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ANALYSIS OF BALMER LINES EMISSION AND RADIATION NON-ISOTROPY OF SS 433 JETS

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ABSTRACT. *The relative intensities of Balmer emission lines formed in the relativistic jets of SS 433 were selected from data of long-term observations. The Balmer decrements are notably different for red and blue jets. We have found that there are very dense and small clouds in the SS433 jets. The front side of the gas cloud is probably brighter in Hα line than the back side. The cloud itself radiates nonisotropically in two antiparallel directions, and its axis does not coincide with that of the jet. Such an asymmetry of the jet cloud radiation could be caused both by the non-spherical shape of the cloud and by shocks in the clouds, which can raise the escape probability for line radiation in the direction of a shock.*

I. INTRODUCTION

The peculiar object SS 433 is of great interest because it displays such properties as supercritical accretion onto the relativistic star and outflow of jets from the accretion disk. The system SS 433 loses about 10^{-4} $M_\odot$ y^{-1} as a strong wind from the accretion disk and about 10^{-8} - 10^{-6} $M_\odot$ y^{-1} in the two antiparallel jets (van den Heuvel,1981). The velocity of the jets is v_j = 0.26*c*, their opening angle is $\theta_j \approx 1^\circ$. The jets consist of gas clouds (Davidson & McCray, 1980; Fabrika & Borisov, 1987), whose temperature is enough for emission in hydrogen and HeI lines. It follows from optical observations that the length of the jet at the Hα emission maximum is about $R_m \approx 4\cdot10^{14}$ cm, but one can trace the jet gas emission to a distance of $3\cdot10^{15}$ cm (Borisov & Fabrika, 1987). The jet base is located at the accretion disk funnels. It is known from X-ray observation (Brinkmann et al., 1991) that at a distance $\approx 10^{12}$ cm the jet already has the same velocity, $0.26c$. The jets show the precession and nodding (nutation) motions (Margon, 1984) with the periods $P_{pr} = 162.5$ days and $P_n = 6.28$ days, respectively. In the course of precession the jet emission lines move along the spectrum. The kinematic model of these motions is well known, the full opening angle of the precession cone is 40° and the angle between the precession axis and the line of sight is 79°. Since the minimum angle between the jets and the line of sight is 59°, let us define the precession phase when it happens to be $\psi=0$.

The structure of the optical jets of SS 433 and physical parameters of their gas clouds (such as gas density and temperature) are not well known. We are trying to determine these factors here. We have found the Balmer line intensities of the moving lines and compared them with the published emission line spectrum calculations. In the last section we analyse nonisotropy of radiation of the gas clouds.

2. BALMER LINE INTENSITIES. PARAMETERS OF CLOUDS

We have used SS 433 spectra, obtained with the 6-meter telescope at SAO RAS, for the last 10 years (Kopylov et al., 1989). The equivalent widths of the moving hydrogen lines Hα, Hβ and Hγ were collected. All the data were obtained over 70 nights of observations. We also used equivalent widths of the moving Hα lines (for 96 nights of observation) by Wagner et al. (1981), Vittone et al. (1983) and Margon et al. (1984). The absolute intensities have been found in a standard way, $J = W_\lambda \cdot F_\lambda$, where W_λ is the equivalent width of a line, F_λ is the continuum radiation flux at the line wavelength corrected for the interstellar absorption. The fluxes F_λ have been found by interpolation from UBVRI photometric data. For most of our data (where we have no simultaneous photometric data) we used the averaged precession and orbital light curves, which have been produced from the UBVRI data of 85 nights of observation by V. Rakhimov on the 1-m telescope at Sanglok Observatory. We assumed the normal interstellar absorption (Luud, 1978) for the SS 433 direction and accepted the value of absorption in the V band $A_V = 7^{m}_{.}8 \pm 0^{m}_{.}5$ (Cherepashchuk et al., 1982; Wagner, 1986). The mean error in equivalent widths falls within the range from 4% to 10% (depending on the value of W_λ), and r.m.s. of the flux approximation is 6% - 20%, so that the error of the absolute line intensities will be no greater than 30%. Uncertainty of the A_V value or the interstellar absorption approximation could result in a larger error in the blue region.

