THE ASTRONOMICAL JOURNAL VOLUME 85, NUMBER 11 NOVEMBER 1980

EXTRAGALACTIC RADIO SOURCES: RAPID VARIABILITY AT 90 GHz

EUGENE E. EPSTEIN
Electronics Research Laboratory, The Aerospace Corporation, Los Angeles, California 90009

ROBERT LANDAU
University of Minnesota, Department of Astronomy, Minneapolis, Minnesota 55455

JOHN D. G. RATHER
The BDM Corporation, McLean, Virginia 22102

Received 14 April 1980; revised 16 June 1980

ABSTRACT

Thirty-three extragalactic variable radio sources have been observed at 90 GHz (3.3 mm) over two several-day-long periods in a search for daily and hourly variations. OV−236 (1921−29) showed a decrease in flux density by a factor of 2.7 over a three-day interval, recovering its previous flux density two days later. (OV−236 began a dramatic outburst a few months later.) The other sources exhibited no significant variations $\gtrsim 20\%$. A summary of previous radio observations of rapid variability is contained in the appendix.

I. INTRODUCTION

Many of the important physical parameters describing compact extragalactic radio sources, such as the relativistic electron energy density; the energy content in radiation, particles, and magnetic fields; and the ratio of magnetic to electron energy, depend directly on the size of the source. Thus, a measurement of source size can determine the energetics of the source and constrain models of energy generation. Source size can be inferred from the properties of the spectrum or can be calculated from an angular size from VLBI data and a redshift-determined distance.

Another way to estimate the linear size of a source component is to observe the minimum time scale of variability. Because the effective radiating size of a compact source is, according to many models (van der Laan 1966; Condon and Dressel 1973; Peterson and King 1975; Marscher 1977), a function of the observing wavelength, the variability time scale should also be a function of wavelength. Variations of compact extragalactic sources are well established at millimeter and centimeter wavelengths on time scales of months and weeks and, in a few sources, on time scales of 1 to 3 days; evidence for variations over a period of hours is more limited. See the appendix.

Our objective here has been to place lower bounds on the rapidity of radio variations. We have searched for hourly and daily variability at 3.3 mm (90 GHz). We chose this short wavelength because the time scale of variations often decreases as the wavelength decreases (Epstein *et al.* 1981).

II. OBSERVING PROCEDURES

Twenty-seven sources were observed for variability over the 7-day period 1–8 December 1978; these and six more sources were observed over the 5-day period 2–7 July 1979. With a few exceptions, sources fainter than 1.6 Jy were observed only once a day and thus were not candidates for detecting hourly variability. The (18) stronger sources were placed in groups of three and four by proximity on the sky and observed in "round robin" fashion from rising to setting. Thus, variations in the system or the atmosphere should affect all sources in a group, and should not be mistaken for real variations in a source. The selection of sources and detailed observing procedures are described in a previous paper (Landau, Epstein, and Rather 1980). Observations were made with the NRAO* 11-m telescope at Kitt Peak.

Table I lists the sources observed for variability together with their average flux density, the number of days each was observed, and the total number of observations made during each observing period. The error quoted is the standard error of a single observation derived from the statistics of the set of individual measurements over the observing period. To this amount should be added (quadratically) an error of about 10% to account for uncorrected variations in the pointing and in the antenna and receiver gains, and uncertainties in atmospheric attenuation corrections. The resulting combined error is, for nonvarying sources, the upper limit of variability; for variable sources it is approximately the range of variation.

The time history of all sources was examined by eye. No source was taken to be variable if merely one measurement was divergent nor if a suggested variation vanished upon the reversal of the order of any pair of

---

* The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

0004-6256/80/111427-07$00.90

TABLE I. 90-GHz flux densities (Jy) of sources observed for daily and hourly variability.

