Astron. Astrophys. 149, 351–356 (1985)

ASTRONOMY AND ASTROPHYSICS

Near infrared and radio observations of active galactic nuclei *

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Received July 25, 1984; accepted March 4, 1985

Summary. We present near infrared photometry and radio observations of a sample of 15 compact flat spectrum radio sources. The sample includes ten QSOs, four BL Lac type objects and one Seyfert galaxy. The infrared observations were performed with the 3.6 m ESO telescope in four periods in 1980 and 1981; the radio observations at 22 GHz were made with the 13.7 m Itapetinga radiotelescope. Time scales of variability are derived from our data and previous works.

The time scales of variability are interpreted in terms of a model in which the variability is only due to synchrotron energy loss and is not related to the size of the source. Some characteristics of the injection mechanism for relativistic electrons are derived.

Key words: galaxies: nuclei of – quasars – radiation mechanisms: synchrotron radiation – infrared radiation

1. Introduction

There is presently almost unanimous agreement on the similar nature of QSOs, BL Lac objects and active nuclei of Seyfert and N galaxies. While the ultimate energy source of these objects is believed to be accretion of mass on a supermassive black hole, the process by which the energy distributes itself along the overall energy spectrum is still little known. In the radio-millimeter region, the synchrotron-inverse Compton nature of the emission is well established, but there is a competition between models concerning the electron energy distribution and the structure of the source, like multiple homogeneous source versus single homogeneous source models, with optically thin or optically thick emission. In the visible-near infrared region, in addition to the synchrotron process, thermal emission from dust or from an accretion disk and line blends are likely.

Among active nuclei a class with flat radio spectra ($|\alpha| \leq 0.5$) has been recognized (e.g. Owen et al., 1978; Rieke et al., 1979), which is associated with the most compact and highly variable sources. There are reasons to believe that a relatively simple situation occurs in these objects, in which the synchrotron component of the source responsible for the radio emission still dominates at higher frequencies, in the near IR-optical region; their study may therefore provide important clues to a better understanding of both regions of the spectrum. Determination of the slope in the critical infrared-millimeter range, and long term monitoring of both radio and infrared variability are possible ways of restricting models. We present in this paper *JHK*(*L*) photometry and 22 GHz radio measurements of 15 flat radio spectrum objects, selected among relatively strong radio sources (> 1 Jy), so that they were expected to be detectable in the near infrared with the 3.6 m ESO telescope. The selection was based on radio data compiled by Condon et al. (1978) and by Kühr et al. (1981). Our sample includes ten QSOs, four BL Lac objects and one Seyfert galaxy, 3C120. We combine our data with other radio, infrared and optical measurements available in the literature, to discuss the spectra and variability of the sources. 3C120 is the only object of our sample reported in the Point Source Catalog of the IRAS mission (IRAS, 1985). Based on a simple model, we interpret the characteristic time scales of variability as a function of wavelength to infer some properties of the mechanism of injection of relativistic electrons into the source.

2. Observations

The 22 GHz observations were made with the 13.7 m Itapetinga radiotelescope, near São Paulo, Brazil, in 1981 October and 1982 May. An on-off beam switching technique was used, with two linearly polarized feed horns 20′ separated; the receiver was a double sideband mixer of about 1000 K system temperature. Antenna temperatures were corrected for antenna gain degradation with zenith angle, radome and atmospheric attenuation, and converted to flux units using Virgo A as calibration source. The results of the radio observations are presented in Table 1, together with the identifications and the redshifts, taken from the catalogs of Kühr et al. (1981) and Hewitt and Burbidge (1980).

The near infrared observations have been carried out with the standard InSb infrared photometer attached at the *f*/8 focus of the ESO 3.6 m telescope at La Silla, Chile. Most of the data were collected in 1980 December and 1981 December; additional observations were made in 1981 February and June. The pointing of the telescope was achieved by applying offsets with respect to nearby reference stars in finding charts, based on the coordinates given by Hewitt and Burdidge (1980); in most cases the objects were directly seen on the TV guider. All the data were obtained with a 10″ diaphragm in the *J*, *H*, *K*, and *L* bands; the results are presented in Table 2. For conversion to flux units we used the calibration given by Wamsteker (1981).

