Kinematics of SS 433 radio jets: interaction of jets with ambient medium

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Abstract

The problem of the interaction between the precessing mildly relativistic radio jets of SS 433 and an ambient medium has been often invoked in interpretations of the jets behaviour. The dynamical interaction could be responsible for disagreements between the kinematic model and observations of the jets. To estimate the relative ram pressure of the jet and impinging matter we used the profile along the radio jets of brightness of synchrotron radiation. From this we estimated magnitude of possible deceleration and twisting of the jets, and compare model locus of the jets with observations. The magnitude is enough big to be observed, that addresses an applicability of the kinematic model, based mostly on the optical observations, to the radio jets and a problem of the kinematic distance to the object in particular.

Deviation from kinematic model

Jets of the X-ray binary star SS 433, the prototype of microquasars, are best studied. The kinematic model (e.g., Hjellming & Johnston 1981) was developed mainly on the base of data on the optical jets (extended to distances of $\sim 10^{15}$ cm), and assumes the independent of each other blobs in the SS 433 precessing jets move at a constant velocity (rectilineally and uniformly). This model is a basement for any physical model of the jets. However, observations evidence about deviation of the radio jets from the kinematic model by more than 10 percents (e.g., Schillemat et al. 2004; Roberts et al. 2008), in particular about regular shift in the precession phase (Stirling et al. 2004) — evidently that the optical and radio jets are some decoupled in kinematics. Moreover, the published kinematic modelings of morphology of the radio jets at distances from source of 10^{16}–10^{17} cm (e.g., Hjellming & Johnston 1981) might be accommodated to a jet velocity and a distance to the object essentially varied simultaneously around those of the canonical kinematic model $v_{\rm j} = 0.26\,c$ and $D = 5.5$ kpc, respectively, where c is the speed of light.

Model of dynamics of radio jets

Powerful wind from supercritical accretion disk in SS 433 outflows at a rate of $\sim 10^{-4}$ $M_\odot$/yr with the velocity $v_{\rm w} \sim 1500$ km/s. In the model of Begelman, King & Pringle (2006) this wind is able even to transmit the precession and nutation rotations of the disk to the jets near by the source. Therefore the jets may decelerate while a movement through this wind.

The polarization observations of Roberts et al. (2008) reveal that the jets magnetic field is aligned with the spiral of the precessing jets, and not with the jet velocity vector (also see Stirling et al. 2004), and the apparent at 15 GHz leading edge of the jets is the most bright and sharp. This suggests a significant interaction of the jets with a surrounding medium, influencing on morphology of the jets. In particular, this interaction might affect jets dynamics.

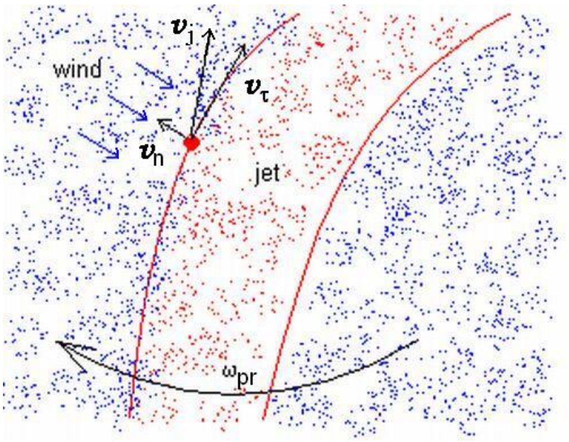

Figure 1: The sketch of precessing jet. The relative ram pressure of the jet and wind is determined by the component of jet velocity normal to jet-ambient medium interface.

The sketch of precessing jet ploughing through ambient medium is shown in Fig. 1. Our model of the dynamical interaction of precessing jets with ambient medium supposes the followings: the surrounding matter at rest as $v_{\rm w} \ll v_{\rm j}$; the jet as a rather continuous flow, whose local velocity vector is somehow inclined to the jet precession spiral; in the jet co-moving reference frame the surrounding gas impinges the jet front surface, not penetrating into, with the resulting ram pressure $p_{\rm dyn} = \rho_{\rm a} v_{\rm n}^2$, where $\rho_{\rm a}$ is the density of the surrounding gas, $v_{\rm n} = v_{\rm j}(1 + 1/(\omega_{\rm pr} t \sin\theta_{\rm pr})^2)^{-1/2}$ is the component of the jet velocity normal to the surface, $\omega_{\rm pr}$ and $\theta_{\rm pr}$ are the precession frequency and the opening half-angle of the precession cone, respectively, t is the jet flight time.