Source		July 1979			December 1978		
		S_{90} σ[a]	Days	n[b]	S_{90} σ[a]	Days	n[b]
0007+10	III Zw 2	1.6 ± 0.1	5	11	2.6 ± 0.4	5	19
0048−09		0.8 ± 0.1	5	7	1.2 ± 0.3	4	5
0133+47	DA 55	2.1 ± 0.2	5	15	2.1 ± 0.3	7	12
0235+16		1.6 ± 0.1	4	8	2.4 ± 0.2	6	8
0306+10	OE 110	1.1 ± 0.2	4	7	1.1 ± 0.3	5	6
0316+41	3C 84	44. ± 1.	6	19	41. ± 3.	6	40
0355+37	4C 50.11	5.8 ± 0.1	4	14	5.0 ± 0.8	5	23
0415+37	3C 111	2.2 ± 0.1	5	16	1.5 ± 0.5	6	23
0420−01		4.4 ± 0.7	3	8	4.3 ± 0.5	5	15
0422+00		1.2 ± 0.2	3	7	2.8 ± 0.4	5	15
0430+05	3C 120	1.2 ± 0.3	4	9	1.9 ± 0.5	5	17
0735+17		1.2 ± 0.4	4	7	1.6 ± 0.2	5	9
0851+20	OJ 287	3.2 ± 0.2	4	10	3.7 ± 0.5	5	34
1219+29	W Com	1.3 ± 0.3	4	5	1.5 ± 0.4	5	8
1226+02	3C 273	14.8 ± 0.9	5	20	12.9 ± 1.0	5	36
1228+12	Virgo A	6.6 ± 0.5	5	11	7.1 ± 1.0	4	14
1253−05	3C 279	6.4 ± 0.4	5	11	7.1 ± 0.8	5	30
1308+32		1.7 ± 0.1	5	6			
1335−12		7.5 ± 0.6	5	11	4.4 ± 0.6	5	28
1418+54	OQ 530	3.0 ± 0.3	5	5			
1510−08		2.4 ± 0.4	5	5			
1514−24	AP Lib	1.8 ± 0.1	5	7	1.1 ± 0.4	4	5
1641+39	3C 345	6.9 ± 0.6	4	9	7.2 ± 0.9	5	15
1730−13		4.1 ± 0.3	5	6			
1739+52		1.3 ± 0.2	5	10	1.5 ± 0.3	7	7
1749+09		3.2 ± 0.4	5	5	6.7 ± 0.8	5	14
1921−29	OV−236	9.8 ± 0.5	5	10	4.4 ± 2.2	6	21
2037+51	3C 418	2.7 ± 0.3	6	14	3.4 ± 0.6	6	22
2200+42	BL Lac	1.8 ± 0.1	5	14	1.4 ± 0.4	6	13
2201+31	4C 31.63	1.9 ± 0.1	5	13	2.7 ± 0.6	5	11
2216−03		2.1 ± 0.2	5	9			
2223−05	3C 446	5.6 ± 0.4	5	11	3.9 ± 0.5	5	20
2251+15	3C 454.3	3.9 ± 0.3	5	11	4.5 ± 0.4	5	19

[a] Standard error of a single observation.
[b] Total number of observations.

measurements. The set of time scales of variability to which our procedures are sensitive depends on the declination of the source and (somewhat) on its strength. For equatorial sources of a few Janskys, we cannot detect variations in less than two hours or more than 10 days, quasiperiodic changes in multiples of 24 hours, and certain variations in 8–14 hr if in phase with the rising and setting of the source.

III. RESULTS

Except for OV−236 (1921−29) in December 1978, none of the sources exhibited statistically significant variations within either observing period. Figure 1 shows the time history of four well studied, but otherwise typical nonvarying sources during the July 1979 period. The error bars shown are 2σ in total length and are derived from the scatter of individual beam-switched integrations of 30-s duration within the observation. Of all the "nonvarying" sources, OJ 287 comes closest to showing variability; all other sources behaved more like II Zw 2 and BL Lac.

The flux density of OV−236 decreased from an average value of 6.4 ± 0.9 Jy during the interval 1–4 December 1978 to 2.4 ± 0.9 Jy on 7 December, then rose to 6.5 ± 0.3 Jy on 9 and 10 December. Its behavior is

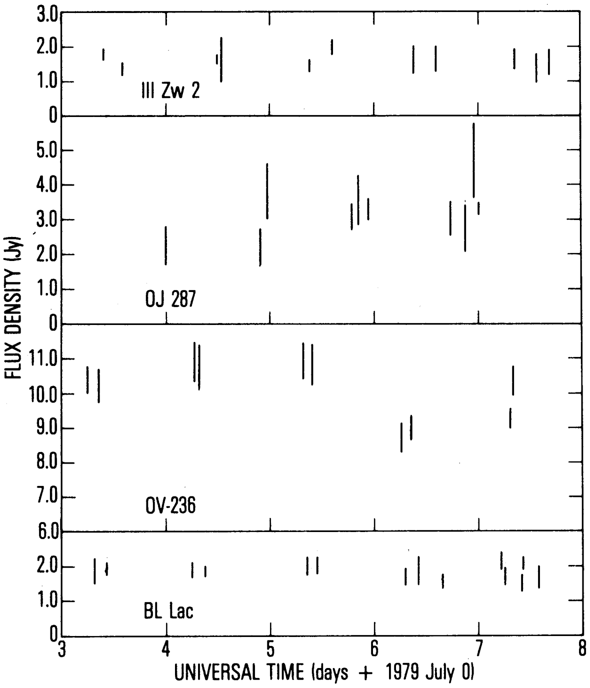

FIG. 1. The 90-GHz flux density of four typical nonvarying sources vs time, over the period 2–7 July 1979.

