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THE BROAD-BAND SPECTRA AND VARIABILITY OF COMPACT NONTHERMAL SOURCES

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ABSTRACT

Coordinated radio observations in the centimeter and millimeter bands of compact nonthermal sources have been carried out at approximately six month intervals from 1977 November to 1979 May. The especially broad wavelength coverage of these data (11 cm $\geq \lambda \geq$ 1 mm) provide an unusual opportunity to study the spectra and variations of these sources. In about a dozen sources, nearly simultaneous infrared and/or visual spectra are available, allowing us to examine the relationship between the infrared-visual and radio regimes. Supplementary published radio data at adjacent epochs have been included in our analysis as well.

The sources were selected for their millimeter strength, but still have remarkably flat spectra in this wavelength regime. A simple transition to the steeper infrared spectra seems likely with a mean break wavelength $\lambda \approx 300$ μm in the rest frame. These observations point to a tapered source geometry, with the smallest structures roughly on the order of 10^{16} cm as estimated from the spectral break, consistent with scales estimated from optical variability time scales. Large amplitude variations on a six month time interval are seen to be fairly infrequent in most of the sources.

We suggest a relatively model-independent way of categorizing flux variations as due to changes in source *scale*, or *structure* or the *slope* of the electron energy spectrum. This categorization may be helpful in understanding the overall construction of sources. Possible examples of each category are identified from our data. Observationally, only very broad-band flux monitoring programs can distinguish between these different types of behavior. The recent (since mid-1972) evolution of 3C 120 is interpreted in the first approximation as a change in the scale of this source. The superluminally separating components seen by VLBI in 3C 120 may simply be bright features in this overall expansion.

Subject headings: infrared: sources — radio sources: spectra — radio sources: variable

I. INTRODUCTION

Compact nonthermal radio sources are currently one of the most active subjects of extragalactic astrophysical study because they are believed to relate closely to the primary engine in active galactic nuclei. Determination of the spectral and polarization properties of such sources and how they evolve with time is a necessary part of our efforts to understand them. We report here flux density measurements of $\sim$20 sources at centimeter and millimeter wavelengths made between 1977 November and 1979 May. For the first time we are able to report flux density measurements at λ1 mm for nine of these sources. This extension to shorter millimeter wavelengths is especially important since it helps define the spectral break which must generally occur between the radio and infrared spectral regions. The location of this break may provide important clues about the structure of these sources. Our radio measurements are supplemented in 12 cases with nearly simultaneous infrared or visual photometry or both, from Puschell (1979) and Puschell and Stein (1980).

Our measurements were obtained at approximately six month intervals, with up to four epochs of broad-band spectra for some sources. For a number of our sources measurements were also made in 1977 January and reported by Owen *et al.* (1978) and O'Dell *et al.* (1978). Since these data were all obtained in a consistent fashion, they provide a very useful broad-band picture of the time-histories of these sources over a $2\frac{1}{2}$ year period. Additional radio spectral data obtained in early 1978 by Owen, Spangler and Cotton (1980) for most of these sources help to define their spectra at that epoch.

Most of these sources are also part of our coordinated centimeter-millimeter polarimetry program. The polarization results will be reported elsewhere.

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II. OBSERVATIONS

a) *Summary*

Most of the observations took place in four sessions, each starting with measurements at λ11.1 cm and λ3.7 cm using the Green Bank Interferometer, or at λ6 cm and λ2 cm using the Very Large Array (VLA). Each centimeter session was then followed by observations at λ3.3 mm or λ9.6 mm or both using the 10.6 m telescope at Kitt Peak. Measurements on a single source were usually spread out over the sessions; we therefore label the dates of observations as follows:

1. At λ11.1 cm, λ3.7 cm on 1977 November 22–23; at λ9.5 mm on 1977 December 2–5; and at λ3.3 mm on 1977 December 5–7.
2. At λ11.1 cm, λ3.7 cm on 1978 April; and at λ9.5 mm, λ3.3 mm on 1978 April 28–May 3.
3. At λ6 cm, λ2 cm on 1978 November 17–19, and at λ3.3 mm on 1978 November 26–29.
4. At λ6 cm, λ2 cm on 1979 April 21–23, and at λ3.3 mm on 1979 May 5–9.

The prime focus of the 5 m Hale telescope on Palomar Mountain was used for observations at λ1 mm for these and a number of other epochs throughout this period as well. These additional results will be listed individually by date. Visual and infrared data has been taken from Puschell (1979) and Puschell and Stein (1980), who used the UM-UCSD 1.5 m telescope on Mount Lemmon.

b) *Technique*

At both the Interferometer (Altschuler and Wardle 1976) and the VLA (e.g., Owen *et al.* 1978), 3–7 short (5–10 minute) observations were made for each source. The flux densities were fixed to the KPW scale, using 3C 286 as the primary calibrator. The random noise was negligible compared to calibration and other systematic errors; the latter have been conservatively estimated at 5% (λ11.1 cm and λ6 cm), and 10% (λ3.7 cm and λ2 cm), and can differ between observing sessions.

At λ9.6 mm, we employed a dual-channel mixer receiver at the Cassegrain focus of the 10.6 m telescope. The system temperature was $\sim$650 K, and the instantaneous bandwidth was 1 GHz. Nutating the subreflector at 2 Hz created two "beams" on the sky, which were alternately pointed at the source every 10–30 seconds. Either 3, 4, or 5 such pairs of measurements constituted a "scan." During one scan, the two receiver channels were sensitive to horizontal, linear and vertical, linear (Stokes parameters $[I-Q]$ and $[I+Q]$, respectively).[2] For alternate scans, a ferrite switch reversed the polarizations to vertical and horizontal, respectively. The outputs of the two receivers were recorded separately and summed to form the Stokes parameter I.

The corrections for atmospheric attenuation were determined from observing the increase in atmospheric emission as a function of zenith distance. Errors introduced by this procedure were less than 1%. The receiver gains were monitored through firing of a broadband noise tube. The flux density scale was tied to DR 21 by assuming a total flux density of 18.7 Jy at 31.4 GHz, and then correcting for dilution by the 210″ beam (B. L. Ulich, private communication). Calibration errors led to an estimated uncertainty of 5–10% in the derived flux density of each source.

