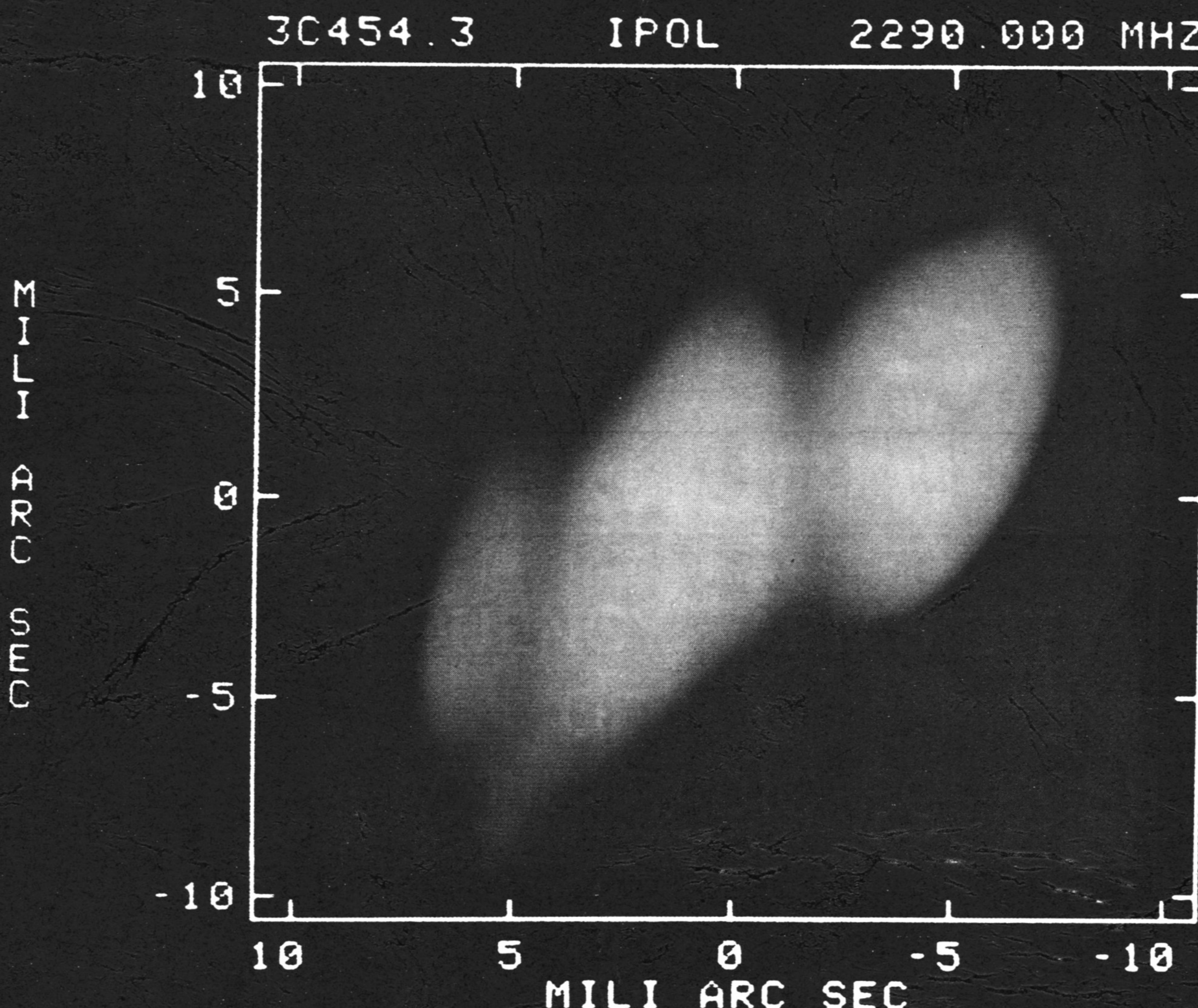
LOW FREQUENCY VARIABILITY OF EXTRAGALACTIC RADIO SOURCES

Proceedings of a Workshop held at the National Radio Astronomy Observatory Green Bank, West Virginia April 21-22, 1982



Edited by W. D. Cotton and S. R. Spangler

Proceedings of the
National Radio Astronomy Observatory*
Workshop on

Low Frequency Variability of Extragalactic Radio Sources

Held in Green Bank, West Virginia
April 21 – 22 1982

Edited by William D. Cotton and Steven R. Spangler

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From ghoulieſ and ghoſtieſ and long leggedy beaſtieſ and thingſ that go bump in the night, good Lord deliver uſ.

Old Scottish prayer

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CONTRIBUTIONS

EDITORS' COMMENTS

This volume comprises the proceedings of the NRAO workshop on "Low Frequency Variability of Extragalactic Radio Sources", held at Green Bank on April 21-22, 1982. Appropriately, the conference occurred ten years after the appearance of the paper, "Four Variable Radio Sources at 408 MHz", by R.W. Hunstead (*Astrophysical Letters*, **12**, p. 193, 1972). This paper is generally considered to have established the existence of significant variability of extragalactic radio sources at frequencies below 1000 MHz.

The subsequent ten years have seen the development of a modest literature on the subject, consisting of both theoretical and observational works. However, it is probably fair to say that we have not yet arrived at a generally-accepted observational description of the phenomenon, let alone an understanding of the astrophysical mechanisms at work. Our goal in organizing this workshop was to provide an opportunity for the workers in this field to get together, communicate recent observational results, and discuss the merits of theoretical ideas. The contributions to this workshop address a large number of topics related to Low Frequency Variability, and should provide a valuable resource for researchers in this field.

We are grateful to the participants in this workshop for making it such a valuable scientific meeting. We especially thank Professor T. W. Jones of the University of Minnesota for his fine summary of the workshop. We appreciate the excellent support of the NRAO personnel at Green Bank, especially Bob Moore, Becky Warner, Wally Oref, and Jane Chestnut.

W.D. Cotton S.R. Spangler

Charlottesville, Virginia
August 10, 1982

National Radio Astronomy Observatory

Workshop on

LOW FREQUENCY VARIABILITY OF EXTRAGALACTIC RADIO SOURCES

April 21-22, 1982

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List of Participants

Participant	Institution
Hugh Aller	University of Michigan
Margo Aller	University of Michigan
Norbert Bartel	Massachusetts Inst. Technology
Frank Briggs	University of Pittsburgh
John Broderick	Virginia Polytechnic Institute
Wayne Christiansen	University of North Carolina
James Condon	NRAO
James Cordes	Cornell University
William Cotton	NRAO
Brian Dennison	Virginia Polytechnic Institute
William Erickson	University of Maryland
David Garrett	University of Texas
Barry Geldzahler	Naval Research Laboratory
Edsko Hummel	University of New Mexico
Thomas Jones	University of Minnesota
Kenneth Kellermann	NRAO
Robert Leacock	University of Florida
Alan Marscher	Boston University
Bruce McAdam	University of Sydney
Kenneth Mitchell	NRAO/Penn State University
Richard Moore	California Inst. Technology
Chris O'Dea	NRAO/University of Massachusetts
Stephen O'Dell	Virginia Polytechnic Institute
Andre Pacholczyk	University of Arizona
Lucia Padrielli	University of Bologna
Harry Payne	NRAO
Jon Romney	Max Planck Inst. fur Radioastronomie
Richard Simon	California Inst. Technology
Alex Smith	University of Florida
Steven Spangler	NRAO
Kurt Weiler	National Science Foundation

RESULTS FROM THE BOLOGNA 408 MHz MONITORING PROGRAM

L. Padrielli
Istituto di Radioastronomia, Bologna, Italy

Abstract

A 5 years monitoring program with the East-West arm of the Bologna Radiotelescope at 408 MHz allowed us to derive statistical results on the low frequency variability (L.F.V.) phenomenon. Generally the pattern of the variations is very complex and only in a minority of cases the light curve can be described in terms of outbursts over a relatively stable flux level. In the majority of the sources the light curve is a sequence of maxima and minima and it is very difficult to establish the level of a possible underlying stable component.

Typical time-intervals from a relative maximum to a minimum, range from a few months to a few years. The derived time scales of variability, with the most conservative definition usually adopted, have a mean value of about 2-3 years.

Using an homogeneus sample of flat spectrum sources, the occurrence of L.F.V. has been examined. The phenomenon is very common in samples of flat spectrum sources, (30-50)% of which show fractional changes DS/S greater than 5-10%.

1) Description of the Bologna sample

The Bologna monitoring program started in May 1975. It consists of monthly observations, carried on at 408 MHz using the EW arm of the Northern Cross. The initial observing program included a sample of 50 radiosources (known or suspected L.F. variables) and known variables at high frequency. In 1977 we increased the sample adding a) a homogeneus sample of 45 flat spectrum sources, b) an homogeneous sample of 32 compact radiosources selected from scintillation studies and c)19 sources for which L.F.V. was found or suggested by Cotton (1976 a,b).The total number of sources observed until 1980 was about 100.

Details of the observing procedure and a tabulation of the flux density measures are given in Fanti et al (1980). Now the program continues in collaboration with the University of Michigan observing about 50 sources, well established or probable L. F. variables.

2) The general behaviour of the variability

The general pattern of variability is very complex and it is almost impossible to give a simple description of the light curve.

Only in a minority of cases the light curves can be described as one positive outburst or as a sequence of positive outbursts, lasting for a few months or a few years; in a few other cases the outbursts are partially overlapping, but they can be still recognizable, as also the underlying component.

In the largest majority of the sources, however the variations show more complex behaviour with a succession of maxima and minima in the light curve so that it is not easy to fully recognize neither the individual outburst nor the level of the underlying component. These light curves can be described equally well when seen upside down, and this means that an alternative description can be that of "dips" or "negative outbursts".

Mc Adam first drew attention to this interpretation, based on unpublished data on PKS 0736+017 .This source however after the deep minimum of 1975 shows in 1979 and 1981 evidence of positive flux variations, making therefore the situation very complex.

In our data the only source that,perhaps can be better described in terms of "negative outburst" is 3C 345 (1641+39),while the best example of positive outburst is 1524-13, where superimposed to a slow change in flux lasting about two years a very fast flash was luckily observed with rising time and decreasing time of about one month.

In fig 1 examples of light curves are shown.

Even highly variables sources have sometimes long periods of stable flux level lasting from few to several years. This is the case of 3C454.3 during 1973-74 and CTA 102 since 1967. While CTA 102 is at a minimum in the quiescent period, 3C454.3 shows a quasi stable level definitely higher than the well defined minima observed in 1970 and 1977 (see figure 2).

3) Time scale of variability

The definition generally adopted for the time scale of the variability is dependent on the assumptions one makes about the variation itself.Two extreme cases can be considered.
1) the variation is due to a transient component on top of a stable level, with a maximum flux equal to DS. In this case the time scale is the time interval between the maximum and adiacent minimum Dt.
2) No stable underlying component exists. At any instant the observed flux is a superimposition of many bursts and the observed maxima are just the top of the iceberg. In this case the time scale is defined as (Smax/DS)Dt.

The first assumption leads to shorter time scales. We assume the second one which is more conservative.

The figure 3 shows the time scale distribution for well defined outbursts. The median value is around 2 years. The distribution is similar to that observed at cm. wavelengths.

This distribution has to be viewed with some caution. The relative scarcity of sources with time scales greater than 6 years may be due to our observatinal selection. But even adding the observations of the two last years, this part of the distribution does not change. Furthermore we can miss time scales of the order of few months because of our sampling time.

If the variability is intrinsic to the source on the basis of "causality arguments" we can derive linear radius, angular sizes and then brightness temperatures of the varying component.

With the conservative value of q0 =1 and H=100 (Km s-1 Mpc-1) the obtained brightness temperature range from 10^{14} to 10^{15} K with a tail of values extending to 10^{16} K (fig 4). These values exceed by 1 to 3 order of magnitudes the 10^{12} limit for incoherent sinchrotron radiation (see figure 4).

4) Occurence of L.F.V. in representative samples of flat and steep spectrum sources

Using homogeneus subsample of flat and steep spectrum sources we can derive the frequency of occurrence of L.F.V. in samples of sources with flat and steep spectrum.

The distinction between the two classes is made on the basis of the spectral index around 400 MHz . Out of 44 flat spectrum (α <0.4) 16 are found V and 7 possibly V. Out of 16 steep spectrum sources only 1 possible variable was found.

In fig. 5 we show the comulative probability disribution of occurence of fractional L.F.V. greater than DS/S for flat spectrum sources. The phenomenon appears very common in flat spectrum sources 50% of which shows a fractional flux density changes greater than 5%.

In order to search for a possible correlation between probability of L.F.V. and spectral class we have used all the sources of our list with the following spectral classification. If the spectral index is "flat" in all the frequency range, the source is classified as flat straight (FS). Flat spectrum sources that show a steepening at frequencies higher than 400 MHz, reaching a value of the spectral index steeper than 0.4 above 1 GHz, are called FC-. The sources with a further flattening at higher frequencies are classified FC+. Among sources with steep spectrum ($\alpha_{408} > 0.4$), we classify steep straight (SS) the sources with a spectrum straight in the all frequency range or with a further steepening at higher frequency; SC- the sources showing a flattening ($\alpha < 0.4$) at lower frequency (< 400 MHz); and SC+ the sources with a significant flattening at higher frequency.

In table 1, we give the percentages of variables for the different spectral classes. We expect in this table a higher percentage of variables because the complete list contains about half sources selected on the basis of variability. But no selection was made on the basis of spectral morphology and therefore we can compare the percentages of the different classes.

Concluding the sources with a radio spectral index flat in a very large range of frequency from .4 to 10 GHz have the highest probability to show L.F.V. Furthermore, the sources with flat spectrum only near the frequency at which the variability is seen, also have a high probability, although smaller than the previous one. A small percentage of L.F. variables with steep spectrum certainly exists, but no significant differences between the subclasses can be seen because of the poor statistic.

Table 1

	V	P	not V	% of L.F.V.
FS	16	5	7	57 - 75
FC-	8	6	20	24 - 41
FC+	4		3	- 58
SS	2	3	27	7 - 18
SC-			19	- 6
SC+		1	0	-

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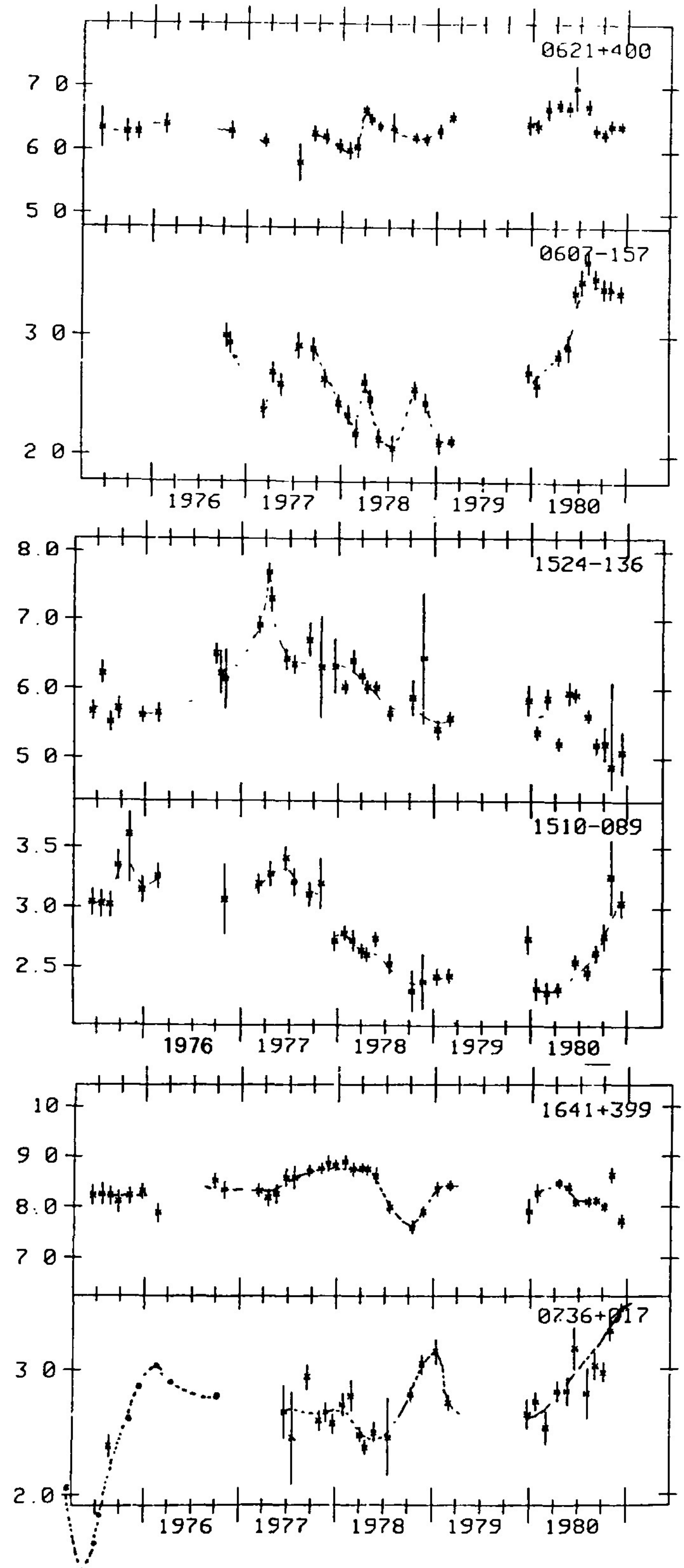


Fig. 1 Flux density at 408 MHz vs. time.

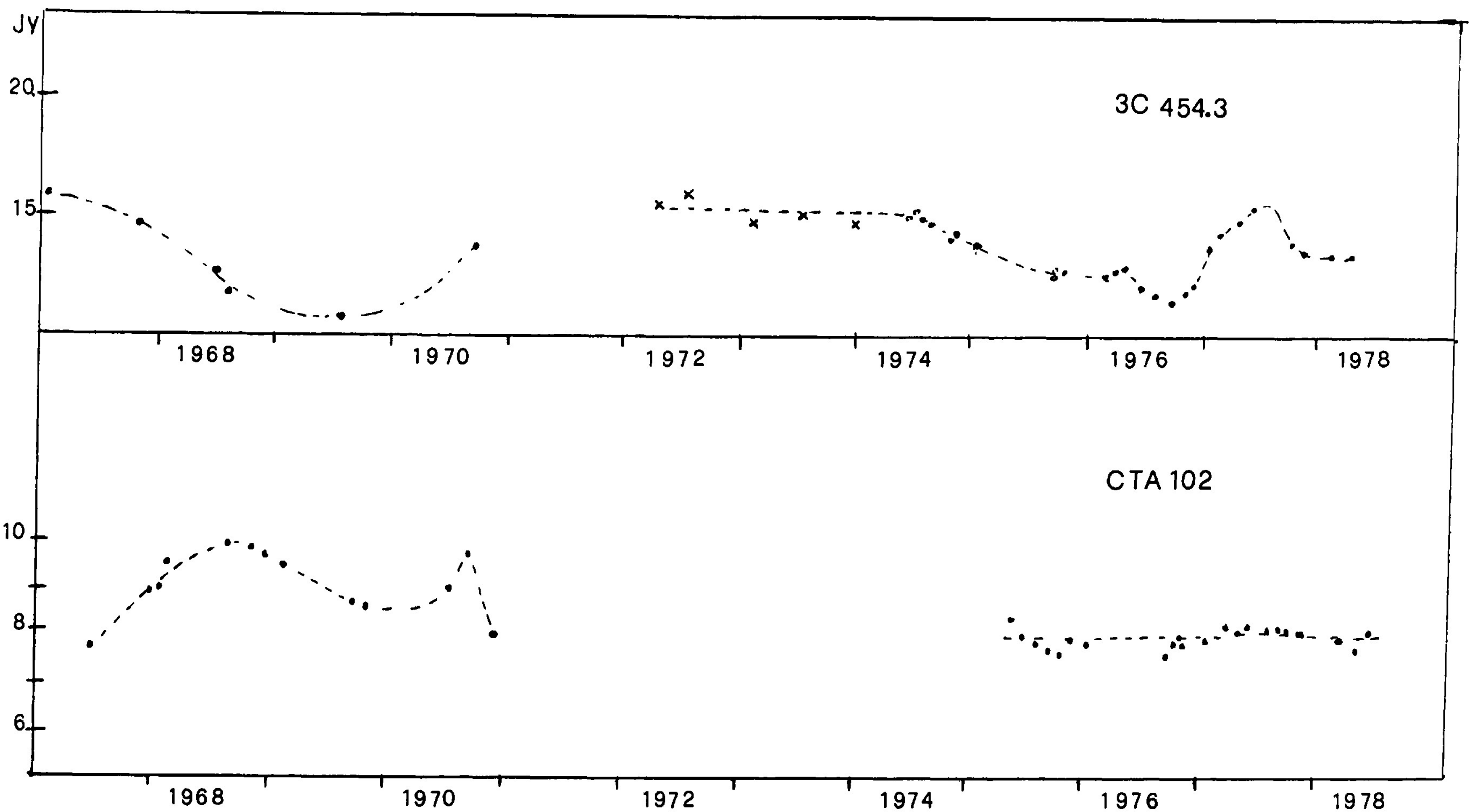


Fig. 2 Observatins at 408 MHz of the sources 3C 454.3 and CTA 102.

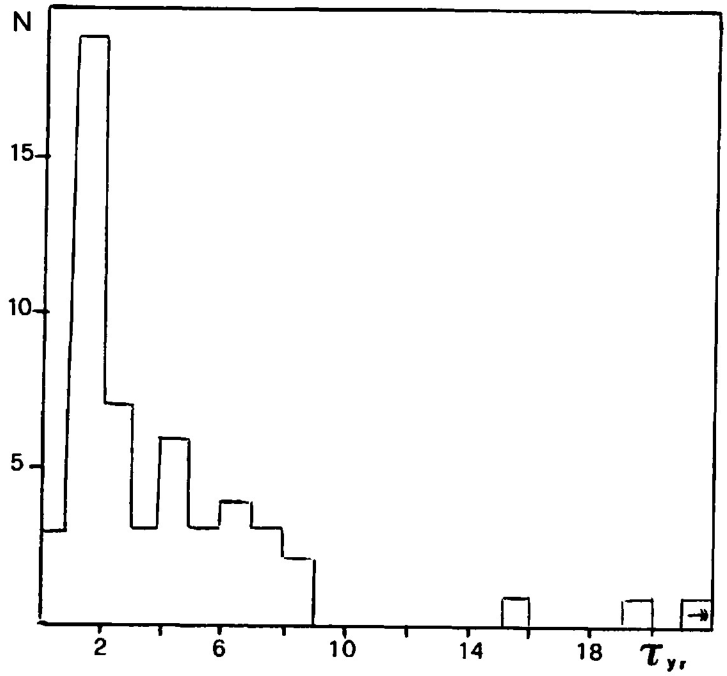


Fig. 3

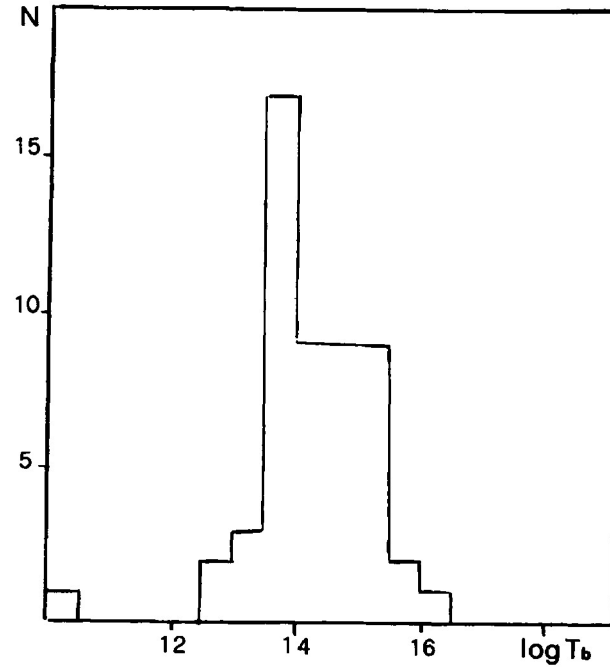


Fig. 4

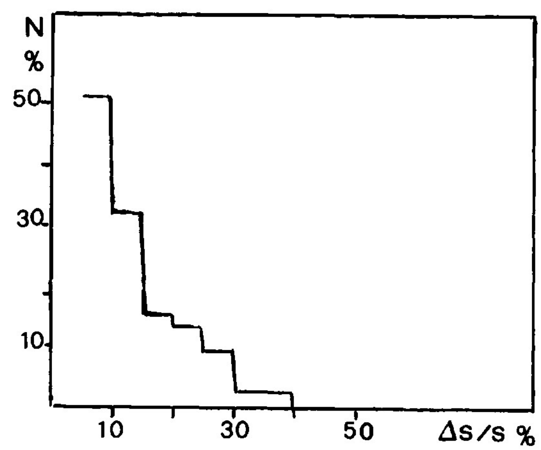


Fig. 5

Fig. 3 Time scale distribution for well defined outbursts of the sources observed in the period 1975-1980.

Fig. 4 Brightess temperature distribution derived from the time scale variability.

Fig. 5 Probability of accurence of fractional variability greater than DS/S for the flat spectrum sources.

PRELIMINARY RESULTS FROM A 0.3 - 1.4 GHz MONITORING PROGRAM

H. E. Payne,[*,†] D. R. Altschuler,[**] J. J. Broderick*,
J. J. Condon,[†] B. Dennison,[*] and S. L. O'Dell*

I. INTRODUCTION

The VPI monitoring program is designed to discern the spectral character of low-frequency variations in order to provide constraints and/or input for theoretical models. Toward this end we are monitoring about 30 low-frequency variables found in complete samples (Condon et al. 1979; Dennison et al. 1981). The frequencies covered are 318, 430, and 606 MHz (Arecibo), and 880 and 1400 MHz (91-m, NRAO). We have now accumulated about ~2 years of data. In this paper we present preliminary light curves of some sources which have undergone significant variations during this interval.

II. OBSERVATIONS

Observations at 430, 880 and 1400 MHz are carried out at eight-week intervals, and those at 318 and 606 at 16-week intervals (as required by major feed changes at Arecibo). This timetable allows us to resolve at all 5 frequencies major events such as those already observed in CTA 102 (Hunstead 1972), 3C 454.3 (Hunstead 1972; Condon et al. 1979; Fanti et al. 1979; Spangler and Cotton 1981), and DA 406 (Cotton and Spangler 1979). More rapid variations, such as that seen in 1524-136 (Fanti et al. 1979), cannot be resolved by us, and are better left to monitoring programs employing more frequent observations with a dedicated instrument (i.e. the Bologna program).

Each Arecibo session consists of drift-scan measurements at 430 MHz and at either 318 or 606 MHz (depending upon which feed and receiver

* Physics Department, Virginia Polytechnic Institute and State University

† National Radio Astronomy Observatory

** Physics Department, University of Puerto Rico, Rio Piedras

system is up). There is alternation between 318 and 606 MHz from session to session. A noise tube is fired at the beginning of each scan for calibration purposes. All drift scans are repeated at identical telescope angles (azimuth and zenith) to insure that the antenna gain and confusion are reproducible from run to run. Gain stability is achieved using transistor front ends at 318 and 430 MHz, and a noise adding radiometer at 606 MHz (Yerbury 1975).

The 91-m observations consist of drift scans with a noise tube fired at 30 second intervals. The receivers were PAR amps, until about 1982.0 when we switched to more stable, low-noise GaS FET amplifiers. Two orthogonal polarization channels are recorded simultaneously, and are averaged together after calibration.

Solar interference is occasionally a problem, especially with the 91-m telescope. It is necessary to inspect all of the data, and discard scans severely affected by solar or terrestrial interference.

A set of standard steep-spectrum sources which do not yield fringes on the Arecibo-Green Bank baseline at 430 MHz (Broderick and Condon 1975) are used for calibration at all five frequencies. For the purpose of assessing the repeatability this monitoring, we included the steep-spectrum source 0038+32 (3C 19) as a program source. Since it lacks VLBI fringes at 430 MHz (Broderick and Condon 1975) it is nonvariable. The low-frequency flux density of this source is quite comparable to that of the variable program sources. As shown in Table 1 we have achieved a level of repeatability of a few percent at all five frequencies.

TABLE 1

RMS DEVIATIONS OF 0038+32

Frequency (MHz)	RMS (%)
318	0.9
430	2.7
606	2.7
880	2.0
1400	2.3

III. PRELIMINARY RESULTS

In Figures 1-6 we present preliminary light curves of some interesting sources in our program. The error bars as shown are probably overestimates of the actual errors. Additional minor revisions in these light curves may be required through further data analysis. In what follows we comment on the sources individually.

3C 454.3 (2251+15). A major outburst peaked during early 1981. The maximum was approximately simultaneous at the three lowest frequencies. At 880 MHz the outburst is marginally detected, and at 1400 MHz it cannot be detected. Spangler and Cotton (1982) observed an essentially nonvarying flux at 1400 MHz, in agreement with our results. At higher frequencies (15-90 GHz) they observed an outburst which peaked just after the flux density declined at low frequencies. No exceptional variations in the optical flux occurred during this period (Smith 1982).

CTA 102 (2230+11). Some minor activity was observed at the lowest frequencies, apparently fading with increasing frequency. At 880 and 1400 MHz variations were not detected. Again Spangler and Cotton (1982) found the source to be quiescent at 1400 MHz. No clear correlation exists between the variations in the range 318-606 MHz, and those observed by Spangler and Cotton at 4.9 GHz and above.

NRAO 140 (0333+32). A brief event was recorded at 430 MHz around 1981.5, with only a relatively weaker, broader maximum occurring simultaneously at 606 MHz. Apparently this fast event was quite narrow band in its spectral properties. (Conceivably it may have been missed between observation sessions at 606 or 318 MHz. To have missed it at 606 MHz, however, would require a time delay between that frequency and 430 MHz.) A gradual increase is apparent at 606, 880 and 1400 MHz.

PKS 1117+14. A brief intense outburst occurred during 1981, having the following remarkable properties: The amplitude was greatest at 318 MHz and diminished with increasing frequency. At 1400 MHz, any variation was marginally detectable. The timescale was shortest at 318 MHz (~ 6 months) and increased to about a year at 606 MHz.

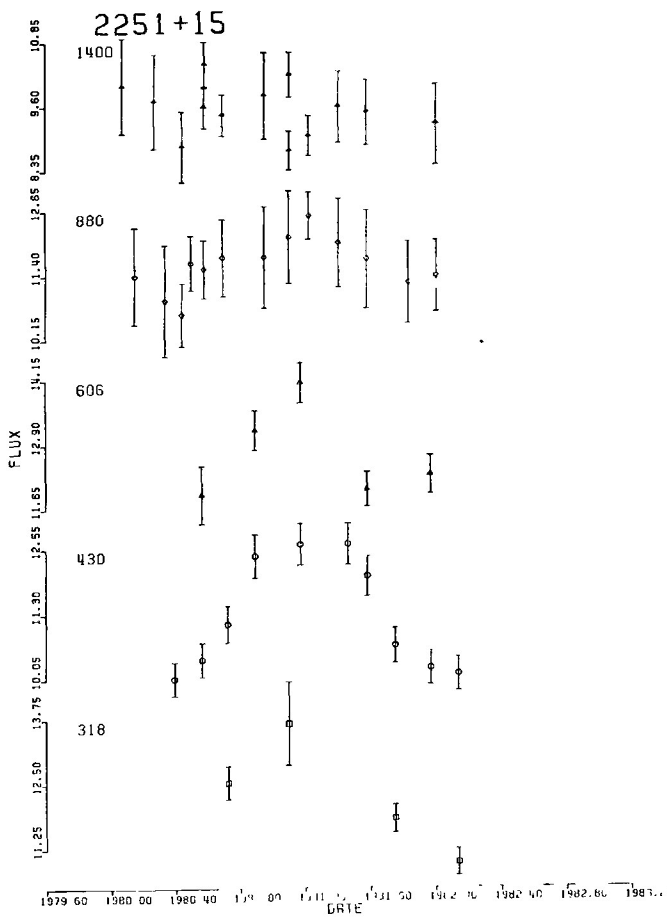


Fig. 1. **Preliminary light curves of 3C 454.3.**

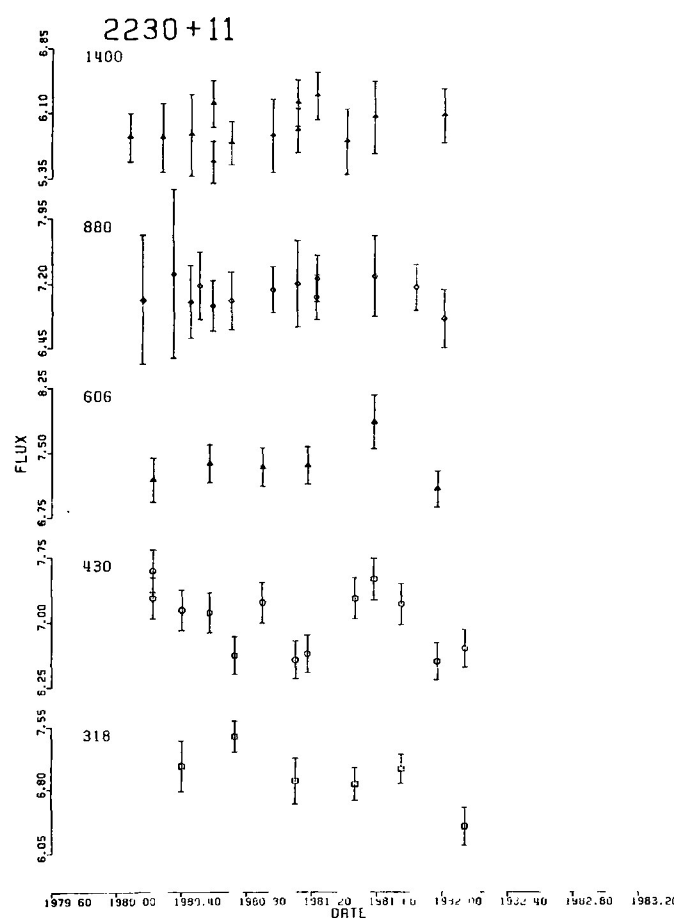


Fig. 2. **Preliminary light curves of CTA 102.**

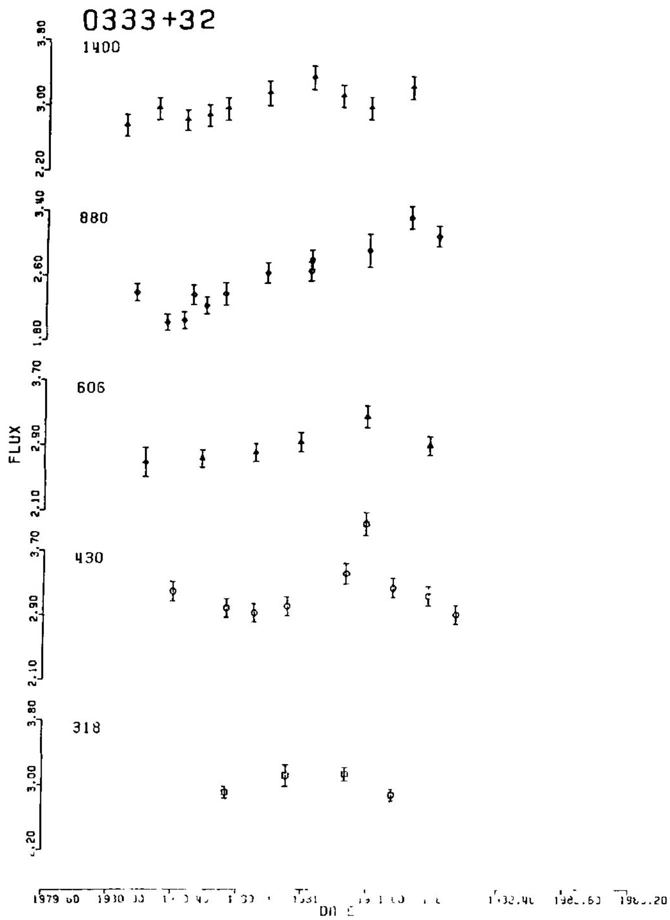


Fig. 3. Preliminary light curves of NRAO 140.

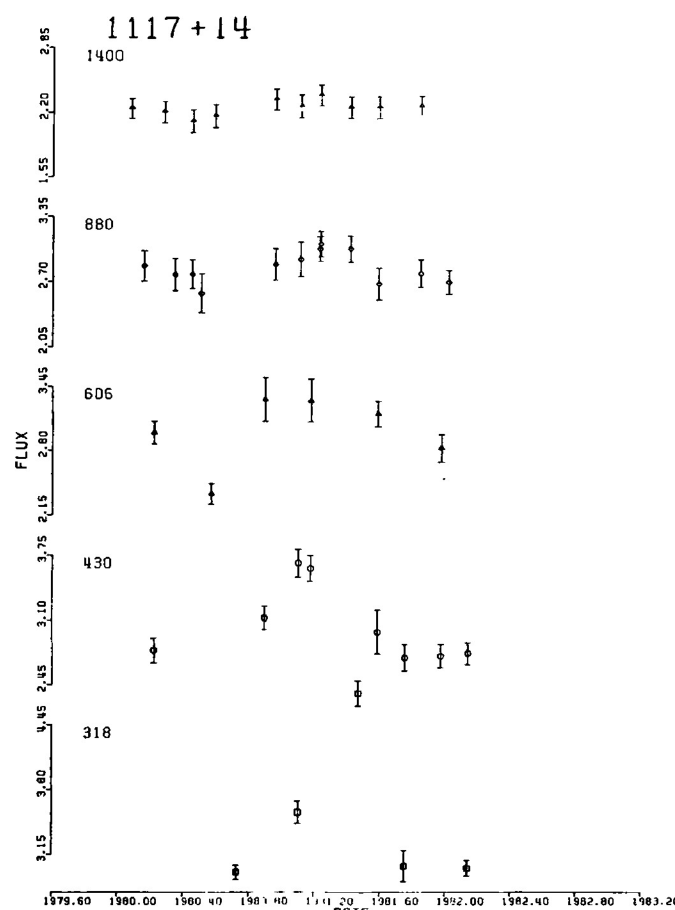


Fig. 4. Preliminary light curves of PKS 1117+14.

