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MULTIFREQUENCY OBSERVATIONS OF BLAZARS. I. THE SHAPE OF THE 1 MICRON TO 2 MILLIMETER CONTINUUM

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ABSTRACT

We present near-simultaneous measurements in 11 wavebands between 1 μm and 2 mm of a sample of 13 "blazars" (BL Lac objects and optically violent variable quasars). These measurements represent the first comprehensive attempt to determine the infrared-to-millimeter–wave properties of this class of object, which emit the bulk of their luminosity in the far-infrared region. Most of the sources have very flat millimeter/submillimeter spectra up to the highest observed frequency. However, 3C 279 and 3C 446 show evidence of turnovers in their submillimeter spectra. The 1–4 μm spectra can be characterized by simple power laws, all steeper than -0.9; several sources, however, show evidence of spectral beaks in the 10–20 μm region, suggestive of energy losses. We show that the spectral properties are consistent with synchrotron emission from relativistic jets aligned close to the line of sight and discuss our observations in relation to such models.

Subject headings: BL Lacertae objects — infrared: sources — quasars — radiation mechanisms

I. INTRODUCTION

Virtually all strongly polarized extragalactic objects have remarkably similar properties, namely, violent variability, a flat radio spectrum with VLBI maps showing very compact core regions, often with an associated "jet," and a smooth optical/infrared continuum. These objects are therefore generally regarded as a single class and are called "blazars" (Angel and Stockman 1980).

It has become clear in recent years that the best way to discriminate between various models of the continuum emission in these objects is to measure the spectral shape over as wide a range in frequency as possible, and most importantly, as close in time as possible. A number of multifrequency studies of compact radio sources have been published (Beichmann *et al.* 1981; Bregman *et al.* 1981, 1982, 1984; Worrall *et al.* 1982, 1984*a*, *b*; Glassgold *et al.* 1983); all these papers, however, have lacked data in the crucial submillimeter/far-infrared region. This spectral domain is essential for determining the properties of the most compact regions (see e.g., Gear *et al.* 1984; Marscher and Gear 1985; Marscher 1983) where the transition from optically thick to optically thin emission occurs. We have previously shown that the millimeter-wave spectral index of almost all flat-spectrum radio sources remains close to zero up to 1 mm (Gear *et al.* 1984), and that in the case of 3C 273, the millimeter-to-infrared emission arises in the same region (Clegg *et al.* 1983, Robson *et al.* 1983). This paper extends our single-epoch, submillimeter and infrared observations to a sample of 13 sources. The variability of this class of object is often complex and difficult to relate to simple models (see, e.g., Epstein *et al.* 1982; Holmes *et al.* 1984*a*), except perhaps when there is a single well-defined outburst such as the 1983 event in 3C 273 (Robson *et al.* 1983). This paper therefore also provides a database for our continuing multifrequency monitoring program. Variability will be discussed in Paper II (Gear *et al.* 1985).

II. OBSERVATIONS

a) *Sample*

A list of sources was compiled using the following criteria: (1) the source was classified either as a BL Lac object, an optically violently variable quasar (OVV), or one exhibiting apparent superluminal motions on VLBI maps; (2) the extrapolated radio flux at 1 mm was greater than 1 Jy; (3) the source was observable from UKIRT (decl. range $-40°$ to $+60°$). Time and weather limitations have so far prevented us from observing our full sample of 22 sources; the observations presented here therefore do not represent a complete sample. Of the sources observed, eight, namely 0235+164, 0420−014, 0735+178, 0851+202, 1308+326, 1413+135, 1921−293, and 2200+420 are BL Lac objects, while five, namely 0736+017, 1253−055, 1641+399, 2223−052, and 2251+158 are OVV quasars. From this list, 1253−055, 1641+399 and 2200+420 are known to exhibit superluminal motions (Porcas 1984).

b) *Techniques*

The United Kingdom Infrared Telescope (UKIRT) was used to obtain measurements at 1.25, 1.65, 2.20, 3.45, 10, 20, 380, 770, and 1070 μm over the periods 1982 September 10–13, 1983 February 2–5, and 1983 March 4–7. UKIRT was also used to make submillimeter measurements 1983 August 4–7 and 1983 September 15–19 and some of the infrared measurements 1983 September 15–19. The NASA Infrared Telescope Facility (IRTF) was used to make the 1–10 μm measurements 1983 August 4–7 and the 10 μm measurement of 1983 September 15.

