Chin. J. Astron. Astrophys. Vol. 8 (2008), No. 2, 219–229
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Correlated Radio-Optical Variations on Intraday Timescales

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Received 2007 May 31; accepted 2007 July 17

Abstract Correlated radio-optical variations on intraday timescales have been observed (e.g. in BLO 0716+714) and such radio intraday variability is suggested to have an intrinsic origin. Recently, multi-wavelength observations, simultaneous at radio, mm-submm, optical and hard X-rays, of 0716+714, show that during a period of intraday/interday variations at radio and mm wavelengths, the apparent brightness temperature of the source exceeded the Compton-limit ($\sim 10^{12}$ K) by 2–4 orders of magnitude, but no Compton catastrophe (or no high luminosity of inverse-Compton radiation) was detected. It is also found that the intraday/interday variations at mm-submm wavelengths are consistent with the evolutionary behavior of a standard synchrotron source and for the intraday/interday variations at centimeter wavelengths opacity effects can play a significant role, which is consistent with the interpretation suggested previously by Qian et al. Thus the apparent high brightness temperatures may probably be explained in terms of Doppler boosting effects due to bulk relativistic motion of the source. We will argue a scenario to simulate the correlations between the radio and optical variations on intraday timescales observed in BLO 0716+714 in terms of a relativistic shock propagating through a jet with a dual structure.

Key words: optical and radio continuum: galaxies — galaxies: intraday variability — quasars: individual: BLO 0716+71

1 INTRODUCTION

IDVs (Intra-Day Variations) of flux and polarization in compact extragalactic sources have been intensively studied in recent years. As is well known, the apparent brightness temperatures directly derived from their timescales are very high ($\sim 10^{16} - 10^{21}$ K), which exceed the Compton limit ($\sim 10^{11} - 10^{12}$ K, Kellermann & Pauliny-Toth 1969; Readhead 1994) by 4–9 orders of magnitude. When the bulk relativistic motion of the compact sources is taken into account, most of these IDVs at centimeter wavelengths can be interpreted in terms of refractive scintillation by the continuous interstellar medium (Heeschen 1987; Witzel 1986; Qian 1994a,b, 2001a; Rickett et al. 1995, 2002; Kedziora-Chudczer et al. 1997; Jauncey et al. 2000; Dennet-Thorpe & de Bruyn 2002) and focusing-defocusing effects by individual interstellar clouds (Fiedler et al. 1987; Wamsganess et al. 1989; Qian & Zhang 2004). The annual modulation of IDV timescales observed in a few sources provides a strong support (Dennet-Thorpe & de Bruyn 2000; Qian & Zhang 2001b; Rickett et al. 2001; Jauncey et al. 2001; Bignell et al. 2004) for this interpretation.

However, there is still evidence that some IDVs observed at centimeter wavelengths with apparent brightness temperatures of $\sim 10^{16} - 10^{18}$ K could be due to some intrinsic mechanism. The radio IDV event detected by Quirrenbach et al. (1991) and Wagner et al. (1996) in BLO 0716+71 is an outstanding example, because it is closely correlated with the optical intraday variations (Qian et al. 1995; Wagner et al. 1996; Wagner & Witzel 1995; Spada et al. 1999). However, the reality of the reported optical-radio correlations is still under debate (e.g. Kellermann 2002).

Recently, some new results have been obtained for 0716+714, which seem to be useful for understanding the optical-radio correlations.

During the period of November 10–17, 2003 (JD 2452954–2452961) multi-wavelength observations of 0716+714 were carried out simultaneously with high time-resolution at radio, mm-submm, optical and hard X-rays (INTEGRAL) (for details see Ostorero et al. 2006; Fuhrmann et al. 2006; Agudo et al. 2006). The aim of the campaign was to test the Compton catastrophe scenario during intraday/interday variations at radio and mm wavelengths. We summarize here the main results relevant to the topic of this paper: correlated radio-optical intraday variations.

The radio (6 and 2.8 cm) and mm (9 and 3 mm) lightcurves can be divided into two parts in which the source have different behaviors. During MJD 2954.0–2957.5 the intraday ($\lesssim$1 day) variations at 6 cm have a peak-to-peak amplitude $\sim$3% and the amplitude at 2.8 cm is much less. The timescale changes at $\sim$MJD 2957.5 and during MJD 2957.5–2962.0 the light-curves at 6, 2.8, 0.9 and 0.3 cm are dominated by a monotonic increase of the flux density on timescales $\gtrsim$4 days. The amplitude increases with frequency (in contrast to the previous sub-period), reaching $\sim$35% at λ 3 mm. This feature implies that its interpretation in terms of refractive scintillation is impossible, because the modulation index of weak scintillation decreases with increasing frequency. Moreover, these variations are found to be correlated across the bands with increasing time-lag toward lower frequencies.

