The Outburst of the Blazar S5 0716+71 in 2011 October: Shock in Helical Jet

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We present the results of γ-ray monitoring along with optical (R band) photometric and polarimetric observations of the blazar S5 0716+714 during the outburst in 2011 October. We observed monotonic rotation of the EVPA at a rate of $\gtrsim 50^\circ$ per night coinciding with a sharp maximum of γ-ray and optical flux. We analyze the total and polarized intensity images of the blazar obtained with the VLBA at 43 GHz during and after the outburst. The multi-frequency behavior of S5 0716+714 can be explained within the framework of a shock wave propagating along a helical path in the blazar's jet.

1. Introduction

The blazar S5 0716+71 (z~0.3) is one of most intensively studied BL Lac objects. Optical variability has been studied by many teams; the blazar demonstrated persistent activity on both long and short (intraday) timescales as shown by, e.g., Hagen-Thorn et al. (2006), and by results of several WEBT campaigns (Chen et al. 2008). Violent polarimetric variability of S5 0716+71, among other blazars, was studied by Ikejiri et al. (2011). Larionov et al. (2008) reported that a huge optical outburst of S 50716+71 in 2008 April was accompanied by an 360˚ rotation of the position angle of the electric vector (EVPA) of linear polarization. We report the results of our observations of S5 0716+71 during a major optical outburst in 2011 October, which coincided with an unprecedented γ-ray outburst (Blinov et al. 2011).