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Both telescopes use f/35 focuses, with matched sets of 1–20 μm filters.

The submillimeter measurements were made with the QMC/Oregon photometer system (Ade *et al.* 1984) using narrow-band filters described by Cunningham (1982) and also shown in Robson (1982). FWHM beamwidths, obtained by scanning through Mars, were 55″, 58″, and 65″ at 380, 770, and 1070 μm respectively. Calibration was made with respect to the planets (Griffin *et al.* 1985); the assumed brightness temperatures of the planets are shown in Table 1. Calibration procedure is described in Rowan-Robinson, Clegg, and Ade (1975) and Cunningham *et al.* (1981). The spectral index α ($S_\nu \propto \nu^\alpha$) was assumed to be zero for all sources, but because of the narrow-band nature of our filters, changing α from zero to -1 would only mean a 3% decrease to our derived fluxes.

The 1–20 μm observations were made with the UKIRT and IRTF common-user instrumentation; calibration was performed against standard stars from Longmore and Williams (1985). Since most of the sources observed are at high galactic latitude, no extinction corrections were needed. However, in the case of 0735+178, 0736+017, 0851+202, and 2200+420, galactic extinction needs to be considered. Because the literature contains multifrequency observations where (*a*) extinction corrections have been ignored, (*b*) a crude cosecant galactic latitude correction applied, and (*c*) more sophisticated corrections applied, we choose to present our results in Table 2 with no corrections. However, using the data of Lucke (1979) and the extinction relations given in Savage and Mathis (1979), we have determined extinction corrections for these sources; we used $A_v = 0.9$ for 0735+178, 0736+017 and 2200+420, $A_v = 0.6$ for 0851+202, and $A_v = 0.3$ for 1921−293. In the case of these sources, the extinction-corrected fluxes were used to calculate the spectral slopes given in Table 3. None of the conclusions drawn in § III are affected by the extinction corrections.

The 1.3 and 2.0 mm measurements were made 1983 April 6–10 with the NRAO millimeter continuum system (Radostitz *et al.* 1985) mounted at the f/13.8 Cassegrain focus of the 12 m dish on Kitt Peak. Calibration was performed against the planets (Table 1).

III. RESULTS

The results of the observations and calibration procedure are presented in Table 2 and Figure 1. The uncertainties quoted are the statistical and photometric uncertainties added in quadrature. Derived spectral indices are given in Table 3. We now briefly discuss each source:

a) *0235+164*.—This source has a very steep infrared spectrum, and our limited simultaneous spectral coverage shows no evidence for any breaks.

b) *0420−014*.—The submillimeter spectrum of this source is flat from 280 to 800 GHz; the infrared spectrum is also a simple power law.

c) *0735+178*.—This is the original "Cosmic Conspiracy" source (Cotton *et al.* 1980), but unfortunately we do not have sufficient millimeter data to determine the millimeter/submillimeter spectral index. The 20 μm upper limit suggests there may be a spectral break in the 10–20 μm region.

d) *0736+017*.—The simultaneous 1–1100 μm data show no evidence of any breaks. The 1.3 and 2.0 mm data taken one month later, however, show an inverted millimeter-wave spectrum. This source also has a very steep infrared spectrum and is therefore reminiscent of the millimeter-wave and infrared properties of 1413+135 found by Bregman *et al.* (1981) and Beichmann *et al.* (1981).

e) *0851+202* (*OJ 287*).—OJ 287 is remarkable for the consistency of its power-law behavior both in the submillimeter from 1100 to 400 μm and the infrared from 1 to 20 μm. Extrapolating the two well-defined slopes gives a value 2×10^{12} Hz for the turnover, indicating that this source must be extremely compact, consistent with its short infrared variability timescale (Holmes *et al.* 1984*b*). We note that our measurements were taken shortly after a dramatic infrared burst in 1983 January, reported by Holmes *et al.* (1984*b*).