More physically, the radio-mm (sub-mm) spectra obtained during the 7 day simultaneous observations at nine wavelengths (21, 18, 6, 2.8, 0.9, 0.35, 0.13, 0.087 and 0.045 cm) show that they have a consistent form of inverted synchrotron spectrum with its turnover frequency near $\nu_m\sim$ 90 GHz. The spectral peak flux density increases continuously during the first 4 days (MJD 2955–2958) with a (possible) slight decrease of the turnover frequency. During the later 3 days (MJD 2959–2961) the spectral peak flux density remains nearly constant. Combined with the results described above, the cm-mm interday variations are considered to have an intrinsic origin. The change of timescale at λ 6 cm (from $\lesssim$1 day to $\gtrsim$4 days) at MJD 2957.5 is most likely caused by opacity effects related to the low-level mm-submm flaring state of the source. Since the flux densities at cm wavelengths (6 and 2.8 cm) are much higher than the extrapolation of the mm-flux with a spectral index α=–2.5 for the optical thick branch of a homogeneous synchrotron source ($S_\nu \propto \nu^{-\alpha}$), we would assume that besides the mm-submm (and optical) emitting component, there is an additional emitting component which is responsible for the cm emission. Thus the intraday/interday variations at λ 6 and 2.8 cm could be due to the shift of the turnover frequency of the cm-component (caused by its evolution due to opacity effects). This inference is consistent with the interpretation for the correlated radio-optical IDV event of 0716+714 observed in 1990 February by Quirrenbach et al. (Qian et al. 1995; Quirrenbach et al. 1991). We will further explore this scenario below.

The redshift of 0716+714 is not known. Kadler et al. (2004) showed evidence of line emission at $\sim$5.8 keV in its XMM/Newton X-ray spectrum which could imply z=0.1 if interpreted as iron K_α emission emitted from the material in the rest frame. Sbarufatti et al. (2005) suggested $z \gtrsim$0.52 through the estimation of an upper limit to the brightness of the host galaxy measured by Hubble Space Telescope. Wagner et al. (1996) set a lower limit z=0.3 from the non-detection of its optical host galaxy. Due to the uncertainty of the redshift for 0716+714, we assume z=0.3 as in Quirrenbach et al. (1991) and Wagner et al. (1996)[1]. Thus the luminosity distance D_l=1.51 Gpc, and 100 μas = 0.44 pc. In this case, the lower limits to the apparent brightness temperatures derived from the observed flux density and timescales (on the assumption of light-travel-time effect for the source size) are $\sim10^{14}$ K in the mm-band and $\sim10^{15}-10^{16}$ K in the cm-band. Both exceed the inverse-Compton limit ($\sim10^{12}$ K). Since the simultaneous X-ray observations with INTEGRAL (at 3–200 keV) do not detect strong inverse-Compton emission during the interday cm-mm variations, implying non-existence of Compton catastrophe and no intrinsic high brightness temperatures (i.e. the intrinsic brightness temperatures $\lesssim10^{12}$ K). Thus the derived extremely high brightness temperatures imply the existence of relativistic beaming effects. The Doppler factor derived from relativistic boosting is δ_c>5–22, while that derived from the upper limits to the inverse-Compton flux density observed by INTEGRAL is $\delta_{\rm IC}\sim$15. These values are in good agreement with those derived from the VLBI observations ($\delta_{\rm VLBI}$=20–30, which implies a very small viewing angle of the jet ($<2^\circ$), Bach et al. 2005). During the VSOP observations of 0716+714, Bach et al. (2006) found that in less than one day the 5 GHz flux density varied by $\sim$5% and by $\sim$40% in the linear polarization. Assuming a core component size <0.1 mas,

[1] In this paper we adopt a standard ΛCDM cosmology model: Ω_Λ=0.7, Ω_m=0.3 and H_0=71 km s^{-1} Mpc^{-1} (Hogg 1999; Spergel et al. 2003).

Bach et al. (2006) derived an apparent brightness temperature $T_{\rm b}{\sim}3{\times}10^{15}$–$10^{16}$ K and a Doppler factor $\delta{>}20$ is required to bring it down to the inverse-Compton limit. We emphasize that if a greater redshift is assumed, it would lead to a larger apparent brightness temperature and would require a larger Doppler factor. However, it would not affect the results of this paper, because we will study only the evolution of the observed or apparent (not intrinsic) spectrum.

2 CORRELATED RADIO-OPTICAL IDV AND SCINTILLATION

In the following we will take the correlated radio-optical IDV event observed by Quirrenbach et al. (1991) and Wagner et al. (1996) in 0716+714, as an example, to explore plausible scenarios for its explanation.