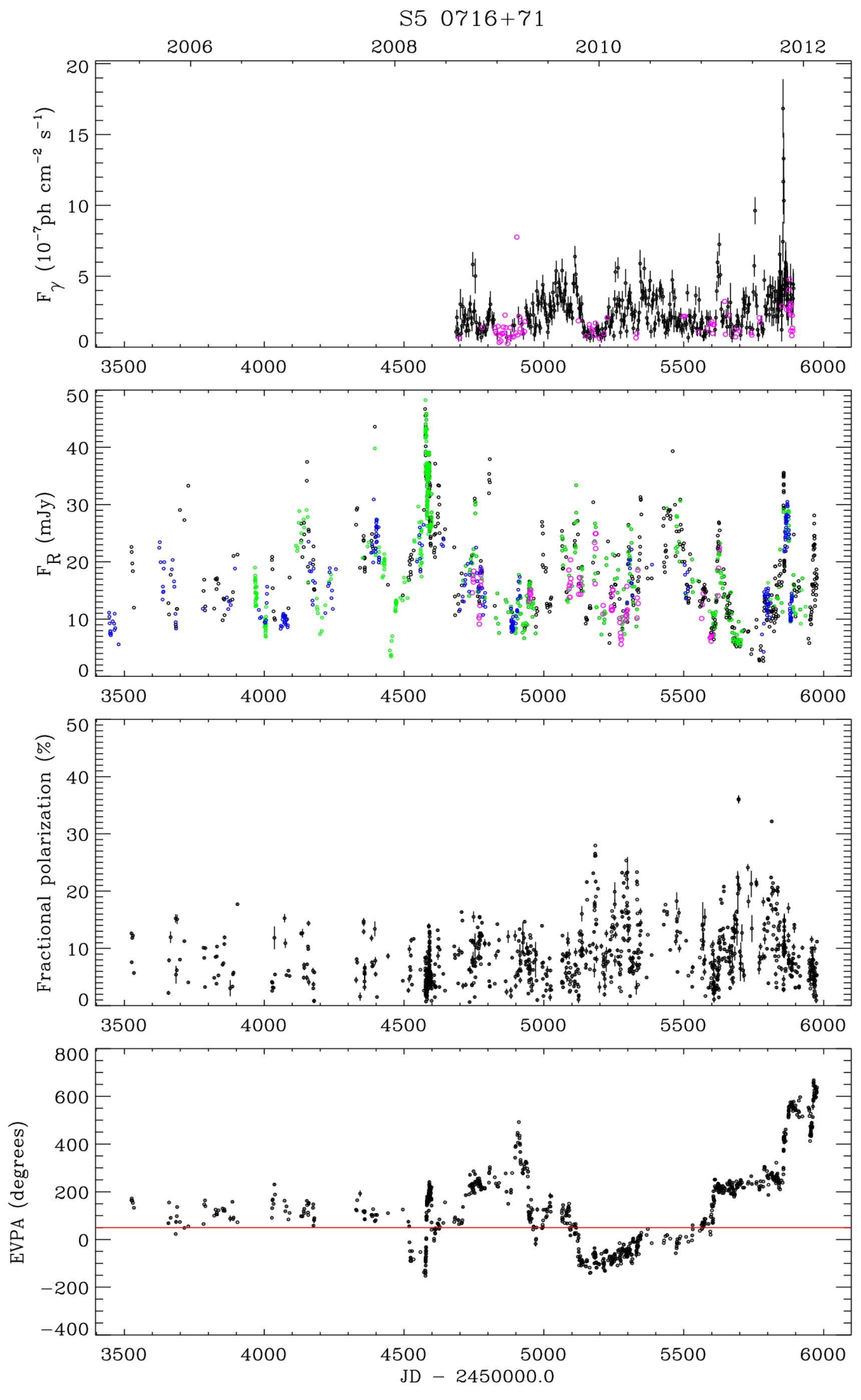

Fig. 1.— From top to bottom: evolution of γ-ray flux, R-band flux, and degree and position angle of polarization of S5 0716+71 during 2005–2011.

