1986ApJ...304..295G

THE ASTROPHYSICAL JOURNAL, **304**:295–304, 1986 May 1

MULTIFREQUENCY OBSERVATIONS OF BLAZARS. II. THE VARIABILITY OF THE 1 μm TO 2 mm CONTINUUM

W. K. GEAR,[1,2,3,4] L. M. J. BROWN,[1,3] E. I. ROBSON,[1,3] P. A. R. ADE,[2,3,5] M. J. GRIFFIN,[2,3,5]
M. G. SMITH,[3,4,6] I. G. NOLT,[2,3,7] J. V. RADOSTITZ,[2,3,7] G. VEEDER,[4,8] AND L. LEBOFSKY[4,9]

Received 1985 June 27; accepted 1985 October 11

ABSTRACT

We present the results of monitoring, over a period of two years, a sample of 12 blazars, in 11 wave bands between 1 μm and 2 mm. All sources exhibit some variability, both in flux density and spectral shape. The infrared variability is consistent with repeated injections or reaccelerations of electrons, which subsequently suffer radiative losses. For OJ 287, 3C 279, and 3C 345 a decay and steepening of the infrared spectrum occurred as the submillimeter turnover evolved to lower frequencies, consistent with expansion of the emitting region. The peak flux, however, increased during this evolution. This behavior is inconsistent with most models for compact extragalactic sources, but it is naturally explained by shock waves traveling in an adiabatically expanding relativistic jet (Marscher and Gear).

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

I. INTRODUCTION

Blazars (BL Lac objects and optically violent variable [OVV] quasars) are variable at all observed wavelengths (see, e.g., Angel and Stockman 1980; Moore and Stockman 1984). The variations are often complex and difficult to fit with simple models (e.g., Epstein *et al.* 1982; Holmes *et al.* 1985; O'Dea, Dent, and Balonek 1984).

A simple extrapolation of the radio and optical/infrared spectra of most blazars indicates that the transition from flat (optically thick) to steep (optically thin) emission usually must occur in the millimeter/submillimeter region of the spectrum. Since the self-absorption turnover frequency of a synchrotron source is inversely proportional to its size, radiation at these wavelengths must originate in the *most compact* regions of a radio source.

Gear *et al.* (1985; hereafter Paper I) measured a sample of blazars in 11 wave bands between 1 μm and 2 mm, finding that all sources in the sample had steep 1–4 μm spectra and that several exhibited spectral breaks around 10 μm, indicative of energy losses. Some of the sources exhibited spectral breaks close to 1 mm (300 GHz), while some remained flat, even up to 800 GHz (400 μm). We showed that the spectral shape can, in general, be interpreted in terms of an inhomogeneous jet. However, to discriminate clearly between the various jet models requires variability measurements at these wavelengths. It is only in this spectral region that electron lifetimes are short enough that individual flares can be isolated; overlapping flares have proved a serious problem in interpreting longer wavelength data (see, e.g., O'Dea, Dent, and Balonek 1984).

Here we report the results of monitoring the infrared to millimeter emission of a sample of blazars. We compare our data with current models and with the shock-wave model of Marscher and Gear (1985).

II. OBSERVATIONS

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 in 1982 September, 1983 February, and 1983 March. UKIRT was also used to make submillimeter measurements in 1983 August, 1983 September, and 1984 January/February, and some of the infrared measurements in 1983 September and 1984 January/February. The NASA Infrared Telescope Facility (IRTF) was used to make the 1–10 μm measurements of 1983 August and the 10 μm measurements of 1983 September and 1984 January/February. We have not attempted to correct the infrared fluxes for galactic extinction, as was done in Paper I, since we are interested in the relative behavior of each source.

The 1.3 and 2.0 mm measurements were made in 1982 January and 1983 April with the NRAO 12 m dish on Kitt Peak. The instrumentation and data reduction techniques are described in Paper I. In addition, 3.3 mm observations were made in 1984 February/March using the NRAO 12 m dish and their common-user heterodyne receiver in double-sideband continuum mode, calibration was against the planets (Griffin *et al.* 1985; Paper I).

III. RESULTS

We present the data in Table 1 and Figures 1–11. In Table 2 we give spectral indices for each epoch. We now describe the behavior of each source, followed in §§ IV and V by discussion and interpretation of these results.

a) 0235+164

The limited millimeter-wave data suggest that this source has a flat millimeter spectrum at least to 1 mm. The data show no significant variation in the millimeter flux densities, except

---

[1] School of Physics and Astronomy, Lancashire Polytechnic.

[2] Visiting Astronomer, US National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract to the National Science Foundation.

[3] Visiting Astronomer, United Kingdom Infrared Telescope Facility.

[4] Visiting Astronomer at the Infrared Telescope Facility, which is operated by University of Hawaii under contract to the National Aeronautics and Space Administration.

[5] Department of Physics, Queen Mary College, University of London.

[6] Royal Observatory, Edinburgh.

[7] Department of Physics, University of Oregon.

[8] Jet Propulsion Laboratories.

[9] Lunar and Planetary Laboratories, University of Arizona.

TABLE 1

FLUXES OF THE BLAZARS[a]