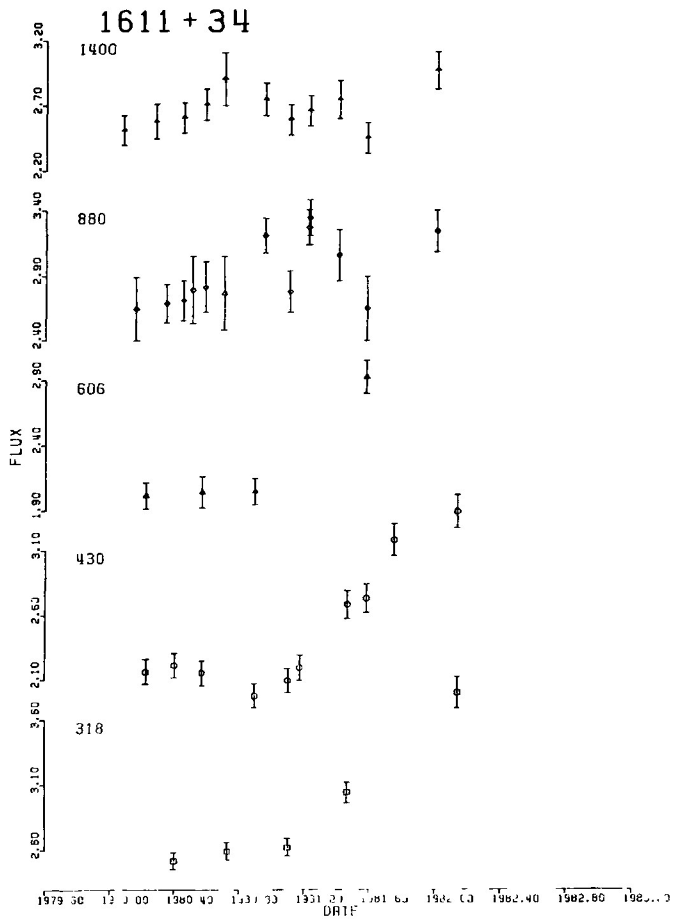
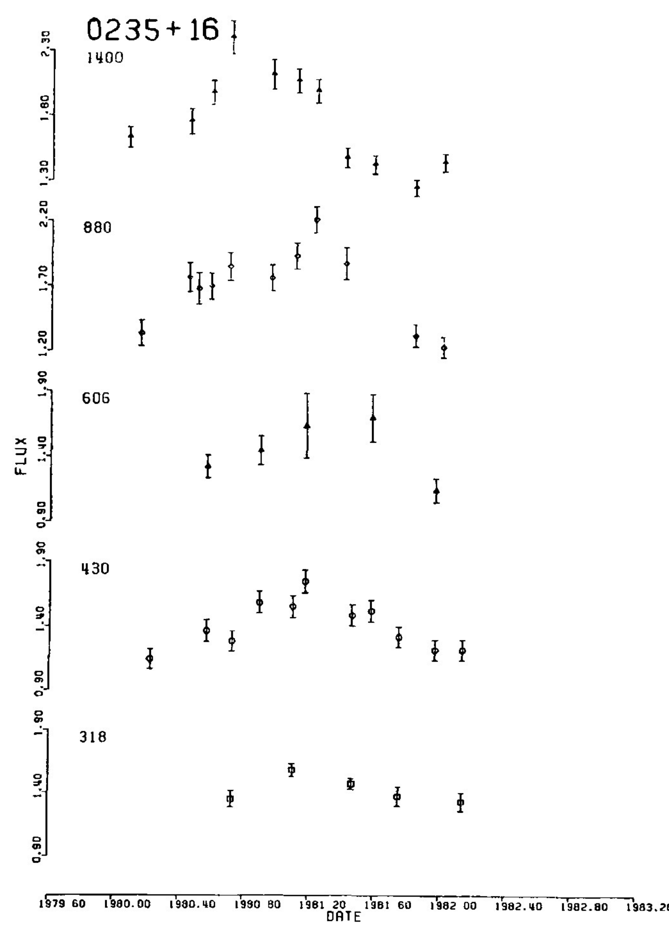


Fig. 5. Preliminary light curves of DA 406.

Fig. 6. Preliminary light curves of AO 0235+16.



DA 406 (1611+34). A strong increase is underway as of early 1982. Tentative indications are that the amplitude is largest at low frequencies and is appreciably smaller at 880 and 1400 MHz.

AO 0235+16. The behavior of this source was quite unlike the others. In this case the most active frequency appears to be 1400 MHz. The burst magnitude appears to be lower at lower frequencies. Also the peak may have occurred earlier at 1400 MHz than at lower frequencies. These characteristics are qualitatively similar to that expected on the basis of (relativistically) expanding cloud models.

IV. CONCLUSIONS

The most striking conclusion to be drawn has to do with the manner in which the variations seen over 318-606 MHz tend to taper off by 1400 MHz. Typically, low-frequency variables are rather quiescent at 1400 MHz. (It is important to note the possible selection bias that the sources in our program were selected on the basis of their 318-MHz variability. Condon et al. 1979; Dennison et al. 1981). Thus, we confirm the conclusion of Spangler and Cotton (1981) that there exists a gap at these intermediate frequencies in which the variation amplitude is small. In general, it appears that the "intermediate-frequency gap" (IFG) extends from 1 to about 3 to 10 GHz, based upon these results and Spangler and Cotton (1981). At present, the data do not support the view that variations occur simultaneously across the gap. In the future, it will be important to find out whether there is any correlation between the high- and low-frequency variations, and if any time delay is involved. This may require broadband monitoring of considerable duration since high frequency events are quite numerous, and disentangling the various outbursts may be quite complicated, particularly if a long time delay is present. Conceivably, the low- and high-frequency events could be quite unrelated to one another. Either finding would have important theoretical implications.

Significantly, not all low-frequency variables exhibit an obvious IFG. In our program AO 0235+16 seems to display quite the opposite, in a manner qualitatively reminiscent of expanding-cloud models. Fisher and Erickson (1980) observed major simultaneous changes in the flux density of BL Lac over the band 321-920 MHz. If anything the variation amplitude (~ 50% peak to peak) was largest at 920 MHz. (Smaller, ~ 10%, variations in 3C 454.3 were observed by these investigators to be simultaneous over this band. However, in this case the variation amplitude seems to be slightly larger at the low-frequency end.) Since AO 0235+16 is a blazar, we plan to add several blazars to our program in order to determine whether the lack of an IFG is a property of this population of objects. Further monitoring will reveal how widespread the IFG phenomena is, and in what populations of objects it is found.

With the possible exception of AO 0235+16, the outbursts observed by us appear to be approximately simultaneous over our frequency band.

Which sources exhibit an IFG and which do not? Is the IFG a source property, or is it merely a property of individual outbursts, perhaps changing significantly from outburst to outburst within a given source? Is there any variability correlation across the IFG? Is there any correlation between low-frequency variations and optical variability? Are low-frequency variations always simultaneous, at least when an IFG is present? Are non-IFG outbursts and/or sources fundamentally different from IFG outbursts and/or sources with respect to time delay? The answers to these observational questions will provide detailed guidance and constraints for a theoretical understanding of low-frequency variability.

We thank M. Davis, P. Shames, R. Vance, and J. Coe for assistance with the instrumentation, observations, and data reduction. This monitoring program is supported by NSF grants AST 79-25345 and AST 81-17864 to VPI and NSF grant AST 80-18384 to the University of Puerto Rico. The National Astronomy and Ionosphere Center is operated by Cornell University under contract with the National Science Foundation. The National Radio Astronomy Observatory is operated by Associated Universities under contract with the National Science Foundation.

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Polarization Rotations at 2.7 GHz

W.A. Dent, C.P. O'Dea, and W. Kinzel
University of Massachusetts

Our group at the University of Massachusetts has been studying the evolution of active extragalactic sources for several years. We regularly make flux density measurements at 89 and 31 GHz with the NRAO 36-ft, and at 15 and 8 GHz with the Haystack antenna.

Our lowest observing frequency is 2.7 GHz using the 300-ft antenna of the NRAO. The frequency range of 1-3 GHz is important to the study of variable radio sources since these are transition frequencies linking low frequency variations with those observed at high frequencies.

Our 2.7 GHz measurements of 4 sources out of the more than 200 sources in this program are shown in Figures 1 through 4. In addition to the total flux density we also measure the polarization at 2.7 GHz. We have recently begun a program of polarization measurements at 89 GHz with the FCRAO 14-m antenna. The 2.7 GHz polarization measurements are made by letting the source transit 3 beams, two of which are polarization switched giving Q and U, while the third is load switched to give total flux.

0048-09 (Figure 1) is much more variable at 2.7 GHz than it is at millimeter wavelengths. The position angle, χ, was very stable while the polarized flux changed by a factor of 7. This source, like many, varies more rapidly in flux density than in polarization. This is just the opposite of the usual pattern at higher frequencies where the polarization tends to be more highly variable than flux.

0607-15 (Figure 2) is another example showing the same pattern of greater variability in flux density than polarization. The Michigan group observed an ~180 degree rotation at 8 GHz in 1977. This rotation was not seen at 2.7 GHz probably because the source is opaque at this frequency as suggested by the turndown in the radio spectrum.

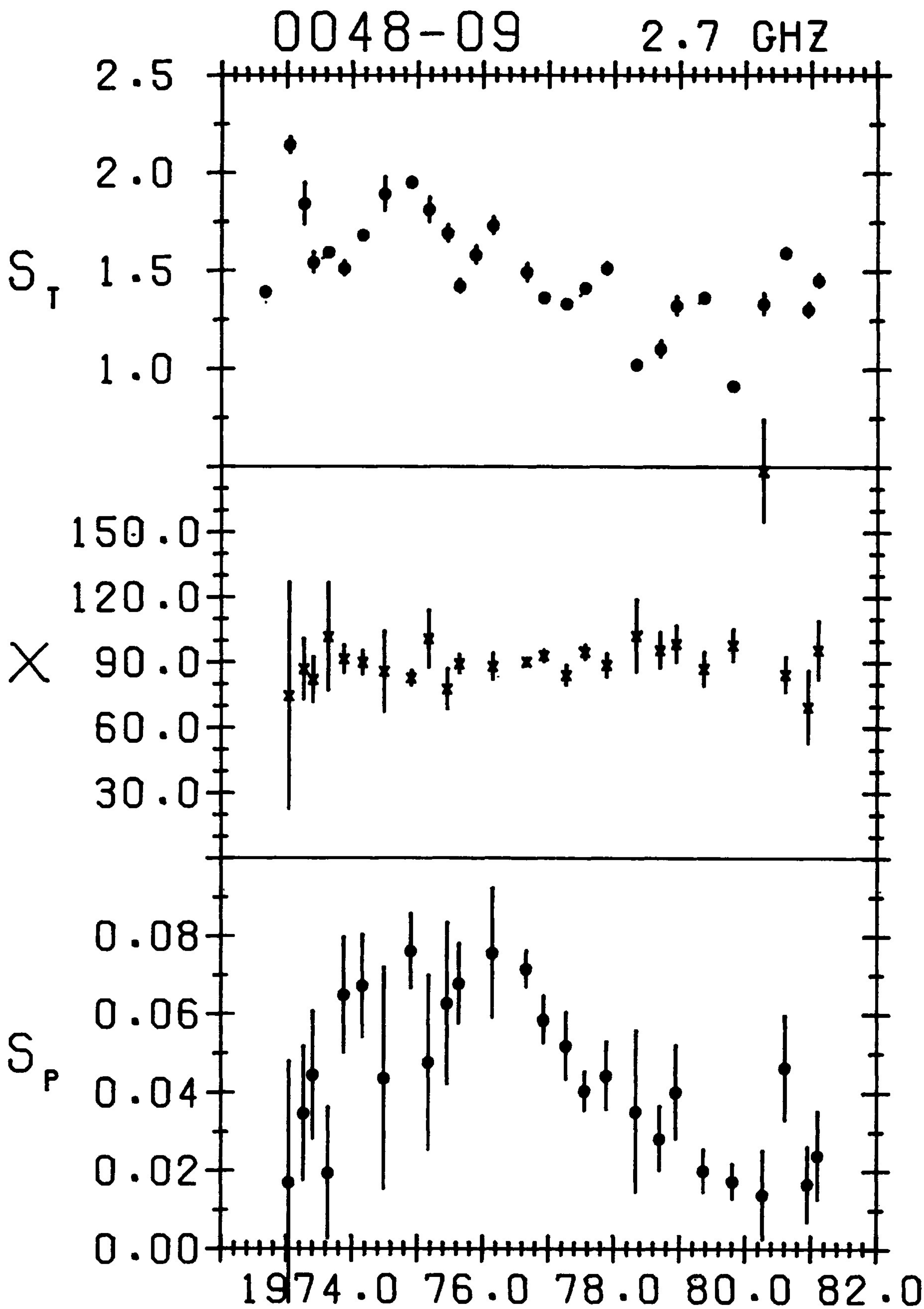
0727-11 at 2.7 GHz (Figure 3) does not show the ~400 degree rotation in 1977 through 1980 observed at Michigan for frequencies greater than 4.8 GHz. We see a 90 degree change at most.

One of our most interesting sources at 2.7 GHz is the quasar (Z = .86) 0133+47 (DA55). We observe (Figure 4) very large and rapid changes in χ which suggest this source may be a polarization rotator. Plots of Q and U show sinusoidal oscillations and confirm a continuous sense for the change in position angle. When we remove the 180° ambiquities we find an ~600 degree rotation between 1975 and 1979. The change in χ is not always linear but becomes constant at times reminiscent of the behavior seen in 0727-11 at 8 GHz. Most of the rotation occurs during the decaying phase of the outbursts. The times when the position angle stops rotating occur before and near the flux density peaks when the outbursts are opaque.

The Allers' data on this source is sparse before 1980 but there does not seem to be a large rotation at 8 GHz. This could imply that at 2.7 GHz we are not seeing an intrinsic change in magnetic field orientation, but a change in Faraday rotation (which increases as λ^2) due to a changing N_e or B.

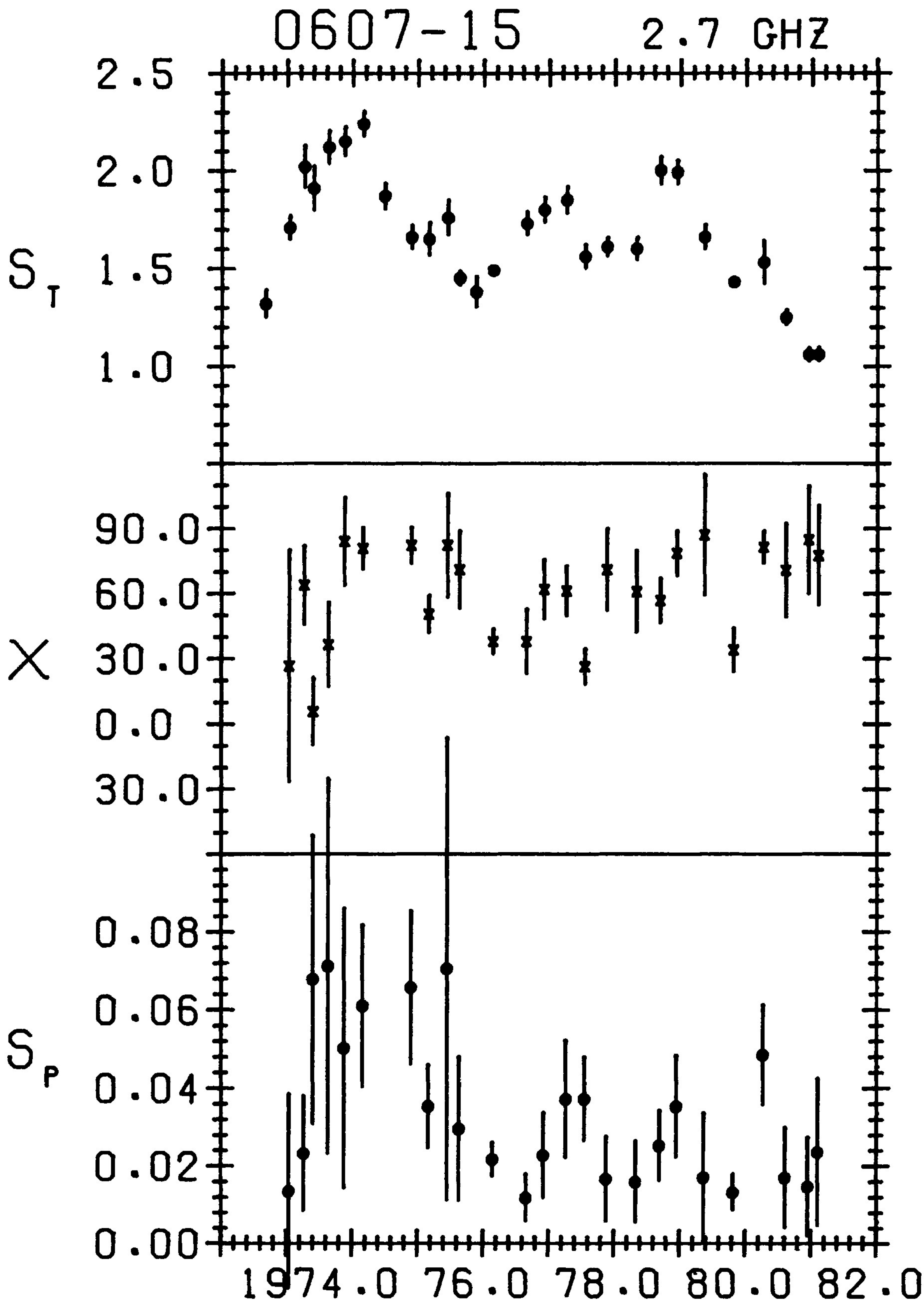
Another interesting phenomena in 0133+47 is the abrupt drop in flux density between 1978.3 and 1978.7. This drop is much faster than the usual decay seen in the outbursts. The outbursts in 1974 and 1977 observed at 31 GHz (Figure 5) show a close correspondence with those seen at 2.7 GHz. However, in mid 1978 there was a rapid increase at 31 GHz at the same time the drop occurred at 2.7 GHz.

If an outburst is triggering an abrupt drop at lower frequencies, one might interpret the drop as being due to thermal absorption caused by an increase in electron density along the line-of-sight. The turndown in the radio spectrum near 2.7 GHz and the evidence for Faraday rotation support this hypothesis. The increase in electron density associated with the outburst could, as suggested by Alan Marscher, be due to ultraviolet radiation emitted during the outburst or from a compression of the gas in the region by a blast wave or particle beam. In a later paper (O'Dea et al.) we present more evidence for low frequency absorption in active sources.



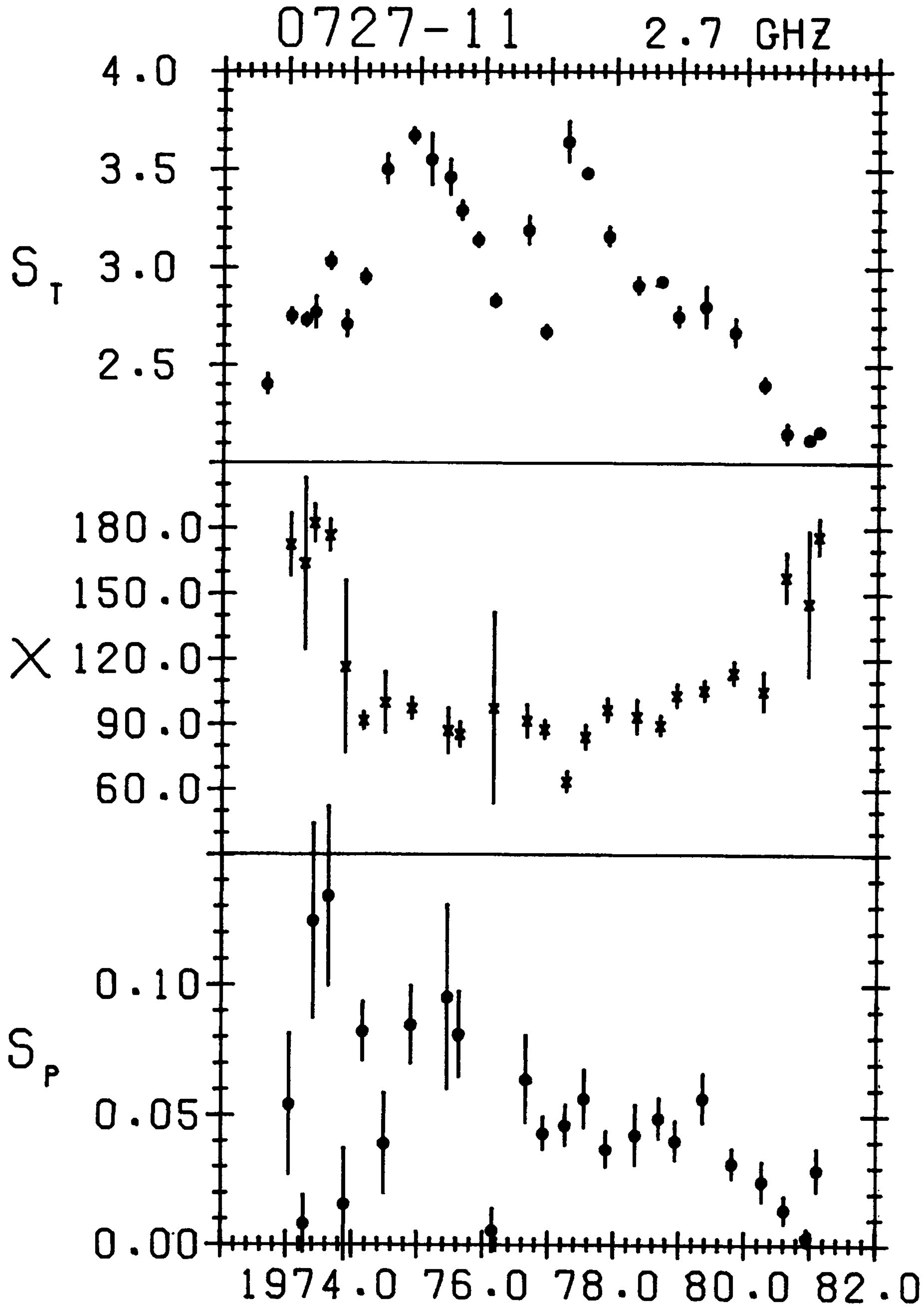
0048-09
2.7 GHZ
S_T
2.5
2.0
1.5
1.0
X
150.0
120.0
90.0
60.0
30.0
S_P
0.08
0.06
0.04
0.02
0.00
1974.0
76.0
78.0
80.0
82.0

Figure 1



0607-15
2.7 GHZ
2.5
2.0
1.5
1.0
S_T
90.0
60.0
30.0
0.0
30.0
X
0.08
0.06
0.04
0.02
0.00
S_P
1974.0
76.0
78.0
80.0
82.0

Figure 2



0727-11
2.7 GHZ
4.0
3.5
3.0
2.5
S_T
180.0
150.0
120.0
90.0
60.0
X
0.10
0.05
0.00
S_P
1974.0
76.0
78.0
80.0
82.0

Figure 3

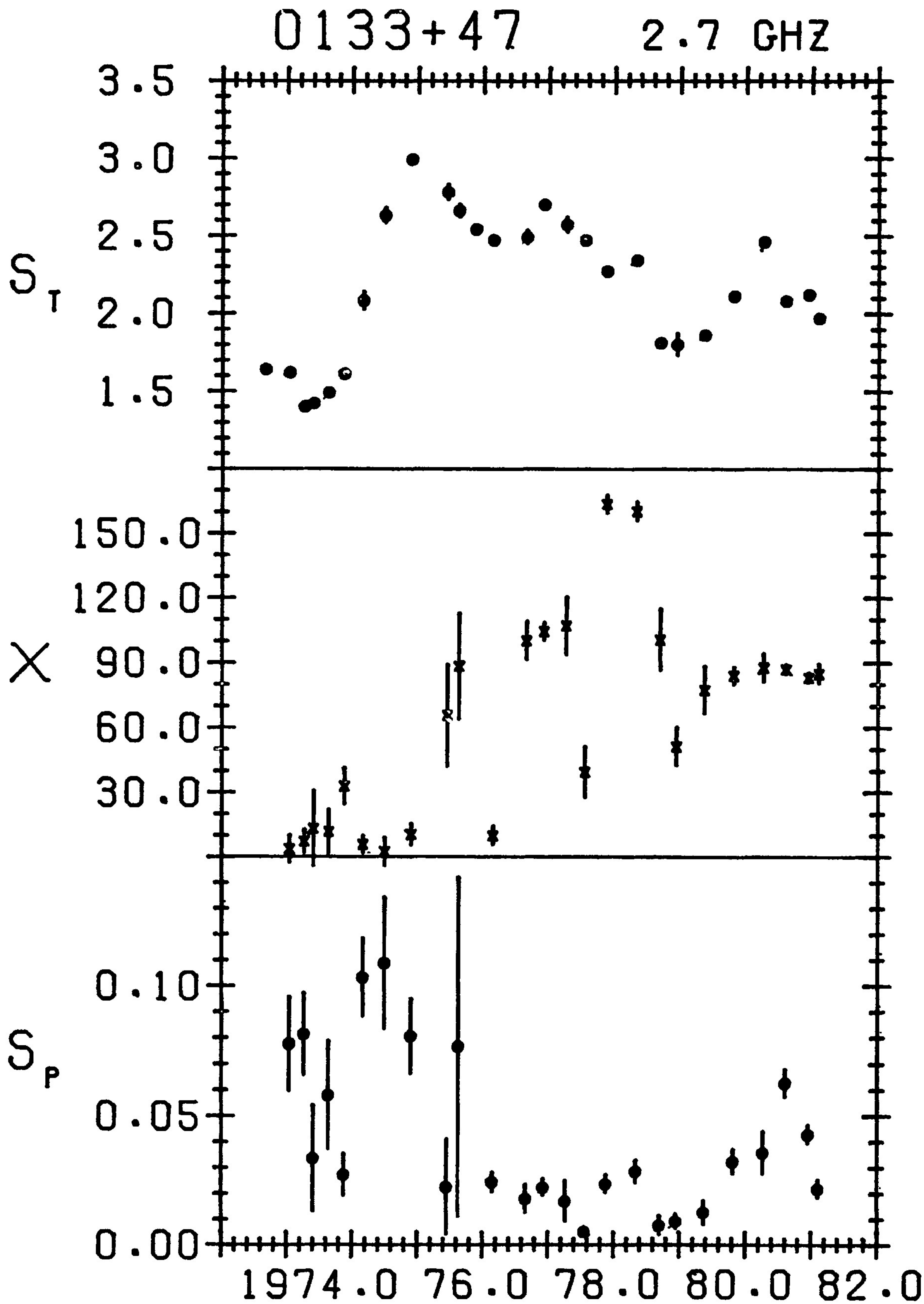

0133+47 2.7 GHZ
S_T
3.5
3.0
2.5
2.0
1.5
X
150.0
120.0
90.0
60.0
30.0
S_P
0.10
0.05
0.00
1974.0
76.0
78.0
80.0
82.0

Figure 4

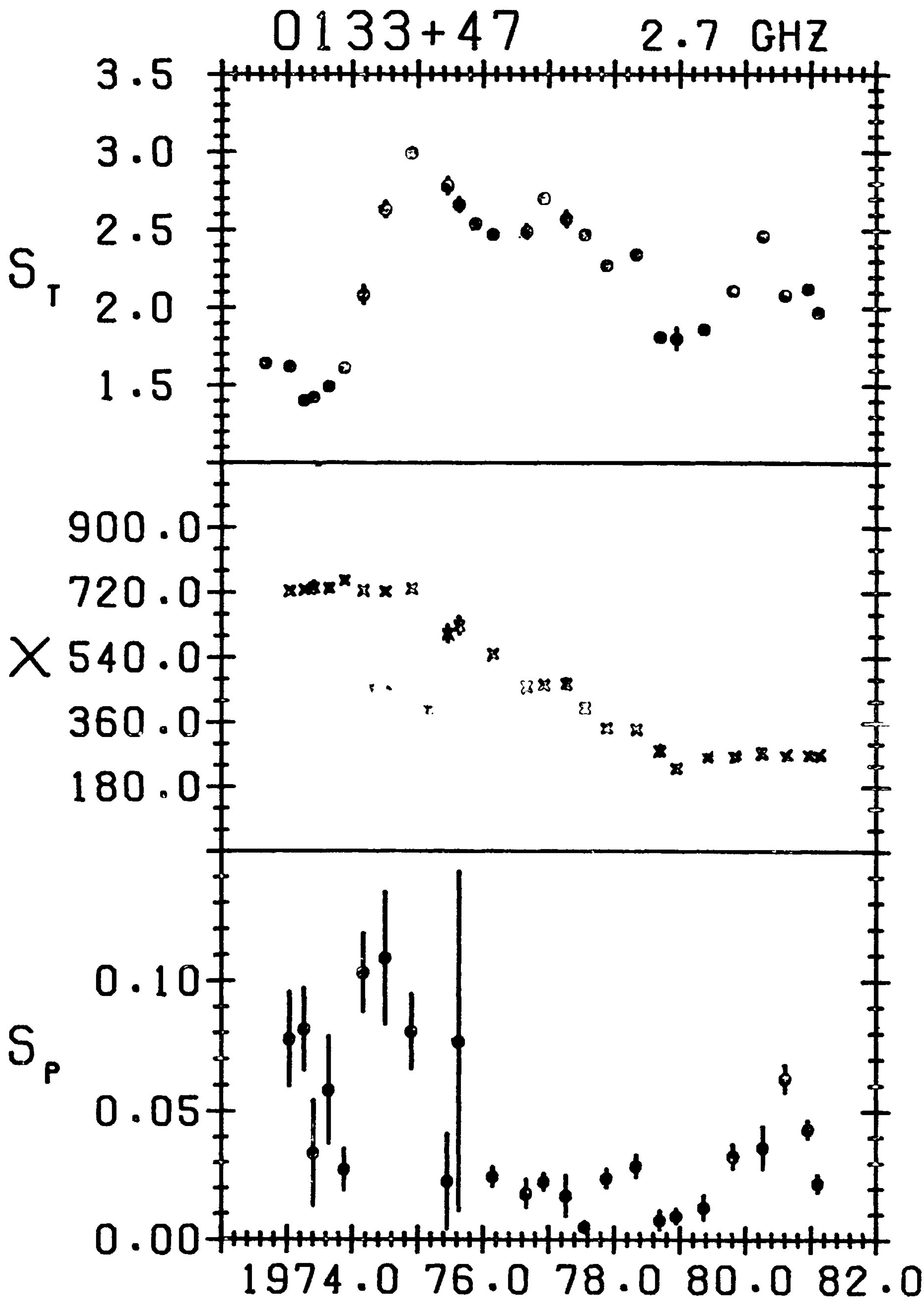

0133+47
2.7 GHZ
3.5
3.0
2.5
2.0
1.5
S_T
900.0
720.0
540.0
360.0
180.0
X
0.10
0.05
0.00
S_P
1974.0
76.0
78.0
80.0
82.0

Figure 5

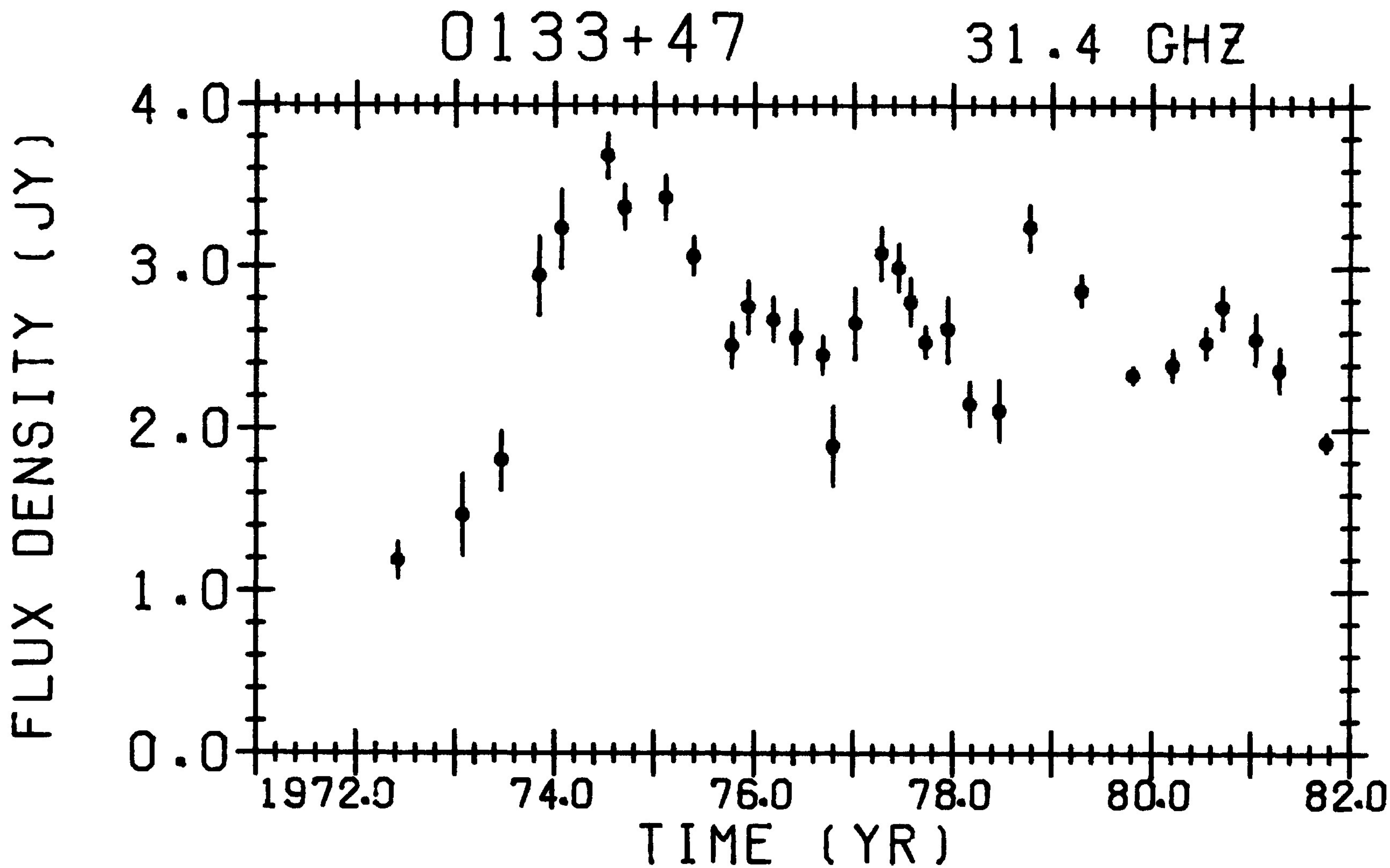

0133+47
31.4 GHZ
FLUX DENSITY (JY)
4.0
3.0
2.0
1.0
0.0
1972.0
74.0
76.0
78.0
80.0
82.0
TIME (YR)

Figure 6

THE STATISTICS OF LOW-FREQUENCY VARIABILITY

Brian Dennison, J. J. Broderick, J. E. Ledden, S. L. O'Dell
Virginia Tech

and

J. J. Condon
National Radio Astronomy Observatory

Introduction and Summary

Here we summarize the statistical results of a search for 318-MHz variability in complete samples of extragalactic radio sources. We have already described in detail the observational procedures and measurements (Condon *et al.* 1979; Dennison *et al.* 1981) and discussed at some length the statistical results and theoretical implications (Dennison *et al.* 1981).

The samples searched are the BDFL sample (Bridle *et al.* 1972) -- complete to 3 Jy at 1400 MHz -- and the NRAO S1, S2, and S3 surveys (Kellermann, Pauliny-Toth, and Davis 1968; Pauliny-Toth *et al.* 1972; Pauliny-Toth and Kellermann 1972) -- complete to 1 Jy at 5000 MHz. Using the Arecibo telescope, we obtained 318-MHz flux densities for these samples during the two epochs 1969-1971 (Jauncey, Niell, and Condon 1970; Condon 1972; Condon and Jauncey 1974 a, b) and 1979.2, and during the intermediate epoch 1974.2 for a subset of the NRAO samples.

For each source observed, we define a "variability measure" V_{ij} to be the difference in the 318-MHz flux density between the i^{th} and j^{th} epochs, divided by the corresponding errors -- comprised of flux-proportional and flux-independent components -- added quadratically.

$$V_{ij} \equiv (S_j - S_i)/(\sigma_i^2 + \sigma_j^2)^{1/2}$$

The primary criterion for classifying a source as a "probable variable" is $2.0<|V| \equiv |V_{13}|<2.5$; that for calling a source "variable" is $|V| \equiv$

$|V_{13}|>2.5$ (where epoch 1 is 1969-1971 and epoch 3 is 1979.2). The intermediate-epoch data of 1974.2 provides important supplementary information (on the characteristic timescale and incidence of variability) for a subset of the complete samples.

In order to examine the relationship of sub-GHz variability to low-frequency spectrum and structure, we compute for each source an effective spectral index $\alpha \equiv -[\Delta(\ell nS)/\Delta(\ell n\nu)]$ between 318 MHz and the survey frequency (1400 MHz for the BDFL sample, and 5000 MHz for the NRAO sample). For purposes of discussion, we shall call sources with $\alpha > 0.5$ "steep-spectrum" and those with $\alpha < 0.5$ "flat-spectrum". Steep-spectrum radio sources (defined according to the above criterion) are almost always dominated at sub-GHz frequencies by transparent, extended components (Broderick and Condon 1975).

The major statistical conclusions of our 318-MHz search for sub-GHz variability in complete samples of extragalactic radio sources are as follows:

(1) About 40% of the flat-spectrum sources exhibit variability with amplitudes exceeding ~ 8%. Steep-spectrum sources do not vary.

(2) The fractional amplitude of detected variations seems to be inversely correlated with the low-frequency spectral index (or flux density).

(3) The duration of detected variations is typically $\lesssim$ 5 years.

(4) The attributes sub-GHz variability and optically violent variability are statistically associated at a high confidence level.

(5) There is no statistical evidence that sub-GHz variability occurs during propagation through structures in the Galaxy. Indeed, the association of sub-GHz variability with optically violent variability essentially excludes this hypothesis.

Below, we discuss each of these results. For more details, see Dennison et al. 1981.

Statistical Results

(1) Fraction of sources exhibiting sub-GHz variability:

Figure 1 shows the distribution of 318-MHz variability measures $V = V_{13}$ for all flat-spectrum ($\alpha < 0.5$) sources in the complete samples. This distribution can be fitted by a gaussian with mean $\simeq 0$ and dispersion $\simeq 1$ resulting from measurement errors, plus very broad wings coming from the sources which are definitely variable at 318 MHz. In contrast, the distribution of variability measures for the steep-spectrum sources exhibits no broad wings, but only a gaussian with the dispersion and mean expected from the measurement uncertainties.

In order to estimate the fraction of sources exhibiting sub-GHz variability, we must take into account the fact that our search can detect only very large fractional variations in 318-MHz flux density $\Delta S/S$ for the weaker sources ($S \lesssim 2$Jy). This, of course, is a consequence of the fact that flux-independent errors dominate in the weaker sources, whereas flux-proportional errors dominate in the stronger sources. Figure 2 displays the rapid decrease in sensitivity to fractional variations which occurs for sources weaker than about 2 Jy. Based upon the sources stronger than 2 Jy at 318 MHz, we estimate that at least ~ 40% of the flat-spectrum sources vary at the 8% level or greater.

