THE ASTRONOMICAL JOURNAL VOLUME 86, NUMBER 6 JUNE 1981

VARIABILITY OF EXTRAGALACTIC SOURCES AT 2.7 GHz. IV. EVIDENCE FOR WEAK EXTENDED EMISSION AND FOR RAPID VARIABILITY

J. F. C. WARDLE
Brandeis University, Waltham, Massachusetts 02154

A. H. BRIDLE [a] AND M. J. L. KESTEVEN
Queen's University, Kingston, Ontario K7L 3N6, Canada
Received 7 July 1980; revised 17 February 1981

ABSTRACT

The results of two programs to monitor the λ 11.1-cm flux densities of extragalactic radio sources are compared. The programs were carried out between 1972 and 1974 on the NRAO 300-ft telescope and the NRAO three-element interferometer. The two sets of data are generally in excellent agreement. Fifteen sources show the presence of extended structure in the vicinity of the compact variable component, indicated both by the interferometer visibility functions and by systematic excesses of the pencil-beam flux densities over those measured by the interferometer. The composite flux density data show that four sources exhibit significant variability on time scales of less than 50 days. At this wavelength, such rapid fluctuations imply apparent brightness temperatures in the range 10^{14}–10^{16} K.

I. INTRODUCTION

We have previously published the results of extensive programs to monitor the flux densities of extragalactic radio sources at 2.695 GHz (λ 11.1 cm) (Kesteven, Bridle, and Brandie 1976; Altschuler and Wardle 1976). These programs were carried out contemporaneously but independently on the NRAO* 300-ft (91.4 m) telescope and three-element interferometer and have 61 sources in common (see Table I). Detailed comparison of their results allows us to assess the accuracy and reliability of the published flux densities and of the associated instruments. This assessment is important since (a) the claimed accuracy of both sets of measurements is high, (b) the classification of a source as "variable" depends critically on the estimated errors in a series of flux densities, and (c) sporadic rapid variations may be represented in the data by only a few "deviant" points whose reliability must be assessed. Such a cross-checking of two extensive variability monitoring programs has not hitherto been possible.

The observations by Kesteven *et al.* (1976, referred to henceforth as KBB) were made using the NRAO 300-ft transit telescope and three-feed system during eight sessions between September 1972 and August 1974. The adopted flux density scale is that of Kellermann *et al.* (1968) and the internal accuracy of a single measurement (usually the average of several scans, made on successive days) was estimated to be typically about 1%.

The observations by Altschuler and Wardle (1976, referred to henceforth as AW) were made using the NRAO three-element interferometer. The program started in 1971 and continued until September 1978. Fifteen sets of observations, made between June 1972 and October 1974, can be compared directly with the measurements by KBB. The adopted flux density scale was also nominally that of Kellermann *et al.* (1968). The accuracy of a single measurement (a single scan of about 10-min duration) was estimated conservatively from the internal scatter between the six independent correlators and from the system noise to be about 3.5%.

The two sets of published measurements are generally in excellent agreement. However, for some sources the flux densities observed at the interferometer are systematically low by a few percent. In Secs. II and III of this paper we isolate two phenomena which lead to small but systematic discrepancies between the two sets of flux densities: (1) the presence of low-level extended emission near some of the monitored sources (see Table II), and (2) a residual dependence of the gain of the interferometer on zenith angle resulting from the use of the Automatic Voltage Control (AVC) circuits in the interferometer electronics (see Fig. 1). In Sec. IV we assess the errors and variability criteria in KBB and AW after taking account of these effects, and in Sec. V we discuss the evidence for rapid variability of the sources that the two programs have in common.

II. EXTENDED EMISSION NEAR VARIABLE SOURCES

Several of the sources monitored during our programs are Seyfert galaxies; their variable components are known to be in the nuclei of galaxies which also have appreciable extended emission (e.g., NGC 1068, NGC 1275, 3C 120). In these cases we can expect the flux

[a] Present address: NRAO VLA Program, P.O. Box 0, Socorro, New Mexico 87801.