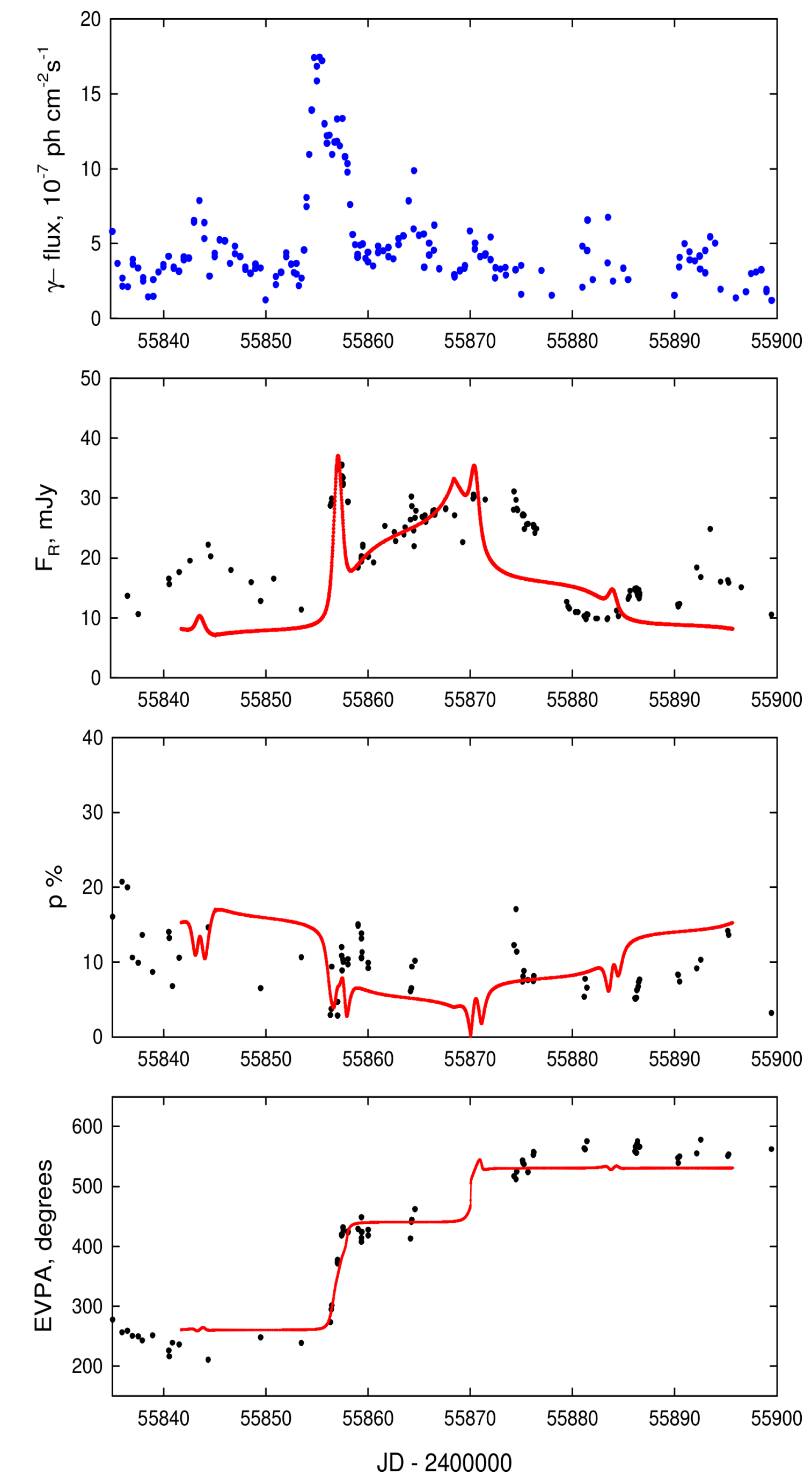

Fig. 6.— Enlarged part of Fig. 1 with model fitting.

2.1. Optical observations and results

Observational data were obtained at the 70-cm AZT-8 reflector of the Crimean Astrophysical Observatory, 40-cm LX-200 telescope in St. Petersburg, both equipped with identical photometers-polarimeters based on ST-7 CCDs, and 1.8-m Perkins telescope of Lowell Observatory. Polarimetry at AZT-8 and the Perkins telescope was made in Cousins R band, while and in white light at LX-200, with effective wavelength close to R. The photometric errors do not exceed $0.^{m}02$.

Our regular photometric and polarimetric monitoring of S5 0716+71 started in 2005. Since then, we have obtained more than 1000 data points almost uniformly spread over a 7-year time interval, although we intensify our observations during periods of highest activity of the source. Figure 1 presents the flux and polarization behavior of S5 0716+71 for 2005–2011. We supplement this plot with a panel showing the γ-ray behavior of S5 0716+71 from Fermi LAT open access data in order to show that most prominent gamma-ray activity ever recorded was observed during the October 2011 optical outburst.

The optical light curve of S5 0716+71 displays violent variability on both long (months-years) and short (days-weeks) timescales. Changes in the degree of polarization seem to occur erratically; within the time interval 2005–2009 it varied from 0 to 15%, while later the mean level of polarization increased, reaching a record value of 36% on the night of 2011 May 14 (JD 2455696). The EVPA also exhibits prominent changes. To solve the ±180˚ ambiguity, we have added/subtracted 180˚ each time that the subsequent value of EVPA is 90˚ less/more then the preceding one.

2.2. Radio observations and results

The BL Lac object S5 0716+71 is monitored monthly by the BU group with the VLBA at 43 GHz within a sample of bright γ-ray blazars (http://www.bu.edu/blazars).

Figure 2 shows the total and polarized intensity images of the object from 2011 October to 2012 April. The VLBA data were calibrated, imaged, and modeled in the same manner as discussed in Jorstad et al. (2005). The angular resolution is 0.1 mas, which corresponds to 0.45 pc at the source distance (H_0 = 70, λ_m = 0.3, λ_Ω= 0.7). Figure 2 shows 3 prominent features, the core and knots K1 and K3. The EVPA in the core and K1 is mostly along the jet (from −10 to +40). Figure 3 shows the motion of knots K1 and K3 with respect to the core (a presumably stationary feature) and an approximate fit to the motion.

K1 had a superluminal apparent speed β_{app} = 43 ± 2c and coincided with the core at epoch MJD 55650 ± 54 (2011.23 ± 0.15), during (within the error) the previous optical and gamma-ray outburst, which was centered on MJD 55625. Given the uncertainty, the optical outburst could have occurred upstream of the radio core. We note that either K1 decelerated to app = 3.5±0.5c over 300 days, or it excited emission (by acceleration of electrons and compression of the magnetic field) of a stationary feature, perhaps a standing shock wave. Such quasi-stationary features that brighten as a disturbance passes have been observed in other blazars, and are especially common in BL Lac objects (Jorstad et al. 2005). Another knot, K3, was more closely related to the main outburst analyzed here. K3 was observed over 5 epochs, crossing the core at MJD 55850±10, which coincides within the errors with the occurrence of the most prominent γ-ray and optical event. This strongly implies that the γ-ray, optical, and radio events were co-spatial. Our data indicate that K3 was also very highly relativistic, β_{app} = 21 ± 2c. We are also able to identify other components (see Fig. 3) that did not move significantly during the period of our observations. It is possible that knots A2 and K2 are "trailing components" (see Agudo et al. (2001)) of K1.