2.1 Characteristics of the IDV Event

The IDV event was observed in Feb. 1990 (J.D.=2447925–7929). It can be described by following three features:

1. The overall campaign was conducted in a period of 4-weeks (2447924–2447950) at two radio frequencies (5 and 8.4 GHz) and three optical frequencies (4400, 5500 and 6500 Å) with high sampling rates. Quasi-periodicity of 1-day was noticed in the period MJD 7925–7929 with the variability amplitude larger at 5 GHz than at 8.4 GHz. The timescale of the radio and optical variations changed simultaneously from 1-day to 7-days on MJD 7930. Analyses with structure function and cross-correlation (details see Quirrenbach et al. 1991 and Wagner et al. 1996) have confirmed these features.
2. During the IDV period MJD7925–7930 the optical flux is tightly associated with the radio spectral index α(5–8.4 GHz), the optical flux increasing with the radio spectrum flattening ($S_{\nu}{\propto}\nu^{-\alpha}$, α varied in the range 0.10–0.35), and this correlation held for four intraday circles. Moreover, the optical peaks are associated with the troughs of the 5GHz light curve and vice versa. The optical peak at MJD7927.5 is particularly apparent (Qian et al. 1995; Wagner et al. 1996; Wagner & Witzel 1995). We should also point out that during the period (MJD7930–7935) the timescale has already changed into 7 days, but the 5 GHz peak was still associated with an optical minimum. This seems to indicate that the physical nature of the correlation between the optical and radio intraday/interday variations did not change with the change of timescale.
3. The apparent brightness temperature for the 5 GHz intraday variations is estimated to be a few$\times10^{17}$ K. In usual scenarios of relativistic beaming, $\delta{\sim}100$ is required to bring it down to the Compton limit of 10^{12} K. Spada et al. (1999) have proposed a specific model to explain the high brightness temperatures of ${\sim}10^{17}$ K (z=0.3) with a Doppler factor of ${\sim}15$. Also in the scenario suggested by Qian et al. (1995) Doppler factors of 10–20 are required to interpret these high brightness temperatures.

Since the high brightness temperature problem for compact extragalactic radio sources (including 0716+714) has been tackled (e.g., Slysh 1992; Merlose 1999, 1994; Spada et al. 1999; Qian et al. 1991, 1995, 2006; Marscher et al. 1992; Marscher 1996), in this paper we will only discuss the first two characteristics of the correlated radio-optical intraday variations.

As argued by several authors (Quirrenbach et al. 1991; Qian et al. 1995; Wagner & Witzel 1995; Wagner et al. 1996; Spada et al. 1999), the correlation between the radio and optical variations favors an intrinsic origin of the radio IDV event (although scintillation could give rise to slight interference imposed on the intrinsic variations), because scintillation cannot produce the associated simultaneous optical variations. Moreover, the observations were so densely sampled that the light-curves at the five frequencies (two radio and three optical) were sufficiently determined to show all the peaks and troughs, and the correlation can be recognized for four cycles. It seems not possible to interpret this correlated radio-optical IDV event in terms of a chance coincidence between intrinsic optical variations and radio scintillation.

2.2 Change of Timescale and Scintillation

We further point out that besides the correlated optical and radio IDVs, the simultaneous change of the timescales in radio and optical is also a significant feature favoring an intrinsic origin. For example, for explaining the simultaneity in time in the scintillation scenario, it would be supposed that the change of the timescale from 1-day to 7-days is due to an increase of the source angular size ($\theta_{\rm s}$) by a factor of

$\sim$7, which would cause correspondingly both the increase of the timescale of scintillation at 5 GHz [2] and the timescale of the intrinsic optical variations. However, this is impossible. First, this would require a relativistic expansion of the source with a superluminal speed of $\gtrsim 50c$ (for example, expansion from $\sim$50 μas to $\sim$300 μas in 7 days or $\sim$6 mas yr^{-1}, $z = 0.3$), which has never been observed by VLBI. Secondly, the scintillation theory predicts that in the case of weak scattering the modulation index $m_{\rm I} \propto {\theta_{\rm s}}^{-7/6} \nu^{-2} {S_{\rm M}}^{\frac{1}{2}} L^{-\frac{1}{6}}$ (ν–frequency, $S_{\rm M}$–scattering measure; Goodman 1997). Thus $m_{\rm I}$ should decrease by a factor of $\sim$9 with the increasing angular size. But the observation showed that the variability amplitude did not change so much when the timescale changed (cf. Quirrenbach et al. 1991).

It seems unlikely to attribute the change of the timescale to the parameters of the interstellar medium (e.g. velocity of the scattering screen, its scattering strength, scattering pattern size or screen distance to the observer), since a multitude of chance-coincidences would result in a very small probability for occurrence, if the correlation between the radio and optical variations is also taken into account.

Therefore, we come to conclusion that, since is difficult to explain the correlation between the optical and radio IDV events in terms of scintillation, it is probably due to some intrinsic causes in the source (although some interferences caused by scintillation can not be ruled out).

