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MILLIMETER-WAVE OBSERVATIONS OF FLAT SPECTRUM RADIO SOURCES

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ABSTRACT

We present measurements at wavelengths between 0.4 and 2.0 mm of a sample of 26 compact, flat spectrum radio sources. These observations extend the known radio spectra of this class of sources to higher frequencies and show that most of these sources are still flat at short millimeter wavelengths. The spectral shapes are consistent with an inhomogeneous synchrotron model (with some degree of relativistic beaming); however, the lack of concurrent multifrequency data prevents us from making more definite conclusions at this stage.

Subject headings: radiation mechanisms — radio sources: galaxies

I. INTRODUCTION

Compact, nonthermal radio sources are one of the most intense subjects of extragalactic research because they are believed to relate closely to the primary engine in active galactic nuclei. Determination of the spectral shape (and polarization properties) of such objects and how they evolve with time is crucial to our understanding of them. It is especially important to measure millimeter-wave flux densities since this helps define the spectral break which must occur between the generally flat radio spectra and the much steeper infrared continuum. The position of this break can provide information on source parameters which can be compared with derivations by other means.

Many compact radio sources are characterized by spectra which are flat over a wide range in frequency (Owen *et al.* 1978; Owen, Spangler, and Cotton 1980). This flatness can be interpreted in terms of several models: (1) a superposition of a number of homogeneous self-absorbed synchrotron components (Kellermann and Pauliny-Toth 1969), this model is sometimes referred to as a "cosmic conspiracy" (Cooke and Spangler 1980; Marscher 1980*a*; Wittels, Shapiro, and Cotton 1982); (2) an optically thin synchrotron source with an energy distribution index of unity (Marscher 1977*a*); (3) a single source with an appropriate energy distribution such as relativistic Maxwellian (Jones and Hardee 1979; Spangler 1980); (4) a single source with inhomogeneities of the electron energy distribution and magnetic field strength (Condon and Dressel 1973; de Bruyn 1976; Marscher 1977*b*); (5) relativistic beaming effects (Blandford and Königl 1979; Marscher 1980*b*; Königl 1981; Reynolds 1982).

We have observed a sample of 26 sources chosen on the basis of having a radio spectral index, α, of order zero [where $S(\nu) \propto \nu^{\alpha}$] and an extrapolated one millimeter flux density greater than 1 Jy.

II. OBSERVATIONS

The observations at 1.4 and 2 mm were made with the NRAO millimeter continuum system (Radostitz *et al.* 1984) mounted at the Cassegrain focus of the 36 foot (11 m) dish at Kitt Peak. The average beam size was 70″ FWHM, and the chop amplitude and frequency were 4′ and 9 Hz, respectively. Calibration was performed primarily against Mars, with Uranus and Jupiter being secondary calibrators. The brightness temperatures of Mars were linearly interpolated using the model of Wright (1976), which establishes the 350 μm temperature, and the empirical model of Ulich (1981), which establishes the 3.3 mm temperature. The brightness temperatures assigned to Uranus assume an equatorial radius of 25,563 km, an ellipticity of 0.024, and a correction for polar inclination angle toward the observer. Physical data for Jupiter and Mars were taken from the American Ephemeris and Nautical Almanac.

The submillimeter data were obtained with the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea. The 1981 observations used the f/9 Queen Mary College (QMC)

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photometer system described by Robson *et al.* (1978) and Cunningham (1982), and the 1982 observations used the f/35 Cassegrain focus with the QMC-Oregon photometer (Ade *et al.* 1984). The beam sizes for the f/9 and f/35 systems were determined by scanning through Mars, giving the following FWHM: 80″ for 1.1 mm at f/9, while at f/35 the beam sizes were 65″ at 1.1 mm, 58″ at 0.8 mm, and 55″ at 0.4 mm. The chop throw and frequency for the f/9 observations were 145″ at 80 Hz, and for the f/35 data the chopper throw was either 140″ or 128″ at 12.5 Hz. The observations employed narrow-band filters centered on atmospheric transmission windows at 400, 800, and 1100 μm and a broad-band millimeter search filter extending from 700 μm to 1.3 mm. The filter profiles are shown in Robson (1982) and Cunningham (1982). Calibration was against Mars with Uranus as a secondary calibrator (Griffin *et al.* 1984); the calibration procedure for all observations is described in Rowan-Robinson, Clegg, and Ade (1975) and Cunningham *et al.* (1981). The spectral index, α, of the sources was assumed to be zero except for 3C 273 and NGC 1275, for which a value of $\alpha = -0.7$ was assumed (Clegg *et al.* 1983; Longmore *et al.* 1984). However, because of the narrow-band nature of our filters, changing α from zero to -0.7 makes only a difference of less than 3% in the derived fluxes.