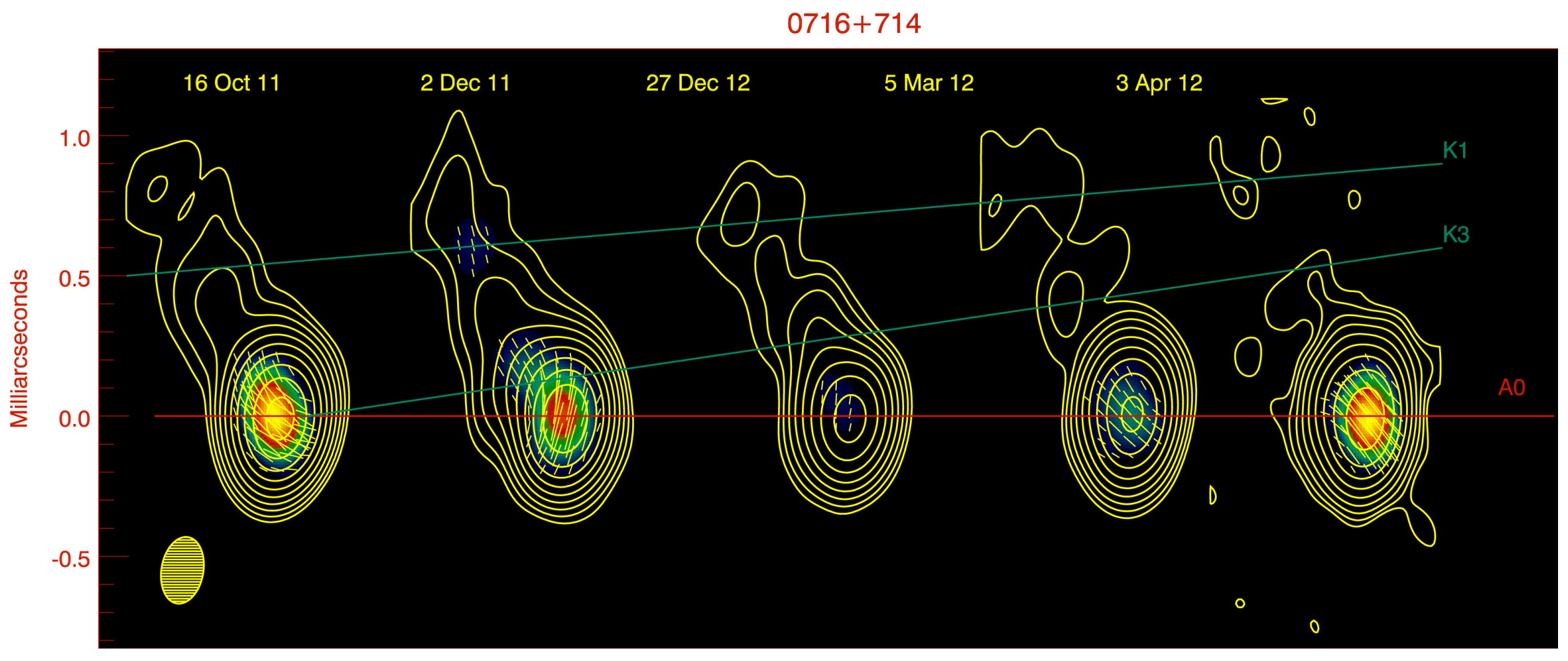

Fig. 2.— The total (contours) and polarized (color scale) intensity maps of S5 0716+714 at 43 Ghz with the total intensity peak of 2.51 Jy/beam and polarized intensity peak of 65 mJy/beam; the beam is 0.24×0.15 mas² at PA=−10˚ (plotted in the bottom left corner); yellow linear segments over color scale indicate direction of polarization;