f) *1253−055* (*3C 279*).—3C 279 shows the usual flat 1100–800 μm spectrum, but has a break near 800 μm. More data are required at 10 and 20 μm to determine whether the submillimeter spectrum connects smoothly with the infrared.

g) *1308+326*.—The upper limit at 10 μm indicates there may be a break in the region 4–10 μm. The 1 mm upper limit also lies below the 2 mm measurement, although the 2 mm point was taken one month after the 1–1100 μm measurements.

h) *1413+135*.—This empty field object (Rieke, Lebofsky, and Kinman 1979) is known to have a very steep infrared spectrum. We have only obtained submillimeter data, which show a flat spectrum.

i) *1641+399* (*3C 345*).—Like 0420−014 and OJ 287, 3C 345 has a submillimeter spectral index of zero from 280 to 800 GHz. The infrared data indicate that there may be a break at 10 μm; alternatively, the 10 μm datum may show excess emission over the 1–20 μm continuum. Further data are obviously required.

j) *1921−029* (*OV 236*).—This source shows a flat millimeter-wave spectrum with the upper limit at 800 μm, suggesting a possible break near 1 mm. The 2–10 μm spectrum is a single power law, with some curvature at 1 μm. We have previously measured this source during an outburst when its submillimeter spectrum was inverted and the 1–4 μm spectrum was curved, indicating a high-energy cutoff in the electron energy distribution (Gear *et al.* 1983).

TABLE 1

ASSUMED PLANETARY BRIGHTNESS TEMPERATURES

Effective Wavelength (mm)	Mean Frequency (GHz)	Brightness Temperature (K)		
		Jupiter	Uranus	Neptune
0.40.........	808	144.1 ± 2.6	73.9 ± 1.9	61.1 ± 3.5
0.80.........	392	166.6 ± 2.4	84.3 ± 1.2	79.6 ± 3.8
1.10.........	279	168.0 ± 2.5	91.1 ± 1.1	86.4 ± 3.9
1.30..........	227	170.2 ± 3.4	94.6 ± 1.9	91.5 ± 2.8
2.00.........	151	171.9 ± 3.6	108.4 ± 2.3	107.3 ± 4.5

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TABLE 2

1 μm to 2 mm Flux Measurement of a Sample of 13 Blazars[a]

Source	Date[b]	J	H	K	L	N	Q	400	800	1100	1300	2000
0235+164	1983 Feb	3.9 (0.2)	5.8 (0.6)	9.6 (0.6)	19.6 (1.3)	...	$3\sigma < 320$	...	$3\sigma < 1.5$	1.4 (0.3)	...	1.9 (0.3)
0420−014	1983 Mar	3.3 (0.1)	4.6 (0.2)	7.0 (0.2)	...	$3\sigma < 60$	...	3.7 (1.1)	2.9 (0.3)	3.0 (0.4)	...	...
0735+178	1983 Feb	7.4 (0.2)	10.5 (0.3)	15.8 (0.4)	27.9 (1.3)	163 (37)	$3\sigma < 350$	...	...	0.8 (0.2)	...	$3\sigma < 1.1$
0736+017	1983 Mar	2.3 (0.1)	3.8 (0.3)	6.1 (0.4)	10.3 (1.2)	...	$3\sigma < 1000$	...	$3\sigma < 2.2$	2.0 (0.3)	1.3 (0.3)	0.8 (0.2)
0851+202 (OJ 287)	1983 Feb	32.6 (0.4)	44.9 (0.4)	61.8 (0.5)	101.6 (3.0)	300 (70)	580 (115)	3.9 (0.8)	4.0 (0.4)	4.0 (0.4)	...	4.9 (0.5)
1253−055 (3C 279)	1983 Feb	2.2 (0.1)	3.5 (0.2)	5.1 (0.2)	10.9 (1.3)	...	...	0.9 (0.2)	2.8 (0.4)	2.8 (0.4)	2.5 (0.3)	2.7 (0.4)
1308+326	1983 Mar	6.8 (0.3)	9.4 (0.6)	12.7 (0.9)	21.7 (1.0)	$3\sigma < 50$	...	...	...	$3\sigma < 1.0$	...	1.5 (0.5)
1413+135	1983 Feb	...	...	...	...	...	...	1.0 (0.3)	1.7 (0.3)	1.7 (0.4)	...	1.0 (0.3)
1641+399 (3C 345)	1983 Feb	8.4 (0.2)	13.0 (0.4)	18.9 (0.1)	35.2 (3.0)	200 (40)	275 (30)	5.5 (1.0)	6.8 (0.7)	6.1 (0.3)	...	5.2 (1.0)
1921−293 (OV 236)	1983 Aug	4.5 (0.2)	7.5 (0.3)	10.6 (0.4)	...	77 (11)	...	...	$3\sigma < 4.0$	4.8 (0.4)	4.5 (0.8)	4.3 (0.5)
2200+420 (BL Lac)	1983 Aug	14.1 (0.2)	23.5 (0.2)	30.0 (0.2)	...	118 (15)	$3\sigma < 400$	...	...	1.9 (0.2)	...	2.4 (0.4)
2223−052 (3C 446)	1982 Sept	12.4 (0.2)	17.6 (0.2)	23.5 (0.7)	49.9 (3.8)	150 (35)	370 (120)	...	3.9 (1.0)	6.8 (1.7)	...	5.8 (0.4)
2251+158 (3C 454.3)	1983 Aug	1.6 (0.1)	2.0 (0.1)	2.6 (0.1)	...	60 (13)	...	...	3.0 (1.0)	2.0 (0.3)	2.0 (0.3)	$3\sigma < 3.0$