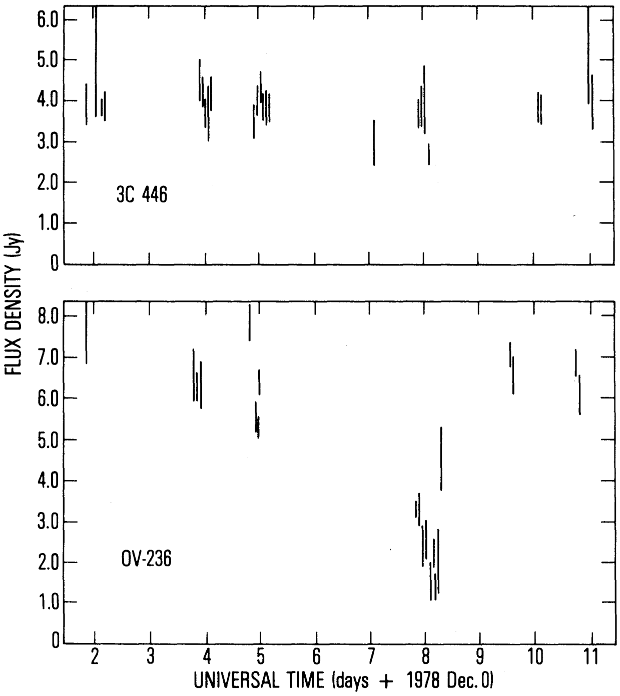

FIG. 2. The 90-GHz flux density of 3C 446 and OV−236 vs time, over the period 1-10 December 1978. For clarity in display of the OV−236 drop, the time scale around 0ʰUT 8 December has been expanded by a factor of 4.

shown in Fig. 2, together with that of 3C 446, which is near OV−236 on the sky. That the entire antenna and receiver system was functioning properly throughout the run is indicated by the constancy of 3C 446. Observations of these two sources and of the calibration source DR 21 were interspersed during the measurements on 7/8 December. (Observations of OV−236 and 3C 446 on 9 and 10 December were kindly made by L. J. Rickard and J. M. van der Hulst.)

A real drop in flux density by a factor of 2.7 within a few days would be quite remarkable. We have therefore investigated as many alternative explanations for this variation as we could imagine. However, any such explanation must account for the constancy of 3C 446 during this time. Since 3C 446 trails OV−236 by 2 hr in R.A. (and is 25° north), any change in the system (such as pointing) would have to have been confined to declinations well to the south of 3C 446 and/or to have moved across the sky with OV−236 so as not to affect 3C 446. Moreover, any such anomaly would have to have reversed itself exactly by the time the flux density of OV−236 was measured two days later at its pre-drop value.

Table II is a journal of measurements of OV−236. Observations made close together have been grouped, and σ is the error of a single observation (the rms deviation of the observations within a group). For groups of one, σ is the the rms deviation of 11 30-s integrations comprising the observation.

Pointing. Known pointing corrections are automatically applied to the telescope's position every 20 s during tracking. Second-order corrections are derived from accurate position measurements of the planets and other strong sources at many places in the sky and entered as offsets to the commanded position of the telescope. They change and must be reentered as a source is followed across the sky. A third-order correction in azimuth is required as a function of ambient temperature; it amounts to about 1 arcsec/°C. Our December observing period immediately followed a day dedicated to re-determining the pointing corrections, which we inherited (Ulich 1978) and augmented. By 7 December we had obtained a dense grid of 120 second-order corrections as a function of azimuth and elevation, as well as their approximate dependence on temperature. Pointing corrections for the part of the sky through which OV−236 passed were derived from observations of Mars, whose path was only 5 deg north of that of OV−236. We see from Table II, however, that the observations on 7/8 December were made at an ambient temperature 7°C below those of 3 December and 13°C below those of 4 December. If we assume a maximum error in our pointing corrections of $\epsilon = 13$ arcsec owing to this temperature effect, the diminution of the flux density expected for a Gaussian beam profile of half-power width HPBW = 76″ is $1 - \exp\{-0.693[\epsilon/\tfrac{1}{2}\,(\mathrm{HPBW})]^2\}$ or ≈8%, not nearly enough to account for the observed signal drop. A pointing error of 46″ would be required to account for the drop; in our experience with the 11-m antenna we have never measured so large a sudden

TABLE II. Journal of 90-GHz observations of OV−236 in 1978 December.