3 SYNCHROTRON EMISSION OF A HOMOGENEOUS SOURCE

As shown in the Introduction, the recent multi-wavelength campaign carried out on 0716+714 by Fuhrmann et al. (2006) have indicated that intrinsic low-amplitude 5 GHz variations (RMS $\sim$2%, timescale of $\sim$4 days) with apparent brightness temperatures of $\sim 10^{16}$ K could be associated with mm-variations and due to opacity effects. This finding potentially implies the reality (or possible existence) of intrinsic intraday variations at cm wavelengths. Moreover, it is also in good agreement with the scenario suggested previously by Qian et al. (1995) for explaining the correlated radio-optical IDV event observed in 0716+714 in February 1990. In that scenario the 5 GHz intraday variations were caused by a back-and-forth shift of the turnover frequency near 5 GHz. In the following we further discuss this scenario and a simulation of the correlation between the radio and optical light curves.

First, in order to explain the radio-optical correlation, we assume that the jet has a dual structure with the optical-mm emission produced in a region near the jet axis and the radio emission produced in the outer (sheath) region. Such dual structures are observed in the jet of the well known radio galaxy M87 (e.g. Biretta 1996) and have been suggested by some authors (e.g. Benitez et al. 1999). Thus when a electron-sheet (or a shock) propagates along the jet outward, optical and radio flaring will occur simultaneously. We assume that both the optical-mm and radio emitting regions can be described approximately by a homogeneous synchrotron source.

3.1 Standard Formula

Following Pacholczyk (1970) the synchrotron spectrum of a homogeneous source with a power-law distribution of relativistic electrons and disordered magnetic field can be described by a self-absorption synchrotron spectrum:

$$S_\nu = S_m \frac{J(\frac{\nu}{\nu_1}, s)}{J(\frac{\nu_m}{\nu_1}, s)}, \tag{1}$$

where s is the power law index of the energy distribution of the electrons (spectral index α=(s-1)/2, $S_\nu \propto \nu^{-\alpha}$), and

$$J(x, s) = x^{\frac{5}{2}} [1 - \exp(-x^{-\frac{s+4}{2}})] \,, \tag{2}$$

where ν_1 is the frequency at which the optical depth (τ_ν) is equal to 1, τ_m is the optical depth at the spectral turnover frequency (ν_m). We have

$$\nu_1 = \nu_m {\tau_m}^{\frac{2}{s+4}} \,, \tag{3}$$

and τ_m satisfies the equation

$$e^{\tau_m} = 1 + \frac{s+4}{2} \tau_m . \tag{4}$$

[2] According to scintillation theory (Goodman 1997) in the case of weak scattering, the timescale of refractive scintillation is $t \propto \theta_{\rm s} L {v_\perp}^{-1}$, here L–distance of the scattering screen, $\theta_{\rm s}$–angular size, and $v_\perp$–transverse velocity of the screen.

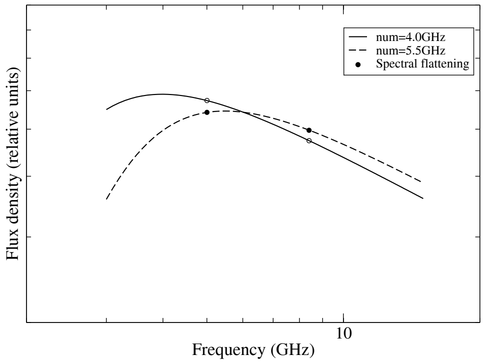

Fig. 1 An example to show the anti-correlation between the 5 GHz flux density and the spectral index α (5–8.4 GHz): The 5 GHz flux increases with spectral steepening and vice versa. $S_m \propto {\nu_m}^{-0.25}$ and ν_m shifts between 4.0 GHz and 5.5 GHz. A quasi-oscillating variation in the turnover frequency ν_m can produce a quasi-oscillating variation in the radio flux and the spectral index.

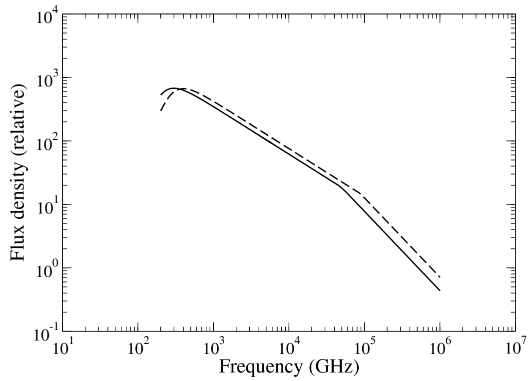

Fig. 2 Spectral evolution of the optical emitting component: $S_m \propto {\nu_m}^{-0.05}$. The turnover frequency ν_m varies between 300 GHz and 400 GHz, the break frequency $\nu_{\rm b}$ varies between 5×10^4 GHz and 1.58×10^5 GHz, producing the variations of optical flux density. A quasi-oscillating shift of the turnover frequency and the break frequency can produce a quasi-oscillating variation of the optical flux density.

In the case of a broken power-law with break frequency $\nu_{\rm b}$ and a spectral break of $\Delta\alpha$=0.5 (e.g. due to the synchrotron loss for high energy electrons) we have the flux at a frequency above $\nu_{\rm b}$,

$$S_\nu = S_{\rm b}(\nu/\nu_{\rm b})^{-(\alpha+0.5)}, \tag{5}$$

where

$$S_{\rm b} = S_m J(\frac{\nu_{\rm b}}{\nu_1}, s)/J(\frac{\nu_m}{\nu_1}, s). \tag{6}$$

These are applicable to the optical emission below.