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* Based on observations collected at ESO and Itapetinga Observatory, which is operated by CNPq/INPE

Table 1. Radio fluxes of the sources at 22 GHz

object	S^1 (Jy)	S^2 (Jy)	type of object	Z
0048 - 097		3.66 ± .25	BL Lac	
0113 - 118	1.21 ± .20	1.46 ± .29	QSO	-
0202 - 172		1.07 ± .26	QSO	1.74
0336 - 019		2.46 ± .27	QSO	.852
0422 + 004	1.09 ± .24	1.36 ± .31	BL Lac	
0430 + 052	2.47 ± .35	2.38 ± .32	Seyf. Gal	.032
0735 + 178	2.46 ± .55	2.00 ± .33	BL Lac	.424
0736 + 017	2.62 ± .20	2.25 ± .26	QSO	.191
0743 - 006		.86 ± .23	QSO	
0823 + 033		2.68 ± .37	QSO	
0906 + 015		2.32 ± .32	QSO	1.018
1034 - 293		1.94 ± .21	BL Lac	
1055 + 018	2.32 ± .41	3.27 ± .22	QSO	.888
1244 - 255		2.38 ± .30	QSO	.633
1253 - 055	15.78 ± 1.03	10.86 ± .29	QSO	.536

Observations performed (1) October 1981, (2) May 1982

3. Remarks on individual sources

Most of the sources studied in this work have been monitored at optical wavelengths (e.g. Usher et al., 1974; Pollock et al., 1979; Pica et al., 1980; Barbieri et al., 1982) and show short-term flickering with about 10% amplitude and time-scales of a few days and long term variations with amplitudes reaching a few magnitudes and time-scales of years. Monitoration at radio wavelengths of many of the sources is reported by Andrew et al. (1978) at 6.7 and 10.7 GHz; by Dent and Kojoian (1972) at 7.8 GHz; by Dent et al. (1974) at 15.5 GHz, and by Landau et al. (1980) at 90 GHz; typical time-scales os variations are about a year. We consider some of the sources individually in the following remarks in order of PKS identification number.

0048–097: Flickering of 0.8 mag in less than a week, and long term variations of almost 3 mag were observed at optical wavelengths; optical polarization of up to 14% was reported (Kinman, 1976). Previous measurements in the near infrared were performed by Glass (1981) and Allen et al. (1982). Comparison of our 1980 December measurement with that of Allen et al. taken 5 months before shows a variation of about 1 mag in K. The shortest time-scale of variability $dt/d\ln S$ observed at 10.7 GHz (Andrew et al. 1978) is about 8 months. The radio data including our 22 GHz measurement show that the total amplitude of variability in the centimeter region is about a factor of 3, one of the largest amplitudes in our sample of sources. The polarization at radio frequencies reaches about 5% and is variable (Altschuler and Wardle, 1975). VLA observations at 1465 MHz (Wardle et al., 1984) show that this source consists of a single component.

0336–0.19 (CTA 26): Optical monitoring shows short-term activity of about 0.4 mag and long term variability of 0.75 mag on a time scale of years. It is a faint source in the infrared; our observations show a variation of almost 1 mag in H in one year. The shortest time scale of variability at 15.5 GHz (Dent et al., 1974) is slightly greater than a year. A well defined maximum in the 15.5 GHz curve in the first half of 1972 is possibly related to a maximum in the optical curve about one year before. A cross correlation analysis performed by Pomphrey et al. (1976) showed the phase lag between the 2.8 cm radio and optical curves to be one year. The radio spectrum from simultaneous observations is flat (Owen et al., 1978, 1980).