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

 0004-6256/81/060848-06$00.90

TABLE I. The 61 sources common to both monitoring programs. The variability assessment by AW refers only to the common period of observations, and may differ from that given in Altschuler and Wardle (1976). Sources marked with an asterisk are at low declinations, and a variability assessment was not made by KBB. Sources marked with a dagger exhibit the greatest range of variation in the data of KBB, and have $(S_{max} - S_{min})/[1/2(S_{max} + S_{min})] > 30\%$.

Source	Variability	
	AW	KBB
0048−097	Yes	Yes†
0106+013	Yes	Yes†
0133+476	Yes	Yes†
0235+164	Yes	Yes†
0316+413	Yes	Yes
0316+162	No	No
0333+321	No	Yes
0366−019	Yes	Yes†
0355+508	No	Yes
0420−014	No	No
0430+052	Yes	Yes
0440−003	No	Yes
0458−020	Yes	Yes
0500+019	No	No
0518+165	No	No
0552+398	No	Yes
0605−085	Yes	Yes
0607−157	Yes	*
0642+449	No	Yes
0723−008	Yes	Yes
0735+178	Yes	Yes
0736+017	No	No
0738+313	No	Yes
0814+425	Yes	Yes
0831+557	No	No
0851+202	Yes	Yes†
0859−140	No	*
0906+430	No	No
0923+392	No	No
0953+254	No	Yes
0954+556	No	No
1055+018	No	Yes
1116+128	No	No
1127−145	No	*
1148−001	No	No
1334−127	Yes	*
1345+125	No	No
1354+195	Yes	Yes
1354−152	Yes	*
1404+286	No	No
1442+101	No	Yes
1502+106	Yes	Yes
1510−089	Yes	Yes†
1548+056	Yes	Yes
1555+001	No	No
1611+343	No	No
1624+416	No	No
1641+399	No	Yes
1656+053	No	No
1730−130	No	*
1741−038	Yes	Yes†
1749+096	Yes	Yes
2037+511	No	Yes
2134+004	No	Yes
2145+067	No	Yes
2155−152	Yes	*
2200+420	Yes	Yes†
2216−038	No	Yes
2223−052	No	Yes
2230+114	No	Yes
2251+158	No	Yes

densities measured with the interferometer by AW to lie systematically below those measured at the 300-ft telescope by KBB. We also find that some of the other variable sources monitored during these programs show evidence for partial resolution by the interferometer. This indicates that their compact variable components are associated with low-level extended emission, or that the variable components are confused with nearby weak sources.

Over four years of observations, the interferometer was used by AW in many different configurations, with antenna separations ranging from 100 to 2700 m. (At λ 11.1 cm these correspond to lobe spacings of 4 arcmin to 9 arcsec, respectively.) We have searched the interferometer data for evidence of extended structure by plotting the fringe visibility as a function of baseline for each source. Because nearly all the sources were clearly variable, the fringe visibilities have been normalized to the amplitudes measured at either the 1800- or 1900-m spacing, which occurred in all but three of the configurations used by AW.

We have found that 18 sources show evidence of extended structure or confusion. These sources are listed in Table II, together with a description of their extended structure. Since all observations were made close to transit, the angular sizes listed are measured along a position angle of 65° (the azimuth of the NRAO interferometer in 28° S of west). For 1730−130 our data are in excellent agreement with the recent VLA observations by Perley *et al.* (1980)

TABLE II. Eighteen sources that show evidence for extended structure. The three sources marked with an asterisk have flat visibility functions, but show a constant offset between the sets of flux density measurements. We assume that the extended structure is completely resolved by the interferometer. For the remaining 15 sources the structure is determined from the interferometer measurements alone. The description of the structure is the simplest interpretation of the fringe visibilities.