A dual-channel cooled mixer was used at λ3.3 mm (89.6 GHz), again at the 10.6 m Cassegrain focus.[3] The system temperatures ranged from 300 to 400 K, depending on weather conditions and diode behavior, and the instantaneous bandwidth was 1 GHz. The observing procedure was similar to that outlined above for λ9.6 mm, with the subreflector nutating at 6.7 Hz. Switching between horizontal and vertical linear polarizations was done at a rate of 0.67 Hz, by means of a pair of quarter-wave plates, and the Stokes parameter I was then calculated by the on-line computer. At λ3.3 mm, the flux densities were calibrated assuming a brightness temperature of 178 K for Jupiter (Ulich *et al.* 1980). Pointing and calibration errors in general dominate the errors due to system noise, and result in an $\sim$10% uncertainty for the derived flux densities. These λ3.3 mm total intensity measurements appear to be systematically high by $\sim$20% with respect to those of Landau, Epstein, and Rather (1980). The reader is therefore cautioned against comparing these two sets for variability, although derived spectra would be only slightly affected.

At λ1 mm (300 GHz), an incoherent detection system was used for the observations. The detector was a liquid-helium–cooled composite bolometer (Hauser and Notarys 1975) consisting of a gallium-doped germanium chip as the temperature sensing element, thermally connected to a bismuth-coated sapphire substrate providing the radiation absorption. The electrical noise-equivalent power of the bolometer was 1×10^{-14} W Hz$^{-1/2}$. The short wavelength limit at $\sim$700 μm in the overall system spectral response was set by a 2.5 mm thick fluorogold filter cooled to liquid helium temperatures (Muehlner and Weiss 1973) in combination with absorption by atmospheric water vapor. The passband cuts off at wavelengths longer than 1.5 mm due to diffraction at the telescope aperture. The half-power beam diameter was 55″, close to the diffraction limit of the 5 m telescope. This beam size was defined by the entrance aperture of a Winston light collector (Hinterberger and Winston 1966; Winston 1970; Harper *et al.* 1976) used to concentrate the incident radiation onto the detector. The surface of the collector was molded out of lead which, in operation, was cooled to liquid-helium temperatures thus maximizing its reflectivity due to the phase transition of lead to the superconducting state below 7.2 K.

The observing procedure was as described in Elias *et al.* (1978). At λ1 mm, the flux densities were calibrated using the measured brightness temperatures of the planets

[2] Horizontal and vertical, in this sense, were fixed with respect to the altazimuth mount of the telescope, and thus rotated on the sky with time.

[3] The center frequency was sometimes varied by a few GHz to optimize receiver performance. Often, only one of the two receiver channels was used.

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TABLE 1

FLUX DENSITIES (Jy)

Source	Epoch or Date	Wavelength (cm) 11.1	6.0	3.7	2.0	0.96	0.33	0.1
0007+10, III Zw 2	3	…	0.67	…	1.9	…	…	…
	1979 Jan. 8	…	…	…	…	…	…	2.0(0.6)
	4	…	0.77	…	…	…	…	…
0235+16	1	1.92	…	2.1	…	2.8	…	…
	2	1.90	…	2.3	…	…	…	…
	1979 Feb. 16	…	…	…	…	…	…	1.7(0.4)
	4	…	2.11	…	1.8	…	1.6	…
0300+47	1	2.16	…	2.7	…	…	…	…
	2	2.06	…	2.7	…	2.3	…	…
	3	…	1.97	…	2.3	…	…	…
	1979 Feb. 18	…	…	…	…	…	…	1.0(0.3)
	4	…	1.92	…	2.5	…	…	…
0355+50	2	7.50	11.6	…	…	12.1	…	…
0420−01	2	1.24	…	3.0	…	…	…	…
	3	…	2.97	…	5.8	…	5.2	…
	1979 Jan. 12	…	…	…	…	…	…	2.5(0.8)
	4	…	3.16	…	4.9	…	…	…
0430+05, 3C 120	1	6.31	…	5.1	…	…	…	…
	2	5.44	…	3.9	…	…	…	…
	3	…	4.58	…	4.1	…	…	…
	1979 Jan. 10	…	…	…	…	…	…	<2.2
	4	…	3.76	…	2.4	…	…	…
0735+17	1	1.84	…	1.9	…	1.7	…	…
	2	1.78	…	1.9	…	…	…	…
	4	…	2.13	…	1.9	…	1.7	…
0736+01	1	2.15	…	2.4	…	2.9	…	…
	2	2.09	…	2.0	…	…	…	…
	4	…	2.27	…	2.5	…	…	…
	1979 Apr. 10	…	…	…	…	…	…	3.6
0754+10, OI 090.4	4	…	714	…	820	…	…	…
0851+20, OJ 287	1	1.95	…	3.6	…	5.2	4.7	…
	2	2.24	…	3.0	…	3.9	…	…
	1978 Oct. 17	…	…	…	…	…	…	5.1(1.0)
	1978 Nov. 9	…	…	…	…	…	…	4.9(1.0)
	3	…	3.12	…	5.1	…	4.7	…
	1979 Jan. 11	…	…	…	2.6	…	…	3.0(0.7)
	1979 Mar. 14	…	…	…	…	…	…	2.9(0.7)
	4	…	2.24	…	…	…	2.3	2.2(0.5)
1055+01	1	2.49	…	2.7	…	…	…	…
	2	2.56	…	2.7	…	…	…	…
	3	…	2.99	…	3.1	…	…	…
	1979 Jan. 13	…	…	…	…	…	…	<1.2
	4	…	3.00	…	3.0	…	…	…
1219+28	3	…	2.04	…	1.7	…	…	…
	1979 Apr. 12	…	…	…	…	…	…	<3.5
	4	…	2.94	…	2.6	…	…	…
1226+02, 3C 273	1	37.1	…	33	…	29	14.6	…
	2	37.8	…	33	…	25	…	…
	3	…	34.0	…	27.6	…	15.3	18.0(3.6)
	1979 Jan. 12	…	…	…	…	…	…	14.0(2.8)
	1979 Apr. 11	…	…	…	…	…	…	17.0(3.4)
	4	…	32.3	…	22.4	…	…	…
1308+32	1	1.57	…	2.7	…	3.2	…	…
	2	1.67	…	2.9	…	3.4	…	…
	3	…	2.66	…	2.9	…	…	…
	4	…	2.35	…	2.6	…	1.73	2.3(0.6)
1510−08	3	…	2.91	…	4.5	…	2.8	…
	1979 Mar. 15	…	…	…	…	…	…	2.7(0.9)
1641+39, 3C 345	1	7.39	…	7.2	…	7.2	…	…
	2	7.21	…	7.1	…	7.6	…	…
	3	…	7.41	…	7.7	…	9.0	…
	1979 Apr. 10	…	…	…	…	…	…	7.2(1.5)
	4	…	6.86	…	7.9	…	7.9	…
1749+09	2	0.92	…	2.0	…	3.2	…	…
	3	…	1.49	…	3.8	…	10.6	…
	4	…	1.60	…	2.5	…	4.3	…