Universal Time	Air mass	τ	Ambient temperature	S_{90} σ[a]	n[b]
1978 Dec 1ᵈ20ʰ30ᵐ	2.41	0.085	+13.9°C	7.53 ± 0.68	1
3 21 30	2.15	0.053	+3.5	6.35 ± 0.17	3
4 20 25	2.37	0.085	+9.4	7.73 ± 0.45	1
4 22 50	2.19	0.089	+9.4	5.70 ± 0.60	3
7 22 53	2.1-2.3	0.060	−3.0	2.83 ± 0.56	4
8 0 26	2.9-3.8	0.060	−4.4	2.30 ± 1.28	5
9 22 39	2.20	0.070	+3.9	6.78 ± 0.29	2
10 21 36	2.08	0.070	+8.0	6.53 ± 0.49	2

[a] Standard error of a single observation (except for $n = 1$, σ is the rms error of 11 30-s integrations which comprise the observation).

[b] Number of 5-min observations made at each time.

1980AJ.....85.1427E

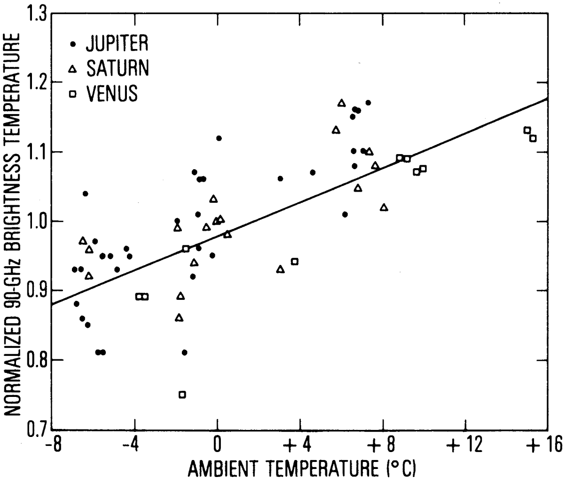

FIG. 3. The 90-GHz brightness temperatures of Jupiter, Saturn, and Venus measured with the NRAO 11-m radio telescope over the period 1–8 December 1978 and normalized to the average brightness temperature of each planet vs the ambient temperature at the time of measurement. The slope of the regression line is +1.3%/°C; the correlation coefficient is 0.74.

pointing change.

Antenna gain variations. Sixty-four measurements of the brightness temperatures of Jupiter, Saturn, and Venus were made with the 5-point-grid procedure during the December 1978 observing period and analyzed for variations as a function of zenith distance and ambient temperature. No variation with zenith distance was found. However, there is a strong dependence of the brightness temperatures (normalized to the average brightness temperature for each planet) on ambient temperature—see Fig. 3. The regression line has a slope of +1.3%/°C, and the correlation coefficient is 0.74. Assuming this trend represents a variation of antenna aperture efficiency with temperature, and that it affects point sources and planets similarly, then the change of ≈10°C between 4 or 9 December and 7/8 December could lead to a diminution of the flux density of OV−236 by *at most* 13%. The mechanism by which the temperature affects the antenna aperture efficiency is unknown; astigmatism is apparently not the agent, since we found no variation of beamwidth with ambient temperature.

Extinction. Because of its large negative declination, OV−236 was always observed through at least 2 air masses. However, the opacity of the atmosphere was uniformly low throughout the observing period. The zenith optical depths τ are given in Table II. A 100% error in determining τ produces an error of only ≈20% in the flux densities.

Sky conditions. Sky conditions were monitored by frequent visual inspection throughout both observing runs; the sky was completely clear most of the time. Since it was obvious after the first 5-min observation of OV−236 on 7/8 December that a significant drop had occurred, the sky conditions were noted for every subsequent OV−236 observation. The sky was generally clear, but there were scattered alto-stratus clouds present. The analog records of the receiver's switched and total power outputs readily indicated when a cloud was actually in the antenna beam; two OV−236 observations were rejected. Our conclusion from visual inspection that there were no atmospheric irregularities in the antenna beam during the remaining nine observations was confirmed by the smoothness of these analog records.

Sun in sidelobes. The Sun was ≈22 deg away from OV−236. Five of the nine observations on 7/8 December were made after sunset. There was no significant change in flux density after sunset.

In summary, no anomalous behavior of the system or atmosphere was noticed during any of the observations of OV−236 reported here. Furthermore, the other sources observed at the same time (3C 446, 3C 418, DR 21) remained constant within the observational errors of ≈20%. We conclude that the large drop in OV−236's flux density on 7/8 December was intrinsic to the source.

IV. DISCUSSION

a) The Nonvarying Sources

None of the variable sources we observed were undergoing outbursts during our measurements. Our remarks therefore apply only to their "quiescent" phases. Except for OV−236, we observed no variability time scale t shorter than ≈10 days. (The variability of an object varying on a time scale of $\lesssim$10 days would have been detected during a 5- to 7-day observing run.) In the absence of relativistic motions within these sources, this limit implies 3-mm regions larger than $R = ct/(1+z)$, or 2×10^{16} cm for a redshift z less than 0.3.