0422+004: The light curve showed a sudden fading of about 2 mag in early 1979, after being nearly constant for 2 years (Pica et al., 1980); this event is possibly related to a decrease of the 90 GHz flux by a factor 2 between 12/1978 and 7/1979 (Landau et al., 1980). The average of our near infrared observations is in agreement with the result of Allen et al. (1982); individual measurements taken 4 days apart indicate variation of 0.6 mag in *H* and *K*. Simultaneous observations (Owen et al., 1978, 1980) show its radio spectrum is very flat; VLA observations at 1465 MHz (Wardle et al., 1984) show that the emission originates in a single unresolved component coincident with the optical nucleus.

0430+052 (*3C120*): The light curve obtained by Pollock et al. (1979) shows fluctuations of up to 1 mag in a few months superimposed on a steady decline of about 1 mag from 1972 to 1979. A similar long term decline by a factor of three between 1972 and 1978 was observed in the near infrared (Rieke and Lebofsky, 1979). Our 1980 near infrared measurements are in agreement with those obtained in 1977 by O'Dell et al. (1978). A phase lag of about 2 months of the 6.7 GHz radio curve with respect to that at 10.7 GHz (Andrew et al., 1978) can be noticed. The phase lag seems to be still larger at 1.6 GHz (Webber et al., 1980), the outburst that appears at the beginning of 1973 in the curves of Andrew et al. is delayed to the end of 1973 in the curve of Webber et al. The steady

Table 2. Near infrared photometry of the sources

object	J	H	K	L	date
0048 - 097	14.41 ± .15	13.82 ± .15	12.97 ± .12		12.18.80
	13.97 ± .15	13.33 ± .12	12.54 ± .10	9.96 ± .18	06.16.81
	14.73 ± .10	13.86 ± .10	12.71 ± .10		12.12.81
	14.68 ± .10	13.85 ± .10	12.87 ± .10		12.16.81
0113 - 118		15.92 ± .22	15.01 ± .24		06.17.81
0202 - 172		15.63 ± .18	14.71 ± .23		12.17.80
		16.81 ± .15	15.14 ± .30		12.16.81
0336 - 019	15.45 ± .25	15.00 ± .20	14.57 ± .15		12.20.80
		15.90 ± .20	14.97 ± .22		12.12.81
		15.96 ± .12	14.99 ± .25		12.16.81
0422 + 004	14.03 ± .10	13.16 ± .10	12.26 ± .10	9.35 ± .20	12.18.80
	13.85 ± .10	13.09 ± .10	12.21 ± .10	9.52 ± .20	02.16.81
	14.50 ± .10	13.80 ± .07	12.99 ± .08		12.12.81
	14.09 ± .07	13.20 ± .07	12.30 ± .07	9.81 ± .20	12.16.81
0430 + 052	12.51 ± .10	11.69 ± .10	10.64 ± .10	9.01 ± .24	12.17.80
0735 + 178	13.32 ± .10	12.39 ± .10	11.80 ± .10		12.19.80
	12.31 ± .06	11.46 ± .06	10.94 ± .06	9.45 ± .30	02.18.81
	14.09 ± .09	13.43 ± .08	12.72 ± .09		12.17.81
0736 + 017	15.22 ± .15	14.24 ± .15	13.65 ± .13		12.18.80
	14.61 ± .10	13.95 ± .10	13.04 ± .07		12.12.81
	14.38 ± .08	13.56 ± .06	12.60 ± .06	10.03 ± .30	12.16.81
0743 - 006	15.10 ± .14	14.75 ± .10	14.02 ± .11		12.17.81
0823 + 033	15.30 ± .15	14.84 ± .20	14.16 ± .11		12.20.80
	13.91 ± .08	13.24 ± .06	12.79 ± .08		12.12.81
	13.92 ± .07	13.12 ± .06	12.51 ± .07		12.16.81
0906 + 015	15.96 ± .20	15.23 ± .22			12.20.80
		14.65 ± .20	14.14 ± .15		02.16.81
	15.69 ± .13	15.42 ± .12	14.20 ± .21		12.16.81
1034 - 293	14.62 ± .13	13.61 ± .10			12.20.80
	14.56 ± .10	13.61 ± .10	12.49 ± .10		02.18.81
	14.44 ± .15	13.45 ± .13	12.36 ± .10	10.18 ± .15	06.15.81
	15.02 ± .14	13.92 ± .07	13.31 ± .11		12.12.81
1055 + 018	15.10 ± .11	14.44 ± .08	13.28 ± .10		12.12.81
1244 - 255	15.47 ± .13	14.95 ± .11	13.90 ± .13		06.17.81
	15.52 ± .12	14.44 ± .08	13.99 ± .10		12.16.81
1253 - 055	15.34 ± .15	14.45 ± .15	13.72 ± .15		12.20.80
	13.57 ± .06	12.65 ± .06	11.81 ± .06	9.45 ± .12	06.17.81*
	14.84 ± .08	13.77 ± .07	12.80 ± .07		12.16.81

