MULTIFREQUENCY LIGHT CURVES OF LOW-FREQUENCY VARIABLE RADIO SOURCES

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ABSTRACT

We present detailed multifrequency light curves, spanning the range 0.3–1.4 GHz, for the low-frequency variable sources AO 0235 + 16, NRAO 140, PKS 1117 + 14, DA 406, CTA 102, and 3C 454.3. Of these sources, only AO 0235 + 16 has exhibited definite "canonical" variability at low frequencies, in which the variations appear first at the higher frequencies and propagate to lower frequencies with diminished amplitude. The five other sources show moderate to strong variations at low frequencies (0.3–0.6 GHz), but with severely reduced amplitude at 0.9 and 1.4 GHz. We argue that the variations observed in AO 0235 + 16 are due to changes in relativistically moving synchrotron components, but that the low-frequency variations observed in NRAO 140, PKS 1117 + 14, DA 406, CTA 102, and 3C 454.3 are of a quite different character, which suggests a distinct low-frequency variability mechanism.

I. INTRODUCTION

Low-frequency (< 1 GHz) variability in extragalactic radio sources was unexpected when it was discovered in the quasars CTA 102 (Sholomitskii 1965; Hunstead 1972) and 3C 454.3 (Hunstead 1972). These early results were initially regarded with some skepticism since early attempts to confirm them were negative (Readhead *et al.* 1977; and other works cited in O'Dell 1979). Several more recent investigations of low-frequency variability leave no doubt about the reality of this phenomenon (e.g., papers in Cotton and Spangler 1982).

The main theoretical difficulty is that the variability time scales suggest brightness temperatures greatly exceeding the 10^{12} K Compton upper limit for nonrelativistically evolving incoherent electron-synchroton sources (e.g., Jones and Burbidge 1973). A variety of solutions have been proposed, including noncosmological redshifts (Jones and Burbidge 1973), extrinsic modulation (Shapirovskaya 1978; Marscher 1979), ultrabright ($T_b \gg 10^{12}$ K) emission mechanisms (e.g., Petschek *et al.* 1976; Cocke *et al.* 1978), and relativistic bulk motion (e.g., Blandford and Königl 1979; Marscher 1978, 1980).

In order to distinguish among the various theoretical possibilities, we are monitoring about 30 low-frequency variable sources using the NAIC* Arecibo 305-m radio telescope and the NRAO Green Bank 91-m radio telescope. These sources were chosen from the complete samples of extragalactic sources searched for variability at 318 MHz by Condon *et al.* (1979) and Dennison *et al.* (1981).

Here we present light curves for the sources 0038 + 32 (3C 19), 0235 + 16 (AO), 0333 + 32 (NRAO 140), 1117 + 145 (PKS), 1611 + 34 (DA 406), 2230 + 11 (CTA 102), and 2251 + 15 (3C 454.3). The extended nonvariable source, 0038 + 32 (3C 19), was included as a program source (but not as a calibrator) in order to check the validity of our measurements. In a separate paper (Dennison *et al.* 1984), we discuss the dynamic spectra of these sources, which exhibit remarkable changes in shape (with the exception of 0038 + 32).

II. OBSERVATIONS

a) Arecibo

The Arecibo 305-m telescope was used for measurements at 318, 430, and 606 MHz. Since only two of these frequencies can be available simultaneously at Arecibo, the bimonthly sessions alternated between 318 and 606 MHz, whereas 430 MHz was always used. Highly stable transistor amplifiers were used in the total power mode at 318 and 430 MHz, and a noise-adding radiometer was used at 606 MHz to stabilize the gain of a parametric amplifier. An internal calibration signal was turned on briefly at the beginning of each drift scan. A linear baseline was fit to the source-free portions of each drift scan and subtracted, after which a Gaussian beam shape was fit to the source response. The calibration sources listed in Table I were observed and used to convert the peak source response (in units of the internal calibration amplitude) to Janskys, on the scale of Baars *et al.* (1977). All flux-density measurements were corrected for the zenith-angle gain dependence of the telescope. To eliminate changes due to source polarization, residual zenith-angle gain variations, and changing contributions due to confusing

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TABLE I. Adopted calibrator flux densities (Jy).

Source	S_{318}	S_{430}	S_{606}	S_{880}	S_{1400}
0017 + 15	—	—	—	3.41	2.11
0127 + 23	8.55	6.60	5.42	3.97	2.94
0433 + 29	—	—	—	66.25	47.83
0528 + 06	12.99	9.94	6.97	4.99	3.29
0710 + 11	11.37	8.41	5.83	3.95	2.56
1005 + 07	18.87	15.44	12.29	9.21	6.48
1140 + 22	—	—	—	4.58	3.09
1328 + 25	15.29	13.14	11.18	—	—
1328 + 30	27.18	24.49	21.50	18.40	14.84
1509 + 01	—	—	—	3.26	2.21
1627 + 23	—	—	—	3.54	2.56
1756 + 13	6.98	5.79	4.73	3.28	2.39
2121 + 24	—	—	—	17.62	12.23
2203 + 29	9.45	7.28	5.51	3.93	2.72

sources, each source was always observed at the same sidereal time.

b) Green Bank

The Green Bank 91-m transit telescope was used for the bimonthly measurements at 880 and 1400 MHz. Parametric amplifiers were used until about 1982.0. These measurements consisted of drift scans with an internal calibration signal fired at 30-s intervals. More recent measurements employed stable, low-noise GAsFET amplifiers, used on a total power observing mode. Two orthogonal polarization channels were simultaneously recorded and averaged together. After correction for the declination dependence of the telescope gain, the scans were calibrated using the calibration sources listed in Table I.

c) Flux-Density Error Analysis

Flux-density errors are of two general types: the intensity-independent receiver noise and residual confusion errors; and intensity-proportional errors, produced by telescope pointing errors, modeling errors in the antenna-gain curves, detector nonlinearities, noise-tube instabilities, uncalibrated gain fluctuations, and ionospheric and interplanetary scintillation (Condon 1972). (Confusion does not contribute directly to the *time dependence* of the measured flux density.) Also contributing to the intensity-proportional error in any error is the derived calibration constant used to transform telescope deflection to flux density during a given run. The intensity-independent and intensity-dependent errors are independent, and thus add quadratically to yield the total flux-density error associated with a given scan:

$$\sigma_s = \sqrt{\sigma_i^2 + (f^2 + f_c^2) S^2},$$

where σ_i is the intensity-independent error (in Jy), f is the intensity-proportional error associated with a scan (expressed as a fraction), f_c is the intensity-proportional error associated with the calibration, and S is the source flux density.

The intensity-independent errors were measured directly at each frequency from multiple drift scans of weak sources, all observed during the same run. Values for σ_i are: 0.05 Jy at 318, 430, and 606 MHz; 0.07 Jy at 880 MHz; and 0.03 Jy at 1400 MHz. (The values at 880 and 1400 MHz are for both polarization channels averaged together.)

Values for f were determined from the scatter in calibrator measurements, and were monitored for each run. (The calibrator flux densities, given in Table I, have been adjusted to minimize residuals over all the observation sessions reported in this paper. Hence, errors in the tabulated flux densities should not contribute, to first order, to the scatter in calibrator measurements during a run.) Nominal values of f at each frequency are: 0.025 at 318, 430, 606, and 880 MHz; and 0.020 at 1400 MHz. These values were used for a given run, unless the scatter in the calibrators necessitated the use of a larger value.

The values for f_c were based on the formal error in the fitted calibration constant for a given run at a given frequency, and are generally small compared with f.