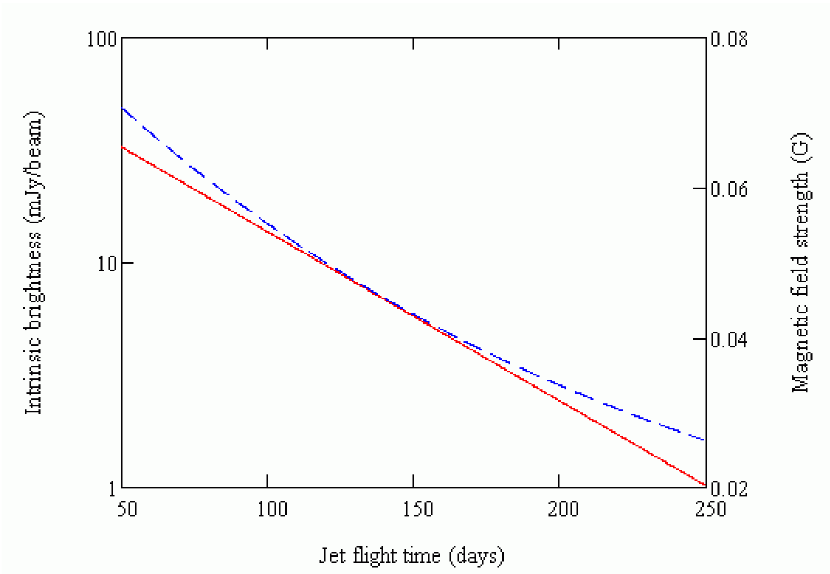

Figure 2: Intrinsic brightness (solid line) at 4.86 GHz and the equipartited magnetic field (dashed line) of the jets of SS 433 in dependency on the jet flight time, for parameters of the model given in the text.

As the jets propagate through the slow wind the shock waves develop at the jets surface, providing energetics of synchrotron radiation of the jets. The minimum pressure in the jets — the lower limit of the jets internal pressure p — can be evaluated from brightness of the radiation in an approximation of energy equipartition between relativistic particles and magnetic field, as $p_{\rm min} = H^2/4\pi = A(\beta_{\rm e} L_{\rm r}/fV)^{4/7}$, where the dependency on the index α and frequency range of the synchrotron spectrum is involved in the coefficient A, L_r is the radio luminosity in this range of an optically thin jet region of the volume V, f is the filling factor of the region, β_e is the ratio of the total particle energy density to the electron energy density, H is the strength of the equipartited magnetic field (Pacholczyk 1970). The profiles of intrinsic brightness (in a jet co-moving reference frame) of the jets in SS 433 at 4.86 GHz and derived from it magnitude of the equipartited magnetic field in the jets are shown in Fig. 2 as functions of the jet flight time. The brightness is adopted from the fit of Roberts et al. (2010) over 60 – 150 days of jet age, as $B = 32.7 \exp(-(t-50)/57.7)$ mJy/beam, where the jet age t is in units of days. The dependency $B(t)$ is extrapolated beyond the definition region. This simplification is justified by the posteriority that most of jet deceleration takes place in this region (see below). The magnetic field is derived for $\alpha = 0.7$ (for $B \propto \nu^{-\alpha}$), $\beta_e = 100$ and $f = 10^{-3}$.

Above mentioned data suggests the front side of the jets undergoes an essential ram pressure of the impinging gas, therefore the internal jet pressure should approximately equal the dynamical pressure at the jet surface: $p_{dyn} \approx p \geq p_{min}$. So, the model allows to evaluate the dynamical pressure on the jets, which the surrounding matter renders, from minimum energy of the relativistic particles and the magnetic field in the jets. To find space disposal of the jets, i.e. the overall jets kinematics, the kinematics of each enough small segment of the jets was calculated, taking into account an action of the dynamical pressure on jets movement. In this procedure the segments were supposed independent of each other. Initial conditions of the kinematic task were determined by the canonical kinematic model of the jets with the parameters collected in Panferov (2010).

Manifestation of dynamical interaction from modeling

1. Estimation of the ram pressure on the jets, from brightness of the jets synchrotron radiation, shows that density of the wind falls as t^{-2} in the region of most of jet deceleration $t \leq 260$ days (see below) and is approximately two order less than could be expected in the case of the isotropical wind from supercritical accretion disk in SS 433 with an outflow rate of 10^{-4} $M_\odot$/yr.