The brightness temperatures for the calibrators at the effective wavelength of observation are presented in Table 1. The results of our observations are presented in Table 2, which lists the source, date of observation, and the measured flux in the five bands from 0.8 to 2.0 mm. Table 3 tabulates additional observations made at 400 μm in good weather conditions. The errors quoted are purely statistical; we estimate absolute calibration errors to be $\sim$10% for the calibration flux and 5% due to photometric uncertainty. We note that the preliminary analysis of some of our 1981 data by Cunningham (1982) used a slightly different calibration, being based on earlier measurements of the planetary brightness temperatures made with a different filter set.

TABLE 1

Assumed Brightness Temperatures of Planetary Calibrators

Planet	Date	Effective Wavelength (mm)	Mean Frequency (GHz)	Brightness Temperature (K)
Mars	1982 Jan	2.0	161	204.3
		1.4	227	207.3
	1982 Feb	1.1	279	208.8
		1.0	337	209.0
		0.8	392	210.3
		0.4	808	212.5
	1982 Apr	1.1	279	207.7
		1.0	337	208.0
		0.8	392	208.6
		0.4	808	210.0
	1982 Sep	1.1	279	205.5
		1.0	337	206.0
		0.8	392	206.0
Jupiter	1981 Feb	1.1	279	168.0
		0.8	392	161.6
Uranus	(all)	2.0	161	108.4
		1.4	227	94.6
		1.1	279	91.1
		1.0	337	88.9
		0.8	392	84.3
		0.4	808	73.9

III. DISCUSSION

a) *Spectral Shape*

VLBI observations of flat spectrum sources (see, e.g., a review by Readhead and Pearson 1982) gives increasing support to the idea that the flatness of the spectrum over a wide range in frequency arises from the superposition of a number of individual synchrotron components, the so-called cosmic conspiracy theory. Although our measurements show that the spectra are also flat up to submillimeter frequencies, it is clear that the superposition cannot continue indefinitely because the spectrum must eventually steepen to connect with the infrared continuum. Indeed, in the case of 3C 273 we see the turnover at $\lambda \approx 5$ mm and the millimeter-submillimeter continuum not only connects smoothly with the infrared (Clegg *et al.* 1983) but varies almost simultaneously with it (Robson *et al.* 1983), indicating that the emission over this range arises in the same region of the source. We therefore assume that the millimeter-submillimeter emission in this type of object arises in a *single*, very compact region near the core of the source and seek a model for the continuum emission *independent* of the cause of flatness at longer wavelengths.

A relativistic Maxwellian electron energy distribution (Jones and Hardee 1979; Spangler 1980) can almost certainly be ruled out because this model produces a continuum spectrum which is steeply falling at millimeter wavelengths (Ennis, Neugebauer, and Werner 1982).

If the flat spectra arise solely from homogeneous, optically thin synchrotron emission with energy distribution index $s = 1$ [$N(\gamma) \propto \gamma^{-s}$, where γ is the Lorentz factor of the relativistic electrons], then an upper cutoff in the electron energy distribution would be required to produce a cutoff in the spectrum at wavelengths below 1 mm. However, this would produce a very steep exponential cutoff in the high frequency spectrum, much steeper and more powerful than is usually observed in the infrared (Marscher 1977*a*; Ennis, Neugebauer, and Werner 1982), although a model with $s = 1$ may be viable if there is steepening due to expansion losses in a relativistic jet (see below).