TABLE 1—*Continued*

Source	Epoch or Date	Wavelength (cm) 11.1	6.0	3.7	2.0	0.96	0.33	0.1
2134+00	2	6.87	...	8.9	...	4.9	...	...
	3	...	10.7	...	6.9	...	...	...
	4	...	9.93	...	6.5	...	1.7	3.6
2200+42 BL LAC	1979 Apr. 10	...	...	...	...	...	...	
	1	3.39	...	3.3	...	2.6	2.1	...
	2	3.02	...	3.1	...	3.1	...	1.9
	3	...	2.57	...	2.1	...	...	
	4	...	2.39	...	2.2	...	2.3	...
2251+15, 3C 454.3..........	1	9.52	...	7.7	...	...	...	...
	2	9.18	...	6.9	...	5.9	...	...
	3	...	7.97	...	6.1	...	...	...
	4	...	7.32	...	5.5	...	4.5	...

NOTE.—Flux densities. The errors at 5% at $\lambda\lambda$11.1 cm and 6.0 cm and 10% at $\lambda\lambda$3.7, 2.0, 0.9 and 0.3 cm. Errors for 1 mm flux densities are given parenthetically in janskys. Epoch numbers are as in Figure 1, with individual dates listed for λ1 mm measurements, where necessary. Upper limits at λ1 mm are 3.

(Werner *et al.* 1978). The atmospheric water vapor content was determined by measuring the transmission of the atmosphere along the line of sight to the Sun in and out of the 1.9 μm water band (Westphal 1974). This information was then combined with atmospheric water vapor and oxygen absorption line data (Burch 1957) to calculate the atmospheric attenuation in the bandpass. Although the statistical errors for the brightest sources are small, calibration errors led to an estimated uncertainty of 20% in the derived flux densities.

c) *Results*

The results of the observations are presented in Table 1. Column (1) lists the source and date of observation (either 1–4, or as a specific date for the λ1 mm measurements). Columns (2)–(8) contain the flux densities (in Jy) at λ11.1 cm, 6 cm, 3.7 cm, 2 cm, 9.6 mm, 3.3 mm, and 1 mm, respectively.

Flux density measurements are shown in Figure 1 for each epoch of observation from 1977 January to 1979 May, including epoch 0 from Owen *et al.* (1978). When they are available we have supplemented these with a few additional λ3.3 mm measurements from Landau *et al.* (1980) (uncorrected for the possible 20% bias between our set of measurements and theirs) made approximately coincident with epochs 3 and 4. In addition some of the fluxes obtained over a range of wavelengths by Owen, Spangler, and Cotton (1980) near epoch 1 are included. Figure 2 shows the spectra over the entire radio-infrared-visual domain.

III. DISCUSSION

a) *Spectral Information*

Our sources were selected to be relatively strong in the millimeter band, yet it is still remarkable that most of the spectral distributions in Figure 1 are very flat. It is especially remarkable that the spectra remain flat all the way to λ1 mm, as, for example do 0851 + 20, 1308 + 32 and 2251 + 15. Thus, those sources show no clear signs even at the shortest radio wavelengths, of the spectral break which must occur in the far-infrared or submillimeter band.

The flatness of the radio spectra is probably an indication of partially opaque source structures. The wavelength dependence of polarization observed for many of the sources (paper in preparation) argues in general against simple transparent sources (e.g. Marscher 1977*b*), although this or partially opaque, non–power-law sources or both are possible in some cases (Jones and Hardee 1979).

In most sources the flat spectra, if they are due to opacity, require the existence of several structural components or of "tapered" source structures (Condon and Dressel 1973; de Bruyn 1976; Marscher 1977*a*; Blandford and Königl 1979; Cook and Spangler 1980). The term "tapered" indicates that magnetic fields and relativistic particle densities within the source change smoothly from regions of high to low values. In some specific models, the higher frequency emission, produced in strong field regions, is thus generated closer to the power source. To produce a flat spectrum such sources must, of course, also have substantially larger radiating volumes associated with the weaker field low density regions. VLBI observations do sometimes indicate fairly well-defined "components," but in a number of cases the data seem to require "quasi-linear," possibly jetlike, distributions of brightness (e.g., Readhead *et al.* 1978). Models involving only homogeneous source components whose physical properties are statistically independent tend (according to unpublished numerical experiments we have performed) to produce spectra which are dominated by one component and, therefore, are not very flat. Cook and Spangler (1980) have concluded specifically that the spectra obtained by Owen, Spangler, and Cotton (1980) are hard to interpret as superposed homogeneous com-