[a] The uncertainties of measurement (described in the text) are indicated by parentheses. Cols. J to Q in mJy; cols. 400 to 2000 in Jy.

[b] All values in cols. 1300 and 2000 from 1983 April.

TABLE 3

SPECTRAL INDICES AND LUMINOSITIES DERIVED FROM OBSERVATIONS

Source	Redshift	1–4 μm Spectral Index	$L/L_\odot$ (h^{-2})
0235+164.........	0.582	-1.6 ± 0.2	4.2×10^{12}
0420−014.........	0.915	-1.3 ± 0.2	5.9×10^{13}
0735+178.........	0.424	-1.1 ± 0.1	2.0×10^{13}
0736+017.........	0.191	-1.4 ± 0.2	9.4×10^{12}
0851+202.........	0.306	-1.0 ± 0.1	6.2×10^{11}
1253−055.........	0.538	-1.5 ± 0.2	1.4×10^{13}
1308+326.........	0.996	-1.1 ± 0.1	4.4×10^{13}
1641+399.........	0.595	-1.4 ± 0.1	4.4×10^{13}
1921−293.........	0.352	-1.4 ± 0.2	6.2×10^{12}
2200+420.........	0.07	-1.0 ± 0.1	2.6×10^{11}
2223−052.........	1.404	-1.2 ± 0.1	4.1×10^{14}
2251+158.........	0.859	-0.9 ± 0.3	3.5×10^{13}

k) *2200+420* (*BL Lac*).—Our measurements are consistent with this source having a flat submillimeter spectrum and a single infrared power law, although there is some evidence of a cut-off at ~1.5 μm.

l) *2223−052* (*3C 446*).—This source has a spectral break in the infrared and also shows evidence of a break in its submillimeter spectrum. The 1100 and 800 μm data extrapolate to the 20 and 10 μm points with a slope of −0.8, steepening to the 1–4 μm slope of −1.2. This behavior is very reminiscent of the quiescent millimeter-to-infrared spectrum of 3C 273 (Clegg *et al.* 1983).

m) *2251+158* (*3C 454.3*).—Our limited spectral data show a 1–2 μm power law with no departure (outside the errors) from a flat millimeter spectrum. There does, however, appear to be an excess at 10 μm over the 1–2 μm power law. More complete spectral coverage is required to determine the possibly unusual spectral shape of this object.