* M = 7.38 ± .25

decrease of the flux after 1973 observed at shorter wavelengths also appeared in the radio curves. The shortest time scale of variability observed at 10.7 GHz is of the order of 6 months. Our 22 GHz observations do not exhibit evidence of variability, but indicate that the source was at a minimum by that time. Simultaneous multifrequency observations were performed by Owen et al. (1978, 1980), O'Dell et al. (1978), and Landau et al. (1983); they show the radio spectral index is variable. VLA maps were obtained by Balick et al. (1982) and superluminal expansion is quoted by several authors (e.g. Walker et al., 1981). The near infrared and millimeter measurements can be smoothly joined over by the recent data obtained by IRAS in the 10–100 μm range (Fig. 1a).

0735+178: The fluctuations of the radio flux are relatively small, as compared to other objects of our sample; the characteristic time of variability $dt/d\ln S$ is about 2 years at 15.5 GHz (Dent et al., 1974). In the near infrared, our data and many other measurements (Rieke et al., 1977; O'Dell et al., 1978; Allen et al., 1982; Impey et al., 1981) show strong variability. We do not show all data in Fig. 1b to avoid crowding. Our measurement of 1980 December

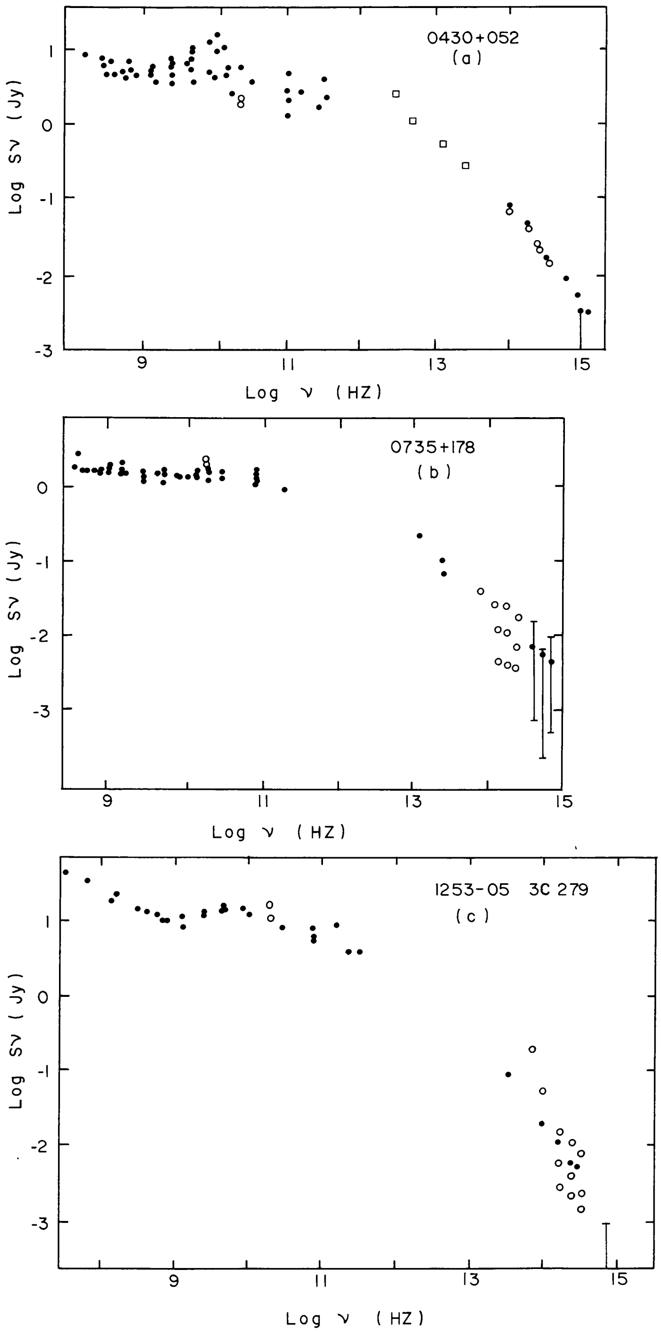

Fig. 1a–c. Energy distribution of 3 sources: **a** 0430+052, **b** 0735+178, **c** 1253−05. Open circles represent our radio and infrared data; filled circles data from Rieke et al. (1977), Condon et al. (1978), O'Dell et al. (1978), Neugebauer et al. (1979), Landau et al. (1980, 1983), Kühr et al. (1981), Jones et al. (1981), and Gear et al. (1984). The range of *UBV* variations observed Pollock et al. (1979) and Pica et al. (1980) are indicated by bars. Squares in **a** stand for the IRAS fluxes as reported in the Point Source Catalog (IRAS, 1985) and corrected for a spectral index of 1.25

combined with the measurement of Allen et al. (1982) indicates a variation in *K* of about 1.5 mag within one month, but measurements in consecutive days (e.g. Impey et al., 1982) do not show large variations, so that the characteristic time of variability is about 2–3 weeks. The source shows strong and variable polarization in the infrared-optical region; the degree of polarization is about 20% in *K* and increases