Before proceeding, it is important to recognize that some care must be taken in the determination of spectral indices and the subsequent categorization into "flat-spectrum" and "steep-spectrum" sources. Firstly, it is necessary to compute the effective spectral index, $\alpha \equiv -[\Delta(\ell n S)/\Delta(\ell n \nu)]$, over a moderately broad spectral range

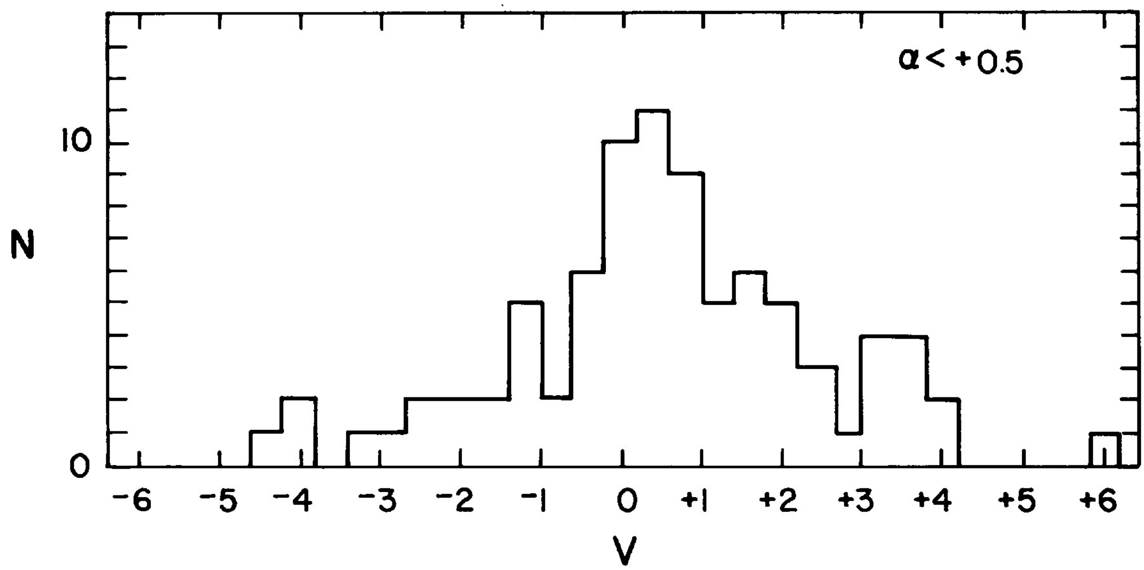


Fig. 1. Histogram of the variability measure V of flat-spectrum sources.

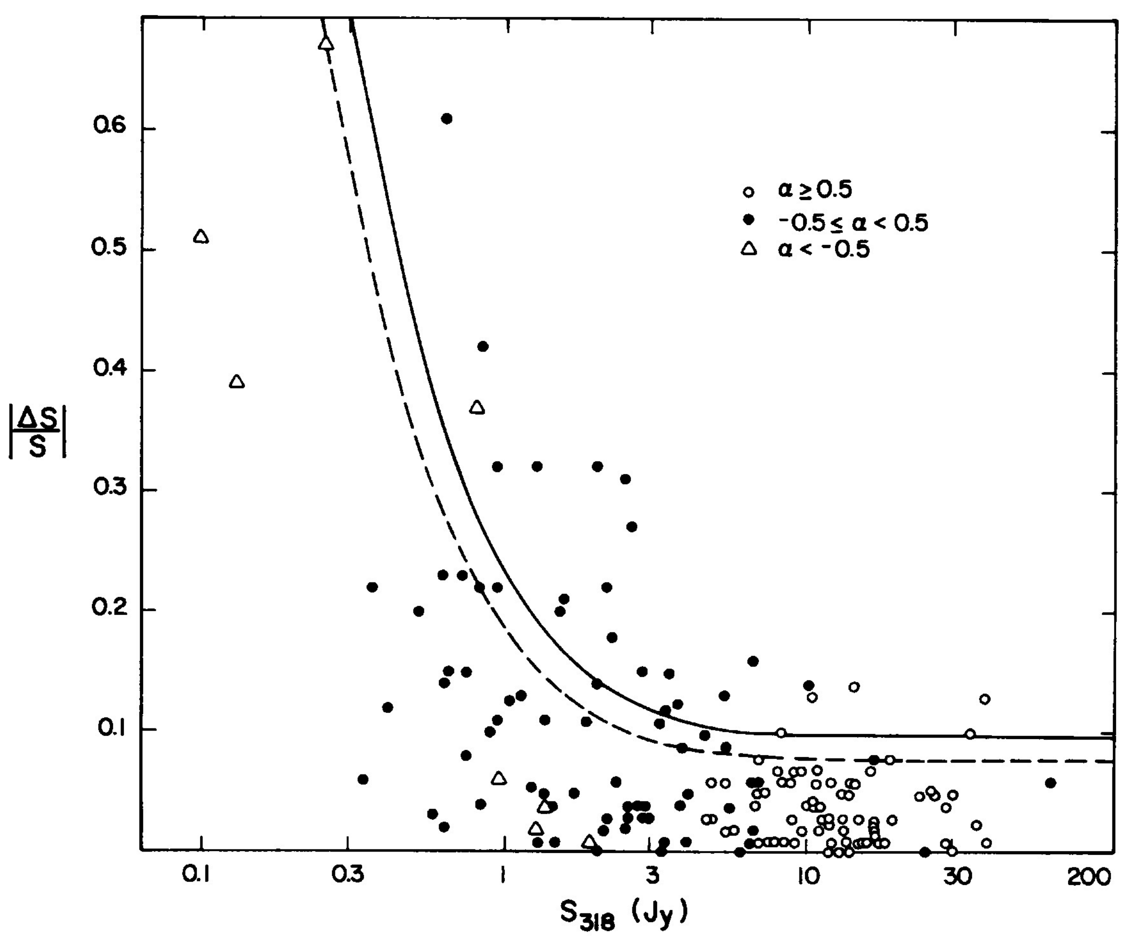


Fig. 2. Fractional variability |ΔS/S| versus 318-MHz flux density for all sources in the complete samples. Curves approximately represent the minimum detectable, fractional flux density change at the 2σ (dashed) and 2.5σ (solid) levels.

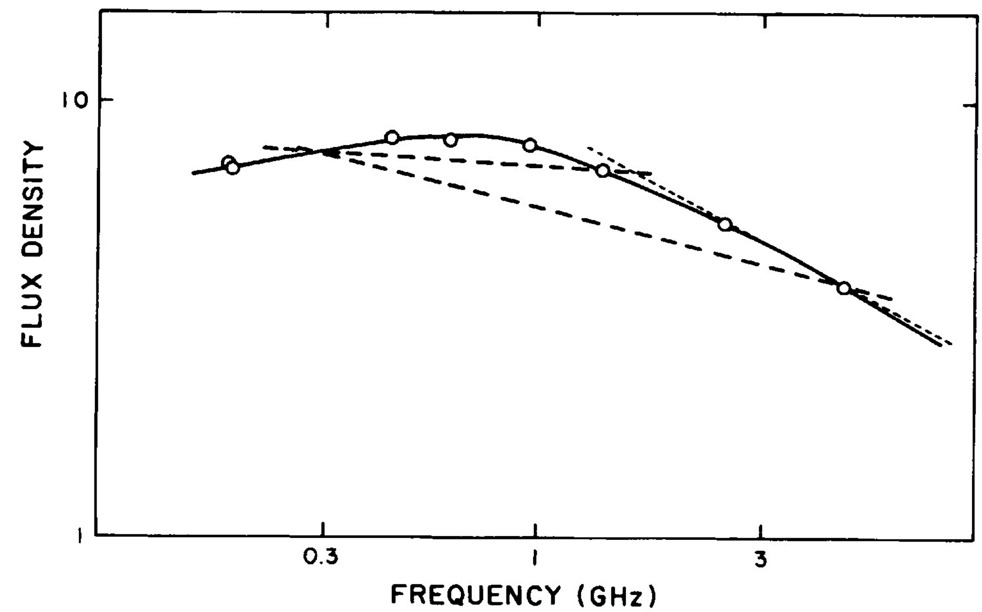


Fig. 3. Radio flux-density distribution of CTA 102 for epoch 1967 (after Wills 1975).

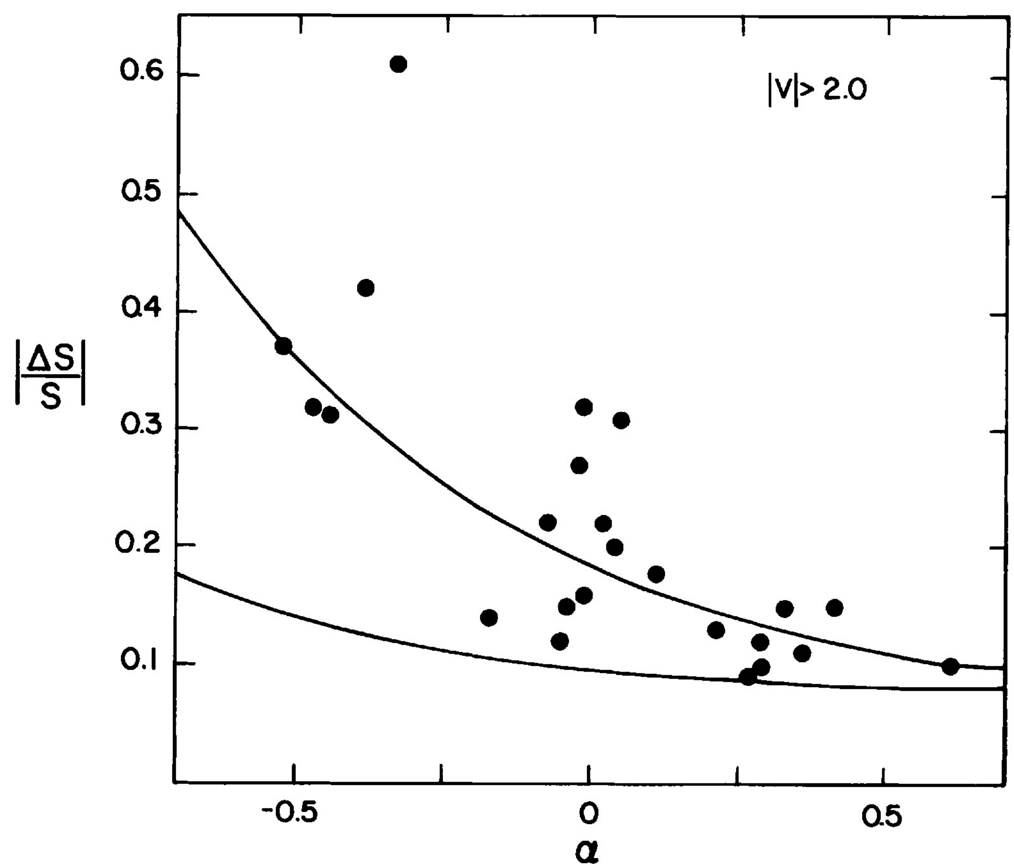


Fig. 4. Fractional variability $|\Delta S/S|$ versus spectral index for possible variables and variables. Curves correspond to the 2σ variability detection limits at the completeness limits of the 1400-MHz sample (lower curve) and the 5000-MHz sample (upper curve) extrapolated to 318 MHz.

[$\Delta(\ell n\nu) \simeq$ 1-3] in order to assess more effectively the role of emission from extended (nonvariable) components and to reduce (through a large lever arm) uncertainties in spectral index resulting from non-simultaneous observations or measurement errors. Secondly (and perhaps more importantly), the spectral index used to characterize the spectrum of a sub-GHz source must be determined at sub-GHz frequencies. The 1967 spectrum (Wills 1975) in figure 3 emphatically demonstrates this point. Since the effective spectral index is 0.1 between 318 MHz and 1400 MHz or 0.3 between 318 MHz and 5000 GHz, we classify this as a flat-spectrum source. However, if one were to have used the effective spectral index of 0.6 between 2.7 GHz and 5 GHz, say, one would have called this a "steep-spectrum" source. The source is CTA 102!

(2) Inverse correlation of fractional variability with spectral index:

As figure 2 shows, the largest fractional variations occur in the weaker variable sources. We interpret this as an inverse correlation between the fractional variability $|\Delta S/S|$ and the spectral index α. Since the sources were selected at either 1400 MHz or 5000 MHz, those sources with the smallest spectral indices α(318, 1400) or α(318, 5000), respectively, are necessarily also the weakest sources at 318 MHz. Figure 4 displays the dependence of $|\Delta S/S|$ upon α for the variables and possible variables in the complete samples. Taking into account the smallest fractional variation detectable at the completeness limit of each sample, we test the statistical significance of the trend apparent in figure 4. The (binomial) statistical tests confirm (at >95% confidence) that <u>the incidence of large fractional variations is highest in the inverted-spectrum sources.</u>

(3) Duration of detected events:

Using the three-epoch data, we can to some degree examine the duration of events in sub-GHz variables. Figure 5 is a plot of the variability measure V_{23} between second and third epochs against the variability measure V_{12} between first and second epochs. If variations were long-term ($\gtrsim$ 10 years), the variable sources would be clustered near $V_{12} \simeq V_{23}$, reflecting a monotonic change over the decade between

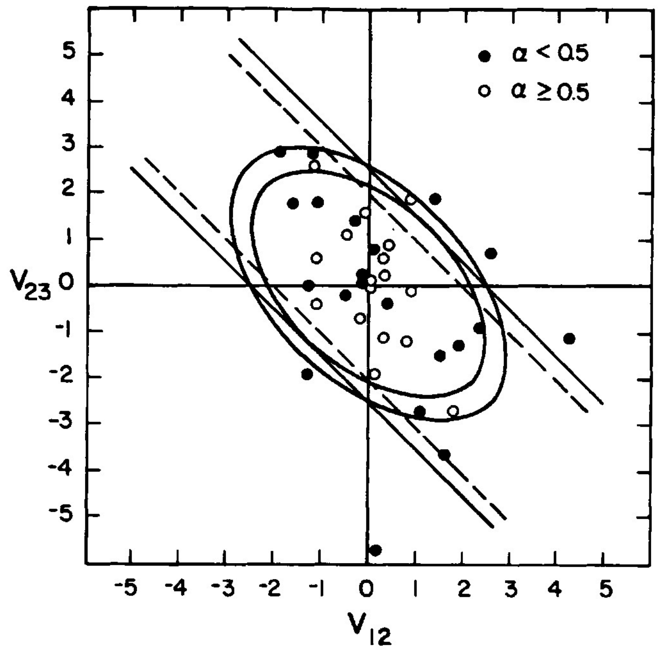


Fig. 5. Three-epoch observations, showing 2-3 epoch variability measure V_{23} versus 1-2 epoch variability measure V_{12}. Straight lines approximately represent 2σ (dashed) and 2.5σ (solid) variability for the 1-3 epoch variability measure $V_{13} \equiv V$. The ellipses approximately represent 95.5% confidence (inner ellipse) and 98.8% confidence (outer ellipse) variability based upon a χ^2 test including all three epochs.

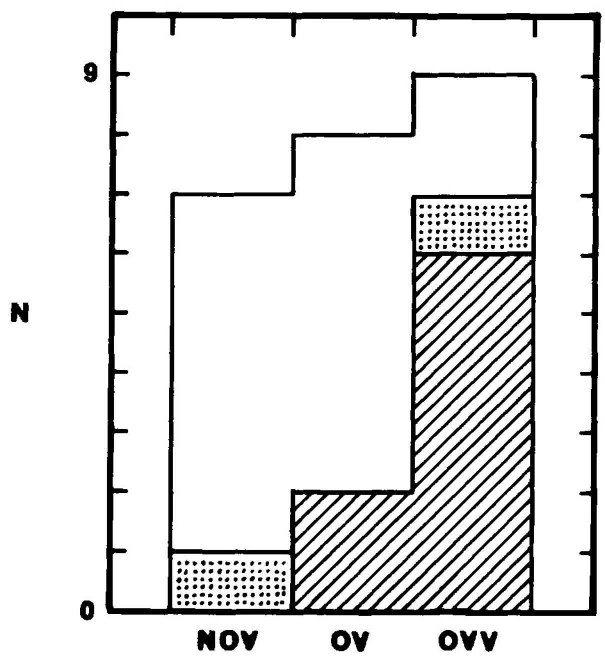


Fig. 6. Histogram of optical variability for all sources in the complete samples in common with the Florida optical monitoring program. NOV = not classified as optically variable; OV = optically variable; OVV = optically violent variable. Shading denotes degree of low-frequency variability: unshaded = not variable; dotted = possible variable; hatched = variable.

first and third epochs. From the general scatter of variable sources in the (V_{12}, V_{23}) plot, we conclude that detected sub-GHz events typically last $\lesssim$ 5 years.

(4) Association of sub-GHz variability and optically violent variability:

In order to compare the incidence of sub-GHz variability with that of optical variability, we identified all sources in our complete samples which have been observed in the Florida optical monitoring program (McGimsey *et al.* 1975; Scott *et al.* 1976; Pollock *et al.* 1979; Pica *et al.* 1980). There are 24 sources in common, which are shown in the histogram of figure 6, classified according to degree of optical variability and sub-GHz variability. This histogram indicates and (binomial) statistical tests confirm at a high confidence level (> 99%) that the incidence of optically violent variability correlates with that of sub-GHz variability.

(5) Absence of relationship between sub-GHz variability and propagation in the Galaxy:

Shapirovskaya (1978) suggests that low-frequency variability might result from focusing (in the geometrical-optics limit) by irregularities in diffuse structures in the Galaxy, and claims that 15 low-frequency variables lie behind loops, spurs, and ridges in diffuse galactic radio emission. Using the complete samples of radio sources which we searched for 318-MHz variability, we tested the hypotheses that the positions of sub-GHz variables are correlated with diffuse structures as designated by Berkhuijsen (1971) or with the 820-MHz foreground brightness-temperature of diffuse galactic emission (Berkhuijsen 1971). In neither case did we find a statistically significant correlation.

There is even more compelling evidence against any influence of structures in the Galaxy upon sub-GHz variability -- namely, the association of sub-GHz variability with optically violent variability. We thus conclude that propagation effects in the Galaxy are not responsible for sub-GHz variability.

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High Frequency Observations of Low Frequency Variables: Preliminary Results from a Monitoring Program

S. R. SPANGLER AND W. D. COTTON

National Radio Astronomy Observatory*

June 1982

In 1976–1978 we carried out a program of monitoring potential Low Frequency Variables at a number of frequencies between 325 MHz and 15000 MHz (Cotton and Spangler 1979; Spangler and Cotton 1981). The best observed events were those of the sources 1611+343 and 3C454.3. Both events showed a decrease in burst amplitude as one went from frequencies of a few hundred megahertz to a couple of gigahertz, indicating that Low Frequency Variability is, in some sense, a "low pass" process. In the case of 3C454.3, variability was also observed at high frequencies (of order 15 GHz or more) during this time. Spangler and Cotton (1981) suggested that the high and low frequency enhancements might be related, so the outburst spectrum would be saddle–shaped.

These results are of considerable importance to an understanding of the radiation mechanism responsible for Low Frequency Variability. The (well–established) fact that the burst amplitude decreases in the frequency range of about 400 MHz to about 2 GHz indicates that this type of variability is intrinsically a low–frequency phenomenon, and not merely the low frequency "tail" of a process which is more pronounced at high frequencies. In addition, the outburst spectrum of 1611+343 was sufficiently steep as to be only marginally consistent with synchrotron radiation from a monoenergetic electron spectrum. In other cases (such as the outburst of 3C454.3), the outburst spectrum may be even steeper. Such conclusions are not entirely solid, insofar as they are dependent on the determination of a pre–event "base level", and even on the assumption that such a level is a meaningful concept. The existence of related high and low frequency events with an "intermediate frequency gap" could suggest the operation of two radiation mechanisms driven by a common agent. Both the steep outburst spectrum and the "intermediate frequency gap" would lead one to suspect that the Low Frequency Variable radiation mechanism is not synchrotron radiation.

While interesting and potentially of great significance, the above discussion is at the present time dependent on limited observational material. Further broadband observations are needed to measure the spectral shapes of outbursts, and to address the relationship between high and low frequency enhancements.

Since May 1981, we have been carrying out an observational program which complements low frequency monitoring projects at a number of observatories, and

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

should assist in the elucidation of the aforementioned topics. Observations are being made with a six antenna subarray of the Very Large Array and the NRAO millimeter–wavelength radio telescope on Kitt Peak. Observations with the VLA are typically made once a month at frequencies of 1.46, 4.9, 15.0, and 22.5 GHz. Observations at Kitt Peak are made at a frequency of 89.6 GHz and at intervals of about six weeks. We are observing eleven sources, known from previous studies to be Low Frequency Variables. The sources observed are 0607 — 157, 0723 — 008, 0736 + 017, 1055 + 108, 1358 + 624, 1510 — 089, 1611 + 343 (DA406), 1633 + 382, 1641 + 399 (3C345), 2230 + 114 (CTA102), and 2251 + 158 (3C454.3).

At the present time, we are still in the process of developing techniques for data reduction. A number of effects must be compensated for before the VLA observations reach their potential precision. Such effects, and the frequencies at which they are most pronounced are variable atmospheric attenuation (22.5 GHz), antenna pointing errors (15 and 22.5 GHz), and extended structure associated with compact sources (1.46 GHz). At the present time, corrections for these effects are not routinely made, and so the results presented in this paper must be considered preliminary.

Of the eleven sources in our sample, eight show definite variability during the course of our observations. We now briefly discuss the preliminary results on a few of these sources.

0607 — 157

An enhancement, beginning near the end of 1981, is seen at 15, 22.5, and 89.6 GHz. There is no indication of an increase at 4.9 GHz. Observations during the coming year should indicate whether the enhancement "propagates" down to 4.9 GHz, or whether this event is exclusively restricted to high frequencies. Variations at 1.46 GHz appear unrelated to the shorter wavelength changes.

0736 + 017

The beginning and maximum of an event are seen at frequencies between 4.9 and 89.6 GHz. The behavior is qualitatively similar to that of many previously–reported events in that the time of maximum occurs later at lower frequencies. However, the decrease in burst amplitude with decreasing frequency is not compatible with simpler versions of an expanding source model. The behavior at 1.46 GHz appears unrelated to that at higher frequencies, again indicating that low frequency variability is a distinct phenomenon.

1611 + 343 (DA406)

The low frequency event reported by Payne *et al.* 1982 which peaked in early 1982 can be seen in our 1.4 GHz measurments but is completely absent at 4.9 GHz.

Our 89.6 GHz results suggest a weak high frequency event approximately coincident with the low frequency event.

1633 + 382

An enhancement is seen at frequencies from 4.9 to 89.6 GHz, with evidence of a frequency–dependent time of maximum. Once again, there is no simple relation between the behavior at 1.46 GHz and that at higher frequencies.

2230 + 114 (CTA102)

There is no evidence in out data at frequencies below 15 GHz for a high frequency extension of the weak low frequency event peaking in 1981.6 suggested by the data of Payne *et al.*

2251 + 158 (3C454.3)

Our data on 3C454.3 are the most interesting to date. A complete enhancement (rise, peak, and decline) is seen at the three highest frequencies. The 4.9 GHz flux density rose steadily during the time of the observations, but has not reached maximum as of the writing of this paper. Observations during the coming year should indicate whether this trend is part of the enhancement at higher frequencies, or is unrelated. The flux density at 1.46 GHz was constant to a high degree of precision. Observations made by Payne *et al.* at frequencies below 1 GHz show an enhancement of similar morphology and duration , but which reached maximum several months before the peak of the event shown in our data. The high and low frequency variation are most probably unrelated, but a longer record will be necessary to decide this question.

Our observations to date, though preliminary and of limited duration, are hinting at some interesting characteristics of source outbursts. A number of sources have shown enhancements at the three highest frequencies. At 1.46 GHz, the source is typically constant, or shows variations which appear to be unrelated to the highest frequency events. Variations at 4.9 GHz are typically slower than at higher frequencies, or absent altogether. Since large amplitude, relatively fast variations are seen at frequencies below 1 GHz, our data are beginning to hint at a "crossover" frequency band roughly between 1 and 5 GHz. Observations currently in progress, or to be made in the near future, will allow us to see if this conclusion is borne out, and also indicate whether high and low frequency variations are temporally related.

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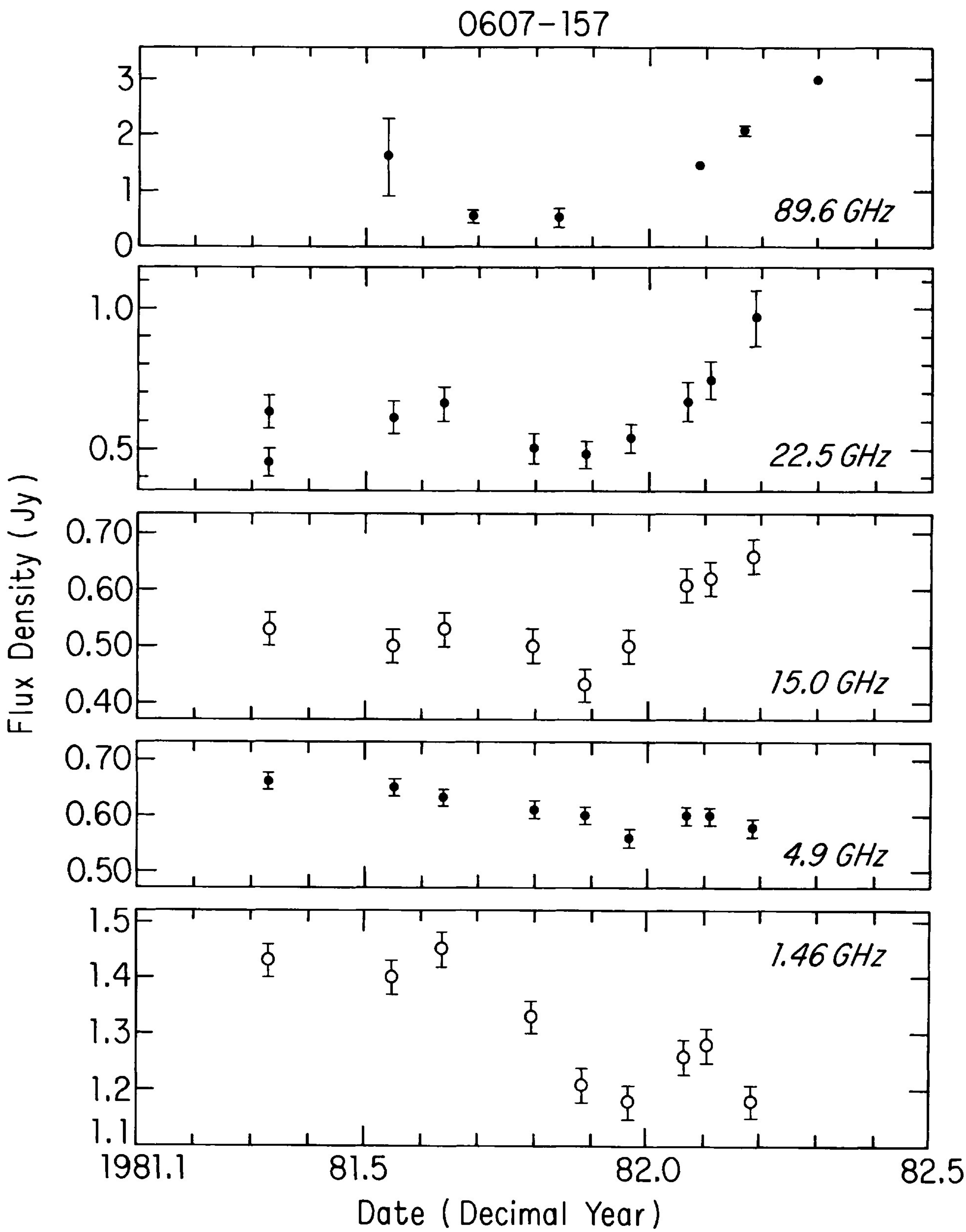
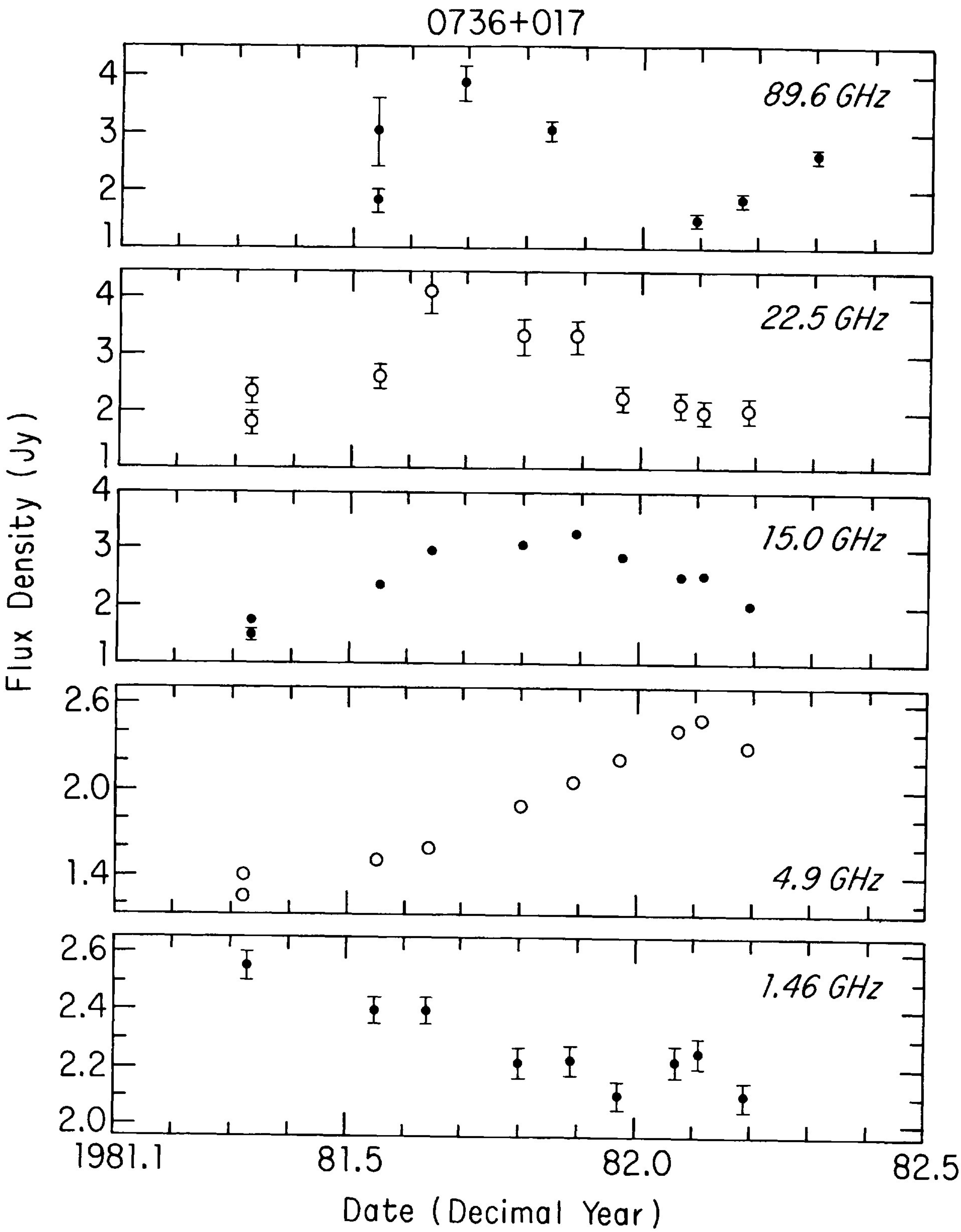


0607-157
89.6 GHz
22.5 GHz
15.0 GHz
4.9 GHz
1.46 GHz
Flux Density (Jy)
Date (Decimal Year)
1981.1
81.5
82.0
82.5
3
2
1
0
1.0
0.5
0.70
0.60
0.50
0.40
0.70
0.60
0.50
1.5
1.4
1.3
1.2
1.1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22.5 GHz
15.0 GHz
4.9 GHz
1.46 GHz
Flux Density (Jy)
Date (Decimal Year)
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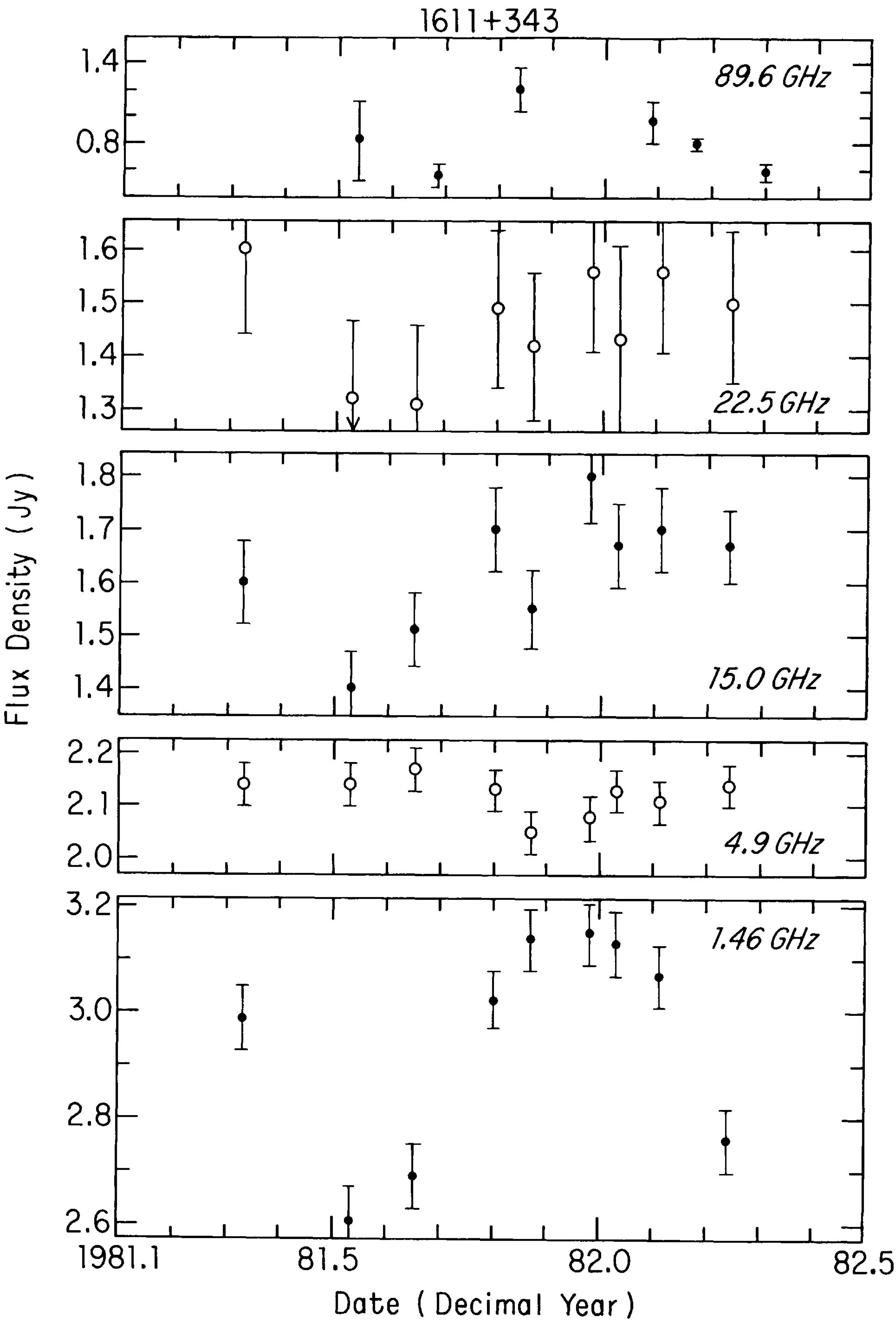
81.5
82.0
82.5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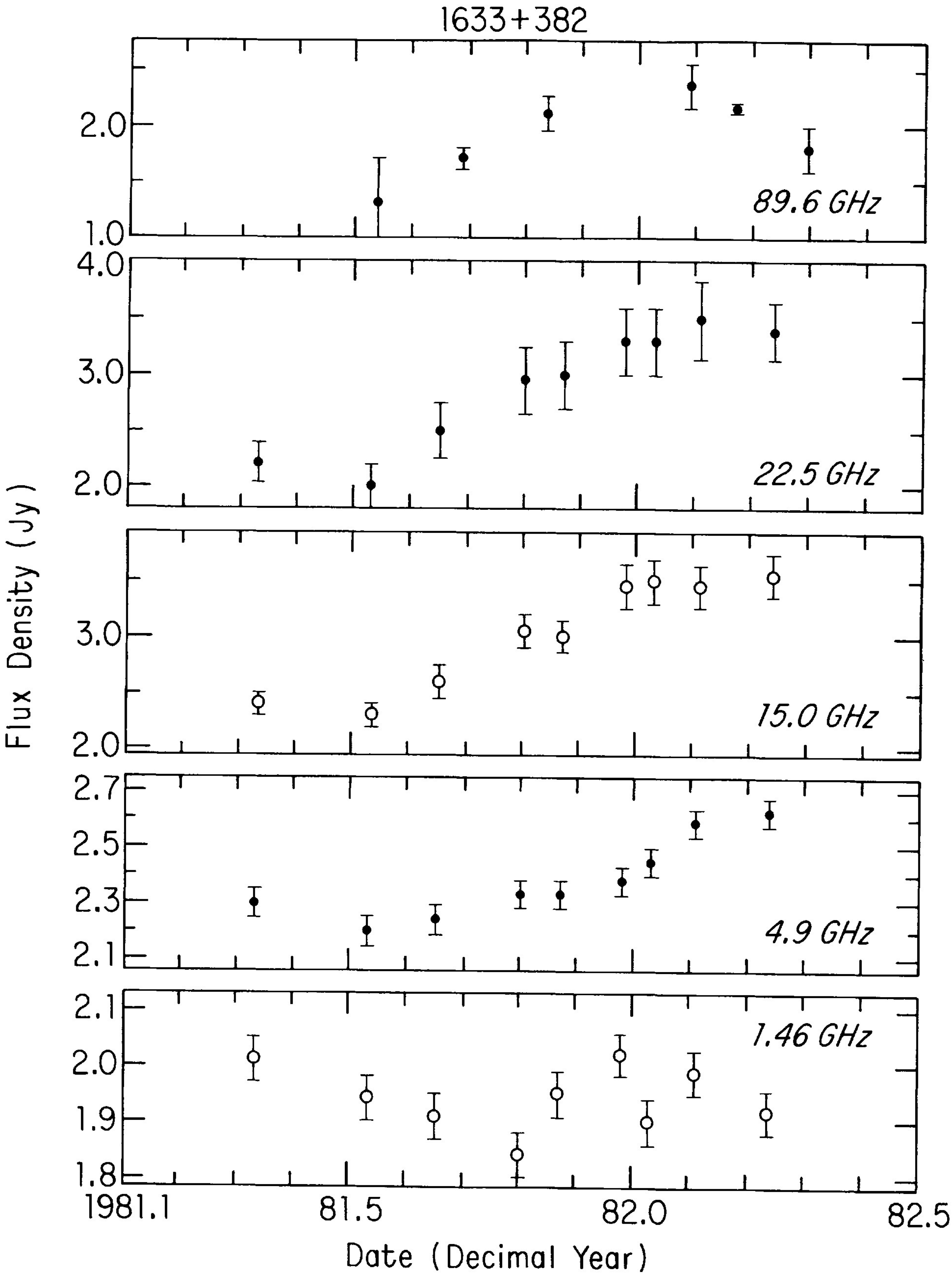
0.8
89.6 GHz
1.6
1.5
1.4
1.3
22.5 GHz
1.8
1.7
1.6
1.5
1.4
15.0 GHz
2.2
2.1
2.0
4.9 GHz
3.2
3.0
2.8
2.6
1.46 GHz
Flux Density (Jy)
1981.1
81.5
82.0
82.5
Date (Decimal Year)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15.0 GHz
4.9 GHz
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Flux Density (Jy)
Date (Decimal Year)
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82.5
2.0
1.0
4.0
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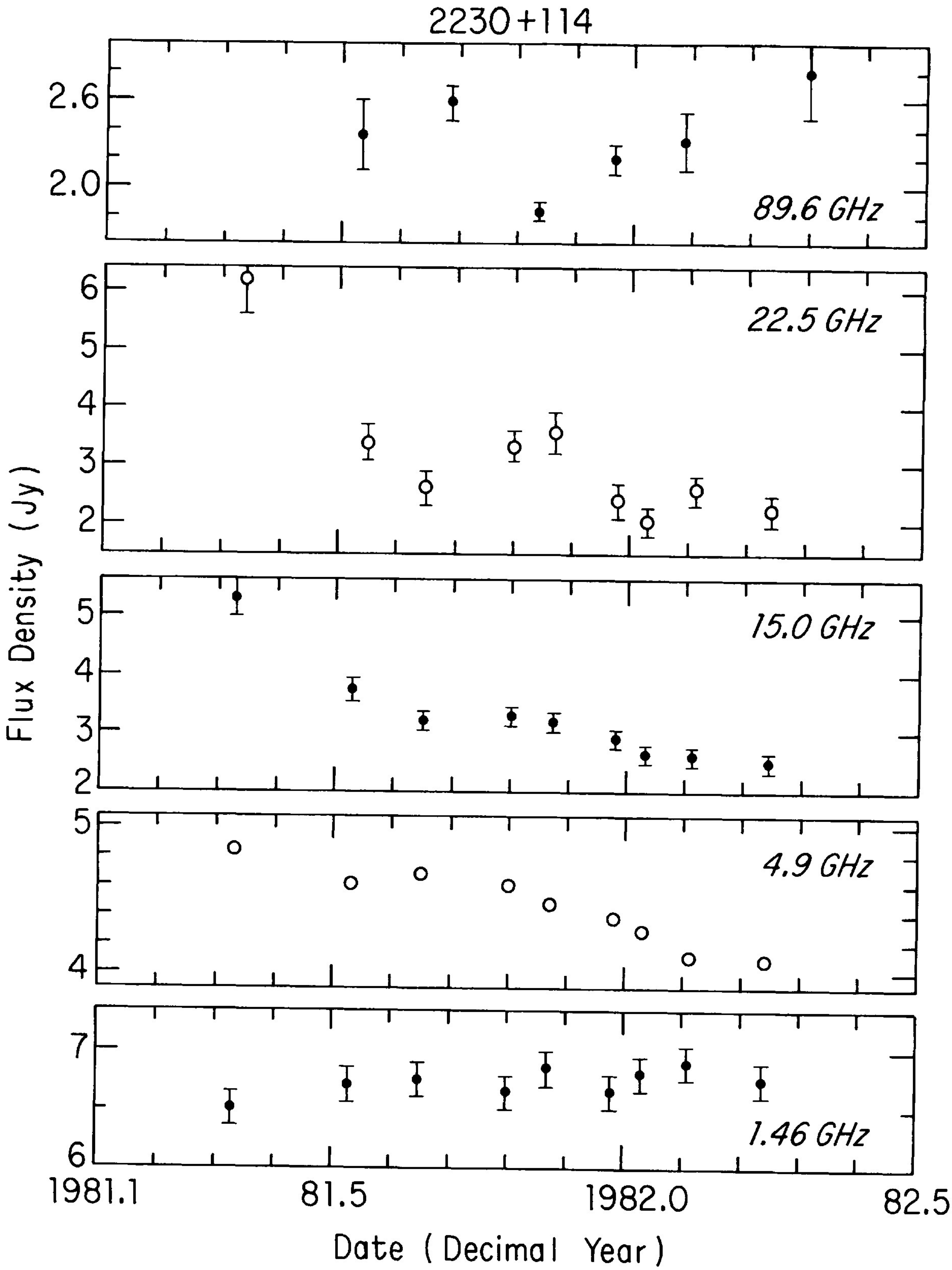
1.8