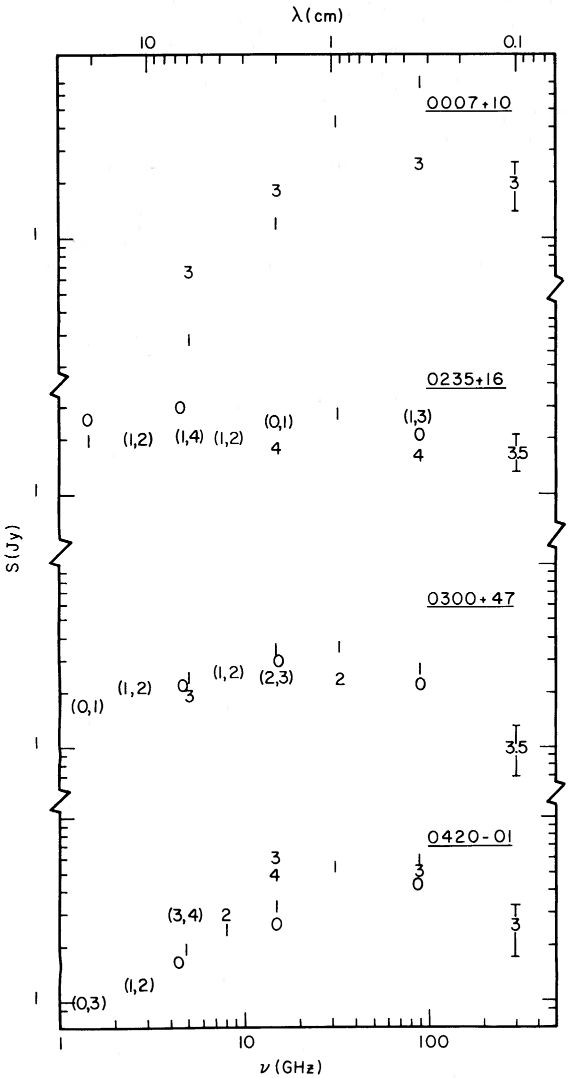

FIG. 1*a*

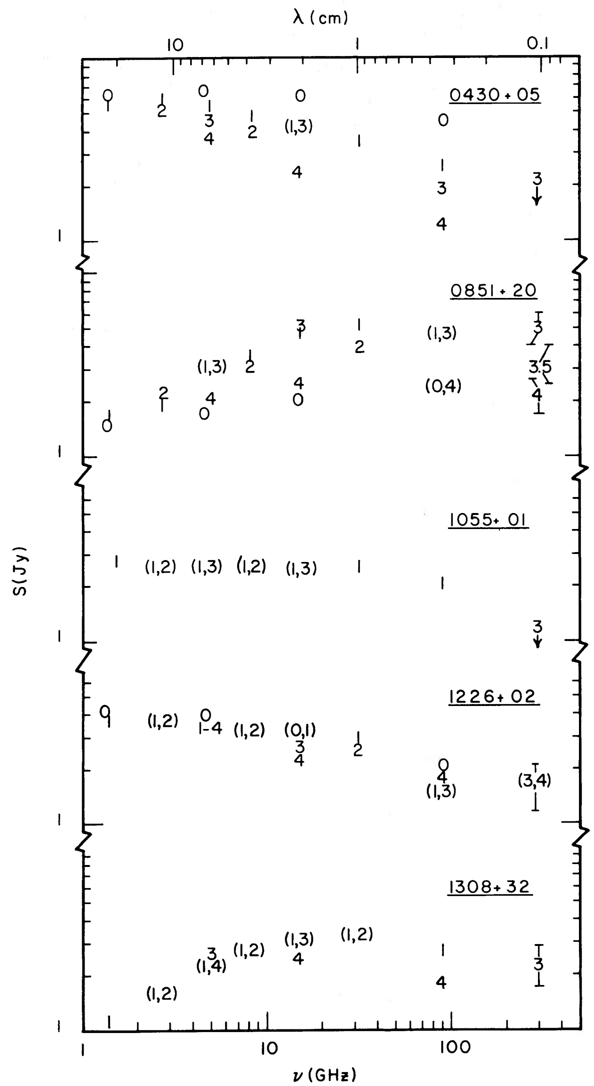

FIG. 1*b*

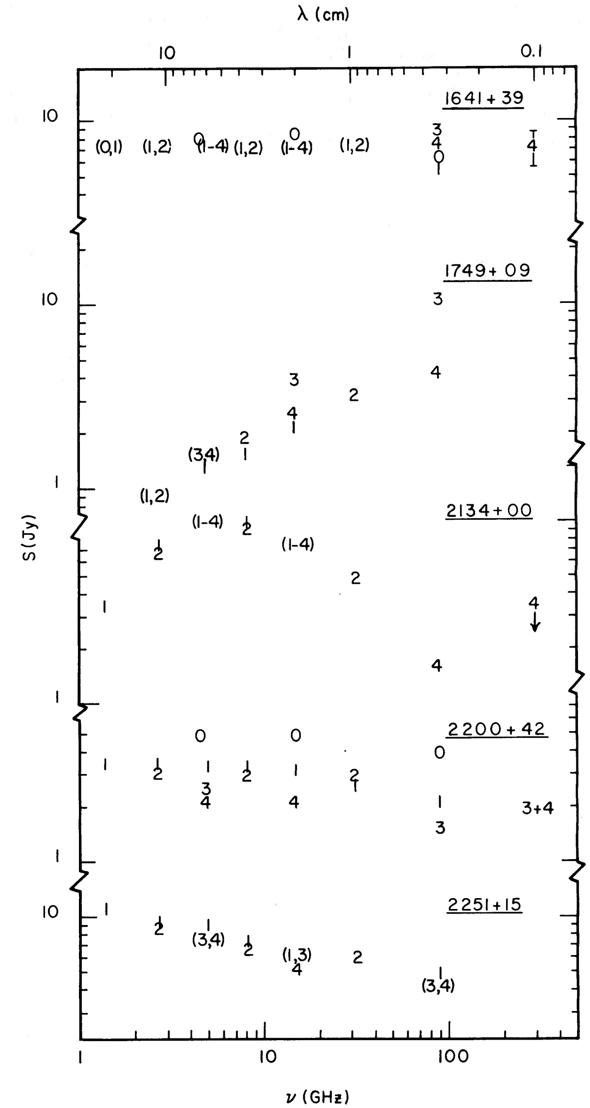

FIG. 1*c*

FIG. 1.—Radio spectra 1977–1979. Fluxes are labeled by epoch number: 0 = 1977 January, 1 = 1977 November–December, 2 = 1978 May, 3 = 1978 November, 4 = 1979 May. Fluxes measured at λ1 mm during February 1979 and labeled 3.5. Our measurements have been supplemented by data from Owen *et al.* (1978), Owen *et al.* (1980), and Landau *et al.* (1980). In cases where data from more than one epoch overlap, a number pair, e.g., (1, 2), is centered on the measurements. The symbol (1–4) represents overlapping data at epochs 1, 3, and 4.