We consider the jets radiation in the co-moving reference frame, so all the line intensities were corrected for the relativistic boosting effect for an isotropic source. The transformation of the line radiation from an observer's reference frame to a comoving one is:

$$J = J_{\rm obs}\gamma\ (1 + z)^3, \qquad (1)$$

where $z = (\lambda_{\rm obs} - \lambda_0) / \lambda_0$, $\gamma = (1 - v_j^2/c^2)^{-1/2}$. This takes into account the relativistic aberration effects for a point-like source and the effect of the variable number of clouds in the jet, which are simultaneously visible to an observer: $N_{\rm obs} = N\ (1 + z)\ \gamma^{-1}$ (Panferov & Fabrika, 1993).

As a rule, the moving lines consist of a few components, one of them being stronger than others. This stronger component is new, or younger, and is formed at the distance $R_{\rm m}$ from the accretion disk. We selected only such stronger components of the moving line profiles to find the Balmer decrements (BDs), which therefore represent the SS 433 jets in their brightest part at the distance $R_{\rm m}$. There is not enough data on fainter moving line-traces to consider the BDs of the outer parts of the jets. In Table 1 we present the mean BDs over the precession for the blue (-) and red (+) jets, their 1 σ standard deviation, the number of the ratios which have been used, and the change in BDs at the variation of the accepted absorption by $\Delta A_V \pm 0^{\rm m}\!.5$. Deriving the mean $H\alpha^+/H\beta^+$ line intensity ratio we have excluded the precession phase range $0.83 < \psi < 0.17$, where $H\alpha^+$ line falls whithin the O_2 atmospheric absorption band (the A band), and its intensity could be strongly underestimated (see Fig. 1 below).

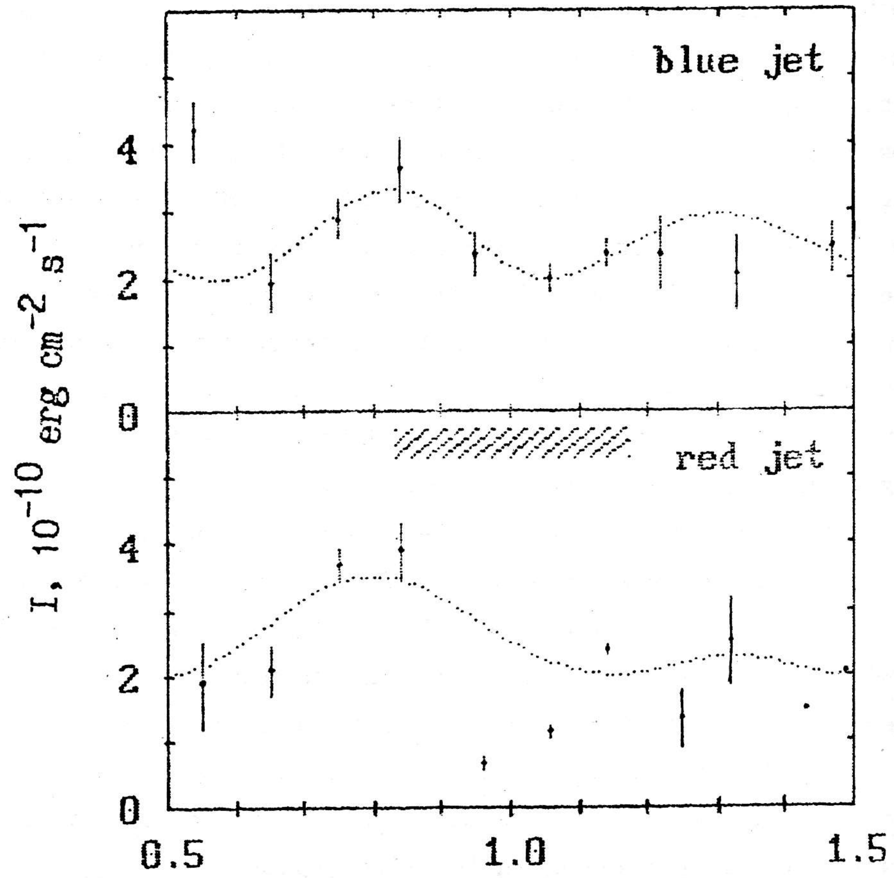

Fig. 1. The moving $H\alpha^{\pm}$ line intensities versus the precession phase.