3.2 Spectral Evolution

As in the shock-in-jet model proposed by Marscher & Gear (1985), the spectral evolution of the emitting source is described by the following relationship of S_m–ν_m,

$$S_m \propto {\nu_m}^{\beta}. \tag{7}$$

For the synchrotron stage (synchrotron loss dominant) and the adiabatic stage (adiabatic loss dominant), the power-law index β has different values[3].

In Figure 1 are shown two radio spectra with turnover frequencies 4.0 and 5.5 GHz (with $\beta = -0.25$), which can explain the anti-correlation between the 5 GHz flux and the spectral index α (5–8.4 GHz) (i.e. 5 GHz flux increases with the steepening of the spectral index).

Figure 2 shows that the shift of the turnover frequency ν_m from 300 GHz to 400 GHz (with $\beta = -0.05$) can lead to the variations in the optical flux density (optical flux increases with increasing turnover frequency).

Combining the features demonstrated in Figures 1 and 2 and assuming a simultaneous variations of the turnover frequency of the radio and optical component (i.e. simultaneous evolution of the radio and optical component), both of which are produced by a shock propagating through a jet with a dual structure, we will be able to explain the features of the correlated radio-optical IDV observed in 0716+714 (in 1990 February, Quirrenbach et al. 1991).

[3] Here we do not discuss the Compton stage at which Compton loss dominates.

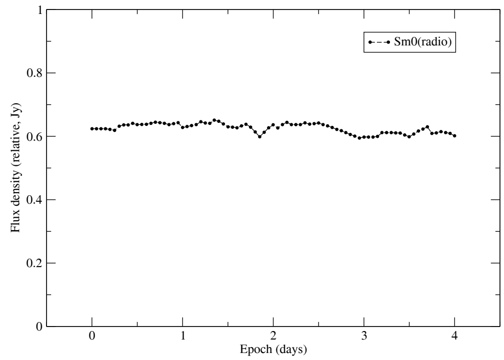

Fig. 3 Coefficient $S_{m0,r}(t)$ for the model-fitting of the turnover flux density $S_{m,r}(t)$.

Table 1 Parameters for Model-fitting the Radio IDVs

epoch t	a	b	$\theta_r(t)$
0.0–0.4	5.34	0.46	$\pi(t-0.15)$/0.5
0.4–1.2			$\pi(t-1.4)$/2.0
1.25–1.45	4.86	1.07	$\pi(t-0.9)$/1.10
1.45–2.0			$\pi(t-2.1)$/1.30
2.05–2.60	4.23	1.63	$\pi(t-1.6)$/2.0
2.60–3.15			$\pi(t-3.2)$/1.2
3.2–3.6	4.15	1.28	$\pi(t-3.0)$/1.2
3.6–4.0			$\pi(t-4.2)$/1.2

4 MODEL-FITTING OF RADIO IDV

In order to model-fit the radio IDV (the light curve of the 5GHz flux density and the variation of the spectral index α_r (5–8.4 GHz)), we will assume that the spectral evolution follows $S_{m,r}{\propto}\nu_{m,r}{}^{-0.25}$ ($\beta_r = -0.25$) and s_r=2 (the observational data are taken from Wagner et al. 1996).

For brevity we introduce a parameter t = epoch-2447925.00, thus for the period of the IDV, t is in the range (0.0,4.0). The turnover flux $S_{m,r}(t)$ and the turnover frequency $\nu_{m,r}(t)$ are

$$\nu_{m,r}(t) = a + b\sin^2\theta_r(t), \tag{8}$$

$$S_{m,r}(t) = S_{m0,r}(t)\Big(\frac{\nu_{m,r}(t)}{4.0}\Big)^{-0.25}, \tag{9}$$

$S_{m0,r}(t)$ is shown in Figure 3. The coefficients (a, b) and the parameter $\theta_r(t)$ are given in Table 1.

The radio flux density at frequency ν_r can be calculated,

$$S_{\nu,r} = S_{m,r}(\nu_r/\nu_{m,r})^{2.5}\frac{1-\exp\left[-(\nu_{1,r}/\nu_r)^{2.5+\alpha_r}\right]}{1-\exp\left[-(\nu_{1,r}/\nu_{m,r})^{2.5+\alpha_r}\right]} \tag{10}$$

(cf. Sect. 3 above), and the two-point spectral index is

$$\alpha_r(5-8.4\,\mathrm{GHz}) = \frac{\log(S_5/S_{8.4})}{\log(8.4/5)}\,. \tag{11}$$

In Figure 4 is shown the tracks of $\nu_{m,r}(t)$ and $S_{m,r}(t)$, respectively. In Figure 5 is shown the evolutionary track for the third radio peak ($t = 2.05 - 3.15$). The results of model-fitting to the observed 5GHz flux density and the spectral index α_r (5–8.4 GHz) are shown in Figure 6. It can be seen clearly from the two figures that the correlation between the 5 GHz flux density and the spectral index α_r (5–8.4 GHz) (the 5 GHz flux density increases with the spectral steepening) is well explained. That is, the radio IDV can be interpreted in terms of quasi-oscillating spectral evolution of a synchrotron source with $S_{m,r} \propto \nu_{m,r}{}^{-0.25}$.