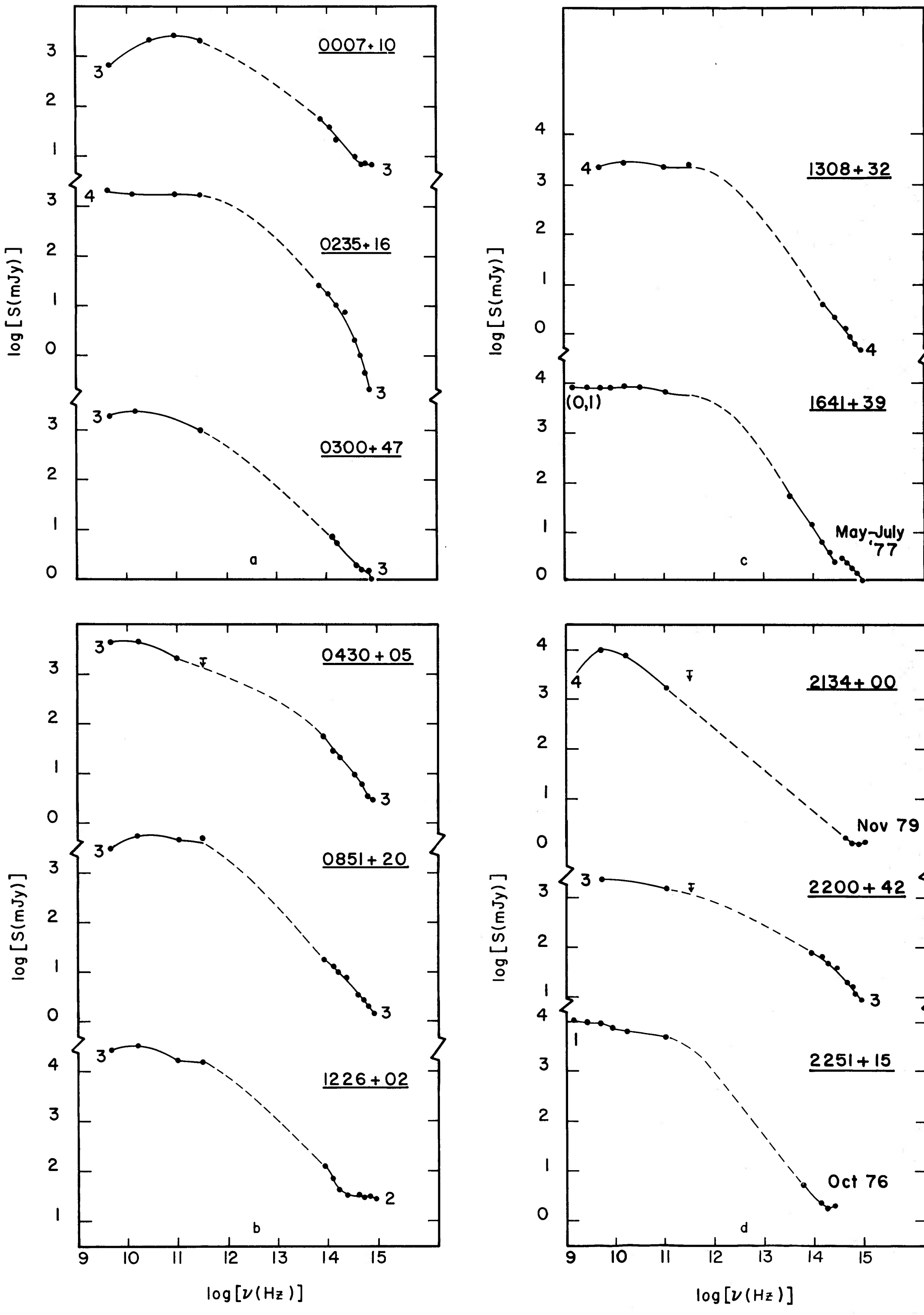

FIG. 2.—Radio, infrared, and visual spectra. Numbers to left and right of spectra indicate epochs of radio and visual-infrared measurements, respectively. Curves through the radio points were guided in part by additional data from Fig. 1. Optical-infrared data taken from Puschell and Stein (1980) or Puschell (1979) except for 1641+39 and 2251+15 (Neugebauer *et al.* 1979) and 2134+00 (our unpublished data). Lines connecting the visual-infrared and radio regimes are suggestive only.

ponents. Therefore, some degree of tapering within the sources does seem to be called for.

Figure 2 shows the radio to optical spectra of those sources for which we have data in all spectral regimes. O'Dell *et al.* (1978) have published spectra for 1977 January of 0235+16, 0430+05, 0851+20, 1226+02, and 1308+32 as well. In each of these sources some spectral changes occurred between their measurements and ours, but the general appearances of the radio-visual spectra did not change substantially. Spectral variations and their interpretation are discussed in more detail below.

All of the spectra in Figure 2 suggest a simple transition from the rather flat radio spectra with $\alpha \approx 0$ to the relatively steep near-infrared spectra, with $\alpha \gtrsim 1$.[4] In some cases such as 0235+16, 2134+00, and 2200+42 signs of the necessary transition in slope may be appearing within the spectral bands already observed. For the remaining sources, the transition apparently occurs almost entirely in the wavelength interval between $\lambda 1$ mm and $\lambda 3$ μm. For the spectra in Figure 2 the intersection of the radio and infrared extrapolations occurs at a mean wavelength $\lambda \approx 300$ μm in the source rest frame.

From the simple overall forms of the spectra and the general similarity from one to another it seems likely that the same physical processes are occurring in each source, and that there is a fairly simple relationship between the optical-infrared and radio emissions. The simplest interpretation would associate all of this emission with incoherent electron synchrotron radiation. The optical-infrared sources would most likely be transparent. Some sources with flat optical spectra (e.g., 1226+02 [3C 273] and 2134+00) probably violate this interpretation in the optical portion of the spectrum. However, in these cases, infrared spectra do seem to indicate a relationship to the radio spectrum; especially in sources such as 0235+16 and 2200+42 the curvature apparent in the infrared spectrum reinforces a radio-infrared relationship.

A synchrotron self-Compton interpretation of the infrared-visual emission is possible in principle. But in most cases, the spectral index of a simple extrapolation through the infrared has a value less than 1 (in fact, $\langle\alpha\rangle = 0.77 \pm 0.2$).[5] Therefore, the infrared-visual luminosity generally exceeds that of the radio. According to canonical synchrotron self-Compton models (e.g., Hoyle, Burbidge, and Sargent 1966; Jones, O'Dell, and Stein 1974), a self-Compton explanation of the visual spectrum would require even larger X- and γ-ray luminosities. Although many compact sources are now being found to be X-ray sources it is in most cases at or below the visual luminosity (e.g. Tananbaum *et al.* 1979). We note that a synchrotron interpretation of the infrared-visual spectra in a number of cases is also supported by strong polarization sometimes seen in these bands (e.g., Rudnick *et al.* 1978; Puschell *et al.* 1979; Puschell and Stein 1980).

[4] $\alpha = -d(\ln S)/d(\ln \nu)$.

[5] Although this radio-infrared spectral index is fairly typical of sources with flat radio spectra (see also O'Dell *et al.* 1978) it should not be taken as typical of all QSOs. For example, many radio-quiet QSOs have $\alpha \lesssim 0$ over this interval (Condon *et al.* 1980).