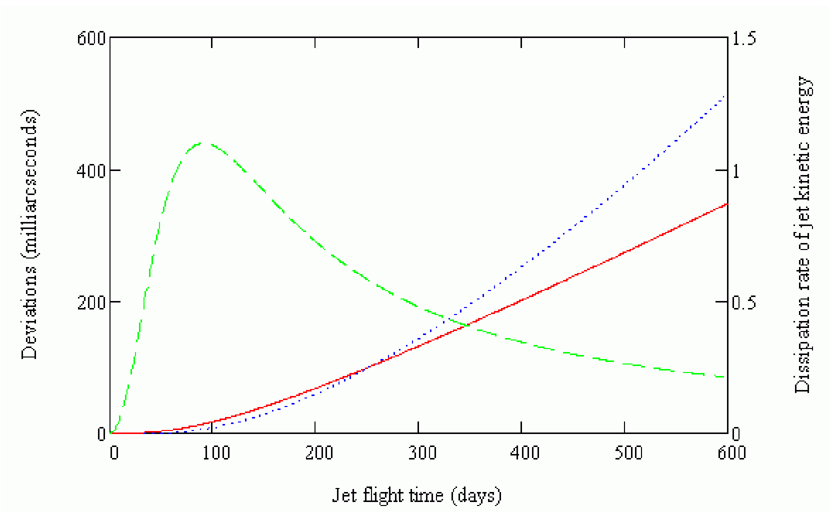

Figure 3: Transverse (solid line) and longitudinal (dotted line) deviations of the kinematics of a jet of SS 433 from free ballistic movement, represented by the canonical kinematic model, as functions of the jet flight time, laid out along the left axis. And dissipation rate of the kinetic energy of a jet (dashed line), laid out along the right axis, in units of a thousands of initial kinetic energy flux of the jet per a day. The plots are calculated for the wind ram pressure corresponding to the magnetic field in Fig. 2.

2. Deviations from the kinematics of a free ballistic movement prescribed by the canonical kinematic model, across and along the jets, are calculated with described above dynamical model. They are shown in Fig. 3 as functions of the flight time, for the ram pressure corresponding to the magnetic field in Fig. 2.

These deviations can also be viewed in Fig. 4 as a difference between the tracks of the canonical kinematic model and the dynamical model. The tracks are overlaid on the image of the jets, taken from Blundell & Bowler (2004).

The dynamical model for a filling factor of a synchrotron radiation region of $\sim 10^{-3}$ is in compliance with the observed deviations magnitude, $\sim 10\%$: the deviations developed in the precessing jets flowing through the medium can be as much as several 100 mas at the jet length of $\sim 4''$. It seems from Fig. 4 the brightness ridge of the jets lies somewhere between models for $f = 10^{-3}$ and 10^{-2}.

