Astron. Astrophys. 353, 937–943 (2000)

ASTRONOMY AND ASTROPHYSICS

Infrared, radio and optical variability of the BL Lacertae object 2007+777*

B. Peng[1,2], A. Kraus[1], T.P. Krichbaum[1], S.A.H. Müller[3,4], S.J. Qian[1,2], A. Quirrenbach[5], S.J. Wagner[6], A. Witzel[1], J.A. Zensus[1], C. Jin[1,2], and H. Bock[6]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[2] Beijing Astronomical Observatory, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, P.R. China
[3] Max-Planck-Institut für Astronomie, Königstuhl, 69117 Heidelberg, Germany
[4] Ruhr-Universität Bochum, Universitätsstrasse 150, Postfach 102148, 44801 Bochum, Germany
[5] University of California San Diego, Center for Astrophysics and Space Sciences, Department of Physics, Mail Code 0424, La Jolla, CA 92093-0424, USA
[6] Landessternwarte Heidelberg, Königstuhl, 69117 Heidelberg, Germany

Received 10 September 1999 / Accepted 23 November 1999

Abstract. We present infrared observations at wavelengths of 60 and 100 μm and contemporaneous radio (five frequencies) and optical (R band) monitoring of the BL Lac object 2007+777. During a three-week campaign with the ISO[1] spacecraft, the VLA[2], the Effelsberg 100 m radio telescope, and optical telescopes in Heidelberg and on Calar Alto, Spain[3], we observed variability on time scales of a few days at 100 μm, at radio, and at optical frequencies. We discuss briefly several generic models which could account for our observations. The attempt at explaining the results by an intrinsic mechanism requires an extremely small source angular size of the order of a few μas[4], which can be reconciled with the 10^{12} K inverse Compton limit only when the Doppler factor of the bulk flow is about 40. The general behavior of the variability of the BL Lac object 2007+777 found in this IR-radio campaign follows the expectations of a shock-in-jet model, and we argue that this is the most likely explanation of our observations.

Key words: galaxies: active – galaxies: BL Lacertae objects: individual: 2007+777 – radio continuum: galaxies

1. Introduction

BL Lacertae objects constitute a class of extragalactic sources whose spectra are characterized by the absence of optical emission lines, by high polarization, and rapid variability. The superluminal radio source 2007+777 (Witzel et al. 1988) was identified as a BL Lac object because of its almost featureless optical spectrum at the time of the observation (Biermann et al. 1981). During studies of Intraday Variability (IDV) with the VLA (Quirrenbach et al. 1999), variability on time scales of several days was found in this source.

The physical cause of rapid variability in extragalactic radio sources has been a puzzle ever since the detection of this effect (Witzel et al. 1986, Heeschen et al. 1987, Quirrenbach et al. 1989). Intrinsic explanations require extremely high Doppler factors of the bulk flow in the jet, whereas propagation effects such as interstellar scattering or gravitational microlensing have difficulties reproducing the polarization variations. Quirrenbach et al. (1991) and Wagner et al. (1996) found intriguing evidence for correlated variability in the radio and visible ranges in the BL Lac object 0716+714; such a correlation would almost certainly point to an intrinsic origin of the variations. This motivated us to search for correlations between the infrared and radio variations in a BL Lac object using the ISO satellite and ground-based radio observations. 2007+777 appeared to be the best target object, given the constraints on visibility by ISO, the absence of strong confusion in the mid-IR, and earlier reports of simultaneous occurrence of IDV at radio and optical frequencies by Wagner et al. (1990).

In the high energy regime, 2007+777 was detected by HEAO2/IPC in the 0.1 – 3.5 keV energy band with a flux of 3.64 μJy at 1 keV (Worrall & Wilkes 1990, Ciliegi et al. 1993). In addition, 2007+777 was observed twice by the ROSAT/PSPC in a pointed mode at 0.1 – 2.0 keV with no detectable variability found, but the flux density at 1 keV of 0.17 μJy (Urry et al. 1996) was at least 20 times weaker than the value measured previously by HEAO2/IPC. There is no γ-ray detection reported for this source in the literature.

The redshift of $z = 0.342$ for this BL Lac object was derived from very weak [O III] and [O II] emission lines (Stickel et al. 1989). The optical image (Stickel et al. 1993) shows 2007+777

Send offprint requests to: B. Peng (bpeng@mpifr-bonn.mpg.de)

* Based on observations made with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with participation of ISAS and NASA.