Source	Flux density in extended structure (Jy)	Description of structure
0048−097	0.13 ± 0.02	Core-halo? halo diameter 9 arcsec
0106+013	0.10 ± 0.04	Visibility = 0.94 at 24 000λ
0316+413	0.85 ± 0.19	Core-halo? halo diameter 29 arcsec
0430+052	0.59 ± 0.04	Core-halo? halo diameter 11 arcsec
0518+165	0.21 ± 0.05*	Core-halo? halo diameter > 60 arcsec
0605−085	0.14 ± 0.04	Core-halo? halo diameter 11 arcsec
0723−008	0.14 ± 0.01	Double? separation 8 arcsec
0735+178	0.08 ± 0.02*	Core-halo? halo diameter > 60 arcsec
0906+430	0.24 ± 0.05	Visibility = 0.81 at 24 000λ
1055+018	0.14 ± 0.03	Core-halo? halo diameter 11 arcsec
1334−127	0.16 ± 0.02	Core-halo? halo diameter 8 arcsec
1345+125	0.16 ± 0.03*	Core-halo? halo diameter > 60 arcsec
1354+195	0.40 ± 0.02	Core-halo? halo diameter 14 arcsec
1641+399	0.27 ± 0.10	Core-halo? halo diameter 11 arcsec
1730−130	0.13 ± 0.05	Double? separation 6 arcsec
2155−152	0.11 ± 0.03	Visibility = 0.88 at 24 000λ
2216−038	0.08 ± 0.01	Double? separation 13 arcsec
2251+158	0.53 ± 0.11	Visibility = 0.94 at 24 000λ

In most cases, the fraction of the total flux in extended structure is only a few percent, and is visible only after summing the data from many observing sessions. The flux densities measured by the interferometer for these sources will be systematically lower than those obtained at the 300-ft telescope, which has a 4.7-arcmin pencil beam at λ 11.1 cm. The errors quoted by AW contained a contribution from the scatter between the three baselines used for each observation, so the variability assessments are not affected significantly by this partial resolution.

The partial resolution found from the interferometric measurements alone is generally confirmed by reference to the flux densities measured at the 300-ft telescope. The two exceptions are 0106+013 and 0605−085. However, the direct comparison of the two sets of flux densities for these sources may be misleading since both vary rather rapidly.

III. THE GAIN–ZENITH ANGLE CORRECTION FOR THE INTERFEROMETER

It was noted in AW that a small residual error was present in the data owing to the dependence of the interferometer gain on zenith angle. This was not removed since (a) the effect was small and not well determined, and (b) the observations of each source were always made at the same zenith angle (close to meridian transit) so that the effect was constant for any particular source and did not affect the variability assessment.

Figure 1 shows the ratios of the flux densities measured with the 300-ft telescope to those measured with the interferometer, plotted as a function of zenith angle. For sources judged to be nonvariable in both data sets, the averages of all the data are used, and are plotted as closed circles. For variable sources, we compare interferometer data taken on 6 February 1974 with data obtained at the 300-ft telescope between 1 and 6 February 1974; these ratios are plotted as open circles. For both classes of sources, the interferometer data have been corrected for partial resolution according to the analysis of the visibility function described in Sec. II.

Figure 1 shows that there is a systematic variation of the gain of the interferometer with zenith angle, relative to that of the 300-ft telescope, with a range of about 6%. This variation can be attributed to the change of the interferometer's system noise temperature with zenith angle. At small zenith angles, ground radiation enters directly into the feeds, since the dishes are somewhat overilluminated. At large zenith angles, ground radiation enters the side lobes. The increase in system noise temperature depresses the gain of the interferometer because of AVC circuits in front of the IF amplifiers (Coe 1973).

In what follows, we have corrected all interferometer measurements for the zenith angle effect using the mean curve drawn through the data in Fig. 1.