IV. DISCUSSION

a) *Spectral Shape*

The radio spectral indices of all these objects remain close to zero up to 1 mm (Jones *et al.* 1981; Ennis, Neugebauer, and Werner 1982; Gear *et al.* 1984). However, by extending our

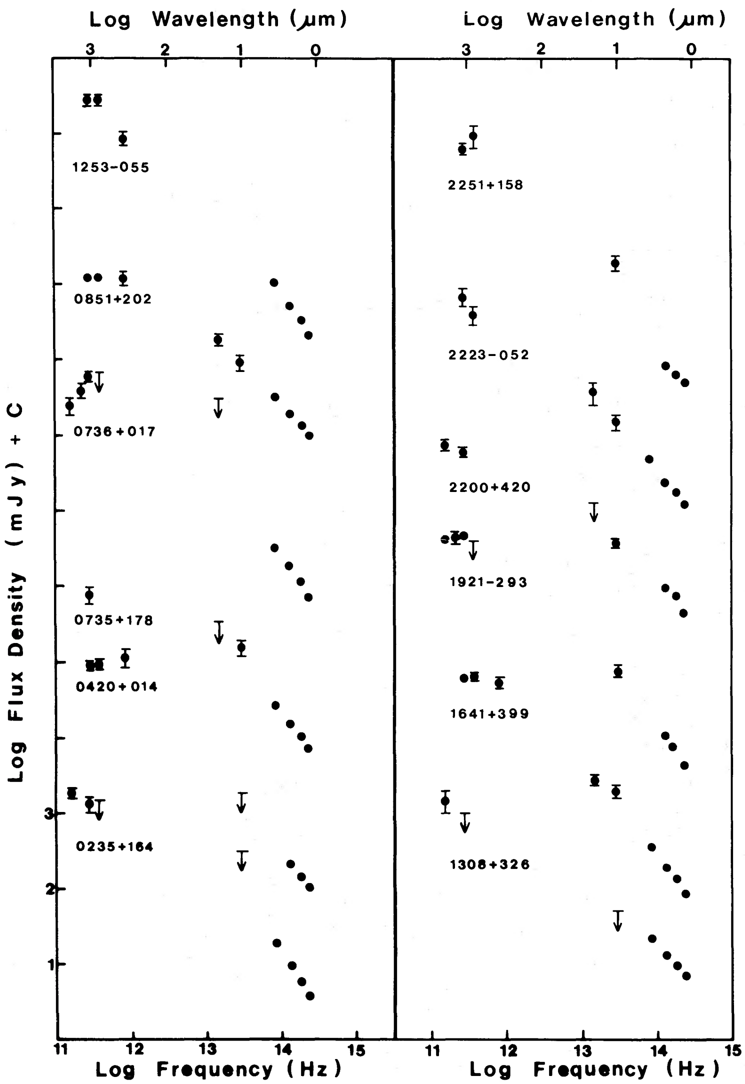

FIG. 1.—Infrared to millimeter-wave spectra of 12 blazars. The 1–1100 μm data for each source were taken over periods of no more than four days (see Table 2). For those sources which were detected at only one submillimeter wavelength we have also plotted the nonsimultaneous 1.3 and 2.0 mm data taken in 1983 April. Apart from 0235+164 and 1308+326, all sources have been displaced upward for clarity.

observations into the submillimeter we begin to see a break in 3C 279 and 3C 446, with possible evidence of breaks in two others (0736+017 and OV 236), confirmation of which requires more submillimeter data. The rest of our sample show no signs of a turnover; in fact, 0420+014, OJ 287, and 3C 345 have submillimeter spectral indices of zero up to 800 GHz. We find it very hard to believe that such consistency of behavior in these sources could arise through the *chance* superposition of *unrelated* synchrotron self-absorbed components (see Cook and Spangler 1980 and § IV*c*). Rather, we believe that this indicates some common property of the most compact regions in these objects.

The 1–4 μm spectral indices of our sample vary between -0.9 and -1.6, compared to a mean value of -0.8 found by Neugebauer *et al.* (1979) for a sample of quasars (note that Landau *et al.* 1983 incorrectly concluded that the millimeter-to-optical spectral indices of some objects common to our sample were all in fact close to -0.7 because they were lacking submillimeter and infrared data). These steeper spectral indices suggest that the electron-energy distribution in these objects has been modified by energy losses. This hypothesis is supported by the fact that several sources show breaks in their spectra near 10 μm. We also note that OV 236 and BL Lac show some curvature at 1 μm, possibly indicating a cutoff in the electron-energy distribution.