At 318 and 606 MHz, the flux in a single mode of linear polarization was recorded, and thus changes in ionospheric Faraday rotation (Hagfors 1976) could produce spurious variations in the flux of linearly polarized sources. The effects of this are not totally incorporated into the formal errors, as the calibrators tend to be somewhat more depolarized at low frequencies than the compact variable sources (Conway *et al.* 1972; Haves *et al.* 1974; Weiler and Wilson 1977). Nevertheless, the effect should rarely exceed 3% or 4%, the typical polarizations of the variable sources at low frequencies. This is considerably less than the amplitudes of the major variations which we discuss here. This effect is nonexistent at 430 MHz, at which right circular polarization was recorded, and at 880 and 1400 MHz, at which orthogonal linear modes were recorded and averaged together.

III. RESULTS

The results for all seven sources are listed in Table II, and displayed in Figs. 1(a)–1(g). For each frequency, the percentage rms scatter in the data is shown in Table III. Figure 1(a) shows the measurements for the nonvariable source 0038 + 32 (3C 19). Since 0038 + 32 was treated as a program source, and not as a calibrator, this scatter provides a good estimate of the level of repeatability of the measurements ($\leqslant 3\%$). A chi-squared analysis for each of the five frequencies (assuming a nonvarying flux density) is within acceptable bounds, although the errors may be slightly overestimated at 880 MHz. In what follows, we comment on the variable sources individually:

0235 + 16 (AO): This well-known BL Lac object tends to display correlated light curves over a very broad portion of the electromagnetic spectrum (MacLeod *et al.* 1976; Ledden *et al.* 1976; Rieke *et al.* 1976; Balonek and Dent 1980). Each of the two outbursts seen here [Fig. 1(b)] was preceded by an outburst observed by Aller *et al.* (1982) at 4.8, 8, and 14.8 GHz, the first peaking at high frequencies around 1980.8, and the second around 1981.6. At both high and low radio frequencies the outburst peaks tended to shift to progressively lower frequencies with diminished amplitude. Hence, we interpret the low-frequency variability in AO 0235 + 16 as due primarily to expansion of synchrotron-emitting material undergoing relativistic motion directed close to the line of sight. Such motion is required if the rapid time scales seen in this source are to be accounted for in the context of incoherent electron-synchrotron radiation models. Preliminary analysis of the time scales and variability amplitudes observed in AO 0235 + 16 suggests that a relativistic Doppler factor in the range of 6 to 12 could adequately account for these results.

VLBI observations show this source to be extremely compact (Johnston *et al.* 1979; Jones *et al.* 1984a,b). This, combined with its x-ray flux, has led to the conclusion that most of the radio-emitting material must be undergoing bulk rela-

TABLE II. Flux densities and errors of program sources.

0038+32 (3C 19)

DATE	318 MHZ	430 MHZ	606 MHZ
	FLUX (ERROR) IN JY		
1980.22		7.65 (.15)	5.67 (.28)
1980.40	9.73 (.26)	7.97 (.24)	
1980.57		8.14 (.18)	5.81 (.15)
1980.73	9.78 (.18)	7.90 (.19)	
1980.90		7.74 (.23)	5.73 (.11)
1981.10	9.82 (.26)	7.84 (.21)	
1981.26		7.72 (.20)	5.51 (.11)
1981.47	9.73 (.18)	8.23 (.25)	
1981.58		7.97 (.31)	6.00 (.27)
1981.75	10.09 (.26)	8.06 (.48)	
1981.97		8.04 (.39)	5.64 (.13)
1982.14	9.76 (.18)	7.72 (.21)	
1982.29		7.83 (.21)	5.65 (.14)
1982.45	9.58 (.18)		
1982.66		8.07 (.21)	5.81 (.21)
1982.79	10.22 (.27)	8.33 (.22)	
1982.89	8.86 (.25)	8.45 (.51)	
1982.97		7.91 (.29)	5.85 (.12)

DATE	880 MHZ	1400 MHZ
	FLUX (ERROR) IN JY	
1980.08		3.26 (.07)
1980.16	4.30 (.13)	
1980.28		3.36 (.05)
1980.34	4.49 (.14)	
1980.45	4.51 (.16)	3.28 (.07)
1980.50	4.48 (.10)	
1980.58	4.54 (.14)	3.24 (.07)
1980.70	4.52 (.14)	3.15 (.07)
1980.96	4.56 (.14)	3.37 (.08)
1981.11	4.52 (.14)	3.25 (.05)
1981.23	4.56 (.19)	3.23 (.07)
1981.41	4.58 (.16)	3.29 (.12)
1981.58	4.59 (.20)	3.28 (.05)
1981.84	4.43 (.13)	3.28 (.08)
1982.01	4.60 (.14)	3.21 (.12)
1982.17	4.40 (.10)	3.24 (.07)
1982.30	4.45 (.08)	3.29 (.06)
1982.45	4.46 (.13)	3.27 (.08)
1982.66	4.47 (.14)	3.29 (.05)
1982.79	4.46 (.10)	3.31 (.11)

0235+16 (AO)

DATE	318 MHZ	430 MHZ	606 MHZ
	FLUX (ERROR) IN JY		
1980.22		1.27 (.04)	
1980.57		1.49 (.05)	1.60 (.07)
1980.73	1.44 (.04)	1.44 (.07)	
1980.90		1.78 (.07)	1.71 (.05)
1981.10	1.70 (.05)	1.73 (.07)	
1981.26		1.95 (.07)	1.91 (.05)
1981.47	1.55 (.06)	1.62 (.07)	
1981.58		1.69 (.08)	1.97 (.10)
1981.75	1.48 (.05)	1.47 (.10)	
1981.97		1.40 (.08)	1.36 (.05)
1982.14	1.43 (.04)	1.35 (.06)	
1982.29			1.44 (.07)
1982.45	1.39 (.06)	1.45 (.07)	
1982.66		1.48 (.06)	1.84 (.10)
1982.79	1.49 (.05)	1.58 (.06)	
1982.97		1.82 (.08)	1.81 (.05)

DATE	880 MHZ	1400 MHZ
	FLUX (ERROR) IN JY	
1980.08		1.77 (.05)
1980.16	1.39 (.08)	
1980.45	1.82 (.09)	1.92 (.05)
1980.50	1.73 (.06)	
1980.58	1.76 (.08)	2.15 (.05)
1980.70	1.91 (.09)	2.57 (.06)
1980.96	1.83 (.08)	2.34 (.06)
1981.11	2.02 (.09)	2.25 (.05)
1981.23	2.35 (.12)	2.12 (.05)
1981.41	1.94 (.09)	1.62 (.09)
1981.58		1.56 (.03)
1981.84	1.38 (.08)	1.35 (.04)
1982.01	1.29 (.08)	1.56 (.06)
1982.17	1.54 (.08)	1.75 (.05)
1982.45	1.72 (.08)	2.13 (.06)
1982.66	1.93 (.09)	2.12 (.04)
1982.79	1.85 (.06)	1.93 (.07)

TABLE II. (continued)

0333+32 (NRAO 140)