The corresponding angular sizes are greater than $\theta(3\ \mathrm{mm}) = tH(1+z)/z$, or about 3×10^{-6} arcsec for a Hubble constant $H = 75\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. The observed brightness temperatures of compact synchrotron sources fall in the range $\approx 10^{11}$ to $\approx 10^{12}$ K (Kellermann and Pauliny-Toth 1969). This small range is a result of the insensitivity of angular sizes (thus T_B) to such important physical parameters as the magnetic and electron energy densities (Burbidge *et al.* 1974). The upper limit is also set by inverse Compton cooling (Kellermann and Pauliny-Toth 1969). Regardless of the explanation, this limited range of brightness temperatures leads to the result that the apparent angular size of the source scales directly with the observing wavelength throughout the region where the spectrum is flat. Thus, the absence of 3-mm variability on a time scale of ≈10 days means that for a wavelength of, for example, 6 cm (a typical VLBI wavelength), the angular size of the 6-cm emitting region, $\theta(6\ \mathrm{cm})$, is $\gtrsim 6 \times 10^{-5}$ arcsec. This value is just below the limit of VLBI resolution at 6 cm of $\approx 2 \times 10^{-4}$ arcsec (Kellerman *et al.* 1971). Unresolved sources with variability time scales $\gtrsim$10 days therefore cannot be much smaller than those which have been resolved.

These sizes are also consistent with the shape of the spectrum, particularly with the wavelength at which these flat spectra begin to turn down. This turndown point, separating radiation from the optically thick and optically thin regions, occurs at a wavelength

$$\lambda(\mathrm{mm}) \approx 0.1 \left(\frac{t}{\mathrm{days}}\right)\left(\frac{0.01}{z}\right)\left(\frac{\mathrm{Jy}}{S}\right)^{1/2}$$

(see O'Dell *et al.* 1978 and Blandford and Rees 1978). Thus for a typical source flux density of ~1 Jy and a z value of, say, 0.03, the turndown would be at ~1 mm for a source varying on a 1-month time scale and at ≈30 μm for a source with a 1-day time scale. Since, as a class, our sample of compact sources vary with time scales of months, but not days, we expect the turndown to occur shortward of ≈1 cm; that is, we expect spectral indices around zero between 6 cm and 3 mm. The results of Owen *et al.* (1978) and Landau *et al.* (1980) demonstrate that this is so.

b) *OV−236*

The Ohio radio source OV−236 is identified with an optically variable, red, emission-line object with a redshift of 0.35 (Peterson *et al.* 1973; Wilkes *et al.* 1980). Astrometry of ESO films shows the identification of Radivich and Kraus (1971) to be in error; the VLBI position of Gubbay (1978) or the VLA position $19^{\mathrm{h}}21^{\mathrm{m}}42^{\mathrm{s}}\!.18$, $-29°20'24''\!.9$ (Fomalont and Perley 1980) is to be preferred.

OV−236 was noted to be variable at 2.8 cm by Kraus and Andrew (1971) and at both 9.5 and 3.3 mm by Conklin *et al.* (1972). At 3.3 mm the flux density dropped from 3.8 ± 1.3 to 0.9 ± 1.1 Jy between 30 June and 5 July 1970, while at 9.5 mm it decreased ≈25% (from 6.5 ± 0.35 to 4.9 ± 0.26 Jy) between 1 and 4 July 1970. Further measurements at 3.3 mm showed flux densities of 2.7 in September 1971, 4.7 in March 1972, and 2.1 in September 1974 (Conklin 1980). Monitoring at 2.8 and 4.5 cm (Medd *et al.* 1972; Andrew *et al.* 1978) has shown fluctuations of about 10% from month to month and a 20% decrease from 1970 to 1976. From 1976 to early 1979 the millimeter and centimeter flux densities gradually increased; the December 1978 3-mm drop we report here occurred a few months prior to a pronounced acceleration in this increase (Aller *et al.* 1979; Dent and Balonek 1980).

[We note that sharp, large drops on time scales of days have now been observed in OV−236, OJ 287 (Kinman and Conklin 1971; Epstein *et al.* 1981), and 3C 273 (Epstein *et al.* 1981). It is our impression that equally sharp and large *rises* have not been observed.]

The spectra in 1970 (Conklin *et al.* 1972) and December 1978 (Aller *et al.* 1979) are both rising between 10 and 2 cm with a spectral index $\alpha = -0.4$ ($S \sim \nu^{-\alpha}$). The 3-mm flux densities, however, are always lower than the 2-cm values, implying a maximum in the spectrum near 1 cm.