The most promising model of the continuum spectrum of compact, flat spectrum sources appears to be incoherent synchrotron radiation from an inhomogeneous distribution of relativistic electrons and magnetic field. In order to explain the rapid variability of many of these objects and the apparent superluminal motion well observed in at least five of them (Cohen and Unwin 1982; Browne *et al.* 1982), relativistic beaming effects have been incorporated in the more successful models. Königl (1981) has investigated theoretically the continuum emission from a conical relativistic beam with a radial dependence of magnetic field and electron density distribution of the form

$$B(R) = B_1 R^{-m} \,, \tag{1a}$$

$$N(\gamma, R) = K_1 \gamma^{-(2\alpha+1)} R^{-n} \,, \tag{1b}$$

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TABLE 2

MILLIMETER AND SUBMILLIMETER FLUX DENSITIES[a] OF FLAT SPECTRUM RADIO SOURCES

		EFFECTIVE WAVELENGTH[b]				
SOURCE	DATE	2.0	1.4	1.1	1.0	0.8
0235+164	1982 Jan 17, 19	2.1 ± 0.5	2.1 ± 0.5	...	...	...
	1982 Sep 10–13	...	...	1.7 ± 0.4	...	...
0300+470	1982 Jan 18–20	1.8 ± 0.3	...	...	...	...
0316+413	1980 Aug 27	...	...	25.1 ± 3.5	...	30.7 ± 6.4
(3C 84)	1981 Feb 14–19	...	...	18.9 ± 1.4	...	19.5 ± 3.4
(NGC 1275)	1982 Jan 18–23	42.0 ± 4.2	30.0 ± 3.0	...	...	...
	1982 Feb 4	...	...	...	16.0 ± 1.0	12.3 ± 1.5
	1982 Sep 10–13	...	...	...	26.0 ± 0.7	17.5 ± 0.9
0406+121	1982 Jan 19	2.2 ± 0.5	...	...	...	...
0415+379	1982 Jan 20, 23	2.3 ± 0.3	...	...	...	...
(3C 111)						
0420−014	1982 Jan 21	1.8 ± 0.3	...	...	...	...
	1982 Feb 4	...	...	...	1.6 ± 0.3	
0430+052	1982 Jan 18–23	2.6 ± 0.3	...	...	...	...
(3C 120)						
0716 + 714	1982 Jan 23	3.2 ± 0.3	...	...	...	...
0735+178	1982 Jan 19, 20	1.6 ± 0.2	...	...	...	...
	1982 Feb 4	...	...	...	1.1 ± 0.2	...
	1982 Apr 22	...	...	...	$3\sigma < 2.3$	...
0736+017	1982 Jan 19, 20	1.5 ± 0.2	...	...	...	...
0851+202	1982 Jan 23	4.1 ± 0.4	...	...	...	...
(0J 287)	1982 Feb 4	...	...	...	1.5 ± 0.3	...
	1982 Apr 19, 20	...	...	3.3 ± 0.6	3.4 ± 0.5	2.2 ± 0.4
0923+393	1982 Jan 20	0.9 ± 0.2	...	...	...	...
1055+018	1982 Jan 20, 23	0.9 ± 0.2	...	...	...	...
	1982 Feb 3	...	...	...	$3\sigma < 1.2$	$3\sigma < 1.6$
1219+285	1982 Jan 23	1.7 ± 0.4	...	...	...	...
1226+023	1981 Feb 14–20	...	...	11.0 ± 1.0	...	8.7 ± 1.5
(3C 273)	1981 Mar 16	19.0 ± 2.0	14.0 ± 1.8	...	...	...
	1982 Jan 18–21	14.5 ± 0.7	10.9 ± 0.6	...	...	...
	1982 Feb 3	...	...	8.3 ± 0.9	8.0 ± 0.6	7.1 ± 1.1
	1982 Apr 19–22	...	...	9.9 ± 0.5	...	7.3 ± 0.4
1253−055	1982 Jan 20, 23	6.4 ± 0.6	3.2 ± 0.4	...	...	...
(3C 279)	1982 Feb 4	...	...	...	3.2 ± 0.6	...
1308+326	1982 Jan 23	1.9 ± 0.5	...	...	...	...
	1982 Apr 23	...	...	1.3 ± 0.3	...	...
1413+135	1982 Jan 18	3.0 ± 0.5	2.0 ± 0.7	...	...	...
	1982 Feb 4	...	...	...	1.5 ± 0.3	...
	1982 Apr 22	...	...	1.2 ± 0.2	1.4 ± 0.3	1.2 ± 0.2
1514−241	1982 Apr 23	...	...	...	0.9 ± 0.2	...
(AP Lib)						
1641+399	1981 Feb 14–20	...	...	4.9 ± 1.2	...	...
(3C 345)	1981 Mar 16	10.5 ± 1.3	...	...	...	...
	1982 Jan 17–23	6.7 ± 0.3	7.0 ± 0.3	...	...	...
	1982 Apr 19	...	...	6.9 ± 0.7	6.5 ± 0.7	7.4 ± 0.7
1749+096	1982 Apr 23	...	...	...	0.8 ± 0.1	...
1921−293	1982 Sep 10	...	...	7.1 ± 1.2	...	11.3 ± 1.2
(OV 236)						
1928+738	1982 Jan 22	1.6 ± 0.4	...	...	...	...
2200+420	1982 Jan 18, 22	4.1 ± 0.4	...	...	...	...
(BL Lac)	1982 Sep 10	...	...	3.5 ± 0.7	...	...
2223−052	1982 Sep 10	...	...	6.0 ± 1.2	...	3.3 ± 0.8
(3C 446)						
2251+158	1982 Jan 19	5.9 ± 0.6	...	...	...	...
(3C 454.3)	1982 Sep 10	...	...	5.1 ± 0.9	...	...