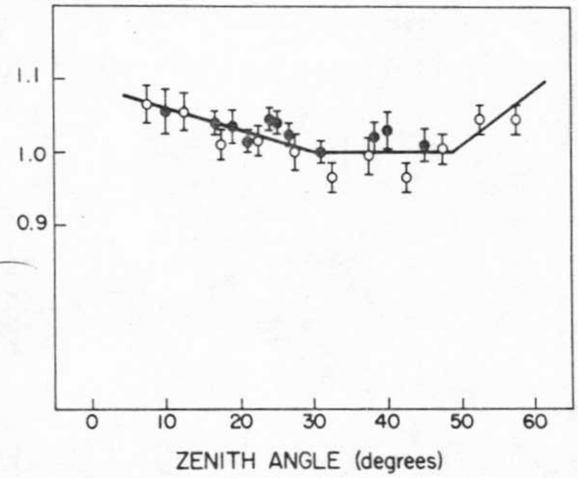

FIG. 1. The gain–zenith angle curve for the interferometer. R is the ratio of the flux densities measured with the 300-ft telescope to those measured with the interferometer. The interferometer data have been corrected for resolution effects (see Table II). Closed circles represent sources judged to be nonvariable in both data sets, and averages of all the data are used. Sources observed at the same zenith angle have been averaged together. Open circles represent the variable sources, and compare only data taken between 1–6 February 1974 at the 300-ft telescope with data taken on 6 February 1974 with the interferometer. The variable sources have been averaged together in 5° intervals in zenith angle.

IV. DETAILED COMPARISON OF THE DATA SETS

a) The Relative Accuracy of the Interferometer Data

The mutual consistency of the interferometer and 300-ft measurements can be estimated from Fig. 2, in which we compare the interferometer data taken on 6 February 1974, with the 300-ft data taken between 1 and 6 February 1974. The interferometer data have been corrected for partial resolution and for the zenith angle effect as described in Secs. II and III. It should be noted that, although the corrections to the interferometer data reduce the scatter about the mean line, these corrections are significant only for the few sources that are resolved or at extreme zenith angles. For most sources, the corrections to be applied to the published data of AW are negligible.

The rms scatter about the unit line in Fig. 2 is 3.4%. We note, however, that many of the most discrepant points are for sources that show the largest range of variation (marked with daggers in Table I, and closed circles in Fig. 2). The rms scatter of these sources alone is 5.5%, while the rms scatter of the remainder is only 2.6%. Using Fisher's F test, the probability that this is due to chance is less than 0.001. Although no one source shows a significant discrepancy between the measurements made with the two instruments, we suggest that *as a class*, the sources marked with daggers in Table I exhibit detectable variations with an amplitude of a few percent on a time scale of less than six days (see also Sec. V).

As noted above, the rms scatter about the unit line of the less variable sources is 2.6%. It therefore seems rea-

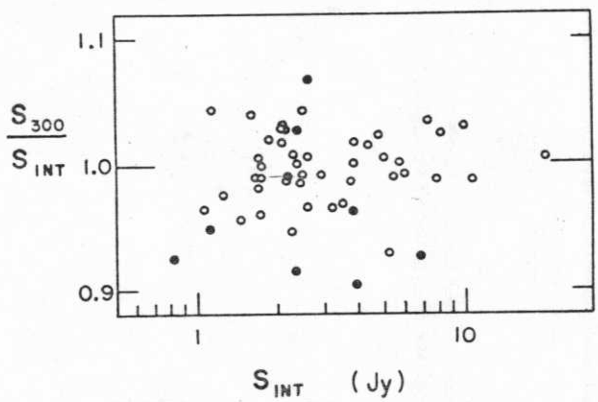

FIG. 2. Direct comparison of the interferometer and 300-ft measurements, made in February 1974. The interferometer flux densities are corrected for resolution and for the gain–zenith angle effect. Closed circles represent the sources (marked with a dagger in Table I) that exhibit the largest total range of variations.

sonable to assess the overall accuracy of the corrected interferometer data at about 2.5% (comfortably within the 3.5% claimed in AW).

b) The Variability Criteria of KBB and AW

Slightly different variability criteria were used by KBB and AW, and it is of interest to compare these.