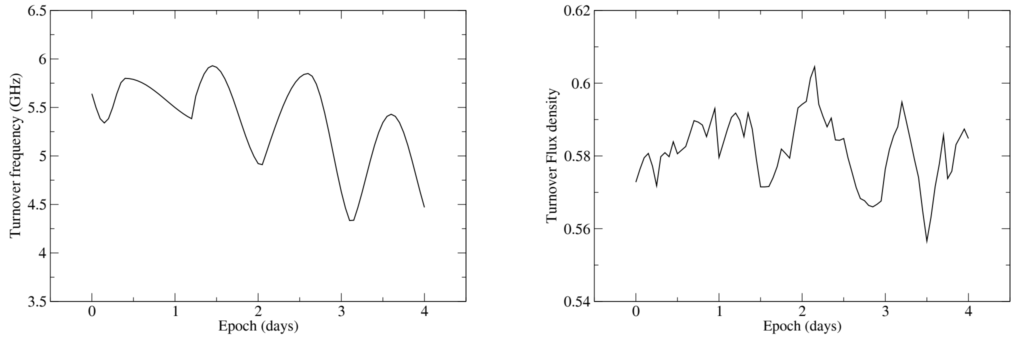

Fig. 4 Radio IDV. Left: Model for the evolution of the turnover frequency $\nu_{m,r}(t)$. Right: Model for the evolution of turnover flux density $S_{m,r}(t)$.

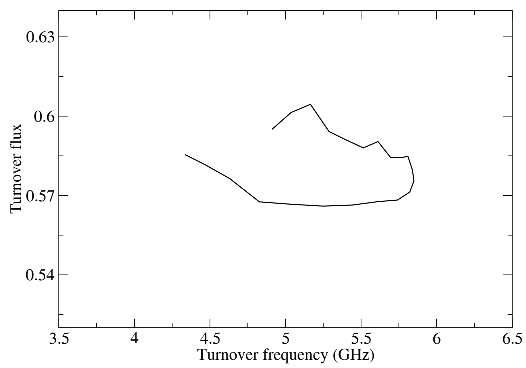

Fig. 5 Model for the evolutionary track $\nu_{m,r}$–$S_{m,r}$ for the third peak ($t = 2.05 - 3.15$).

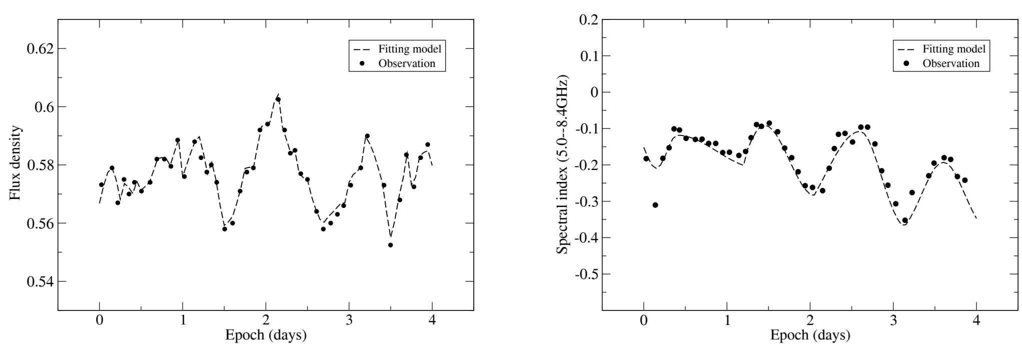

Fig. 6 Left: Model-fitting to the 5 GHz light-curve: points – observation. dashed line – model. Right: Model-fitting to the observed spectral index α(5–8.4 GHz): points – observation. dashed line – model.

5 MODEL-FITTING OF OPTICAL IDV

In order to explain the optical IDV, we have to make a few more assumptions. Firstly, in the relativistic shock case the optical emitting region may be different from the radio one, i.e., the optical-emitting region may be concentrated in the center part of the jet and the radio emitting region in the outer part. This is just