[1] Infrared Space Observatory

[2] The Very Large Array, New Mexico, is operated by Associated Universities, Inc., under contract with the National Science Foundation.

[3] The German-Spanish Astronomical Centre, Calar Alto, is operated by the Max-Planck-Institut für Astronomie, Heidelberg, jointly with the Spanish National Commission for Astronomy.

[4] $1\mu as = 10^{-6}$ arcsec

to be unresolved, lying only $\sim 25''$ away from a bright star. The neighboring galaxy $\sim 30''$ to the west (G1) may be a highly inclined spiral and has a redshift of $z = 0.165$. The optical spectrum of the galaxy (G2) $\sim 30''$ to the southeast is remarkable in showing only a single, strong emission line at λ6970 Å, which – if identified with [O II] λ3727 Å – gives a redshift of $z = 0.87$.

2007+777 has a VLBI jet extending along a PA of about $-95°$, with one of the components separating from the core at 0.223$\pm$0.015 mas/yr, corresponding to β=5.78$\pm$0.38 for about 9 years (Eckart et al. 1987, Witzel et al. 1988, Gabuzda et al. 1994). The dominant magnetic field in 2007+777 is transverse, as is typical for radio-selected BL Lacertae objects, although one jet component does have a longitudinal magnetic field (Kollgaard et al. 1996).

In this paper, we report on observations of the source 2007+777 by a space borne instrument (ISO) and ground-based telescopes (VLA, Effelsberg 100 m radio telescope, Heidelberg 0.7 m and Calar Alto 1.2 m optical telescopes). In the following section, we describe the observations and the data reduction. In Sect. 3, we present and analyze the results, including light curves, structure functions and the radio, IR to optical spectrum of 2007+777, and point out some of their properties. Subsequently we briefly discuss different scenarios which could account for the variability. In Sect. 5 we summarize our observational findings and draw the conclusions. Throughout the paper the radio spectral index is defined by $S_\nu \propto \nu^{-\alpha}$, and a Hubble constant of $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ is used.

2. IR, radio and optical observations and data reduction

We monitored the flux density of 2007+777 for three weeks with the ISO satellite to search for short-term variations, and obtained additional concurrent radio observations with the VLA and at Effelsberg. We also made some optical observations in the same period. The whole campaign is summarized in Table 1. Observations and data reduction for each of the experiments are briefly described in the following sections.

2.1. ISO observations and data reduction

ISOPHOT (PHT hereafter) is the imaging photo-polarimeter on board the ISO satellite. Its wavelength range is not accessible from the ground and only with poor sensitivity from airborne instruments. Between Feb. 20 and Mar. 10, 1997, 2007+777 was monitored by using the detectors P1 at 11.5 μm, P2 at 25 μm and C100 at 60 μm and 100 μm. The observations were carried out daily in the mode of single element photometry for the four wavelengths, apart from Mar. 7 and 9. For the P-detector, each run consisted of the observing sequence of 11.5 μm, 25 μm and the FCS (Fine Calibration Sources), for the C100, of 60 μm, 100 μm and the FCS. The output of each of the integrating PHT detectors consists of the read-out value as a function of time. A number of non-destructive integrating read-outs (NRDs) are followed by a destructive read-out at which the integration plateau is reset, in principle, to zero. Each sequence of NRDs defines a ramp (voltage as a function of time). The slope of the ramp is proportional to the signal level (and the power on the detector). The P-detector data at 11.5 μm and 25 μm were observed by a non-standard aperture without background measurements and proper calibrations, and therefore will not be presented in this paper.

The data were reduced by using current PIA[5] software, basically consisting of removal of instrumental effects, and the performance of the flux calibration. Following the standard ISO data reduction procedure (see PIA User Manual), firstly, we discarded all destructive read-out, and the first half of signals per chopper plateau because of detector drift; secondly we applied all standard corrections. In addition, we used the IDL program developed by Müller (1999) to analyze the data with the method of the Fast-Fourier-Transformation.

