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Twenty-Five Years with SS 433

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Abstract. SS 433 was catalogued twenty five years ago, and yet, very little is known about the true identity of the compact component. We present a brief review of the behaviour of this enigmatic object with a special emphasis on the more recent results and their interpretation. We also speculate on some of the properties of the observed jet components.

1. Introduction

SS 433 was first cataloged by Stephenson and Sanduleak in 1977 as a very bright and variable optical line emitter (Stephenson & Sanduleak 1977). It is associated with a supernovae remnant W 50 which has been found to be deformed in the same general direction as the very powerful and elongated jets produced from SS 433. It is believed to be the first known micro-quasar in our galaxy with jets moving at a speed of $0.26c$ (though the term micro-quasar itself was coined much later, in 1994, in the context of a galactic black hole candidate, GRS 1915+105, whose jets have superluminal motion [Mirabel & Rodriguez 1994]). A very good review has been written by Margon (1984) almost two decades ago. Since then, although a great deal of new data have enriched the literature, the general understanding has not improved very significantly. On the other hand, a number of microquasars have been discovered last eight years and are well studied. One could compare and contrast the properties of these objects with SS 433 to gain more insight into what might be going on in this system.

2. Vital-statistics of SS 433

SS 433 is located roughly 3 kpc away from us and it is sufficiently bright to be studied in detail even with a small optical telescope. For instance, most of the early discoveries of the nature of the line-emission were made through a 24″ telescope. The compact object is located at the centre of the supernovae remnant W 50. The two, highly (within a degree or so) collimated jets move with virtually constant velocity of $0.26c$ but they are precessing around an axis (presumed also to be the axis normal to the binary-plane) in 162.5 days. The angle of the instantaneous jet direction and the binary-plane axis is $\sim 20°$. This axis makes an angle 78.9° along the line of sight.

That the system belongs to a binary has been known from a long time. Unambiguous variation of the light-curves in optical and X-rays have definitely pointed to a 13.1 d periodicity. The light curve has two unequal minima and points to the fact that the disk and companion are both alternatively eclipsed periodically. Not much is known in detail about the companion star which is perhaps an OB-type early star losing mass at no less than $10^{-4} M_\odot$ year^{-1}. The jets also undergo a nodding motion at 6.38 d on the top of the precession. Though no convincing evidence is present, it is widely believed that the precession of the disk is due to its subservient to the precession of the companion star.

The existence of the jets was inferred from the shifting of the blue and red-shifts of H_α, H_β emission lines. The jets are ejected along the instantaneous radial directions, possibly normal to the instantaneous disk-plane close to the compact object. Due to the precession of the disk, the radial direction changes and the velocity component projected along the line of sight also changes in the precession period. As a result, the amount of red and blue-shifts are not constant but are varying with the precession phase. Also, since the Lorentz factor corresponding to $v = 0.26c$ is $\Gamma = 1.035$, there is an intrinsic time dilation by this factor due to relativistic motion of the jet. Thus, the emission from the object is intrinsically blue shifted by a factor 1.035. The blue and red-shifted variation are not symmetric around zero red/blue-shift, but are symmetric around blue-shift $z = 1.035$. The so-called kinematic model of Abell & Margon (1979) has successfully been able to predict the general nature of the red and blue-shifts of the optical lines as a function of time. Recently, twenty years of data have been compiled (Eikenberry et al. 2001) and it is shown that the kinematic model, though originally constructed using only 3–4 years of observation, remains valid, although there is some indication that the precession of the disk could be slowing down at a rate $\dot{P} < 5 \times 10^{-5}$. There is also some indication of an intrinsic variation of the jet velocity and the average velocity may be written as, $v_{jet} = 0.254c$ with a standard deviation of $0.024c$. There is no clear estimated value of the masses of the compact object or the companion. The estimates wildly vary between $M_\mathrm{x} = 1.3\,M_\odot$ to $M_\mathrm{x} = 62\,M_\odot$ (Antokhina & Cherepaschuk 1985). The confusion is mainly because the entire system, including the companion is shrouded by an enormous dust cloud which is formed by the lost matter from the secondary. The velocity variation during the companion's orbital motion is not known very accurately and therefore the mass function is not well determined. Earlier estimation (Crampton & Hutchings 1981) suggests that the mass function could be around $10.6\,M_\odot$ which naturally leads to very large masses of the components. For instance, Zwitter & Calvani (1989) came up with a mass of $\sim 10 M_\odot$ for the compact object which means that it has to be a stellar black hole. Brinkmann, Kawai, & Matsuoka (1989) used the Ginga results of X-ray variation and found the masses of the compact object and the companion to be $M_\mathrm{x} \approx 2.1\,M_\odot$, and $M_* \approx 14\,M_\odot$ respectively. Recent analysis of the optical data suggests an estimate of the mass ratio $q = M_\mathrm{x}/M_*$ to be around 0.4 to 1.2 while the models of X-ray light curves give a lower value of $q \approx 0.15 - 0.25$ (see Gies et al. 2002 and references therein). However, from simultaneous measurements in optical and X-rays, Stewart et al. (1987) came to the conclusion that $q \approx 1$ and each of the mass components is larger than $\sim 10 M_\odot$.