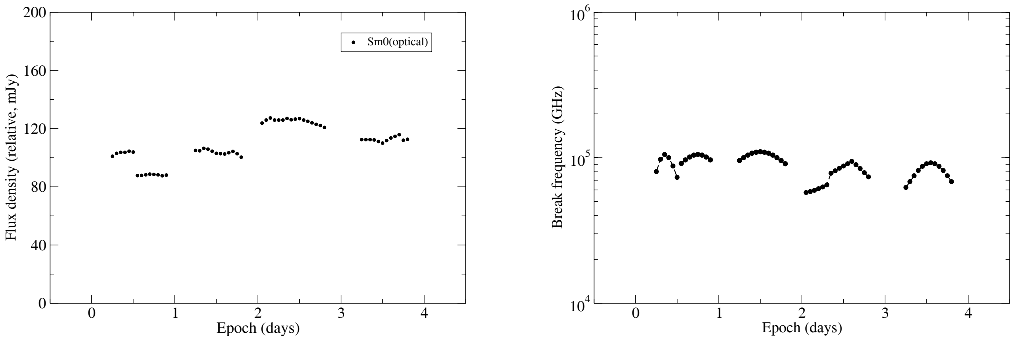

Fig. 7 Optical component. Left: coefficient $S_{m0,\mathrm{opt}}(t)$ which is applied to the model-fitting of the turnover flux density $S_{m,\mathrm{opt}}$. Right: evolution of the break frequency $\nu_{b,\mathrm{opt}}$.

Table 2 Coefficients (c, d) in units of 100 GHz and parameter $\theta_{\mathrm{opt}}(t)$ in the model-fitting of the optical IDV.

epoch t	c	d	$\theta_{\mathrm{opt}}(t)$
0.25–0.35	3.255	1.095	$\pi(t-0.15)/0.40$
0.40–0.50			$\pi(t-0.60)/0.50$
0.55–0.75	3.630	7.200	$\pi(t-0.30)/0.90$
0.80–0.90			$\pi(t-1.20)/0.90$
1.25–1.50	3.645	0.8025	$\pi(t-0.90)/1.20$
1.50–1.80			$\pi(t-2.10)/1.20$
2.05–2.30	3.169	1.219	$\pi(t-1.80)/2.80$
2.35–2.60			$\pi(t-1.60)/2.80$
2.65–2.80			$\pi(3.20-t)/1.66$
3.25–3.55	3.113	0.9600	$\pi(t-3.10)/0.90$
3.60–3.80			$\pi(4.00-t)/0.90$

like a shock propagating along a dual jet structure, the optical emitting region may be much smaller than the radio one, but their emissions vary in step. Secondly, in the optical case, we may need to consider radiative loss due to synchrotron and possible acceleration of the electrons. So we assume different values of β and s for the optical component, similar to the synchrotron stage of the scenario proposed by Marscher & Gear (1985): $S_{m,\mathrm{opt}} \propto \nu_{m,\mathrm{opt}}{}^{-0.05}$ (β_{opt}=–0.05) and s_{opt}=1.5. Thirdly, for the optical component, the turnover frequency $\nu_{m,\mathrm{opt}}$, as usual, may be in the mm-submm band and the observing optical frequency may be above the break frequency, $\nu_{\mathrm{b,opt}}$. Thus we have to introduce an additional relation between the turnover frequency and the break frequency in the form $\nu_{\mathrm{b,opt}} \propto \nu_{m,\mathrm{opt}}{}^{\eta}$. In the following we assume η=2,

$$\nu_{\mathrm{b,opt}}(t) = 5\,10^4[\nu_{m,\mathrm{opt}}/300]^2, \tag{12}$$

here $\nu_{\mathrm{b,opt}}$ and $\nu_{m,\mathrm{opt}}$ are in units of GHz. Similar to the case of the radio IDV, the variations of $\nu_{m,\mathrm{opt}}$ and $S_{m,\mathrm{opt}}$ are expressed as

$$\nu_{m,\mathrm{opt}}(t) = c + d\sin^2\theta_{\mathrm{opt}}(t), \tag{13}$$

$$S_{m,\mathrm{opt}}(t) = S_{m0,\mathrm{opt}}(t)\Big(\frac{\nu_m(t)}{300}\Big)^{-0.05}. \tag{14}$$

The coefficients (c, d) (in units of 10^3 GHz) and the parameter θ_{opt} are given in Table 2. $S_{m,\mathrm{opt}}$ and $\nu_{\mathrm{b,opt}}(t)$ are shown in Figure 7.

In Figure 8 is shown the evolutionary track $S_{m,\mathrm{opt}}$–$\nu_{m,\mathrm{opt}}$ for the third optical peak ($t = 2.05 - 2.80$). The optical flux are calculated according to

$$S_{\mathrm{opt}}(t) = S_{\mathrm{b,opt}}(t)(\nu_{\mathrm{opt}}/\nu_{\mathrm{b,opt}}(t))^{-(0.5+\alpha_{\mathrm{opt}})}, \tag{15}$$

