow rate is around $10^{18}$ g s$^{-1}$, and if most of it is in the form of bullets ejected at 50–1000 s intervals, the mass accumulated in each bullet should be in the range of $10^{19}$–$10^{21}$ g.

The above data imply that the essential features that one must explain when attempting to produce bullets out of the accretion disks are (*a*) the disk should be a sub-Keplerian flow, (*b*) the object (black hole or a neutron star) and its surroundings should be in a low/hard state, (*c*) bullets should be ejected in 50–1000 s timescales under normal circumstances, (*d*) the mass of each bullet should be around $10^{19}$–$10^{21}$ g, and, finally, (*e*) there should be occasional flaring with an anticorrelation of radio and X-ray emission. We now discuss several scenarios and present what we believe to be the most probable picture of what is going on in SS 433. The four processes are schematically shown in Figures 1*a*–1*d*.

### 2.1. *Cooling of the Jet Base by Comptonization and Separation of Blobs*

It was shown by several numerical simulations that significant outflows are produced from regions very close to the inner edge of the accretion flow, possibly from the centrifugal pressure–dominated region (Molteni et al. 1994, 2001). These jets are launched subsonically but quickly pass through the inner sonic point to become supersonic. In the subsonic region while the matter moves slowly, the density is high and the optical depth could be large enough ($\tau > 1$) to undergo Compton cooling (Fig. 1*a*) *provided there is a Keplerian disk underneath to supply soft photons*. A part of the outflow, which was subsonic previously, becomes supersonic because of this rapid cooling and separates from the base of the jet. This separation of blobs is expected to occur at the sonic surface $r_c$ which is $\sim(2–3)r_s$, where $r_s$ is the size of the centrifugal barrier (see Chakrabarti 1999)

This possibility, though attractive, and in fact likely to be a major mechanism for rapid state change in objects like GRS 1915+105 (Chakrabarti & Manickam 2000), is untenable in SS 433 because the latter is a wind accretor: thus no significant Keplerian disk is expected in this system to supply the soft photons, and indeed none has been detected so far (Watson et al. 1986; Yuan et al. 1995).

### 2.2. *Resonance Oscillation of Accretion Shocks in the Presence of Bremsstrahlung Cooling*

Numerical simulations of accretion flow show that in cases where the cooling timescale nearly matches the infall timescale, a shock forms, but it then starts oscillating and ejects matter quasi-periodically (Langer, Chanmugam, & Shaviv 1983; Molteni, Sponholz, & Chakrabarti 1996, hereafter MSC; see Fig. 1*b*). In order to have an oscillation period of around 50 s, the shock must be located at the large distance of $r_{s,\mathrm{MSC}} \approx 6400 r_g$ for a black hole of mass $M = 10\ M_\odot$, where $r_g = 2GM/c^2$. The mass of the postshock region is computed by equating the bremsstrahlung (which we assume to be the major cooling mechanism) cooling time and the infall time in the postshock region (MSC):

$$T_{\mathrm{MSC}} \simeq \frac{\mathcal{E}}{\dot{\mathcal{E}}} \simeq \frac{r_{s,\mathrm{MSC}}}{v_f} \simeq \left(\frac{R r_{s,\mathrm{MSC}}}{r_g}\right)^{3/2} \frac{r_g}{c}, \tag{1}$$

where $\mathcal{E}$ is the specific thermal energy, $v_f$ is the infall velocity, and $R = (\gamma + 1)/(\gamma - 1) \simeq 4–7$ (these limits are for a strong shock with $\gamma = 5/3$ and $\gamma = 4/3$, respectively) is the compression ratio at the shock. Assuming the gas density ($n$) and temperature ($T$) scale as $n \sim r^{-3/2}$ and $T \sim r^{-1}$, respectively, the mass of the sub-Keplerian region of $r < r_s$ turns out to be $7 \times 10^{19}$ g (with $M = 10\ M_\odot$, $\gamma = 5/3$). This is indeed of the same order as the mass of the bullets observed in SS 433. However, one has to have both the angular momentum and energy of the injected material comparable to the marginally bound values determined by the central object in order to achieve such an oscillation. On the other hand, if the mass expulsion from the system takes place at the similar radius of $r_{ex} \sim 10^4 r_g = 2 \times 10^9 M/M_\odot$ cm due to the centrifugal force, the specific angular momentum of the flow is approximately $[r_{ex}/(2r_g)]^{1/2} r_g c \sim 70 r_g c$, which is very large compared to the marginally bound value of $2r_g c$. So it is unlikely that this mechanism works in SS 433.

