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Simulations of SS 433 Jets at Super-Eddington Luminosities

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The galactic microquasar SS 433 is a super-critically accreting black hole candidate and their relativistic jets have been interpreted to originate in the acceleration by the radiation pressure in the inner accretion disk. Based on the initial 1D models of supercritical accretion disk with mass loss and advection, we examine the disk and jets of SS 433 with $\dot{M} = 10^3\dot{M}_{\rm c}$ by two-dimensional radiation hydrodynamical calculations. Depending on the viscosity parameter α, we obtain the total luminosities more than 10 times higher than the Eddington luminosity, the jets mass-outflow rates of $\sim 10^{-6} - 5\times10^{-5} M_\odot$ yr^{-1}, and the wind mass-outflow rates of $\sim 10^{-6} - 10^{-4} M_\odot$ yr^{-1}, which are generally compatible with the observed rates of SS 433. In addition, for a case of large viscosity parameter α, we find a new type of instabilities of the accretion rates near the inner edge and the disk luminosity. These instabilities grow into recurrent hot blobs which develop outward and upward, and result in QPOs of the total luminosity with an amplitude of a factor 1 – 2 and a quasi-period of $\sim$ 30 sec. This may explain a massive jet ejection and QPOs-like phenomena observed recently in SS 433.

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1. Introduction

When the accretion rate is not too high, the accretion disk luminosity is directly proportional to the accretion rate and can be successfully described by the Shakura-Sunyaev model[1]. However, for the supercritical accretion flow, matter flows out of the disk and the rate of accretion onto the central black hole is reduced, repressing the luminosity to the Eddington limit. Such supercritical accretion disk models around black holes have been developed together with discoveries of very luminous accreting objects whose luminosities exceed the Eddington luminosity. The X-ray source SS 433 is the promissing super-critically accreting sterllar-mass black hole candidate. The supercritical disk models have been examined by two-dimensional radiation hydrodynamical calculations[2, 3, 4, 5], especially focussing on the very puzzling X-ray source SS 433. These works leave something to be desired as far as SS 433 is concerned, because the accretion rates adopted in the calculations are still very small compared with that expected for SS 433. Therefore, it has still open questions of the disk and jets.

2. Supercritical accretion disk models with mass loss and advection

The previous our works of SS 433 [4, 5] are based on the initial disks by the standard Shakura-Sunyaev disk model with $\dot{m}_0 \leq 10$. Here, $\dot{m}_0$ is the input accretion rate normalized to the Eddington critical accretion rate $\dot{M}_{\rm c}$ (= $48\pi GM/c\kappa$), G the gravitational constant, M the black hole mass, κ the Thomoson scattering opacity. We consider here $M = 10M_\odot$ and a more plausible value of $\dot{m}_0 = 10^3$ for SS 433. The Shakura-Sunyaev disk model with such high accretion rate is too geometrically thick and becomes invalid against assumptions used. In this respect, the supercritical disk models with mass loss and advection were proposed and discussed on SS 433 and the ULXs[6, 7]. In their models with mass loss, it is assumed that a fraction $\varepsilon_{\rm W}$ of the radiation energy flux is spent on the production of the outflow below a spherization radius $r_{\rm sp}$. For $\varepsilon_{\rm W} = 1$, we obtain analytical solutions of the disk variables on the disk plane, where $r_{\rm sp}/3r_{\rm g}$ is estimated to be $\sim \frac{5}{3}\dot{m}_0$. The disk solutions correspond to the S-S model above the spherization radius. On the other hand, the disk models with advection are numerically obtained. Based on these initial 1D models of the supercritical accretion disks, we examine actual properties of SS 433 jets by two-dimensional radiation hydrodynamical calculations.

In Table 1, we show the parameters of the models with mass loss (ML) or advection (AD). Under these disk models, we investigate the time evolutions of the disks and jets until a quasi-steady solution is obtained. The numerical schemes used are basically the same as that described previously[4, 5].