Such a rapid, large-amplitude variation at 3 mm as reported here for OV−236 and as reported for OJ 287 and 3C 273 (see the appendix) cannot be explained as the expected behavior of a nonrelativistically evolving, incoherent, synchrotron source. If these results are confirmed, a different model, perhaps one exhibiting relativistic expansion, one in which the radiating electrons have much shorter lifetimes, or one involving an orbiting pair of source components will be needed to explain the rapidly variable component of the flux densities.

We thank L. J. Rickard and J. M. van der Hulst for the OV−236 and 3C 446 measurements of 9 and 10 December 1978; M. F. Aller for making the Michigan data available in advance of publication; Don Cardarella, Dave Meyers, Werner Scharlach, Cal Sparks, and John Weaver for observing assistance at the 11-m telescope; and T. W. Jones for clarifying discussions. The work of one of us (E^3) was partially supported by the U. S. Air Force under contract F04701-80-C-0081.

APPENDIX: PREVIOUS RADIO OBSERVATIONS OF RAPID VARIABILITY

Variations of compact extragalactic radio sources at millimeter and centimeter wavelengths on time scales of months are well known: for example, see Fogarty *et al.* (1971), Hobbs and Dent (1977), and Landau *et al.* (1980) for 3.3 mm; Dent and Hobbs (1973) for 9 mm; Andrew *et al.* (1978) for 2.8 and 4.5 cm; and Altschuler and Wardle (1976) for 3.3 and 11.1 cm.

Several reports exist of *inter*day variability at radio wavelengths. Wills (1971) observed interday variations of 2–4% in the 11.1-cm emission from 0106+01, 0336−01 (CTA 26), 0440−00 (NRAO 190), and 1510−08 during 1969. During two 26-hr intervals in 1969 she found no evidence in the 11.1-cm emission from several sources for *intra*day variability larger than the noise level of ≈2%. The data of Kinman and Conklin (1971) suggest a *drop* of ~40% and of less than 4 days' duration in OJ 287's 3.5-mm emission in May 1971; there was some suggestion of a correlation with optical variations. Andrew *et al.* (1971) also observed OJ 287 in the spring of 1971; they found variations in the 4.5-cm signal of ≈±8% on a time scale as short as 1 day. Harvey *et al.* (1972) observed 19 sources at 2.8 cm daily for 20 days in October/November 1971; BL Lac exhibited a rise of ≈6% in one day followed by a decline of ≈12% in one day; and OJ 287 exhibited an outburst of ≈5% lasting ≈5 days. The 17 other sources showed no variations. Gorshkov *et al.* (1972) reported a decrease of ~20% in the 3.5-cm flux density of 3C 273 from 23 to 27 May 1969, but the published observational data are limited.

Epstein *et al.* (1972) made coordinated multifrequency searches for intraday variability in 3C 120, BL Lac, and OJ 287. Their 3.5-mm OJ 287 data reveal a change of ~40% in ~2 hr on 18 February 1972 and suggest smaller changes with the same time scale on three adjoining days. (The 2.2-μm OJ 287 data show an increase of ~25% in ~1 hr on 17 February 1972; the increase was not correlated with the suggested 3.5-mm change on that night.) There were suggestions of 3.5-mm interday variability of ~20% for OJ 287 and BL Lac, but not 3C 120. A subsequent coordinated search of these same three sources during the winter of 1972/73 resulted only in upper limits of ~25% for 3.5-mm intraday variations and ~20% for interday variations (Epstein, unpublished). During this same coordinated search, Kikuchi *et al.* (1973) observed a 20% decrease in the 7.2-cm flux density of OJ 287 over 100 min on 8 February 1973. Huchtmeier and Wright (1973) observed in March 1973 the 6-cm flux density of III Zw 2 rise ≈13% in one day, then decline ≈20% during the subsequent five days. Kinman *et al.* (1974), in a coordinated multifrequency study of OJ 287 in January 1972, found variations of ~10% on time scales of 1–3 days at 3.5, 28, 37, and 45 mm. Efanov *et al.* (1977) found declines of ≈15% and ≈20% in the 13.5-mm flux density of 3C 273 in just ≈4 hr on 22 and 29 March 1976, respectively; on both occasions the partial recoveries took 1 to 2 days. Kellermann (1974) found a decline of ~40% in the 3.4-mm flux density of Cen A between 27 and 28 March 1974. Kaufmann *et al.* (1977) observed a possible variation of ~30% in the 13.5-mm signal of Cen A on a time scale of about 5 days in November/December 1976. Kaufmann and Raffaelli (1979) then observed Cen A at 7 and 14 mm daily for 46 days in July/August 1978; they found repeated 7-mm variations of amplitudes up to ≈±20% on time scales of 1 or 2 days. Indicated variations at 14 mm were much smaller and less certain. Epstein *et al.* (1981) observed drops of ~50% in the 3-mm flux density of 3C 273 on a time scale of 1 to 2 days in July and November 1969 and a drop by a factor of ~2 in OJ 287 in March 1972, on a time scale of ≈2 days.