The background flux densities at both 60 and 100 μm are very stable, with standard deviation of less than 4% of the mean value. Additionally, we calibrated the flux sets of 2007+777 with the mean background flux at each wavelength. In total there are 17 epochs measured at each wavelength, but only 8 detections succeeded at 60 μm, 13 at 100 μm, with signal-to-noise ratio above 3. We failed to get detections in some measurements either because of source variability, or technical problems or both.

The successful observations are summarized in Table 1, where the Columns 1-3 list the observing wavelength, number of detections, and the telescope used. The resultant light curves at these two wavelengths are plotted in the top two panels of Fig. 1, which will be analyzed in Sect. 3.1.

2.2. VLA multi-frequency observations and reduction

From Feb. 25 to Mar. 7, 1997, we observed 2007+777 several times but at irregular intervals with the full VLA in B configuration. In parallel, additional radio observations were performed with the Effelsberg telescope at four frequencies (see Sect. 2.3). The successful observations are also summarized in Table 1.

With the VLA, the data for 2007+777 were recorded in two IFs at frequencies of 1.46, 4.88, 8.44, 14.96 and 22.48 GHz (λ = 20, 6, 3.6, 2 and 1.3 cm). The primary calibrator sources 3C48 and 3C286 were also measured at each frequency.

Since both 3C48 and 3C286 were resolved by the VLA at all frequencies we used, point source models for these two were only accurate over a limited range of baseline length. Flux densities were calibrated with 3C48 and 3C286 by using the AIPS[6] task CALIB. Finally we determined a mean flux by averaging the two IFs which showed almost no significant difference in flux density. The resulting light curves at the five frequencies are displayed in the five panels in Fig. 1 below the ISO data.

2.3. Effelsberg 100 m observations and data reduction

The flux density of 2007+777 was also determined at Effelsberg several times, using cross-scans at λ=7 mm, 1.3 cm, 2.8 cm and

[5] PHT Interactive Analysis
[6] Astronomical Image Processing System

Table 1. Summary of the (Optical-)IR-radio observing campaign during Feb. 20 to Mar. 10 in 1997 on the BL Lac object 2007+777. Note that, N denotes number of observations (or detections), $\langle S \rangle$ mean flux, m the modulation index, Y variability amplitude and χ^2_{red} the reduced χ^2 value. For the statistical analysis(m, Y and χ^2_{red}), only data sets with N $\geq$ 7 are taken into consideration (see Sect. 3.1).

λ	N	Telescope	$\langle S \rangle$ Jy	m [%]	Y [%]	χ^2_{red}
650 nm	7	Heidelberg + Calar Alto	0.000279 ± 0.000111	42.86	127.70	176.218
60 μm	8	ISO	0.133 ± 0.027	20.34	59.84	1.123
100 μm	13	ISO	0.197 ± 0.042	21.50	63.38	3.379
7 mm	2	Eff.	0.987 ± 0.080			
1.3 cm	9	VLA + Eff.	1.212 ± 0.058	5.05	13.92	15.154
2 cm	9	VLA	1.301 ± 0.047	3.84	9.84	12.244
2.8 cm	3	Eff.	1.330 ± 0.020			
3.6 cm	9	VLA	1.343 ± 0.037	2.89	8.13	10.601
6 cm	14	VLA + Eff.	1.278 ± 0.029	2.36	6.41	26.169
20 cm	9	VLA	0.848 ± 0.008	1.04	0.85	1.627

6 cm. We followed the standard data analysis procedure as used in the past to reduce the IDV experiments (Quirrenbach et al. 1992, Kraus 1997, Kraus et al. in preparation). Systematic elevation and time-dependent effects in the light curves were removed by using polynomial corrections derived from frequent observations of the secondary calibrator sources 0836+710 and 0951+699. Finally we linked our observations to the absolute flux density scale (Baars et al. 1977) by observing the primary calibrators 3C286 and 3C48. The measurement errors are composed of the statistical errors from averaging the individual samples in a scan, and a contribution from the calibration errors, which are reflected by apparent residual fluctuations of the non-variable sources. The results are combined with the VLA data and shown in Fig. 1.