DATE	FLUX (ERROR) IN JY 318 MHZ	430 MHZ	606 MHZ	DATE	FLUX (ERROR) IN JY 880 MHZ	1400 MHZ
				1980.08		2.92 (.07)
				1980.16	3.02 (.10)	
1980.22			2.81 (.08)	1980.28		3.17 (.07)
1980.40		3.48 (.08)		1980.45	2.78 (.10)	
				1980.50	2.98 (.09)	
1980.57		3.23 (.11)	2.96 (.16)	1980.58	2.93 (.09)	3.09 (.07)
1980.73	3.13 (.10)	3.32 (.12)		1980.70	2.97 (.09)	3.20 (.07)
1980.90		3.27 (.11)	3.17 (.07)	1980.96	3.27 (.11)	3.38 (.08)
1981.10	3.36 (.07)	3.34 (.10)				
1981.26			3.19 (.07)	1981.23	3.42 (.13)	3.49 (.08)
1981.47	3.32 (.07)	3.72 (.12)		1981.41	3.49 (.13)	
1981.58		3.98 (.16)	3.50 (.16)	1981.58	3.60 (.14)	3.17 (.07)
1981.75	3.13 (.13)	3.60 (.22)				
				1981.84	3.41 (.11)	3.40 (.08)
1981.97		3.60 (.18)	3.25 (.08)	1982.01	3.21 (.11)	
1982.14	3.55 (.10)	3.22 (.10)		1982.17	3.13 (.11)	3.15 (.07)
1982.29		2.74 (.09)	3.08 (.11)	1982.30	3.12 (.07)	3.14 (.08)
1982.45		2.79 (.12)		1982.45	2.79 (.10)	3.14 (.08)
1982.66		2.83 (.09)	2.68 (.14)	1982.66	2.99 (.11)	3.45 (.06)
1982.79	3.12 (.10)	2.72 (.09)		1982.79	2.92 (.07)	3.13 (.10)
1982.97		2.79 (.11)				

1117+14 (PKS)

DATE	FLUX (ERROR) IN JY 318 MHZ	430 MHZ	606 MHZ	DATE	FLUX (ERROR) IN JY 880 MHZ	1400 MHZ
				1980.08		2.45 (.06)
				1980.16	2.98 (.07)	
1980.22		3.10 (.05)	3.52 (.06)	1980.28		2.39 (.06)
				1980.34	2.89 (.10)	
1980.40	3.23 (.09)			1980.45	2.86 (.08)	2.32 (.06)
				1980.50	2.79 (.10)	
1980.57			2.86 (.16)	1980.59		2.35 (.06)
1980.73	3.17 (.10)					
1980.90		3.49 (.11)	3.87 (.05)	1980.96	3.00 (.11)	2.53 (.06)
1981.10	3.83 (.06)	4.08 (.08)		1981.11	3.07 (.11)	2.48 (.06)
1981.26		4.02 (.08)	3.83 (.06)	1981.23	3.16 (.14)	2.59 (.06)
1981.47	5.02 (.10)			1981.41	3.22 (.12)	2.48 (.13)
1981.58		3.29 (.21)	3.63 (.12)	1981.58	2.98 (.10)	2.44 (.06)
1981.75	3.27 (.05)	3.03 (.09)				
				1981.84	2.91 (.10)	2.47 (.06)
1981.97		3.14 (.11)	3.28 (.06)	1982.01	2.91 (.10)	2.41 (.09)
1982.14	3.23 (.05)	3.06 (.07)		1982.17	3.02 (.11)	2.49 (.04)
1982.29		3.06 (.07)	3.24 (.06)	1982.30	2.99 (.05)	2.44 (.05)
1982.45	3.34 (.05)	2.99 (.09)		1982.45	2.97 (.10)	2.47 (.04)
1982.66		4.07 (.28)	3.12 (.08)	1982.66	2.91 (.10)	2.36 (.06)
1982.79	5.10 (.08)	3.73 (.10)		1982.79	2.89 (.10)	2.40 (.08)

TABLE II. (continued)

1611+34 (DA 406)

DATE	FLUX (ERROR) IN JY 318 MHZ	430 MHZ	606 MHZ
1980.22		2.37 (.06)	2.34 (.17)
1980.40	2.72 (.06)	2.39 (.09)	
1980.57		2.36 (.09)	2.16 (.09)
1980.73	2.79 (.09)	2.24 (.09)	
1980.90		2.18 (.08)	2.25 (.05)
1981.10	2.83 (.06)	2.30 (.08)	
1981.26		2.41 (.08)	
1981.47	3.23 (.07)	2.90 (.10)	
1981.58		2.98 (.12)	3.19 (.15)
1981.75		3.51 (.21)	
1982.14	4.10 (.08)	3.73 (.11)	
1982.29		3.79 (.11)	3.23 (.12)
1982.45	3.85 (.11)	3.72 (.15)	
1982.66		3.59 (.11)	3.23 (.12)
1982.79	3.94 (.08)	3.42 (.10)	
1982.89	3.81 (.10)	3.75 (.29)	
1982.97		3.54 (.11)	3.03 (.08)

DATE	FLUX (ERROR) IN JY 880 MHZ	1400 MHZ
1980.08		2.66 (.06)
1980.16	2.72 (.07)	
1980.28		2.71 (.06)
1980.34	2.74 (.10)	
1980.45	2.74 (.11)	2.77 (.05)
1980.50	2.85 (.10)	
1980.58	2.88 (.10)	2.86 (.05)
1980.70	2.88 (.10)	
1980.96		2.89 (.07)
1981.11	2.85 (.10)	2.76 (.06)
1981.23	3.09 (.14)	2.85 (.07)
1981.41	3.11 (.12)	2.93 (.11)
1981.58	2.79 (.13)	2.58 (.04)
1982.01	3.34 (.11)	3.19 (.12)
1982.17	3.27 (.11)	3.02 (.05)
1982.30	3.39 (.08)	3.01 (.08)
1982.45	3.07 (.11)	2.88 (.05)
1982.66	3.14 (.11)	2.94 (.05)
1982.79	3.30 (.11)	2.94 (.10)

2230+11 (CTA 102)

DATE	FLUX (ERROR) IN JY 318 MHZ	430 MHZ	606 MHZ
1980.22		8.15 (.23)	8.70 (.43)
1980.40	7.64 (.14)	7.90 (.23)	
1980.57		7.97 (.24)	8.03 (.30)
1980.73	8.05 (.15)	7.45 (.25)	
1980.90		8.19 (.17)	8.30 (.11)
1981.10	7.61 (.14)	7.38 (.20)	
1981.26		7.47 (.20)	8.26 (.16)
1981.47	7.23 (.14)	8.02 (.25)	
1981.58		8.41 (.32)	8.76 (.39)
1981.75	7.70 (.29)	8.15 (.48)	
1981.97		7.62 (.37)	8.08 (.26)
1982.14	6.94 (.13)	7.51 (.20)	
1982.29		7.56 (.14)	8.32 (.28)
1982.45	7.54 (.20)	8.42 (.23)	
1982.66		7.65 (.20)	
1982.89	6.65 (.18)	7.92 (.48)	
1982.97		7.31 (.27)	8.15 (.16)

DATE	FLUX (ERROR) IN JY 880 MHZ	1400 MHZ
1980.08		6.43 (.14)
1980.28		6.39 (.14)
1980.34	7.33 (.14)	
1980.45	7.30 (.24)	6.53 (.10)
1980.50	7.26 (.20)	
1980.58	7.33 (.21)	6.47 (.14)
1980.70	7.35 (.20)	
1980.96	7.51 (.21)	6.59 (.15)
1981.11	7.66 (.21)	6.68 (.14)
1981.23		6.94 (.15)
1981.41		6.45 (.23)
1981.58	7.76 (.32)	6.76 (.10)
1981.84	7.59 (.21)	
1982.01	7.23 (.20)	6.70 (.24)
1982.17	7.44 (.21)	6.77 (.14)
1982.30	7.61 (.12)	6.76 (.12)
1982.45	7.65 (.21)	6.73 (.11)
1982.66	6.96 (.19)	6.62 (.10)
1982.79	7.26 (.14)	6.78 (.21)