The fact that the value of the $H\gamma^- / H\beta^-$ looks very large may be a result of overestimation of absorption in the U band, if some deviation from the normal absorption exists. Besides, only the most intensive $H\gamma^-$ lines were probably selected, as the star is too faint in the blue region and the SS 433 spectrum is very complicated and crowded at 3500 - 4000AA. We will not consider the ratio $H\gamma^-/H\beta^-$. Another feature of the BDs is that the $H\alpha/H\beta$ ratio of the red jet is greater than that of the blue one. This could be a result of the difference between the front and back sides of the jet clouds. We will discuss that below.

The line intensity ratios $H\alpha/H\beta \approx 1.5 - 2.0$ and $H\gamma/H\beta \approx 1$ could be produced only in gas with a high enough density, $n_e > 10^{12}$ cm^{-3}, where collisional processes are significant. In order to find the emitting gas parameters, we have chosen the emission-line spectrum calculations by Drake & Ulrich (1980) performed for a homogeneous slab with an optical thickness in $L\alpha$ line from 10^4 to 10^6, where the electron density ranges from 10^8 to 10^{15} cm^{-3}, and the Stark wings effect on an escape probability is included. The SS 433 jets emit the hydrogen and HeI lines whose equivalent widths ratio is about 10. This means the gas temperature $T_e = (1 - 2)\cdot 10^4$ K, probably nearer to $2\cdot 10^4$ K, which is within the temperature range of the calculations. The calculations (Drake and Ulrich, 1980) were realized for the case of low photoionization rate at the number of photoionizations $R_{1c} = 3\cdot 10^{-4} - 3$ s^{-1}. For the UV radiation from the SS 433 accretion disk one can expect $R_{1c} \approx 10^{-1} - 10$ s^{-1} at the accretion disk temperature $T_* \approx (3 - 5)\cdot 10^4$ K, its size $R_* \approx 1\cdot 10^{12}$ cm (Cherepashchuk et al., 1982; Wagner, 1986), the dilution factor $\approx 10^{-5}-10^{-7}$ allowing for the relativistic effects. In the case of collimated X-ray radiation from the disk (Fabrika & Borisov, 1987) this is $R_{1c} \approx 10^{-1}$ s^{-1}. The last case is preferable as it provides a uniform source function across a cloud. We find below that the back side of the jet clouds, which is exposed to the accretion disk radiation, is dimmer than the front side. This means the uniform source function is an important point, if the gas cloud is heated by the radiation. In any case the BDs from Table 1 require high gas electron densities, $n_e > 10^{12}$ cm^{-3}, where the collisional and selfabsorption processes predominate. So we can conclude that the ranges of the parameters in the Drake and Ulrich's calculations are quite appropriate for the gas of the SS 433 jets.

Table 1. The Balmer lines decrements at A_V=7.8

	$H\alpha^- / H\beta^-$	$H\gamma^- / H\beta^-$	$H\alpha^+ / H\beta^+$	$H\gamma^+ / H\beta^+$
Mean	1.2	1.3	1.6	0.9
σ	0.1	0.2	0.15	0.1
N	42	14	20	25
$\Delta(\Delta A = \pm 0^{m}.5)$	$\mp$ 0.2	$\pm$ 0.1	$\mp$ 0.3	$\pm$ 0.1

We used two main criteria to find the gas cloud parameters: the Balmer line ratios (Table 1) and the kinetic luminosity of the jets, which must not be too high. Probably the kinetic luminosity of ejected gas can not be greater than a few percent of a bolometric luminosity (Kundt, 1987). The bolometric luminosity of SS 433 falls within the range $10^{39} - 10^{40}$ erg s^{-1} (Murdin et al., 1980; Cherepashchuk et al., 1982; Wagner, 1986), so we will keep the kinetic luminosity $L_k \leqslant 10^{39}$ erg s^{-1}. We write $L_k =$

$V\cdot n\cdot m_p\cdot v_j^3/(2\cdot\alpha\cdot R_j)$, where V is the total volume of the jet clouds, n, the number density, R_j, the jet's length, α, a fraction of Hα-gas clouds in the total kinetic luminosity of the jet. The jet luminosity in the Hα line is $L_\beta = \varepsilon_\beta\cdot V$, where ε_β is the total emission measure in the Hβ line per unit volume. Combining these two luminosities we obtain an important relation:

$$\varepsilon_\beta / n = 2.8\cdot 10^{-13}\ (\alpha\ L_{k39})^{-1}, \tag{2}$$

where the $L_{k39} = L_k/10^{39}$ erg·s^{-1} and we accepted $L_\beta = 4.7\cdot 10^{35}$ erg·s^{-1} (following from our data at the distance to SS 433 accepted to be 5.1 kpc) and $R_j = 6.7\cdot 10^{14}$ cm (Borisov & Fabrika, 1987). Fitting the gas clouds parameters to satisfy both the observed BDs and not too large L_k we find from Drake and Ulrich's net of calculations the electron temperature T_e, optical depth of the Lα line $\tau_{L\alpha}$, electron density n_e, total density n, ε_β and optical depth of the Hα line $\tau_{H\alpha}$.