Similarly, the polarization at infrared and radio wavelengths is fairly difficult to understand in models of the radio-optical spectra based on multiple Compton scattering by dense nonrelativistic plasmas (e.g., Colgate and Petschek 1978; Katz 1976). We conclude, therefore, that the differences in the visual-infrared and radio spectra probably represent differences in physical conditions in the emitting regions or in the particle energy spectra, or both.

Since we argued above in favor of a tapered source interpretation of the flat radio spectra it is interesting to explore the significance in that model of the location of the far-infrared break. For a tapered source producing a flat spectrum, $\alpha = 0$, and a constant brightness temperature, the wavelength of the spectral break provides a measure of the smallest scale of the taper (e.g., Marscher 1977*a*), since angular size $\Theta_S \propto \lambda$. For brightness temperatures typical of compact sources $T_b \approx 10^{11}$ K, redshifts $z \approx 1$, and typical flux densities $S \approx 1$ Jy in the radio, a spectral break near $\lambda \approx 300$ μm in the rest frame, the average for the spectra in Figure 2, corresponds to a smallest source scale $r \approx 10^{16}$ cm, or about 10 light-days. This size is, of course, close to that indicated in numerous cases from visual-infrared variability arguments (e.g., Stein, O'Dell, and Strittmatter 1976). This may suggest that the visual-infrared source constitutes the core of the tapered structure producing the radio emission. Perhaps it is also relevant that the synchrotron lifetime of an electron of energy γmc^2 radiating at a wavelength λ (namely, $t_s \approx 10\, \gamma^3\, \lambda^2$ s) is also a few days when $\lambda \approx 300$ μm and when γ is a few hundred, as implied by brightness temperatures (see, e.g., Burbidge, Jones, and O'Dell 1974; Seielstad *et al.* 1979).

b) Variability

Radio sources with flat spectra are well known to be variable at centimeter and millimeter wavelengths (e.g., Altschuler and Wardle 1976, 1977; Andrew *et al.* 1978; Hobbs and Dent 1977). Although our data do not constitute a serious monitoring program the broad frequency coverage offers a valuable opportunity to study variability. Figure 3 shows a histogram of the fractional flux variations observed between successive measurements by us at $\lambda\lambda 11$, 6, 3.7, and 3 cm and 9 mm and 3 mm. To increase the sample at $\lambda 3$ mm we have included for this purpose flux measurements by us during 1979 October, which will be reported in more detail elsewhere.

The quantity shown is $|(S_i - S_j)/(S_i + S_j)|$, where S_i and S_j are flux densities measured approximately 6 months apart at a given wavelength. Similar histograms for $\lambda\lambda 6$ cm and 3 mm were constructed by Owen, Spangler, and Cotton (1980) for measurements separated by about a year. At each wavelength it is clear that the fractional change between successive measurements is usually small. Most of the data are consistent with little or no variation. Only a few measurement pairs indicate large amplitude variations. This is consistent with the results of more complete monitoring programs. For example, Altschuler and Wardle found in their sample of variable

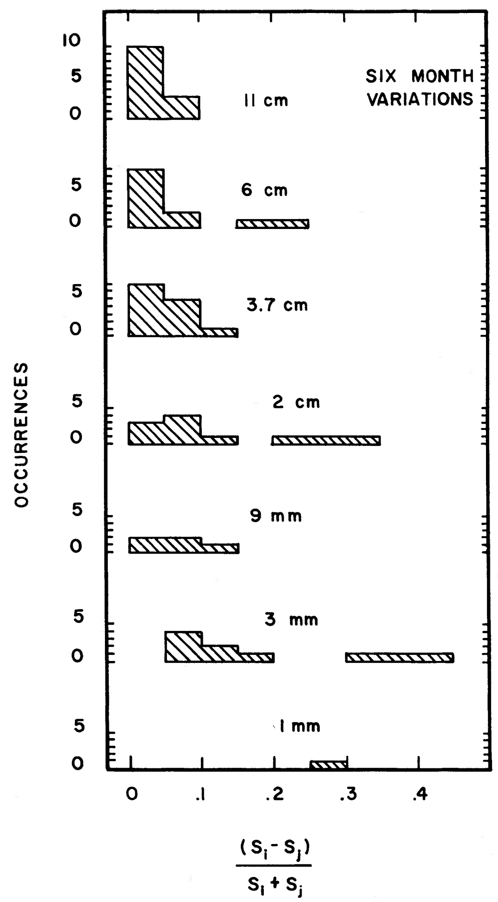

FIG. 3.—Fractional flux variability at various wavelengths. Pairs of measurements (S_i and S_j) made approximately 6 months apart have been compared at each observed wavelength. Histograms indicate the resulting number of occurrences of $|S_i - S_j|/(S_i + S_j)$ in 0.05 bins. These values have *not* been corrected for the expected variations due to errors alone.

sources that *peak-to-peak* variations at λ11.1 cm and λ3.7 cm are characteristically $\sim$40–60%. Randomly sampling their "light curves" at 6 month intervals would yield a typical variation of $\sim$10%. This is consistent with our measurements for most sources at $\lambda\lambda$11 cm, 6 cm, and 3.7 cm. At λ2 cm, λ9 mm, and λ3 mm most measurement pairs agree to within 20% or so; the measurement uncertainties are larger at these wavelengths, but the sources may also be intrinsically more variable. For example, if one compares the quantity $(S_{\max} - S_{\min})/S_{\text{avg}}$ from the Hobbs and Dent (1977) λ3 mm monitoring data with those on the same sources at λ2.8 cm (Andrew *et al.* 1978), there is a clear indication of larger *fractional* variations at the shorter wavelength; however, the amplitudes of the flux variations are approximately the same at both wavelengths. Our data also include a few of the large changes seen in those monitoring programs. The lack of large variations at λ11.1 cm and λ3.7 cm in our data is most likely just the result of small number statistics. In their most active phases, sources appear to exhibit these rapid large flux excursions, but only $\lesssim$50% of the time.