Given a set of flux densities S_i, each with an estimated standard error σ_i, KBB computed the statistic

$$x^2 = \sum_{i=1}^{n} (S_i - \langle S \rangle)^2/\sigma_i^2,$$

where $\langle S \rangle$ is the weighted mean flux density measured over the n observing periods. For a Gaussian distribution of errors, x^2 is distributed like χ^2. A source was classified as definitely variable by KBB if the probability of exceeding x^2 by chance was less than 0.001, after discarding the single most discrepant measurement.

The variability "INDEX" of AW was defined as

$$\text{INDEX} = \frac{-1}{n} \sum_{i=1} \log\left[1 - (2/\pi)^{1/2} \times \int_0^{(S_i - \langle S \rangle)/\sigma_i} \exp(-t^2/2)dt\right].$$

This is similar to calculating a mean value of χ^2 for the observations. AW classified a source as variable if INDEX$\geqslant$1.0, which corresponds to a mean value of χ^2 of 2.7. The probability of this being exceeded by chance (with $\sim$24 observations per source) is $\leqslant$0.001, so AW's criterion is more conservative. The criterion used by KBB is computationally simpler, and also takes proper account of the total number of observations.

The assessments of variability are compared in Table I. Twenty sources are classified as variable in both the interferometer and 300-ft data sets, and 17 are classified as nonvariable in both data sets. A further 17 sources appear variable in the 300-ft data but not in that from the interferometer. This is understandable in view of the greater sensitivity of the measurements made with the 300-ft telescope. Most important, *no* source was classified as variable from the interferometer data by AW but nonvariable from the 300-ft data by KBB. The two published variability assessments are therefore in excellent agreement.

c) Sample Flux Density Plots

Figures 3 and 4 show selected flux density plots from the combined data. The interferometer measurements have been corrected for resolution and for the gain–zenith angle effect. The sources whose flux densities are plotted in Fig. 3 show little evidence for short-term (<50 days) variability, but those plotted in Fig. 4 show some evidence for short-term variations (see Sec. V).

V. SHORT-TERM VARIABILITY OF THE SOURCES

The minimum time scales for variability in extragalactic radio sources are of interest to models of their activity, since they provide constraints on the linear sizes and brightness temperatures of the active regions. In Sec. IV a, we presented evidence that some sources may vary by a few percent in less than six days, based on the direct comparison of flux densities measured almost simultaneously on the the two instruments. We have also searched all of the composite flux density plots constructed from the combined 300-ft and corrected interferometer data for further evidence of short-term variability by comparing *all* pairs of flux density measurements separated by time intervals within a given set of windows that range from 50 to 450 days. Specifically, we constructed the quantity

$$T(n) = N_n^{-1} \sum_{i>j} |S_i - S_j|/(\sigma_i^2 + \sigma_j^2)^{1/2}.$$

S_i is the flux density measured at time t_i; S_j at time t_j; and σ_i, σ_j are their associated errors. The data S_i, S_j are separated by a time interval $50(n-1) < |t_i - t_j| \leqslant 50n$ days, $n = 1$ to 9; and N_n is the number of pairs of data falling in the nth time interval. Sources with significant short-term variability exhibit enhanced values of T at low values of n, while long-term variables have values of T which tend to increase monotonically with n until $50n$ days exceed the typical time scale of their outbursts. An example of each type of behavior is shown in Fig. 5.