2.4. Optical observations

The infrared data were supplemented by observations at 650 nm (R-band filter) taken at one of the 0.7 m telescopes of the Landessternwarte Heidelberg, Germany and the 1.2 m telescope of the Calar Alto Observatory in Spain. Bad weather severely limited the amount of data that could be collected. In particular our intention to search for variability on time scales shorter than one day suffered from the incomplete time coverage. Data from both telescopes were reduced in the standard manner (Wagner et al. 1996). Simulated aperture photometry was carried out for 2007+777 as well as for the comparison stars[7]. These stars also permitted a relative calibration of the two data sets. Errors of $\sim$ 5% for the relative photometry were estimated from the rms scatter of field stars with fluxes comparable to those of 2007+777. They are larger than expected from photon and read-noise and slightly above the average of similar campaigns (Wagner et al. 1996) owing to the lack of twilight flats, caused by persistent rain in twilight periods. Absolute calibrations were made with a large flux uncertainty of about 20% because of non-photometric conditions on all of the nights involved. The resulting light curve is plotted in the last panel of Fig. 1. The limited data are consistent with structure functions measured for 2007+777 during earlier campaigns.

3. Results

3.1. Light curve, structure function and statistic analysis

We only consider data sets with more than 7 data points for the variability analysis, but we include other measurements for the spectral analysis.

In Fig. 1 we plot the light curves at wavelengths of 60 μm and 100 μm obtained with the ISO, at 1.3, 2, 3.6, 6 and 20 cm with the VLA and Effelsberg telescopes, and at 650 nm with the Heidelberg 0.7 m and Calar Alto 1.2 m telescopes. 2007+777 appears to be variable throughout the optical, IR and radio regimes in the same period with an exception at 20 cm, and no statistically significant variability at 60 μm.

The radio data show a variability of ~ 5%, the IR data of ~ 20%, and the optical data of ~ 50%. Given the relatively large uncertainties of the flux density measurements in the IR and the coarse and unevenly sampled time coverage, we performed a more detailed variability test as follows.

We measure the strength of the variability by deriving the variability amplitude, $Y[\%] = 3 \times \sqrt{m^2 - m_0^2}$. Here $m[\%] = 100 \times \frac{\sigma_S}{\langle S \rangle}$ is defined as the modulation index ($\langle\ \rangle$ denotes the mean), and m_0 the modulation index of a non-variable source (Heeschen et al. 1987). To see whether a source is variable, we performed a χ^2 test. The statistical results are presented in Table 1, where Columns 4 and 5 give the mean flux density with estimated error and the modulation index. In Column 6, the variability amplitude is obtained by taking typical values m_0 = 1% and 2% for frequencies lower and higher than 15 GHz respectively in the radio regime, 4% (see Sect. 2.1) in the IR regime, and 5% (see Sect. 2.4) in the optical R band. Finally the reduced χ^2_{red} value is calculated in the last column. Obviously, the statistical results confirm that 2007+777 is variable at a confidence level of more than 99.95% at 650 nm, 100 μm and most of the radio wavelengths. At 60 μm there is no significant variability detection, which is probably due to the fact that

[7] For details see the web page http://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/2007+777.html