In order to examine source behavior in as unbiased a fashion as possible and to relate variations to ideas about source structure and energization it is useful to describe flux changes in relatively model-independent terms. Generally, we can say that flux changes in a synchrotron source are associated with changes in source *scale*, *structure*, and/or in energy *slope*. Changes in scale occur if the physically important parameters such as magnetic field or electron density are scaled by a relatively constant factor throughout the source, or if the structure changes homologously. An isolated source obeying the canonical adiabatic expansion (e.g., Pauliny-Toth and Kellermann 1968) would be an example of such a source change, as would be an increase in the particle flux of a jet, once steady state was reachieved. *To a first approximation the net effect of a scale change will be a simple translation in* log S–log ν *space of the source spectrum.*

By changes in structure we mean changes which alter the relative flux contributions of different portions of the source, i.e., different portions of the source evolve independently. The appearance of a new component is a simple type of change in structure. Similarly, two source components evolving through scale changes but at different rates would also produce a net change in structure of the source as a whole. *In partially opaque sources, the overall spectral form will generally change as a result of a structural change.*

Finally, the *slope of the electron energy spectrum can change* through such processes as acceleration or radiative energy loss. Although these changes may occur throughout a source they are difficult, in general, to distinguish from changes in structure, on the basis of integrated spectral data alone. Supplemental data such as polarization or VLBI structural histories may help in making this distinction, however.

Our simple characterization of the types of variations ignores the finite response time of a source to changes; this depends heavily on details of each model. Real variations may involve some of each of the three types of changes, of course. However, identification of changes dominated by one or another of these categories provides useful insight into source behavior. An especially good example is scale change, which demonstrates clear physical connections between different portions of a source. We can tentatively identify, in our data, behavior which resembles that expected for each category.

The behavior of 0851+20 (OJ 287) during 1977–1978 resembled source *scale* variations. From 1977 January to 1977 November, this source underwent a substantial outburst at all but the longest wavelengths ($\lambda \gtrsim 11$ cm). It remained strong through 1978 November. From 1978 November to 1979 May, flux levels dropped again. As is evident in Figure 1, the amplitude of the radio variation was approximately a factor of 2 for $\lambda \lesssim 2$ cm. It is interesting to note that the visual-infrared fluxes also rose between 1977 January and 1977 March by a similar factor (O'Dell *et al.* 1978; Puschell and Stein 1980). Later they dropped by the same amount between 1978 October and

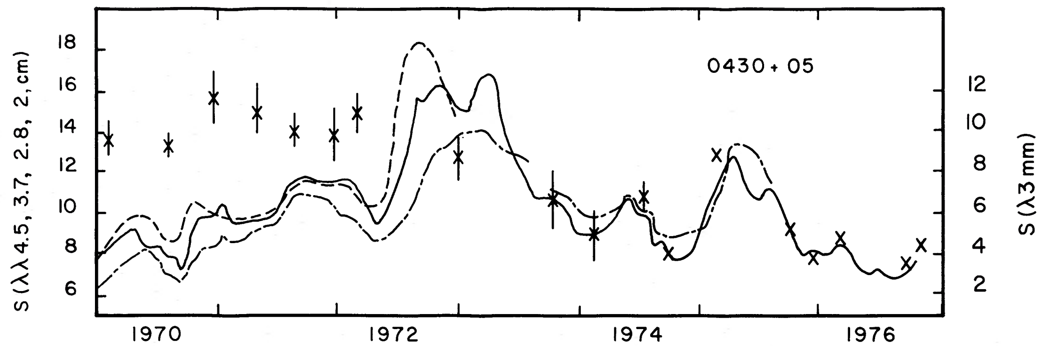

FIG. 4*a*

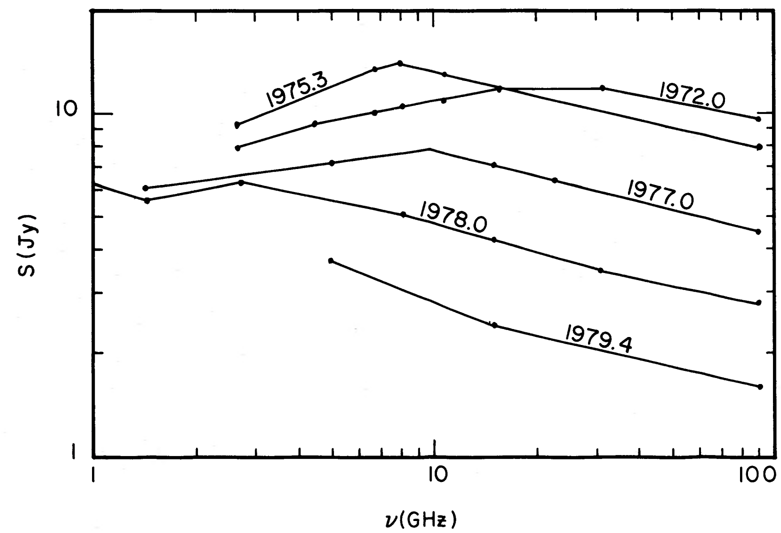

FIG. 4*b*

FIG. 4.—Flux variations of 0430+05 (3C 120). (*a*) Light curves 1970–1976 at λ4.5 cm (*dot-dashed line* before late 1973), λ3.7 cm (*dot-dashed line* after late 1973), λ2.8 cm (*solid line*), λ2 cm (*dashed line*), λ3 mm ($\times$s). Data from Altschuler and Wardle (1976); Andrew *et al.* (1978); Dent, Kapitzky and Kojoian (1974); Hobbs and Dent (1977). (*b*) Evolution of spectrum, 1972–1979. Data in addition to our own, from Altschuler and Wardle (1976), Andrew *et al.* (1978), Hobbs and Dent (1977), and Owen *et al.* (1980). These spectra were selected to illustrate the long-term evolution of 3C 120. On shorter time scales, small fluctuations around this mean trend are also present.

1978 December. By 1979 March the visual-infrared flux levels were nearly as large as in 1978 October (Puschell and Stein 1980). Our radio observations in 1979 (to be published) also show an increase over those obtained 6 months earlier. The spectral shape in this portion of the spectrum remained constant throughout. In the first approximation the centimeter to visual source underwent scale changes; however, the detailed time-histories are somewhat different, possibly indicating the finite propagation time for these scale changes. We note that polarization data (to be published) show clearly that this event was *not* simply the injection of electrons into an optically thin emitting region.

The variations seen for 0430+05 (3C 120) in Figure 1 may also represent *scale* changes within that source. As a first approximation one could interpret the changes as due to the 1977 January spectrum sliding down and to the left (longer wavelengths) with time. In fact, examination of previously published data suggest that this is merely the continuation of scale changes within 0430+05 which began as early as 1972 (see Fig. 4*b*). The spectrum of 0430+05 prior to the very large outburst of early 1972 (see Fig. 4*a*) was similar to that for the epoch 1972.0 shown in Figure 4*b*. Spectra in the 1973–1977 interval are similar to the 1975.3 and 1977.0 spectra of Figure 4*b*, with peaks around $\lambda \approx 3$ cm. Since early 1977 the spectral peak has drifted down to $\lambda \gtrsim 10$ cm.