The requirement that the kinetic luminosity should be not too high limits the gas electron density $n_e > 10^{12.5}$ cm^{-3}.

3. NON-ISOTROPY OF THE CLOUDS RADIATION

The non-isotropy of the jet clouds radiation in Hα line was discussed by Asadullaev and Cherepashchuk (1987). It is possible to study this effect as the jet position changes in the course of precession. We suppose the red and blue jets are the same for a long period and use the line intensities in a co-moving frame (1). Figure 1 shows the $H\alpha^\pm$ line intensities versus the precession phase. The intensity unit is 10^{-10} erg cm^{-2} s^{-1}. The data were binned into the precession phase intervals $\Delta\phi = 0.1$ and $\pm\ 1\sigma$ bars are shown (or individual measurements in the case the number of points per bin being less than 4). It can be seen that there is an increase in the moving line intensities near the precession phase 0.8, where the Hα line intensity from both jets is $\approx 3.5\cdot 10^{-10}$ erg cm^{-2} s^{-1}, and that the intensities of the jet radiation are very similar in the region of crossovers, 0.34 and 0.66, with their average of $\approx 2\cdot 10^{-10}$ erg cm^{-2} s^{-1}. In the precession phase interval 0.83 - 1.17 the $H\alpha^+$ line of the red jet falls whithin a strong O_2 atmospheric absorption band. This phase interval is shaded on the diagram. The Hβ moving line intensities show the same behaviour with the precession, but these data are more scarce.

One can suspect from Fig. 1 the anisotropic Hα radiation of the jets: each jet radiates mainly in two, almost antiparallel directions, which do not coincide with the jet axis. The jet axis approaches the line of sight at the precession phase $\phi=0$, and the intensity maximum of both jets at the phase $\phi \approx 0.8$ means that the direction of the maximum radiation is inclined to the jet axis at some angle towards the precession motion. We favour the interpretation of this as an intrinsic asymmetry of the jet cloud radiation, which could be due both to the non-spherical shape of the clouds and to shocks in the cloud gas, which increases an escape probability for a line radiation in the direction of the shock. To develop this interpretation, we have carried out a modelling of the jet cloud radiation (the lines in Fig. 1). It was supposed that the cloud radiation intensity in each hemisphere is $I(\theta) = C + A \cos^k(\theta)$, where C is a constant part of the intensity, A is different for the back and front of the cloud, k is a power parameter, which forms the radiation intensity distribution over θ (the polar angle in the cloud comoving frame whose origin is in the direction of the peak line radiation). We have taken into account the angle relativistic aberration effect. The best curves representing the observational data are shown in Fig. 1. The cloud parameters at the best fit are $C = 2$ (for the whole jet the intensity unit corresponds to 10^{-10} erg cm^{-2} s^{-1}), $A_f = 3.2$ for the front hemisphere and $A_b = 1.8$ for the back one, $k = 2$, and the angle between the direction of the line radiation maximum and the jet axis falls whithin the range of $20^\circ - 40^\circ$. This axis of peak intensity radiation is about tangential to the precession cone surface (a possible deviation from the surface is $\pm 30^\circ$) and it is deflected from the jet axis towards the precession motion. The front of the cloud is brighter than its back by the value $(A_f + C) / (A_b + C) \approx 1.4$ in the cloud co-moving frame. It is interesting that the cloud line radiation is peaked in two antiparallel directions, which do not coincide with the jet direction. The different widths of the maxima in the figure, the secondary maximum of the Hα^- intensity are a result of the relativistic aberration effect. This abberation effect is also responsible for the fact that the intensity maxima of both jets at the phase $\phi \approx 0.8$ have the same amplitudes, though the intrinsic intensities of both hemispheres are different.

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