With the possible exceptions of 3C 345 and 2251+158 at 10 μm, there is no evidence of any excess emission caused by thermal radiation from either warm dust in the infrared or cool dust in the submillimeter. Clegg *et al.* (1983); Harvey, Wilking, and Joy (1982); and Robson *et al.* (1985) also found no evidence for thermal emission from 3C 273, 3C 345, and a sample of optically selected quasars respectively. It has been suggested that optically thin emission from silicate grains at a gradient of temperatures may produce the observed power law in Seyfert galaxies; however, the variability of blazars at these wavelengths (Angel and Stockman 1980; Impey *et al.* 1982, 1984; Paper II) argues against this mechanism.

b) Luminosity

Having determined the millimeter and infrared spectra of these sources, we can estimate the 1 μm to 2 mm luminosity (provided we know the redshift). Since in the absence of a strong, hard X-ray component the bolometric luminosity is dominated by this region, we can effectively determine the total luminosity of each source.

The luminosity in the comoving frame of the blazar, assuming cosmological redshift and isotropic emission, and taking $q = 0$, is given by

$$L = 4\pi(c/H)^2 z^2 (1 + z/2)^2 S \,, \qquad (1)$$

where S is the total flux in the observer's frame, integrated over frequency. To obtain an *underestimate of* S and hence L, we have integrated the observed spectra between 1 μm and 2 mm taking a straight line connecting the highest observed submillimeter frequency and the lowest observed infrared frequency. The values thus obtained are given in Table 3 (using the value $H_0 = 100h$ km s^{-1} Mpc^{-1}) along with the adopted redshifts. It is important to note, however, that these are only *apparent* luminosities; the true luminosity may be very much less if beaming obtains (see § IV*c*). It is therefore possible that sources with very high apparent luminosity have a high degree of beaming (see, e.g., Urry and Schafer 1984).

Our sample is obviously biased toward the brightest objects; as submillimeter sensitivity increases we should be able to detect fainter sources and sample a wider range of the luminosity function.

c) Interpretation

The fact that the millimeter-to-infrared spectra of these sources connect smoothly (see also Ennis, Neugebauer, and Werner 1982; Clegg *et al.* 1983) and show strongly correlated variability (Robson *et al.* 1983; Paper II) suggests that a single mechanism is producing the emission over this region. It is known from VLBI measurements that the flat radio spectrum of at least one source (0735+178) may be due to the superposition of a number of individual synchrotron components becoming self-absorbed at different frequencies, the so called "Cosmic Conspiracy" (Cotton *et al.* 1980). However, our conclusion is unaffected by this hypothesis, since at higher frequencies a greater proportion of the flux arises in an unresolved core (see, e.g., Jones *et al.* 1984), which we identify with the regions discussed here.

In order to be self-absorbed at such high frequencies, these sources must be very compact. A simple calculation using the formalism of Burbidge, Jones, and O'Dell (1974) results in angular sizes in the range 10^{-3} to 10^{-4} milli-arcsec. This calculation treats the emission as arising in a single homogeneous region. The problem with such a model is well known; it predicts an optically thick spectral index of 2.5 rather than the observed value of zero; thus we would have to appeal to a "Cosmic Conspiracy" argument to fit the observations. It is possible that millimeter VLBI will reveal such subcomponents all conspiring to produce the observed flatness; however, in order for this to occur, it is necessary to assume some relation between the magnetic fields and electron densities of the individual components (Cook and Spangler 1980). As the number of subcomponents required increases this becomes equivalent (at current spectral resolution) to considering a single region with smoothly inhomogeneous field and density.

A flat spectrum can arise more naturally in an inhomogenous model, since at different frequencies the emission is dominated by different parts of the source (Condon and Dressel 1973; de Bruyn 1976; Marscher 1977). Many other properties of compact sources such as low-frequency variability, apparent superluminal motion, and lack of strong X-ray emission (see, e.g., Porcas 1984) also arise naturally if the emitting region is considered to move relativistically. The energy requirements are also greatly reduced if the bulk motion is confined to a jet flow. Jets are also required to supply energy to the large-scale jets and hot spots seen in extended radio sources (Blandford and Rees 1974).