In the absence of variability, the quantity $|S_i - S_j|/(\sigma_i^2 + \sigma_j^2)^{1/2}$ is distributed as a one-sided unit Gaussian. If N_n is large, we can apply the central limit theorem, and the probability distribution of $T(n)$ tends towards a Gaussian with a mean of $(2/\pi)^{1/2}$ and a variance of

$$\frac{(1 - 2/\pi)}{N_n}.$$

We find six sources for which $T(1)$ is larger than $(2/\pi)^{1/2}$ by more than three standard deviations. These are 0048−097, 0235+164, 0336−019, 0851+202, 1510−089, and 2200+420. In the cases of 0235+164 and 1510−089, the major contribution to $T(1)$ appears to be the gradient of longer-term large-amplitude fluctuations (see Fig. 3). However, we suggest that the four

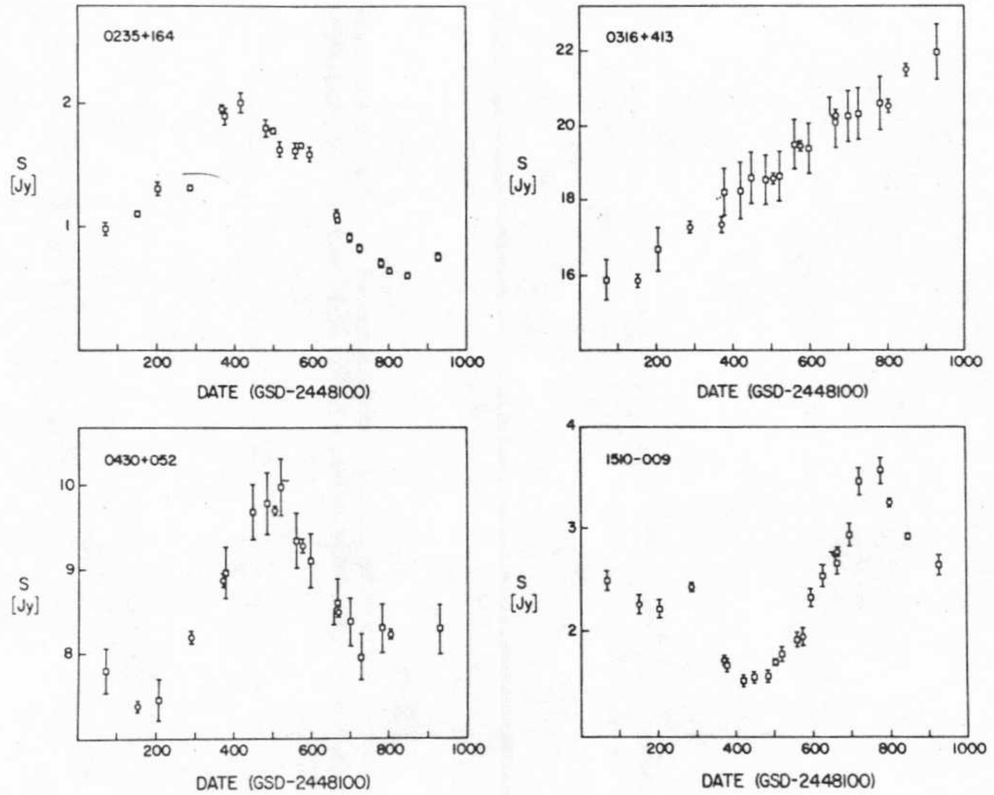

FIG. 3. Composite flux density plots for four sources that show little evidence for short-term variability. Open circles represent data taken at the 300-ft telescope. Squares represent data taken at the interferometer, and have been corrected for resolution and for the gain–zenith angle effect.