### 2.3. *Nonsteady and Nonlinear Shock Oscillation*

A standing shock can form in a sub-Keplerian flow only if there are two saddle-type sonic points and the Rankine-Hugoniot relation is satisfied at least at one point in between these two sonic points. However, Chakrabarti (1990) showed that there is a large region of the parameter space where there are two

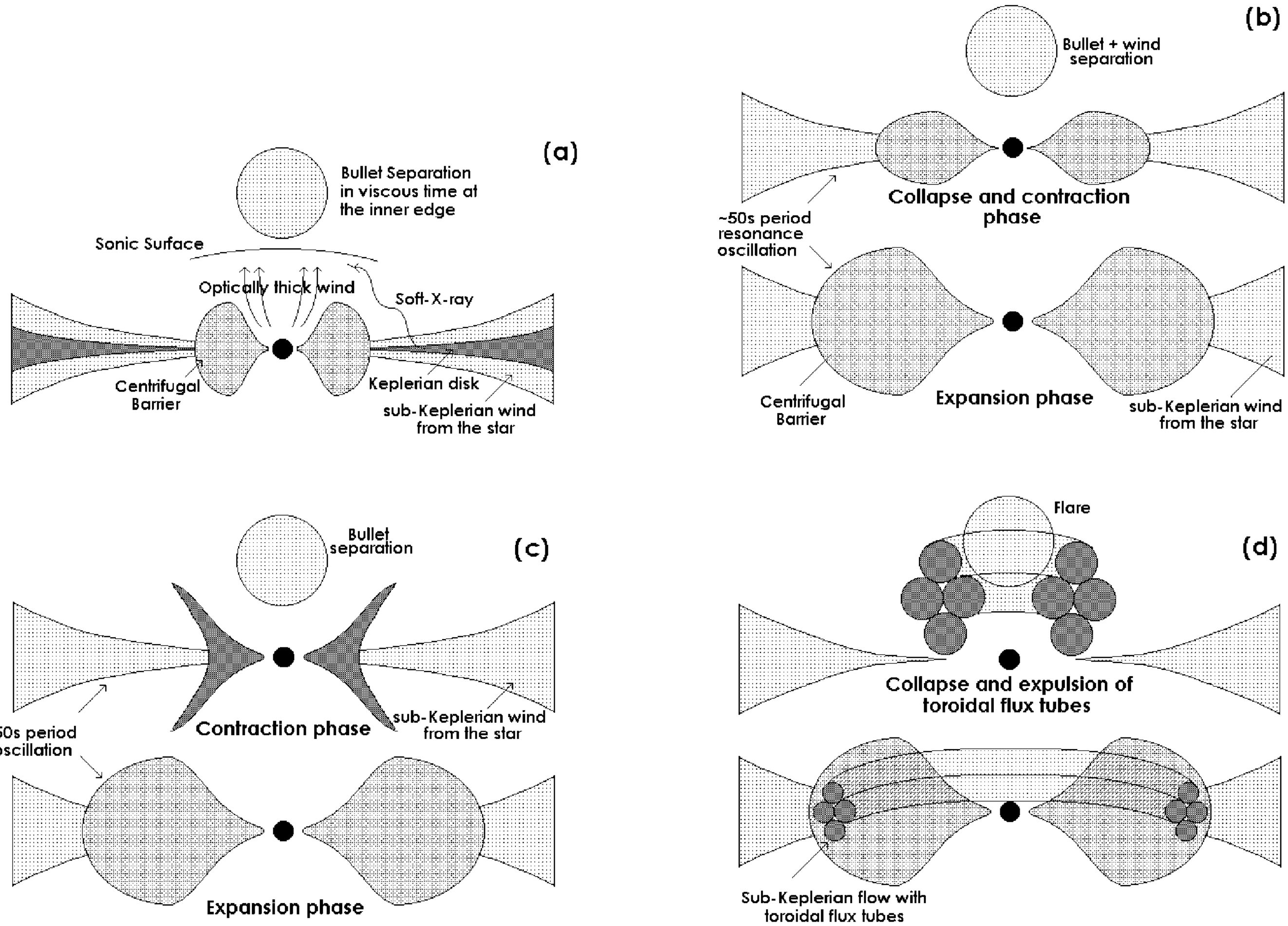


FIG. 1.—Four scenarios of bullet separation in SS 433 are schematically shown. (*a*) The base of the jet is cooled down by soft photons from a Keplerian disk and detaches when it becomes supersonic. (*b*) Resonance oscillation of the sub-Keplerian region due to the near matching of the infall time with the cooling time produces discrete ejecta during the phase when the centrifugal barrier contracts. (*c*) Nonsteady motion of the centrifugal barrier due to the inability of the flow to find a steady shock solution. (*d*) Magnetic tension from toroidal flux tubes (shown as shaded narrow tori) causes them to collapse catastrophically in a hot ambient medium in rapid succession, which evacuates the centrifugal barrier. The recurrence time of (*a*) is the viscous timescale in the inner part of the disk, ~10 s; (*b*–*c*) is ~50 s; and (*d*) is random and dictated by the enhanced magnetic activity.

saddle-type sonic points but the shock conditions are not satisfied. Even an initially supersonic accretion (such as the wind from the companion) can fall into this category.

What will happen to such a realistic flow, especially when the specific entropy at the inner sonic point is greater than that at the outer sonic point? RCM discovered that a flow injected with these parameters exhibits yet another type of shock oscillation (Fig. 1*c*). Here the shock searches for a stable location and oscillates without finding it. In the first half of the cycle, the shock recedes far away, the postshock region fills up, but the accretion is essentially completely