There is no measurement on the X-ray emission from the inner edge of the disk around the compact object because of the high degree of obscuration. This has lead to the difficulty that the criteria which are normally applicable to identify a black hole or a neutron star cannot be used here. For instance, the variation of the state (soft state to hard state and vice versa) cannot be studied in this case. There are certain things which could be said from what we have learned about other micro-quasars and we discuss these speculative issues later in this review.

3. Observation in different wavelengths

SS 433 has been observed from radio to very high energy γ rays. We discuss briefly each of these observations, not necessarily following any order.

3.1. Optical

In the optical band SS 433 has a luminosity of $10^{37}\,\mathrm{erg\,s^{-1}}$ (Margon 1984) and a polarization of about $2 - 3\%$ (Dolan et al. 1997). It is a 14(V) magnitude eclipsing binary with two unequal minima in the light curve: the primary one is conventionally assumed to be due to the eclipse of the accretion disk and the secondary one is due to the eclipse of the companion.

Much of the early observation of the red- and blue-shifted lines came from a $24''$ optical telescope. The nature of the shifts, when fitted by kinematic model were symmetric with respect to the intrinsic blue-shift of 1.035 due to the relativistic motion of the jets. In the formula of red-shifts in the kinematic model, there was a clear degeneracy between the half angle of the precession cone and the angle of the binary-plane axis with the line of sight. Subsequent radio observations (Hjellming & Johnston 1981) clearly showed that blobs of matter are aligned on a cork-screw of an opening angle of around 20° (and not $\sim 78.9°$). This breaks the degeneracy. High resolution observations showed variation of the red/blue-shifts with the nodding motion (Gies et al. 2002). The stationary H_α line is very strong with an equivalent width of $\sim 300\,\mathrm{\AA}$ and is coming from the gas stream of the binary companion hitting the disk. The moving H_α lines originate in jets very far away. The He-II line variation is widely considered to trace the companion (Crampton & Hutchings 1981) as the velocity reaches maximum when the companion is receding. This yielded a binary period of 13.1 d.

The blobs in the jet components were found to appear suddenly at specific wavelengths and then decay away on time scales of a few days at the same red- or blue-shifted positions. Since, on a given radial direction, the wavelength shift remains the same Borisov & Fabrika (1987) and Vermeulen (1993) suggested that the ejection must be bullet-like. Gies et al. (2002) pointed out that the physical emission flux ratio of the approaching and receding jets $[W_\lambda(\mathrm{H}_{\alpha-})/W_\lambda(\mathrm{H}_{\alpha+})](\lambda_+/\lambda_-)^4$ (where λ_+ and λ_- are the observed wavelengths from the jets, W_λ is the equivalent width) indeed agrees with the bullet model and not the continuous jet model (Urry & Padovani 1995; Gies et al. 1995). Later, we shall comment on the possible origin of the bullets.