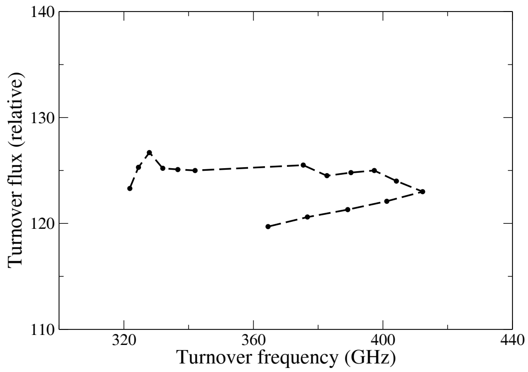

Fig. 8 Optical IDV: Model-fitting to the evolutionary track S_m–ν_m for the third peak ($t = 2.05 - 2.80$).

$$
\begin{aligned}
S_{\mathrm{b,opt}}(t) \;=\; & S_{m,\mathrm{opt}}(t)\Big(\frac{\nu_{\mathrm{b,opt}}(t)}{\nu_{m,\mathrm{opt}}(t)}\Big)^{2.5} \\
& \Big[1-\exp\Big(-\Big(\frac{\nu_{1,\mathrm{opt}}(t)}{\nu_{\mathrm{b,opt}}(t)}\Big)^{2.5+\alpha_{\mathrm{opt}}}\Big)\Big] \\
& \Big[1-\exp\Big(-\Big(\frac{\nu_{1,\mathrm{opt}}(t)}{\nu_{m,\mathrm{opt}}(t)}\Big)^{2.5+\alpha_{\mathrm{opt}}}\Big)\Big]^{-1},
\end{aligned}
\tag{16}
$$

and

$$
\nu_{1,\mathrm{opt}}(t) = \nu_{m,\mathrm{opt}}(t)\tau_{m,\mathrm{opt}}{}^{\frac{1}{2.5+\alpha_{\mathrm{opt}}}}. \tag{17}
$$

In Figure 9 the model-fit to the optical light-curve is shown. It can be seen that the observed optical light curve is well simulated. Comparing Figure 9 with Figure 6, it can be found that the anti-correlation between the 5 GHz flux density and the optical flux density is explained and that the correlation between the optical flux density and the spectral index α (5–8.4 GHz) (or the spectral steepening) is also explained. That is, if a shock propagates through a jet with a dual structure and the radio and optical components have a simultaneous spectral evolution as assumed above, then the correlated radio and optical IDV event, as observed in 0716+714, can be reproduced. Although our model is not unique, it demonstrates that an interpretation for correlated radio and optical IDV can be found. This scenario may also be applicable to simultaneous radio-optical variations at longer timescales (weeks and months, e.g. for some instances observed in BL Lac objects, Valtaoja et al. 2000; Tornikoski et al. 1994).

Finally, we emphasize that in the above we interpreted both the radio IDV and optical IDV with an application of the scenario of the shock-in-jet model proposed by Marscher & Gear (1985), but the values assumed for the parameters β_r, s_r, β_{ops}, s_{ops}, η and others are not unique, and they are only selected for demonstrating the validity of the interpretation, the available observational data being incapable of providing proper values for these parameters. Moreover, these values could also depend on particle acceleration and field amplification mechanisms which may be different from those considered in the model of Marscher & Gear (1985).

6 CONCLUSIONS

We have shown that the properties of the correlated radio and optical IDV event observed in 0716+714 (Quirrenbach et al. 1991; Qian et al. 1995) can be interpreted in terms of a shock propagating through a jet that has a dual structure, in which the optical emission originates from the region close to the axis of the jet, while the radio emission comes from its outer region. The spectral evolution of both optical and radio component has the form of $S_m \propto \nu_m{}^{\beta}$, as in the shock-in-jet model proposed by Marscher & Gear (1985).

Generally, there could be three cases in which intraday variations are due to intrinsic causes: (1) Characteristic spectral evolution, like the one observed in 0235+164 (Qian et al. 2000); (2) Continuous

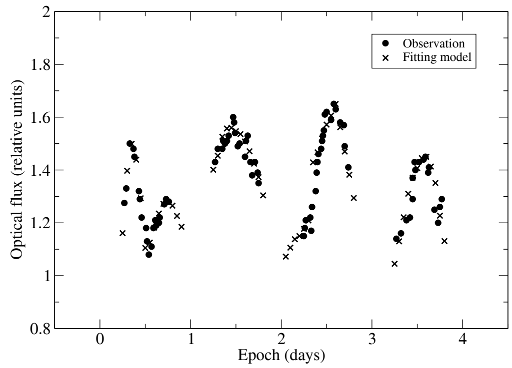

Fig. 9 Model-fitting to the optical light-curve (flux in relative units): Points – observation, crosses – model.

polarization angle swing of 180° on intraday timescales (Quirrenbach et al. 1989; Qian et al. 2004); (3) Correlation between radio and optical intraday variations, as observed in 0716+714. Intrinsic IDV requires the condition that the angular size of the source should be large enough to make any scintillation negligible, and some special geometry to produce intraday timescales and to solve the problem of high brightness temperature (e.g. Spada et al. 1999; Qian et al. 2006, 1991; Slysh 1992). More observations for distinguishing intrinsic IDV from the IDV due to scintillation are needed.

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