toward shorter wavelengths (Impey et al., 1982); at optical wavelengths the polarization reaches 30% (Kinman, 1976). Many authors monitored this object at optical wavelengths (e.g. Bregman et al., 1984 and references therein). The most rapid time scale for a variation of 1 mag in *B* is about 8 days; day-to-day flickering of 10%–15% is observed. A number of simultaneous observations at many wavelengths has been performed. Bregman et al. (1984) extended the simultaneous observations to UV and X-rays. In summary, as one moves from radiofrequencies towards the UV, the amplitude of variability is smoothly increasing, the characteristic time scale of variability is decreasing, and the polarization is increasing. The VLBI map of Bååth et al. (1981) shows a dense core of about 5 milliarcsecond diameter with a weak extension which could be a jet.

0736+017: Netzer et al. (1979) report optical variability, large variations occurred in the continuum while the emission lines remained constant. Pica et al. (1980) observed fluctuations of about 0.5 mag on time scales of weeks. Our near infrared data and previous measurement by Hyland and Allen (1982) show variations of about 1 mag in *K*; in December 1981 we observed variation of ~0.4 mag in four days. The shortest $dt/d\ln S$ is about 6 months at 10.7 GHz (Andrew et al., 1978). Simultaneous multifrequency observations were performed by Owen et al. (1978), O'Dell et al. (1978), and Landau et al. (1983). The spectrum is flat up to 10^{11} Hz.

1253−055 (3C279): This QSO is a well known violently variable source. Previous near infrared photometry was performed by Rieke et al. (1977) and by Neugebauer et al. (1979). We found variation of about 2 mag in *K* in 6 months. Our observations at 22 GHz show that the flux dropped by about 5 Jy (30%) between 10/1981 and 5/1982, which may be related to the fading in *K* by one magnitude between 6/1981 and 12/1981. A correlation seems to exist between the radio curves of Andrew et al. (1978) and the observations in *K* performed between 1967 and 1977 by Neugebauer et al. (1979), with a phase-lag of the order of half year. VLBI observations suggest the presence of a jet-like structure extending from a compact core, with superluminal motion (Pauliny-Toth et al., 1981). The spectrum is shown in Fig. 1c.