		WAVELENGTH (μm) FREQUENCY (THz)											
OBJECT	DATE	1.25 240	1.65 181	2.20 136	3.45 87	10.5 29	20.0 15	370 0.81	770 0.39	1070 0.28	1320 0.23	1990 0.15	3350 0.09
0235+164.........	1982 Jan 17–19	…	…	…	…	…	…	…	…	…	2.1 (0.5)	2.1 (0.5)	…
	1982 Sep 11–12	2.4 (0.1)	3.9 (0.2)	5.8 (0.3)	12.5 (1.6)	$3\sigma < 110$	…	…	…	1.2 (0.3)	…	…	…
	1983 Feb 2–5	3.9 (0.4)	5.8 (0.6)	9.6 (0.6)	19.6 (1.3)	…	$3\sigma < 320$	…	$3\sigma < 1.5$	1.4 (0.3)	…	…	…
	1983 Apr 6–10	…	…	…	…	…	…	…	…	…	…	1.9 (0.3)	…
	1983 Aug 4–7	2.1 (0.1)	4.4 (0.2)	6.0 (0.2)	…	52 (17)	…	…	…	$3\sigma < 1.2$	…	…	…
	1983 Sep 15–19	4.8 (0.2)	8.6 (0.2)	12.6 (0.3)	20.2 (0.3)	…	…	…	$3\sigma < 3.7$	1.4 (0.3)	…	…	…
	1984 Feb 3–7	3.0 (0.1)	5.0 (0.3)	7.4 (0.6)	…	…	…	…	…	1.4 (0.5)	…	…	…
	1984 Feb 29–Mar 6	…	…	…	…	…	…	…	…	…	…	…	1.2 (0.2)
0420−014.........	1982 Jan 21	…	…	…	…	…	…	…	…	…	…	1.8 (0.3)	…
	1983 Mar 4–7	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)	…	…	…
	1984 Feb 4–7	0.59 (0.04)	0.63 (0.05)	1.07 (0.04)	…	…	…	…	…	2.1 (0.4)	…	…	…
	1984 Feb 29–Mar 6	…	…	…	…	…	…	…	…	…	…	…	4.7 (0.7)
0735+178.........	1982 Jan 19–20	…	…	…	…	…	…	…	…	…	…	1.6 (0.2)	…
	1983 Feb 2–5	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)	…	…	…
	1983 Apr 6–10	…	…	…	…	…	…	…	…	…	…	$3\sigma < 1.1$	…
	1983 Sep 15–19	9.6 (0.2)	13.5 (0.3)	18.4 (0.3)	29.6 (1.4)	…	…	…	…	$3\sigma < 2.7$	…	…	…
	1984 Jan 29–31	6.9 (0.1)	10.3 (0.1)	14.0 (0.1)	26.0 (0.6)	101 (18)	$3\sigma < 518$	…	…	…	…	…	…
	1984 Feb 29–Mar 6	…	…	…	…	…	…	…	…	…	…	…	1.5 (0.2)
0736+017.........	1982 Jan 19–20	…	…	…	…	…	…	…	…	…	…	1.5 (0.2)	…
	1983 Mar 4–7	2.3 (0.1)	3.8 (0.3)	6.1 (0.4)	10.3 (1.2)	…	$3\sigma < 900$	…	$3\sigma < 2.2$	2.0 (0.3)	…	…	…
	1983 Apr 6–10	…	…	…	…	…	…	…	…	…	1.3 (0.3)	0.8 (0.2)	…
	1984 Feb 1–3	2.5 (0.1)	3.8 (0.1)	5.3 (0.1)	9.8 (0.7)	…	…	…	…	1.9 (0.3)	…	…	…
	1984 Feb 29–Mar 6	…	…	…	…	…	…	…	…	…	…	…	1.8 (0.3)
0851+202.........	1982 Jan 23	…	…	…	…	…	…	…	…	…	…	4.1 (0.4)	…
	1983 Feb 2–5	32.6 (0.5)	44.9 (0.6)	61.8 (1.0)	101.6 (2.4)	300 (66)	520 (100)	3.9 (0.8)	4.0 (0.6)	4.0 (0.4)	…	…	…
	1983 Mar 4–7	38.5 (1.3)	51.4 (3.4)	69.0 (3.9)	119.0 (10)	220 (29)	450 (70)	4.5 (1.5)	4.2 (0.3)	4.3 (0.5)	…	…	…
	1983 Apr 6–10	…	…	…	…	…	…	…	…	…	…	4.9 (0.5)	…
	1984 Feb 1–8	13.4 (0.5)	19.5 (0.6)	26.8 (1.5)	47.9 (1.0)	158 (14)	320 (64)	3.0 (0.3)	3.9 (0.3)	5.6 (0.4)	…	…	…
	1984 Feb 29–Mar 6	…	…	…	…	…	…	…	…	…	…	…	8.0 (0.8)
1253−055.........	1982 Jan 20–23	…	…	…	…	…	…	…	…	…	3.2 (0.4)	6.4 (0.6)	…
	1983 Feb 2–5	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)	…	…	…
	1983 Apr 6–10	…	…	…	…	…	…	…	…	…	2.5 (0.3)	2.7 (0.4)	…

TABLE 1—*Continued*

		WAVELENGTH (μm) FREQUENCY (THz)											
OBJECT	DATE	1.25 240	1.65 181	2.20 136	3.45 87	10.5 29	20.0 15	370 0.81	770 0.39	1070 0.28	1320 0.23	1990 0.15	3350 0.09
	1984 Feb 1–6	1.4 (0.1)	2.3 (0.1)	3.3 (0.1)	7.6 (0.4)	...	...	1.3 (0.5)	2.4 (0.3)	3.3 (0.4)	...	...	...
	1984 Feb 29–Mar 6	...	...	...	...	...	...	...	...	...	...	...	5.0 (0.5)
1308+326.........	1982 Jan 23	...	...	...	...	...	...	...	...	...	...	1.9 (0.5)	...
	1983 Mar 4–7	6.8 (0.3)	9.4 (0.6)	12.7 (0.9)	21.7 (1.0)	$3\sigma < 50$	...	...	$3\sigma < 1.0$	...	...	...	...
	1983 Apr 6–10	...	...	...	...	...	...	...	...	...	...	1.5 (0.5)	...
	1984 Feb 1–4	2.1 (0.1)	3.2 (0.1)	4.5 (0.2)	8.8 (0.8)	$3\sigma < 30$	...	...	1.4 (0.3)	2.1 (0.4)	...	...	...
	1984 Feb 29–Mar 6	...	...	...	...	...	...	...	...	...	...	...	2.0 (0.2)
1641+399.........	1982 Jan 17–23	...	...	...	...	...	...	...	...	...	7.0 (0.3)	6.7 (0.3)	...
	1983 Feb 3–5	8.4 (0.2)	13.0 (0.4)	18.9 (0.1)	35.2 (3.0)	200 (40)	275 (30)	5.5 (0.6)	6.8 (0.7)	6.1 (0.3)	...	...	...
	1983 Mar 4–7	13.8 (0.2)	17.6 (0.1)	23.9 (0.2)	46.0 (2.0)	...	$3\sigma < 410$	4.1 (0.9)	5.1 (0.2)	5.8 (0.4)	...	...	...
	1983 Apr 6–10	...	...	...	...	...	...	...	...	...	...	5.2 (1.0)	...
	1983 Sep 15–19	4.5 (0.2)	7.3 (0.3)	11.0 (0.4)	23.6 (2.0)	111 (14)	327 (92)	$3\sigma < 7.0$	6.1 (0.7)	6.9 (0.5)	...	...	...
	1984 Feb 1–6	2.4 (0.1)	4.1 (0.1)	6.1 (0.2)	11.5 (0.7)	...	...	1.7 (0.6)	3.3 (0.7)	4.8 (0.5)	...	...	...
	1984 Feb 29–Mar 6	...	...	...	...	...	...	...	...	...	...	...	9.5 (1.0)
1921−293.........	1982 Sep 10–13	7.0 (0.2)	11.9 (0.6)	17.3 (0.6)	$3\sigma < 97$	100 (20)	365 (112)	...	9.0 (2.0)	5.6 (1.2)	...	...	...
	1983 Apr 6–10	...	...	...	...	...	...	...	...	...	4.5 (0.8)	4.3 (0.5)	...
	1983 Aug 4–7	4.5 (0.2)	7.5 (0.3)	10.6 (0.4)	...	82 (12)	...	...	$3\sigma < 3.7$	4.8 (0.5)	...	...	...
	1984 Feb 29–Mar 6	...	...	...	...	...	...	...	...	...	...	...	8.2 (1.3)
2200+420.........	1982 Jan 18–22	...	...	...	...	...	...	...	...	...	...	4.1 (0.4)	...
	1982 Sep 10–13	13.1 (0.1)	18.7 (0.4)	23.3 (0.3)	31.4 (4.1)	63 (20)	...	...	$3\sigma < 2.8$	4.0 (1.0)	...	...	...
	1983 Apr 6–10	...	...	...	...	...	...	...	...	...	...	2.4 (0.4)	...
	1983 Aug 4–7	14.1 (0.2)	23.5 (0.2)	30.0 (0.2)	...	118 (15)	$3\sigma < 400$	...	...	1.9 (0.2)	...	...	...
	1983 Sep 15–19	14.7 (0.2)	21.3 (1.2)	28.0 (0.9)	42.0 (0.8)	...	...	...	...	...	...	...	...
	1984 Feb 29–Mar 6	...	...	...	...	...	...	...	...	...	...	...	1.7 (0.3)
2223−852.........	1982 Sep 10–13	12.4 (0.2)	17.6 (0.2)	23.5 (0.7)	49.9 (3.8)	158 (35)	285 (90)	...	3.9 (1.0)	6.8 (1.7)	...	...	...
	1983 Apr 6–10	...	...	...	...	...	...	...	...	...	...	5.8 (0.4)	...
	1983 Aug 4–7	13.7 (0.2)	22.1 (0.2)	29.0 (0.2)	...	170 (19)	...	...	5.3 (0.6)	6.3 (0.5)	...	...	...
	1983 Sep 15–17	8.9 (0.2)	15.0 (0.2)	23.8 (0.4)	53.0 (1.5)	142 (30)	...	...	7.6 (1.1)	8.3 (1.3)	...	...	...