[a] In janskys.
[b] In millimeters.

TABLE 3

ADDITIONAL OBSERVATIONS AT 400 MICRONS

Source	Date (1982)	Flux (Jy)
0316+413 .... (3C 84)	Feb 4	13.3 ± 3.2
1226+023 .... (3C 273)	Apr 22	4.4 ± 0.9

where R is the distance from the apex of the cone and B_1 and K_1 are the magnetic field and coefficient of the electron distribution at a distance of 1 pc, respectively. Königl has shown that the continuum emission may be described as a broken power law, with spectral index in the partially optically thick region of the spectrum given by

$$\alpha_1 = \frac{4 + m - 5k_m}{2k_m}\,, \qquad (2)$$

where

$$k_m = \frac{(3 + 2\alpha)m + 2n - 2}{5 + 2\alpha}\,. \qquad (3)$$

From this relation we can see that a flat spectral index can result from the assumptions $m = 1$ and $n = 2$. These values have a simple physical interpretation. The value of n ensures that the equation of continuity for the electrons is satisfied; this, combined with the value of m and neglecting radiative and adiabatic losses, means that the ratio of particle to magnetic field energy densities remains constant.

In inhomogeneous synchrotron models radiation at the turnover frequency, ν_m, originates from the smallest radius at which optically thin radiation is produced (Jones *et al.* 1981). Ennis, Neugebauer, and Werner (1982) have used the model of Königl (1981) with these assumptions to derive an equation for the turnover frequency ν_m which is independent of α, namely,

$$\nu_m = \frac{2.4 \times 10^9 \Gamma \beta z^{0.4} D(\theta)^{0.4} S_m{}^{0.2}}{\phi^{0.2}(1 + z)^{1.2}(\sin\theta)^{0.2} B_1{}^{1.4}}\,, \qquad (4)$$

where Γ is the Lorentz factor of the bulk motion, β is the velocity of the jet in units of c, ϕ is the semiangle of the jet ($\sim$0.1 rad), $D(\theta) = \Gamma^{-1}(1 - \beta\cos\theta)^{-1}$ is the relativistic Doppler factor, θ is the angle between the jet axis and the line of sight, and S_m is the flux density in janskys at ν_m (for $\alpha \approx 0$, $S_m \approx S_{1\,\mathrm{mm}}$).

Taking $\nu_m > 300$ GHz and a typical value of $\Gamma \approx 5$, we can obtain an estimate of the magnetic fields in these sources, and for the blazars they are typically of order 0.2 gauss.

The usual relation $\alpha = (1 - s)/2$ for optically thin synchrotron emission shows that a flat spectrum can also be produced by the choice of $s = 1$. The spectral steepening required in the submillimeter is then achieved by adiabatic expansion losses. If we consider the model of Marscher (1980*b*) (see also Clegg *et al.* 1983), then for a Blandford-Rees jet whose radius r is related to distance R from the core region by $r \propto R^{\epsilon}$ there will be a steepening due to expansion losses to $\alpha = -(1 - \epsilon)/3\epsilon$ up to a frequency ν_2 where synchrotron losses begin to dominate. Recent observations (see, e.g., Rieke, Lebofsky, and Wizniewski 1982) have shown that some compact objects have steep infrared spectra consistent with a cutoff in a synchrotron spectrum. This may indicate that ν_2 lies in the mid-infrared region for these sources.