3.2. X-rays

In soft X-rays (2 – 10 keV) SS 433 manifests itself as a relatively undistinguished source with a luminosity around $10^{35}\,\mathrm{erg\,s^{-1}}$ (Brinkmann et al. 1989). Early observations by Ariel, Uhuru and HEAO found highly variable X-rays. However, the EXOSAT satellite showed an Fe line from the very inner region of the jet (10^{11-12} cm) (Watson et al. 1986; Stewart et al. 1987). No evidence was found for significant variabilities on timescales less than 300 s, suggesting an extended source. What is more, the Fe line is blue shifted already by this distance, strongly rejecting models such as line-locking mechanism (Milgrom 1979) which required slow and gradual acceleration. The X-ray luminosity of the source is very low ($10^{36}\,\mathrm{erg\,s^{-1}}$).

More recently, Kotani et al. (1996) have found that the line emission from both the approaching and the receding jet components could be separated clearly. From the measurements of the intensity of iron line ratios they determine the initial temperature to be about 20 keV. The minimum number density $n_\mathrm{p} \approx 10^{13}\,\mathrm{cm^{-3}}$ implies a lower limit of the kinematic luminosity of $L_\mathrm{jet} \approx \frac{1}{2} m_\mathrm{p} v_\mathrm{jet}^2 (n_\mathrm{p} v_\mathrm{jet} \pi R^2 \theta^2) \approx 3 \times 10^{38}\,\mathrm{erg\,s^{-1}}$. The outflow rate in a narrow jet of $\sim 2^\circ$ would be around $10^{21}\,\mathrm{g\,s^{-1}}$ or few $10^{-6}\,M_\odot\,\mathrm{yr^{-1}}$. This is truly remarkable, as this implies that inflow could be super-Eddington even for a $10\,M_\odot$ black hole at the centre. It was concluded that the X-ray continuum could have contributions both from the jet and the disk. There was no evidence for thermal X-rays as would be expected from a Keplerian disk, and the continuum resembles a hard state, even with so much of accretion. In the precession phase of 0.48, evidence for only the receding component was found while at precession phase of 0.08, both the components were seen. This was interpreted to be due to an obscuring large disk roughly in the plane of the binary. Zwitter, Calvani, & D'Odorico (1991) mentioned such an extended disk in order to explain the observed light curve. Chakrabarti & Matsuda (1992), through extensive numerical simulations, showed that a so-called excretion disk should exist if the companion is massive enough. This outflow was essentially accomplished by the presence of variable spiral shock patterns produced on the disk due to non-axisymmetric forcing of the massive companion. More evidence of this extended matter came from radio observation which will be discussed later.

A recent observation (Safi-Harb, private communication) indicated that there was a distinct anti-correlation between the hard X-ray and radio observation. In X-rays, 50 – 1000 s variability has been detected. This time is expected to be the interval at which individual bullets are ejected. This phenomenon is easily interpreted using the inner disk evacuation phenomenon discussed in the context of GRS 1915+105 (see Nandi et al. 2001 and references therein). If the observation is verified in subsequent flares, this would be a direct hint of X-ray emissions from the inner accretion disk itself.

A new region of X-ray emission has puzzled the astronomers. It has been observed that at least at a distance of $10^{17} - 10^{18}$ cm from the centre, there was a significant increase in the X-ray intensity. It was modelled by colliding bullets with disparate velocities (Migliari, private communication). Collisions can take place only if the blobs are along the same radial direction and velocities are different. If the velocity dispersion is δv, then time taken to catch-up the earlier bullet is $162.7(v/\delta v)$ d which is very large unless the size of the bullet itself is also very large.

An interesting observation on X-ray jets has recently been reported by Marshall, Canizares & Schulz (2001). They find that the jet in the east-west direction (which is roughly co-aligned with the radio jet) is distinctly different from that in the north-south direction (aligned with the disk). In fact when a difference in intensity is taken of the north-south component from the east-west component, the core (less than $0.5''$) is eliminated, while there is a distinctly bright component at least $1.5''$ away from the source. This indicates that significant X-ray energy *is* produced in the jet itself.