TABLE II. (continued)

2251+15 (3C 454.3)

DATE	FLUX (ERROR) IN JY 318 MHZ	430 MHZ	606 MHZ
1980.22		10.12 (.20)	
1980.40	11.25 (.30)	10.87 (.32)	
1980.57		10.83 (.23)	13.26 (.35)
1980.73	12.83 (.24)	12.36 (.41)	
1980.90		12.78 (.27)	14.70 (.27)
1981.10	14.12 (.60)	13.78 (.36)	
1981.26		14.12 (.37)	15.82 (.41)
1981.47		12.93 (.39)	
1981.58			13.90 (.62)
1981.75	12.17 (.32)	12.39 (.73)	
1981.97		11.51 (.56)	13.79 (.31)
1982.14	11.40 (.21)	11.30 (.30)	
1982.29		11.22 (.21)	13.44 (.44)
1982.45		11.56 (.45)	
1982.66		10.98 (.29)	
1982.89	11.85 (.43)	12.74 (.77)	
1982.97		11.64 (.43)	14.81 (.28)

DATE	FLUX (ERROR) IN JY 880 MHZ	1400 MHZ
1980.08		10.95 (.16)
1980.16	12.00 (.32)	
1980.28		10.63 (.22)
1980.34	11.61 (.22)	
1980.45	11.24 (.36)	10.17 (.20)
1980.50	12.17 (.23)	
1980.58	12.14 (.33)	10.91 (.23)
1980.70	12.33 (.33)	10.79 (.23)
1980.96	12.39 (.33)	10.99 (.24)
1981.11	13.03 (.35)	10.29 (.21)
1981.23	12.72 (.50)	10.66 (.23)
1981.41	12.80 (.40)	10.65 (.38)
1981.58	12.40 (.50)	10.49 (.15)
1981.84	11.86 (.32)	
1982.01	12.14 (.33)	10.15 (.37)
1982.17	12.05 (.32)	10.80 (.23)
1982.30	11.98 (.18)	10.94 (.19)
1982.46		10.88 (.17)
1982.66	11.81 (.32)	11.29 (.17)
1982.79	11.94 (.22)	11.68 (.36)

tivistic motion (Dennison *et al.* 1978; Jones *et al.* 1984a). Also, the absence of fast interstellar scintillations in AO 0235 + 16 (Scheuer 1976; Condon and Dennison 1978) seems to indicate that the source is not as compact as a naive interpretation of its variability time scale would suggest, thus requiring relativistic motion if the variations are intrinsic.

AO 0235 + 16 is also noteworthy in several other respects. It is one of the few sources showing optical absorption-line systems ($z = 0.524$ and 0.852) and H I absorption at one of these redshifts (0.524) (Burbidge *et al.* 1976; Wolfe *et al.* 1978). It exhibited the largest fractional centimeter-wavelength variation of any extragalactic source (MacLeod *et al.* 1976; Ledden *et al.* 1976). It is further characterized by being the only source which showed a similar rotation rate of its linear polarization angle for two independent outbursts (Ledden and Aller 1979; Altschuler 1980).

BL Lac is the only other low-frequency variable source shown to exhibit such canonical variability over the entire radio spectrum (Stannard *et al.* 1975; Fisher and Erickson 1980; Fanti *et al.* 1981; Aller and Aller 1982; Fanti *et al.* 1983). It is important to delineate those features (if any) that are peculiar to sources exhibiting this class of variability. Since BL Lac is also quite active at centimeter wavelengths, we suggest that the sources with the most active "naked" radio cores are most likely to exhibit detectable variability extending into the low-frequency domain.

0333 + 32 (NRAO 140): At centimeter wavelengths, this source displays quite gradual variations spanning time scales of about a decade. The variation amplitude appears to increase with increasing frequency, becoming a major portion of the flux at 15.5 GHz (Altschuler and Wardle 1976; Andrew *et al.* 1978; Balonek 1982). Despite the obviously long time scales observed at high frequencies, we observed an event of significant amplitude ($\sim 30\%$ at 430 MHz), and fairly rapid time scale (~ 1 yr) at frequencies below 1 GHz [Fig. 1(c)]. This event is hardly noticeable at 1400 MHz, however. Marscher and Broderick predicted (1981 a,b) and discovered (1982) relativistic motion in this source (at $\lambda = 2.8$ cm).

1117 + 14 (PKS): A very rapid, large-amplitude event was observed at 318 MHz [Fig. 1(d)]. The existence of three drift scans at 318 MHz confirms the 1981.47 flux-density rise at 318 MHz. Significantly, the flux returned to this level on 1982.79. These events were much weaker at higher frequencies; indeed, at 1400 MHz, the data are consistent with no variation whatsoever.

1611 + 34 (DA 406): This source appears to be only moderately variable at 2.7, 4.9, and 8.0 GHz (Altschuler and Wardle 1976; Spangler and Cotton 1982; Aller and Aller 1982), although it is more active at 90 GHz (Spangler and Cotton 1982). We observed a major flux increase below 880 MHz, but with severely diminished amplitude at 880 and 1400 MHz [Fig. 1(e)]. This event is quite similar to the one observed in 1977 by Cotton and Spangler (1979), and provides a dramatic illustration of the absence of variations around 1 GHz (the Intermediate Frequency Gap—IFG—Spangler and Cotton 1981). The sharp quenching of variability at 880 and 1400 MHz places very severe constraints upon the spectrum of any varying component (if the variation is intrinsic), requiring either a very steep spectrum ($\alpha > 2$) above 606 MHz (Dennison *et al.* 1984), or an energy cutoff.

2230 + 11 (CTA 102): Since Hunstead's (1972) report of low-frequency variability, this source has not shown large variations at low frequencies (Readhead *et al.* 1977; Fanti *et al.* 1983). During this same time period, it has been only moderately variable between 1 and 10 GHz (Altschuler and Wardle 1976; Andrew *et al.* 1978; Spangler and Cotton 1982). Above 10 GHz, however, it appears to be quite active