We consider synchrotron emission from a relativistic jet of the type described by Marscher (1980), inclined at an angle θ to the line of sight. An initially confined beam becomes free at a distance R_+ from the center of the source and the protons become nonrelativistic in the frame of the flow, so that flow is inertial with constant bulk Lorentz factor Γ_j. The jet has a constant opening angle, so that the channel width $r \propto R$. The relativistic electron internal energies will be converted to bulk kinetic energy, so that for a power-law distribution of electron energies $N(\gamma_e) = K\gamma_e^{-s}$, $K \propto R^{-2(s+2)/3}$; the magnetic field $B \propto R^{-1}$ for the component perpendicular to the flow and $B \propto R^{-2}$ for the component parallel to the flow. Marscher (1980) shows that the optically thin emission will be dominated by R_+ and that the variation of self-absorption with radius R

gives an optically thick spectral index

$$\alpha = -\frac{(s-1)}{2} + \frac{(5s-2)(s+4)}{[2(5s+7)]} = 0.98 \quad \text{for} \quad s = 2.4 \quad (2)$$

if the field component parallel to the flow dominates, and

$$\alpha = -\frac{(s-1)}{2} + \frac{7(s-1)(s+4)}{[2(7s+8)]} = 0.56 \quad \text{for} \quad s = 2.4 \quad (3)$$

if the component of the field perpendicular to the flow dominates. Therefore, although this model produces some flattening of the optically thick spectrum, it cannot be made entirely consistent with the observed values of the optically thick *and* optically thin spectral indices (except possibly for 0736+017).

Blandford and Königl (1979) have suggested that if a succession of mild shocks continually reaccelerates the electrons, then we may regard the jet as effectively isothermal (see also Blandford and Konigl 1979), in which case $K \propto R^{-2}$ and the field parallel to the shock (i.e., perpendicular to the flow) will be enhanced so that $B \propto R^{-1}$. The optically thin emission is once again dominated by R with spectral index $-(s-1)/2$ up to a frequency ν_2, where the synchrotron loss time at R_+ becomes comparable to the reacceleration time scale (see also Konigl 1981). The submillimeter turnover frequency will then be the turnover at R_+, with the flux S_m at ν_m given by

$$S_m = \frac{C_1(s)(1+z)^{(3-s)/2} K_+ D_j^{(s+3)/2} B_+^{(s+1)/2} R_+ r_+^2}{4d_l^2[(s-1)/2]\nu_m^{(s-1)/2}}, \quad (4)$$

where d_l is the luminosity distance, $D_j = \Gamma_j^{-1}(1 - \beta_j \cos\theta)^{-1}$ is the bulk Doppler factor, $C_1(s)$ is a function given by Hutter (1983), B_+ and K_+ are the magnetic field and coefficient of the electron energy distribution at R_+ respectively, and $R_+ \approx \Gamma_j r_+$. In the optically thick regime, the minimum radius from which we receive emission is a function of frequency

$$R_{\min}(\nu) = (1+z)^{-1} \times [C_2(s) K_+ D_j^{(s+2)/2} B_+^{(s+2)/2} R_+^{(s+6)/2}]^{2/(s+4)} \nu^{-1}, \quad (5)$$

where the function $C_2(s)$ is given by Hutter (1983). We therefore have for the received flux S_ν:

$$S_\nu \propto \nu^{-(s-1)/2} \int_{R_{\min}(\nu)}^{R_{\max}(\nu)} K B^{(s+1)/2} D_j^{(s+3)/2} r^2 dR, \quad (6)$$

where $R_{\max}(\nu)$ and $R_{\min}(\nu)$ are the maximum and minimum radii of the jet from which we receive emission at the frequency ν. Therefore:

$$\begin{aligned} S_\nu &\propto \nu^{-(s-1)/2} \int_{R_{\min}(\nu)}^{R_{\max}(\nu)} R^{-(s+1)/2} dR, \\ &\propto \nu^{-(s-1)/2} R_{\min}^{-(s-1)/2} \quad [s > 1], \\ &\propto \nu^0 = \text{constant}, \end{aligned} \quad (7)$$