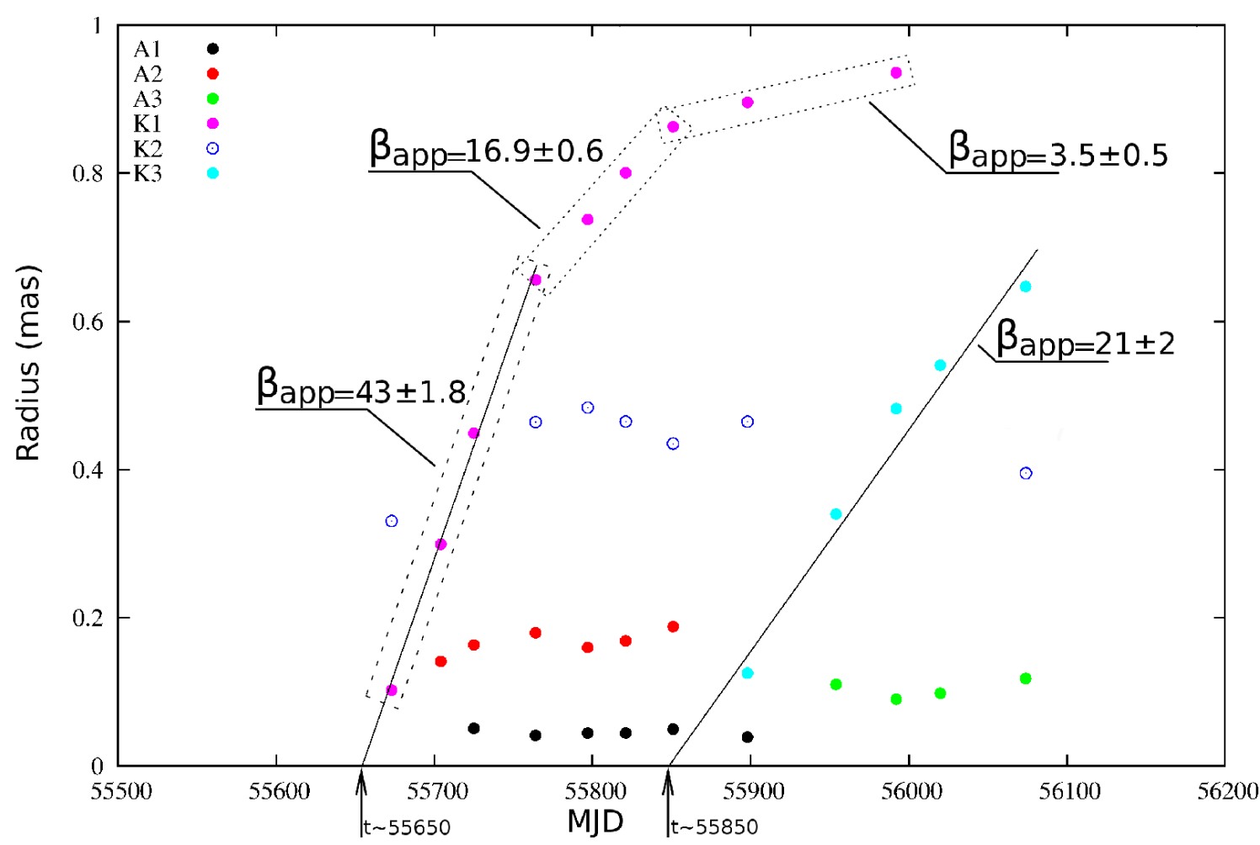

Fig. 3.— Separation of radio knots from the core as function of time.

2.3. Gamma-ray Observations

The γ-ray emission from S5 0716+71 was detected throughout the entire period of Fermi observations, although most of the time at a level of $5 \cdot 10^{-7}$ph · cm^{-2}s^{-1}. We analyze the Fermi LAT data for the period of 2011 January-November with 2-day binning, as well as binning as short as 0.25 days, during the huge γ-ray outburst of 2011 October, when the flux from the source was close to 2×10^{-6} ph cm^{-2}s^{-1}. This was to avoid missing any possible short-lived events and to make the correlation analysis more robust. We calculate the discrete correlation function (DCF) of the optical and γ-ray flux variations during 2011. The results are given in Fig. 4. Optical variations lag those at γ–ray energies by 1.4 days (DCF centroid position).