[a] The uncertainties of measurement are indicated by parentheses. Cols. 1.25 to 20.0 in mJy; Cols. 370 to 3350 in Jy.

TABLE 2

Spectral Indexes of the Blazars

Object	Date	1–4 μm	400–1100 μm
0235+164………	1982 Sep	−1.57 ± 0.10	…
	1983 Feb	−1.61 ± 0.11	…
	1983 Aug	−1.73 ± 0.10[a]	…
	1983 Sep	−1.25 ± 0.03	…
	1984 Feb	−1.63 ± 0.14[a]	…
0420−014………	1983 Mar	−1.31 ± 0.07[a]	0.2 + 0.3
	1984 Feb	−1.12 ± 0.13[a]	…
0735+178………	1983 Feb	−1.32 ± 0.05	…
	1983 Sep	−1.11 ± 0.04	…
	1984 Jan	−1.22 ± 0.02	…
0736+017………	1983 Mar	−1.57 ± 0.10	…
	1984 Jan/Feb	−1.27 ± 0.06	…
0851+202………	1983 Feb	−1.12 ± 0.03	−0.02 ± 0.21
	1983 Mar	−1.08 ± 0.08	0.07 ± 0.26
	1984 Jan/Feb	−1.24 ± 0.05	−0.58 ± 0.12
1253−055………	1983 Feb	−1.49 ± 0.09	…
	1984 Jan/Feb	−1.61 ± 0.08	−0.9 ± 0.3
1308+326………	1983 Mar	−1.14 ± 0.06	…
	1984 Jan/Feb	−1.36 ± 0.09	…
1641+399………	1983 Feb	−1.39 ± 0.04	−0.08 ± 0.11
	1983 Mar	−1.05 ± 0.02	−0.36 ± 0.18
	1983 Sep	−1.58 + 0.08	…
	1984 Jan/Feb	−1.51 + 0.06	−1.01 + 0.33
1921−293………	1982 Sep	−1.58 + 0.08[a]	…
	1983 Aug	−1.46 + 0.10[a]	…
2200+420………	1982 Sep	−1.01 + 0.03	…
	1983 Aug	−1.15 + 0.02[a]	…
	1983 Sep	−1.04 + 0.02	…
2223−052………	1982 Sep	−1.22 + 0.05	…
	1983 Aug	−1.18 + 0.03[a]	…
	1983 Sep	−1.72 + 0.03	…

[a] Spectral index derived from JHK measurements only.

possibly in 1983 August, when we failed to detect the source; however, the signal-to-noise ratio of the measurements would mask variations smaller than ~25%. On the other hand, the infrared spectrum increased between 1982 September and 1983 February, then decreased again by 1983 August, with no significant change in spectral index in either case. However, the 1983 August data show some evidence of downward curvature at 1 μm, possibly indicating a cutoff in the electron energy distribution. Between 1983 August and 1983 September the infrared flux doubled and the spectrum flattened considerably, although there was still evidence of curvature near 1 μm. By 1984 February the flux had decreased and the spectrum had steepened.

b) 0420−014

We observed this source on only two occasions, nearly a year apart. The 1983 March submillimeter data show a spectral index of zero from 280 GHz (1100 μm) to 800 GHz (400 μm), indicating that this source must be extremely compact. The 1984 February spectral coverage is not as complete. However, the infrared fluxes decreased by almost an order of magnitude between the two epochs. The 1984 February spectrum appears to show an excess at 1.25 μm. It is possible, therefore, that when the nonthermal flux is at a minimum we begin to see the emergence of an underlying flatter optical continuum, as found by Malkan and Sargent (1982) in a sample of quasars and Seyfert galaxies.

The 1984 March 3.3 mm datum suggests a possible steepening of the millimeter-wave spectrum.

c) 0735+178

The weakness of this source precluded measurement of the submillimeter spectral index; the infrared data, however, show

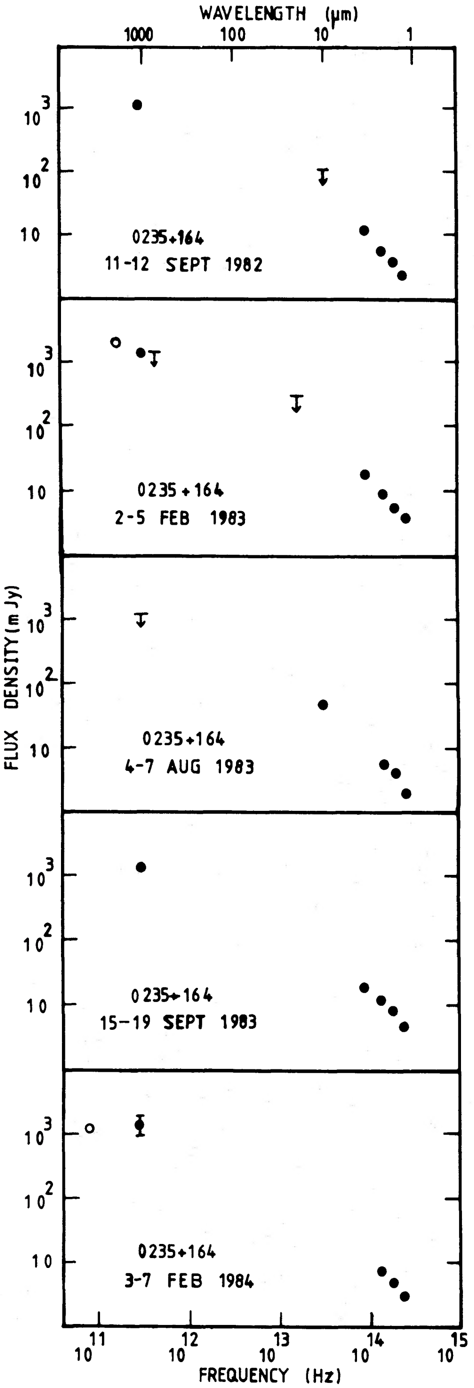

Fig. 1.—The evolution of the infrared-to-millimeter spectrum of 0235+164, 1982–1984. Open circles plotted with the 1983 and 1984 February spectra are millimeter-wave data from 1983 April and 1984 March, respectively.