2230+114
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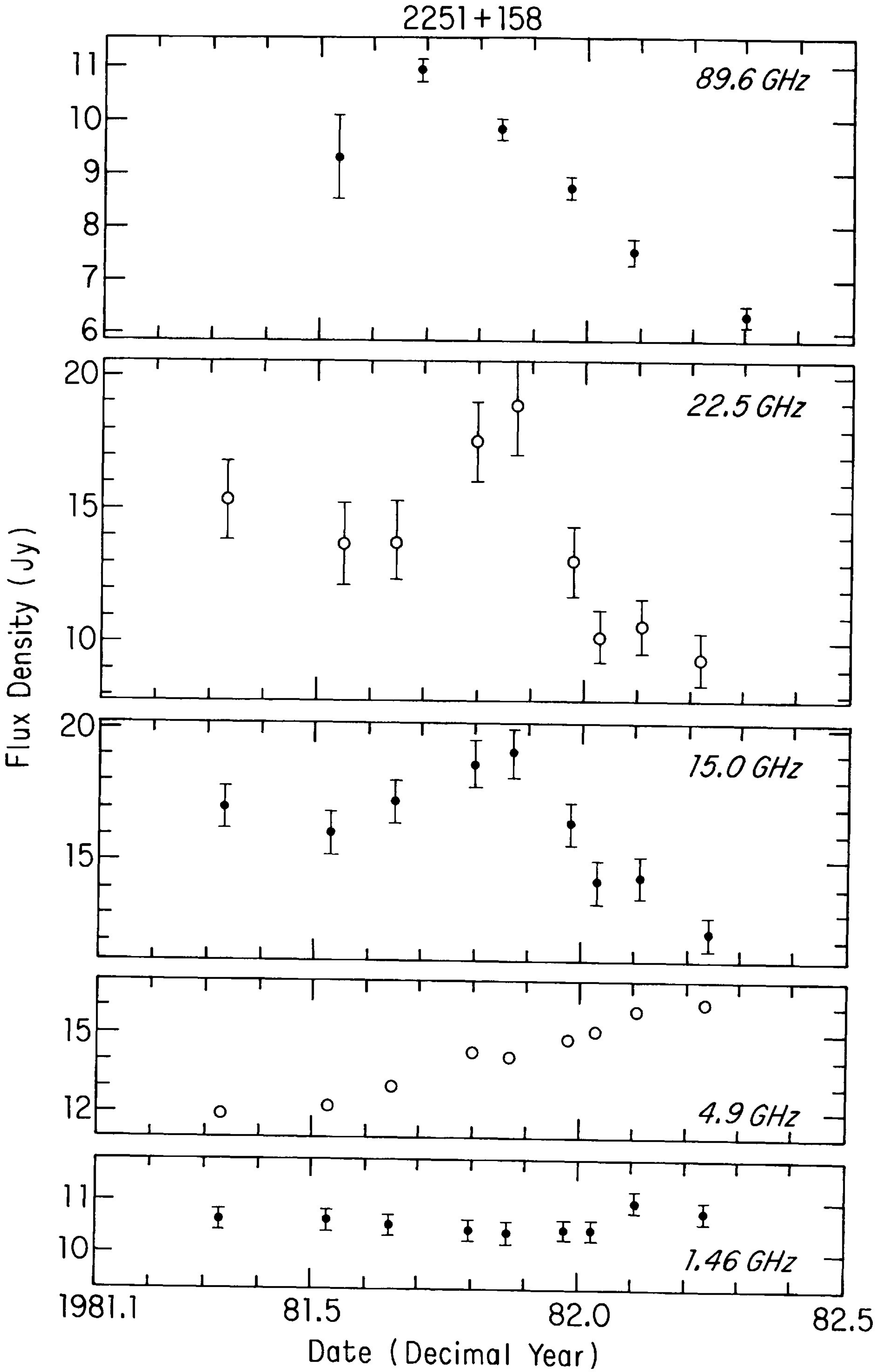
2.0
89.6 GHz
6
5
4
3
2
22.5 GHz
5
4
3
2
15.0 GHz
5
4.9 GHz
4
7
6
1.46 GHz
Flux Density (Jy)
1981.1
81.5
1982.0
82.5
Date (Decimal Year)



2251+158
89.6 GHz
22.5 GHz
15.0 GHz
4.9 GHz
1.46 GHz
Flux Density (Jy)
11
10
9
8
7
6
20
15
10
20
15
15
12
11
10
1981.1
81.5
82.0
82.5
Date (Decimal Year)

THE RELATIONSHIP BETWEEN LOW-FREQUENCY VARIABILITY AND OPTICAL POLARIZATION OF QSOs

R. L. Moore

Owens Valley Radio Observatory
California Institute of Technology

I. INTRODUCTION

In recent years, we have made an extensive survey of the optical linear polarization of QSOs. The results of this survey show that there are two basic types of QSOs which can be distinguished on the basis of their optical polarization. The majority of radio-loud QSOs (~85%) and essentially all radio-quiet QSOs have relatively stable low polarization (P < 2%). A small fraction of radio-loud QSOs (~15%) exhibit high polarization (P ~ 4-20%) which is rapidly variable on time scales of days.

The differences between "normal" low polarization QSOs and highly polarized QSOs (HPQs) extend beyond their polarimetric properties. In general, the HPQs exhibit rapid photometric variability, steep relatively smooth optical/infrared continua, and compact radio structure (Moore and Stockman 1981). Normal QSOs exhibit moderate photometric variability, have flatter optical continua, and may be either radio-loud or radio-quiet. Despite these differences, HPQs are certainly related to normal QSOs - both classes have similar distributions of redshift, luminosity, and emission line strengths (Moore and Stockman 1982).

The question to be examined in this paper is whether there is a relationship between low-frequency variability and optical polarization. If a relationship exists, it would not only provide a clue to both phenomena but it would also establish that theoretical explanations of low-frequency variability must ultimately address the characteristics of these objects at all wavelengths.

II. RESULTS

We have cross-referenced all QSOs in our polarization survey against those QSOs which have been monitored for low-frequency variability. The QSOs are polarimetrically distinguished only in terms of whether they exhibit high or low polarization. The references searched for low-frequency monitoring are Hunstead (1972), Cotton (1976), McAdam (1976), Condon et al. (1979), Fanti et al. (1979 and 1981), and Spangler and Cotton (1981). The classifications for low-frequency variability are taken from the references as variable, possibly variable, or not variable. If any reference reported variability, this was adopted as the appropriate classification.

A total of 69 QSOs have been observed polarimetrically and also monitored for low-frequency variability. This sample is not a complete sample as the selection criteria vary widely for various radio surveys and our polarization survey. However, the arguments to be made are not seriously compromised by this heterogenous sample.

The results are summarized in Table 1. The number of QSOs with each polarimetric and low-frequency variability classification are given. In addition, two percentages are given for each category; the upper right is the fraction the number represents for that polarimetric class, while the lower left is the percentage for the given low-frequency variability class. For completeness, we include variability information for the ten BL Lac objects which have been monitored.

It is clear that there is not a one-to-one correspondence between high polarization and low-frequency variability. However, the occurrence of low-frequency variability is much higher among HPQs (64%) than normal radio-loud QSOs (19-24%). This result suggests that high polarization and low-frequency variability are associated.

If one were to measure the optical polarization of known low-frequency variables, Table 1 shows that ~40% would be HPQs while 60% would have low polarization. However, this is not evidence that low-frequency variability is associated with low polarization. Only ~15% of raido-loud QSOs are HPQs; the fact that the occurrence of high polarization among low-frequency variables is 40% (>15%) confirms that low-frequency variability is preferentially associated with HPQs.

Table 1: Low Frequency Variability and Optical Polarization Classifications of QSOs

	Low-Frequency Variability			
	N	P	Y	Total
HPQs	4 36% / 8%	–	7 64% / 39%	11 100% / 16%
Low Pol QSOs	44 76% / 92%	3 5% / 100%	11 19% / 61%	58 100% / 84%
Total	48 70% / 100%	3 4% / 100%	18 26% / 100%	69 100% / 100%
BL Lac Obj.	6	–	4	10

One selection effect which must be considered is whether the correlation between low-frequency variability and high optical polarization is due to the fact that both characteristics are associated with compact, flat-spectrum radio sources. Condon et al. (1979) have found that ~25% of flat-spectrum sources are low-frequency variables while few, if any, steep-spectrum sources are variable. Essentially all HPQs have flat spectra. Since the low polarization QSOs in our survey have both flat and steep spectra, this could produce a correlation in the sense observed.

The only evidence addressing this point is that 64% of the (flat-spectrum) HPQs are low-frequency variables. If one includes the flat-spectrum BL Lac objects, 11 of 21 (52%) "blazars" are low-frequency variables. These percentages are higher than the 25% variability detection rate which Condon et al. (1979) have found among flat-spectrum sources. Thus, although the numbers are small, it appears that low-frequency variability is more strongly correlated with high optical polarization than would be expected if this correlation were due just to their flat radio spectra.

We conclude from these results that there is a correlation between high optical polarization and low-frequency variability. It is not a one-to-one correlation; rather, we can say that the two properties are frequently associated.

III. DISCUSSION

While not all HPQs are low-frequency variables (or vice-versa), we have established that HPQs are more likely than normal QSOs to exhibit low-frequency variability. Similarly, of five superluminal radio sources which have been observed polarimetrically, two are HPQs. These correlations enhance the general picture of HPQs as extreme objects which pose serious theoretical problems.

There are two important conclusions to be drawn from the correlation between high optical polarization and low-frequency variability. First, the correlation argues against any "extrinsic" theories to account for low-frequency variability (e.g. galactic spurs). More generally, such a correlation illustrates that nature is providing a broad spectrum of clues concerning active sources. Any models to explain phenomena such as high optical polarization, low-frequency variability, or superluminal motion must ultimately incorporate all the related properties of these sources.

A relativistic beaming model (e.g. Blandford and Rees 1978, Scheuer and Readhead 1979) is attractive in that it addresses many of the diverse observational results. In this model, the HPQs and low-frequency variables are those QSOs viewed close to the jet axis; problems posed by variability measurements can be minimized given a sufficient Lorentz factor for the jet. We would point out that only about half of superluminal sources or low-frequency variable QSOs are HPQs. This may be evidence that the beaming angle for optical emission (presumably very close to the central engine) is narrower than the angle for radio emission.

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Long-Term Optical Monitoring of a Sample of Low Frequency Radio Variables

Alex G. Smith, R. J. Leacock, and A. J. Pica
Rosemary Hill Observatory
University of Florida

A program of long-term optical monitoring of variable extragalactic sources has been carried on at Rosemary Hill Observatory since 1968. The principal instrument used in this work is the 76-cm reflector; our work is done photographically at the f/4 Newtonian focus. Currently we are monitoring about 230 extragalactic sources, often in collaboration with radio observers or with groups using spacecraft such as the I.U.E.

In the fall of 1979 we entered into an agreement with John Broderick of VPI to begin long-term optical monitoring of a group of low-frequency radio variables (LFVs). Broderick provided us with a list of 29 candidates, all of which he classified as definite or probable low-frequency variables, and all of which would also be monitored regularly by the V.P.I. group at low radio frequencies. It turned out that 14 of these sources, or nearly half, were already on the Florida observing list (see Pica et al., 1980, and Pollock et al., 1979), so we had to add only 15 new fields. The objective of the program is of course to search for radio/optical correlations that might place constraints on the several models that have been proposed to account for the LFV phenomenon (see discussions elsewhere in this volume).

Table 1 displays the complete list of program objects. The sources are listed in order of increasing right ascension, with the second column giving common names where these are more familiar. The third column lists the number of Florida observations of each source, with the year in which observations were begun shown in parentheses. Where multiple observations were made on a single night, these are counted as a single observation. The fourth column lists Broderick's identification of the type of object, while the last column includes comments based on our observations. In 4 cases the object was not visible (NV) at our plate limit of about 19th magnitude for the 103a-0 emulsion or 21st magnitude for hydrogenated IIIa-J. Two of the galaxies, 0116+31 and 1345+12 are too diffuse for reliable iris photometry, so they were not pursued. Sixteen of the objects are definite optical variables, with 6 of these being OVV's or "optically violent variables". Three sources are possible optical variables, based on our records to date. We have a possible faint identification in one of Broderick's empty fields (EF), which will be pursued further.

Table 1. Low frequency variable observing list. Objects on the original Florida program are designated by an asterisk. G = galaxy, Q = quasar, Lac = BL Lac object, N = N galaxy, NV = not visible, EF = empty field.

Parkes Desig.	Other Desig.	No. Obs.	I.D.	Comments
0038+32		2 ('80)	G	NV
*0056-00		39 ('69)	Q	17^m, non-var.
0116+31			G	Too diffuse
0202+14		2 ('80)	EF	NV
*0235+164		98 ('75)	Lac	OVV, 15.5-20^m
0256+07		4 ('80)	N	NV
*0333+32	NRAO 140	38 ('71)	Q	Var., 16.5-17.5^m
*0336-01	CTA 26	59 ('69)	Q	Var., 17-18^m
0400+25		10 ('80)	Q	Faint var., ∿18.5-20^m
*0420-01		124 ('69)	Q	OVV, 16-19.5^m
0446+11		4 ('69)	G	Faint var., ∿20^m
0723-00		17 ('80)	N	Var., 17.6-19.1^m
*0735+17		237 ('70)	Q	OVV, 14-17^m
*0851+20	OJ287	257 ('69)	Lac	OVV, 13-17^m
1039+02		4 ('80)	EF	Poss. I.D. on IIIa-J
1117+14		4 ('80)	Q	NV
*1345+12		3 ('71)	G	Too diffuse
1422+20	4C 20.33	12 ('80)	Q	∿18^m, poss. var.
*1548+05	4C 05.64	22 ('71)	Q	∿19^m, poss. var.
*1606+10	4C 10.45	22 ('71)	Q	Slightly var., ∿16.5^m
1611+34	DA 406	15 ('80)	Q	∿17.5^m, poss. var.
1901+31	3C 395	18 ('80)	Q	∿17.5^m, var.
*2144+09	OX 074	119 ('69)	Q	OVV, 16-18^m
*2145+06	4C 06.69	67 ('69)	Q	16^m, non-var.
2201+31	4C 31.63	17 ('80)	Q	Var., 15.4-16.1^m
2223+21		14 ('80)	Q	Var., 17.8-18.7^m
*2230+11	CTA 102	37 ('73)	Q	Var., 17-18^m
*2251+15	3C 454.3	79 ('68)	Q	OVV, 16-17.5^m
2319+27		9 ('80)	G	16.5, non-var.

OVV's represent 27% of the 22 objects in Table 1 that we have been able to observe successfully. This proportion suggests that OVV's are over-represented among the LFV's by a factor of from 2 to 3 relative to the general population of QSO's. A similar conclusion, also based on our optical data, was reached by Dennison et al. (1981). Obviously this carries with it implications of small optical emission regions with high brightness temperatures.

Figure 1 shows light curves for 8 of the sources in Table 1. These have been updated to April of 1982. The figure includes the light curves of all 6 OVV's. Inspection of the figure reveals a wide diversity of event timescales, amplitudes, and morphologies. Event rise or fall times range from days (AO 0235+164) to years (OJ 287). Clearly there is no such thing as a "typical"

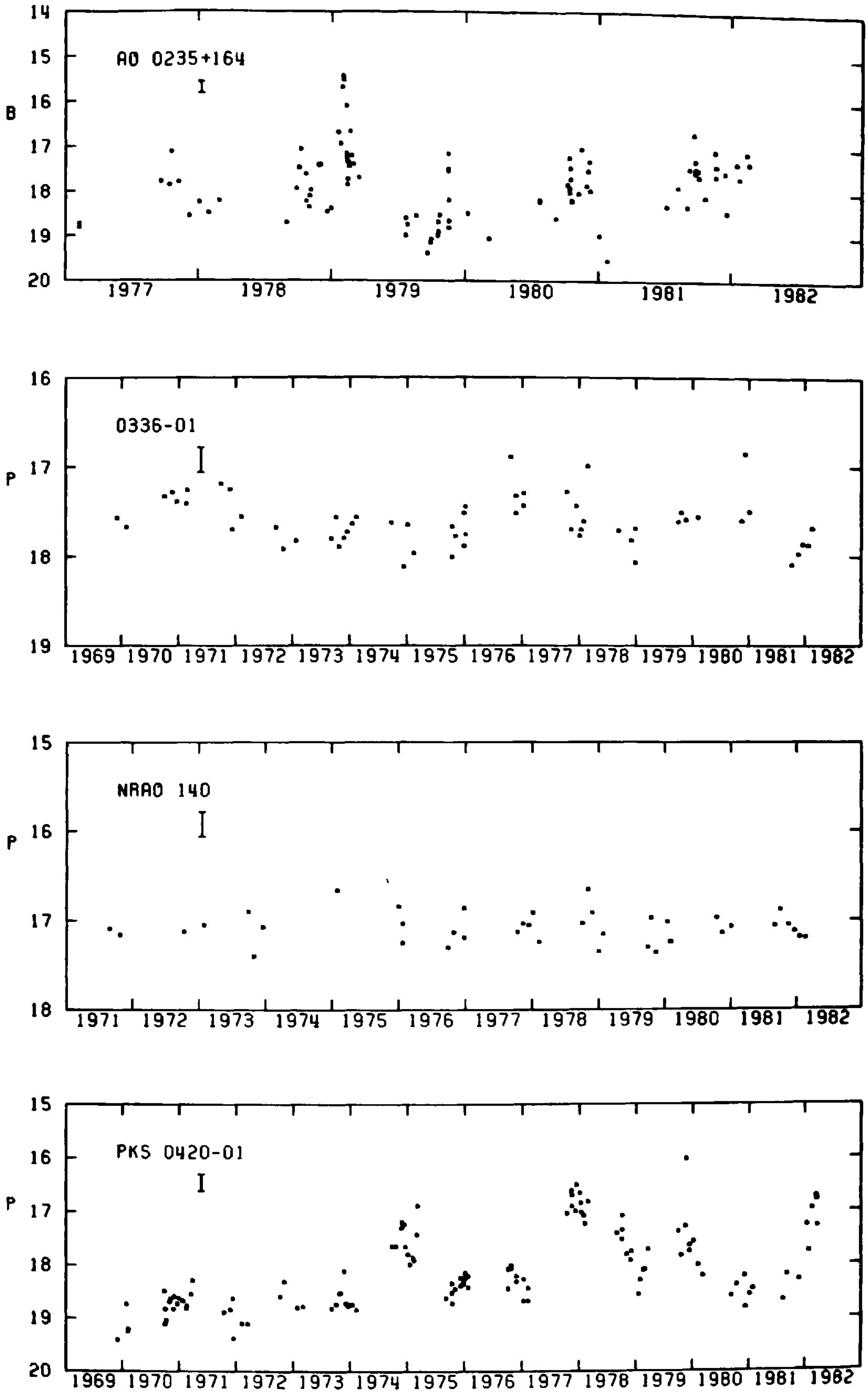


Fig. 1. Florida light curves for eight LFV's.

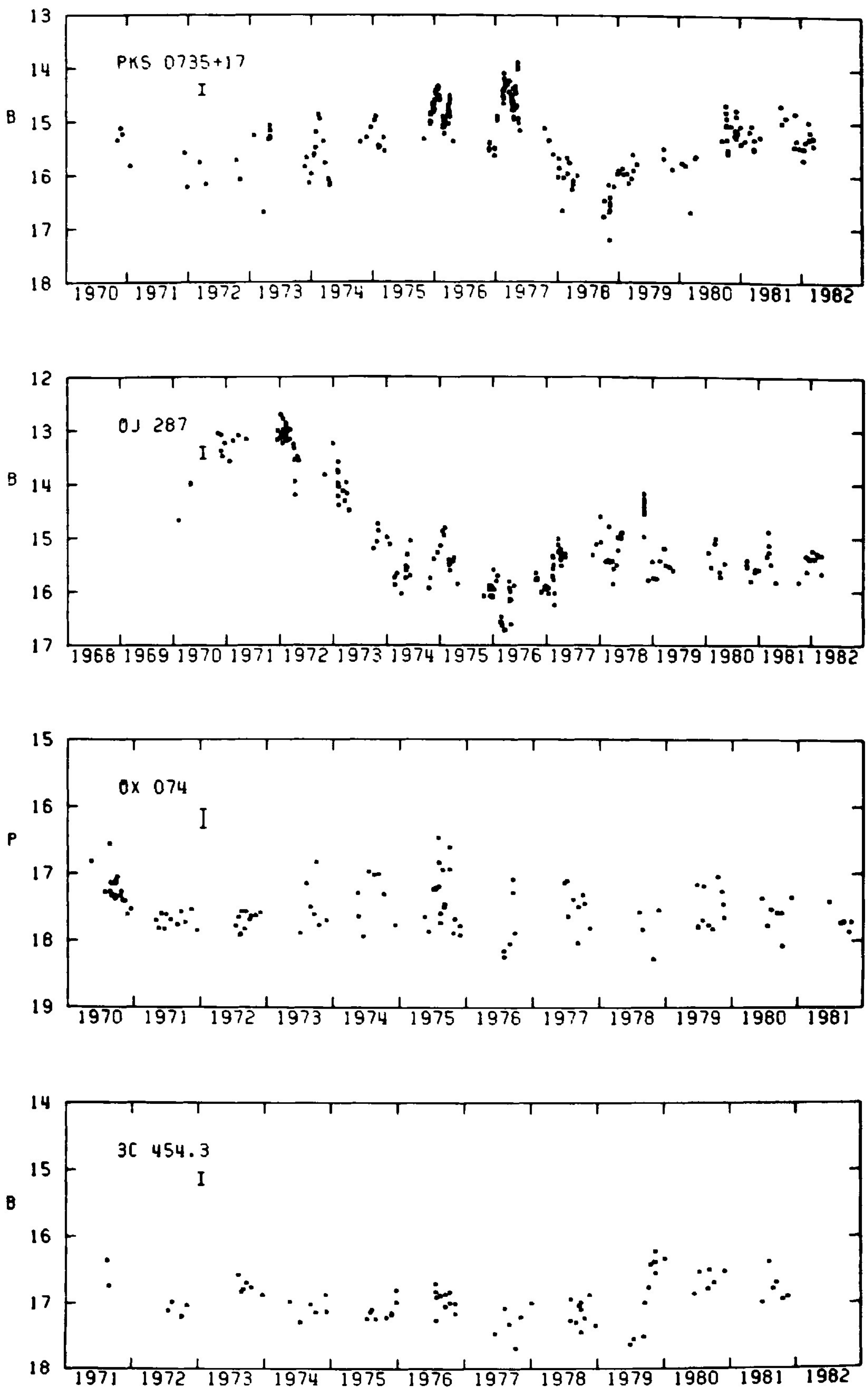


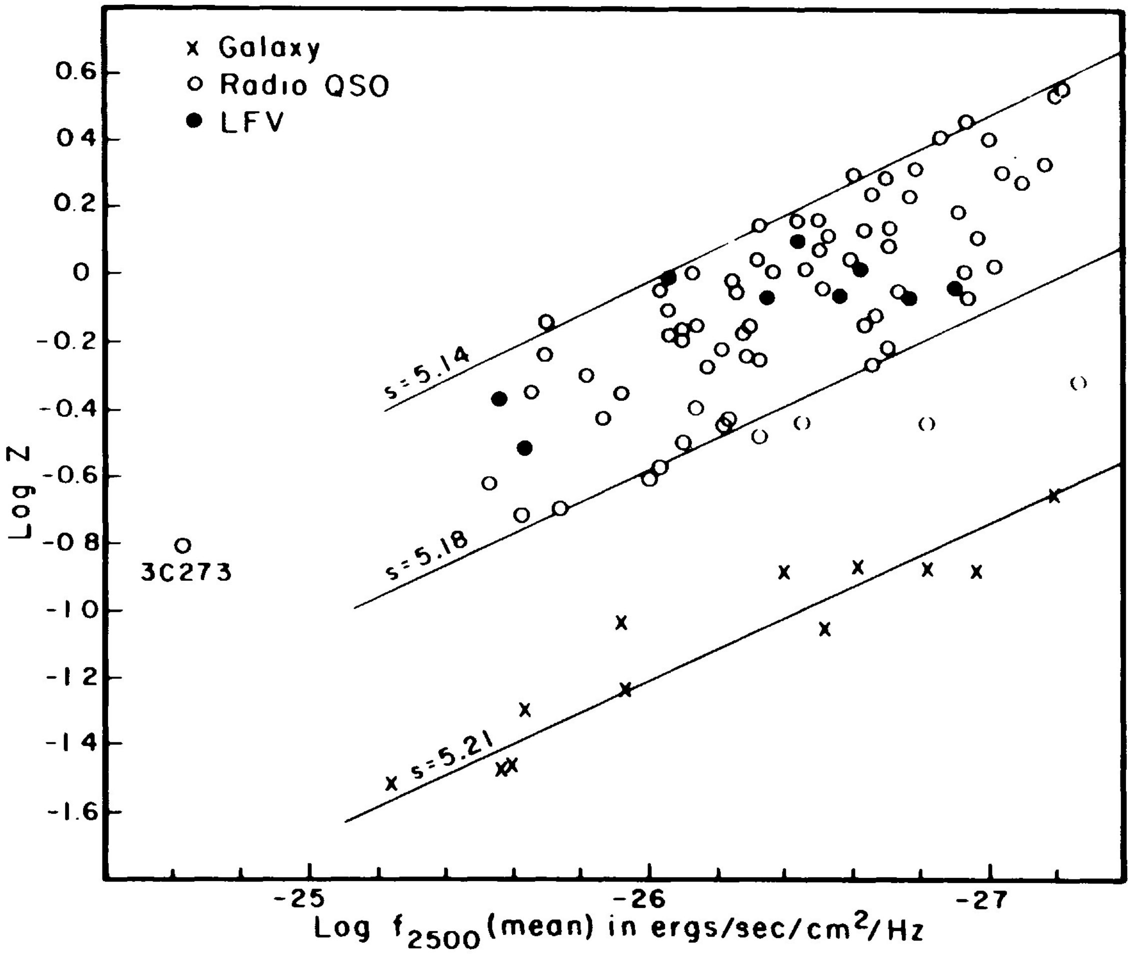
Fig. 1. Continued.

light curve for a low frequency variable. Some objects (e.g., OJ 287) seem to display multiple timescales, with rapid "flickering" superimposed on long-duration events.

Some years ago a member of our group, R. B. Pomphrey, made a study of the correlation between our long-term light curves and concurrent long-term centimeter-wavelength curves for 22 extragalactic variables (Pomphrey et al., 1976). The one object showing striking correlation was one of our low-frequency variables, OJ 287. The next-best correlation was for 3C 454.3, another low-frequency variable; 0735+17 showed marginal evidence of correlation. Dent and his colleagues subsequently showed good correlation between their radio observations of two outbursts of the LFV 0420-1 and our optical data (see Dent et al., 1979). During the NRAO LFV Workshop, McAdam called attention to a remarkable dip or "antiflare" that occurred in 1975 in the Molongolo 408-MHz flux from 0736+017. At virtually the same time the Florida records (Pica et al., 1980) show 0736+017 flaring to the brightest level reached during the 9-year span of those records. This is precisely the behavior expected if the radio dip was due to photoionization of an absorbing screen by ultraviolet flux from the optical event. While caution must be exercised in overinterpreting a single example, this event is indicative of the way in which radio/optical correlations can be used to support proposed models of the LFV phenomenon. Overall, there is a strong suggestion that radio and optical observations of LFV's show an above-average tendency to correlate, as compared with the general population of radio QSO's. If so, this presages well for the future of the V.P.I./Florida collaboration.

We are currently engaged in a study of the cosmological properties of a sample of 130 extragalactic sources (Pica, 1982). Since this sample includes a third of our low-frequency variables, it is interesting to examine them from that point of view.

Figure 2 is a Hubble plot of monochromatic flux density f_{2500} vs. log z. The parameter f_{2500} represents the observed flux converted to a rest-frame wavelength of 2500 Å via the redshift and the optical spectral index. This procedure is, in effect, equivalent to computing K-corrections; f_{2500} has also been corrected for galactic extinction and the presence of emission lines in the observed UBV bands. The Florida variability data were used to compute mean values of f_{2500}, which empirically proved to give a significantly tighter Hubble relationship than either the base or the peak fluxes. Radio QSO's are represented by circles, with the low frequency variables designated by filled circles. The sloping lines define the upper and lower envelopes of the QSO's. Their slopes (s) are quite near the theoretical value of 5 magnitudes per decade in log z expected from standard cosmologies



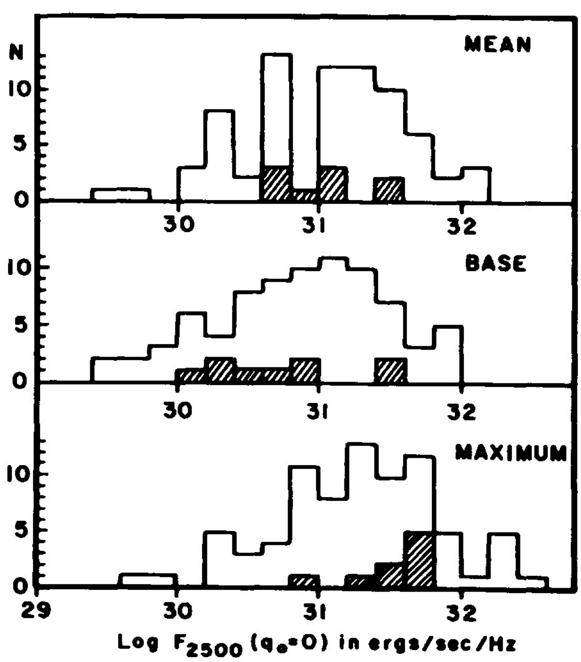


Fig. 2 (above). Hubble diagram including LFV's.

Fig. 3 (left). Absolute luminosities of QSO sample, including LFV's (shaded bars).

(such as a Friedmann universe with $q_o = 1$). The distribution of the LFV's seems unremarkable except for a weak tendency toward higher luminosities.

Figure 3 plots distributions of absolute monochromatic luminosities F_{2500}, again using a standard cosmology with zero pressure, zero cosmological constant, and H_o = 75 km/sec/Mpc. Here the distributions are shown for the mean fluxes, the base-level fluxes, and the peak fluxes, all again derived from our long-term variability studies. In the first two cases the low frequency variables, shown as shaded bars, seem to follow the general distribution. In the case of the peak (maximum) values, however, the LFV's are decidedly skewed toward high absolute luminosities. In fact, over half of them have the same peak luminosity, 5×10^{31} ergs/sec/Hz.

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PULSAR ISS AND CONSTRAINTS ON THE ANGULAR SIZES OF LOW-FREQUENCY VARIABLE SOURCES

James M. Cordes
Cornell University
Ithaca, New York

ABSTRACT

Measurements of interstellar scintillations of pulsars are used to put constraints on the scale height and level of turbulence of electron-density fluctuations in the ISM. There is sufficient uncertainty to prohibit a strong conclusion favoring relativistic bulk motion in LFV's from the fact that scintillations are not seen from LFV's. In particular, it is possible that intrinsic source sizes are small (necessitating a coherent radiation process with $T_B >> 10^{12}$°K and so that inverse-Compton x-rays be less than limits from the Einstein Observatory) and angular broadening occurs in an intergalatic medium or in a galactic halo so as to quench scintillations. Such broadening may be due to cold plasma ($\theta \propto \lambda^2$) or from scattering off a stochastic background of gravity waves of fairly low energy density ($\Omega_{GW} \lesssim 10^{-7}$). Angular broadening from gravity waves would be wavelength independent.

PULSAR SCINTILLATIONS

Scattering of radio waves off of electron-density fluctuations in the interstellar medium is manifest in several ways: (1) scintillations in frequency and time of compact radio sources with a characteristic bandwidth $\Delta\nu_{ISS}$; (2) angular broadening going approximately as λ^2 (distance)$^{1/2}$ and (3) temporal broadening of pulsar pulses over a time τ due to multipath propagation. Pulsar observations of $\Delta\nu_{ISS}$ and τ indicate that electron-density fluctuations are consistent with power-law irregularity spectra of the form C_N^2(wavenumber)$^{-\alpha}$ with $\alpha \stackrel{\sim}{\sim} 3.6$ and extending over at least several decades in wavenumber (Armstrong et al. 1981). Pulsars are distributed with a scale height $\sim$300-400 pc and have dispersion measures due to electrons with a scale height $\sim$1 Kpc (Lyne 1981; Harding 1981). The electron-density turbulence that causes interstellar scintillations (ISS) is not necessarily coincident with the medium causing pulsar dispersion measures. Measurements of $\Delta\nu_{ISS}$ and τ yield estimates for C_N^2, the "level of turbulence" along the line of sight, that suggest a smaller scale height than the dispersing electrons. If we model the distribution of C_N^2 with galactic altitude, z, as

$$C_N^2(z) = C_{N_o}^2 \exp(-|z|/H_s) \qquad (1)$$

then both $C_{N_o}^2$ and H_s can be constrained by observations of pulsars with different values of z, as shown below. The results discussed here disagree with those of Hall (1981) who attributes (theoretically) a narrow-band irregularity spectrum to the scattering medium and a very small scale height, $H_s \sim 71$ pc. It appears that Hall's determination of H_s (based on only 31 pulsars) is contaminated by objects with large path lengths through the galactic plane. Some of these lines of sight evidently encounter enhanced regions of scattering (HII regions, shock fronts?) that have small scale height and small filling factor. Searches for ISS from extragalactic sources usually involve path lengths of high galactic latitude which have a small probability of passing through enhanced scattering regions. Consequently, determination of H_s for the purposes of putting constraints on low-frequency variable radio sources must use pulsars that have similar galactic latitudes.

