SS433: on the uniqueness of cool relativistic jets

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Abstract. The relativistic jets of SS433 are outstanding for their optical thermal radiation. The radiation is produced by small clouds (10^8 cm) whose lifetime is about 10^{3} times larger than the gas-dynamical crushing time. We show that the clouds reside in thermal and dynamical balance as long as they collisionally interact with the wind of the supercritical accretion disk. The interaction is caused by the precessional movement of the jets and takes place only in the sweep-out zone. Beyond the sweep-out zone the interaction ceases and optical jets just terminate. The cloud magnetic field amplified in course of movement through a medium could play a role in containing a cloud. Thus, the clue to the uniqueness of the optical jets of SS433 is thought to be their precessional movement which provides an opportunity for collisional interaction of the clouds with the wind.

Key words: Stars: individual: SS 433 – ISM: jets and outflows

1. Introduction

Since the discovery of jets in SS433 in 1978, there has been discussion about their uniqueness. By now the zoo of various jets has enlarged. There have already been detected hundreds relativistic jets of AGNs, low velocity jets of young stars and a dozen jets of compact stars. Jets of SS433 stand out among the others for they harbour cool clouds within the relativistic flow. It is not clear, however, how the clouds could survive in the relativistic jets and be observed. It is also worth mentioning, that the thermal fraction is likely to be dominant in the jets of SS433. On the contrary, the lack of observational evidence of thermal gas in AGN jets strongly restricts its volume-filling factor (< 10^{-8}) and implies that it cannot be important in the energy budget of these jets (Celotti et al. 1998). These peculiarities make the jets of SS433 unique.

Jets of SS433 are highly collimated, \( \theta_j \leq 1^\circ.4 \), mildly relativistic, \( v_j = 7.8 \cdot 10^8 \text{ cm s}^{-1} \), and powerful, with kinetic luminosity \( L_k \approx 10^{39} \text{ erg s}^{-1} \). They appear from funnels of the supercritical accretion disk and follow its precession rotation with a half opening angle of about 20° and a period of \( P_{pr} = 162^{+5}_{-5} \) (see Fig. 1). At the distance of a few 10^{12} cm the jets rapidly cool and radiate in the X-ray domain. The X-ray emission does not show any structure of the jets. Therefore, the X-ray jets are thought to be continuous (Stewart et al. 1987). By contrast, the optical jets are observed as fragmented (Vermeulen et al. 1993). Their clumpiness may be roughly deduced from energetic considerations. The gas must be dense enough to radiate the bulk of the emission:

\[ L_\text{H}_\alpha = \epsilon_\text{H}_\alpha n_e^2 f V, \]  
and mass loading of the jet by dense gas must approximately satisfy:

\[ L_k = M_j v_j^2, \]

where \( V \approx \theta_j^2 R_j^3/4 \) is the volume of the jet, \( R_j \) is its length, \( n_e \) is electron density, \( \epsilon_\text{H}_\alpha \) is the H\( \alpha \) emission rate. Thus, one finds that \( n_e \approx 5 \cdot 10^{11} \text{ cm}^{-3} \) and a volume-filling factor of \( f \approx 10^{-5} \) for appropriate parameters: luminosity in H\( \alpha \) line \( L_{H_\alpha} = 10^{36} \text{ erg s}^{-1} \), total jet kinetic luminosity \( L_k = 10^{39} \text{ erg s}^{-1} \), \( \epsilon_\text{H}_\alpha = 10^{-24} \text{ erg cm}^3\text{s}^{-1} \), \( R \approx R_e \approx 8.4 \cdot 10^{14} \text{ cm} \) — length of e-folding H\( \alpha \) line brightness. It seems that the jets become lumpy in the gap between the X-ray part and the optical jet beginning at about \( R_{in} \approx 2.3 \cdot 10^{14} \text{ cm} \) (Borisov & Fabrika 1987). The gas could condense there due to a thermal instability as Brinkmann et al. (Brinkmann et al. 1988) have shown in a simulation of the thermal evolution of the X-ray jets. The instability takes place only in the interior jet, until a distance of 10^{13} cm. The parameters of the clouds found in their work are close to those obtained by Panferov & Fabrika (Panferov & Fabrika 1997) from the Balmer decrements of the jets: hydrogen density \( n \geq 10^{13} \text{ cm}^{-3} \) and size of the clouds \( l \leq 10^8 \text{ cm} \). It should be noted that these parameters as well as the filling factor \( f \approx 4 \cdot 10^{-6} \) found there are more appropriate for the distance of maximum optical brightness of the jets \( R_m \approx 4 \cdot 10^{14} \text{ cm} \). These parameters will be representative ones in what follows. The clouds are grouped in clusters with sizes of about 10^{12} cm (Panferov & Fabrika 1997). Still bigger structures are
quite possible in the jets as may be deduced from the structure of the jet emission line.