In order to distinguish between optically thick and optically thin models it will be necessary to obtain simultaneous multifrequency spectra of these sources to compare with the models; continued monitoring over long periods should determine the correlation (if any) of variations at different frequencies (see, e.g., Epstein *et al.* 1982).

Ennis, Neugebauer, and Werner (1982) found evidence for simultaneous variations at 2 cm and 1 mm for a small sample of blazars, which would seem to favor the optically thin models. Further investigations are obviously required.

b) *Variability*

We have monitored the millimeter emission of NGC 1275 and 3C 273 over the past 2 yr. The data are also presented in Table 2, and it can be clearly seen that NGC 1275 shows conclusive evidence for variability over a time scale of years. In the case of 3C 273 our data, plotted in Figure 1, show

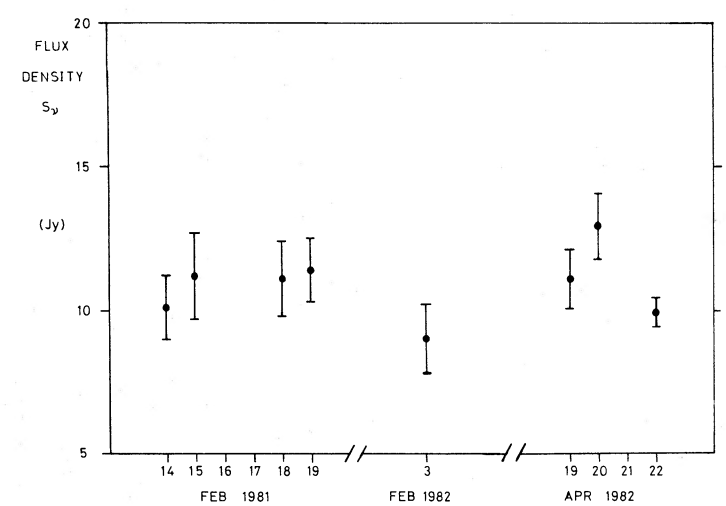

FIG. 1.—1.1 mm observations of 3C 273 (1 σ statistical errors)

no evidence for variability or spectral change in the millimeter and submillimeter region from 1981 February to 1982 April. Ennis, Neugebauer, and Werner (1982) have claimed evidence for variability; however, there is no overlap between the respective sets of observations, since all their data were obtained prior to 1981. Sherwood *et al.* (1982) have also claimed evidence for variability of 3C 273 at one millimeter wavelength, and in this case the data were obtained in 1981 July, within the time scale covered by our observations. Clearly more attention to the monitoring of 3C 273 on all time scales is vital, and we are currently engaged in such a program (Robson *et al.* 1983).

IV. CONCLUSIONS

We have presented millimeter-wave fluxes for a sample of 26 strong, compact, flat spectrum radio sources. We have monitored NGC 1275 and 3C 273 over a period of years.

1. These data represent a significant increase in the published millimeter-wave data on extragalactic sources.
2. Almost all the sources observed remain flat to the shortest wavelength observed (2 mm for nine sources and 1 mm for the remaining 17).
3. The shape of the spectra can be interpreted in terms of an inhomogeneous synchrotron model with some degree of beaming.
4. In order to make more definite conclusions about the emission mechanisms obtaining to these sources, further measurements are necessary in conjunction with concurrent observations over a wide range of wavelength. We are currently engaged in such a program.
5. It is important to monitor the variability of these sources in order to determine the evolution of spectral shape and the correlation of variations at different frequencies. These data will provide a base for further study.
6. We see clear evidence for variations of NGC 1275 on a time scale of years, but over the period of our observations (2 yr) we see no evidence for significant variability from 3C 273 on time scales from hours to years (but see note added in manuscript, below). We are currently engaged in millimeter and submillimeter monitoring of 3C 273 on daily and monthly time scales.

Note added in manuscript.—More recent observations of 3C 273 have shown a dramatic outburst in the millimeter to infrared emission during 1983 (see Robson *et al.* 1983).

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