3.3. Radio

SS 433 is being observed in radio very extensively. Red-shift observation of the jet with both the VLA and VLBI in the $0\overset{''}{.}1$ and $0\overset{''}{.}01$ resolutions ($\sim 4.5 \times 10^{14}$ cm at 3 kpc) agree with the kinematic model very well and showed the corkscrew motion of the blobs of radio emission. Radio emission is presumed to be due to synchrotron radiation and the total luminosity is around $10^{32}\,\mathrm{erg\,s^{-1}}$. Synchrotron self-absorption produces a low-frequency cut-off at around 10^9 Hz at VLBI scale. The observed flux density decreases from 1 Jy at 10^9 Hz to 0.1 Jy at 10^{11} Hz (Rose 1995). The jets are found to be extended on a few arc seconds and are highly polarized (more than 20%) pointing to a very strong and somewhat aligned magnetic field. These jets are positively interacting with the supernovae remnant W 50 deforming it significantly. Individual flaring events in which more intense radio blobs are ejected have been detected quite often (Vermeulen 1989). Recently, similar events have been reported by Safi-Harb (private comm.) as well. Vermeulen et al. (1988) also detected a so-called radio-brightening zone at a distance of about 50 mas ($\approx 2.2 \times 10^{15}$ cm) from the centre, where, it is as though the individual blobs get brightened. It was speculated that this brightening may be due to passage of bullets through the bow shocks of their predecessors.

A detailed analysis of the inner radio jet region has been reported by Paragi et al. (1999) through multi-frequency VLA and VLBA observation. They detected motion on individual components and also excretion disk type morphology in a direction normal to the jets. They find evidence of both the synchrotron self-absorption and free-free absorption in the inner most AU scale region and came up with the conclusion that the compact object is surrounded by a disk-like matter distribution embedded inside a spherical dust cloud of about 50 AU radius. The presence of the equatorial outflow has also been verified by Blundell et al. (2001). It has been suggested that the outflow is produced by slow winds due to matter literally flying away with some excess angular momentum (Chakrabarti & Matsuda 1992) transported at the spiral shocks. There are other reasons to believe that the matter is perhaps centrifugal pressure driven and not radiation pressure driven. This will be discussed later.

3.4. Ultra-Violet

We know that SS 433 is very bright in the UV. Dolan et al. (1997) mention a flux of $10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,\mathring{A}^{-1}}$ which yields a luminosity of $3.3 \times 10^{32}\,\mathrm{erg\,s^{-1}}$ at 3000 Å. Polarization measurements show a significant intrinsic value: of 13.7 ±

3.0% at a position angle (PA) of $< \theta_0 > = 81° \pm 10°$ which means on an average of 6 times larger than the value at the optical band. The scattering component in the polarization is best explained by a combination of the Rayleigh scattering (where the wavelength dependence $\propto \lambda^{-4}$) and Thomson scattering (Dolan et al. 1997). It is argued that the scattering medium could not be located in the jets since they are oriented at PA of $100° \pm 20°$ on the sky which is nearly parallel to the observed PA. If scattering is the only mechanism, the PA of polarization should be orthogonal to the scattering media. Thus the scattering medium must be located roughly in the plane of the disk. This is yet another indication of a giant equatorial dust cloud, presumably formed from the excretion disk.

3.5. Infra-red

There are several IR observations and the flux density is about a thousand times lower than that from the optical bands. General photometry in IR also shows similar behaviour as that of the UBV bands. Some recent observations have been reported by Fuchs, Koch-Miramond, & Abraham (2002) who demonstrated that in the $2.4 - 80\,\mu$m region of the spectrum of SS 433 remarkably matches with that of WR stars. These authors concluded that possibly the companion is a WR star. See also an earlier analysis by van den Heuvel (1983).

3.6. γ-rays

There was some report by Lamb et al. (1983) of intense γ-ray line emissions which meant that the γ-ray luminosity is about $2 \times 10^{37}\,\mathrm{erg\,s^{-1}}$, quite a large fraction of the total emitted energy. Existence of these lines required impossible viscosity parameters for the disk (Chakrabarti 1986). The observation has not been re-confirmed.

3.7. Very high energies?

Since the jets deposit their mechanical energy at the terminating shock, it is expected that some high energy particles could be produced at these sites and possibly contribute to the high energy cosmic rays. Aharonian & Atoyan (1998) argued for inverse Comptonization of cosmic microwave background radiation by hot electrons at these terminal shocks. Rowell (2002), on behalf of the HEGRA collaboration gave a 99% upper limit of 0.12 Crab flux units at one of the termination shocks. The lower limit of the magnetic field at this site was found to be $13\,\mu$G very close to interstellar medium. For a better determination of the magnetic field in this region a tighter upper limit was necessary.