Brown et al. [Brown et al. 1993] consider cloudy structure of the jets as a result of a temporal switch on and off of conditions for thermal instability. They found that the parameters of SS 433 are just suitable for the instability to occur. However, the instability can work with a wide range of the parameters and in SS 433 jets the conditions for cloud generation exist rather continuously in time. Indeed, the data on optical emission of the jet (e.g., Vermeulen et al. 1993) demonstrate that the generation of the clouds in the jets is continuous and the disappearance of the optical jets happens very rarely. The intermittent structure of the jets is natural if the radiating clouds form in such in situ variable process as the thermal instability. The optical jets terminate at a distance reflecting an evolution of “bullet” along the jets (Borisov & Fabrika 1987). Thus, the clouds form in the interior jets and further exist a long time giving a signature of the optical jets.

The actual problem is how do the clouds evolve and survive in the relativistic jets? As long as the clouds are involved in a motion through a medium, that is, the dense wind of the accretion disk, the applied ram pressure are involved in a motion through a medium, that is, the wind on the equilibrium is most essential (see Sect.3). Density in the wind scales as \( \rho \propto r^{-2} \), where \( r \) is the radial distance from the source of the jets. Under plausible conditions of approximate constancy of temperature and mass of a cloud this implies the following dynamical dependences of cloud parameters:

\[
\begin{align*}
  n &= 1.6 \times 10^{14} r^{-2}_{14} \text{ cm}^{-3}, \\
  l &= 4 \times 10^{7} r^{-2/3}_{14} \text{ cm}, \\
  f &= 1.6 \times 10^{-5} r^{-1}_{14},
\end{align*}
\]

where \( r_{14} = r/(10^{14} \text{ cm}) \) and we have used the values of the cloud parameters at \( R_m \) given in Sect.1. In what follows, we assume these to be valid everywhere along the optical jets.

Let us compare the rates of cloud heating by the impinging gas and by radiation. The jets sweep out the gas of the wind due to the change of the jet direction in the course of the precession and nodding motions and a small amplitude jitters of unclear nature (Margon & Anderson 1989). The energy deposition into a cloud by crossing protons with energy \( \epsilon_p = m_p c^2/2 \) depends on the collisional thickness, measured by the ratio \( \sigma_c = N/N_s \), where \( N = n t = 6.4 \times 10^{21} r_{14}^{-4/3} \text{ cm}^{-2} \) is the column density of the cloud, and \( N_s \) is the column density required to stop a proton. The rate of energy loss of a high energy proton in an ionized gas is approximately (Ginzburg & Syrovatskii 1964):

\[
\begin{align*}
  \Gamma_p &= \frac{2.2 \times 10^{-8} K_c n}{v_j} \left( 1 + 1.21 \frac{m_p k T}{m_e \epsilon_p} \right)^{-3/2} \text{ erg s}^{-1},
\end{align*}
\]

for temperature \( k T \ll m_e c^2, k T \ll \epsilon_p \). The factor \( K_c = 30 \Lambda/n_a \sim 1 \), where \( \Lambda \) is the Coulomb logarithm. In an ionized plasma almost all of the lost energy goes into heating the electron gas. The stopping column density of a proton with energy \( \epsilon_p = 32 \text{ MeV} \) is:

\[
N_s = n v_j \frac{\epsilon_p}{\Gamma_p} \approx 1.4 \times 10^{23} \text{ cm}^{-3}.
\]

When \( N < N_s \), which is satisfied for the entire jet (see Eq.(3)), the cloud heating rate by the fast protons is:

\[
H_e \approx \sigma_c \epsilon_p n_w v_j l^2 = \epsilon_p n_w v_j n l^3/N_s.
\]