Interday variations have been seen in the optical domain; e.g., see DuPuy *et al.* (1969) for BL Lac, Kinman *et al.* (1974) for OJ 287, and Miller (1978) for 1418+54. Racine (1970) has found BL Lac to vary by 0.1 mag in hours.

REFERENCES

Aller, M. F., Aller, H. D., and Hodge, P. E. (1979). "Partially-opaque extragalactic variable sources at cm wavelengths," Bull. Am. Astron. Soc. **11**, 716.

Altschuler, D. R., and Wardle, J. F. C. (1976). "Observations of the flux density and linear polarization of compact extragalactic radio sources at 3.7- and 11.1-cm wavelength," Mem. R. Astron. Soc. **82**, 1–67.

Andrew, B. H., Harvey, G. A., and Medd, W. J. (1971). "OJ 287: An exceptionally active variable source," Astrophys. Lett. **9**, 151–154.

Andrew, B. H., MacLeod, J. M., Harvey, G. A., and Medd, W. J. (1978). "A ten-year study of extragalactic variable sources at centimeter wavelengths," Astron. J. **83**, 863–899.

Blandford, R. D., and Rees, M. J. (1978). "Extended and compact extragalactic radio sources: interpretation and theory," Phys. Scr. **17**, 265–274.

Burbidge, G. R., Jones, T. W., and O'Dell, S. L. (1974). "Physics of compact nonthermal sources. III. Energetic considerations," Astrophys. J. **193**, 43–54.

Condon, J. J., and Dressel, L. L. (1973). "Synchrotron spectra of nonuniform compact sources," Astrophys. Lett. **15**, 203–207.

Conklin, E. K. (1980). Private communication.

Conklin, E. K., Andrew, B. H., Wills, B. J., and Kraus, J. D. (1972). "Spectra of some Ohio radio sources: list III," Astrophys. J. **177**, 303–307.

Dent, W. A., and Hobbs, R. W. (1973). "31.4-GHz flux density measurements of variable radio sources," Astron. J. **78**, 163–169.

Dent, W. A., and Balonek, T. J. (1980). "A dramatic radio outburst in the quasar 1921–29," Nature **283**, 747.

DuPuy, D., Schmitt, J., McClure, R., van den Bergh, S., and Racine, R. (1969). "Optical observations of BL Lac = VRO 42.22.01," Astrophys. J. Lett. **156**, L135–L138.

Efanov, V. A., Moiseev, I. G., Nesterov, N. S., and Shakhovskoy, N. M. (1977). "Rapid fluctuations of radio flux and polarisation in quasar 3C 273," Nature **269**, 493–494.

Epstein, E. E. Unpublished.

Epstein, E. E., Fogarty, W. G., Hackney, K. R., Hackney, R. L., Leacock, R. J., Pomphrey, R. B., Scott, R. L., Smith, A. G., Hawkins, R. W., Roeder, R. C., Gary, B. L., Penston, M. V., Tritton, K. P., Bertaud, Ch., Veron, M. P., Wlerick, G., Bernard, A., Bigay, J. H., Merlin, P., Durand, A., Sause, G., Becklin, E. E., Neugebauer, G., and Wynn-Williams, C. G. (1972). "3C 120, BL Lacertae, and OJ 287: coordinated optical, infrared, and radio observations of intraday variability," Astrophys. J. Lett. **178**, L51–L59.

Epstein, E. E., Fogarty, W. G., and Mottmann, J. (1981). "Variable extragalactic radio sources: 9 years of 3.3-mm measurements and comparisons with centimeter-wave variations." Submitted to Astron. J.

Fogarty, W. G., Epstein, E. E., Montgomery, J. W., and Dworetsky, M. M. (1971). "Radio sources: 3.3-mm flux and variability measurements," Astron. J. **76**, 537–543.

Fomalont, E. B., and Perley, R. A. (1980). Unpublished internal VLA Calibration Manual.

Gorshkov, A. G., Moiseev, I. G., and Soglasnov, V. A. (1972). "Spectral flux densities of radio emission from discrete sources at 3.5-cm wavelength. II," Izv. Crimean Astrophys. Obs. **45**, 176–181.

Gubbay, J. S. (1978). "Radio source positions from southern and trans-equatorial very-long-baseline interferometers," Astron. J. **83**, 697–703.

Harvey, G. A., Andrew, B. H., MacLeod, J. M., and Medd, W. J. (1972). "A search for rapidly varying radio sources," Astrophys. Lett. **11**, 147–149.