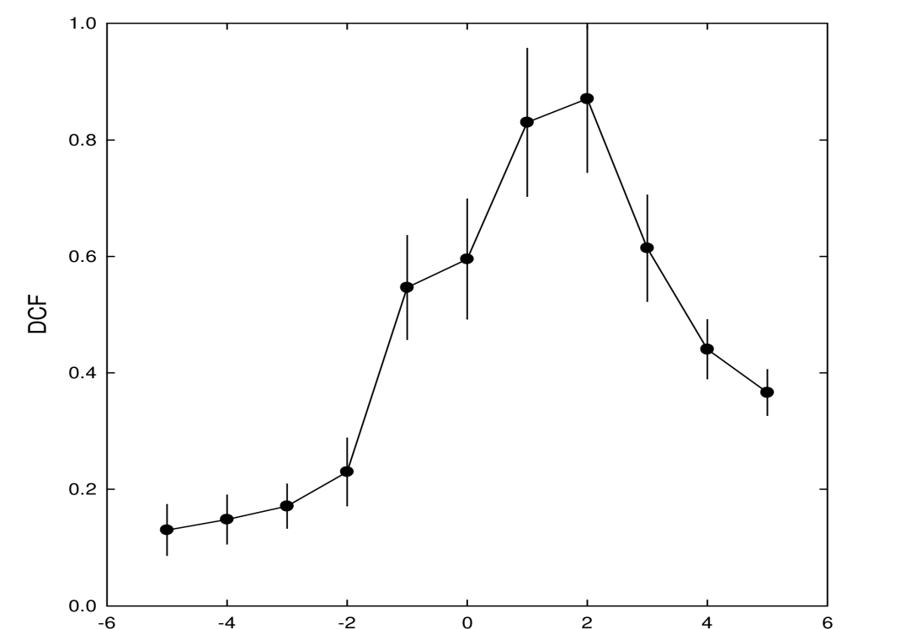

Fig. 4.— Discrete correlation function between optical and γ-ray flux variations of S5 0716+714. Positive lag means that optical variations follow those at γ-ray energies.