This is lowest estimate. The magnetic field may be amplified to an equipartition value at the surface of a cloud moving through a medium with a weak magnetic field

2. Thermal balance of clouds

There are two main ways to heat the clouds: by interaction of jets with the gaseous wind of the supercritical accretion disk and by radiation of the system (Davidson & McCray 1980). Here we consider competition of these two mechanisms. As long as the cloud sound-crossing time is shorter than the dynamical time-scale \( t_d = r/v_j \) of the jet, the clouds are in pressure equilibrium with surroundings. The influence of ram pressure of the wind on the equilibrium is most essential (see Sect.3). Density in the wind scales as \( \rho \propto r^{-2} \), where \( r \) is the radial distance from the source of the jets. Under plausible conditions of approximate constancy of temperature and mass of a cloud this implies the following dynamical dependences of cloud parameters:

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For assumed in Eq. (1) magnetic field the gyro-radius of a 32 MeV proton is $3 \times 10^8 r_{14}$ cm. This is smaller than the clouds radius, therefore the trajectories of protons may be tangled and the heat input boosted.

The clouds could also be heated by the collimated radiation from funnels of the accretion disk (Arav & Begelman 1993; Panferov & Fabrika 1993) and by the disk UV radiation. The heating is realized by $\delta$-electrons — high energy electrons broken away from an atom due to ionization. Already for ionization degree $\geq 0.5$, almost all the energy of $\delta$-electrons is utilized in the heating of the electron gas of a cloud. We take into account radiation only with frequency beyond the Lyman edge. We adopt here $\nu \approx \nu_{le}$ for the UV radiation, however situation is complicated by the screening effect of clouds in the heating of screened clouds.

Then the radius of a source of the collimated radiation, in keV (Arav & Begelman 1993; Panferov & Fabrika 1993) and the cloud UV radiation. The heating is realized by $\delta$-electrons — high energy electrons broken away from an atom due to ionization. Already for ionization degree $\geq 0.5$, almost all the energy of $\delta$-electrons is utilized in the heating of the electron gas of a cloud. We take into account radiation only with frequency beyond the Lyman edge. We adopt here $\nu \approx \nu_{le}$ for the UV radiation, however situation is complicated by the screening effect of clouds in the heating of screened clouds.

Then the heating rate of one cloud is:

$$H_c = l^2 \int_{\nu_1} \nu j_\nu (1 - e^{-\tau_\nu}),$$

(8)

where $\nu_1$ is frequency of Lyman edge. We adopt here $\sigma_\nu \approx 1.73 \times 10^{-22} \epsilon^{-8/3}$ cm$^2$, for photon with energy $\epsilon = 1$ keV $\sim 4$ keV in the range 13.6 eV $\sim 12.4$ keV, for cosmic abundances (Craddock et al. 1974).

Parameters of the collimated radiation are not well known since its orientation to the Earth is unfavourable. Here we adopt rather rough estimates for its luminosity $L_X \sim 10^{39}$ ergs/s$^{-1}$ and temperature $T_X \sim 1$ keV (Arav & Begelman 1993; Panferov & Fabrika 1993). Then the radius of a source of the collimated radiation, in blackbody approach, is $R_X \sim 2 \times 10^3$ cm. The supercritical accretion disk is a source of near isotropic UV radiation, its parameters in blackbody approach are: $T_{UV} \approx 72000$ K, $R_d \approx 1.5 \times 10^{12}$ cm (Dolan et al. 1997). For given parameters and $\tau < 1$ Eq. (8) gives $H_X^{UV}/H_X^{\delta} \approx 3 \cdot 10^5$, i.e. heating by UV radiation of the disk could dominate heating by the X-ray collimated radiation. This ratio might be bigger because the clouds have rather $\tau > 1$ for the UV radiation, however situation is complicated by the screening of the clouds in a jet.