Monitoring at centimeter wavelengths (Fig. 4*a*) shows a clear correlation between variations at different wavelengths, where the slightly inverted spectrum probably requires a partially opaque source structure. The data show, however, that prior to the 1972 outburst λ3 mm data do not show correlation with the longer wavelength data, well on the other side of the spectral peak. After the 1972 outburst (which incidently corresponded to the beginning of possible super-light expansion observed with VLBI [e.g., Seielstad *et al.* 1979]), the $\lambda 3$ mm variations are very well correlated with those at centimeter wavelengths. In fact they are very nearly simultaneous and of similar amplitude. Thus, the spectra of the post-1972 outbursts were essentially flat ($\alpha = 0$) between $\lambda 4$ cm and $\lambda 3$ mm. Such events could be accounted for by scale changes in a tapered source, for example, but since the scale of the emission at $\lambda \approx 4$ cm is observed (e.g., Seielstad *et al.* 1979) to be ~ 1 pc, the near simultaneous changes would involve superlight effects at least as great as indicated by the VLBI data.

A clear example of a *structural* change, as deduced from the spectra, occurred in 0420–01 between 1977 January and 1978 November (see Fig. 1). At $\lambda 20$ cm the flux appears to have remained constant, and at $\lambda 3$ mm the flux was constant to within about 1 Jy. However, at intermediate wavelengths there was a substantial outburst. The simplest explanation is the appearance of a new spectral component peaked around $\lambda \approx 2$ cm. We can estimate the flux contributions of this component to be $\Delta S_{20\text{ cm}} < 0.1$ Jy, $\Delta S_{6\text{ cm}} \approx 1.7$ Jy, $\Delta S_{2\text{ cm}} \approx 3.3$ Jy and $\Delta S_{3\text{ mm}} \lesssim 1$ Jy. The high frequency spectral index is thus $\alpha \gtrsim 0.6$ while below $\lambda 2$ cm $\alpha < -2.2$. These numbers are reasonable values for a fairly homogeneous source component which becomes opaque near $\lambda 2$ cm. Dent *et al.* (1979) observed at $\lambda 2$ cm the early stages of the appearance of this component. They suggested a relationship with an optical outburst seen in 1974.

Thus despite the general need for tapering of source structures, some objects do seem to have fairly well-defined and quasi-independent structural units. It is also possible that these units are contained within the overall tapered structure (e.g., Blandford and Königl 1979).

Changes observed in the spectrum of 2134+00 in the past decade may represent changes in energy *slope*. In 1969 the spectrum peaked around $\lambda \approx 4$ cm and had a short wavelength spectral index $\alpha \approx 0.4$ (Kellermann and Pauliny-Toth 1971). By 1978 (Fig. 1) the short wavelength spectral index had increased to $\alpha \approx 0.7$, while the spectrum peaked around $\lambda \approx 6$ cm, with about the same flux there and at longer wavelengths as in 1969. Significant synchrotron losses over this time interval at $\lambda \approx 2$ cm, for example, would imply a magnetic field strength $B \approx 0.1$ G, and electron Lorentz factors $\gamma \approx 200$ (using $Z = 1.9$). This field is about a factor of 10 stronger than the lower limit derived from synchrotron self-Compton theory by Burbidge *et al.*

These examples serve to emphasize the variety of changes seen in sources and to emphasize the value of obtaining broad frequency coverage. From measurements obtained only at closely spaced frequencies it is not possible in general to discriminate among the various categories of variability. To assess the question of how common changes are in scale, structure, or slope, we may look to the best published data sets of Andrew *et al.* (1978) ($\lambda 2.8$ and $\lambda 4.5$ cm) and Hobbs and Dent (1977) ($\lambda 3.3$ mm). Of the 10 sources observed in common, only three (BL Lac, OJ 287, and post-1972 0430+05) show clear broad-band correlations in their variations. At present, therefore, there is *not* good evidence that source-wide changes (scale or slope) are the rule. However, this conclusion must be treated with caution; inadequate time histories and sampling for many sources, along with propagation time delays, obscure some correlated behavior.

IV. CONCLUSIONS

Consideration of spectra obtained for 20 compact nonthermal sources leads us to the following conclusions.

1) The sources were selected to be strong at millimeter wavelengths, yet it is remarkable how nearly flat most of the spectra are in the radio spectrum. It is especially notable that in most cases the flux density at $\lambda 1$ mm is about as strong as that at $\lambda 3$ mm. Multiple homogeneous components, or (probably more likely) tapered source structures are needed to produce such spectra. Including visual and especially infrared spectral data leads one to believe that the radio and visual spectra have a simple interpolation. For our data the mean intersection of the two spectra occurs around $\lambda \approx 300$ μm (in the source frame). In tapered source models this implies a break in the source structure on a scale $\sim 10^{16}$ cm, possibly implying that this is the scale of the source inner core.

2) Although all flat spectrum sources probably vary, the variations indicated by any random pair of measurements are typically small, $\lesssim$ 10–20%. This is true over the entire radio band. On the other hand, the sources have episodes in which large amplitude variations of 50% or more occur. However, the duty cycle for such large excursions is probably less than $\sim 50\%$, even for the currently most active sources.

3) We can classify source variations into three categories which encompass a wide range of specific models; variations may be grouped as representing changes in source scale and/or structure and/or changes in the slope of the radiating electron energy spectrum. Changes in scale occur when the physically important parameters are altered by similar factors throughout the source. Changes in structure occur when the physical parameters are varied in such a way that the relative contributions of different portions of the source are altered.

All three types of variations probably occur in any given source. Isolating the changes into these categories, as we have done for a few sources, we stand to gain insights into the global nature of source variations. For example, the occurrence of scale changes tells us that a clear physical relationship exists between the various portions of the source, and that all have a common source of energy.

To decipher flux variations in this way it is essential to develop programs of *broad-band* flux monitoring. Such data exist for a few sources now but should be extended. From the present data we can see, for example, that there are no general correlations between changes observed at millimeter and centimeter wavelengths, or between the optical and centimeter bands. However, on occasion some sources (we have identified such changes in 0430+05 and 0851+20 from our data) do exhibit scale changes which result in very broad band correlations.

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