3. Numerical Results

Table 1 also shows the numerical results and the observations[8, 9, 10, 11, 12], where L, $L_{\rm d}$, $\dot{M}_{\rm input}$, $\dot{M}_{\rm wind}$, $\dot{M}_{\rm jet}$, and $\dot{M}_{\rm edge}$ are the total luminosity emitted from the outer boundary surface, the disk luminosity emitted from the disk surface, the mass-inflow rate through the outer disk boundary, the total mass-outflow rate through the entire outer boundary, the mass-outflow rate from the outer surface between the rotational axis and the centrifugal barrier region with an opening angle of

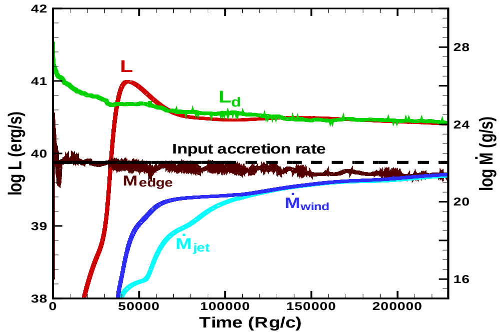

Figure 1: Time evolutions of total luminosity L, disk luminosity L_d, wind outflow rate $\dot{M}_{\rm wind}$, jets outflow rate $\dot{M}_{\rm jet}$, and mass-inflow rate $\dot{M}_{\rm in}$ swallowed into the black hole through the inner boundary for model AD-1, where time is shown in units of r_g/c.

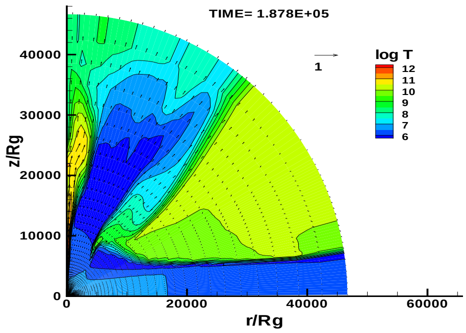

Figure 2: Velocity vectors and temperature contours in logarithmic scale on the meridional plane at $t = 1.87 \times 10^5$ for model AD-1. The reference vector of light is shown by a long arrow. The jets propagate with relativistic velocities of 0.2 – 0.3c along the Z-axis.

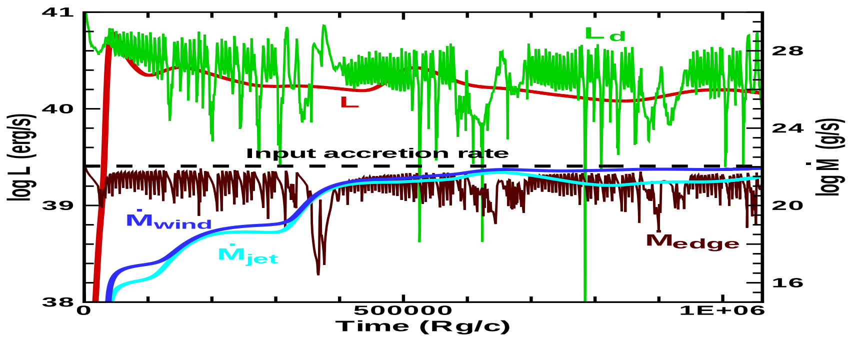

Figure 3: The same as Fig.1 but for model AD-2.

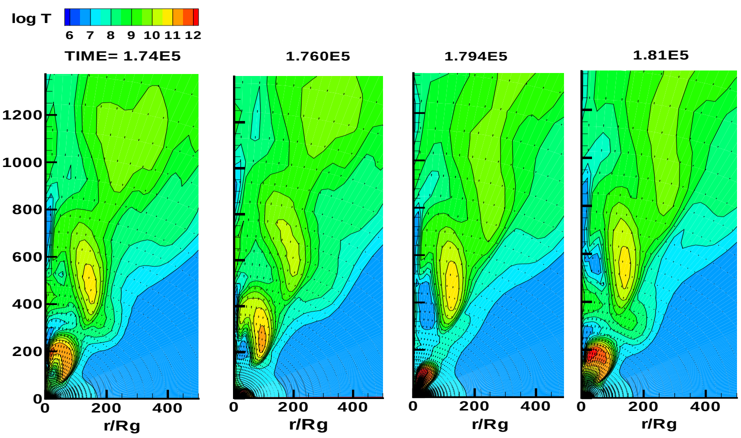

Figure 4: Evolution of temperature contours of hot blobs at $t = 1.74 \times 10^5$, 1.76×10^5, 1.794×10^5, and 1.81×10^5 during a cycle for model AD-2.