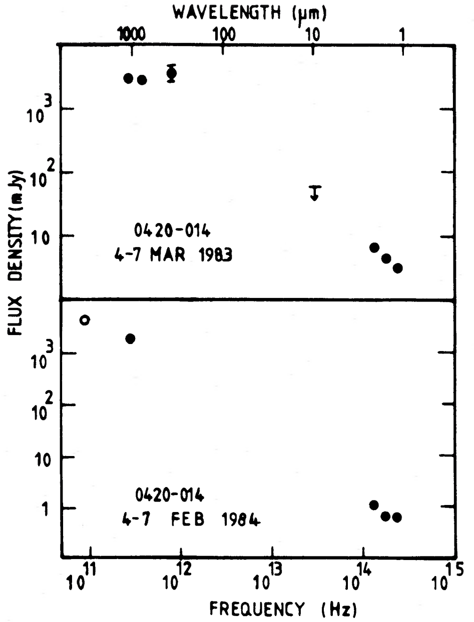

FIG. 2

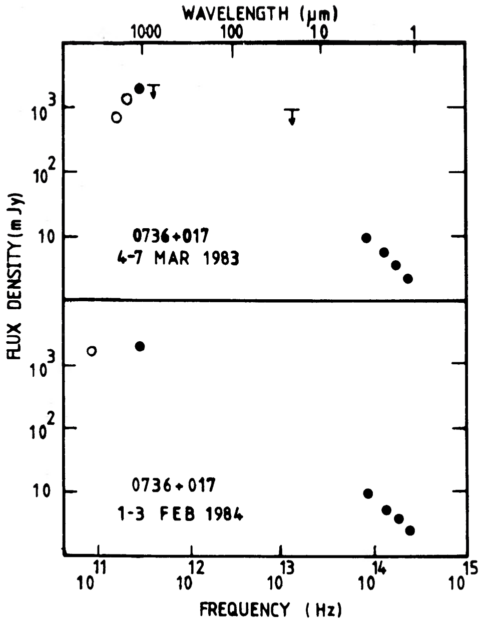

FIG. 4

FIG. 2.—The evolution of the infrared-to-millimeter spectrum of 0420−014, 1983–1984. Open circle plotted with the 1984 February spectrum is a 3 mm datum from 1984 March.

FIG. 4.—The evolution of the infrared-to-millimeter spectrum of 0736+017, 1983–1984. Open circles plotted with the 1983 March and 1984 February spectra are millimeter-wave data from 1983 April and 1984 March respectively.

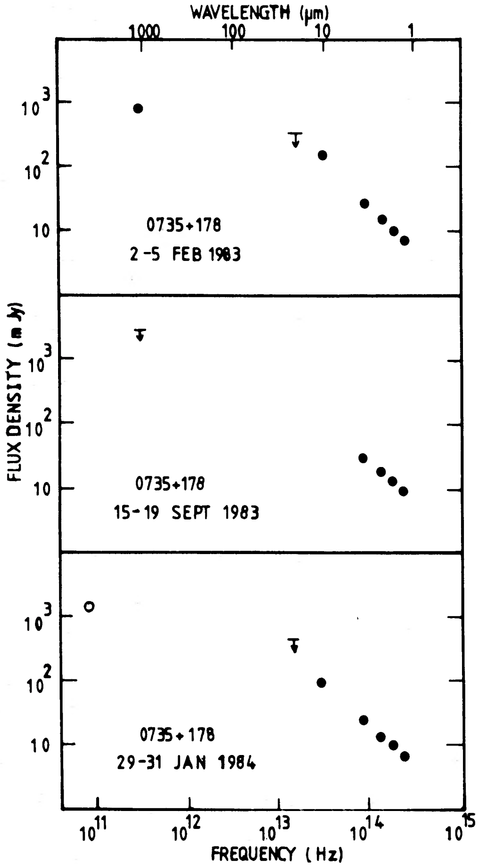

FIG. 3

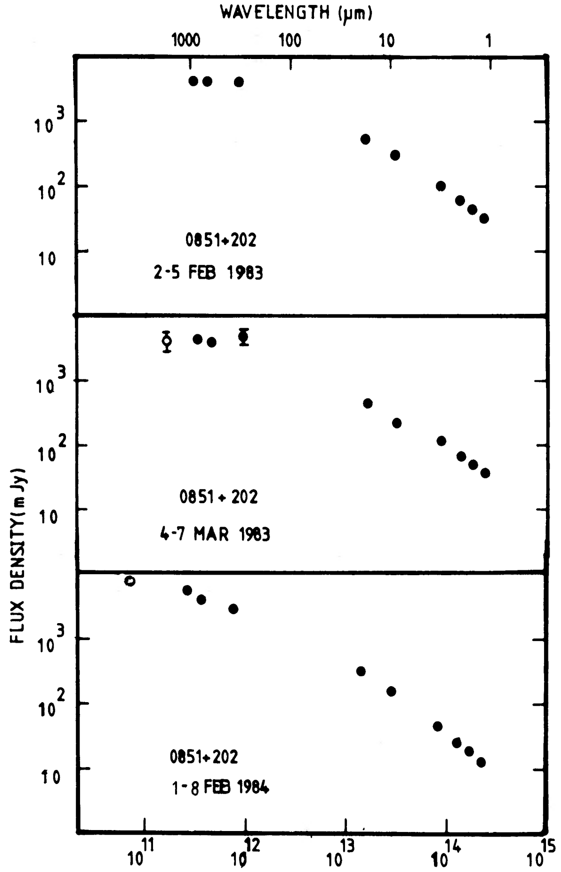

FIG. 5

FIG. 3.—The evolution of the infrared-to-millimeter spectrum of 0735+178, 1983–1984. Open circle plotted with the 1984 January spectrum is a 3 mm datum from 1984 March.

FIG. 5.—The evolution of the infrared-to-millimeter spectrum of 0851+202, 1983–1984. Open circles plotted with the 1983 March and 1984 February spectra are millimeter-wave data from 1983 April and 1984 March, respectively.