4. Possible System Components and the Evolutionary Scenarios

Not much is understood as to what component stars make up SS 433 or how SS 433 came into being at the present stage. Since the beginning of the discovery, focus was on the compact object as a black hole and the companion as an OB type star. More recent reports even discuss possibilities of having a neutron star as the compact body with an ordinary WR star (Fuchs 2002) as the companion. The latter conclusion is based on the similarities in the spectra of WR stars with SS 433 in infra-red.

King, Taam, & Begelman (2000) discussed results from Eggleton's Code for stellar evolution with the following constraints in mind: (a) binary period is 13.1 d; (b) mass transfer rate is larger than the outflow rate; (c) expulsion of matter takes place within the Roche lobe of the accretor; (d) in order that SS 433 is not a common-envelope-evolution system, the companion must not have a deep convective envelope; and finally, (e) judging from the time scale of interaction of the jet with W 50, the mass transfer exceeded the Eddington rate for at least a thousand years. A concrete conclusion was that: (A) a companion star more massive than $5\,M_\odot$ with a neutron star as the compact star would lead to a rapid decrease in the orbital period in a timescale of 1000 years thus possibly eliminating a massive WR star + neutron star scenario mentioned above (unless the WR star is more massive); (B) the mass transfer rate of $7\times10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$ to $4\times10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$ is common for a binary with a period of 13.1 d. This is larger than the Eddington rate. For a radiatively driven outflow, the expulsion radius is estimated to be around 10^8 cm which is of the order of a few ten to a hundred times the Schwarzschild radii for reasonable parameters. Below we show that the expulsion radius is probably larger than this by a factor of a hundred since outflow could be centrifugally driven as well.

5. Analysis of Some of the Observations

It is pertinent to analyse some of the observational results in the light of what is known about other micro-quasars.

5.1. Nature of the accreted matter

Is there any evidence that the disk around the compact object is a Keplerian thin disk? The answer is clearly, "no" because there is no evidence of any thermal emission. So, even though the companion is filling the Roche-lobe, the disk, at least closer to the compact object, need not be a Keplerian disk. On the contrary, because the accretion is mostly from winds, and high-angular-momentum flow is likely to have left the system at the expulsion radius r_{ex} of at least a hundred Schwarzschild radii or more, it is possible that the matter is accreted in the form of a sub-Keplerian flow which is roughly freely falling. Since the time scale of losing angular momentum by viscous processes is much longer than the infall time scale $\sim r_{\mathrm{ex}}^{3/2}$, the flow will rather have almost constant angular momentum causing the formation of a centrifugal barrier from where jets could be produced (Chakrabarti 1999 and references therein). It is to be remembered that if the gas is hot enough, one does not require any viscosity for infall of matter to take place on a black hole. Unless the specific angular momentum is larger than the marginally stable value, this picture is valid for neutron stars as well.

5.2. Nature of the ejected matter

It is proven beyond doubt that the ejection is in the form of bullets. From the variability of 50 – 1000 s as observed in recent X-ray observations (Safi-Harb, private comm.), one could imagine that this is the time scale of ejection of bullets. If one takes the size of the X-ray emitting region of the jet to be around 10^{12} cm, the crossing time at the jet's speed would be about a hundred seconds as well. However, the velocity of the jet is remarkably constant, which means that the environment on *both sides* (at least within a cone of semi-angle 20 degrees) is remarkably clean. Otherwise, significant entrainment could have slowed down the bullets of one side or the other, or at some precession phase as compared to the other. In fact, this may mean that these two conical regions are actually emptied out by the bullets, thus, there need not be any bow-shock formation in the bullets. It is therefore curious what causes the brightening zone at a distance of about 10^{15} cm that was reported (Vermeulen 1988).