blocked. In the second half of the cycle, the shock pushes the matter into the black hole, thereby evacuating the postshock region. In a realistic simulation, RCM find that while the ratio of actually accreted matter to the amount available from the companion, $R_{\rm ai} \equiv \dot{M}_{\rm acc}/\dot{M}_{\rm inj}$, would be around 0.2 during the first half-cycle, $R_{\rm ai} \sim 1.3$ in the second half-cycle. The outflow was also found to be very large. The timescale of oscillation was found to be $T_{\rm RCM} \sim (4000\text{–}6000) r_g/c$ for a $r_s \simeq 20 r_g$ whose infall time is only about $T_{\rm MSC} \simeq (R r_s/r_g)^{3/2}(r_g/c) \sim (350\text{–}400) r_g/c$. Thus, this type of oscillation takes about a factor of $R_{\rm T} = T_{\rm RCM}/T_{\rm MSC} \sim 15$ times longer than the resonance oscillation discussed in § 2.2. For a 50 s oscillation, the location of the shock should be obtained from $(r_{s,\rm RCM}/r_g)^{3/2} \simeq (1/R)(50\ {\rm s}/R_{\rm T})(c/r_g) \sim 10^4$, which gives $r_{s,\rm RCM} \sim 450 r_g$ for a 10 $M_\odot$ black hole, a more physically reasonable value. Even though the size of the oscillating region goes down by a factor of 10 or so, compared with that involved in the resonance oscillation, the ejected mass need not go down (even for the same accretion rate as in the earlier case). This is because nearly all of the accretion flow is accumulated in half the cycle (~25 s in this case) before being ejected (see Fig. 2 of RCM).

Another advantage of this type of nonsteady shock oscillation is that it is driven by centrifugal force and not by thermal cooling. Hence the result is generally independent of the accretion rate. Thus, as long as the viscosity remains low, equivalent to having the Shakura-Sunyaev (1973) parameter $\alpha \le \alpha_c \simeq 0.015$ (Chakrabarti 1990), and $\dot{M}_{\rm inj}$ remains fairly constant, this oscillation, once established, could be sustained indefinitely.