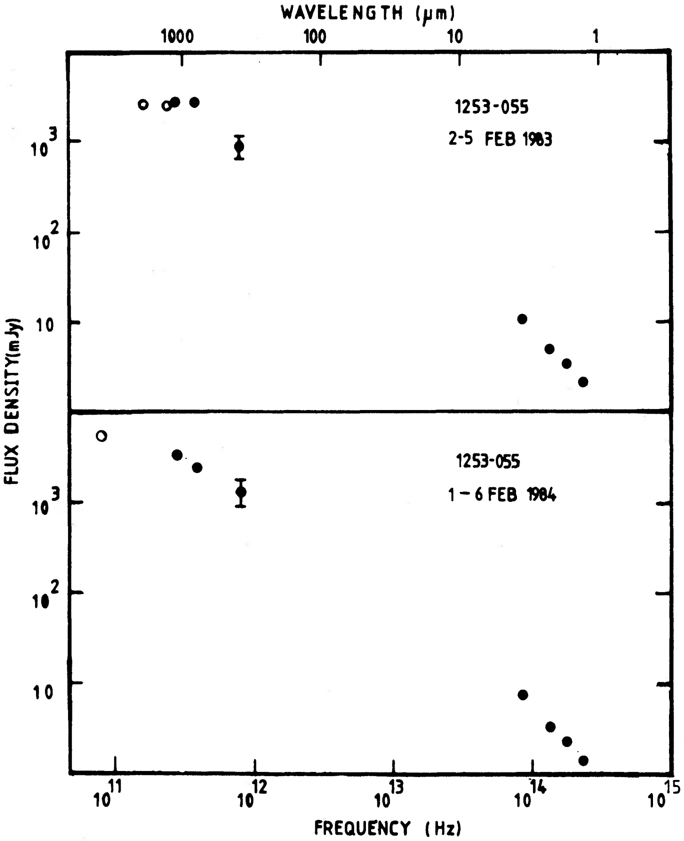

FIG. 6.—The evolution of the infrared-to-millimeter spectrum of 1253–055, 1983–1984. Open circles plotted with the 1983 and 1984 February spectra are millimeter-wave data from 1983 April and 1984 March, respectively.

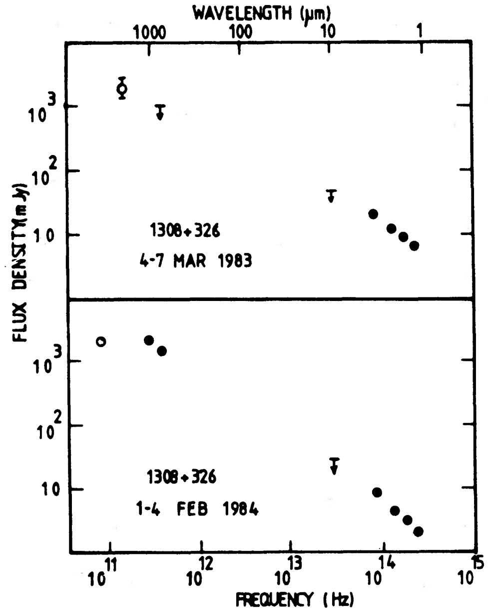

FIG. 7.—The evolution of the infrared-to-millimeter spectrum of 1308+326, 1983–1984. Open circles plotted with the 1983 March and 1984 February spectra are millimeter-wave data from 1983 April and 1984 March, respectively.

interesting properties. Between 1983 February and 1983 September the flux increased and the spectrum flattened; by 1984 January, the flux had decreased and the spectrum had steepened once more.

d) *0736+017*

The 1983 March 1–1100 μm spectrum shows no breaks; however, the 1.3 and 2.0 mm data taken 1 month later indicate an inverted millimeter spectrum with the 2.0 mm flux less than its 1982 value. Between 1983 March and 1984 February the millimeter and infrared fluxes did not vary significantly, although there was marginal evidence for flattening of the infrared spectrum. The 1984 March 3.3 mm measurement also suggests that the millimeter-wave spectrum had flattened.

e) *0851+202*

The 1983 February spectrum of OJ 287 is remarkable for the consistency of the power-law behavior, both in the sub-

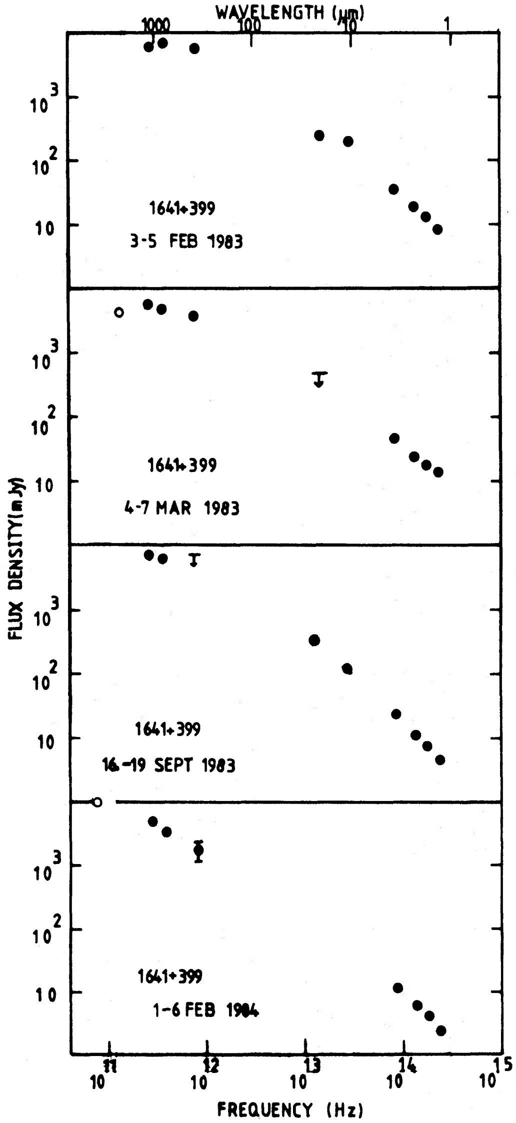

FIG. 8.—The evolution of the infrared-to-millimeter spectrum of 1641+399, 1983–1984. Open circles plotted with the 1983 March and 1984 February spectra are millimeter-wave data from 1983 April and 1984 March, respectively.

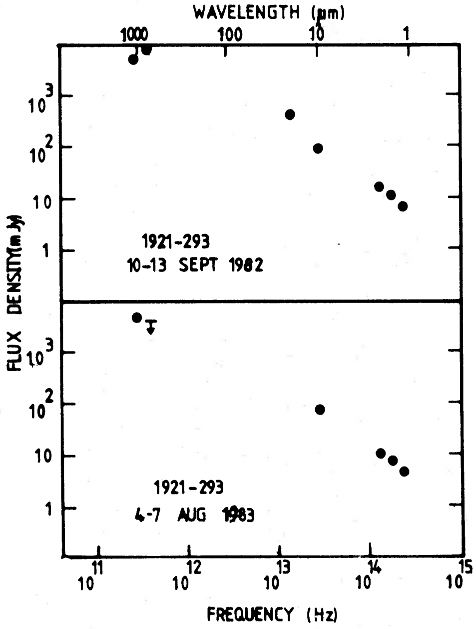

FIG. 9.—The evolution of the infrared-to-millimeter spectrum of 1921 − 293, 1982–1984.

millimeter where the spectral index is zero from 280 to 800 GHz and in the infrared from 1–20 μm. This behavior persists in 1983 March. Holmes *et al.* (1985) reported a dramatic flare in the infrared flux and polarization of OJ 287 in 1983 January. They found that the spectrum retained its shape during night-to-night variations; however, the infrared spectral index during this flare was significantly flatter than during our observations in 1983 February and March.

Between 1983 March and 1984 February the submillimeter spectrum steepened, the 280 GHz flux having risen and the 800 GHz flux having fallen. The 3.3 mm flux measured 1 month later also suggests evolution of the submillimeter spectral break to lower frequencies, with the peak flux increasing by ~100% over the 1983 value. The 1–20 μm spectrum had decreased in flux and steepened marginally.