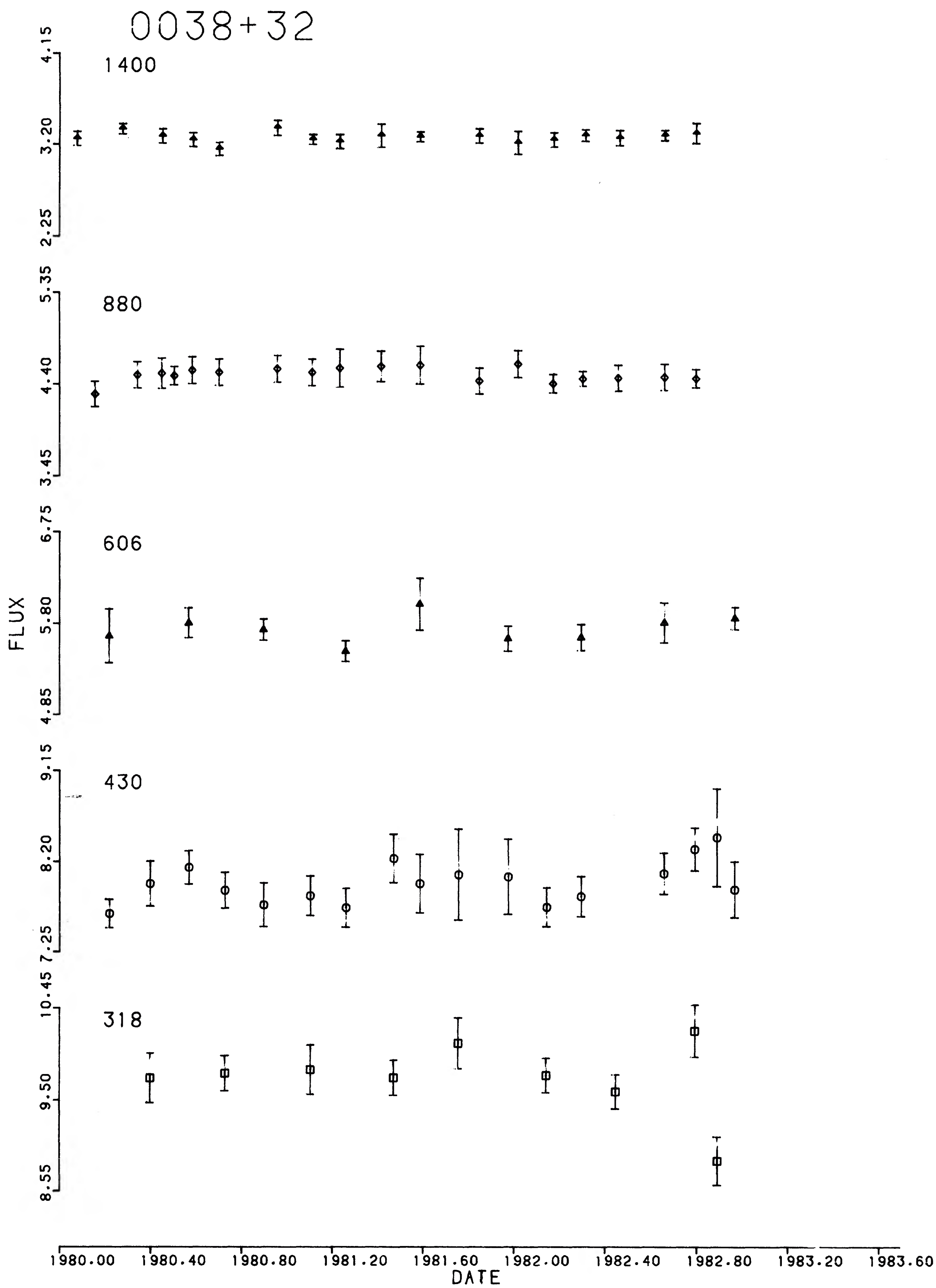

FIG. 1(a). Light curves of 0038 + 32 (3C 19). Note that the flux scale increments are uniform over all five frequencies.

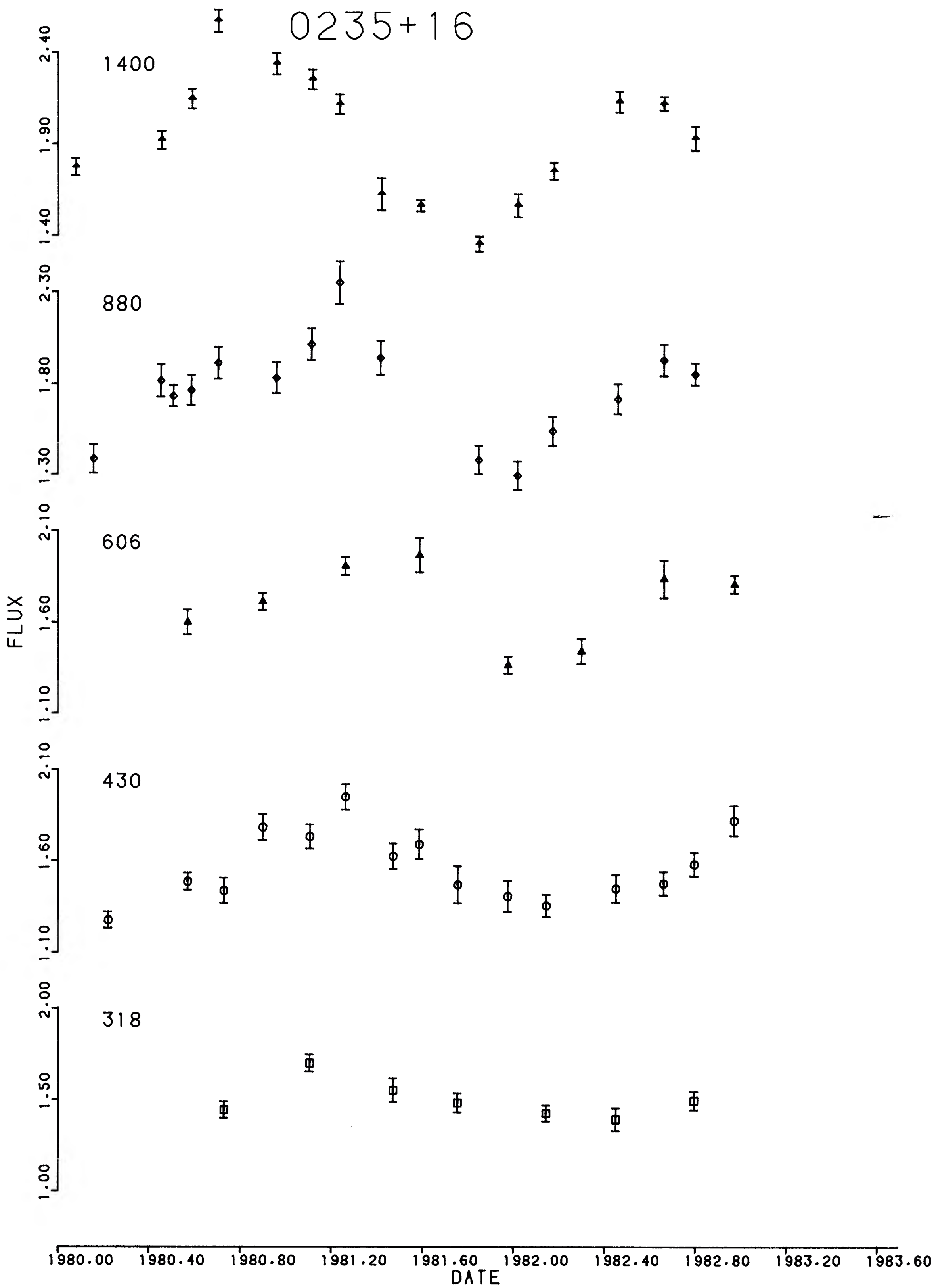

FIG. 1(b). Light curves of 0235 + 16 (AO). Note that the flux scale increments are uniform over all five frequencies.