4. Discussion

For most of the sources that we observed, the flat radio spectrum can be smoothly joined over the spectral gap (10^{11}–10^{14} Hz) to the infrared data. The IRAS observations in the range $3\ 10^{12} - 2.5\ 10^{13}$ Hz of 3C120 (IRAS, 1985) and of five quasars (Neugebauer et al., 1984) fully justify such a smooth interpolation. The near infrared spectral indices in our sample range from $\alpha \cong 0$ to 1.6 (most are $\cong 1$), and the mean spectral index from 1.35 cm to 2.2 μm is 0.74 ± 0.12, typical of optically thin synchrotron emission. The steepening toward infrared occurs around 10^{11}–10^{12} Hz; for two objects, 0133−118 and 0743−006, the break is close to 10^{10} Hz.

The smooth behaviour of the spectrum suggests a unique (or dominant source and a common synchrotron inverse Compton origin of the radio and infrared-optical radiation. The "cosmic conspiracy" that would make random homogeneous components to produce spectra of similar character but different strengths is unlikely. The idea of a dominant source is also supported by the correlation of variability at different wavelengths. Although no systematic monitoring has yet been performed at near infrared wavelengths, a number of simultaneous multifrequency measurements (e.g. Rudnick et al., 1978; Bregman et al., 1984) show that the differences between spectra obtained at different epochs are smoothly increasing functions of frequency. The scattering of the observational data (some examples are shown in Fig. 1) suggests that in most sources the amplitude of variability steadily increases from low radio frequencies to the IR-optical region of the spectrum. There is also a steady decrease of the characteristic time of variation $dt/d\ln S$ from years at centimeter wavelengths to weeks at optical wavelengths and a phase lag of the low frequency variability curves with respect to those obtained at higher frequencies. For many compact radio sources the angular sizes estimated on the basis of the characteristic time of variability are smaller than those directly measured by VLBI, and this discrepancy is successfully accounted for in models in which the relativistic electrons are produced in an expanding blast wave (e.g. Blandford and McKee, 1977; Marscher, 1978). We are therefore encouraged to discuss a model in which the only limitation to the time scale of variability is the decay time of the electron energy by synchrotron radiation (Tucker, 1975):

$$\tau \cong 5\ 10^{11} B^{-3/2} \nu_m^{-1/2} \sin^{-3/2} \varepsilon\,, \qquad (1)$$

where τ is given in seconds, B in Gauss, ε is the pitch angle and ν_m the frequency of the peak of the radiation spectrum

$$\nu_m = 3\ 10^6 B\gamma^2 \sin\varepsilon\,, \qquad (2)$$

where γ is the Lorentz factor of the electron.

The simple model that we shall examine and which is able to explain most of the variability characteristic of "blazars", is based on the following hypotheses: 1) The emission originates in a dominant source which is optically thin over the whole spectrum, 2) The electrons are injected in the source at high energy, with a nearly monoenergetic energy distribution, 3) As the energy of the electrons decays through synchrotron or inverse Compton radiation, the fluctuations in the electron density $N(\gamma)$ propagate to lower energies 4) The characteristic time scale of variability is given by Eq. (1), and is not directly related to the size of the source.

The geometry is not relevant in a simple approach. Equations (1) and (2) are valid in the reference frame of the source; if the source is moving relativistically toward the observer, appropriate Lorentz transformations and Doppler corrections should be applied to yield the observed quantities. The strong polarization usually observed indicates that the magnetic field is not isotropically distributed, but presents large scale uniformity. If the source is concentrated in a thin shell behind the front of a blast wave, the main direction of the magnetic field is parallel to the shell, due to compression of the external medium.

The mechanism that accelerates or injects high energy electrons into the source is very fast and presents rate fluctuations on time scale shorter than a day, as indicated by the flickering observed at optical wavelengths in many sources. If the same mechanism is able to inject electrons over a broad energy distribution (e.g. a power law), we should expect to observe comparably short rise time in radio or IR outbursts, followed by longer decay time given by Eq. (1). If, on the contrary, the electrons just flow down through the energy spectrum, the rise time and decay time, and the phase lag with respect to significantly shorter wavelengths, are all similar, as observed.