We note that this behavior followed directly after the infrared flare (Holmes *et al.* 1985). Given the uncertainty of the contribution from a possible underlying quiescent component in this source, we tentatively assign this behavior to the early stages of a flare similar to that observed in 3C 273 (Robson *et al.* 1983).

f) 1253 − 055 (3C 279)

The 1983 February and April submillimeter and millimeter data suggest a spectral break around ~400 GHz (800 μm). By 1984 January the submillimeter spectrum had steepened to a slope of −0.9. The 1984 March 3.3 mm measurement also

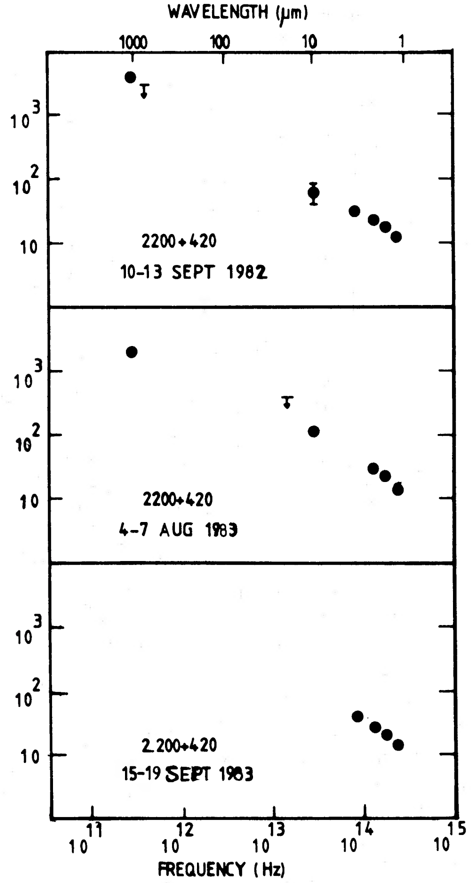

FIG. 10.—The evolution of the infrared-to-millimeter spectrum of 2200 + 420, 1982–1984.

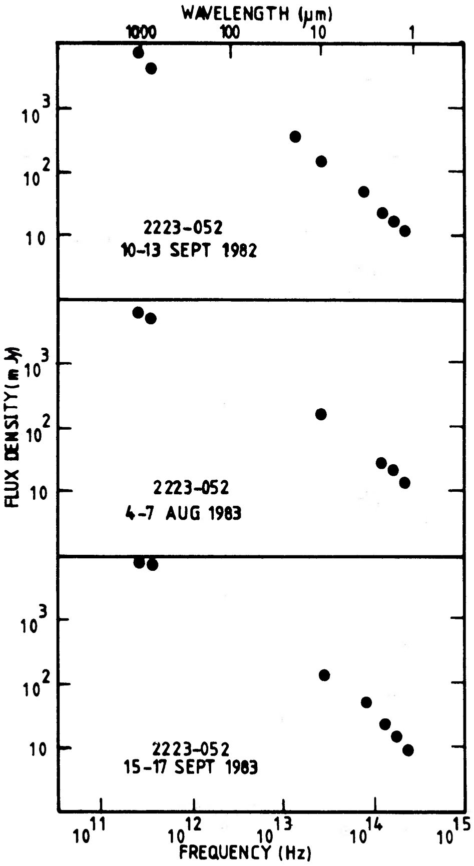

FIG. 11.—The evolution of the infrared-to-millimeter spectrum of 2223 − 052, 1982–1984.

suggests evolution of the submillimeter spectral break to lower frequency with an increase in peak flux. The infrared flux had decreased in 1984 February, but with no significant steepening. Finally, we note that the 1982 January 1.3 and 2.0 mm data also indicate a millimeter spectrum descending to higher frequencies.

g) 1308+326

In 1983 March the 10 μm upper limit indicates a spectral break in the 4–10 μm region. Although we failed to detect the source in the submillimeter, the 1 mm upper limit and the 2 mm measurement taken 1 month later suggest the possibility of a break in the millimeter-wave spectrum. In 1984 February, the submillimeter flux had increased to a point where our measurements at 280 and 390 GHz, combined with the 3.3 mm datum taken 1 month later, showed marginal evidence for a break close to 1 mm. The 1–4 μm spectrum had decreased and steepened since 1983 March, with the upper limit at 10 μm again implying a spectral break in the mid-infrared.

h) 1641+399 (3C 345)

The behavior of 3C 345 is very similar to that of 3C 279. In 1983 February the submillimeter spectrum was flat from 280 to 800 GHz and the infrared spectrum showed evidence for a break at 10 μm. In 1983 March the submillimeter spectrum was not as flat and the upper limit at 20 μm again indicated a break in the mid-infrared from the 1–4 μm continuum, which had increased in flux density and flattened. In 1983 September the infrared spectrum had decreased in flux density and steepened, while the submillimeter fluxes showed marginal evidence of an increase. In 1984 February the submillimeter spectrum had steepened to a slope of -1.0 (with the 1984 March 3.3 mm data again suggesting a decrease of spectral break frequency with an increase in peak flux), while the infrared fluxes had decreased, but with no further steepening.

i) 1921−293 (OV 236)

In 1982 September this source had an unusual spectrum (Gear *et al.* 1983), with signs of excess at 20 and 800 μm. In 1983 August the 1–10 μm fluxes had decreased and the spectrum was a simple power law. The 800 μm upper limit possibly indicates a break in the submillimeter spectrum.

j) 2200+420 (BL Lac)

In 1982 September the upper limit at 800 μm suggests that BL Lac had a spectral break at or longward of 1 mm; there was also some evidence of curvature around 1–2 μm. By 1983 August and September the infrared fluxes had increased, still with a cutoff at 1 μm, whereas the 1 mm flux had decreased.

k) 2223−052 (3C 446)

In 1982 September 3C 446 exhibited a descending submillimeter spectrum which extrapolated to the 20 and 10 μm points with a slope of -0.8, with the infrared spectrum steepening shortward of 10 μm to the 1–4 μm slope of -1.2. In 1983 August the infrared fluxes had increased. In 1983 September the 1–4 μm fluxes had decreased and the slope steepened considerably, and the 10 μm datum also indicated a spectral break between 4 and 10 μm. The submillimeter fluxes, however, had increased. The behavior of the radio through X-ray spectrum of 3C 446 during 1983 is discussed in more detail in Brown *et al.* (1986).

IV. DISCUSSION

From the results presented above, we make the following general observations about the behavior of these sources.

1. The infrared fluxes increase in unison at all frequencies on a time scale of months or less, implying that the emission over this range in frequency arises in a single region.
2. The time scale for the submillimeter variations appears to be longer than that for the infrared; confirmation requires more frequent sampling and higher signal-to-noise ratio.
3. In general, the sources have 1–4 μm spectra steeper than -1.0, and several show evidence of spectral breaks in the 10–20 μm region. This suggests that the infrared spectra of the blazars have been steepened by radiative losses.
4. In general, (*a*) when the infrared fluxes increase the spectrum flattens, and (*b*) when the fluxes subsequently decay the spectrum steepens. Observation (*a*) suggests that an increase in emission results from an injection or reacceleration of electrons with a flatter energy distribution; observation (*b*) then is consistent with these electrons subsequently suffering radiative losses on a time scale of weeks or less.
5. Where we have submillimeter spectral information, the spectra take two forms: (*a*) very flat, with spectral index approximately zero or (*b*) descending, with spectral index -0.6 to -1.0.
6. All three sources observed at three submillimeter wavelengths on more than one occasion evolve from type 5*a* to type 5*b* (i.e., the spectral break moves to lower frequency), with the peak flux increasing (see Figs. 5, 6, 8).