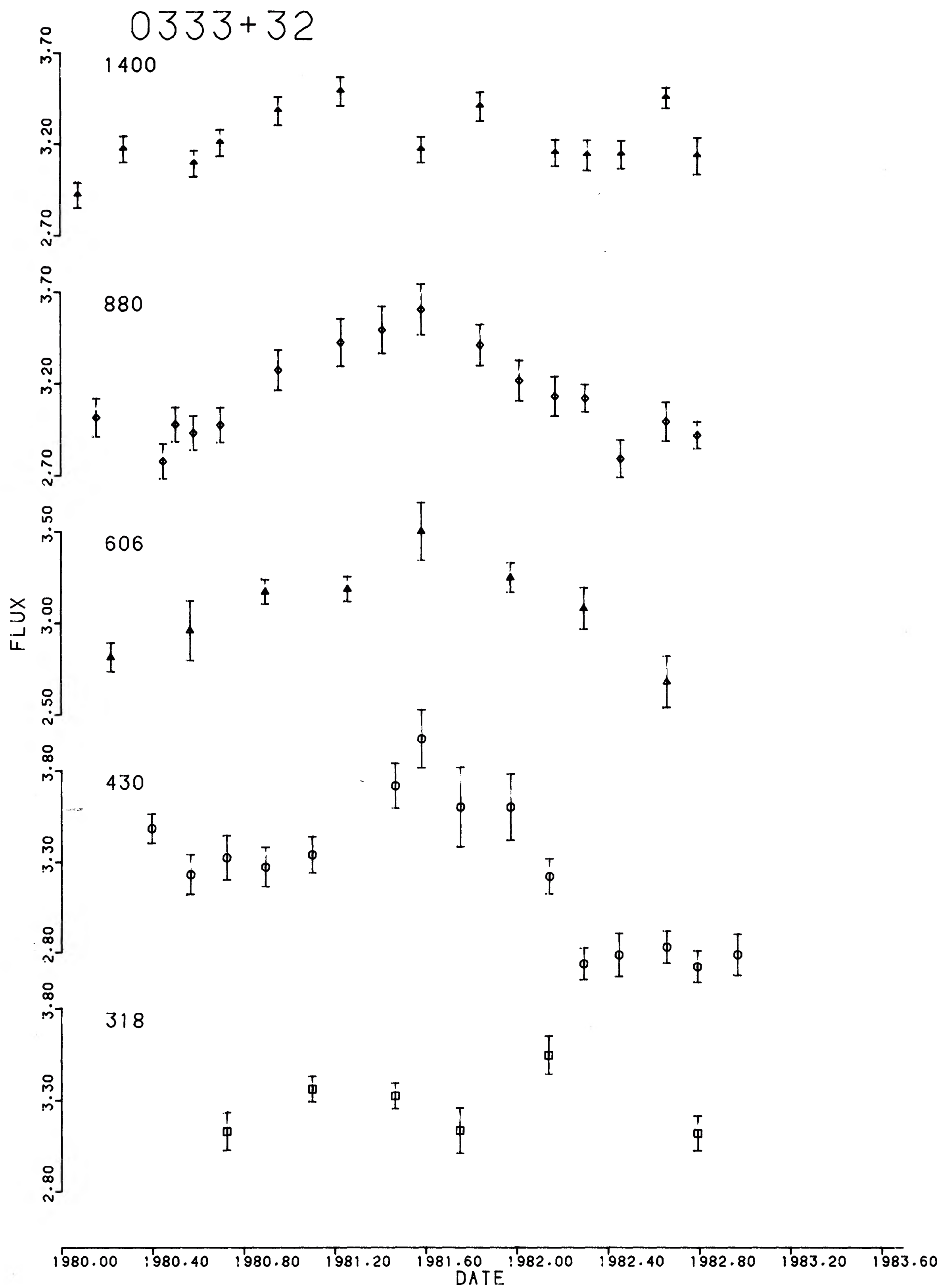

FIG. 1(c). Light curves of 0333 + 32 (NRAO 140). Note that the flux scale increments are uniform over all five frequencies.

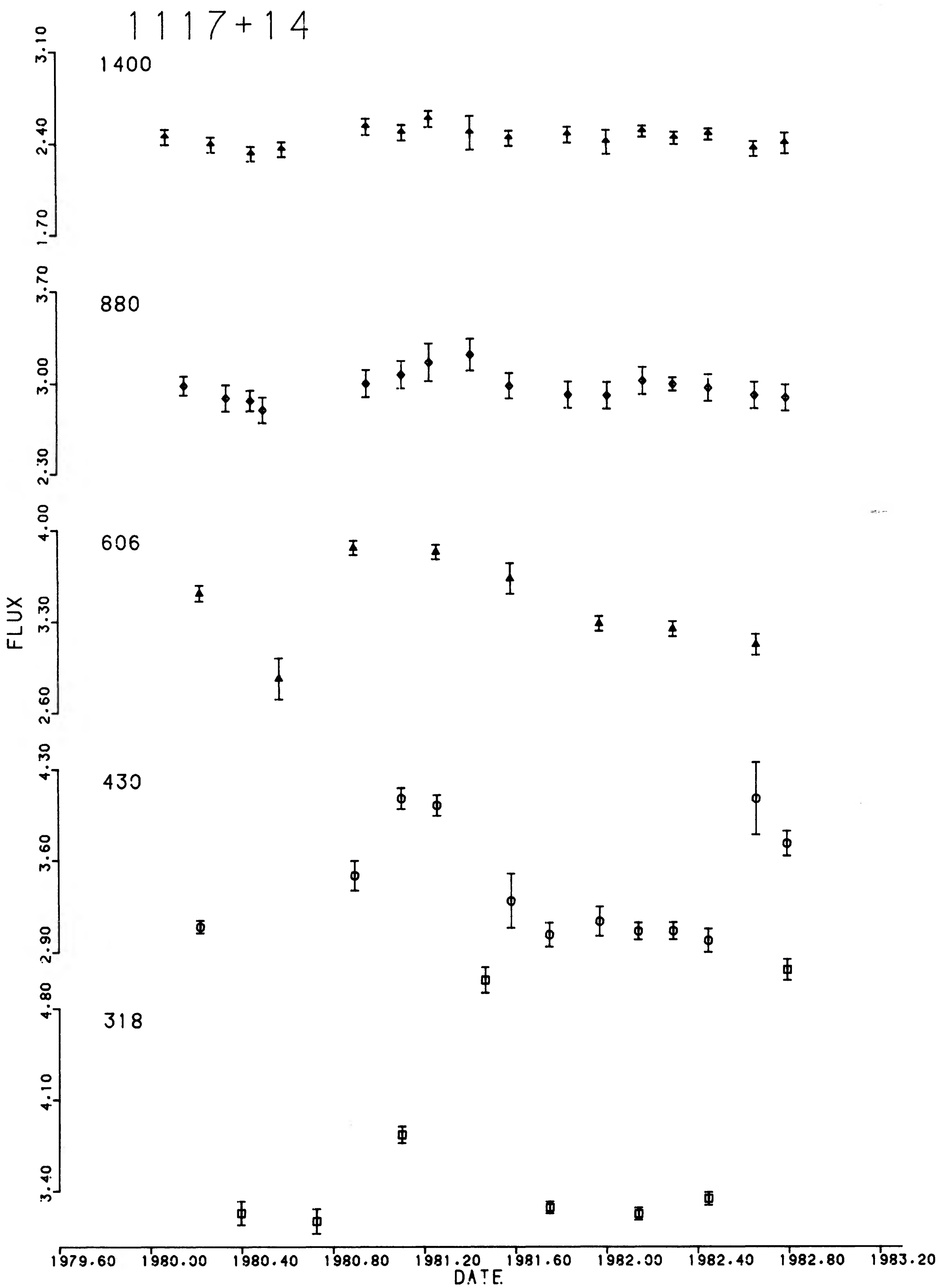

FIG. 1(d). Light curves of 1117 + 14 (PKS). Note that the flux scale increments are uniform over all five frequencies.