### 2.4. *Magnetic Rubber-Band Effect*

In the event of increase in magnetic activity of the disk, as could happen for instance when the accretion disk bends toward the binary companion during its precessional motion, it is not unlikely that a strong magnetic field will be first intercepted, and then advected, toward the inner edge of the disk. In this case the field will preferentially become toroidal due to shear in the rotating flow. Then, as has already been pointed out (Chakrabarti & D'Silva 1994; Nandi et al. 2001), the acceleration due to magnetic tension,

$$a_{\rm T} = -\frac{B_\phi^2}{4\pi r(\rho_e + \rho_i)} \sim -\frac{B_\phi^2}{4\pi r \rho_e}, \quad (2)$$

would be the dominant force in the postshock region of the sub-Keplerian flow (Fig. 1*d*). Here $r$ is the major radius of the toroidal flux tube and $\rho_i$ and $\rho_e$ are the densities of the medium internal and external to the flux tube, respectively. The last step in equation (2) is written because $\rho_i \ll \rho_e$ for a strong flux tube. Since $B_\phi \propto 1/r$ and $\rho_e \propto r^{-3/2}$, we get

$$a_{\rm T} \propto r^{-3/2}, \quad (3)$$

thus increasing rapidly as the tube comes closer to the black hole, and even surpassing the magnetic buoyancy,

$$a_{\rm MB} = \frac{1-X}{1+X}\left(\frac{\lambda_{\rm Kep}^2 - \lambda^2}{r^3}\right) \simeq \frac{\lambda_{\rm Kep}^2 - \lambda^2}{r^3}, \quad (4)$$

where $X = \rho_i/\rho_e \rightarrow 0$ and $\lambda_{\rm Kep}$ and $\lambda$ are, respectively, the specific angular momenta of a Keplerian disk and the disk under consideration. The accelerations in equations (3) and (4) do cross over, since at a location very close to a black hole, $\lambda \rightarrow \lambda_{\rm Kep}$ for a sub-Keplerian flow.

The effect of magnetic tension is dramatic, and the inner part of the disk is evacuated in the Alfvén timescale: $r/v_{\rm A} \sim (r/a_{\rm T})^{1/2} \lesssim 0.1$ s, for a 10 $M_\odot$ black hole with a realistic Alfvén speed, $v_{\rm A} \simeq 0.1c$ (Nandi et al. 2001). The enhanced plasma ejection along the axis presumably causes sporadic magnetic flare events that would be observable as radio outbursts, at the same time reducing the X-ray emission from the disk that forms the base of the jet. Recently, such effects may have been seen (Safi-Harb & Kotani 2002) where simultaneous observations of 2 GHz radio and 2–20 keV X-ray fluxes from SS 433 have been made, and a clear dip in X-ray flux is seen at the same time a strong radio flare is observed. It is worth noting that similar anticorrelated variations are common during flares in GRS 1915+105 (Feroci et al. 1999; Naik et al. 2001), and we suggest that the flares in SS 433 originate in the same way.

## 3. CONCLUDING REMARKS

In this Letter, we have studied various competing processes for the creation of bullets which move ballistically in the jet of SS 433. We showed that blobs may be separated by (1) Comptonization, (2) shock oscillations due to resonance, (3) oscillations due to inherent unsteady accretion solutions, and (4) intense magnetic tension of the toroidal flux tubes. We reject the first possibility because it requires a large Keplerian disk, which is unlikely. We are unable to distinguish at this stage which type of shock oscillation is more capable of producing bullet formation in SS 433, but we prefer the third possibility owing to its impulsive and generic nature and smaller involved region. We believe that the fourth possibility of the inner disk evacuation should produce flaring events but will occur rather rarely, perhaps only once in a single precession period, when the magnetic field of the companion is preferentially tilted toward the accretion disk during precessional motion. This fourth mechanism gives rise to an anticorrelation between radio and X-rays, perhaps already observed in SS 433 (Safi-Harb & Kotani 2002).

S. K. C., A. N., and S. D. acknowledge a grant from the Department of Science and Technology, India, and financial support from CEA/Saclay, where part of this work was performed. P. J. W. is grateful for hospitality at the Department of Astrophysical Sciences, Princeton University, and for support from the Research Program Enhancement program at Georgia State University.