DETERMINATION OF $C_{N_o}^2$ AND H_s

By combining measurements of $\Delta\nu_{ISS}$ and τ from the literature with those obtained recently in a survey at Arecibo (Cordes, Weisberg and Boriakoff 1982), we have measurements of $\hat{C}_N^2$ for 59 lines of sight. Those lines of sight with path lengths $\gtrsim 3$ kpc show a high probability of encountering a region of enhanced scattering. By restricting to pulsars with $|b| \geq 5°$, the sample is reduced to 36 objects. Figure 1 shows $\hat{C}_N^2$ plotted against $z = L \sin|b|$ where $\hat{C}_N^2$ is determined from

$$\hat{C}_N^2 = A_1 \left(\frac{\Delta\nu_{ISS}}{1\ \mathrm{MHz}}\right)^{-5/6} \nu_{GHz}^{11/3} L_{kpc}^{-11/6}\ \mathrm{meters}^{-20/3} \quad (2)$$

with $A_1 = 7.2 \times 10^{-4}$ meters$^{-20/3}$ and where $\Delta\nu_{ISS}$ is determined as the FWHM of the autocorrelation function of the RF scintillation spectra (see Armstrong and Rickett 1981 for details). Pulsar distance, L, was determined from the dispersion measure and assuming $n_e(z) = n_{e_o} \exp(-|z|/H_d)$ with $n_{e_o} = 0.03\ \mathrm{cm}^{-3}$ and H_d = 1 kpc. Also shown in Figure 1 are curves for $\hat{C}_N^2$ that would result from equation (2) if C_N^2 is exponentially distributed as in equation (1) with scale heights H_s = 50 pc to 1 kpc. Values of $C_{N_o}^2$ were chosen so that the product $C_{N_o}^2 H_s$ = constant = 10^{-4} kpc - meters$^{20/3}$. Any fit to the data would yield a very uncertain value for H_s, especially since it is unclear, apriori, which points to discard because the lines of sight pass through HII regions. The line of sight to PSR 1642-03 passes through the HII region ζ Oph (Prentice and ter Haar 1969). There may be no meaningful fit of eqn. (1) to the data because scattering may occur in several different phases of the ISM with different filling factors and scale heights.

IMPLICATIONS OF NO ISS FROM LOW FREQUENCY VARIABLES

If low-frequency variables (LFV's) are smaller than $c\,\Delta\tau$ with $\Delta\tau$ the variability time, then LFV's would have angular sizes $\sim 10^{-6}$ arc sec and therefore should show ISS with 10-100% modulation of the intensity. Dennison and Condon (1981) put an upper limit on the modulation index of m = rms intensity/mean $\lesssim 10^{-3}$. This implies that the angular size is $\theta = m\,\theta_{crit} \gtrsim 10^3\,\theta_{crit}$ where θ_{crit} is a critical angular size that determines when scintillations get quenched (as in stars twinkle, planets do not). The conclusion has been that $\theta_{crit} \propto H_s^{-1}[H_s C_{N_o}{}^2]^{-3/5}$ is about 10^{-7} arc sec at 430 MHz so the LFV's must have angular sizes $\sim 10^{-4}$ arc sec, i.e. sizes consistent with those of incoherent self-absorbed synchrotron sources. If the argument is true, then the small variability time scales can be explained only by relativistic bulk motion with $\gamma_{bulk} \sim 10$.

We must question the arguments favoring relativistic bulk motion in two ways:

1) How well do we know θ_{crit}?

2) Is the angular size "seen" by the ISM the intrinsic angular size of the LFV's?

The answer to the first question is that there may be as much as a factor of 10 uncertainty in θ_{crit} from the pulsar observations alone. Moreover, it is possible that significant scattering occurs in the galactic halo (extending to $z > 10$ kpc) about which we know nothing from the pulsar observations (z_{max} = 1.8 kpc). A large-scale-height halo would produce a smaller value of θ_{crit}, implying that ISS from LFV's would be quenched for angular sizes much less than 10^{-4} arc sec. The second question is impossible to answer with any certainty, but it is quite possible that scattering occurs between the LFV and interstellar medium so as to angularly broaden the sources. The amount of scattering by plasma ($\theta_{scatt} \propto \lambda^2$) is impossible to predict because it requires knowledge of $\delta n_e/n_e$ and the length scale for fluctuations in δn_e. A hard upper limit on λ^2 scattering can be made from the 74 MHz VLBI measurement of 3C287 (Resch 1972) which gave $\theta_{3C287} \approx 0\overset{''}{.}1$ (HW at e^{-1}). Since the scattering angle in the ISM is (for path lengths $\perp$ galactic plane)

$$\theta_{ISM} = 0\overset{''}{.}076\ \nu_{GHz}^{-11/5}\ [H_{s_{kpc}}\ C_{N_o}^{\ 2}]^{+3/5}$$

the 3C287 result yields $H_{s_{kpc}}\ C_{N_o}^{\ 2} \leq 10^{-4}$ (the number used in plotting the curves in Figure 1).

The observed angular size for 3C287 is compatible with it deriving from λ^2 scattering from the same medium sampled by the pulsars. Enough uncertainty exists, however, for one to interpret the measured size to be mostly intrinsic or mostly produced in a halo or IGM. Consequently, it is possible that sufficient λ^2 scattering occurs in an IGM so as to quench ISS from low-frequency variables. It is also possible that λ-independent scattering occurs from stochastic backgrounds of gravity waves.

A lower limit to such scattering is $10^{-2.52}$ mas for a source at redshift z = 1.0 due to gravity waves produced by main-sequence binary stars alone (Simonetti, Cordes, and Wasserman 1982). Figure 2 shows limits on angular broadening as a function of frequency.

CONCLUSION

A survey of pulsar scintillations indicates considerable uncertainty in interpreting the lack of scintillations from low-frequency-variable sources. The argument that low-frequency variables must undergo relativistic bulk motion because ISS is not observed is shown to have a "window of vulnerability" because considerable angular broadening could occur in a galactic halo or in an intergalatic medium..

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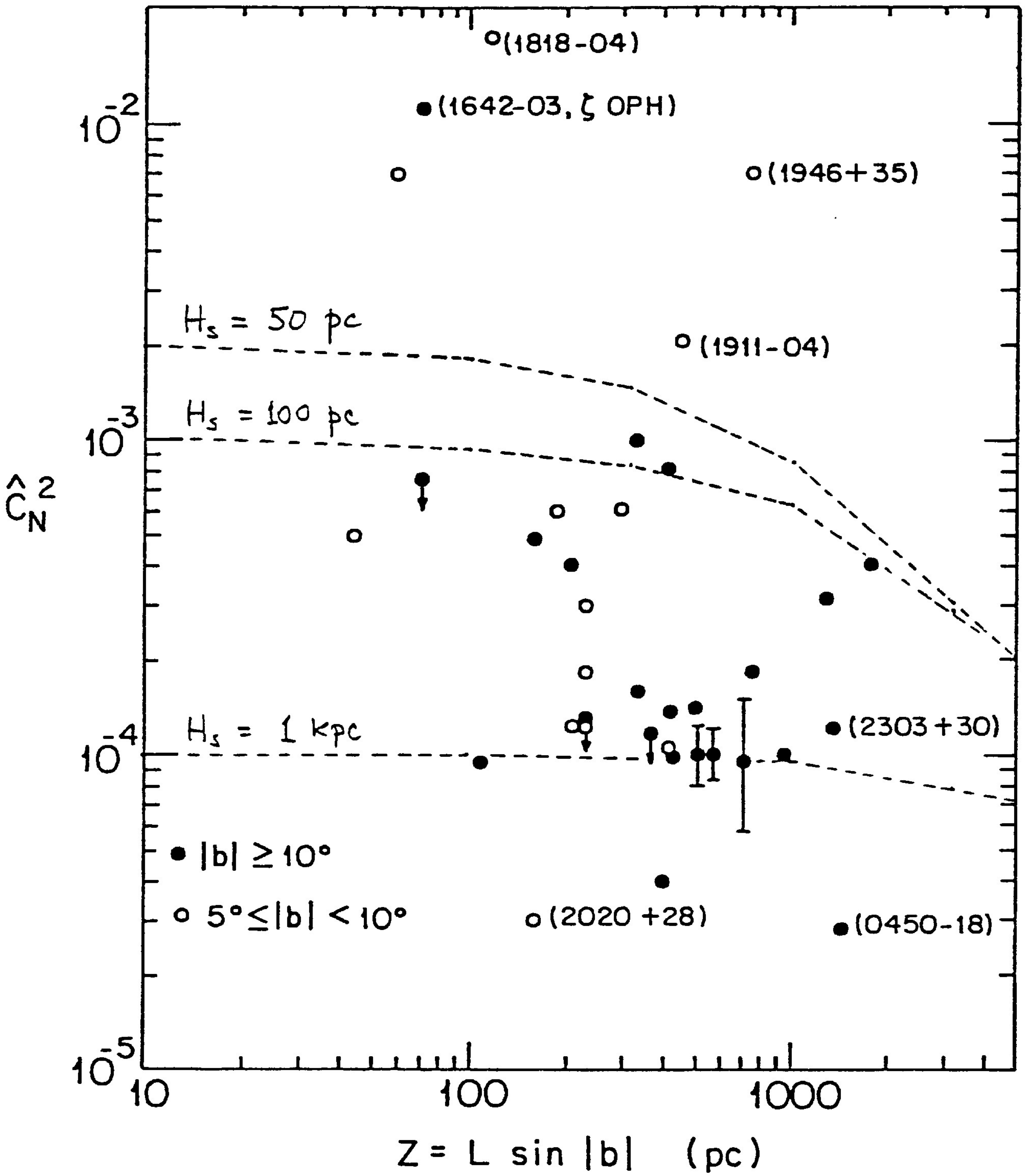
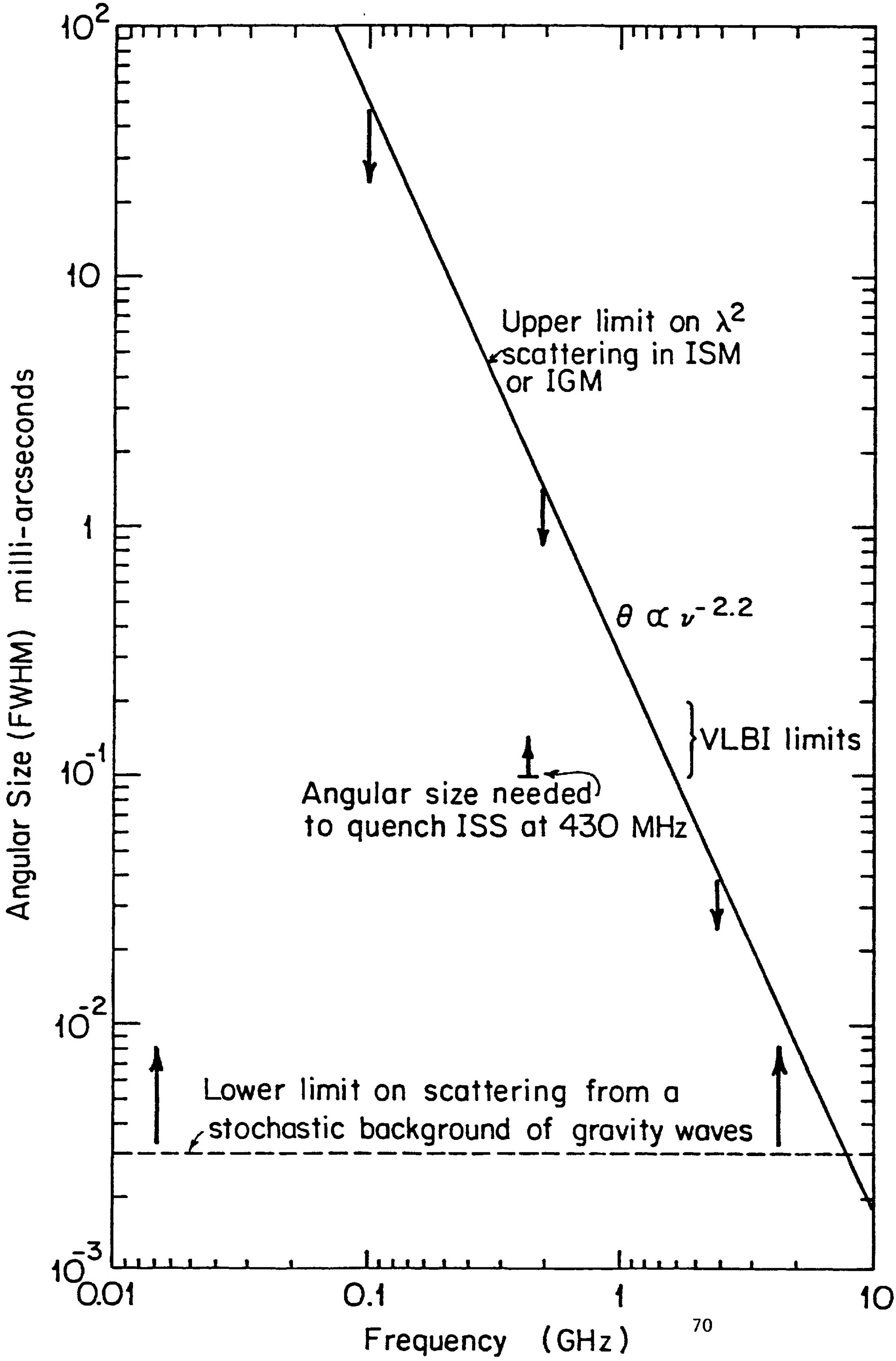


(1818-04)
(1642-03, ζ OPH)
(1946+35)
H_s = 50 pc
(1911-04)
H_s = 100 pc
$\hat{C}_N^2$
H_s = 1 kpc
(2303+30)
|b| ≥ 10°
5° ≤ |b| < 10°
(2020+28)
(0450-18)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10
100
1000
Z = L sin |b| (pc)



Angular Size (FWHM) milli-arcseconds
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
0.01
0.1
1
10
Frequency (GHz)
Upper limit on λ^2 scattering in ISM or IGM
$\theta \propto \nu^{-2.2}$
VLBI limits
Angular size needed to quench ISS at 430 MHz
Lower limit on scattering from a stochastic background of gravity waves

A RE-EVALUATION OF SOME PARAMETERS RELEVANT TO INTERSTELLAR SCINTILLATION

Brian Dennison
Physics Department
Virginia Polytechnic Institute and State University

I. INTRODUCTION

The most direct interpretation of low frequency variations, having observed timescale τ is that they occur in source components smaller than $c\tau/(1+z)$. Assuming a cosmological interpretation of redshift, the angular sizes thus inferred tend to be $\sim 10^{-4.3}$ arcsec, with brightness temperatures ($\gtrsim 10^{15}$ K), well in excess of the 10^{12} K Compton limit for static incoherent electron synchrotron sources. A number of authors have proposed that alternative emission mechanisms are operative, such that the actual brightness temperatures of the varying components are roughly those inferred from the variations, i.e. $\gtrsim 10^{15}$ K (Cocke and Pacholczyk 1975; Colgate, et al. 1975; Colgate, and Petschek 1978; Cocke, Pacholczyk, and Hopf 1978). This class of models (ultrabright) is testable since such small source components are expected to scintillate at the ~1% level when viewed through the interstellar medium (ISM). A number of searches, however, have failed to uncover interstellar scintillations (ISS) in a sizeable number extragalactic sources, most of them low-frequency variables (Condon and Backer 1975; Scheuer 1976; Armstrong et al. 1977; Condon and Dennison 1978; Dennison and Condon 1981). In a number of cases the upper limits to the scintillation index are below that predicted by the direct "ultrabright" interpretation of the low frequency variations (Scheuer 1976; Condon and Dennison, 1978; Dennison and Condon 1981), leading to the conclusion that ultrabright models are inapplicable, unless the apparent angular sizes of such components are substantially broadened by a hitherto unknown medium external to the galactic disk (Scheuer 1976; Armstrong et al. 1977; Condon and Dennison 1978; Dennison and Condon 1981; Hall 1982). Such a possibility might in principle be testable using transcontinental VLBI angular size measurements at ~80 MHz, taking advantage of the λ^2 scaling of the scattered angular size.

The other area of uncertainty concerns the scintillation calibration of the ISM. That pulsar scintillations occur primarily in envelopes surrounding pulsars (Cocke, Pachoczyk, and Hopf 1978; Cocke, Giampapa, and Pacholczvk 1979) has been shown to be an untenable hypothesis in a large majority of cases (Dennison and Condon 1981), owing primarily to the inverse correlation of decorrelation bandwidth with dispersion measure.

Recently, Hall (1980a) suggested that the scale height of the medium responsible for ISS is only 71 pc, and later revised this value to 79 pc (1980b). As it strongly affects the critical angular size for scintillations, the scale height is a very important parameter for predicting the scintillation indices expected for ultrabright source components. In our previous work (Condon and Dennison 1978; Dennison and Condon 1981), the assumed scale height was far more conservative (~0.3 - 1.0 kpc), resulting in expected scintillation indices of the order of one percent. The smaller scale height suggested by Hall (1908a,b) would imply a considerably larger value for the critical angular size, and increase the expected scintillation indices to the ~10% level, thus widening the gap between theoretical predictions (ultrabright) and observation. This would further enhance the possibilities of observing very weak ISS from compact incoherent synchrotron components (~10^{12} K) directly. In what follows, I analyze the scintillation properties of the ISM as applied to extragalactic radio sources, using the set of pulsar data used by Hall (1980a). These data were originally tabulated by Rickett (1977) and Wolszczan (1977).

II. ANALYSIS

From a measurement of decorrelation bandwidth, instantaneous pulse broadening, scintillation scale, or angular broadening, the parameter

$<C_N^2>$ may be calculated (Rickett 1977), where $<C_N^2>$ is proportional to the mean squared electron density fluctuation along the line of sight. Consider a simple model in which C_N (proportional to the rms electron density fluctuation) decreases with distance above or below the galactic plane, $|Z|$, with characteristic scale height, h; i.e.

$$C_N = C_{N_o} e^{-\frac{|Z|}{h}} , \quad (1)$$

where C_{N_o} is the value of C_N in the galactic plane. Then along a line of sight to a pulsar at distance, D, and galactic latitude, b, the mean value of C_N^2 is given by

$$<C_N^2> = C_{N_o}^2 \frac{h}{2D \sin|b|} [1-e^{-\frac{2D\sin|b|}{h}}] \quad (2)$$

Figure 1 shows the values of $<C_N^2>$ (inferred from observations) versus $D\sin|b|$ for all of the pulsar data compiled by Hall (1980a). Clearly the scatter is much too large to permit equation (2) to be fit meaningfully to the data. In his analysis, Hall (1980a) fit equation (2) while ignoring the exponential term, which is valid if h<< the scale height of the pulsar distribution $\simeq$ 0.5-1 kpc.

The wild fluctuations observed in $<C_N^2>$ are no doubt due to major inhomogeneities in the ISM (Rickett 1977). The following model is therefore proposed: In addition to the medium described by equation (1), HII regions are assumed to be present, which when intercepted by a line of sight will seriously affect the scattering (or decorrelation bandwidth) resulting in a very large value for $<C_N^2>$ (Figure 2). The scale height of the HII regions is taken to be $\approx$ 100 pc since they are associated with O and B stars. Any line of sight intercepting an HII region will exhibit a large and almost unpredictable $<C_N^2>$.

Assuming an exponential falloff in the density of HII regions above and below the galactic plane, the number of HII regions expected

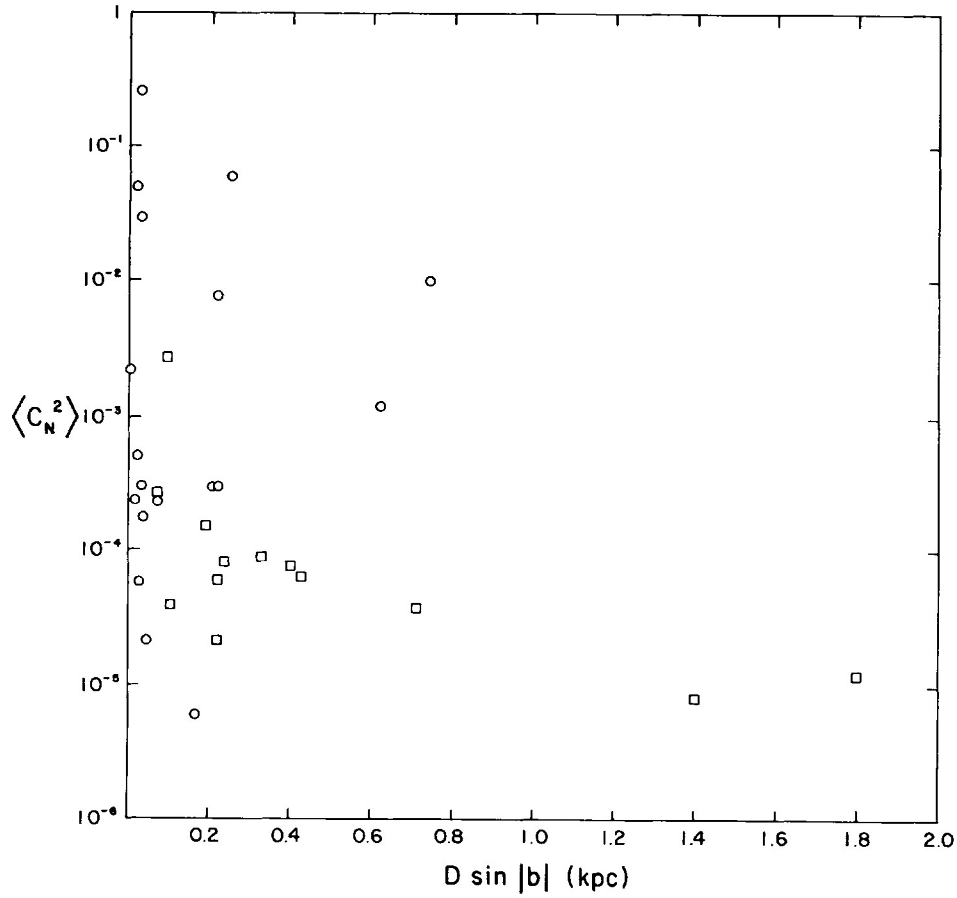


Fig. 1. $< C_N^2 >$ versus Dsin|b| for the full set of pulsar data described in the text. Circles denote low galactic latitude ($b \leq |6^o|$) pulsars, and squares denote high latitude ($b > |6^o|$) pulsars.

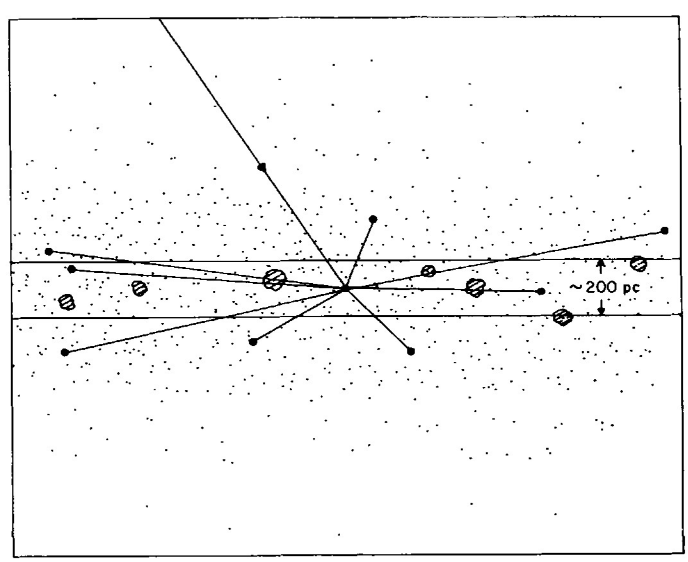


Fig. 2. A simple model for the scintillating medium, consisting of HII regions distributed with scale height ≃ 100 pc, and a more diffuse medium. Most lines of sight from extragalactic sources (shown with arrow) owe their scintillation properties to the latter medium.

along a line of sight to a pulsar is proportional to

$$\frac{100 \text{ pc}}{\sin|b|}\left[1-e^{-\frac{D\sin|b|}{100 \text{ pc}}}\right] \equiv \ell_{HII}$$

The above parameter was computed for all of the pulsars in the data set, and it was found that those pulsars having large measured $\langle C_N^2 \rangle$ also have $\ell_{HII} \gtrsim 1$ kpc. Figure 3 shows the same set of pulsar data minus those pulsars having $\ell_{HII} > 1$ kpc, or seen through HII regions surrounding known O and B stars or OB associations (Prentice and ter Haar 1969). (The Vela pulsar has also been removed as it is seen through the Gum Nebula - Backer 1974.) Clearly the scatter in the data is significantly reduced. Therefore, I conclude that a line of sight confined to the galactic plane would probably intercept one or more HII regions if the pathlength exceeds ~ 1 kpc. (Note that if b=0, then ℓ_{HII}=D.) It seems to be this effect which led Hall to deduce a scale height of 71 pc in his model. Essentially any single component model will be dominated by low scale height HII regions. (HII regions are assumed to be the source of this additional scattering. Presumably some other agent could be responsible provided it is highly inhomogenous, and has a scale height of 70-100 pc.)

The edited data (Figure 3) provide information relevant to most extragalactic sources. This is because the line of sight to an extragalactic source has ℓ<1 kpc as long as $|b| \gtrsim 8^{\circ}$, and thus most extragalactic sources are not seen through HII regions. Of course, scattering and ISS still occur for lines of sight not encountering HII regions, and this is attributed to a medium crudely described by equation (1). It appears that the scale height of this medium may be larger than that deduced by Hall in his single component model. Unfortunately, the scale height can not be accurately determined, owing to the remaining scatter in the data. This scatter is probably indicative of some additional inhomogeity in the medium not accounted for by the model. Unfortunately the data are too sparce to permit analysis of a more complicated model.

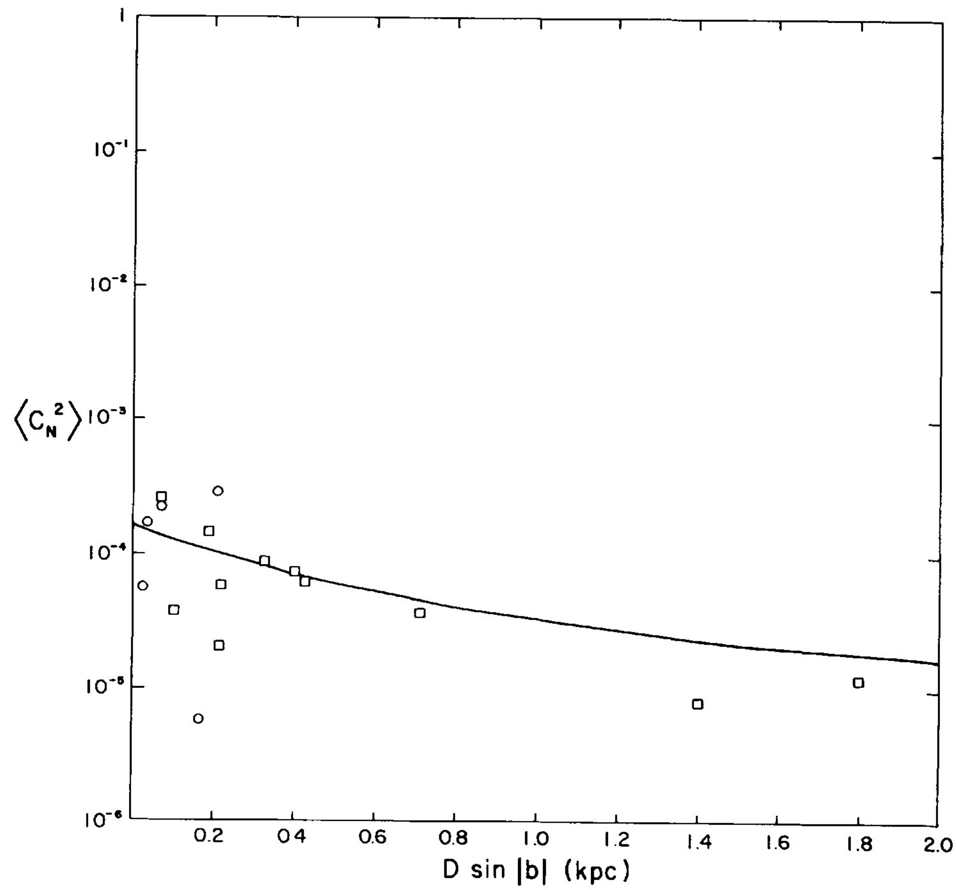


Fig. 3. $<C_N^2>$ versus Dsin|b| for the edited pulsar data. (See text.) Curve shown is the "best fit" to the data with h ≃ 400 pc. Circles denote low galactic latitude (b ≤ |6°|) pulsars, and squares high latitude (b > |6°|) pulsars.

The "best fit" line corresponding to h≃400 pc is shown, although any model with h>70 pc fits the data reasonably well. The data are consistent with earlier conservative assumptions that the relevent scale height is in the range 0.3 - 1 kpc (Armstrong et al. 1977; Condon and Dennison 1978; Dennison and Condon 1981), including the possibility that the scattering medium is the free electron layer responsible for pulsar dispersion. Models with large values of h ($\gtrsim$ 1 kpc) tend to fit the data reasonably well in the χ^2 sense, but as such models tend to approach an average value of $\langle C_N^2 \rangle$ as $h \to \infty$, they do not account for the apparent falloff in the data with increasing $D\sin|b|$. For example, the best fit curve for which h=1 kpc falls above all six data points having $D\sin|b|>0.25$ pc. Thus, it appears that some falloff is required, and that the scale height is probably in the range 70-1000 pc. Since our previous interpretations (Condon and Dennison 1978; Dennison and Condon 1981) tended toward the larger end of this spectrum, these estimates are conservative in that they predict scintillation indices near the low end of the range implied by the uncertainty in h.

The range of acceptable fits suggests that $C_{N_o}^2$ is in the range $10^{-4}\ M^{-6.67}$ to $10^{-3.5}\ M^{-6.67}$. Notably, $C_{N_o}^2$ is moderately well determined. This estimate is roughly consistent with previous assumptions (Armstrong et al. 1977; Condon and Dennison 1978; Dennison and Condon 1981). The critical angular size, and thus the predicted scintillation indices, are only weakly dependent on C_N^2, going as $(C_N^2)^{-0.6}$.

The decorrelation bandwidth is an important parameter, in that observations in the spectral domain (Armstrong et al. 1977; Condon and Dennison 1978; Dennison and Condon 1981) must have adequate spectral resolution for the detection of ISS. At the "conservative" end of the scale (h≃1 kpc; $C_{N_o}^2 \simeq 10^{-4}\ M^{-6.67}$) the expected decorrelation bandwidth for an extragalactic source at b=90° is ≃ 200 kHz (Armstrong et al. 1977). In all previous spectral ISS experiments (Armstrong et al. 1977; Condon and Dennison 1978; Dennison and

Condon 1981), the channel bandwidth was chosen to be a small fraction (typically 10-20%) of the decorrelation bandwidth calculated for each source on the basis of "conservative" parameters. If the scale height is much less than previously assumed, then the relevant paramters ($h \approx 70$ pc; $C_N^2 \approx 10^{-3.5} M_o^{-6.67}$) predict decorrelation bandwidths nearly on order of magnitude larger (≈ 2 MHz at $b=90^o$). Therefore, the previous experiments would have easily resolved ISS of this nature. Baseline and standing wave phenomena at the level of ~0.3% to 1% tend to reduce the sensitivity to scintillations having decorrelation bandwidth $\lesssim 1$ MHz (Condon and Dennison 1978; Dennison and Condon 1981). However, ISS from ultrabright components are expected to be very strong (~10%) under these same assumptions, significantly offsetting any loss of sensitivity.

Extragalactic radio sources are known to be angularly broadened to a diameter ≈ 0.15 arcsec at 81.5 MHz for $|b|>10^o$ (Duffett-Smith and Readhead 1976). The magnitude of this broadening is consistent with the models discussed above, and is in fact most easily reconciled with those models having 70 pc < h $\lesssim$ 500 pc. However, given the various uncertainties, it is not possible to significantly narrow the possibilities further using this observation.

III. CONCLUSIONS

Pulsar data indicate that the ISM would cause ultrabright extragalactic radio sources to scintillate at measurable levels. The scintillation parameters of the ISM as determined by pulsars are somewhat uncertain, however. Most critical is the scale height, which is probably in the range 70-1000 pc. The range of viable models for the ISM combined with an "ultrabright" interpretation of the variability typically yield predicted scintillation indices of 1% to 10%. In a number of cases these predicted scintillation indices exceed observational upper limits (Scheuer 1976; Condon and Dennison 1978; Dennison and Condon 1981). Therefore ultrabright models are invalid unless the apparent angular sizes of such source components are broadened by scattering in a medium external to the galactic disk.

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Observations of Low Frequency Variability in 3C147 Using VLBI

RICHARD S. SIMON

California Institute of Technology

ABSTRACT. I have observed the quasar 3C147 with VLBI twice at 329 MHz, in 1975 and again in 1981. I find that the compact core $\sim$ doubled in flux density in the six years between observations, implying that the core of 3C147 is a strong low-frequency variable. This is the first direct evidence for structural changes in an extragalactic radio source at meter wavelengths. I also find that bulk relativistic motion within the core of 3C147 is required based on two independent arguments. First, the predicted Compton X-ray flux is two orders of magnitude greater than the *Einstein* X-ray flux, unless relativistic motion within the core is assumed. Second, the measured angular size of the core is substantially larger than the size predicted from the variability time scale unless, again, relativistic motion within the core is occuring.

Based on these results, I predict that the core of 3C147 is expanding with an apparent velocity greater than the speed of light. I plan VLBI observations at 18cm to test this prediction.

Also: $T_B <$ Inverse Compton Lim.

RELATIVISTIC COLLISION OF RELIC HIGH-FREQUENCY RADIO COMPONENTS: A POSSIBLE CAUSE OF LOW-FREQUENCY VARIABILITY

Alan P. Marscher
Department of Astronomy, Boston University

ABSTRACT

A model is proposed to explain both the apparent lack of strong variability at intermediate frequencies plus the similarity in Lorentz factors required by relativistic motion models to explain both high and low frequency phenomena. The model requires that the high-frequency components be ejected at different relativistic speeds. Some time after the high-frequency flux density from these components fades to a low level, the faster components collide with the slower. A semi-relativistic (in the rest frame of the component) blast-wave ensues, and causes the colliding components to brighten at low frequencies. In the observer's frame, the low frequency radiation is beamed with a Lorentz factor similar to that of the original high-frequency components.

I. INTRODUCTION

The observations presented at this Workshop reveal an important, albeit tentative, property shared by most low-frequency variables: the existence of an intermediate frequency range ("gap") within which variability is relatively mild. Despite this apparent lack of connection between low and high frequency phenomena, there is also a striking similarity. If both overly rapid flux changes and high-frequency superluminal motions are due to relativistic ejections of the radio components, one finds that the Lorentz factors required to explain low-frequency variability,

$$\gamma_{var} \sim (T_b^*/10^{12}\ K)^{1/3.2}\ (1+z),$$

where T_b^* is the brightness temperature inferred from light-travel-time arguments, are in the same range as those required to explain superluminal motions and high-frequency radio variability: $\gamma \sim 4$ to 20 (e.g., Cohen and Unwin 1982; Mutel, Phillips, and Aller 1980; MacAdam, these proceedings).

VLBI observations of low-frequency variables underscore both points. For example, John Broderick and I (paper in preparation) have observed the low-frequency variable quasar NRAO 140 at three wavelengths with an intercontinental VLB array. We find that the structure consists of four major components (labelled A to D, from NW to SE), aligned along PA 130° or so. Preliminary indications are that the two most compact components are separating at a superluminal speed (Marscher and Broderick 1982). However, if NRAO 140 behaves in a manner similar to other superluminals, the moving component will fade into oblivion long before it reaches the position of the outer components (e.g., Unwin 1982). It is therefore probable that this moving component will require a "re-awakening" if it is to become as bright as the outer components once it travels that far.

Figure 1 shows the radio spectrum of NRAO 140, decomposed into individual component spectra as indicated by the VLBI observations. Although the decomposition below 18 cm is an extrapolation of higher frequency data, continuity of the component spectra renders large deviations from what is drawn unlikely. It is thus clear that any significant low-frequency variability originates in one of the outer components (C or D). In what follows I shall describe a model which allows the moving high-frequency components (such as component B) to be transformed into bright, variable, low-frequency components at some point down the jet.

II. DESCRIPTION OF THE MODEL

There are several mechanisms which could cause a low-frequency radio component to brighten at some distance from its point of origin. Collisions of relativistic jets with cold clouds, changes in energy generation steepening into downstream shocks in relativistic beams, or instabilities within relativistic flows have all been mentioned previously in the literature (Blandford and Königl 1979; Marscher 1980). Two observational details argue against such models, but only weakly. First, there is little evidence for continuous relativistic beams. Most sources have appearances similar to NRAO 140: they contain linear progressions of distinct hotspots. Second, in their present form there is no reason to expect these models to yield a mid-frequency variability gap.

I now propose a model which treats compact radio components as discrete entities(see also Christiansen, Scott, and Vestrand 1978). The only requirement of the model is that successive components be ejected at different relativistic speeds from their point of origin. Soon after ejection, a component will appear to separate from the core superluminally, but will eventually fade (e.g., Unwin 1982). At some later time the component, if ejected at a speed higher than the preceeding one, will catch up and collide tail-on with the older, slower component. This causes a shock wave to form, with variable, low-frequency radio emission occurring as the two components combine. This model explains the observations in the following ways.

(1) The "intermediate frequency gap" represents emission from the nearly constant compact "core," expanded, slowly-varying, high-frequency components which are fading in brightness, and non-variable, large, low-frequency components. The variable low-frequency component contributes only a small fraction of the flux density at these frequencies.