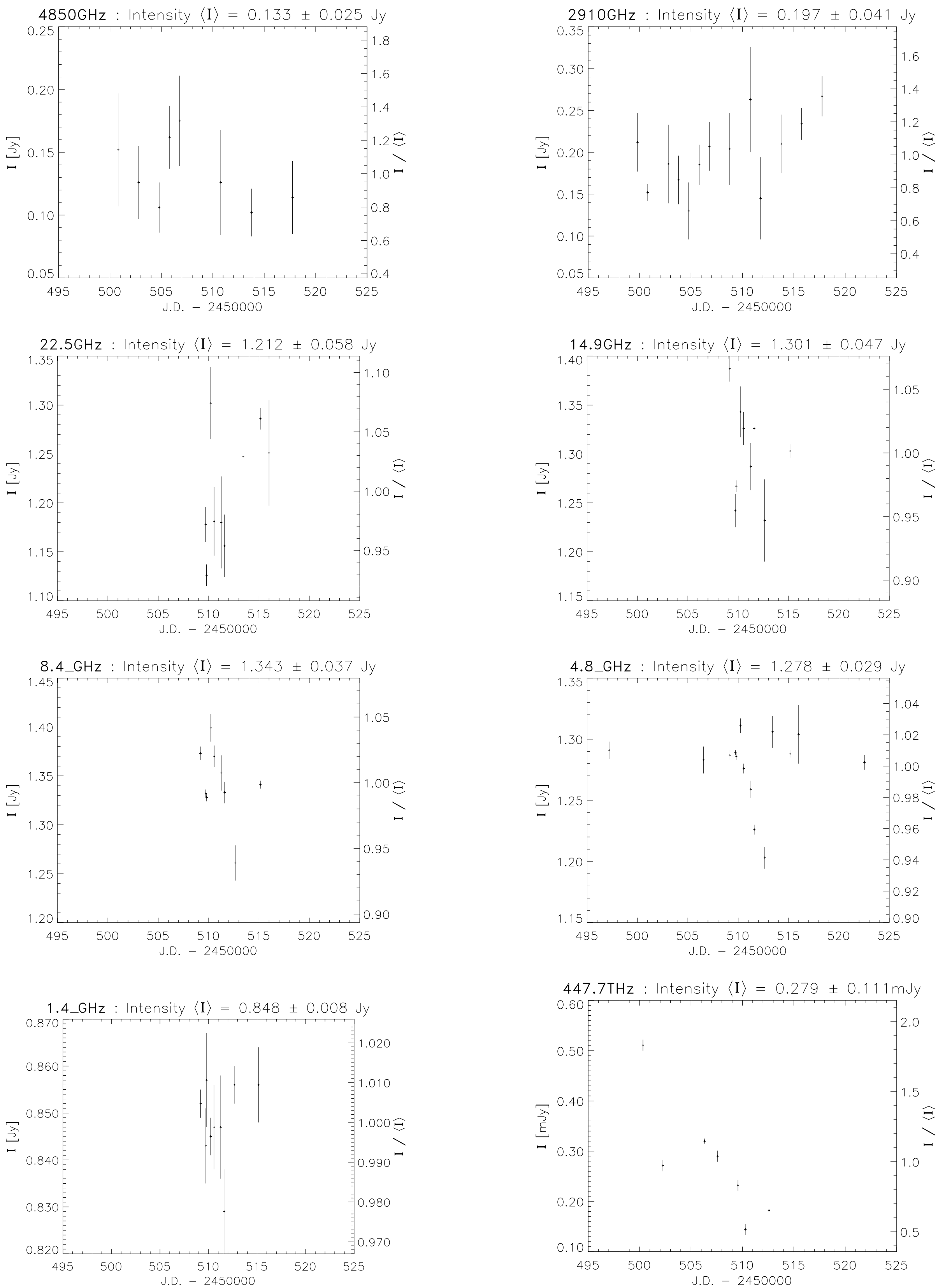

Fig. 1. Light curves of 2007+777 from late Feb. to early Mar. 1997 at 60 μm, 100 μm, 22.5 GHz ($\lambda = 1.3$ cm), 14.96 GHz ($\lambda = 2$ cm), 8.44 GHz ($\lambda = 3.6$ cm), 4.86 GHz ($\lambda = 6$ cm), 1.49 GHz ($\lambda = 20$ cm), and in the optical R band ($\lambda = 650$ nm) (from top to bottom). Plotted is the flux density in Jy (an exception at R band in mJy) versus Julian Date.

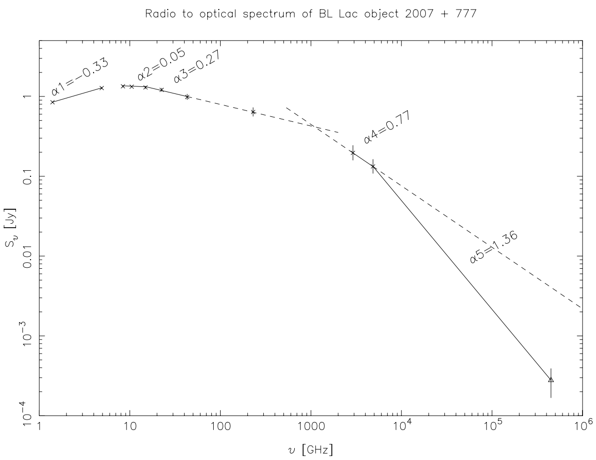

Fig. 2. Radio, IR to optical spectrum of 2007+777.