Hobbs, R. W., and Dent, W. A. (1977). "90-GHz flux density measurements of variable radio sources," Astron. J. **82**, 257–261.

Huchtmeier, W. K., and Wright, A. E. (1973). "Short-term radio variability in the compact galaxy III Zw 2," Astrophys. Lett. **15**, 209–210.

Kaufmann, P., Marques dos Santos, P., Raffaelli, J. C., and Scalise, Jr., E. (1977). "Possible fast variability of the nucleus of Cen A at 13.5 mm," Nature **269**, 311–313.

Kaufmann, P., and Raffaelli, J. C. (1979). "On the possible detection of giant quasi-periodic bursts in the nucleus of Centaurus A at mm-wavelengths," Mon. Not. R. Astron. Soc. **187**, 23P–28P.

Kellermann, K. I., and Pauliny-Toth, I. I. K. (1969). "The spectra of opaque radio sources," Astrophys. J. Lett. **155**, L71–L78.

Kellermann, K. I., Jauncey, D. L., Cohen, M. H., Shaffer, D. B., Clark, B. G., Broderick, J., Rönnäng, B., Rydbeck, O. E. H., Matveyenko, L., Moiseyev, I., Vitkevitch, V. V., Cooper, B. F. C., and Batchelor, R. (1971). "High-resolution observations of compact radio sources at 6 and 18 centimeters," Astrophys. J. **169,** 1-24.

Kellermann, K. I. (1974). "Detection of a strong and possibly variable compact millimeter wave component in Centaurus A," Astrophys. J. Lett. **194,** L135-L137.

Kikuchi, S., Tabara, H., Mikami, Y., Kawano, N., Kawajiri, N., Ojima, T., Tomino, K., Daishido, T., and Konno, M. (1973). "Simultaneous radio and optical observations of OJ 287," Publ. Astron. Soc. Jpn. **25,** 555-561.

Kinman, T. D., and Conklin, E. K. (1971). "Observations of OJ 287 at optical and millimeter wavelengths," Astrophys. Lett. **9**, 147-150.

Kinman, T. D., Wardle, J. F. C., Conklin, E. K., Andrew, B. H., Harvey, G. A., MacLeod, J. M., and Medd, W. J. (1974). "Coordinated observations of OJ 287 at radio and optical wavelengths," Astron. J. **79,** 349-357.

Kraus, J. D., and Andrew, B. H. (1971). "Ohio survey supplement 1," Astron. J. **76,** 103-104.

Landau, R., Epstein, E. E., and Rather, J. D. G. (1980). "Variable radio sources: 90-GHz flux densities," Astron. J. **85,** 363-367.

Marscher, A. P. (1977). "Effects of non-uniform structure on the derived physical parameters of compact synchrotron sources," Astrophys. J. **216,** 244-256.

Medd, W. J., Andrew, B. H., Harvey, G. A., and Locke, J. L. (1972). "Observations of extragalactic variable sources at 2.8 and 4.5 cm wavelength," Mem. R. Astron. Soc. **77,** 109-158.

Miller, H. R. (1978). "1418+54: A new, violently variable BL Lacertae object," Astrophys. J. Lett. **223,** L67-L70.

O'Dell, S. L., Puschell, J. J., Stein, W. A., Owen, F., Porcas, R. W., Mufson, S., Moffett, T. J., and Ulrich, M.-H. (1978). "Coordinated photometric and spectroscopic observations of strong extragalactic 90 GHz sources," Astrophys. J. **224,** 22-31.

Owen, F. N., Porcas, R. W., Mufson, S. L., and Moffett, T. J. (1978). "Observations of radio sources with flat spectra," Astron. J. **83,** 685-696.

Peterson, B. A., Bolton, J. G., and Shimmins, A. J. (1973). "Identification of southern quasi-stellar objects. IV," Astrophys. Lett. **15,** 109-113.

Peterson, F. W., and King, C. (1975). "A model for simultaneous synchrotron and inverse compton fluxes," Astrophys. J. **195,** 753-759.

Racine, R. (1970). "Photometry of BL Lacertae with a time resolution of 15 seconds," Astrophys. J. Lett. **159,** L99-L103.

Radivich, M. M., and Kraus, J. D. (1971). "Identification of radio sources from the Ohio survey," Astron. J. **76,** 683-685.

Ulich, B. L. (1978). Private communication.

van der Laan, H. (1966). "A model for variable extragalactic radio sources," Nature **211,** 1131-1133.

Wilkes, B., Jauncey, D., Peterson, B. A., and Wright, A. (1980). Aust. J. Phys. Astrophys. Suppl. (in preparation).

Wills, B. J. (1971). "Daily and hourly variations in flux density of radio sources," Astrophys. J. **169,** 221-233.