The evolution of the submillimeter spectra of OJ 287, 3C 279, and 3C 345 suggests that they have undergone a transition from optically thick to optically thin emission at these frequencies. In all three sources this evolution is accompanied by a decrease in the infrared fluxes, as would be expected from an expanding region; however, we do not see the large decrease in flux near the turnover that is also expected for simple models (Van der Laan 1966). On the contrary, since the 1983 spectra imply $\nu_m > 800$ GHz while the 1984 January spectra imply $\nu_m < 280$ GHz and the 280 GHz fluxes have not decreased, for OJ 287, 3C 279, and 3C 345, the peak flux S_m must have *increased* while ν_m *decreased*. The 1984 February 90 GHz data for the three sources strengthen this conclusion: in fact, the OJ 287 data suggest that S_m approximately doubled. Similar behavior was also seen during the 1983 infrared-to-millimeter outburst of 3C 273 reported in Robson *et al.* (1983) and discussed in detail by Marscher and Gear (1985). In the next section, we discuss the constraints these observations place on models for the continuum emission from these objects.

V. INTERPRETATION

In Paper I we ruled out a number of models and concluded that a relativistic jet model was necessary to explain the continuum emission of the blazars. Marscher and Gear (1985) have also shown that variable injection of relativistic particles or magnetic field in a uniform model, or both, does not naturally reproduce the observed behavior of 3C 273 during the infrared-to-millimeter flare in 1983. This conclusion is here confirmed for the blazars since the observed behavior is very similar to that of the flare in 3C 273. We are now also able to restrict possible jet models.

Marscher (1980) considered a jet which is confined by the ambient pressure such that the channel width $r \propto R^{\epsilon}$, where R is the distance from the origin of the jet and $\epsilon < 1$. The infrared emission in this model is steepened by radiative and adiabatic losses; however, the model does not produce any significant flattening of the radio spectrum. Clegg *et al.* (1983) described a variation of this model in which the flat radio spectrum is optically thin, with electron energy index $s = 1$ (where we assume a power-law distribution of electrons, $N(E) \propto E^{-s}$), the submillimeter spectral break is determined by expansion losses, with the spectral index above the break being given by $\alpha = -(1 - \epsilon)/3\epsilon$ (Marscher 1980), and any further break in the infrared being caused by radiative losses. The Clegg *et al.* model predicts simultaneous radio-through-submillimeter variations which conflicts with the known behavior of these objects; both it and the Marscher (1980) version also predict that the optically thin flux should increase first at higher frequencies. On the contrary, we have shown that for all the objects we have observed the infrared fluxes increase simultaneously at all frequencies on a time scale of weeks or less. Furthermore, Holmes *et al.* (1984) showed that the infrared spectral shape of OJ 287 did not change significantly during night-to-night variations in flux. We therefore consider both these models to be unsatisfactory.

Ennis, Neugebauer, and Werner (1982) and Gear *et al.* (1984*a*, *b*) prefer the model of Königl (1981) in which the emission arises in a conical, continuously reaccelerated jet. Several authors have used this model to explain the broad-band continuum of quasars and BL Lac objects (Worrall *et al.* 1982; Urry and Mushotsky 1982; Mufson *et al.* 1983; Unwin *et al.* 1985). Its main attraction is that an optically thick spectral index of zero is produced if the jet is assumed to be isothermal (Gear *et al.* 1984*a*). However, this model also predicts a strong frequency dependence of infrared variability; consequently, we regard it as unsatisfactory.

Marscher (1980) discusses the emission from an adiabatic, unconfined jet. In Paper I we applied this model to the single-epoch spectra of our sample of blazars. It was consistent with those observations and gave physically reasonable values for the conditions within these sources. We now show that this model is not consistent with the variability properties of the blazars.

Since the emission above the turnover arises in a small region close to the origin of the unconfined jet, we expect the optically thin spectrum to rise simultaneously, as is observed. The evolution of the turnover frequency is obtained as follows. Consider the emission from a volume element $dV = \pi r^2 dR$ in the jet, where r is measured across the jet and dR is along the jet. The jet has constant bulk velocity $\beta_j = v_j/c$ and bulk Lorentz factor Γ_j and is assumed to be at a small angle to our line of sight so that the emission is Doppler boosted with a bulk Doppler factor $\delta_j = \Gamma_j^{-1}(1 - \beta_j \cos \theta)^{-1}$. Applying the standard relations for the received radiation from a synchrotron-emitting region (e.g., Pacholczyk 1970), we have for the observed peak flux S_m:

$$S_m \propto [K^5 B^{2s+3} dR^5 \delta_j^{3s+7}]^{1/(s+4)} r^2 , \tag{1}$$

and for the observed self-absorption turnover frequency

$$\nu_m \propto [K B^{(s+2)/2} \delta_j^{(s+2)/2} dR]^{2/(s+4)} . \tag{2}$$

In an adiabatic jet, the coefficient of the electron energy distribution $K \propto R^{-2(s+2)/3}$ (Marscher 1980). The magnetic field $B \propto R^{-b}$, where $b = 1$ if the field is perpendicular to the flow and $b = 2$ if it is parallel to the flow. Substituting these dependencies and combining equations (1) and (2), we find for the flux S_m at ν_m:

$$S_m \propto \nu_m^{[3b(s+2)+4(s-1)]/[(s+2)(3b+4)]} . \tag{3}$$

Hence, since $b > 0$ and $s > 0$, any decrease in ν_m should be accompanied by a decrease in S_m. On the contrary, our observations show that for OJ 287, 3C 279, and 3C 345, a *decrease* in ν_m was accompanied by an *increase* in S_m.

A simple injection of new material into the jet cannot therefore fit the data. A more complicated variation in the jet parameters would be required to fit the observations.

Marscher and Gear (1984) considered the consequences of a natural result of variations in the flow parameters—namely, shock waves—applying this model successfully to the 1983 outburst of 3C 273 (Robson *et al.* 1983). Hence, we here apply this model to the blazars.

In this model, the submillimeter and infrared emission arises in a small region behind a shock wave which is traveling in an unconfined relativistic jet. The spectrum of this region evolves through three distinct phases, which correspond to Compton scattering, sychrotron emission, and adiabatic expansion being the dominant energy-loss mechanism.

In the Compton phase, the peak flux rises rapidly while the turnover moves to lower frequency, with $S_m \propto \nu_m^{-5/2}$ for $b = 1$ and $S_m \propto \nu_m^{-3/2}$ for $b = 2$. Since the transition from optically thick to optically thin submillimeter emission in OJ 287, 3C 279, and 3C 345 occurred when the sources were unobservable, we cannot derive empirical S_m versus ν_m laws. This problem is exacerbated by the extreme variability of blazars and the possible existence of an underlying "quiescent" spectrum which should be separated from the variable component(s). However, comparison of the 1983 and 1984 fluxes shows no dramatic (100% or greater) increase in submillimeter flux in any source in our sample, with the exception of OJ 287 (see § III). For OJ 287 we conclude that the Compton stage of a flare may have occurred between 1983 March and 1984 January.