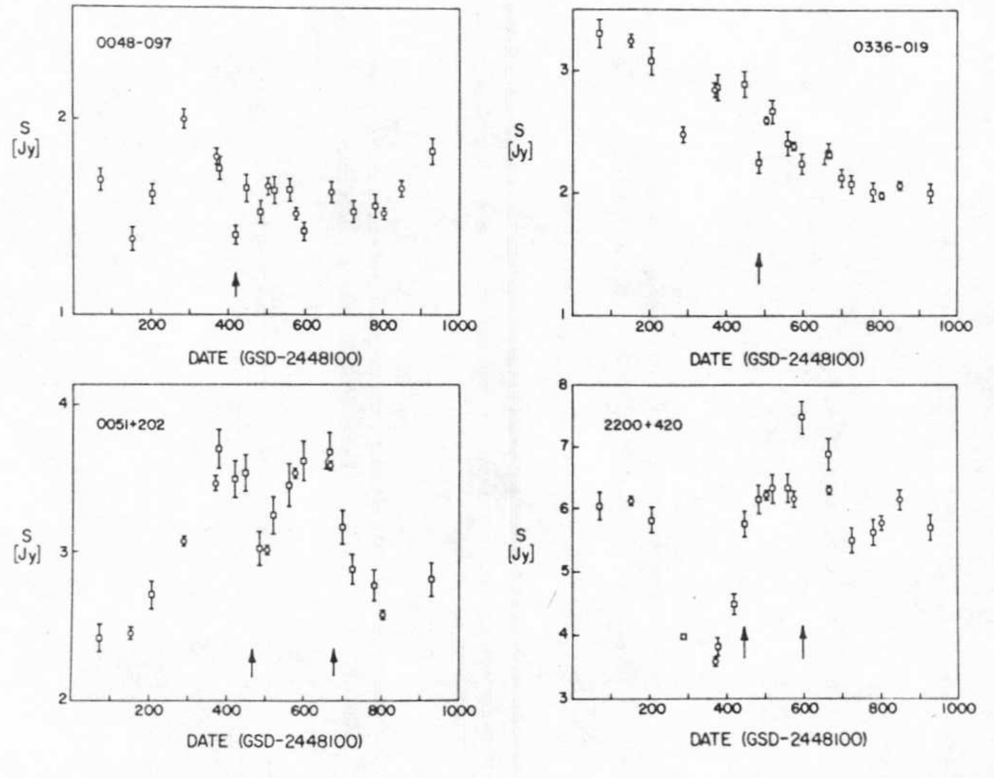

FIG. 4. Composite flux density plots for the four sources that show evidence of variability on a time scale of ⩽50 days. The symbols are as in Fig. 3. Major contributions to the statistic $T(1)$ (see Sec. V) are indicated with arrows along the abscissa.