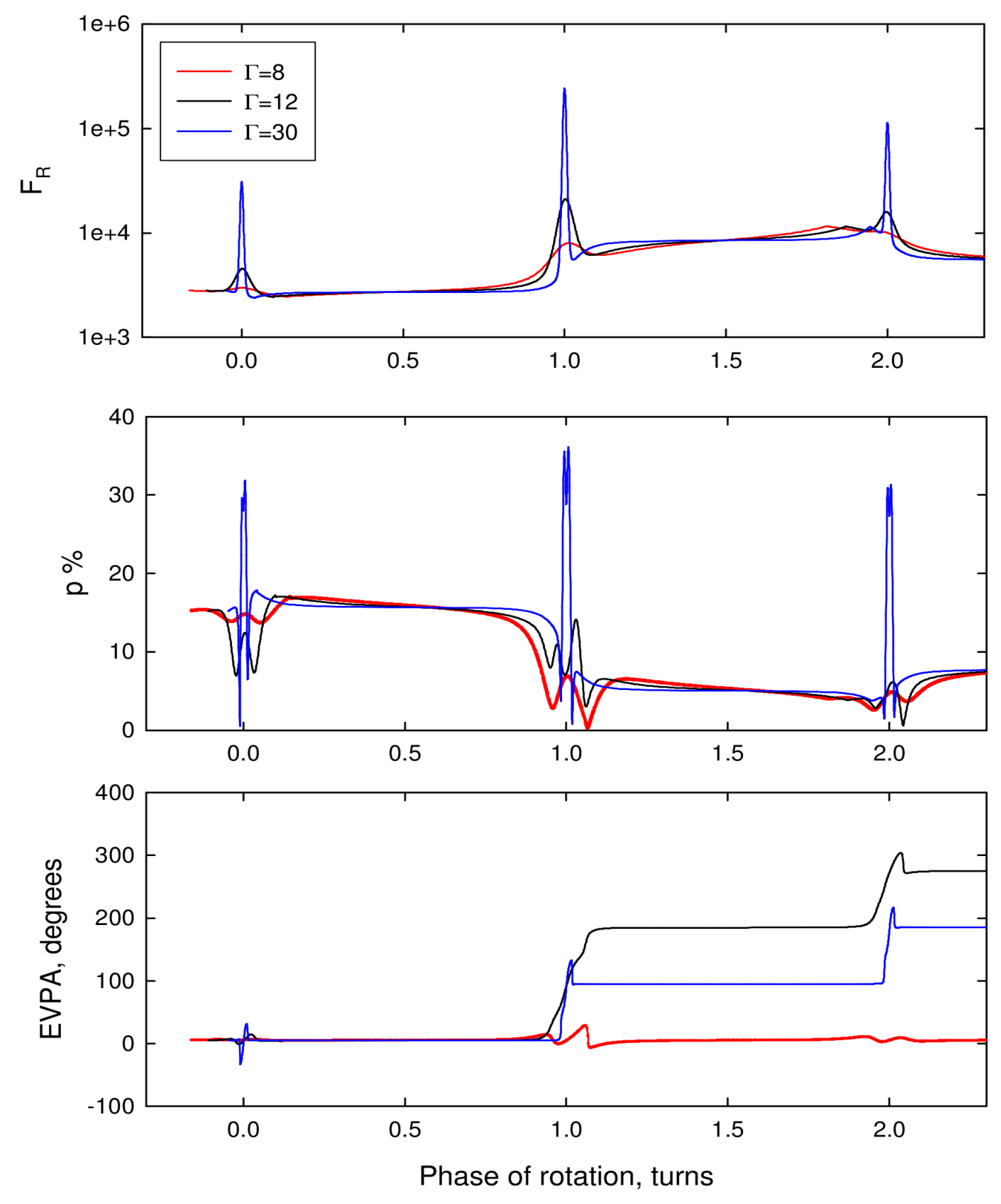

Fig. 5.— Model evolution of flux and polarization parameters with 3 different values of Γ .

Table 1. **Fitting parameters for the photometric and polarimetric behavior of S5 0716+71 in 2011 October-November.**

θ°	ζ°	$p_{\rm jet}$,%	k	Γ	r	$P_{\rm obs}$	$P_{\rm src}$	τ	T_0	$R1$	$R2$	a	η	$t_{\rm del}$	$\Delta\chi^\circ$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
5.8	7.5	22	1.8	10	0.0095	13.2	1.5	0.47	0.11	0.06	132	1.1	1.50	0.47	10

Note. — Units of r are parsecs, $P_{\rm obs}$ – days, $P_{\rm src}$ – years. τ, T_0 and $t_{\rm del}$ are fractions of $P_{\rm src}$.

3. Modeling of Photometric and Polarimetric Behavior

We suppose, following Marscher et al. (2008), that most of optical photometric and polarimetric variability arises when a shock wave propagates downstream from the black hole, following a spiral path, and that the shock wave does not fill all the cross section of the jet. We notice that quite often prominent optical outbursts are preceded and followed by minor flares. We interpret this phenomenon as a manifestation of the movement of a compact radiation region (shock wave) along helical magnetic field lines inside the jet. The observed series of outbursts correspond to the moments when the viewing angle of the shock wave is at a minimum.

The main parameters that determine the visible behavior of the outburst are:

- jet viewing angle θ ; for simplicity, we set the position angle of the jet equal to 0˚, later rotating it to match the jet direction of S5 0716+71.
- bulk Lorentz factor Γ of shocked plasma
- temporal evolution of the outburst $F' = F_0 \cdot \begin{cases} \exp(-|t-t_0|/\tau), t \le t_0 \\ \exp(-|t-t_0|/\kappa\tau), t > t_0 \end{cases}$,the factor κ responsible for different time scales of the rise and decline of the outburst; primed quantities refer to the source reference frame
- Doppler time contraction in the observer's frame, $\Delta t_{obs} = \delta^{-1} \Delta t_{src}$
- shocked plasma compression η
- spectral index of the emitting plasma α
- pitch angle ζ of the spiral motion and helical field; in our model we set $\zeta = 75^\circ/\Gamma$
- period of the shock's spiral revolution in the observer's frame P_{obs}

The viewing angle of the compact emission region φ is obtained from the relation: $\cos\varphi = \cos\theta\cos\zeta + \sin\theta\sin\zeta\cos(2\pi t_{obs}/P_{obs})$(1)

Relativistic aberration leads to a change in direction of the normal to the shock front : $\psi = \arctan[\sin\varphi/(\Gamma(\cos\varphi - \sqrt{1-\Gamma^{-2}}))]$ (2)

The fractional polarization (see, e.g., Hughes, Aller, & Aller 1985) is then: $p \approx \frac{\alpha+1}{\alpha+5/3}\frac{(1-\eta^{-2})\sin^2\psi}{2-(1-\eta^{-2})\sin^2\psi}$ (3)

And the position angle is determined by the direction of the minor axis of the shock wave: $\Theta = \arctan[\zeta\sin t_{obs}/(\zeta\cos t_{obs} - \theta)]$ (4)

The Doppler factor is determined as $\delta = 1/(\Gamma(1-\beta\cos\varphi))$ (5)

The periods of rotation in the source frame P_{src} and observer's frame P_{obs} are connected with the relation

$P_{obs} = P_{src}(1+z)(1-\beta\cos\theta\cos\zeta)$ (6) where z is the source's redshift.