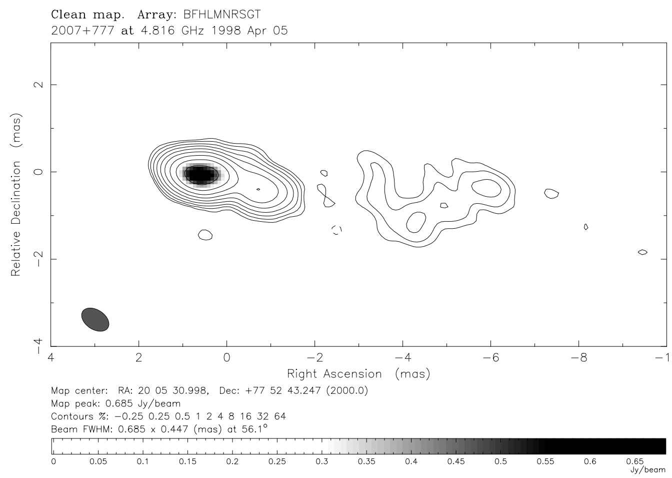

Fig. 3. A multi-component core-jet structure in 2007+777 at 5 GHz observed by VSOP in April 1998.

the signal to noise ratio (SNR) is not sufficient. Because of the large error bars, we cannot claim the detection of variability, but we cannot exclude the same level of variability as at 100 μm, either. At 20 cm we do not detect variability, although we could have measured variations at the level that was observed at shorter wavelengths. This behavior is not at all uncommon. For example, the lightcurves presented by Quirrenbach et al. (1999) are generally much smoother at 20 cm than at 6 cm. It is therefore not surprising that no significant variability was detected over the relatively short time period covered by the 20 cm observations presented in Fig. 1. It is remarkable that the variability strength Y and the modulation index m decrease monotonically with increasing wavelength in the radio regime.

Structure functions (Simonetti et al. 1985) can be used for the analysis of the characteristics of variability. A characteristic time scale in the light curve, defined as the time interval between a maximum and an adjacent minimum or vice versa, is indicated by a maximum of the structure function, while a periodicity in the light curve causes a minimum of the structure function (Heidt & Wagner 1996).

In the radio regime, time scales of 3.5 and 6 days at 1.3 cm, 2 days at 2 cm, and 2.5 days at 3.6 and 6 cm are found by our structure function analysis. 2007+777 did show IDV at cm (Quirrenbach et al. 1992) and at optical wavelengths (Heidt & Wagner 1996). In the IR regime, time scales of 2, 4 and 6 (or 7) days are seen. This is quite fast compared to the IRAS measurements of a sample of BL Lac objects, which demonstrated variability time scales of 15 to 233 days (Impey & Neugebauer 1988, and references therein). In the optical R band, a time scale of 4 days can be identified although the data are very limited.

3.2. Radio–IR–optical spectrum

The radio, IR to optical spectrum of 2007+777 is shown in Fig. 2, with the mean flux densities listed in Table 1. The overall spectrum of 2007+777 provided here can be approximately described by a combination of a few power laws with an overall turnover frequency at around $\nu_m = 8.4\,$GHz. At higher frequencies, which correspond to the optically thin part of the jet, the spectrum can be fitted by three power laws. The spectral index $\alpha 4 = \alpha^{4850\,\mathrm{GHz}}_{2910\,\mathrm{GHz}} = 0.77$ in the IR is larger than $\alpha 3 = \alpha^{43\,\mathrm{GHz}}_{14.9\,\mathrm{GHz}} = 0.27$ in the radio, indicating a spectral break of $\Delta\alpha = 0.5$ between the radio and IR. A flux measurement at 230 GHz (λ= 1.3 mm) from the literature (Steppe et al. 1988) follows the radio power law nicely. We further infer that a spectral break occurs at the crossover of the two power laws, near $\nu_b \approx 1100\,$GHz. The optical flux at 650 nm lies significantly below the extrapolation of the power-law spectrum of the IR. The estimated two-point spectral index is $\alpha 5 = \alpha^{447.7\,\mathrm{THz}}_{4850\,\mathrm{GHz}} = 1.36$. The overall curvature of the spectrum between the radio, IR and optical ranges suggests a multi-component structure and more electron energy losses at higher frequencies.