(2) The collision of two components with speeds $\beta_1 c$ and $\beta_2 c$ occurs at a distance

$$\Delta R = \beta_1 c \Delta t/(\beta_2 - \beta_1)$$

from the core, where Δt is the time between successive ejections. Table 1 gives values of $\Delta R/\Delta t$ for β_1=.980 (Lorentz factor γ=5) and various values of β_2. Since creations of new components are typically spaced by a few years or so, ΔR ranges from roughly 50 to a few hundred parsecs for the chosen parameters, which are also likely to be typical of

Table 1. Values of Parameters for $\gamma_1 = 5$ ($\beta_1 = .980$) for Relativistic Collision of Components

β_2	.986	.990	.992	.994	.995
γ_2	6	7	8	9	10
$\Delta R/\Delta t$ (pc yr^{-1})	48	30	24	21.5	20
γ'	1.02	1.06	1.12	1.18	1.25
β'	.18	.33	.44	.53	.60
$\beta_{app,2}$ (for sin i = 0.2)	5.8	6.5	7.1	7.6	7.9

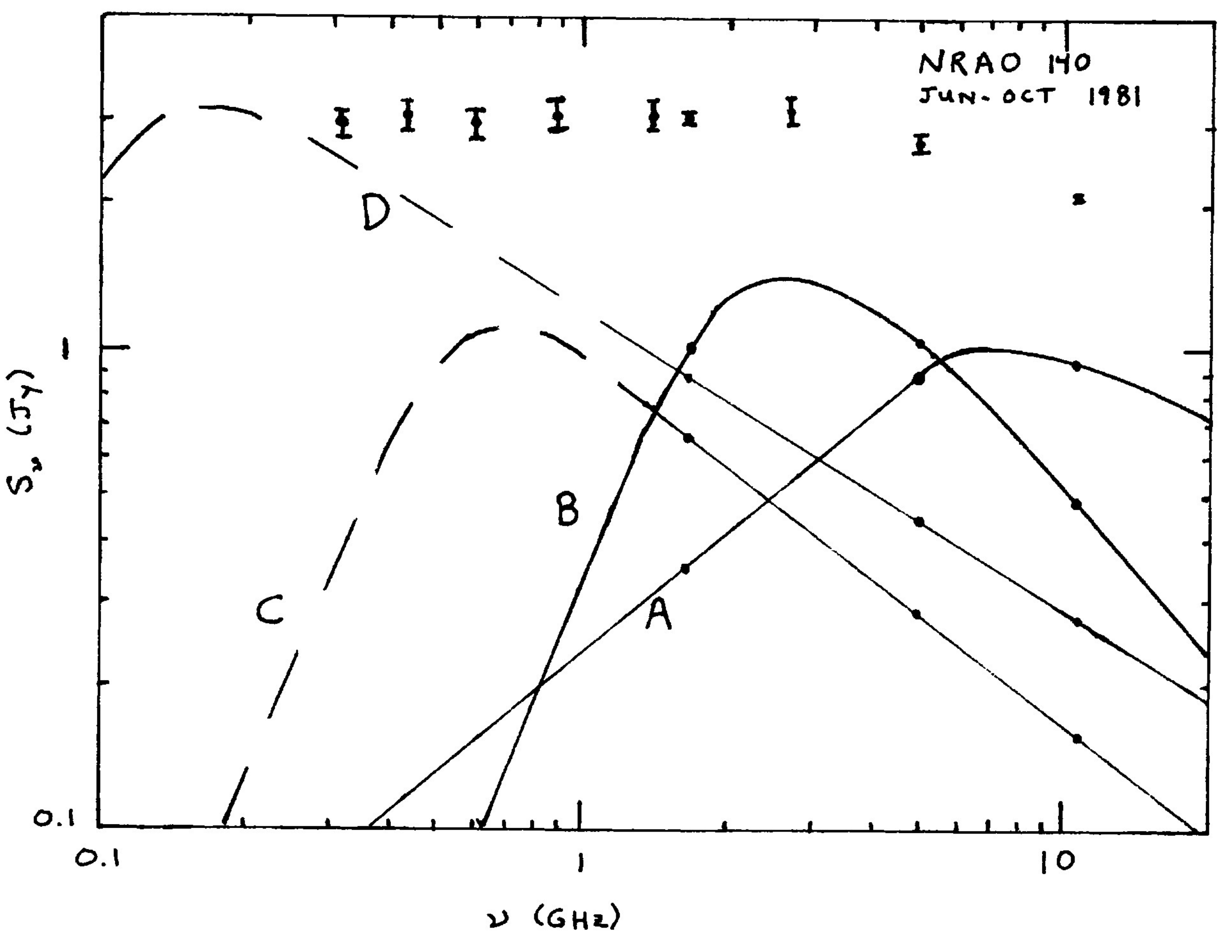

Figure 1

compact extragalactic radio sources. For NRAO 140, the linear separation of the low-frequency component D from the core is anywhere from 30/sin i parsecs (H_o=100, q_o=1) to 90/sin i pc (H_o=50, q_o=0), where i is the inclination angle of the ejection direction to the line of sight. Since sin i $\sim \gamma^{-1}$ for relativistic motion models, component D lies a few hundred parsecs from the core, while component C is about 40% closer to the core. The model therefore reproduces the observed low-to-high frequency component separations quite well.

(3) Relativistic motion of the low-frequency component is required in order to bring the inferred brightness temperature down to a reasonable value. In this model, the component collision occurs in flight, so that all emission is beamed with a Lorentz factor at least equal to that of the slower component. Thus, the same value of γ required to explain superluminal motion can be applied to the low-frequency variability.

The relative Lorentz factor of the collision can be determined from the doppler formula,

$$\gamma' = \gamma_1\gamma_2\ (1-\beta_1\beta_2)$$

Values of γ' and β' are given in Table 1 for the example chosen. The collision is mildly relativistic in the rest frame of either of the components. It is thus likely that a semi-relativistic blast wave will result from the encounter, and that the consequent synchrotron emission will dissipate some of the randomized bulk kinetic energy.

If the shock is radiative, the emission will be confined to a thin shell. The thickness of this shell will depend on frequency, since synchrotron or Compton losses will cause the higher-energy electrons to die off closer to the shock front. The apparent depth of the source along the line of sight (perpendicular to the shock front) will then be

$$s(\nu) \sim 0.4\ B_{eq}^{-3/2}\ \nu_{GHz}^{-\frac{1}{2}}\ \gamma^{\frac{1}{2}}\ \text{parsecs},$$ [1]

where B_{eq} is the magnetic field in the case of synchrotron losses or $(8\pi\ u_{phot})^{\frac{1}{2}}$ in the case of Compton losses, where u_{phot} is the photon energy density. The spectrum will have a steeper slope than normal:

$$S_\nu \propto r^2\ s(\nu)\ \nu^{-\alpha'} \propto \nu^{-(\alpha'+\frac{1}{2})}\ .$$

The extremely high brightness temperatures inferred from variability time scales assume that $r \simeq s$, where $s \lesssim c\ \Delta t_{var}$. This assumption may be in error; in my model, steep-spectrum components have $s << r$ at optically thin frequencies. In this case, brightness temperatures derived from flux variability should be multiplied by $(s/r)^2$, although the brightness temperature "limit" ($\sim 10^{12}$ K) should be multiplied by (s/r) since it depends on the derived photon density. Thus, one obtains a T_b^* lower by $(s/r)^2$ and compares this with $T_{b,max} \sim 10^{12}\ (s/r)$ K.

Clearly, this model depends critically on the assumption of

[1] This discussion ignores expansion losses, which may be important.

variable ejection velocities of radio components. This should manifest itself as a change in apparent velocity $\beta_{app}c$ from one superluminal component to the next. Table 1 gives values of $\beta_{app,2}$ for sin i = γ_1^{-1}=0.2 and various values of γ_2. At one time it was thought that 3C 120 exhibited such velocity variations (e.g., Seielstad *et al.* 1979), but that interpretation is no longer considered to be on solid ground (Cohen *et al.* 1979). VLBI techniques are now at the stage where further monitoring of superluminal sources should be able to answer definitively the question of whether the velocities in a given source are variable.

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PANCAKES AND CIGARS

S. L. O'Dell
Physics Dept., Virginia Tech

Sub-GHz Spectral Variations

Preliminary results from the VPI&SU multi-low-frequency monitoring program (Payne et al. 1982) and published results by Fisher and Erickson (1980) and by Spangler and Cotton (1981) indicate that there may be at least two types of sub-GHz spectral variations -- namely, "delayed" and "nondelayed" ("simultaneous" and possibly "advanced"). Delayed bursts propagate from high frequencies (>GHz) to lower frequencies, with amplitudes decreasing mildly with decreasing radio frequency. Simultaneous bursts occur at the same time with amplitudes comparable at all low frequencies or decreasing sharply with increasing frequency (hence, the "intermediate-frequency gap" found by Spangler and Cotton). Advanced bursts -- for which present evidence is meager -- propagate from low frequencies to higher frequencies with amplitudes decreasing sharply with increasing frequency.

The expanding-cloud model (Shklovsky 1965; Pauliny-Toth and Kellermann 1966; van der Laan 1966; Kellermann and Pauliny-Toth 1968) accounts qualitatively for the spectral behavior of delayed bursts, but not for that of nondelayed (simultaneous or advanced) bursts. My objective here is to examine one possible modification of the expanding-cloud model which can in principle account qualitatively for the spectral behavior of nondelayed bursts. For simplicity, I shall consider nonrelativistically evolving clouds, with the understanding that the rapidity of spectral-flux variations will probably require relativistic effects.

The most straightforward explanation for simultaneous bursts is, of course, that the source is transparent down to the lowest frequencies monitored. However, for any monotonic decrease of magnetic field, density, and / or relativistic electron energy with time or with distance from the origin, the spectral evolution of the radio source should resemble that of an expanding cloud and exhibit delayed-burst behavior. This suggests that nondelayed spectral variations at low radio frequencies occur in a region which is distinctively different from that in which the high-radio-frequency variations occur. The nondelayed bursts would then originate farther from the center, in a region where the magnetic field is compressed and/or relativistic electrons are reheated, re-isotropized, and/or injected. Marscher (1982) and Aller (1982) have also independently arrived at this conclusion.

A second consequence of accounting for simultaneous sub-GHz variations in terms of the evolution of a transparent synchrotron source, is that it aggravates the problem of the high brightness temperature inferred from observed spectral flux and variability time scales. If the brightness temperature of a source is $T_b(\nu)$ at a frequency ν for which it is transparent, then at the frequency ν_1 for which the source has unit absorption depth, the brightness temperature is

$$T_b(\nu_1) = (\nu/\nu_1)^{2+\alpha}\, T_b(\nu) \quad ,$$

where α is the spectral index $[-d(\ell n F_\nu)/d(\ell n \nu)]$. Clearly, the brightness-temperature problem would be even more serious unless $\nu \simeq \nu_1$ -- particularly if the spectrum of the variable component is steep, as may be the case in several instances (Spangler and Cotton 1981).

Neither of the above points is a decisive argument against simultaneous sub-GHz variations occurring in transparent sources; however, they (and the possible existence of advanced bursts) do indicate that alternative explanations should be explored. The alternatives seem to be (1) that some of the sub-GHz emission is not synchrotron, (2) that the sub-GHz radiation suffers extrinsic modulation, or (3) that existing synchrotron models require modification. I adopt the least drastic course here and consider a simple modification of the expanding-cloud model -- namely, nonspherically symmetric evolution of a uniform synchrotron source. With such a model, it is possible (perhaps plausible) to produce simultaneous and advanced bursts -- as well as delayed bursts -- in partially opaque synchrotron sources.

Nonspherical Evolution of a Uniform Cloud

Consider the nonspherical evolution of a synchrotron source under the same basic assumptions made in the standard expanding-cloud model -- namely, (1) uniformity, (2) particle conservation, (3) adiabaticity of relativistic electrons, and (4) frozen-in magnetic field. These assumptions imply the following dimensional scaling laws:

(1) Uniformity results in frequency-independent dimensions at any epoch.

(2) Particle conservation requires that $[(n_\gamma \gamma)V]$ is a temporal constant, where V is the volume of the source and n_γ is the number density of electrons per unit γ (the Lorentz factor).

(3) Adiabaticity of relativistic electrons gives $[\gamma V^{1/3}]$ a temporal constant.

(4) Frozen-in magnetic field (magnetic flux conservation) yields $[BA_B]$ a temporal constant, where A_B is the characteristic area transverse to the magnetic field B.

The spectral flux of a transparent source is then

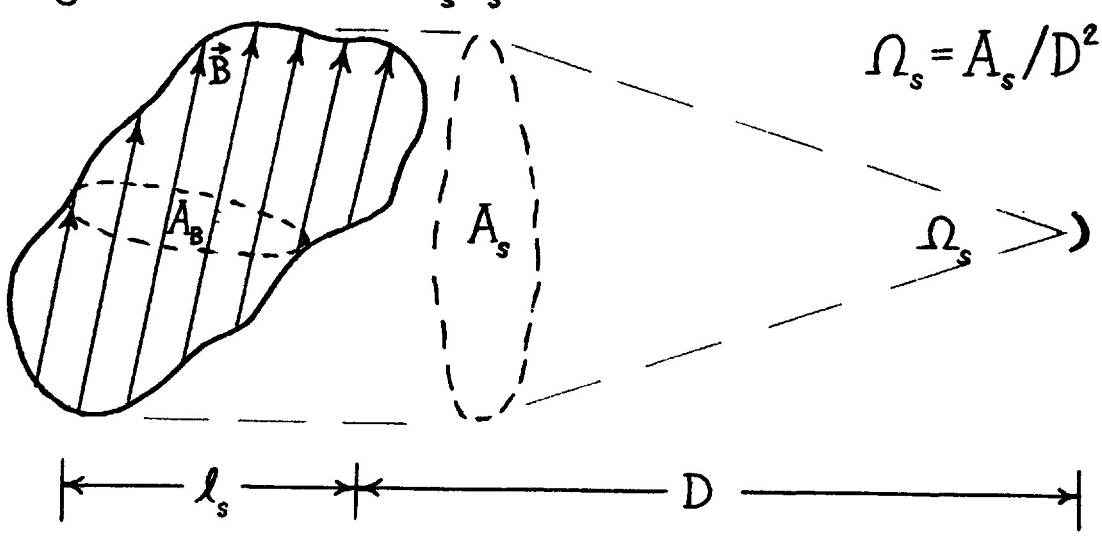
$$F_\nu^t = \eta_\nu \ell_s \Omega_s \propto V^{-\frac{2}{3}\alpha} A_B^{-1-\alpha} \nu^{-\alpha}$$

with η_ν the spectral emissivity, ℓ_s the line-of-sight length of the source, and Ω_s the solid-angle subtended by the source. Note that $\Omega_s = A_s / D^2$ where A_s is the characteristic area of the source transverse to the line-of-sight and D is the distance to the source, and that $A_s \ell_s \approx V$ (see Fig. 1). The spectral flux of an opaque source is

$$F^o_\nu = \frac{\eta_\nu}{\kappa} \Omega_s \propto A_B^{1/2} A_s \nu^{5/2} \quad ,$$

where κ is the absorptivity.

Fig. 1.



Hence, when the source is transparent at ν, the spectral flux changes according to

$$\Delta\ell n F_\nu^t = -\frac{2}{3}\alpha\, \Delta\ell n V - (1+\alpha)\Delta\ell n A_B \qquad (1)$$

$$= -\left[\frac{2}{3}\alpha\, \Delta\ell n \ell_s + \frac{2}{3}\Delta\ell n\, A_s + (1+\alpha)\Delta\ell n A_B\right] \quad ;$$

when the source is opaque at ν, the spectral flux changes according to

$$\Delta\ell n F_\nu^o = [\,\Delta\ell n A_s + \frac{1}{2}\Delta\ell n A_B] \quad . \qquad (2)$$

The frequency at which the absorption depth is unity varies as

$$\Delta\ell n \nu_1 = \frac{-1}{(\frac{5}{2}+\alpha)}\left[\frac{2}{3}\alpha\, \Delta\ell n \ell_s + (1+\frac{2}{3}\alpha)\, \Delta\ell n A_s + (\frac{3}{2}+\alpha)\, \Delta\ell n A_B\right] ; \qquad (3)$$

and the corresponding spectral flux at ν_1 varies as

$$\Delta\ell n F_{\nu_1} = \frac{-1}{(\frac{5}{2}+\alpha)}\left[\frac{5}{3}\alpha\, \Delta\ell n \ell_s + \frac{2}{3}\alpha\, \Delta\ell n A_s + (\frac{5}{2}+2\alpha)\, \Delta\ell n A_B\right] \qquad (4)$$

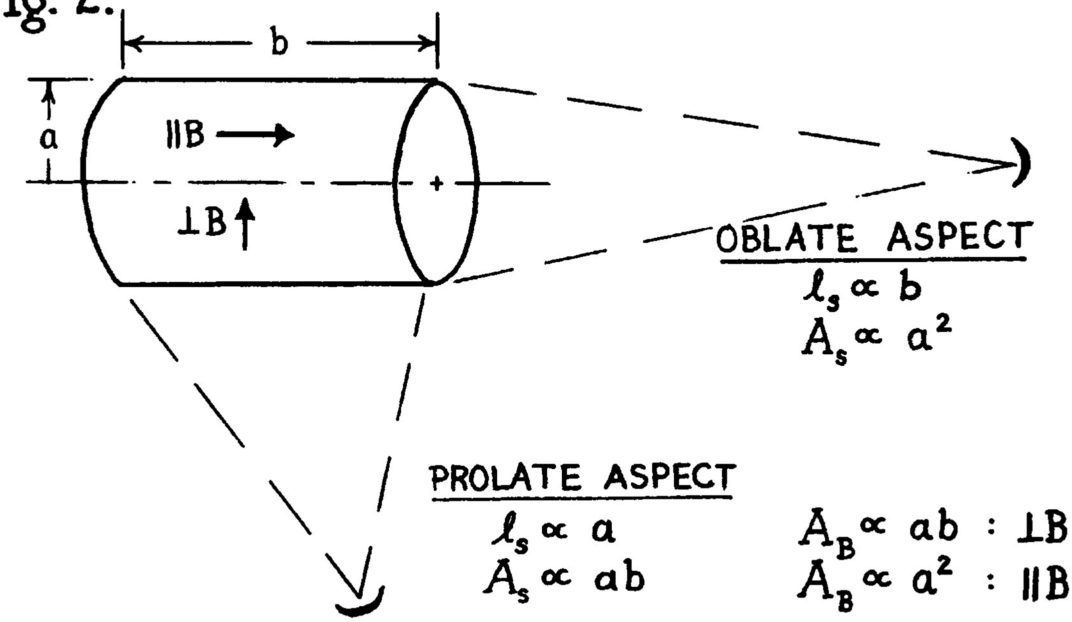
It is clear, from equations (1) and (2), that if all dimensions increase, the transparent ($\nu>\nu_1$) spectral flux F_ν^t must decrease and the opaque ($\nu<\nu_1$) spectral flux F_ν^t must increase. Furthermore, the locus of the spectral peak on the ($\ell n F_\nu$, $\ell n \nu$) diagram, which moves in the direction

$$\frac{\Delta\ell n F_{\nu_1}}{\Delta\ell n \nu_1} = \frac{\frac{5}{3}\alpha\, \Delta\ell n \ell_s + \frac{2}{3}\alpha\, \Delta\ell n A_s + (\frac{5}{3}+2\alpha)\, \Delta\ell n A_B}{\frac{2}{3}\alpha\, \Delta\ell n \ell_s + (1+\frac{2}{3}\alpha)\, \Delta\ell n A_s + (\frac{3}{2}+\alpha)\, \Delta\ell n A_B} \quad , \qquad (5)$$

must have positive slope whenever all dimensions change in the same sense. The behavior is thus qualitatively similar to that of the standard expanding-cloud model. Under the initial assumptions, the only way to effect non-standard behavior (simultaneous and advanced bursts) in a partially opaque source is for one dimension to change in a sense opposite to the others.

As an example, consider a right circular cylinder of radius a and length b (see Fig. 2).

Fig. 2.



There are two extreme aspects of the cylinder -- oblate, for which $\ell_s \propto b$ and $A_s \propto a^2$, and prolate, for which $\ell_s \propto a$ and $A_s \propto ab$. There are two extreme orientations of the magnetic field -- perpendicular to the axis of symmetry, for which $A_B \propto ab$, and parallel to the axis of symmetry, for which $A_B \propto a^2$.

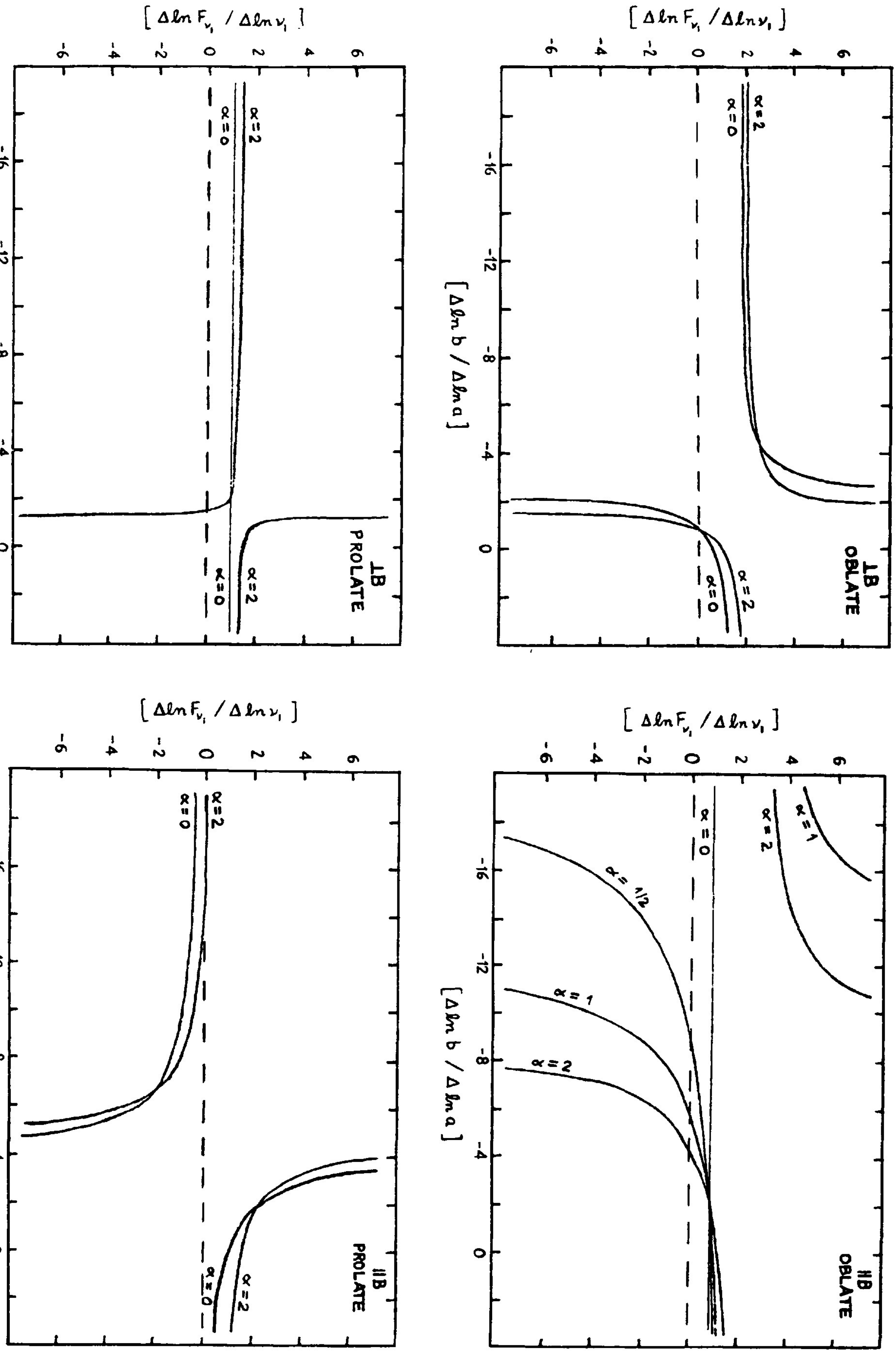

⊥B OBLATE
⊥B PROLATE
∥B OBLATE
∥B PROLATE
[Δln F_ν₁ / Δln ν₁]
[Δln b / Δln a]
α = 0
α = 1/2
α = 1
α = 2

Fig. 3.

Figure 3 exhibits the locus of the spectral maximum--i.e., $(\Delta \ell nF_{\nu_1}/\Delta \ell n\nu_1)$ --as a function of $(\Delta \ell nb/\Delta \ell na) \rightarrow (a/b)(\Delta b/\Delta a)$, for various values of the transparent spectral index α. Setting $(\Delta \ell nb/\Delta \ell na) = 1$, of course, reproduces the spherically symmetric results. There is in general (except by definition, in the symmetric case) no a priori reason for requiring that $(\Delta \ell nb/\Delta \ell na)$ be constant during the evolution of a source. Consequently, the locus of the spectral peak need not -- indeed, most likely would not -- be a straight line on the $(\ell nF_\nu, \ell n\nu)$ diagram. From an observational standpoint, however, departures from straight-line behavior would be readily perceptible in the $\perp B$ cases only over a small range of parameters -- namely, $(\Delta \ell nb/\Delta \ell na) \simeq -2\pm1$ -- for reasonable values of the transparent spectral index α. (This is not an uninteresting range of parameters, since $\Delta \ell nb = -2\Delta \ell na$ corresponds to constant-volume evolution.) In the $\parallel B$ cases, departures from straight-line behavior occur over a much larger range of parameters (Fig. 3).

Remarks on Pancake and Cigar Geometries

The calculations outlined above show that, even under the assumptions of uniformity, magnetic-flux conservation, and relativistic-electron number conservation and adiabicity, a partially opaque synchrotron source can exhibit non-standard spectral evolution -- i.e., $(\Delta \ell nF_{\nu_1}/\Delta \ell n\nu_1)$ not of order (positive) unity. An essential prerequisite to non-standard spectral evolution is that one dimension of the source changes in a sense opposite to the others. Even one-dimensional evolution shows standard spectral behavior -- except for $\alpha = 0$, in the $\parallel B$ prolate-aspect geometry (Pacholczyk 1980).

It is particularly interesting to note that partially opaque sources will even exhibit nearly simultaneous spectral-flux variations whenever

$|(\Delta \ell n F_{\nu_1}/\Delta \ell n \nu_1)|>>1$. This will occur if $(\Delta \ell n b/\Delta \ell n a)$ is -4 ± 2 (for reasonable values of the transparent spectral index α) in the $\parallel B$ prolate-aspect geometry, or -10 ± 4 (for $\alpha = 2$) to -20 ± 6 (for $\alpha = \frac{1}{2}$) in the $\parallel B$ oblate-aspect geometry. A plausible (not implausible?) scenario in which such behavior occurs is in the longitudinal compression of a cloud into a spreading disk or pancake with b<<a, at some distance from the central source. If b<<a, then the oblate aspect is statistically preferred.

An important feature of pancake sources, relatively independent of the considerations discussed so far, is a reduction of the brightness temperatures inferred from variability timescales. For an observer near the axis of the pancake $[\sin\theta \lesssim (b/a)]$, the variability timescale $\Delta t_v \propto b$ whereas the solid-angle of the source $\Omega_s \propto a^2$. Consequently, a brightness temperature inferred from the observed timescale under the assumption of spherical symmetry would exceed the actual brightness temperature of a pancake by a factor $(a/b)^2$. Such considerations may plausibly lower brightness temperature estimates (inferred from timescales) from values as high as $\simeq 10^{15}$ to $\simeq 10^{13}$ K, thus requiring more modest bulk Lorentz factors and implying angular sizes more comparable to those measured in VBLI observations.

Conclusions

Multi-frequency monitoring of sub-GHz variables thus far indicates that there may be at least two different types (or extremes) of low-frequency variability. Some temporal variations appear to be "standard" -- i.e., delayed - bursts; others "nonstandard" -- i.e., nondelayed (simultaneous or, perhaps, advanced) -- bursts.

The nondelayed bursts seem not to be simple extensions of the high frequency behavior; but, rather, they would appear to require compression of the magnetic field and/or injection, reaccleration, or re-isotropization of the relativistic electrons at some distance from the central source. Simultaneous bursts may occur in a transparent synchrotron source or, under the conditions specified above, even in a partially opaque synchrotron source.

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THE BANDWIDTH OF LOW FREQUENCY FLUX VARIATIONS

W. C. Erickson
Astronomy Program
University of Maryland
College Park, MD 20742

A few years ago, J. R. Fisher and I carried out a study of low frequency flux variations with the NRAO 91-m telescope. The project has been terminated and the results are published (1980, Astrophysical Journal, 242, 884) but it is worthwhile to summarize them here because we made nearly simultaneous measurements at more frequencies below 1 GHz than anyone else has attempted. The aim of this study was to determine the bandwidth, spectrum, and relative phases of the flux variations below 1 GHz. Most of our observations were made at six frequencies - 321, 394, 515, 610, 790, and 920 MHz - and we had observing sessions every few months during 1973-1976. Initially we attempted to use several more frequencies down to 100 MHz but the baselines were not stable enough for the sources to be reliably distinguished from the background below 300 MHz.

We drew the following conclusions from this study:

1. The bandwidth of the variations is $\gtrsim$ 300 MHz. As shown in Fig. 1, the sources with the largest, best-observed variations - BL Lac, 3C454.3, and 1504-167 - appeared to vary over a band larger than our range of observing frequencies. In several cases, such as 3C120, CTA102 and NRAO 530, the variations may either decline in amplitude below about 500 MHz or become uncorrelated with the higher frequency variations (see Fig. 2). However, the variations in these latter sources are smaller and are difficult to observe below 500 MHz so we are not certain about these differences.

2. The spectra of the variable components are essentially flat in the 300 to 1000 MHz range. As can be seen from Table 1, we find spectral

indices of about 0.0 ± 0.5 for the variable components. The + 2.5 index of simple, opaque, synchrotron sources is definitely eliminated.

3. There exist no obvious phase shifts in the variations across the 300 to 1000 MHz band. The variations appearing in Figure 1 seem to be simultaneous at all the observed frequencies and display no obvious leads or lags at the lowest frequencies. This argues against expanding source models.

4. Assuming that the angular sizes of the sources are equal to those measured by VLBI techniques, the observed brightness temperatures shown in Table 1 do not exceed the 10^{12} K limit for incoherent synchrotron emission.

These conclusions suggest that the variable source components are optically thin. Source regions of low opacity that are varying in emissivity, angular size, or relativistic approach speed could satisfy the data.

I believe that one of the most interesting observing projects that could be undertaken in this field would be to extend the frequency range of the observations down to about 100 MHz, i.e. down to a frequency at which the variable component becomes opaque. This would test the 10^{12} K limit for synchrotron emission, it would allow a determination of magnetic field strength in the sources, and if an opaque component were observed to vary it must be changing in apparent angular size. For such a project, a sensitive VLB interferometer with 20,000 to 100,000 wavelength baseline would be ideal. Although they involve considerable effort, such observations would be highly desirable.

At Clark Lake we have begun observations of some of the low frequency variable sources in order to search for variations at even lower frequencies. However, our system operates below 100 MHz where the variable components are probably so strongly self-absorbed that they will be unobservable. Some of the well-known variable sources, such as 3C279 and 3C454.3, are easily observable at Clark Lake but we are presumably observing an extended steady component rather than a small variable component. Never-the-less, we will make a series of observations in order to be certain that nothing unexpected is occurring.

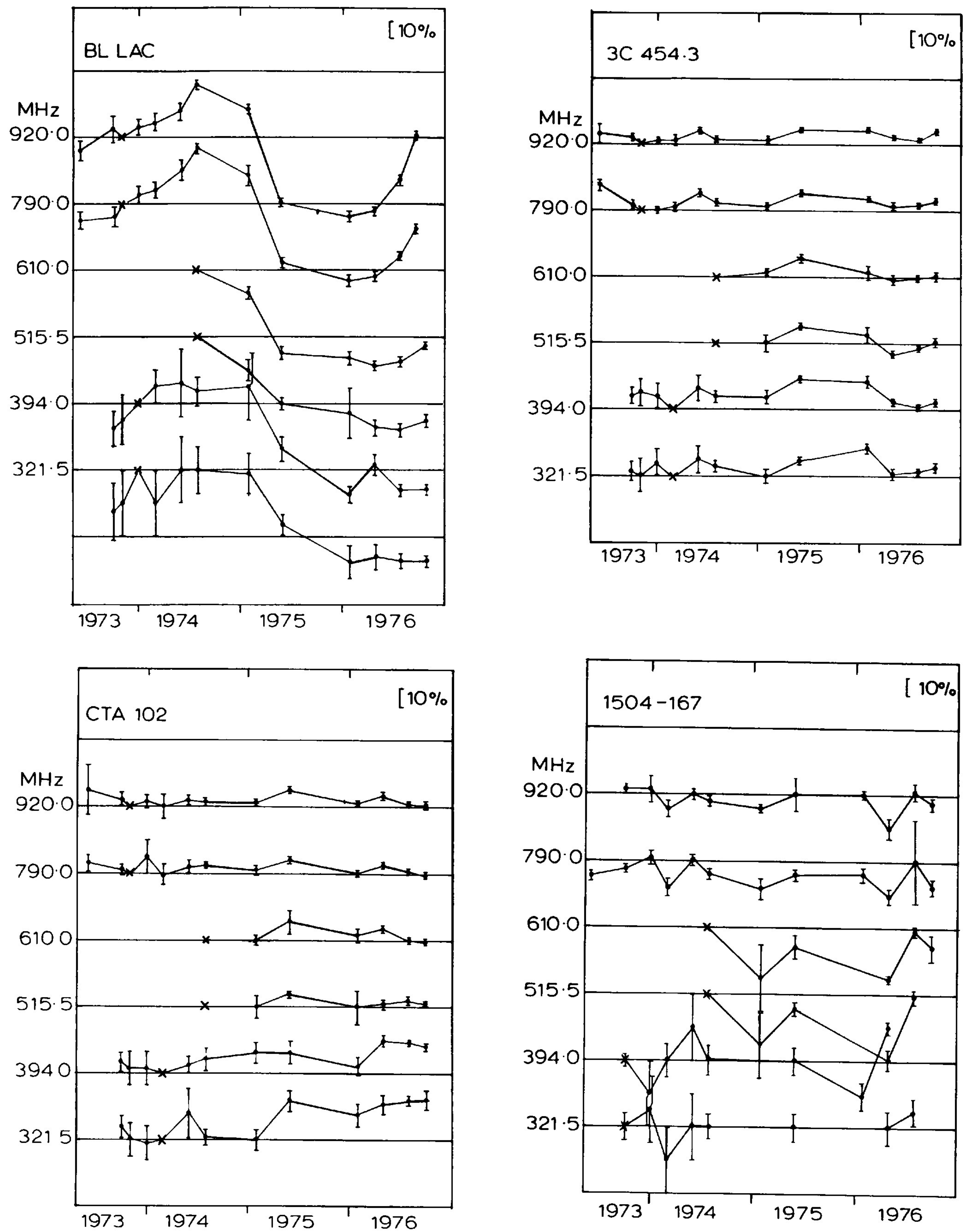

Figure 1. Flux densities measured over a 3½ yr period, expressed as ratios between each measurement and the value obtained at a standard epoch marked with a cross.

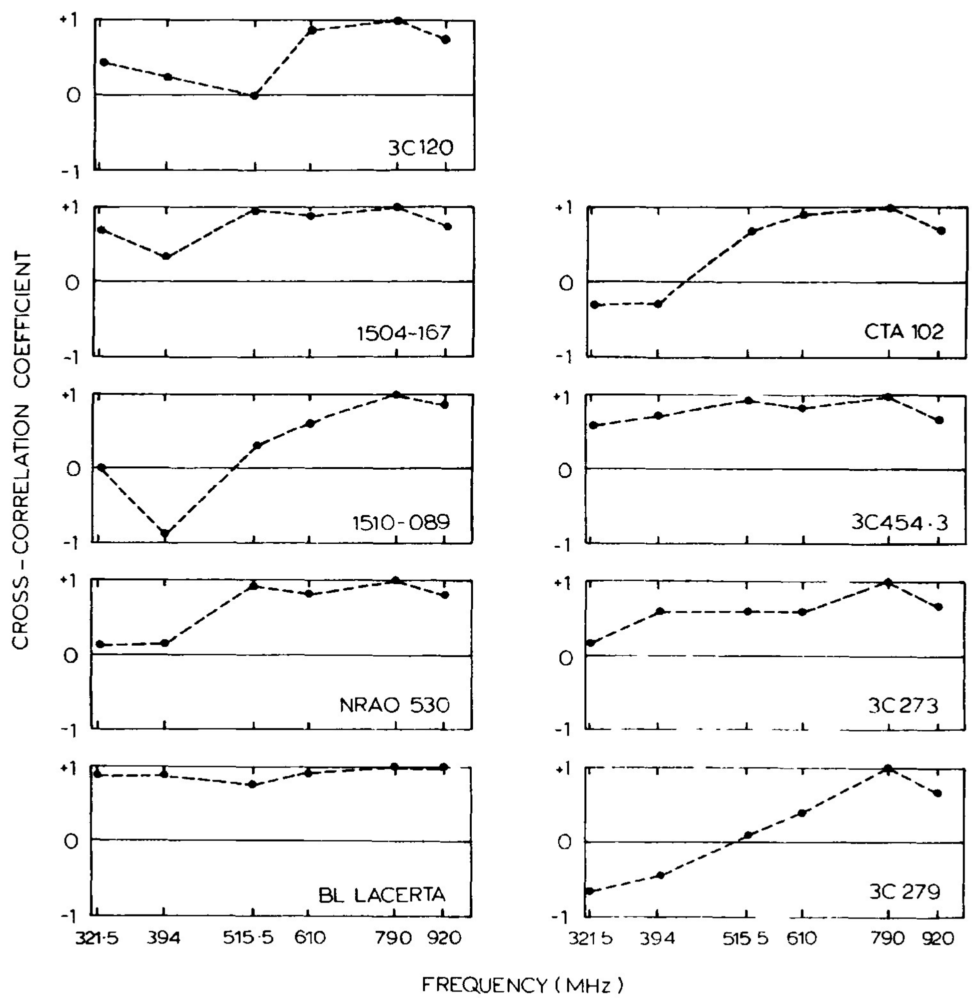

Figure 2. Cross-correlation coefficients between 790 MHz flux density measurements and measurements made at all frequencies. By definition the coefficient is 1.0 at 790 MHz.

Variable Flux Densities (Jy) and Computed Brightness Temperatures (K) Assuming VLBI Source Sizes (Ω)

Source	Other Name	Ω (arc seconds)^2	Ref.	321.5 MHz		394		515.5 MHz		610 MHz		790 MHz		920 MHz	
				S_ν	T_ν	S_ν	T_ν	S_ν	T_ν	S_ν	T_ν	S_ν	T_ν	S_ν	T_ν
0430+052	3C 120	1.0×10^{-3}	1	0.8	1×10^{10}	0.7	6×10^{9}	0.0	...	0.7	3×10^{9}	0.7	2×10^{9}	0.6	1×10^{9}
1504−167	...	2.2×10^{-6}[a]	2	~1	...	~1	...	1.0	...	1.0	...	0.6	...	0.6	...
1510−089	...	1.3×10^{-4}	3	...	...	~0.4	3×10^{10}	1.2	5×10^{10}	0.8	2×10^{10}	1.1	2×10^{10}	0.9	1×10^{10}
1730−130	NRAO 530	8.5×10^{-4}	3	1.5	2×10^{10}	1.2	1×10^{10}	0.6	4×10^{9}	0.7	3×10^{9}	0.9	2×10^{9}	0.7	1×10^{9}
2200+420	BL Lac	3.1×10^{-6}[b]	4	2.4	...	2.4	...	2.6	...	2.7	...	3.3	...	3.2	...
2230+114	CTA 102	6.0×10^{-5}	5	1.4	3×10^{11}	1.2	2×10^{11}	0.6	5×10^{10}	0.9	6×10^{10}	0.8	3×10^{10}	0.7	2×10^{10}
2251+158	3C 454.3	5.5×10^{-5}	5	2.3	6×10^{11}	2.4	4×10^{11}	2.3	2×10^{11}	1.7	1×10^{11}	1.9	8×10^{10}	1.1	3×10^{10}

[a]Angular size at 2.3 GHz.
[b]Angular size at 10.7 GHz.

References.—(1) Broderick and Condon 1975 (430 MHz). (2) Preston 1980 (2.3 GHz). (3) Broten *et al.* 1969 (448 GHz). (4) Clark *et al.* 1973 (10.7 GHz). (5) Wilkinson *et al.* 1979 (609 MHz).