Knowledge of P_{obs} (from the timescale of recurrence of outbursts), estimates of β and θ , made from radio maps, and evaluation of the spiral's radius r allow us to constrain the values of P_{src} and ζ and to calculate the Doppler-contracted time in the observer's frame, t_{obs}.

Doppler boosting of the shock wave radiation leads to $F_{shock} = F'_{shock}\,\delta^{3+\alpha}$ (7)

We notice that in most cases when the source is in a quiescent state and no outburst is detected, there remains polarization on the level of 10%. We assume that this is the polarized radiation of the jet, presumably changing on substantially longer time scale (not taking into account random changes due to turbulence in the jet). In the local frame the ratio R1 = F'_{shock}/F'_{jet} is of the order of a few percent. The radiation from the jet is also subject to Doppler boosting, and we (rather arbitrarily) set Γ_{jet} ~ 0.7Γ. Since the jet is a roughly steady source, its radiation is amplified as $\delta^{2+\alpha}$. Notice that, in spite of the low value of R1, in the observer's frame the boosted radiation of the shock may far exceed that of the ambient jet.

We add emission from the quasi-stationary features — probably standing shocks — whose fluxes become significant after the moving shock crosses them. We postulate that the temporal behavior of this added radiation is of the same form as that of the shock:

$$\Delta F'_{jet} = R2 \cdot F_0 \cdot \begin{cases} \exp(-|t-t_0+t_{del}|/\tau), t \le t_0 \\ \exp(-|t-t_0+t_{del}|/\kappa\tau), t > t_0 \end{cases}$$

Here R2 accounts for the ratio of the shock radiation re-radiated by the jet, with time delay t_{del}. In our model we suppose that this radiation is added to the "constant" radiation of the jet, but not to its polarized part.
Finally, the observed radiation of the jet is $F_{jet} = (F'_{jet} + \Delta F'_{jet})\delta_{jet}^{2+\alpha}$ and total observed flux $F_{total} = F_{shock} + F_{jet}$.

We consider a single variable source plus an initially constant source whose polarization vector is displaced relative to the jet direction by an angle Δχ. We recall that in our model the jet has direction 0˚.

Accounting for the contribution of this "constant" polarized source ($F_{0\,jet}$ and p_{jet}) we get the absolute Stokes parameters:

$$Q = F_{shock}\,p\cos(2\Theta) + F'_{jet}\delta_{jet}^{2+\alpha} p_{jet}\cos(2\Delta\chi)$$
$$U = F_{shock}\,p\sin(2\Theta) + F'_{jet}\delta_{jet}^{2+\alpha} p_{jet}\sin(2\Delta\chi) \qquad (8)$$

Finally, the normalized Stokes parameters are given by

$$q = Q/F_{total}$$
$$u = U/F_{total}. \qquad (9)$$

Figure 5 shows the dramatically different behavior of flux and polarization with all of the above mentioned parameters fixed, allowing only the Lorentz factor of the shock to change. We see that the model of a shock propagating in the helical path may in a natural way explain the successions of outbursts, often observed in blazar light curves, as a manifestation of a single event. A variety of observed patterns of photometric and polarimetric behavior may be explained by the interplay of the shock Lorentz factor, jet viewing angle, helical path pitch angle, and shape and length of the outburst. We do not take into account the light travel delay caused by the finite size of the shock wave; if included, this would result in some smoothing of the model light curve.

4. Discussion and Conclusions

We have obtained densely sampled optical photometric and polarimetric data during an unprecedented gamma-ray outburst in S5 0716+71, and analyzed the changes in the structure of the blazar at 43 GHz. We find a 180˚ rotation of the position angle of linear polarization, which occurred at the epoch of maximum optical brightness. This event would have been missed if our observations did not occur consecutively from 3 sites (St. Petersburg, Crimea, Arizona). Figure 6 shows the time evolution of the observational parameters (γ-ray and optical flux, degree of polarization and positional angle) within the model discussed above. Values of the adjustable parameters are listed in Table 1. The γ-ray outburst started $1.^{d}4$ before the optical, which corresponds to 0.05 pc distance in the source frame. The emergence of knot K3 at the same time as the optical/γ-ray outburst leads to the conclusion that these events were co-spatial. However, we note that our model uses a lower Lorentz factor of the shock wave (Γ = 10) than that obtained from the radio images (Γ= 21). This could reflect acceleration of the plasma flow downstream from the regions where the optical/γ-ray outburst took place.

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