The spectrum is inverted at $\nu \leq 8.4\,$GHz and shows a low-frequency spectral index of $\alpha 1 = \alpha^{4.9\,\mathrm{GHz}}_{1.4\,\mathrm{GHz}} = -0.33$, which is much flatter than the typical value (-2.5) for the self-absorbed part produced by a homogeneous self-absorption synchrotron source. This indicates that the jet contains several components (perhaps shocks) with their turnovers at different frequencies. The most recent VSOP[8] observation at 5 GHz reveals a multi-component structure in the core-jet of 2007+777 (Jin et al. 1999), as demonstrated in Fig. 3. Complex substructure down to less than 1 mas extends all along the inner jet, suggesting that shocks are a persistent phenomenon in this source and the variations shown in this paper are likely to be typical.

The synchrotron spectrum seems to peak above 5×10^{12} Hz, probably in the near IR as shown in Fig. 4.

4. Discussion

In our IR-radio campaign on the BL Lac object 2007+777 in Feb. – Mar. 1997, we found variability on short time scales with an amplitude of about 20% at 100 μm. Although there are some indications that at 60 μm the source is also variable, a χ^2 test

[8] VLBI Space Observatory Programme, a radio astronomy space mission led by the Institute of Space and Astronautical Science and the National Astronomical Observatory of Japan.

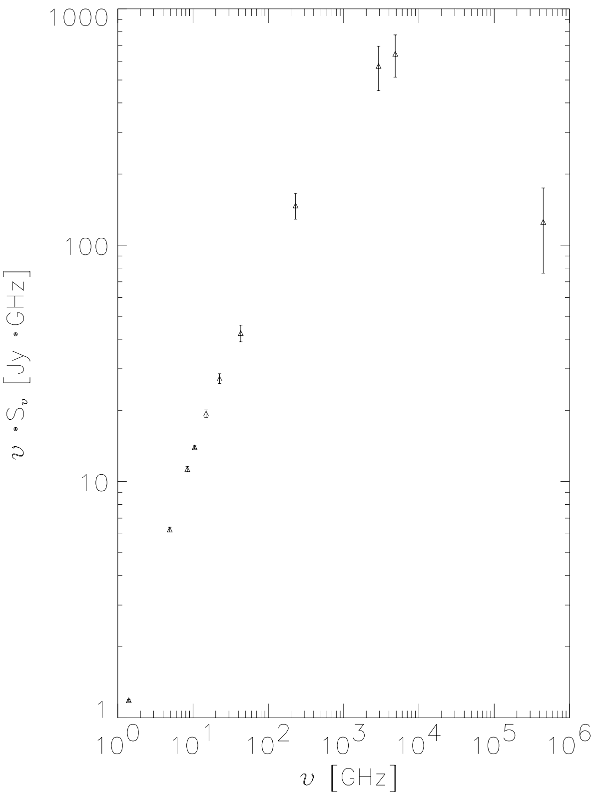

Fig. 4. Broad-band (Radio, IR and optical) energy distribution of 2007+777.

gave no significant variability detection in this band. In the same period, the source was variable at most of the radio wavelengths with modulation indices between $m = 2\%$ and $m = 5\%$, and in the optical R band of about $m = 43\%$. Remarkably the modulation index (and consequently the variability amplitude) decrease with increasing wavelength in the radio regime. Additionally, the first infrared maximum – if connected to the radio events – might be about 2 days earlier, and the radio maxima occur nearly simultaneously.

The sparse data do not allow the construction of detailed models for explaining the results on 2007+777. In the following, we discuss shortly some consequences of our observations.

Taking $q_0 = 0$ and redshift $z = 0.342$, the angular distance D_a (Lang 1974) of 2007+777 is 1.33×10^3 Mpc.