The cross-over path length of some particle moving in the direction of the jet velocity across the jet is determined by the curvature of the jet. The motion of the jet caused by nodding is more rapid than that caused by precession and its rate is $\dot{\phi} \approx 5.7 \cdot 10^{-7}$ rad s$^{-1}$ (Borisov & Fabrika 1987). Using this rate we obtain the cross-over length for a jet with fixed pattern $l_t = v_t \phi / \dot{\phi} = 3.4 \cdot 10^{18}$ cm, with accuracy of factor 2. Column density along this path is:

$$N_t = \int r^{+l_t} dr f n \approx \frac{1.3 \cdot 10^{23}}{r_{14}^2}.$$ \hspace{1cm} (9)

Consequently, we have $N_t < N_e$ everywhere in the optical jets and the jets are transparent for the rapid protons. So, the screening effect is not important for the collisional heating. Meanwhile the screening factor of clouds in the jet $N_t/N_e$ may be essential for the UV radiation. We now determine $N_t = 1/\sigma_\nu (1 - \zeta)$ as the column density of a cloud layer where $\tau = 1$ for the UV radiation. Then the screening factor for the UV radiation is $N_t/N_1 \sim 10^6 (1 - \zeta)$ and essentially depends on the ionization degree. Therefore we will consider heating $H^{UV}_t$ of the cloud by UV radiation as an upper limit of radiative heating (6). Really, this heating is bigger than mean heating rate of one cloud, on average over the whole jet, in $N_t/N_1$ times; the opacity of the jet to UV radiation causes a dominance of the collimated radiation in the heating of screened clouds.

The ratio of the heating rate from fast protons (Eq. (7)) to the radiation heating rate (Eq. (8)) is:

$$\frac{H_c}{H^{UV}_t} = \frac{\epsilon n v \nu l n_w r^2}{\pi n_s R_d^2 \int_{\nu_1} \nu B^{UV}_\nu} \approx 10^{-4/3},$$

(10)

where we have used the reduced form of Eq. (8) for $\tau > 1$, substituting 1 instead of $1 - e^{-\tau_\nu}$, and used density of wind of the accretion disk:

$$n_w = \frac{\dot{M}_w}{4 \pi m_p v^2 w} \approx 1.5 \cdot 10^8 r_{14}^{-2} \text{ cm}^{-3}.$$ \hspace{1cm} (11)

The mass loss rate and wind velocity are taken to be $\dot{M}_w = 10^{-4} M_\odot/\nu$ (van den Heuvel 1981) and $v_w = 2000$ km/s (from the width of the emission lines) respectively. Thus the heating of the jet by fast protons is comparable at least with the radiation heating. Their rates become equal at a distance $5.6 \cdot 10^{14}$ cm, until which the main bulk of the heat input into the jet takes place and equals to 64% of the whole input given by Eq. (1). The collisional heating may be rather much bigger than radiative one, because the value of $H^{UV}_t$ is overestimated approximately in $10^6 (1 - \zeta)$ times due to the screening effect.

This idea concerning the collisional heating of the jet clouds is observationally supported: $H_\delta$ emission of the jets is anisotropic, the maximum of its directional pattern is directed to side of jet movement (Panferov et al. 1997). This implies that some screening effect exists for the impinging protons. It is possible if a magnetic field tangles trajectories of the protons in a cloud and the stopping column density $N_e$ becomes smaller than that given by Eq. (3). However, the directional pattern can not be explained straightforwardly as a result of a head-on collision of the clouds with the wind, because the maximum is inclined to the jet axis. The inclination of the head maximum is towards the direction of the precessional motion and is about 40° to the jet axis. This rather shows that a maximum outcome of the emission line radiation is from jet sides moving in the wind.
As a result of collision with the wind a cloud decelerates at a rate:

$$\frac{\Delta v}{v} \approx \frac{\Delta M}{M} = \int dt \frac{\sigma_v n_{w} v_{j}}{n l} = \int_{R_m}^{R_j} dr \frac{R_w}{N_s} \approx 2 \cdot 10^{-2}. \quad (12)$$

Here we used $R_m$ as the lower limit of the integration because evolution of the jet at distances $< R_m$ is not well established. The deceleration $(12)$ agrees well enough with the observed value of the deceleration $\lesssim 10^{-2}$ (Kopylov et al. 1987). Jets sweep out wind gas with a pattern speed of $\phi r$. Then the rate of the heating of the whole of optical jet provided by fast protons is:

$$H = \int_{R_m}^{R_i} dr \frac{N_f}{N_s} \epsilon_{p} n_{w} (\phi r)(\theta_j r) \approx 2.2 \cdot 10^{37} \text{erg s}^{-1}. \quad (13)$$

This integral is calculated numerically and dependence of $N_f$ on a geometry of the precessing conical jet is taken into account. The calculated value of the whole heat $H$ agrees with the observable radiation output of the jets in H$\alpha$ line $L_{H\alpha} \approx 10^{36} \text{erg s}^{-1}$ (Panferov et al. 1997): a part $< 0.1$ of absorbed energy is emitted in H$\alpha$.