TABLE 1

CENTIMETER-WAVELENGTH SPECTRA OF OUTBURSTS IN LOW-FREQUENCY VARIABLES: THE PROBLEM OF EXTRAPOLATION TO LOWER FREQUENCIES

by

Hugh D. Aller and Margo F. Aller
University of Michigan

ABSTRACT

Selected results are presented from the joint variability program at the University of Michigan Radio Astronomy Observatory (operating at 4.8, 8.0, and 14.5 GHz) and the Bologna Observatory (operating at 408 MHz). A comparison of the monthly averages of the centimeter-wavelength data with the decimeter observations shows very diverse types of behavior which cannot be explained by any single source model. While some objects (e.g. BL Lacertae) exhibit broad-band variability which is qualitatively similar to the predictions of non-homogeneous expanding source models, others (e.g. DA 406) appear to require at least two variable components with quite different physical parameters. A schematic working hypothesis to account for the range of spectral behavior is presented. Key points of this scenario are that 1) the same ensemble of relativistic particles produces the emission in both spectral domains, but the emissions are produced in different regions of the source, and 2) in some sources in-situ reacceleration of particles occurs in the low-density (outer) portion of the radio-emitting region which causes large amplitude, low-frequency variability while producing little effect at high frequencies.

Since the discovery of low frequency variability in the flux densities of extragalactic radio sources (Hunstead 1972), one of the primary questions anout this phenomenon has concerned the relationship between the flux density variability observed at centimeter wavelengths and the decimetric variability. While the variability phenomenon at centimeter wavelengths is at least qualitatively similar to the predictions of non-homogeneous expanding-source type models, the behavior observed at low frequencies is often not consistent with these models and the relation to the high frequency variability is unclear. To study this question The Northern Cross Bologna Radio Astronomy Observatory and The University of Michigan Radio Astronomy Observatory started a joint coordinated program in 1979 to systematically study a sample of 50 variable radio sources. Collaborators in this program are C. Fanti, R.Fanti, A. Ficarra, F. Mantovani, L. Padrielli, L. Gregorini, K.W. Weiler, and P.E. Hodge. Both observatories had already been observing some of the well-known variable sources prior to this time; these programs are decribed elsewhere (Fanti et al. 1981; Aller, Aller and Hodge 1981). In this presentation we will discuss the range of behavior that has been found in the flux density data and a possible mechanism for producing both the high and low frequency flux density variability.

THE OBSERVATIONS

Figures 1 through 8 are arranged sequentially to show events which are qualitatively similar to the behavior predicted by expanding source type models to those which cannot be explained by such models. In each plot of the flux densities versus time, the centimeter wavelength data are presented as monthly averages using the symbols Δ, O, and X to represent the 4.8, 8.0, and 14.5 GHz data rexpectively; the 408 MHz data are shown as +. The curves drawn through the data are smoothing cubic splines (Reinsch 1967).

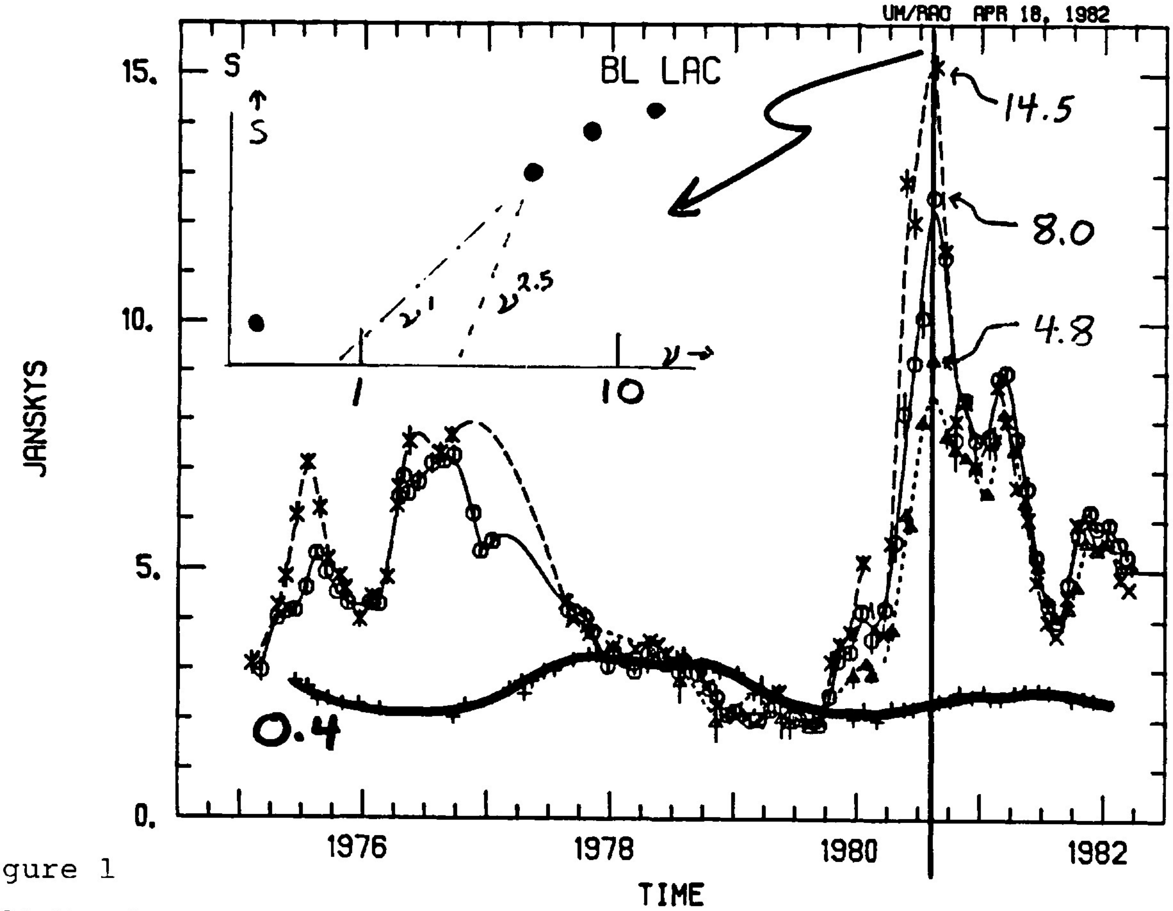

Figure 1

Of the observations presented here the behavior of the flux density in BL Lac (Figure 1) during 1980 through 1981 most nearly follows the predictions of expanding source type models. The variations are of largest amplitude with the shortest time scale at 14.5 GHz and there is apparently a considerable delay between the peaks at centimeter and decimeter wavelengths. The spectral index during the peak in the 1980 burst (see insert in Figure 1) never exceeds +1.0 and is far less steep than the spectral index of +2.5 expected for a homogeneous synchrotron source. However, such flat spectra are quite typical of variable sources and are expected from non-homogeneous, tapered emitting regions (e.g. Aller and Aller 1977). Another source which has apparently exhibited behavior consistent with expanding source models is 3C120 (Figure 2). The variations in this source are also more rapid and of larger amplitude at centimeter wavelengths than at 408 MHz.

The case of 1510-089 (Figure 3) is more complex. While there is an apparent delay in the 408 MHz burst, the amplitude of the low frequency burst is clearly larger than the 4.8 GHz event which according to expanding source type models should have been much stronger. In fact there appear to be two regimes present: the centimeter wavelength flux curves clearly are related to each other but the apparent association with the decimetric burst could be a chance coincidence. Other examples of apparently uncorrelated behavior in the two wavelength regions are shown in Figures 4 and 5. At first glance there appears to be a near simultaneous burst in 0736+017 at 408 MHz and at 8.0 GHz, but note that before early 1981 the 8.0 GHz flux density was decreasing while the decimetric flux density was increasing. Also while the spectrum seen at centimeter wavelengths during late 1981 and early 1982 is consistent with a partially self-absorbed synchrotron source, the

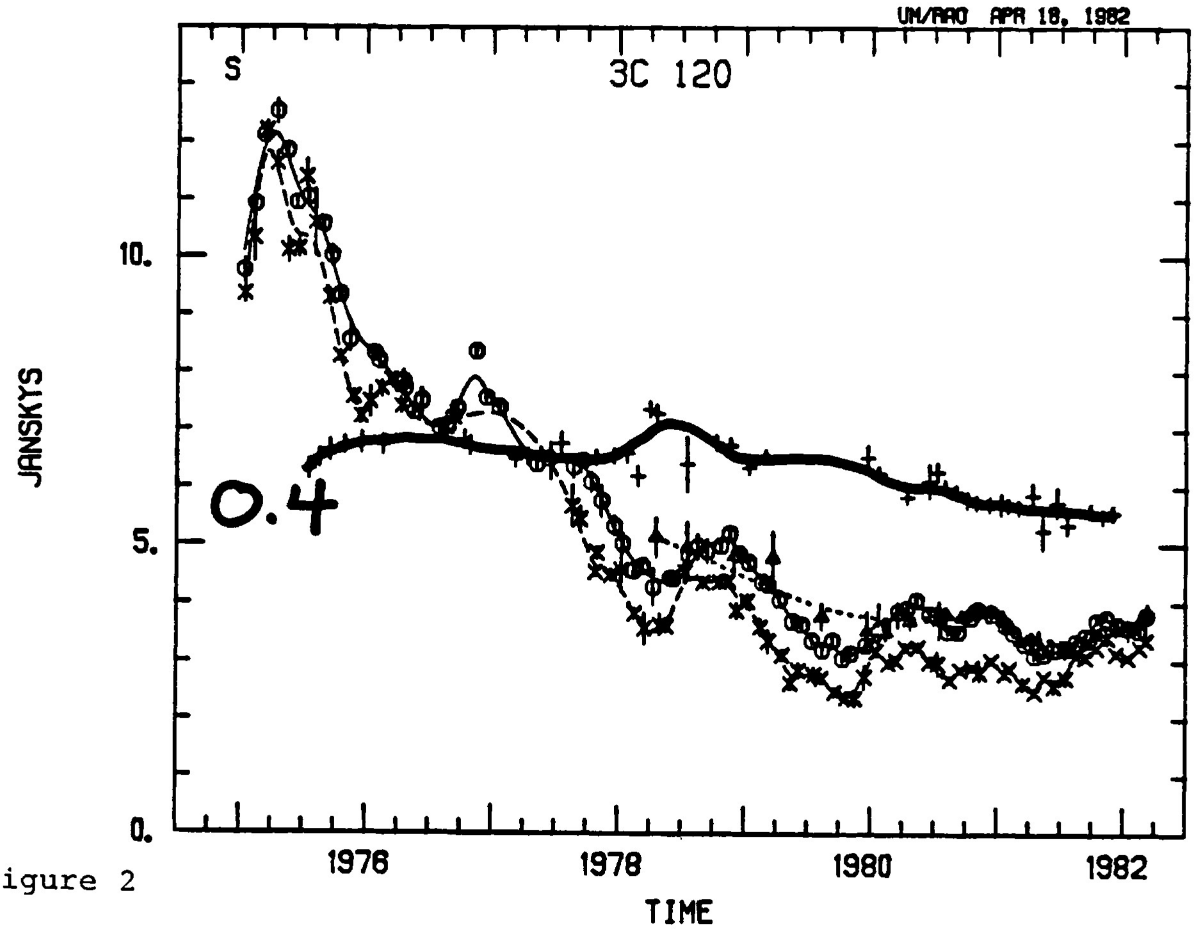

Figure 2

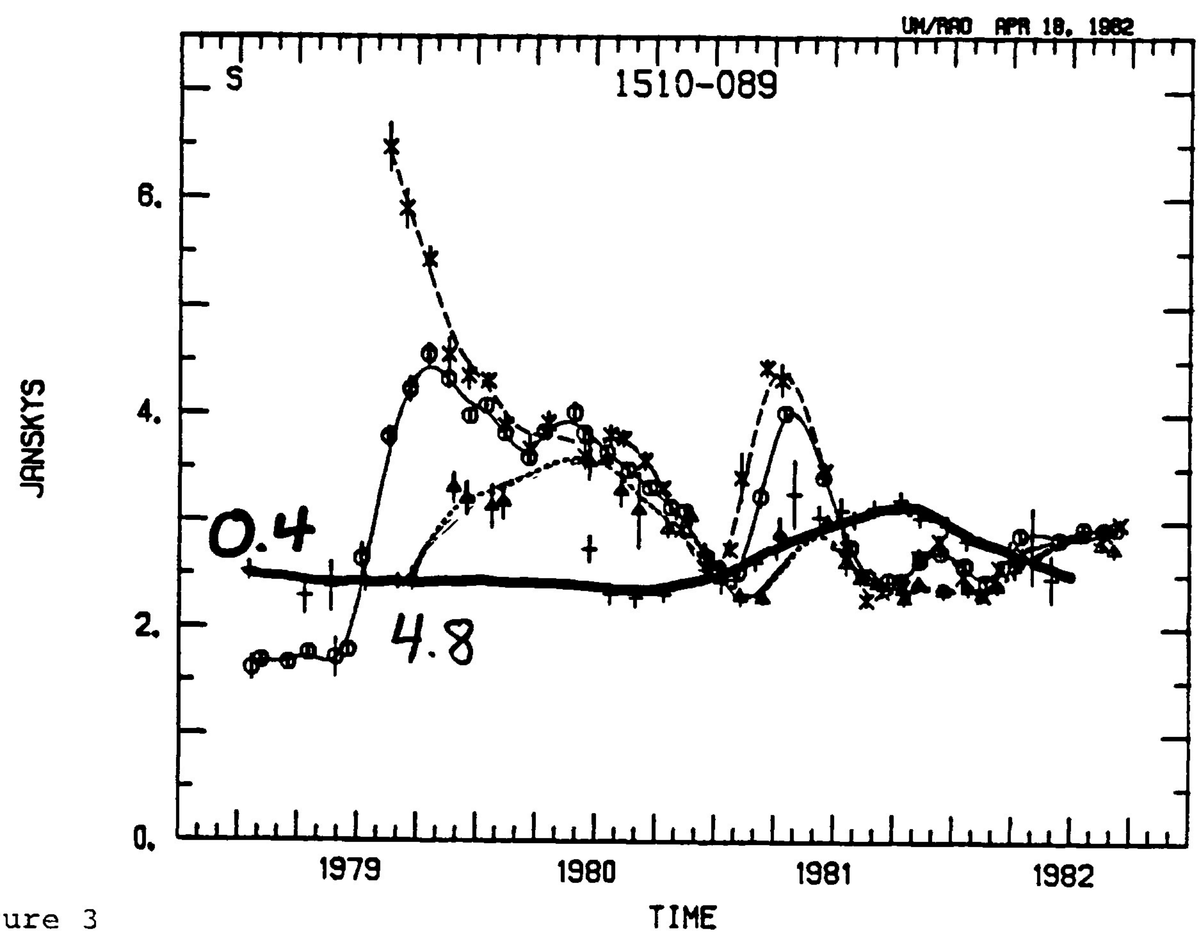

Figure 3

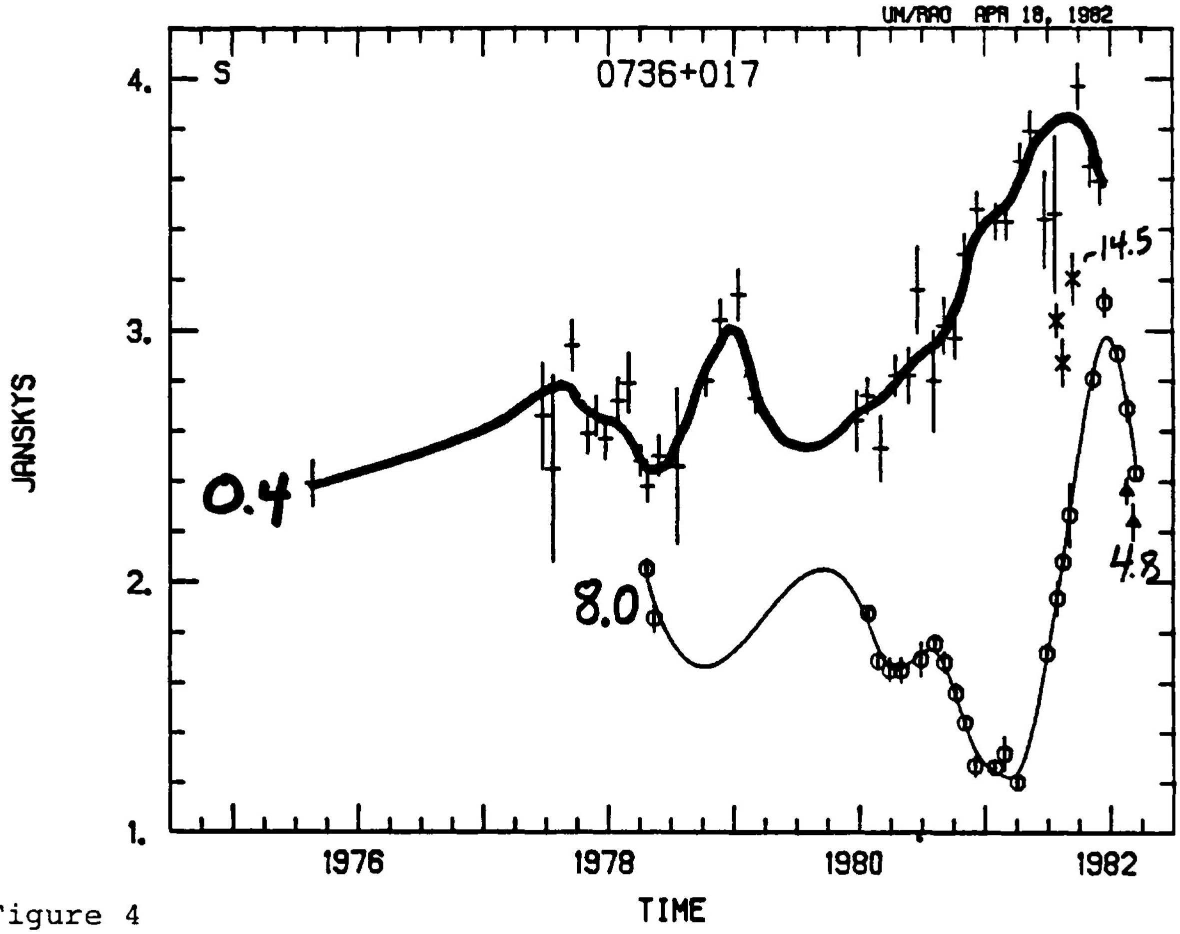

Figure 4

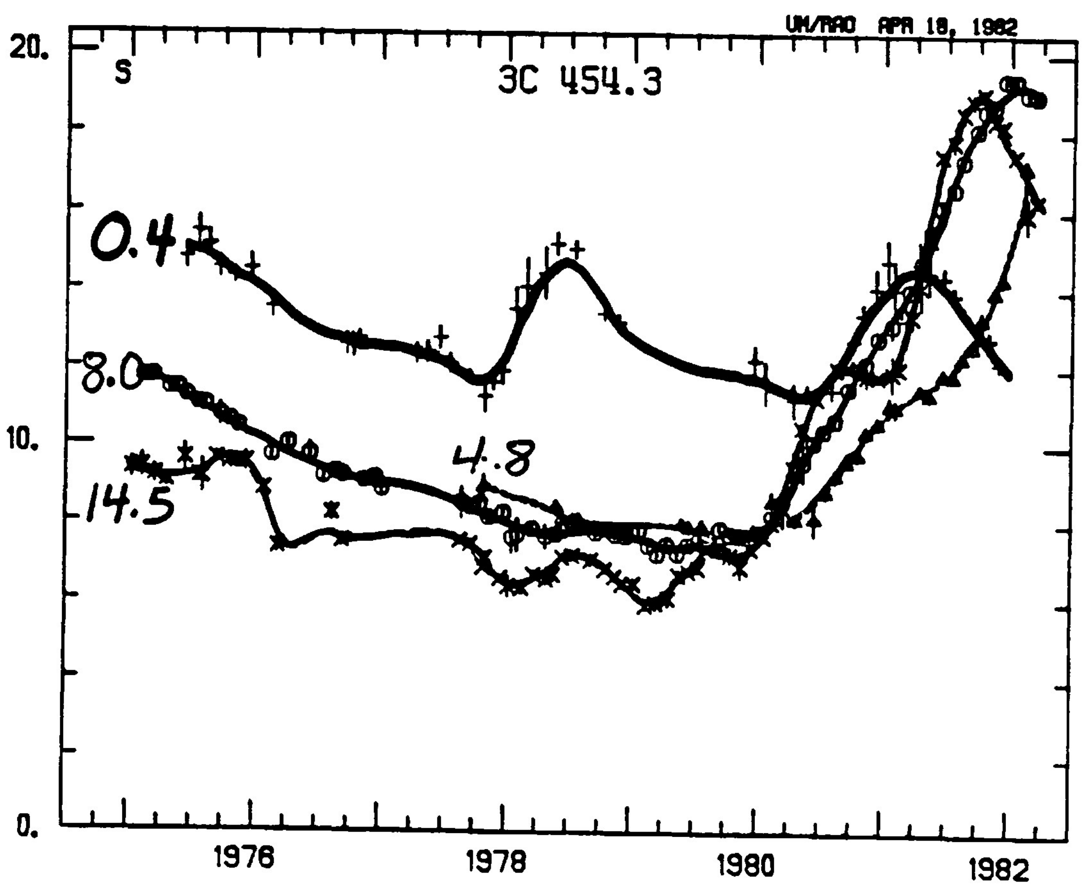

Figure 5

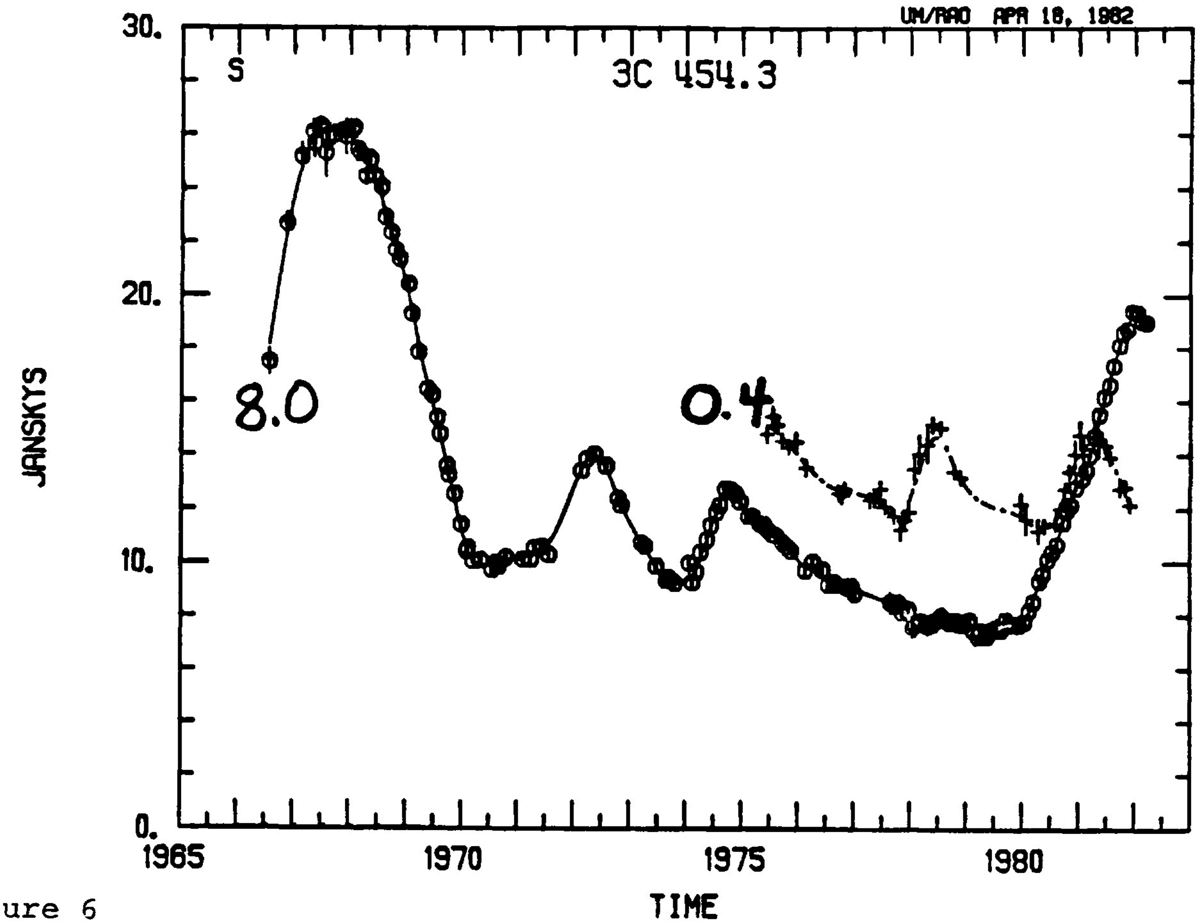

Figure 6

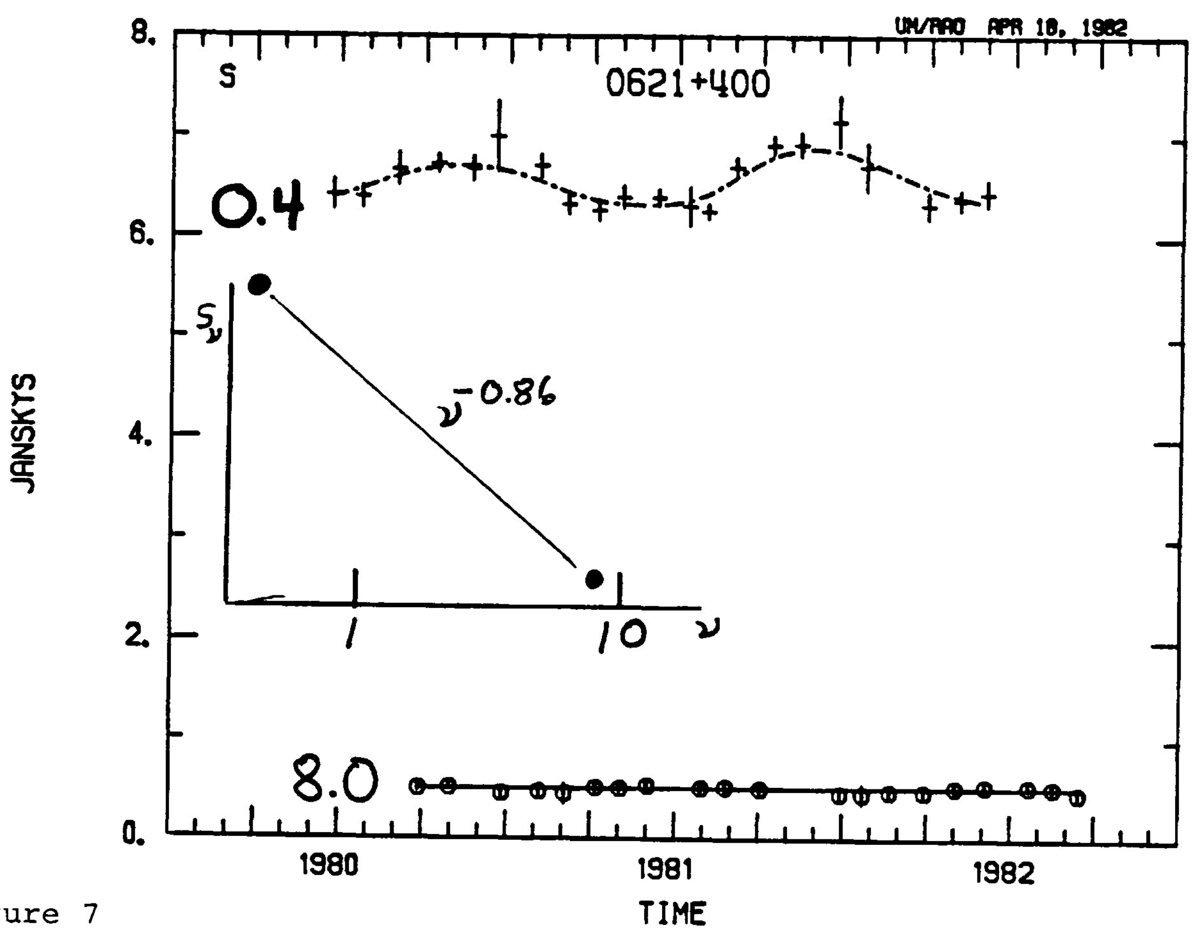

Figure 7

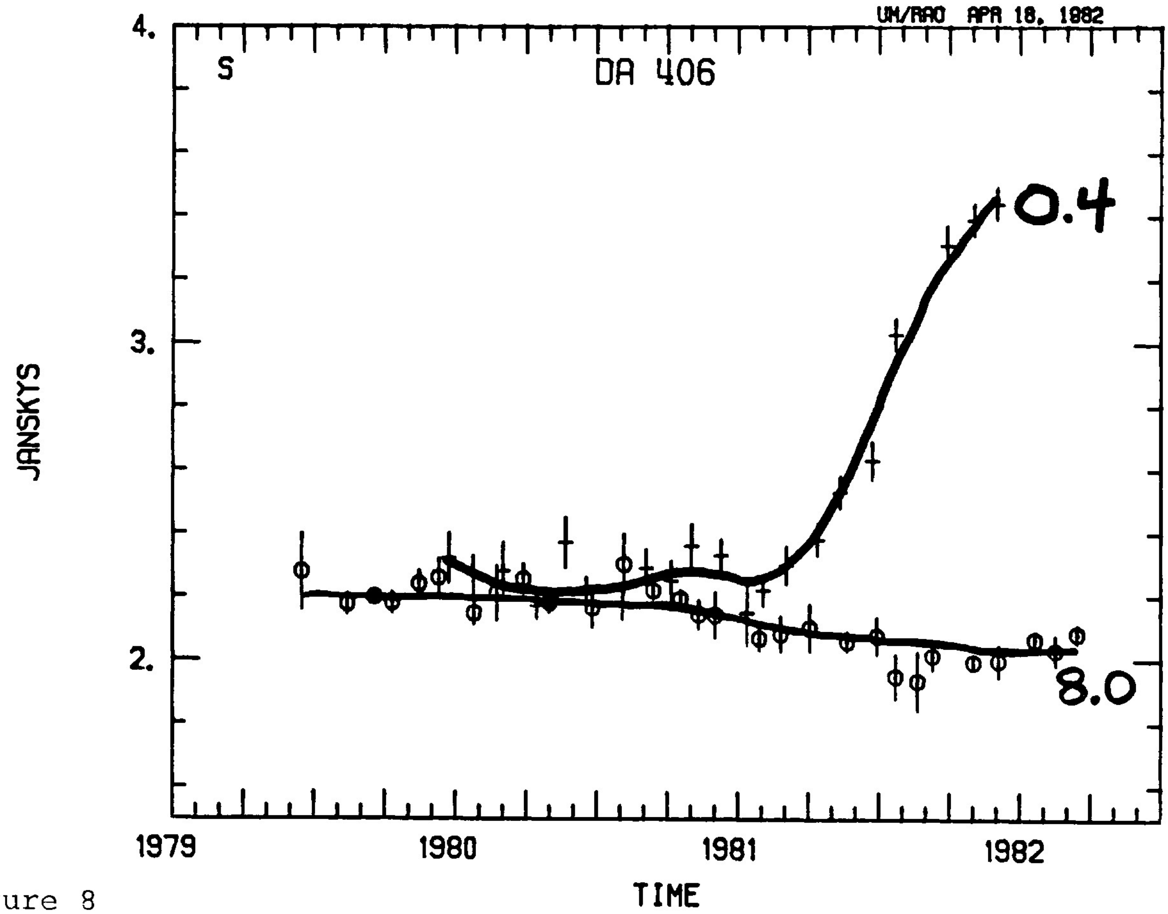

Figure 8

extrapolation of that spectrum to 408 MHz would predict a much smaller outburst than observed. The data for 3C454.3 shown in Figure 5 again appear to show two unrelated emitting regions; but observations over a longer period (Figure 6) reveal a possible relationship. The 0.4 GHz bursts which peaked in 1978 and early 1981 bear a striking similarity to bursts peaking at 8.0GHz in early 1972 and late 1974. The apparent six year delay between events in the different spectral regions illustrates the need for long- term observations of these objects. If these two sets of variations are related, the delay is much longer than the characeristic time scales of the events in any one frequency domain.

Two examples of variable sources whose characteristics run counter to the predictions of expanding source models are 0621+400 and DA 406 (Figures 7 and 8 respectively). During the past two years 0621+400 has exhibited two bursts at 408 MHz but the spectral index remained steeper than -0.8 indicating that the bulk of the source was transparent. The most dramatic deviation from the behavior expected on the basis of expanding source type models is shown in Figure 8 where a large outburst at 408 MHz has no counterpart at 8.0 GHz. This behavior could be produced by a synchrotron source but only if the bulk of the 408 MHz emission is produced in a transparent emitting region.

INTERPRETATION

The almost "standard" working model which has been used to interpret radio variability has been the expanding source type model in which relativistic particles injected or accelerated in a relatively small volume travel outwards through a magnetic field (Van der Laan 1966, Pauliny-Toth and Kellermann 1966). As the particles travel outwards, their "random" motions become radially directed, and this adiabatic cooling of the emitting particles rapidly reduces the emissivity per particle. When the effects of synchrotron self-absorption are also included in this model, the expected flux density variations are strongest and most rapid at the highest frequency, and the variations will appear later at lower frequencies. These types of models, while able to account qualitatively for the centimeter wavelength variability, predict amplitudes at decimeter wavelengths many orders of magnitude less than are often observed. As is illustrated by some of the wideband data shown here, although the data is consistent with the synchrotron emission process, the physical conditions in the regions producing the decimetric variability must be different from those specified by expanding source type models. In particular as was mentioned in the case of DA 406, the radiating particles must be injected into or accelerated in an emitting region which maintains a low absorption depth.

We would like to suggest a mechanism for producing the low frequency variability phenomenon which involves the "reacceleration" of particles which were initially ejected from the core of the radio source. As discussed in the expanding source type models, these relativistic particles cease to emit substantial amounts of radiation because they have adiabatically cooled; but they continue to retain a large amount of energy due their radial outward motion from the core. In the mechanism we are proposing for the low frequency variables, these particles are reaccelerated (scattered) in shock fronts formed at the interfaces between streams of particles moving at different velocities from the core. The particles are "rethermalized" in a relatively low density region so that the emitting region is never opaque even at frequencies below 1 GHz; the time profile of the low frequency burst, under these conditions, is controlled by the rate of acceleration and subsequent cooling of the emitting particles in the shocked region. The time history of the emissivity of a typical particle is illustrated in the upper part of Figure 9 where time is shown increasing to the left. In the lower part of the figure the characteristic spectrum produced in this type of model is sketched. The high-frequency bursts are produced by the relativistic particles as they stream out from the core, cooling adiabatically, and the low frequency emission is dominated by the radiation from shocked material in the outer part of the source. Because of the low density in the region of the shocks, this type of model would predict that the low frequency bursts should have a spectrum which is typical of a transparent synchrotron source.

Note that the short time scales of both the decimetric variability and the centimeter wavelength variability require the emitting regions to travel toward the observer at relativistic velocities in order to avoid brightness temperatures (in the rest frame of the emitting region) which exceed the limit set by the absence of catastrophic inverse-Compton radiation in the

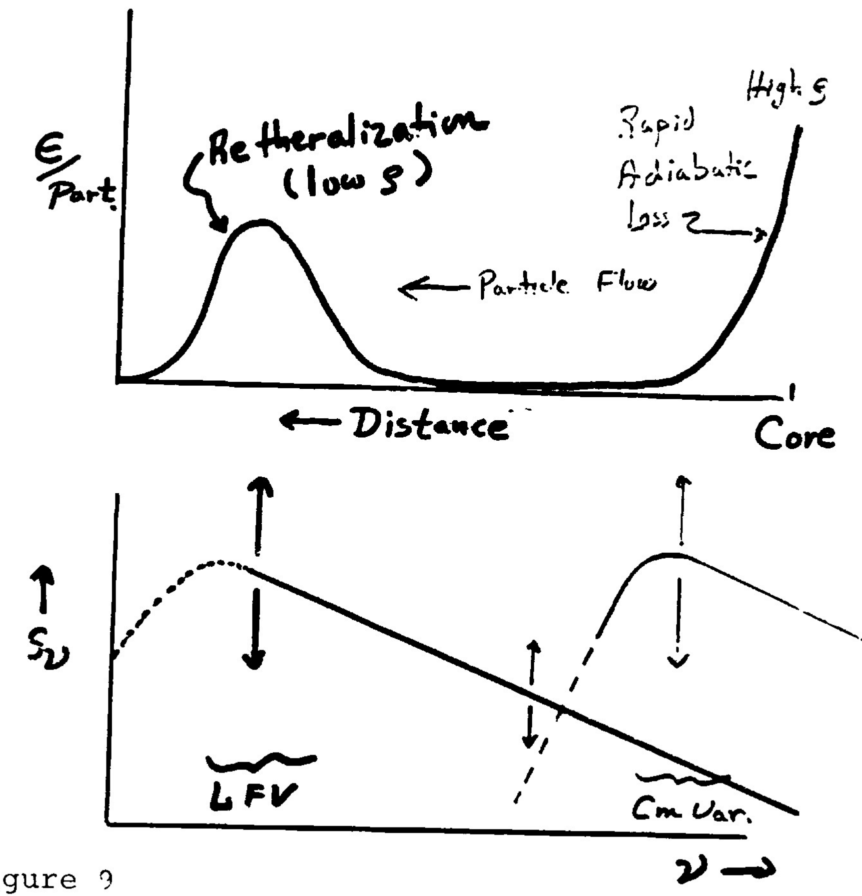

Figure 9

sources (Jones and Burbidge 1973; Ledden, Aller and Dent 1976). Thus the particles which produce the centimetric emission and the shock fronts where the reacceleration of particles take place must be moving toward the observer relativistically (e.g. down a jet) and cannot be stationary.

The schematic model described above is able to at least qualitatively describe the observed characteristics of the low frequency variables. The appearance of large-amplitude, low frequency variations would be enhanced in active variable sources where there is a higher probability that new streams of relativistic particles will collide with previously ejected material. The relative amplitude of decimetric and centimetric bursts would be expected to vary over a wide range depending on the physical conditions in the core and in the shocked regions of the source. The delay between the high frequency and low-frequency bursts would also be expected to vary depending on the distance newly ejected particles must travel before encountering a shock front. In particular the delay can be much longer than the time scale of the bursts, as may have been observed in the case of 3C454.3 (Figure 6). Note that this model favors large amplitude flux density variations at low frequencies (because the low frequency emitting region is transparent) and at high frequencies (because the core tends to be opaque). At intermediate frequencies the flux density variations can be low, as has been observed by Spangler and Cotton (1981), because neither mechanism would produce much emission there. This work was supported in part by the National Science Foundation Grant No. AST 80-21250.