5.3. Jet-disk symbiosis

In black hole candidates, jets have to be ejected from disks, since black holes have no atmospheres. This need not be true for neutron stars. It is often argued that continuous jets can be produced in the hard states or semi-hard states, but not in the soft states (Chakrabarti 1999, 2000) because in the soft states, the centrifugal pressure dominated boundary layer (CENBOL) is cooled down (the compression ratio $R \approx 1$). In other microquasars it is now verified that there is a distinct relationship between the spectral states and the jet formation (Klein-Wolt et al 2001; Corbel et al. 2001) Thus, it is interesting in the context of SS 433 that, even when the matter supply rate is very high (and the object should have been at a soft state), jets are produced quasi-periodically. This implies that the rate at which matter actually accretes into the compact object may be *very low*. Indeed, there is no evidence for any super-critical accretion disk around the compact object.

5.4. Nature of the Bullets and their Ejection

Since the kinematic luminosity is around $10^{39}\,\mathrm{erg\,s^{-1}}$, the mass ejected in each second would be around $10^{18}\,\mathrm{g\,s^{-1}}$. Thus, in every $50 - 1000$ s, a bullet may posses a mass of 10^{20} g or so. There are several ways bullets may be produced quasi-periodically. For instance, Ryu, Chakrabarti & Molteni (1997) showed that when the matter has the wrong parameters to produce steady shocks, it produces very large amplitude oscillations of axisymmetric shocks which periodically eject matter by virtually evacuating the sub-Keplerian disk. Chakrabarti & D'Silva (1994) pointed out that in the hot environment ($T \gtrsim \mathrm{few} \times 10^9$ K) the magnetic tension is the strongest component of force. This so-called rubber-band effect was elaborated and successfully used by Nandi et al. (2001) to explain the flaring events in another micro-quasar GRS 1915+105. In particular, it was shown that the catastrophic collapse of the hard X-ray emitting region causes enhancement in radio, and as a result, hard X-ray and radio emission should be anti-correlated during flare events. Recent observation of such anti-correlation (Safi-Harb, private comm.) perhaps points to this type of phenomenon occurring even in SS 433.

6. A Scenario for SS 433

Given these observations and theoretical developments, one can now bring together several behaviours and construct a scenario of what could be going on close to the compact object. The basic facts are:

i) the bullets can be produced only if the inner region is hotter, i.e., the Keplerian disk does not extend to the inner region;
ii) most of the matter from the donor star is expelled outward at some expulsion radius;
iii) the bullets are produced at $50 - 1000\,\mathrm{s}$ interval;
iv) the bullets are highly collimated;
v) during flaring, there are indications of anti-correlation between radio and X-ray.

Points i) and ii) are consistent with each other, if most of the matter accreted is with low angular momentum λ, i.e., sub-Keplerian $\lambda < \lambda_{\mathrm{Kep}}(r_{\mathrm{out}})$ (which is true for winds from the companion) and when viscosity is low $\lambda \approx$ const. In this case, matter will be expelled at a distance r_{ex} where $\lambda_{\mathrm{Kep}}(r_{\mathrm{ex}}) \approx \lambda$, because of centrifugal force and also perhaps to some extent by radiation pressure; though there in no compulsive signature of radiation dominated flow as yet. Numerical simulations of Eggum, Coroniti, & Katz (1985) do indicate formation of an outflow but the ejected flux is very low. The region $r \leq r_{\mathrm{ex}}$ would be the centrifugal pressure dominated boundary layer (CENBOL) and it would produce bullet-like ejecta due to quasi-periodic collapse and expansion. In this case, the time scale of cooling matches with the infall time scale (Molteni, Sponholz, & Chakrabarti 1996: MSC-type). One interesting distance could be $r_{\mathrm{ex}} \approx 6\,400\, r_g$ (where $r_g = 2GM/c^2$, and M is the mass of the central body) since the infall time $r_{\mathrm{ex}}^{3/2} r_g/c \approx 50\,\mathrm{s}$ for $M \approx 10\, M_\odot$ (Chakrabarti et al. 2002). Even if the time scale is enhanced by a factor $R \approx 4$ (compression ratio at the CENBOL boundary due to slowing down of infall velocity by centrifugal force) the timescale is comparable with the interval of the ejection of the bullets. The mass of this region can be calculated assuming that the bremsstrahlung cooling time $E/\dot{E}$ is comparable to the infall time, and this turns out to be few times 10^{19} g, which is not unreasonable. Though it is difficult to separate the X-ray contribution of the disk from the jet, one could try to observe a QPO at a frequency of $0.01 - 0.02$ Hz in X-rays due to this oscillation.