Table 1: Results and Comparison with observations

Model	α	$\dot{M}_{\rm input}$ ($M_\odot$ yr^{-1})	log L (erg s^{-1})	log $L_{\rm d}$ (erg s^{-1})	log $\dot{M}_{\rm edge}$ (g s^{-1})	log $\dot{M}_{\rm jet}$ (g s^{-1})	log $\dot{M}_{\rm wind}$ (g s^{-1})
ML-1	0.001	2×10^{-4}	40.9	41.0	16.7	21.7	21.8
ML-2	0.1	2×10^{-4}	40.4	40.3	18.0	19.7	19.8
AD-1	0.001	2×10^{-4}	40.4	40.5	21.5	21.1	21.2
AD-2	0.1	2×10^{-4}	40.3 (QPOs)	40.4 (QPOs)	21.0 (QPOs)	21.2	21.4
Observations	–	10^{-4} – 10^{-3} ($M_\odot$ yr^{-1})	39 – 40 (erg s^{-1})	–	–	10^{-7} – 10^{-6} ($M_\odot$ yr^{-1})	10^{-5} – 10^{-4} ($M_\odot$ yr^{-1})

$\sim 30^\circ$, and the mass-flow rate swallowed into the black hole through the inner disk edge. The final mass-outflow rates except ML-2 are compatible to the observational ones and the total luminosities are a few factor $\times 10^{40}$ erg s^{-1} except model ML-1.

Figure 1 shows the time evolutions of the total luminosity L, the disk luminosity $L_{\rm d}$, the mass outflow rates $\dot{M}_{\rm wind}$ and $\dot{M}_{\rm jet}$ of the wind and jets for model AD-1. As far as the luminosity curves are concerned, a quasi-steady state of the disk and jets is attained here. The total luminosities L are more than ten times larger than the Eddington luminosity 1.5×10^{39} erg s^{-1} and are also larger by a factor of several than those given by $L/L_{\rm E} = 0.6 + 0.7 \ln \dot{m}_0$ obtained analytically[6]. Figure 2 shows the velocity vectors and the temperature contours of the disk and jets at $t = 1.878\times10^5$ for model AD-1. This shows a rarefied, hot, and optically thin high velocity jets and a dense, cold, and geometrically thick disk. The jets propagate with relativistic velocities of 0.2 – 0.3c along the Z-axis.

Figure 3 shows the same figure as Fig.1 but for model AD-2 with $\alpha = 0.1$. In this case, we find a new type of instabilities of $\dot{M}_{\rm edge}$ and $L_{\rm d}$. These instabilities grow into recurrent hot blobs, which develop outward and upward. The hot blobs occur near the inner edge and grow typically until $\sim 70 r_{\rm g}$ on the disk plane and decay at $z \sim 2000 r_{\rm g}$. The time evolutions of the hot blobs during a cycle are shown in Figure 4. The modulations of $\dot{M}_{\rm edge}$ consist of two types of variabilities : (1) short time variations with amplitude of more than ten times of magnitude and a quasi-period of $\sim$ 0.6 seconds, (2) a long time variation with amplitude of more than two orders of magnitude and a period of $\sim$ 30 seconds. The disk luminosities also modulate by factors of a few to more than ten, corresponding to $\dot{M}_{\rm edge}$. However, the modulations of $\dot{M}_{\rm edge}$ with the smaller amplitude and short periods are smeared out through their passage to the outer boundary surface. Accordingly, only the large modulations near the inner edge influence on the total luminosity L.