The small clouds in question would be overheated and their H$\alpha$ radiation would have ceased unless the clouds are dense enough to establish a balance between radiative losses and the heating by the fast protons. In the temperature region near $10^{4}$ K, which is the threshold ionization temperature of hydrogen, the efficiency of the radiative cooling $\lambda(T)$ strongly depends on temperature and changes by 3 orders of magnitude: $\lambda = 10^{-25} - 10^{-22} \text{erg cm}^3 \text{s}^{-1}$ (Kaplan & Pikelner 1979). From this and Eq.(4) one finds limits of possible values of the radiative energy loss of the clouds, corresponding to the end and the beginning of the jet:

$$3 \cdot 10^{-3} \text{erg cm}^{-3} \text{s}^{-1} \leq \lambda n^2 \leq 9 \cdot 10^{-4} \text{erg cm}^{-3} \text{s}^{-1}. \quad (14)$$

Since limits on the heating rate $H_c$ from Eq.(5) correspond to:

$$9 \cdot 10^{-2} \text{erg cm}^{-3} \text{s}^{-1} \leq H_c/l^3 \leq 3 \cdot 10^3 \text{erg cm}^{-3} \text{s}^{-1}, \quad (15)$$

for the jet end and beginning respectively, the heating rate can never exceed the cooling capability, given by inequality $(14)$, and the thermal balance of the clouds can be maintained near a temperature of $10^4$ K throughout the whole of the optical jets.

### 3. Evolution and confinement of clouds

The lifetime of the clouds in the jets, about 4 days, is much longer than the sound-crossing time. Therefore, the clouds must be in pressure equilibrium with the ambient medium and should not be exposed to destructive processes. The pressure of the ionizing radiation $p_i = H_{i}^{\text{UV}}/l^2 c \approx 9 r_{14}^{-2}$ dyn is much smaller than the gas pressure in a cloud $p = 2n k T \approx 10^3 r_{14}^{-2}$ dyn, where we use a temperature of $T = 20000 \text{K}$ (Panferov & Fabrika 1997).

Therefore, radiation is not important for dynamical balance of a cloud. The pressure equilibrium of clouds with surroundings imposes constraints on density $n_h = n f \sim 10^7 \text{cm}^{-3}$ and on temperature $T_h = T n_f/n_h \sim 10^{10}$ K of the surrounding gas at a distance $R_m$. In this hot medium the clouds will evaporate with a timescale of:

$$t_{ev} = \frac{m}{\dot{m}} = \frac{\rho l}{6 \rho_h c_h F(\sigma_0)} \ll 10^4 \text{ s}, \quad (16)$$

where $m$ is the mass of the cloud, $c_h$ is sound velocity in the hot medium, $F(\sigma_0)$ is some function (given by equation (62) in Cowie & McKee 1977), which is $\gg 1$ for our case. The evaporation of the clouds with so short timescale contradicts to the lifetime of the clouds. Therefore the clouds evaporation must be suppressed. On the other hand, the ram pressure of the wind is important in pressure balance of the clouds: $p_{\text{ram}} = p = \rho w v_j^2/2 n k T \approx 17$. Ram pressure of the wind gas seems to be strongest and must govern the clouds pressure. But again, gas-dynamical instabilities are capable of disrupting the clouds on a timescale given by Eq.(3). This is the puzzle of SS 433 jets: how can thermal gas survive there?