Because of the flux change $\triangle S$ = 0.16 Jy at 6 cm during $\tau \sim 2.5$ days, the apparent diameter of the variable component based on the causality argument would be $\theta_{app} \leq 2c\tau/D_a \sim 0.6\,\mu$as. This corresponds to an apparent brightness temperature $T_{app} \geq \frac{2c^2\triangle S}{\pi\kappa\nu^2\theta_{app}^2} \sim 2.8 \times 10^{16}$ K, or transforming to the co-moving frame of the quasar, $T'_{app} \geq T_{app}(1+z)^3 \sim 6.8 \times 10^{16}$ K. If the large excess of the brightness temperature over the inverse Compton limit of 10^{12} K (Kellermann & Pauliny-Toth 1969) is due to a relativistic bulk motion (as suggested by Rees 1966 and by Woltjer 1966) of the variable component, a Doppler factor $D \geq (T'_{app}/10^{12})^{1/3} \approx 41$ is needed. The resultant D is thus considerably higher than the “canonical” value of 10, derived from VLBI and X-ray observations (see Ghisellini et al. 1993, Zensus 1997, Wagner & Witzel 1995). An exceptional event has been reported for the quasar 1055+018 (Gopal-Krishna et al. 1984), the Doppler factor was estimated at ~ 65, or even ~ 150 assuming a spherical, incoherently radiating synchrotron source (Terrell 1966, Scheuer & Williams 1968). Begelman et al. (1994) explain the high brightness temperatures with refinements of the general relativistic jet model and find that Doppler factors as high as $D \sim 100$ may be possible. Further consequences of such high Doppler factors are discussed in Wagner & Witzel (1995). By taking $\tau \sim 2$ days at 100 μm, we obtain a $T'_{app} \sim 2.4 \times 10^{11}$ K, which is well below the theoretical upper limit of $\sim 10^{12}$ K.

Propagation of a relativistic shock front through the jet is commonly accepted as one of possible causes of flux density variability in AGN (Blandford & Königl 1979, Marscher & Gear 1985). The time scales usually involved in these models are of the order of weeks to months. A number of modifications have been suggested to account for features such as very rapid (even intraday) flux changes (Kellermann & Pauliny-Toth 1969, Marscher, Gear & Travis 1992, Qian et al. 1991). For this kind of model, we would expect that the flux density reaches its maximum at higher frequencies first, and then the amplitude of the peak decreases towards lower frequencies. This is consistent with the variability behavior in 2007+777 during our observations.

Scattering processes in the interstellar medium are well known to cause flux density variations at radio frequencies (Rickett 1990), but the scattering is typically weak at frequencies above 10 GHz. It would be expected that the time scales of the variations become shorter for decreasing wavelengths, contrary to our observational findings (see Sect. 3.1), implying that interstellar scintillation (ISS) alone is unlikely to explain the present observations. Additionally, interstellar scattering cannot cause variability in the IR and optical regimes. Hence, a possible connection of the optical/IR and the radio variations would rule out ISS as the cause of the observed variability. But since short time scales imply small source sizes, ISS may be present in the radio regime as an additional effect.

Gravitational microlensing by stars in intervening galaxies may introduce variations that are not intrinsic to the source. The foreground object at $z = 0.165$ might host microlenses affecting the emission from 2007+777, but the projected distance is too large to make this explanation likely. This is to be contrasted with the recent unusual radio variability reported in the BL Lac object 0235+164, the basic qualitative features of which could be understood in the microlensing picture without very specific assumptions (Kraus et al. 1999). Wagner (1992) lists a number of further observations which argue against microlensing in objects similar to 2007+777.

5. Conclusions

We have observed the BL Lac object 2007+777 in the IR, at radio wavelengths, and in the optical R band, and found fast concurrent variations in most frequency bands. In the radio regime the amplitude of the variability decreases with increasing wavelength.

The conventional application of the shock-in-jet model may explain all of the observational findings in 2007+777 presented in this IR, radio and optical campaign. The dependence of both the time scales and the modulation indices on wavelength found in this source argue against an explanation by interstellar scattering. Although gravitational microlensing might in principle provide a possible explanation for the observed variations in the radio regime, the probability for gravitational microlensing seems to be low because the only known foreground object is about $30''$ away.

The radio to IR spectrum of 2007+777 provided here can be described by power laws with an overall turnover frequency $\nu_m \approx 8.4$ GHz. The spectral curvature between the radio, IR and optical ranges suggests a multi-component nature of the source, and more energy losses of the electrons radiating at the shorter wavelengths.

We conclude that our observational findings in 2007+777 favor a shock-in-jet model as an explanation for the variations. The apparent correlations between the radio, infrared and optical variations provide strong evidence against alternative extrinsic models.

Acknowledgements. We thank I. Pauliny-Toth for critically reading the manuscript, and the anonymous referee for valuable comments. The ISOPHOT data presented in this paper was reduced using PIA, which is a joint development by the ESA Astrophysics Division and the ISOPHOT consortium. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc. This research has made use of the NASA's Astrophysics Data System Abstract Service and of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.

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