In a stationary condition ($dN(\gamma)/dt = 0$) and with constant magnetic field, conservation of the electron flow over the energy spectrum gives $N(\gamma) \propto \gamma^{-2}$, the resulting spectral index being 0.5, a value that lies between the flat radio spectra and the radio-near IR spectral indices ($\cong 0.7$) of the objects observed in this work. The steeper indices which are observed in the near IR-optical region can be explained in several ways. While γ of individual electrons decreases with time, B may also decrease if the electrons get farther from the injection region; the energy loss rate $d\gamma/dt \propto -\gamma^2 B^2 \beta^2 \sin^2 \varepsilon$ results then equivalent to $d\gamma/dt \propto -\gamma^{+k}$ with $k > 2$. Alternatively the electrons may be injected at right angles to the magnetic field and evolve to smaller pitch angles, which is also equivalent to $k > 2$. Still another possibility to explain $\alpha > 0.5$ in the IR-optical region is subsequent reddening. In the lower portion of the spectrum $\alpha < 0.5$ may be explained as follows: At low electron energies, synchrotron inverse Compton losses become very inefficient, and are possibly overcome by expansion losses. Then a possibility is $d\gamma/dt \propto -\gamma/t$ (Tucker, 1975) which implies a flat energy spectrum and $\alpha \sim -0.5$ for the radiation spectrum; $\alpha > -0.5$ can be obtained if the expansion is not uniform.

The characteristic time scales of variability observed in 0735+178 (about 2 years at 15 GHz, 2–3 weeks in K, and 1 week in B) are in agreement with the $\nu^{-1/2}$ law, and direct use of Eq. (1) implies a magnetic field of about 30 Gauss. If we consider a source moving toward the observer with a bulk Lorentz factor $\Gamma = 10$ with respect to an external medium with $z = 0.424$, the estimated magnetic field in the reference frame of the source is increased by a factor of 14. The fact that X-ray emission of 0735+178 is not variable within the observational limits (Bregman et al., 1984) suggests that the injection energy of the electrons is not large enough to produce synchrotron emission at that frequency; the X-ray emission is attributed to inverse Compton scattering of low frequency photons. The injection energy corresponding to ν_m in the range of 10^{16}–10^{17} Hz, between UV and X-rays, is about 10 GeV (a factor of 14 smaller in the reference frame of the source, in the above hypothesis). If the injection energy effectively corresponds to synchrotron frequancies around $10^{16.5}$ Hz, the 10–15% flickering on time scales of a day observed in the B band must be reminiscent of about 100% fluctuations at the injection frequency, which were subsequently filtered by synchrotron decay time. The strong polarization of the IR-optical region, if extrapolated toward higher frequencies, suggests that at $10^{16.5}$ Hz the polarization is close to the maximum allowable polarization ($\cong 80\%$ for $\alpha \cong 1.5$).

The remaining objects studied in this work clearly bear strong similarity with 0735+178, although in some cases the amount of available data is considerably smaller. Among the objects which are best studied, the BL Lac 0048−097, the Seyfert galaxy 3C120 and the QSO 0736+017 present relatively shorter time scales of variability than 0735+178, which in our model implies stronger magnetic field in the sources. It is remarkable that objects belonging to different classes may present quite similar properties in their continuous spectrum; clearly in these objects the synchrotron emission of the nucleus dominates the continuum, so that the nature of the underlying galaxy is of secondary importance to this respect.

5. Conclusion

From our discussion the picture that emerges for the injection mechanism in blazars is a nearly monoenergetic beam of electrons with energy of the order of GeV's, that presents pulses or strong fluctuations on time scales of a day or less as well as on longer timescales, and have a well defined geometry with fixed angle between the beam and the magnetic field. As indicated by the variability of polarization angles, the geometry is the same for successive pulses, but may change with time scales of months. Our model predicts the possibility of observing individual bursts crossing down the spectrum; about 3 weeks of daily monitoring of a few objects in *UBVRIJK* bands would be sufficient to show up the effect.

Acknowledgements. We wish to thank the European Southern Observatory staff for its efficient assistance and Dr. R. Opher for helpful discussions.

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