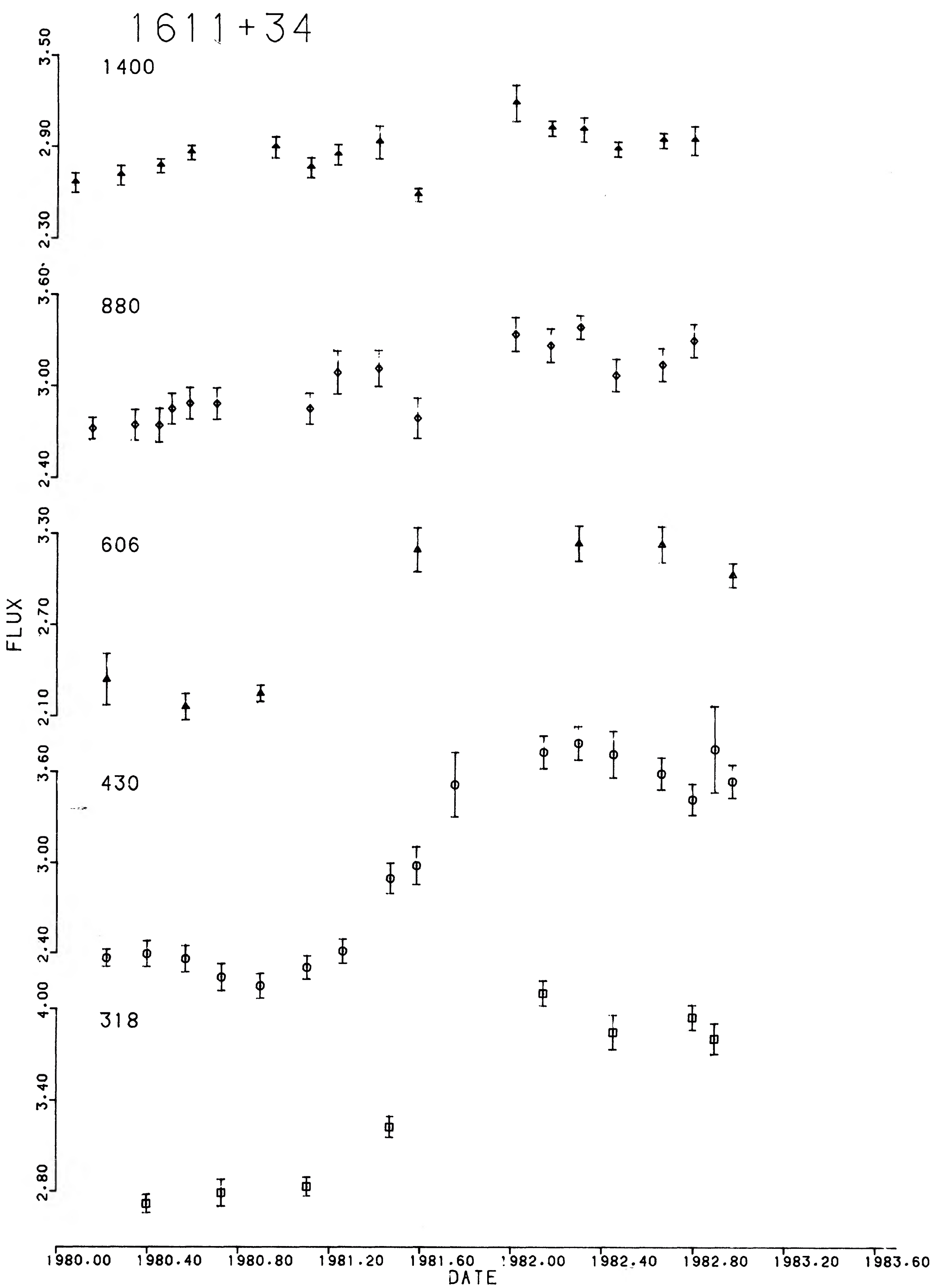

FIG. 1(e). Light curves of 1611 + 34 (DA 406). Note that the flux scale increments are uniform over all five frequencies.

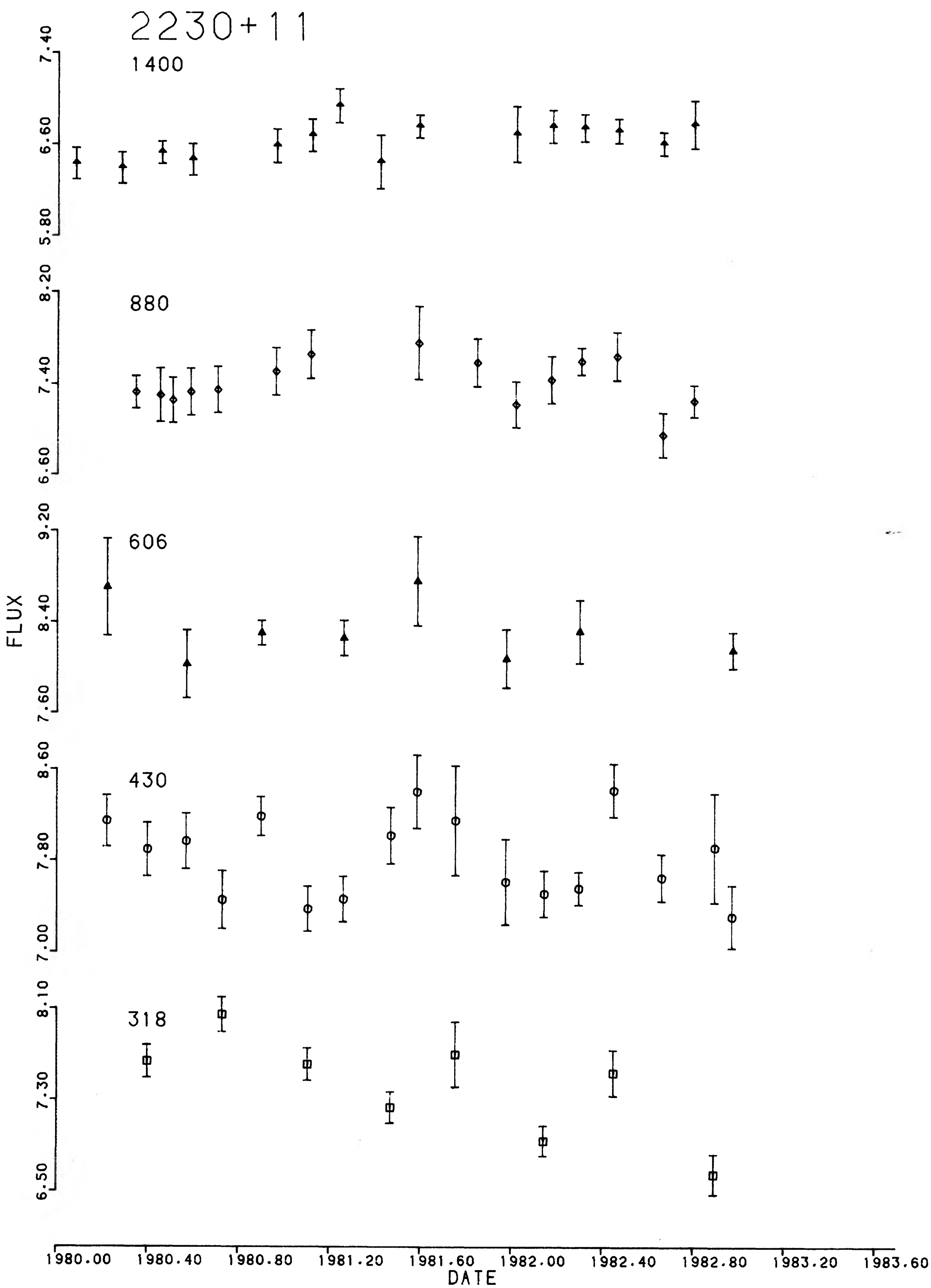

FIG. 1(f). Light curves of 2230 + 11 (CTA 102). Note that the flux scale increments are uniform over all five frequencies.