Another possibility to eject bullets may be by the strong and dynamic oscillation when a sub-Keplerian flow has two saddle-type sonic points, but the standing shock conditions are not satisfied (Ryu, Chakrabarti, & Molteni 1997: RCM-type), very similar to two-handled bellows to blow puffs of air into the fire. In this case, the oscillation period is much longer (by a factor of 10 or more) than the infall time. This means that the CENBOL could be much smaller (factor of $12 - 15$ or so) in size (i.e. around $500 - 1000$ Schwarzschild radii). On the other hand, the ejection is impulsive, as in the first half of the oscillation, the CENBOL accumulates matter blocking accretion almost completely, and in the second half the CENBOL is evacuated. MSC-type oscillation depends on resonance of time scales (accretion rate). It is certainly allowed in a non-flaring and normal circumstances where the CENBOL oscillates and ejects most of the CENBOL quasi-periodically. RCM-type oscillation is more impulsive and less dependent on accretion rates.

During flaring stages, the rubber-band scenario may work, where the magnetic tension increases very rapidly and becomes the most dominant force (Nandi et al. 2001; Chakrabarti et al. 2002) provided the crossing time by Alfvén waves (which is the collapse time of the magnetic rubber band) within $r < r_{\rm ex}$ is much shorter. Matter is expelled along the jet causing flares in radio.

All these processes require the presence of the CENBOL, whose funnel wall may be responsible for initial collimation. However, steady supply of toroidal field (formed due to shear amplification of randomly cannibalized magnetic field from the companion or the surroundings) and their expulsion by buoyancy will ensure very strict collimation at later times.

It is often argued (Katz 1980) that the accretion disk in SS 433 must have a large viscosity in order that the residence time is much shorter than the binary period. This was because the nodding motion of 6.38 d, which is believed to be due to perturbations on the disk by the companion, is transmitted to the bullet motions very faithfully and unless the transmission time is shorter the perturbation would be washed out. In the early eighties, the disks were all believed to be Keplerian while we know from the properties of HMXRBs (such as Cyg X-1) that the low angular momentum sub-Keplerian flows can play a major role (Chakrabarti & Titarchuk 1995; Smith, Heindl, & Swank 2002). Thus the accreting flow in SS 433 could be of low angular momentum and the infall time is roughly the same as the free-fall time. Hence, the transmission time of the perturbation is not a problem.

It is also argued that the outflow may be radiation pressure driven. But the radiation pressure from the Keplerian disk cannot be significant as argued above. Eggum et al. (1985) showed that the radiatively driven outflow rate is only about a percent of the disk accretion rate. This may not explain the large kinematic luminosity of SS 433.

In Fig. 1 we present a diagram of what may be happening close to the compact object. Blobs are presumed to be ejected at every 50 – 1000 s by large scale oscillations (Ryu et al. 1997) of the the sub-Keplerian region of size 6400 – 10 000 $r_{\rm g}$ while the precession takes a 162.5 d period. The description is valid both for a neutron star or a black hole since none of the large length/time scale phenomena we described depend on whether the object is really a black hole or a neutron star (unless the neutron star accretion is always sub-sonic, Chakrabarti 1990). There seems to be no compulsion to favour one way or the other. For instance, a soft/hard state transition, or a hard tail in very soft states etc. (Chakrabarti & Titarchuk 1995) has not been witnessed in SS 433, nor are these are expected to be observed in view of the obscuration. Evolutionary studies showed that a binary system with 2 $M_\odot$ and 8 $M_\odot$ can also have similar mass loss to the companion and a binary period of 13.1 d (King et al. 2000). A neutron star with a magnetic field axis aligned along the spin axis may also produce bullets. But it is unclear, why the bullets should precess. There may be a slight advantage towards having a black hole: the inferred mass of $M_{\rm x}$ is generally large. Either way, the infalling matter could have similar properties to those described above.

7. Concluding remarks: an unending puzzle?

SS 433 does pose some puzzles to the theoreticians, but most of them could be attributed to the present evolutionary phase of the companion in which it is losing matter at a very high rate (at about a thousand times the Eddington rate as seen by the compact object). This en-shrouds the compact object and its vicinity. Indeed recent multi-wavelength studies did point to a large obscuring region of about 50 pc inside of which there is an extended disk formed due to a slowly moving outflow.