as required by the observations. Thus, although the assumption that the shocks are frequent and energetic enough to overcome synchrotron and expansion losses may appear somewhat ad hoc, we feel it is justified by the data, at least to current spectral and temporal resolution. A more detailed discussion of the effects of shocks in relativistic jets will be given in a future paper (Marscher and Gear 1985). We also note that expressions (4) and (5) and hence any derived values of B and K are weakly model-dependent. Thus for the adiabatic jet case, the derived value of B will only be a factor of 2–3 smaller (The weak dependence of B and K on the jet-flow characteristics has been noted previously by Reynolds 1982).

Since the emission at ν_m arises entirely at R_+, we can estimate r_+ (strictly a lower limit) by assuming the brightness temperature in the rest frame T' is close to the Compton limit of 10^{12} K, so that

$$r_+ = \frac{C d_l S_m^{1/2} D_j^{-1/2}}{[2\pi k T']^{1/2}(1+z)^{3/2}\nu_m}. \quad (8)$$

Hence we have the three expressions (4), (5), and (8) for the three model parameters B_+, K_+, and r_+ in terms of the observables ν_m, S_m, s, z, and Γ_j.

We have measured ν_m for two of the sources, and for most of the others we can pin it down to a rather narrow range by extrapolating the infrared and submillimeter spectra. Assuming we are at the optimum angle for Doppler boosting, so that $\Gamma_j \approx D_j$, and taking the mean *observed* value of $\Gamma_j \approx 5$ (Cohen and Unwin 1984), we obtain values of $r_+ \approx 10^{15}$ to 10^{16} cm (10^{-3} to 10^{-2} pc) with $B_+ \approx 10^{-1}$ G and $K_+ \approx 10^8$ to 10^{10} cm^{-3}. The high derived magnetic fields support the hypothesis that the infrared spectra have been steepened by energy losses.

In this model the minimum variability time scale should be the smaller of r_+/c and the synchrotron loss time at R_+, which will be of the order hours for the parameters derived here. If, as the correlation between strong millimeter and X-ray emission found by Owen, Helfland, and Spangler (1980) suggests, the X-rays have a self-Compton origin, then we would expect the X-rays to vary on the same time scale. The model also predicts a frequency dependence of variability in the optically thick regime $t_{\text{var}} \propto \nu^{-1}$, giving predicted minimum time scales of days to weeks at 1 mm.

We have therefore presented a model which, although containing some rather crude assumptions, reproduces the observed spectral shape and gives physically reasonable derived values for the physical properties of the emitting region. More complete spectral data, particularly in the X-ray region where we expect to see Compton emission, will allow a more sophisticated model fitting. Variability studies are also crucial, as only by monitoring the propagation of an individual flare event can we constrain all the parameters of this model. The early 1983 outburst of 3C 273 offered such an opportunity and has been discussed in detail by Marscher *et al.* (1984). Variability of the blazars will be discussed in Paper II.

V. CONCLUSIONS

1. The 1 μm to 2 mm spectra of a sample of 13 blazars are characterized by power laws in the millimeter/submillimeter and infrared regions.

2. The millimeter-wave spectra of all sources are flat up to at least 300 GHz (1 mm), except for 0736+017 which has an inverted spectrum. Four sources, 0420−014, OJ 287, 1413+135, and 3C 345, remain flat up to 800 GHz (400 μm), while 3C 279 and 3C 446 show evidence of turnovers in their submillimeter spectra.

3. The 1–4 μm spectral indices are all steeper than −0.9, the steepest being −1.6. Several sources show spectral breaks around 10 μm, suggestive of energy losses.

4. We interpret the millimeter-to-infrared spectra as being due to synchrotron emission from an unresolved isothermal relativistic jet viewed close to the line of sight.

5. Using this model we derive physically reasonable values

for the core sizes, magnetic fields, and electron densities, and predict minimum-variability time scales less than a day in the X-ray and near-infrared and one week in the submillimeter.

6. More complete spectral coverage and variability data will enable us to fit a more sophisticated model to the continuum emission in these sources.

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