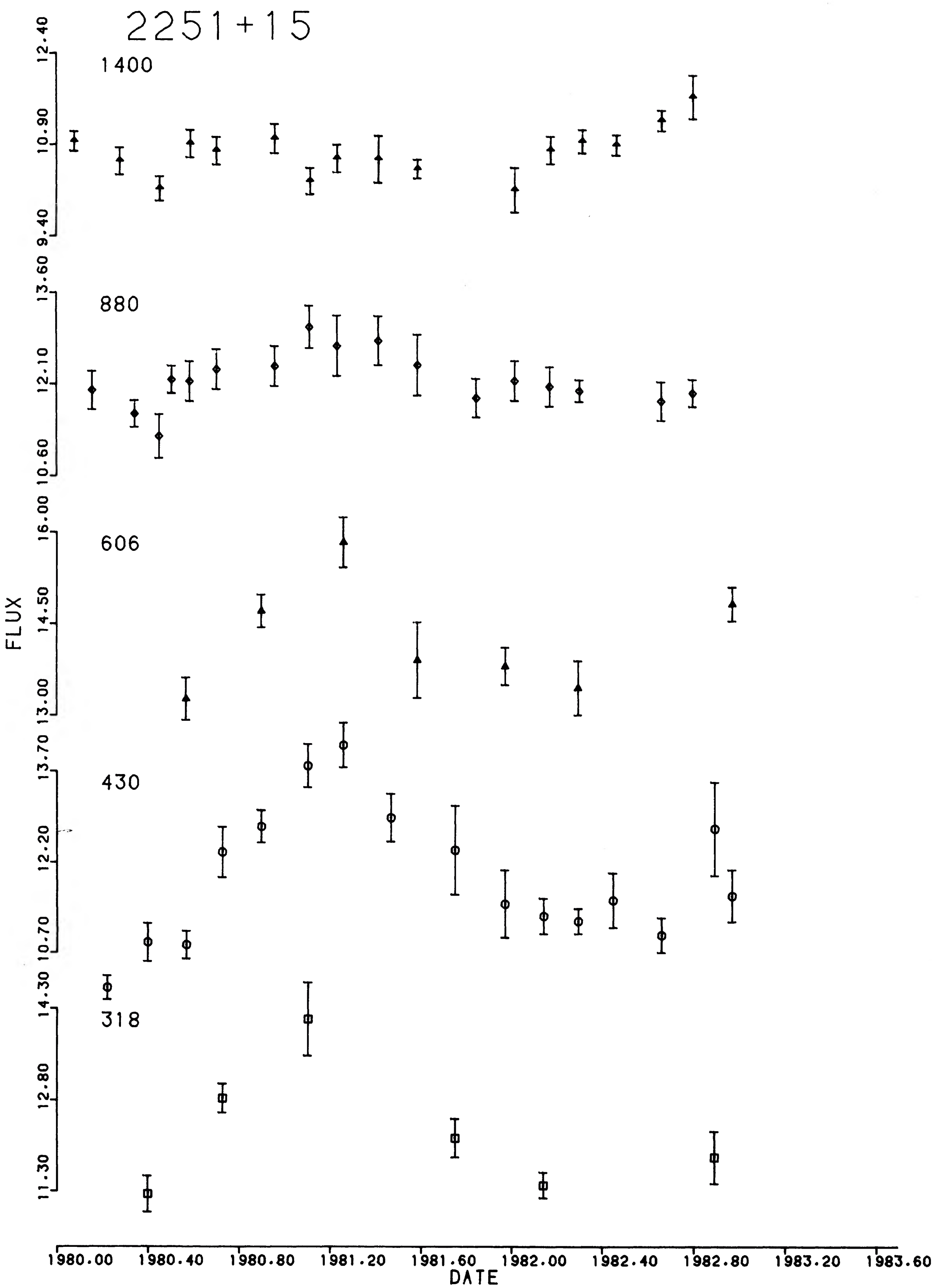

FIG. 1(g). Light curves of 2251 + 15 (3C 454.3). Note that the flux scale increments are uniform over all five frequencies.

TABLE III. RMS fluctuations in 0038 + 32.

Frequency (MHz)	Unweighted RMS (per cent)	Weighted RMS (per cent)
318	3.6	2.5
430	2.8	2.7
606	2.6	2.4
880	1.7	1.6
1400	2.6	2.6

(Spangler and Cotton 1982; Balonek 1982). The moderate variability reported here [Fig. 1(f)] is consistent with the behavior of this source over the last decade. It is significant, however, that the variation amplitude is noticeably diminished at 880 MHz, and particularly at 1400 MHz.

2251 + 15 (3C 454.3): The detailed multifrequency behavior of this source has been discussed by Aller and Aller (1982) and by Fanti *et al.* (1983). Very large centimeter-wavelength variations are often seen, diminishing in amplitude with decreasing frequency, such that the variations are very minor at 1.4 GHz (Spangler and Cotton 1981 and 1982; Payne *et al.* 1982). Below 1 GHz we have seen a significant event, having a noticeably diminished amplitude at 880 MHz [Fig. 1(g)]. At 1400 MHz, this event is not apparent.

IV. DISCUSSION

One source discussed here (AO 0235 + 16) displays more or less canonical variability (delayed, diminished outbursts at lower frequencies), and can thus probably be explained in terms of relativistically moving, evolving synchrotron components. The other five variable sources (NRAO 140, PKS 1117 + 14, DA 406, CTA 102, and 3C 454.3) display low-frequency variations of a radically different character. In these sources, we see significant simultaneous variations at low frequencies (300–600 MHz), always diminished in amplitude at 880 and 1400 MHz. Thus, the existence of the IFG (Spangler and Cotton 1981) is confirmed. One of the most remarkable properties of the IFG is the strong diminution of variation amplitude as the frequency approaches 1 GHz from below. Theoretical models of synchrotron outbursts would necessarily involve steep-spectrum variable components or electron-energy cutoffs. It is also relevant that the low-frequency events in these sources appear to be simultaneous (often to within a few months or less), requiring that varying components not drift in frequency, as is often the case.

The obvious possibility that must be considered is that in sources displaying an IFG, two possibly independent variability mechanisms are operating. At centimeter wavelengths, evolving synchrotron components seem to provide the best explanation, which at least qualitatively accounts for the diminution of variability as the frequency approaches ~ 1 GHz from above. A physically distinct process may be responsible for the variations below 1 GHz. Some of the possibilities include compression, reheating, or isotropization of synchrotron-emitting material within a jet (Marscher 1982; O'Dell 1982; Aller and Aller 1982), ultrabright ($T_b \gg 10^{12}$ K) emission mechanisms (e.g., Cocke and Pacholczyk 1975; Cocke *et al.* 1978; Petschek *et al.* 1976), free-free absorption local to the source (Marscher 1979), and slow scintillation occurring in the interstellar medium of our Galaxy (Shapirovskaya 1978; Rickett *et al.* 1984). The last explanation predicts that low-frequency events ought to have characteristic bandwidths of about an octave (Rickett *et al.* 1984), and mean maximum amplitudes in the time-frequency domain roughly proportional to $\lambda^{1.2}$ to $\lambda^{2.2}$, depending upon intrinsic source structure. Hence, it appears that slow scintillation may be able to account for many of the observed properties (including spectral characteristics, amplitude, and time scale) of low-frequency variability in a straightforward manner. It also has some observational support in observed long-term pulsar intensity fluctuations (Sieber 1982). However, further more detailed observational tests of this and the other theories are required.

In some of the sources most active at high frequencies (e.g., AO 0235 + 16 and BL Lac), canonical variations appear to extend into the low-frequency regime ($\nu \lesssim 1$ GHz), albeit with diminished amplitude. Conceivably, an exclusively low-frequency variability mechanism (i.e., that responsible for low-frequency variability in most other sources) may also operate below 1 GHz, such that the total variability observed at these frequencies may be the result of both mechanisms.

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