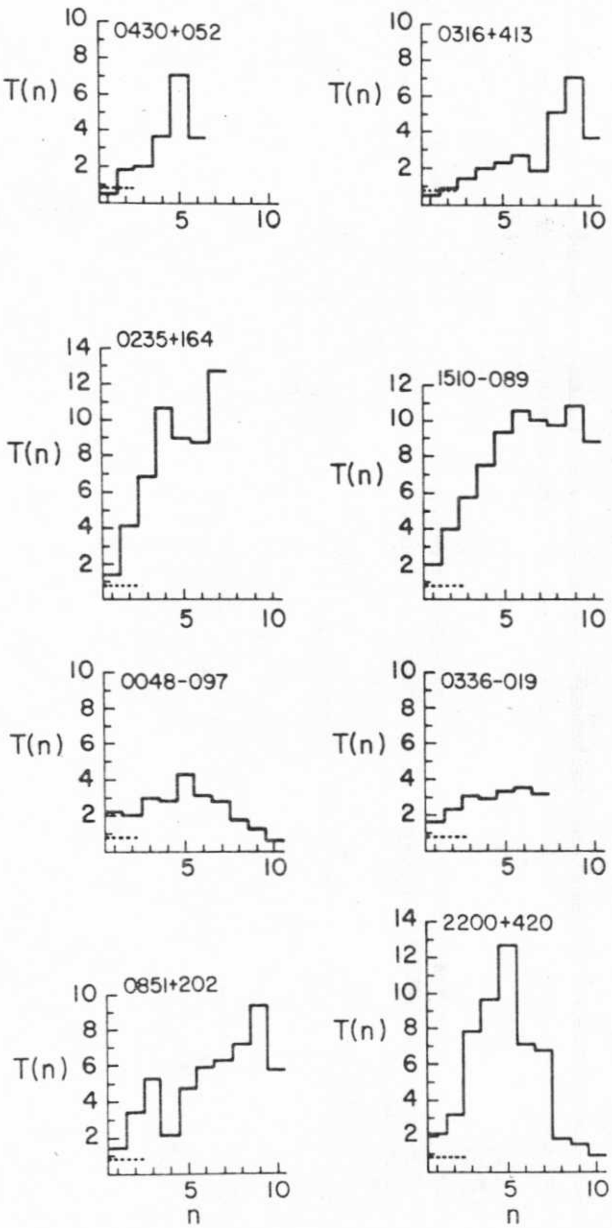

FIG. 5. Plots of $T(n)$ for eight sources, illustrating the behavior described in the text. The dotted line gives the expectation value of $T(n)$ in the absence of variability.

other sources exhibit significant variability on a time scale of $\leqslant 50$ days. Flux density plots for these sources are shown in Fig. 4, where the largest contributions to $T(1)$ are indicated with arrows.

Rapid variations imply small linear sizes for the parts of the source that are varying, and therefore high brightness temperatures. Ignoring relativistic effects, the radius of the varying region is $r \leqslant c\tau(1+z)^{-1}$, where z is the redshift, and $\tau \equiv (d \ln S/dt)^{-1}$. The apparent brightness temperature is given by

$$T \geqslant \lambda^2 SD^2/2k\pi c^2\tau^2(1+z)^2,$$

where D is the luminosity distance. Assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$, then at λ 11.1 cm,

$$T \geqslant 2.3 \times 10^{20}\ S\tau^{-2}z^2(1+z/2)^2(1+z)^{-2}K,$$

where S is in Janskys and τ is in days. We have estimated the apparent brightness temperature for each of the events marked with arrows in Fig. 4. In all cases T lies in the range 10^{14}–5×10^{15} K. This is considerably in excess of the well-known limit of $\sim 10^{12}$ K for a stationary source radiating incoherent synchrotron radiation, but is similar to the apparent brightness temperatures inferred for the "low-frequency" variable sources (Hunstead 1972; Condon *et al.* 1979). A detailed discussion of the problem of high apparent brightness temperatures is given by Burbidge *et al.* (1974), and is beyond the scope of this paper.

The credibility of the evidence presented here is critically dependent on the validity of individual data points and their errors, so it is difficult to confirm the reality of these short-term variations in any individual case. We suggest, however, that the sources marked with a dagger in Table I, and especially those whose flux density plots are shown in Fig. 4, are good candidates for inclusion in future program aimed at detecting rapid variability in extragalactic radio sources.

This research was supported by grants to J.F.C.W. from the National Science Foundation, and to A.H.B. and M.J.L.K. from the National Research Council of Canada (latterly NSERC). Portions of this work were carried out at the Erin Institute of Astrophysics, which is supported by the Canadian Astronomical Society.

REFERENCES

Altschuler, D. R., and Wardle, J. F. C. (1976). Mem. R. Astron. Soc. **82**, 1 (AW).

Burbidge, G. R., Jones, T. W., and O'Dell, S. L. (1974). Astrophys. J. **193**, 43.

Coe, J. (1973). Proc. IEEE **61**, 1335.

Condon, J. J., Ledden, J. E., O'Dell, S. L., and Dennison, B. (1979). Astron. J. **84**, 1.

Hunstead, R. W. (1972). Astrophys. Lett. **12**, 193.

Kellermann, K. I., Pauliny-Toth, I. K. K., and Tyler, W. C. (1968). Astron. J. **73**, 298.

Kesteven, M. J. L., Bridle, A. H., and Brandie, G. W. (1976). Astron. J. **81**, 919 (KBB).

Perley, R. A., Fomalont, E. B., and Johnston, K. J. (1980). Astron. J. **85**, 649.