In the synchrotron-loss phase, the peak flux varies slowly as the turnover continues to lower frequency, with

$$S_m \propto \nu_m^{[(3b+2)(2s-5)]/[3b(s-1)+4(s+2)]} . \tag{4}$$

Thus for $s < 2.5$ and $s > 2.5$ the peak flux increases and decreases slowly, respectively, as the self-absorption turnover evolves to lower frequency with time, consistent with the observed behavior of the blazars other than OJ 287. We postulate that we have not observed the Compton stage in any of these blazars because this phase is very short-lived and our temporal and spectral coverage was insufficient to resolve it. We note that in the Compton phase most of the energy output is in X-rays; therefore, X-ray bursts should precede infrared-to-millimeter outbursts. We are currently engaged in a program of X-ray monitoring of blazars.

Given the rather sparse temporal coverage, each source may have undergone more than one flare between early 1983 and early 1984, such that the emission at the two epochs results from two separate shocks. However, this would not mean that the observed similar peak fluxes are fortuitous or that our conclusions are invalid, since Marscher and Gear (1985) have shown that, at the transition from Compton to synchrotron losses (which for $s \approx 2.5$ will be essentially the peak flux observed throughout the synchrotron phase), the peak flux is a very weak function of the strength of the shock.

Since, in this model, the submillimeter and infrared emission arises in the very small shocked region behind the shock wave, which (at least in its early stages) is effectively homogeneous, we can use the slab approximation of Burbidge, Jones, and O'Dell (1974) to estimate the size and magnetic field. We obtain values for the shock cross-sectional radius of $r \approx 10^{-2}$–10^{-3} pc and magnetic fields of $B \approx 0.1$ gauss.

A test of the model can be made using longer wavelength monitoring and VLBI. We should be able to observe the third predicted stage of evolution, the adiabatic stage. In the adiabatic stage the emitting region will gradually decay with

$$S_m \propto \nu_m^{[3b(2s+3)+4s-19]/[3b(s+2)+2(2s+1)]} . \tag{5}$$

Within the next year or two we would expect new superluminal knots to emerge from the cores of OJ 287, 3C 279, and 3C 345. These knots should decay in accordance with equation (5).

VI. CONCLUSIONS

1. We monitored the infrared to millimeter-wave emission of a sample of blazars and find that each source is variable, both in flux and spectral shape.
2. The infrared variability is consistent with repeated injections or reaccelerations of emitting electrons which subsequently decay radiatively, steepening the observed spectrum.
3. The millimeter and submillimeter fluxes are not highly variable, in general. However, three sources show an evolution of spectral shape, suggesting a transition from optically thick to optically thin emission.
4. The amplitudes of variability are inconsistent with the canonical expanding cloud model and also with most of the relativistic jet models in the literature.
5. Our observations are consistent with the shock-wave model of Marscher and Gear (1985); we predict the emergence of new superluminal knots from the cores of OJ 287, 3C 279, and 3C 345 which should decay in accordance with equation (5).

We would like to thank P. E. Clegg and A. P. Marscher for enlightening discussions and D. G. Vickers, and S. Predko for technical assistance. We are grateful to the staffs of UKIRT, NRAO, and IRTF for their assistance with the observations. W. K. G., M. J. G., and L. M. J. B. acknowledge the receipt of SERC research assistantships and a studentship, respectively. I. G. N. and J. V. R. acknowledge the partial support of NSF 81-20174. We are grateful to an anonymous referee for his thorough reading of the manuscript and clarifying suggestions.

REFERENCES

Angel, J. R. P., and Stockman, H. S. 1980, *Ann. Rev. Astr. Ap.*, **18**, 321.
Brown, L. M. J., *et al.* 1986, *M.N.R.A.S.*, in press.
Burbidge, G. R., Jones, T. W., and O'Dell, S. L. 1974, *Ap. J.*, **193**, 43.
Clegg, P. E., *et al.* 1983, *Ap. J.*, **278**, 58.
Ennis, D. J., Neugebauer, G., and Werner, M. 1982, *Ap. J.*, **262**, 460.
Epstein, E. E., Fogarty, W. G., Mottman, J., and Schneider, E. 1982, *A.J.*, **87**, 449.
Gear, W. K., Robson, E. I., Ade, P. A. R., Griffin, M. J., Smith, M. G., and Nolt, I. G. 1983, *Nature*, **303**, 46.
Gear, W. K., Robson, E. I., Ade, P. A. R., and Nolt, I. G. 1984*a*, in *Proc. Manchester Conf. Active Galactic Nuclei*, ed. J. Dyson (Manchester: Manchester University Press), p. 152.
Gear, W. K. *et al.* 1984*b*, *Ap. J.*, **280**, 102.
Gear, W. K. *et al.* 1985, *Ap. J.*, **291**, 511 (Paper I).
Griffin, M. J., *et al.* 1985, *Icarus*, in press.
Holmes, P. A., *et al.* 1985, *M.N.R.A.S.*, **211**, 497.
Königl, A. 1981, *Ap. J.*, **243**, 700.
Malkan, M. A., and Sargent, W. L. W. 1982, *Ap. J.*, **254**, 22.
Marscher, A. P. 1980, *Ap. J.*, **235**, 386.
Marscher, A. P., and Gear, W. K. 1985, *Ap. J.*, **298**, 114.
Mufson, S. L., *et al.* 1984, *Ap. J.*, **285**, 571.
O'Dea, C. P., Dent, W. A., and Balonek, T. J. 1984, in *Proc. Manchester Conf. Active Galactic Nuclei*, ed. J. Dyson (Manchester: Manchester University Press), p. 63.
Pacholczyk, A. G. 1970, *Radio Astrophysics* (San Francisco: Freeman).
Robson, E. I., *et al.* 1983, *Nature*, **305**, 194.
Unwin, S. C., *et al.* 1985, *Ap. J.*, **289**, 109.
Urry, C. M., and Mushotsky, R. F. 1982, *Ap. J.*, **253**, 38.
Worrall, D. M., *et al.* 1982, *Ap. J.*, **262**, 403.
Van der Laan, H. 1966, *Nature*, **211**, 1131.

P. A. R. ADE and M. J. GRIFFIN: Department of Physics, Queen Mary College, University of London, Mile End Road, London E1 4NS, England, UK

L. M. J. BROWN, W. K. GEAR, and E. I. ROBSON: Division of Physics and Astronomy, Lancashire Polytechnic, Preston PR1 2TQ, England, UK

L. LEBOFSKY: Lunar and Planetary Laboratories, University of Arizona, Tucson, AZ 85721

I. G. NOLT and J. V. RADOSTITZ: Department of Physics, University of Oregon, Eugene, OR 97403

M. G. SMITH: Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, Scotland, UK

G. VEEDER: Jet Propulsion Laboratories, 183-501, 4800 Oak Grove Drive, Pasadena, CA 91109