4. Comparison with SS 433

Our results may be compared with the observations of SS 433, because the input accretion rate $\dot{M}_0 (= 10^3 \dot{M}_{\rm c} \sim 2\times10^{-4} M_\odot)$ is in the reasonable range for SS 433 mass transfer rate[12]. The unique jet velocity $V_{\rm j}$ (=0.26 c) is reasonably explained in terms of the relativistic velocities accelerated by the radiation-pressure force in the inner disk. In the present work, the mass-outflow rates of the wind are almost comparable to those of the jets. Most outflow gas is confined within an opening angle of $\sim 30^\circ$. In the observations, the former are one or two orders of magnitude larger than the latter. This difference may be attributed to the definition of the mass outflows of the wind and jets used here and our computational domain is still limited to a small region compared with the optically observed region. We should pay attention to the remarkable modulations of $\dot{M}_{\rm edge}$ and $L_{\rm d}$ in model AD-2 with larger α. Only the large modulations of $\dot{M}_{\rm edge}$ in this case survive as small modulations of the total luminosity with a quasi-period of ~ 30 seconds. Recently, as rare and short events in SS 433, a variety of new phenomena was reported[13], including a QPO-like feature near 0.1 Hz, rapid time variability, and shot-like activities . They suggest that a massive jet ejection may be caused by the formation of small plasma bullets. We propose that the observed QPO-like phenomena in SS 433 may be explained in terms of the recurrent hot blobs found in model AD-2. The opening angles for the X-ray jets and the optical jets in SS 433 are found to be very small as $\sim 1^\circ$[10]. These X-ray and optical jets are observed in the region of $10^{10} - 10^{13}$ cm and $10^{14} - 10^{15}$ cm, respectively, from the central source. The computational domain treated here locates at the base of the X-ray jets. Our results show that the opening angle of the jets is rather large as $\sim 30^\circ$. However, we notice that the observed expansion velocity of the jets in the transverse direction coincides with the sound velocity $c_{\rm s}$ at a temperature of $\sim 10^8$ K [10] and that the opening angle $\theta_{\rm o}$ should be equal to $\sim 2c_{\rm s}/V_{\rm j}$[10, 12] in the far distant region observed by X-ray. From our hydrodynamical results, $c_{\rm s} \sim 2.5 \times 10^{-3} c$ with $T \sim 10^8$ K in the high-velocity jet region and $\theta_{\rm o} \sim 1^\circ$ which is compatible with the observations.

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References

[1] N. I. Shakura, R. A. Sunyaev, *MNRAS*, **24**, 337 (1973).

[2] G. E. Eggum, F. V. Coroniti, J. I. Katz, *ApJ*, **298**, L41 (1985).

[3] G. E. Eggum, F. V. Coroniti, J. I. Katz, *ApJ*, **330**, 142 (1988).

[4] T. Okuda, *PASJ*, **54**, 253 (2002)

[5] T. Okuda, V. Teresi, E. Toscano, D. Molteni, *MNRAS*, **357**, 295 (2005)

[6] G. V. Lipunova, *Astron. Lett.*, **25**, 508 (1999)

[7] J. Poutanen, G. Lipunova, S. Fabrika, A. G. Butkevich, P. Abolmasov, *MNRAS*, **377**, 1187 (2007)

[8] M. A. Dopita, A. M. Cherepashchuk, *Vistas Astron.*, **25**, 51 (1981)

[9] E. P. J. van den Hueuvel, *Vistas Astron.*, **25**, 95 (1981)

[10] H. L. Marshall, C. R. Canizares, N. S. Schulz, *ApJ*, **564**, 941 (2002)

[11] A. M. Cherepashchuk, R. A. Sunyaev, E. V. Seifina, I. E. Panchenko, S. V. Molkov, K. A. Postnov, *Astron. Astropys.*, **411**, L441 (2003)

[12] S. Fabrika, *Astrophysics and Space Physics Reviews*, **12**, 1 (2004)

[13] T. Kotani, S. A. Trushkin, R. Valiullin, K. Kinugasa, S. Safi-Harb, N. Kawai, M. Namiki, *ApJ*, **637**, 486 (2006).