If the degree of obscuration and the large mass loss rate from the companion is responsible for SS 433 becoming an exotic star, one could discuss briefly another system, V4641 Sgr, which is just one year junior as it was discovered in 1978 (Goranskij 1978). This object, like Cyg X-1 and SS 433, is now confirmed to belong to the HMXRB category as the companion is a massive B3-A2 star and the distance is around 4 – 8 kpc. The orbital period is 2.8173 d. The X-ray shows rapid variabilities (seconds to minutes) during outbursts, as seen in SS 433 during flaring. Normally a 14 (V) magnitude star (similar to SS 433), V4641 Sgr became as bright as 8 (V) during a recent optical outburst. Possible superluminal radio ejecta has been discovered (Hjellming et al. 2000) making it also a microquasar. The mass of the compact object has been determined to be very high at $9.6\,M_\odot$ (Orosz et al. 2001) which makes it a black hole candidate, though unlike SS 433, where M_* is believed to be more than M_X, in V4641 Sgr, $M_* \leq M_\mathrm{X}$. V4641 Sgr has already undergone a rapid mass-transfer phase as the companion star is found to be smaller in size as well as under-luminous compared to a normal companion. It is likely that the fate of SS 433 will be similar to V4641 Sgr in another 10^4 yr or so.

Only after the shroud over SS 433 has dispersed and/or accreted back, will the puzzle perhaps be finally solved.

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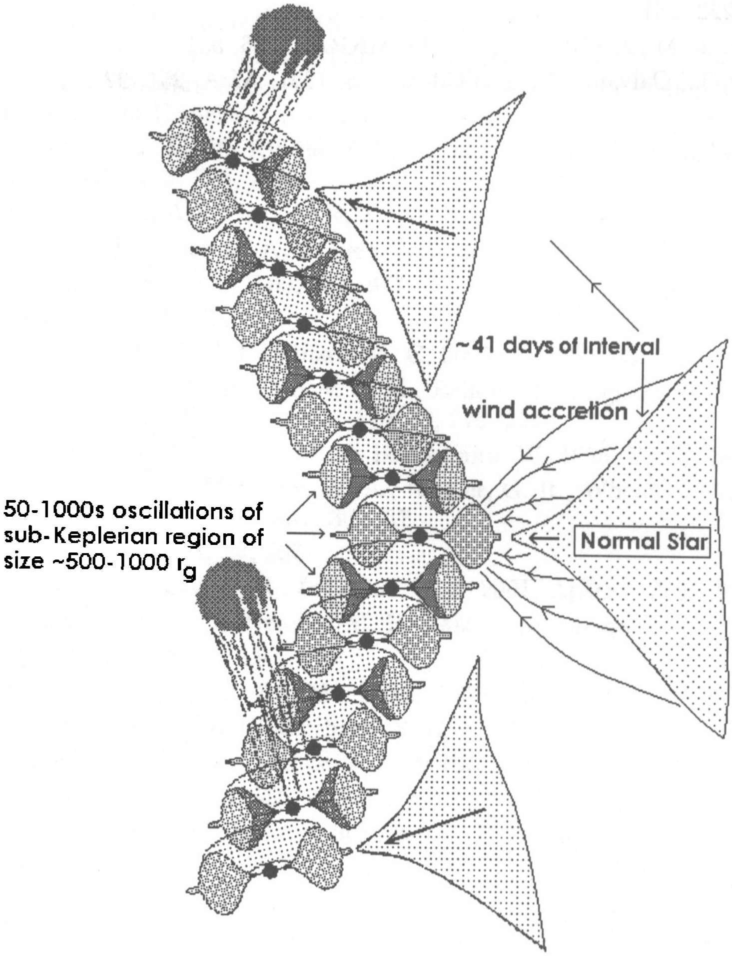

Figure 1. Various phases of the precessional motion and oscillating sub-Keplerian flow. Bullets are ejected when shocks move very close to the funnel wall (deeply shaded region, see Ryu et al. 1997). Flaring may take place by the magnetic rubber-band effect when the sub-Keplerian flow is evacuated completely (Nandi et al. 2001).