## REFERENCES

Abell, G. O., & Margon, B. 1979, Nature, 279, 701
Belcher, J. W., & MacGregor, K. B. 1976, ApJ, 210, 498
Biretta, J. A., Cohen, M. H., Unwin, S. C., & Pauliny-Toth, I. I. K., 1983, Nature, 306, 42
Blundell, K. M., Mioduszewski, A. J., Muxlow, T. W. B., Podsiadlowski, P., & Rupen, M. P. 2001, ApJ, 562, L79
Borisov, N. V., & Fabrika, S. N. 1987, Soviet Astron. Lett., 13, 200
Chakrabarti, S. K. 1990, Theory of Transonic Astrophysical Flows (Singapore: World Scientific)
———. 1999, A&A, 351, 185
———. 2002, in IAU Colloq. 187, Exotic Stars as Challenges to Evolution, ed. W. Vanhamme & C. Tout, in press
Chakrabarti, S. K., & D'Silva, S. 1994, ApJ, 424, 138
Chakrabarti, S. K., & Manickam, S. G. 2000, ApJ, 531, L41
Corbel, S. et al. 2001, ApJ, 554, 43
Das, T., & Chakrabarti, S. K. 1999, Classical Quantum Gravity, 16, 3879
Davidson, K., & McCray, R. 1980, ApJ, 241, 1082
Eggum, G. E., Coroniti, F. V., & Katz, J. I. 1985, ApJ, 298, L41
Feroci, M., Matt, G., Pooley, G., Costa, E., Tavani, M., & Belloni, T. 1999, A&A, 351, 985
Gies, D. R., McSwain, M. V., Riddle, R. L., Wang, Z., Wiita, P. J., & Wingert, D. W. 2002, ApJ, 566, 1069
Klein-Wolt, M., Fender, R. P., Pooley, G. G., Belloni, T., Migliari, S., Morgan, E. H., & van der Klis, M. 2001, Ap&SS Suppl., 276, 291
Kotani, T., & Trushkin, S. 2001, IAU Circ. 7747
Langer, S. H., Chanmugam, G., & Shaviv, G. 1982, ApJ, 258, 289
Lovelace, R. V. E. 1976, Nature, 262, 649
Margon, B. 1984, ARA&A, 22, 507
Mirabel, I. F., & Rodriguez, L. F. 1994, Nature, 371, 46
Molteni, D., Acharya, K., Kuznetsov, O., Bisikalo, D., & Chakrabarti, S. K. 2001, ApJ, 563, L57
Molteni, D., Lanzafame, G., & Chakrabarti, S. K. 1994, ApJ, 425, 161
Molteni, D., Sponholz, H., & Chakrabarti, S. K. 1996, ApJ, 457, 805 (MSC)
Naik, S., Agrawal, P. C., Rao, A. R., Paul, B., Seetha, S., & Kasturirangan, K. 2001, ApJ, 546, 1075
Nandi, A., Chakrabarti, S. K., Vadawale, S., & Rao, A. R. 2001, A&A, 380, 245
Paragi, Z., Fejes, I., Vermeulen, R. C., Schilizzi, R. T., Spencer, R. E., & Stirling, A. M. 2002 in Proc. 6th European VLBI Network Symposium, ed. R. W. Porcas, A. P. Lobanov, & J. A. Zensus (Bonn: MPIfR), 263
Paragi, Z., et al. 1999, A&A, 348, 910
Ryu, D., Chakrabarti, S. K., & Molteni, D. 1997, ApJ, 474, 378 (RCM)
Safi-Harb, S., & Kotani, T. 2002, in Proc. 4th Microquasar Workshop, ed. Ph. Durouchaux, Y. Fuchs, & J. Rodriguez (Kolkata: CSP), in press
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Smith, D. M., Heindl, W. A., & Swank, J. H., 2002, ApJ, 569, 362
Stephenson, C. B., & Sanduleak, N. 1977, ApJS, 33, 459
Stewart, G. C., et al. 1987, MNRAS, 228, 293
Vadawale, S. V., Rao, A. R., Nandi, A., & Chakrabarti, S. K. 2001, A&A, 370, L17
van den Heuvel, E. P. J. 1981, Vistas Astron., 25, 95
Vermeulen, R. C., et al. 1993, A&A, 270, 189
Watson, M. G., Stewart, G. C., Brinkmann, W., & King, A. R. 1986, MNRAS, 222, 261
Yuan, W., Kawai, N., Brinkmann, W., & Matsuoka, M. 1995, A&A, 297, 451