The optical jets end at a distance of about $3 \cdot 10^{15}$ cm. Further, at a distance $3.7 \cdot 10^{15}$ cm, the jets
brighten in radio which is a consequence of jet expansion (Vermeulen et al. 1987). It seems that the expansion is connected with the termination of the optical jet. As long as the jets precess and move through the dense wind of the accretion disk they sweep out the wind gas to the surface of the precession cone. After the passage of the jets the wind fills the jet channels and during the precessional period a region of length \( R_{s \text{w}} = P_{\text{tr}} v_{\text{sw}} \approx 3 \cdot 10^{15} \) cm can be refilled. Consequently, at distances larger than the sweep-out distance the lobe along the precession cone surface is empty (see Fig. 1). Thermal diffusion of wind gas is not capable of filling the lobe: \( c_v P_{\text{tr}} \ll \theta_j r \) at \( r > R_{s \text{w}} \). The dependences of the cloud parameters on a distance and the clouds heating balance have not peculiarities in point \( r = R_{s \text{w}} \). But external to the clouds conditions abruptly change there. Possibly, this forces the confinement of the clouds to switch off and results in the expansion of the jet.

From laws in Eqs. (1) we derive the approximate size of the cloud \( l \approx 4 \cdot 10^8 \) cm and the filling factor \( f \approx 5 \cdot 10^{-7} \) at the end of the optical jets. With these parameters the clouds start to expand freely and fill the whole volume of the jets in time:

\[
t_{\text{ex}} \sim \frac{l}{c_a f^{1/3}} \approx 0^{4.5}, 
\]

where \( c_a \) is sound velocity in the cloud. The estimated time of expansion corresponds well to the time interval required for the jet to move between the end of the optical part and the radio brightening zone. The last could develop due to the increase of the rate of generation of relativistic particles, when the clouds expand and turbulence is enhanced.

The coincidence of lengths of the optical jets and the sweep-out zone indicates that ram pressure of the wind gas causes confinement of the clouds. The ram pressure switch off is equivalent to a “hard wall” which crushes the clouds. However, the ram pressure by itself is not able to prevent clouds from stripping off the gas and thermal evaporation. On the contrary, it seems from Eq. (3) that the higher the ram pressure the shorter the lifetime of a cloud. In reality, ionized clouds and their surroundings harbour magnetic fields, which should be important for stability of the clouds. The magnetic field inferred from radio observations is \( B \approx 0.08 \) G at the distance of radio brightening (Vermeulen et al. 1987). Magnetic flux constancy implies that \( B \) scales as \( r^{-1} \) and we assume magnetic field in the jet is:

\[
B = 3 r_{14}^{-1} \text{ G.} 
\]

This field could not confine the clouds having internal pressure \( \sim 10^3 r_{14}^{-2} \) dyn. Jones et al. (Jones et al. 1996) showed in their numerical simulations that a “magnetic shield” forms around a cloud moving through a medium. The field lines of the medium are caught by a cloud, stretched and the magnetic field is amplified. The “shield” has magnetic pressure comparable to the ram pressure and is able to quench gas-dynamical instabilities and prevent evaporation of a cloud. Energy of the “magnetic shield” is converted from the kinetic energy of the cloud. So, the magnetic field needed for the confinement of the clouds in the jets of SS 433 can be generated by the motion of the clouds through the wind of the accretion disk. This mechanism of the confinement naturally explains the termination of the optical jet beyond the “crushing wall” at a distance \( R_{s \text{w}} \), where collisional interaction of the clouds with the wind ceases.

4. Conclusions

We have considered consequences of collisional interaction of clouds in the jets of SS 433 with the wind of the accretion disk. This interaction appears to be a determining factor of the clouds state and evolution. This is emphasized by the fact that the clouds exist only in boundaries of the sweep-out zone over which the jet sweeps out the wind. We propose that in the sweep-out zone the clouds are prevented from destruction essentially by a magnetic field which is amplified due to a collisional interaction with the wind. The rapid expansion of the clouds after their exit from the sweep-out zone naturally explains the disappearance of the jet hydrogen line emission and the brightening of the jets at radio wavelengths.

The collisional interaction of the jets of SS 433 with its surroundings is possible for two reasons: the powerful wind from the supercritical accretion disk and the precession with cone opening being much larger than the jet opening angle. These factors are necessary for the existence of the cold clouds radiating the hydrogen lines. Their combination may be the clue to the uniqueness of the optical relativistic jets of SS 433.

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