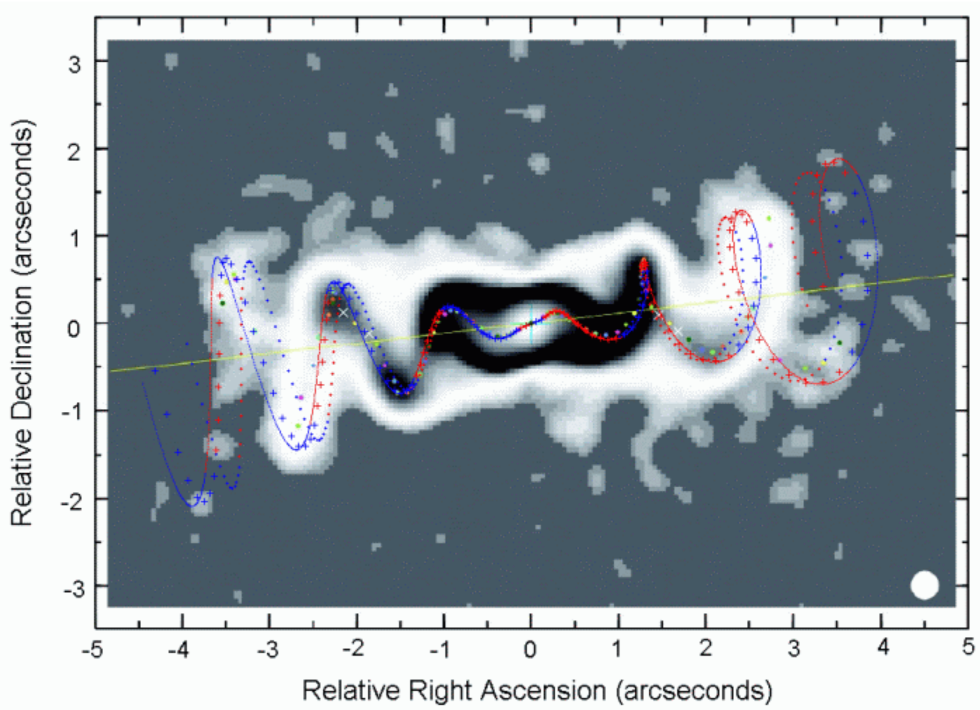

Figure 4: Model tracks of the precessing jets of SS 433 superposed on the VLA image from Blundell & Bowler (2004). The jet brightness ridge is marked by colored points. The solid spiral is the canonical kinematic model, without accounting for the jet-wind dynamical interaction, the dotted spiral, with dots at 5 day intervals, the model with the accounting, assuming the filling factor of a synchrotron radiation region $f = 10^{-3}$, and the crossed spiral, with crosses at 10 day intervals, the model with $f = 10^{-2}$. The blue and red colors of the spirals indicate approaching and receding regions in the jets, respectively. The length of a jet track is 560 flight days.

3. There is also shown in Fig. 3 the distribution along the jets of dissipation rate of the kinetic energy of the jets of SS 433. Most of the dissipation, and of the jets deceleration, takes place in the region 30–260 flight days, and the integrated dissipation rate achieves 10% of the jets kinetic luminosity in the first 130 days.

It should be noted, the energy lost by jets does not go into the jets radiation: the radio luminosity is approximately 10^{-4} times the kinetic luminosity, of the same order is X-ray luminosity of the jets extended to the bounds of W 50 (Brinkmann et al. 2006). However, this contradiction does not restrict the dynamical model because the dissipated energy could be redirected into mechanical energy of the surrounding medium. Indeed, observations evidence that most of the power of the jets is not radiated and is somehow transfered into mechanical energy of W 50 and the surrounding interstellar matter (e.g. Dubner et al. 1998).

Conclusions

None models in Fig. 4 fit acceptably good the jets ridge. Nevertheless, as we have shown the deceleration and azimuthal bending (around the precession axis) of the jets of SS 433 are enough big and should be accounted in interpretation of the observations, which evidence as we know about an essential deviation of the radio jets from the kinematic model. In particular this might affect the kinematic distance to SS 433. In its estimation one usually assumes that velocity of the radio jets equals the value derived for the optical jets, i.e. for the jets region close to the source, that could be rather crude approximation (however, see another approach of Blundell & Bowler 2004). By different estimations the distance to SS 433 is in the range 3–5.5 kpc. Its improving by the kinematic method is an important task. The studying of the jets deceleration needs observations of jets regions as far from the source as possible, where the dynamical jets-wind interaction develops most strongly in jets morphology. Besides, it would be more appropriate to fit the kinematic model track to the overall jet morphology, and not to the bright ridge, because the latter could lie not along the axis of the precessing jets (Aloy et al. 2003; Roberts et al. 2008).

References

Aloy M.-A., Marti J.-M., Gomez J.-L., Agudo I., Müller E., Ibañez J.-M., 2003, ApJ, 585, L109

Begelman M. C., King A. R., Pringle J. E., 2006, MNRAS, 370, 399

Blundell K. M., Bowler M. G., 2004, ApJ, 616, L159

Brinkmann W., Pratt G. W., Rohr S., Kawai N., Burwitz V., 2007, A&A, 463, 611

Dubner G. M., Holdaway M., Goss W. M., Mirabel I. F., 1998, ApJ, 116, 1842

Hjellming R. M., Johnston K. J., 1981, ApJ, 246, L141

Pacholczyk A. G., 1970, Radio Astrophysics, Freeman, San Francisco

Panferov A. A., 2010, preprint (arXiv:1001.5097)

Roberts D. H., Wardle J. F. C., Lipnick S. L., Selesnick P. L., Slutsky S., 2008, ApJ, 676, 584

Roberts D. H., Wardle J. F. C., Bell M. R., Mallory M. R., Marchenko V. V., Sanderbeck P. U., 2010, ApJ, 719, 1918

Schillemat K., Mioduszewski A., Dhawan V., Rupen M., 2004, BAAS, 36, 1515

Stirling A. M., Spencer R. E., Cawthorne T. V., Paragi Z., 2004, MNRAS, 354, 1239