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OPACITY EFFECTS AT LOW FREQUENCIES

C. P. O'Dea[1,2]
T. J. Balonek[1,3]
W. A. Dent[1]
J. E. Kapitzky[1]

We present 2.7 GHz measurements of the total flux density and linear polarization of two BL-Lac type quasi-stellar objects: 1308+326 and 2200+420 made at 2.7 GHz with the NRAO 300-foot transit telescope. The details of the observing techniques and the reduction procedures are given by Kapitzky (1976). Observing sessions were typically of one week duration and were scheduled approximately every four months. Observations taken during this week period were combined to derive an average total flux density and polarization (in order to increase the signal-to-noise). Sufficient signal-to-noise daily measurements are obtained only for strong or highly polarized sources. Thus our data is not sensitive to events occuring on timescales of less than four months.

I. 1308+326

The BL-Lacertae type quasi-stellar object 1308+326 has been the subject of much interest. This source is discussed in detail by Puschell et al. (1979) who observed an optical-infrared outburst in

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[1]University of Massachusetts
[2]NRAO, VLA Program*
[3]University of New Mexico
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early 1978 with a luminosity of ~10^{48} ergs/sec making it one of the most luminous known outbursts. During this outburst, changes in the optical polarization occured on time scales as short as 15 minutes. The centimeter wavelength spectrum was flat with a broad peak near 10 GHz, and a decimeter excess. The polarization position angle was near 90 degrees from 31.4 to 4.8 GHz in mid-1978 and the polarization decreased from ~6% at 31.4 GHz to ~2% at 2.7 GHz.

From 1976.5 to 1978.9 the 2.7 GHz flux density, S_T, increased nearly monotonically from 1.3 Jy to 2.3 Jy (Fig. 1). The flux density then remained roughly constant until early 1980 when a small (-.3 Jy) decrease occurred. The polarization position angle, χ, was roughly constant at about 175 degrees until early 1978. Coincident with the optical outburst in 1978, the position angle began rotating, changing by about 70 degrees by early 1980. It has remained constant at 103 degrees ever since. The polarized flux density, S_p, has fluctuated during this time. It decreased from about .036 Jy in late 1976 to about .014 Jy in early 1977. S_p then increased to .06 Jy in late 1977 and rapidly decreased to .008 Jy in mid-1978 just preceeding the maximum total flux density and the onset of the position angle change. Simultaneous with the time of maximum total flux density (in early 1979), the polarized flux density jumped to .051 Jy after which it decreased to .03 Jy by early 1981.

The evolution of the radio spectrum is presented in Fig. 2. The observations have been obtained from a program to monitor variable radio sources at frequencies between 2.7 and 90 GHz by our group at the University of Massachusetts. The outburst originated at mm wavelengths. The spectrum in 1977.5 had a broad peak near 20 GHz, which increased with time as the frequency of the maximum propagated to lower frequencies peaking at 8.0 GHz by 1979.0. At this time the spectrum appeared to have a sharper, more narrow peak as the flux density at millimeter wavelengths declined. Between 1979.0 and 1981.1 the spectrum below 15.5 GHz fell and the spectrum above 15.5 GHz rose as another outburst began, flattening the total spectrum. The 70 degree position angle rotation occured during the time when the first outburst was becoming transparent at 2.7 GHz.

After the rotation during which the outburst became transparent at 2.7 GHz, the 1.8% polarization is in agreement with the wavelength dependent polarization found by Puschell et al. (1979). The post-rotation angle of 103 degrees is the same at all frequencies from 2.7 to 31.4 GHz.

The observed polarization variations are in good agreement with the predictions of the simple opacity model (Pacholczyk and Swihart, 1967; Aller, 1970; Takarada, 1970; Pacholczyk, 1977). However, the position angle change is 70 instead of 90 degrees and the polarized flux density increased only slightly during the rotation. Thus, the data is not in perfect agreement with the model and some modifications are required. In particular, some amount of inhomogeneity in the magnetic field and the existance of a constant polarized component seem necessary to account for the details of the observations.

Following the analysis outlined in Marscher et al. (1979) and using $\Delta S = 1$ Jy, $\Delta t = 2$ yr, $z = .996$ (Miller, 1978), $H_o = 75$ km/s/Mpc, and $q_o = 0$ we obtain a brightness temperature $T_b \sim 10^{13}$ °K based on a size deduced from the variability timescale. Since the polarization variations indicate that the flux density changes are due to an outburst in an incoherent synchrotron source, the high brightness temperature in this outburst in 1308+326 is probably due to bulk relativistic motion of the emitting material with a relativistic doppler factor $\delta \geq 3$.

II. 2200+420 (BL LAC)

Our 2.7 GHz measurements of the total flux density, polarized flux density, and polarization angle are presented in Fig. 3. The source is very variable in all three quantities and some changes may not be sampled adequately by our observations. The variations in polarized flux density generally follow those in total flux density. The outbursts are strongly polarized, the peaks at 1975.0 and 1977.0 reaching 5%. Though only minor variations in the position angle are observed after mid-1974, a large range of variation is seen in both our data and that of Altschuler and Wardle (1976) prior to that time.

An outburst (ΔS = 5.3 Jy) began in late 1979 and peaked at 7.5 Jy in mid-1980. The polarized flux density peaked at .22 Jy in mid-1980 and (based on 2 points) dropped to .08 Jy in late 1980 and increased again to .19 Jy by early 1981. The position angle rotated by 44 degrees over the same time interval. In mid-1980 Aller, Hodge, and Aller (1981) observed a roughly 12 deg/day nonlinear rotation in position angle with a total range of about 440 degrees. The rotation was observed at 4.8, 8.0 and 14.5 GHz. However, the onset of the rotation at 4.8 GHz was delayed with respect to the higher frequencies (H. Aller, 1982 private communication).

The evolution of the radio spectrum during the 1980 outburst is presented in Fig. 4. The dip in the 1980.2 spectrum near 15.5 GHz suggests that at that time the source consisted of at least two components. There is a broad peak in the spectrum near 31.4 GHz in 1980.6. The curvature in the spectrum indicates that the source was opaque below 2.7 GHz which would explain the lack of a position angle change at 2.7 GHz.

III. SUMMARY

The polarization variations which occured during the 1978-80 outburst in 1308+326 are in good agreement with the predictions of the standard opacity model. The large polarization angle rotations at higher frequencies seen in other sources (e.g. in 0048-097, 0235+164, 0607-157, 0727-115, and BL Lac; O'Dea et al. 1982) are not seen at 2.7 GHz. The large fractional changes in polarized flux density observed in these sources excludes the possibility that the polarization at 2.7 GHz is dominated by a constant polarized component. There are two likely possibilities for the lack of rotation at 2.7 GHz: (1) there is a "low frequency cutoff" near 2.7 GHz which is intrinsic to the rotation; and (2) there is opacity in these sources which prevents us from seeing the rotation. While one cannot a priori rule out the former explanation, the low frequency turndown in the radio spectra suggest that these sources were opaque at 2.7 GHz during the time of the rotation. If the low frequency variability in these (and similar) sources is due to a seperate component (as suggested by Aller et al. and Marscher in these proceedings), then this component must be located outside the opaque region or along a different line of sight.

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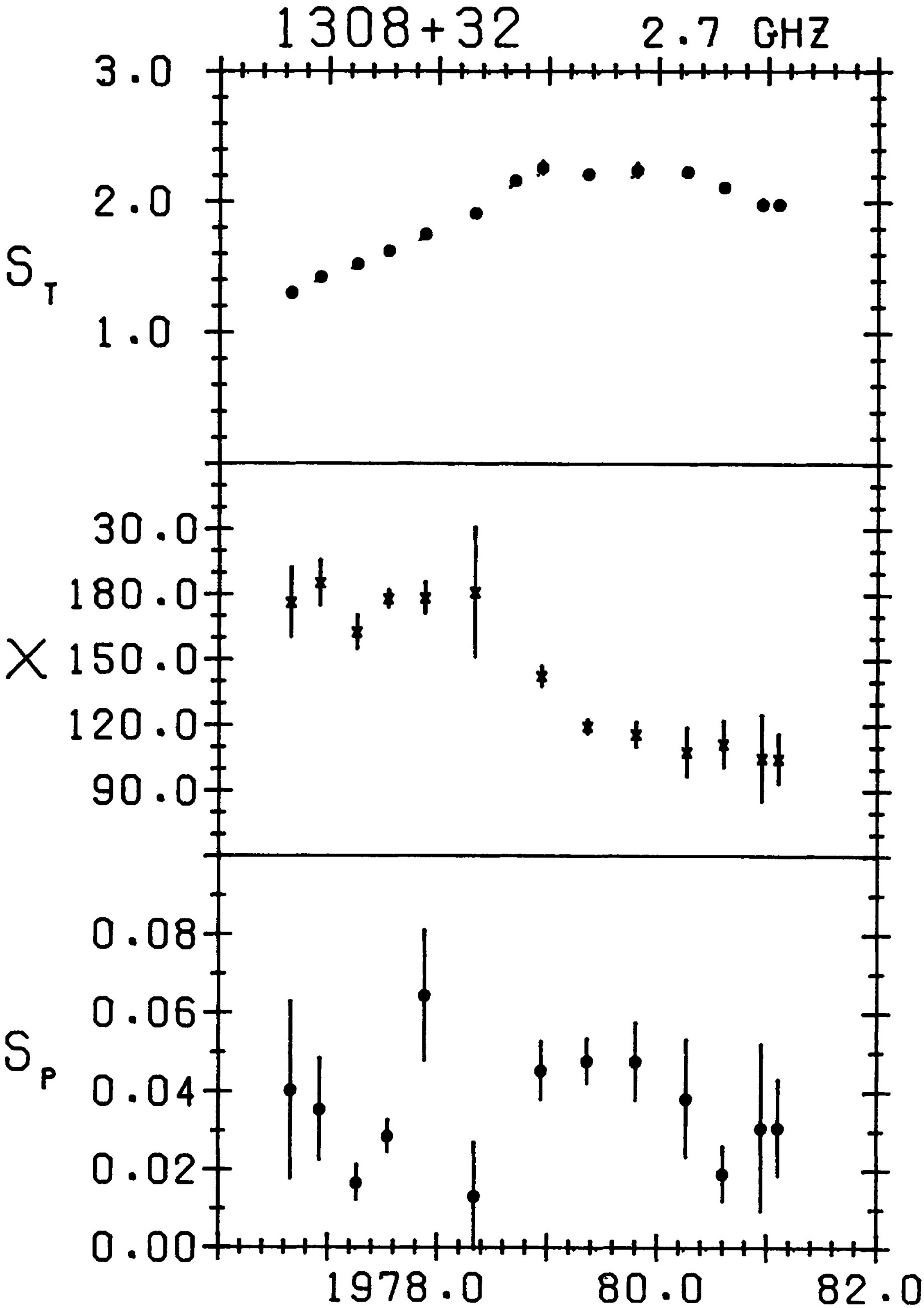

1308+32
2.7 GHZ
3.0
2.0
1.0
S_T
30.0
180.0
150.0
120.0
90.0
X
0.08
0.06
0.04
0.02
0.00
S_P
1978.0
80.0
82.0

Figure 1.

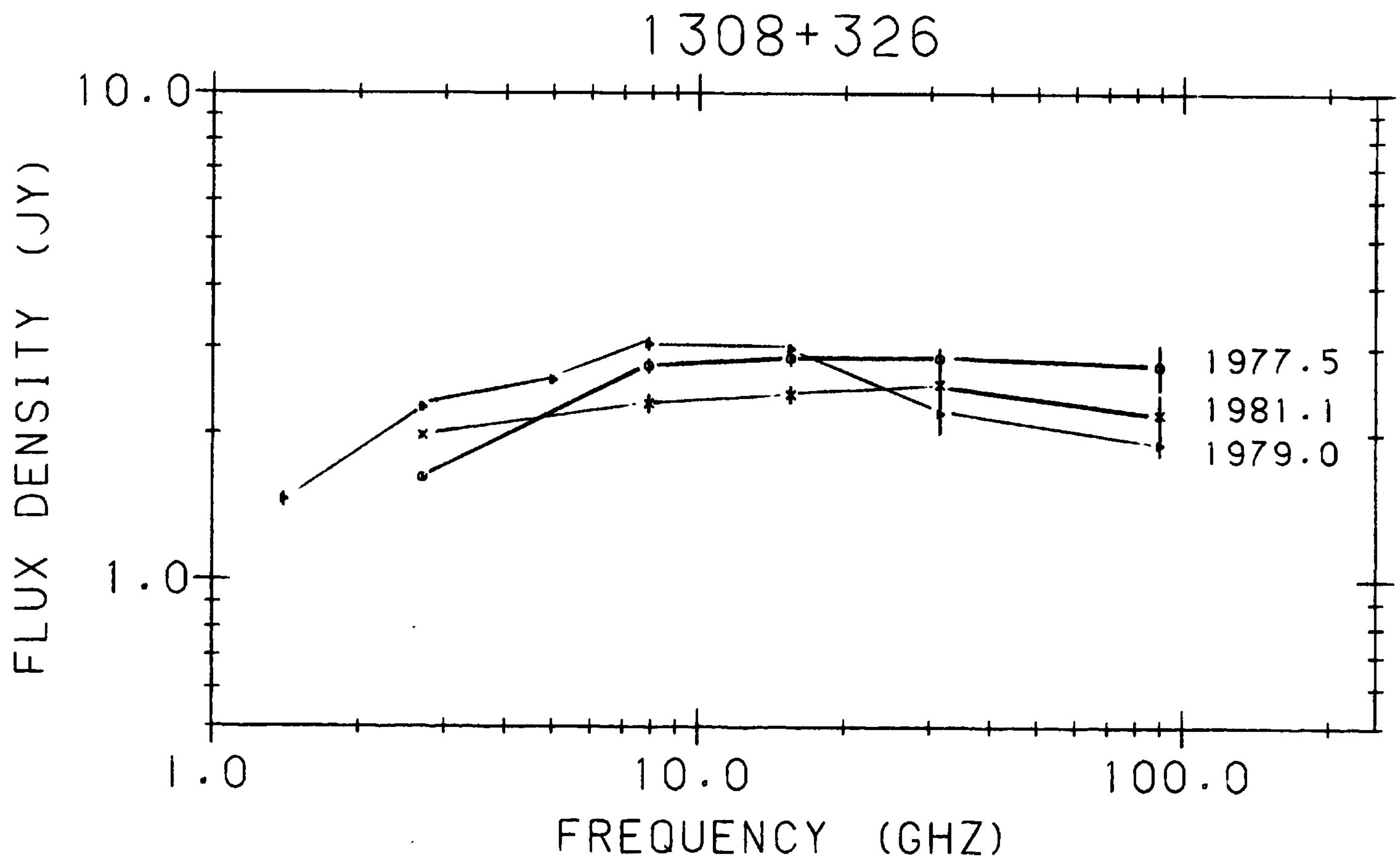
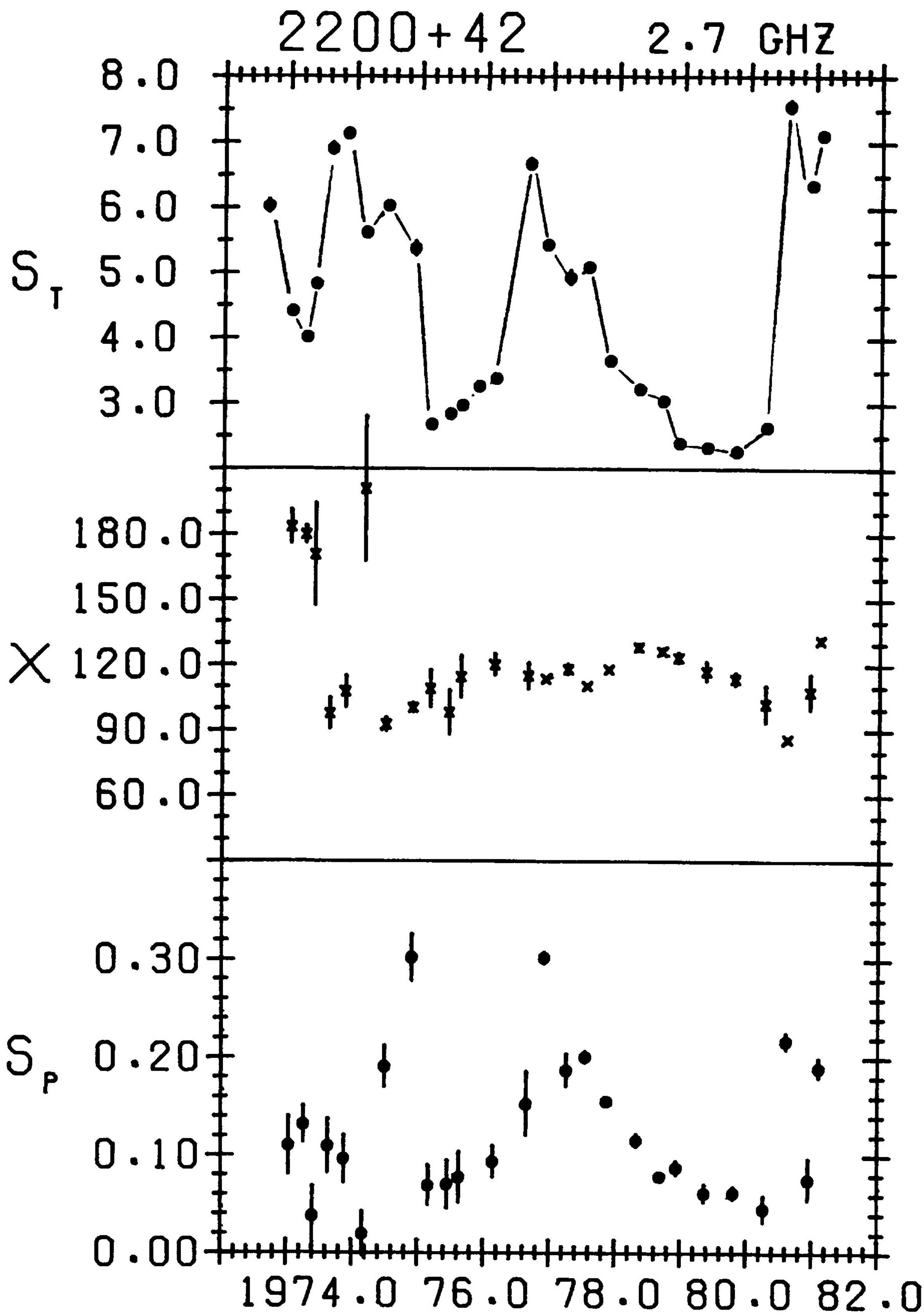

1308+326
10.0
1.0
FLUX DENSITY (JY)
1.0
10.0
100.0
FREQUENCY (GHZ)
1977.5
1981.1
1979.0

Figure 2.



2200+42
2.7 GHZ
8.0
7.0
6.0
5.0
4.0
3.0
S_T
180.0
150.0
120.0
90.0
60.0
X
0.30
0.20
0.10
0.00
S_P
1974.0
76.0
78.0
80.0
82.0

Figure 3.

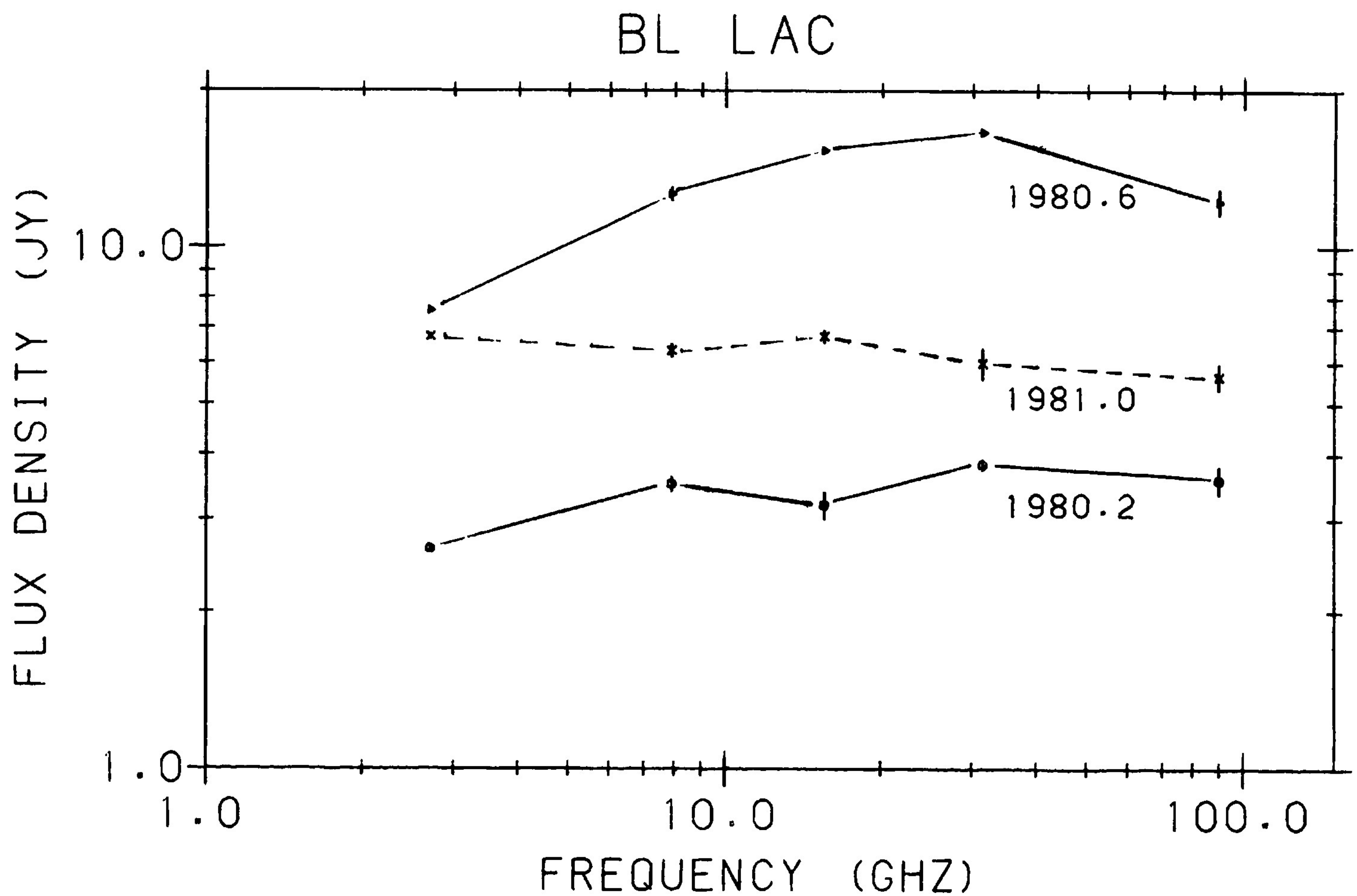

BL LAC
FLUX DENSITY (JY)
10.0
1.0
1980.6
1981.0
1980.2
1.0
10.0
100.0
FREQUENCY (GHZ)

Figure 4.

Steep Spectrum Compact Sources and Low Frequency Variability

W. D. COTTON

National Radio Astronomy Observatory*

June 1982

I. INTRODUCTION

The compact sources which have traditionally been well studied generally have flat spectra in the centimeter wavelength range, indicating an appreciable optical depth if these sources emit *via* the synchrotron process. Recent studies by Cotton (1982) and Mutel *et. al.* (1981) reveal the existence of compact sources with quite steep spectra in the centimeter wavelength region of the spectrum. Several of these sources have exhibited low frequency variability (Cotton 1976). In the following, the theoretical implications of steep spectrum compact sources will be considered, with particular emphasis on the possible relationship with low frequency variability.

II. OBSERVATIONS

The details of most of the observations summarized here have either been or will be published elsewhere. Results from the broadband flux density monitoring program reported in Spangler and Cotton (1981) suggested that several variable or possibly variable (Cotton 1976) sources were dominated by a very steep spectrum compact component. Followup observations of these sources with the VLA are described in Cotton (1982) which confirm dominant steep spectrum compact structure in these sources. In addition, VLBI observations of 2147+145 (Cotton *et al.* 1982) indicate that most of the flux density in this source comes from a region not more than $0\farcs01$ in extent. Another possibly signifigant result is that none of these sources has an optical counterpart to the limit of the Palomar Sky Survey. This indicates that the spectra of these sources remain steep to quite high frequencies.

The spectra of the sources reported on in Cotton (1982) are shown in Figure 1. This figure indicates in addition to being steep, the spectra of these sources do not peak above 400 MHz and in many cases not above 200 MHz. One of these sources, 2147+145, has been studied more extensively and its spectrum is shown in Figure 2. In addition to the data from Figure 1, Figure 2 shows upper limits at 90 GHz (Spangler and Cotton unpublished), 2.2 micron (Owen and Puschell

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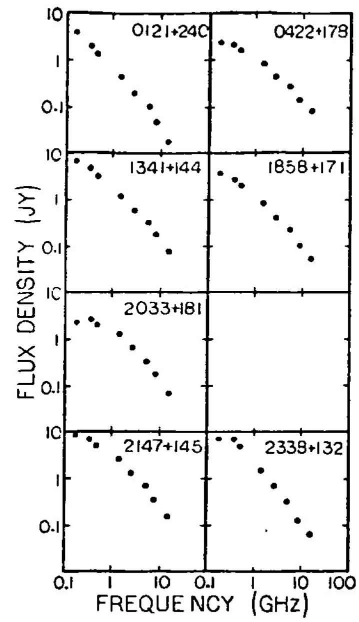

FIGURE 1. This figure shows the source spectra. Flux densities at 0.178 GHz are from the 4C catalogue (Pilkington and Scott 1965 and Cower *et al.* 1967). Flux densities at 0.365 GHz are from Ghigo and Owen (1973), Sharp and Bash (1975) and 0.43 GHz flux densities are from Spangler and Cotton (1981).

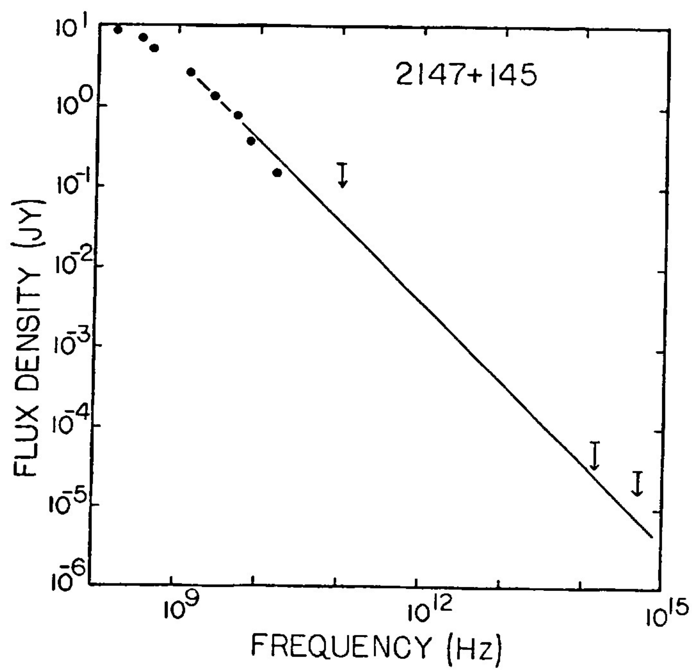

FIGURE 2. The spectrum of 2147+145. The line shown is an extrapolation of the intermediate frequency radio spectrum with a spectral index $\alpha = -1$. See text for an explanation of the upper limits.

private communication) and optical wavelengths corresponding to its absence on the Palomar Sky Survey.

Observed values or limits on angular size and turnover frequency can be used to constrain the magnetic field in a synchrotron source. Following Terrell (1966):

$$B = 2.43 \times 10^{16} \nu_c^5 \theta^4 S_c^{-2} (1+z)^{-1} \text{ mgauss} \quad (1)$$

where

$\nu_c =$ cutoff freq. (GHz),
$\theta =$ diameter (″),
$S_c =$ max. flux density (Jy),
$z =$ redshift.

Since none of the sources under consideration has an optical identification, a value of the redshift (z=1) has been assumed. Another assumption made here is that the structure of the compact component does not change signifigantly with frequency. The observational results and the derived values of, and limits on, the magnetic field strength are shown in Table 1. Since the magnetic field strength depends to high power on poorly determined observational quantities, the derived values are quite uncertain. Although many of the values of the magnetic field strength given in Table 1 are probably severe overestimates, several of these values are quite low. The source for which the highest resolution was available, 2147+145, appears to have a remarkably weak magnetic field.

Table 1
Limits on the Magnetic Field Strength

Source	S_c(mJy)	ν_c (GHz)	θ(″)	B(mgauss)
0121 + 240	$\geq$3700	$\leq$0.2	0.06	$\leq$3.7
0422 + 178	2300	0.2	0.10	73
1341 + 144	$\geq$6800	$\leq$0.2	$\leq$0.09	$\leq$5.5
1858 + 171	$\geq$3700	$\leq$0.2	$\leq$0.05	$\leq$1.8
2033 + 181	2700	0.3	$\leq$0.05	$\leq$25
2147 + 145	9600	0.2	0.01	.0004
2338 + 132	7600	0.2	$\leq$0.05	$\leq$0.4

III. Discussion

The results given above indicate that these compact steep spectrum sources have weak magnetic fields. A weak magnetic field has several severe implications about the physical conditions in the source if the emission is from the synchrotron process. First, since the frequency of the peak emission from a single electron is a function of the magnetic field strength (Pacholczyk 1970), the energy of the electrons radiating at a given frequency increases with decreasing magnetic field strength. Second, the emissivity is proportional to the magnetic field strength (Pacholczyk 1970); this requires that more electrons radiate at a given frequency in a weak field source to produce the same emission as a stronger field source. Finally, since the radio spectrum indicates a steep electron energy spectrum, the two effects described above require that the total relativistic electron density be much higher in a weak field source to produce comparable emission to a strong field source.

The high electron density required by the weak magnetic field will in turn produce very high brightness temperatures near the turnover frequency. The flood of photons from near the spectral peak may, in some cases, cause signifigant inverse Compton losses by the electrons radiating at higher frequencies. Since inverse Compton energy losses are proportional to the square of the electron energy, the relatively high energy of the electrons radiating at a given frequency enhances the observational effects of inverse Compton scattering. This is especially true for electrons which radiate at infrared and optical frequencies. The resulting short inverse Compton lifetime of the high frequency electrons could account for the very steep spectrum observed in these sources. More detailed model calculations described in Cotton (1982) confirm the general nature of these results.

Since low frequency variability has been observed in several steep spectrum compact sources, there may be a relationship between these two phenomena. In particular, the weak magnetic field model presented above for the steep spectrum compact sources may be useful in explaning some aspects of low frequency variability. The weak magnetic field model does not help the well known timescale/brightness temperature problem but may help explain other observational details.

Two aspects of low frequency variability to which the weak magnetic field model may be applied are the low frequency at which the phenomenon is observed and the steep spectrum of the event with apparent steepening during the outburst as observed in 1611+343 by Cotton and Spangler (1979). If the low frequency outburst comes from a plasmoid moving towards us at relativistic speeds with a weak magnetic field, beaming and relativistic time effects could account for the high brightness and timescale, while inverse Compton losses by the more energetic electrons would account for the spectral steepening. The weak magnetic field would cause the strongest variations to appear at low frequencies. If this is the case, the magnetic field in the plasmoid must be weaker than those in the cores of the sources discussed above or the blueshift due to the relativistic motion would have moved the spectral peaks to higher frequencies than are observed.

IV. Conclusion

We have shown that sources with dominant, very steep spectrum compact components exist and that if they radiate by the synchrotron process that they probably have very weak magnetic fields. A weak magnetic field requires a very high relativistic electron density to produce signifigant emission. The high electron density causes a high brightness temperature near the turnover frequency. Photons from the spectral peak deplete the high energy electrons by inverse Compton scattering producing a very steep synchrotron spectrum.

Since low frequency activity has been reported in several very steep spectrum compact sources, there may be a physical relationship. In particular, the weak magnetic field model may be able to explain 1) the low frequency at which the phenomenon is observed, and 2) the steep and steepening spectrum observed in the outburst of 1611+343 reported by Cotton and Spangler (1979).

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National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22901

THE MOLONGLO 408 MHz OBSERVATIONS 1967-1978

W.B. McAdam

The Molonglo Cross Telescope operated with a stable procedure and the same beam shape for more than a decade. Data from most of the observations are held in an archive and describe ~ 60 000 scans of 7500 sources that have flux density $\gtrsim$ 1 Jy. A search of these records for low frequency variables has discovered some sources that increased or decreased steadily for many years and have time scales of 20 to 150 yr. The sizes and brightness temperatures inferred from their cosmological distances are compatible with both the inverse Compton limit and VLBI measurements.

Introduction

The Molonglo Cross telescope was proposed by Mills in 1961 and built during the next 6 years by the University of Sydney to a design that was based directly on the performance of his successful 85 MHz Cross. The primary objectives outlined by Mills followed from the results of this earlier instrument. These were: detailed studies of galactic structure and individual emitting objects in the Milky Way and Magellanic Clouds; structure of normal and radio galaxies; investigations of very distant 'cosmological' radio sources; a survey of the sky south of declination +18°, with positions better than 10 arcsec for some 10 000 sources.

The EW arm was finished in 1965 and used as a fan-beam telescope until the full cross was ready in 1967. Although the sensitivity was improved in four steps during the next decade there were no changes in the reflecting mesh, feed elements or excitation so that, at least within the stability of phase and gain for 200 preamplifiers, the beam size and shape were constant.

Between 17 November 1967 and 23 August 1978 most observations were digitised and after analysis, the magnetic tapes were retained in an archive. (The main exceptions were pulsar observations with short time constants and rapid sampling.) The archive records provide a data bank that specifies the brightness at 408 MHz over the sky south of declination $+18.5^\circ$, and is suitable for examining the flux density from any position - perhaps that of an X-ray source or optical QSO. The survey of the southern sky observed some sources many times. About 30% of the strong sources were measured 3 or more times and ~ 230 small diameter sources, used as calibrators for the survey scans or for other programs, were measured ≥ 50 times.

By August 1978 the major tasks of the Molonglo Cross were finished and the telescope was stopped. The system was then altered and in 1981 the Molonglo Observatory Synthesis Telescope (the MOST) began observing at 843 MHz in an Earth rotation mode that uses the EW arm only.

This paper examines the calibration of flux density for the 408 MHz data in the archive. A search for low frequency variables that have slow, long-term changes has begun and initial results for two of these sources are described.

Observations

The data available in the archive can be divided into three classes according to the observing sequence and flux density calibration.

1. Surveys : The telescope remained at one declination setting for several hours - generally overnight for ~ 17 h. Calibrated by 2 or 3 reference sources at both start and finish.
2. Projects : Short observations (perhaps 1-10 min) of individual objects at various declinations. Calibration sources were intermixed in the transit sequence - perhaps 2 or 3 each hour.

3. Cycle Program : The same sequence of 254 scans was repeated on 3 or 4 successive days each 4 weeks during the year commencing March 1975. Calibration was by comparison with those neighbouring sources within ± 1 hr R.A. that were not variable.

The survey scans cover 7.85 sr south of declination +18.5° and were described by Large et al (1981) in the Molonglo Reference Catalogue (MRC). The analysis procedure fitted collimation, ionospheric and gain corrections to the calibrators in the afternoon and following morning. There were small adjustments for consistency with results from overlapping zones observed on other nights but, because the zones were covered in a fairly sequential manner, diurnal effects would still affect the gain. The flux density errors are assessed at 4.3% for strong sources rising to 7.0% for sources of 1 Jy, at which level the MRC is substantially complete. There are 7347 sources with $S \geq 1$ Jy.

All Molonglo flux densities are based on absolute measurements of 5 primary sources and a list of 37 secondary sources observed in 1966/67 with the fan beam (Wyllie, 1969). Because many of these sources vary (there are 17 known or suspected variables including 3 of the primary scale sources) the reference for the Wyllie scale is now the mean of the non-varying sources among 314 small diameter sources observed in 1968/69 by Hunstead (1972a). Any change in the mean flux density of the 42 Wyllie sources between epochs 1966/67 and 1968/69 would affect the Molonglo scale but the effect should be < 1% and negligible compared with 6% uncertainty in the absolute scale.

The flux density calibration for individual projects depends on the gain stability of the telescope and the selection of reference sources made by each observer. The standard deviation of a single transit scan was 3.7% in 1969 (Hunstead, 1972a) but improvements to preamplifiers along both EW and NS arms reduced this to 1.6% in the cycle observations of 1975/76 (McAdam, 1976; 1980). It should be noted that 1.6% is a short term stability achieved over a session of 3 or 4 days, using a weighted mean of 7 to 15 calibrators observed within ± 1 h in the cycle. For the surveys and projects that have fewer reference sources there are effects from diurnal changes in gain: these have irregular waveform, typically 10 to 15% peak-peak amplitude and a maximum gradient of 15 to 20% per hour.

The first variables at 408 MHz were recognised by Hunstead during the 1969 observations. Five sources had discrepancies in flux density between observing sessions and were listed as possible variables. Further monitoring up to January 1972 gave 4 definite and 7 possible variables with a suggestion that "variable emission at 408 MHz may be a relatively common property of discrete radio sources" (Hunstead, 1972b).

The proportion of small diameter sources that are variable at 408 MHz is difficult to determine at any level of $\Delta S/S$. Among the 254 cycle sources, changes $\geq$ 6% were found in 33% (McAdam, 1980) but this proportion is perhaps too high because the cycle deliberately included 33 known or suspected variable sources. For a lower limit in an unbiased sample, I consider the 314 sources in Hunstead's (1972a) calibration list: although many sources have not been monitored adequately, at present we know of 49 definite or probable variables plus 22 suspects with $\Delta S/S \geq 6\%$, giving a proportion of 23%. For more active variables at a level $\Delta S/S \geq 10\%$, the proportion lies between 9% (cycle) and 7% (Hunstead's list).

Retrospective Search

All archive records, irrespective of original observer or program are being reanalysed in a search for weak sources (flux density > 100 mJy) and variables. The search catalogue lists fluxes for ~ 60 000 scans of

~ 7500 sources that, at some time, have been ≥ 1 Jy. Most sources have only 2 or 3 scans corresponding to the MRC survey scans but there are ~ 900 sources with ≥ 10 scans and ~ 230 sources with ≥ 50 scans.

A preliminary calibration uses a single gain factor for each night, ignoring diurnal changes, and the standard deviation of 6.3% is similar to that for the MRC survey. Because different calibrators were used for the various projects there are systematic effects that must be checked before apparent variability can be confirmed. However, there are two types of variable for which the initial results are useful: (a) highly active sources that are already known to have changes much greater than 6%; (b) sources that have slow changes and many observations that may be averaged over independent sessions.

A companion paper discusses the search results for 9 active QSOs. Three of these, 0537-441 1510-089 and 2345-167 have a dominant slow change over the whole decade. An earlier study of long term changes between 1969, 1975 and 1978 showed that there was no significant grouping in a plot of the flux density ratios for the three epochs. (McAdam, 1979). Only QSO 1510-089 showed a trend continuing over the 9 years. Time scales > 10 yr for a few sources were thought to be due to inadequate sampling with the minimum criterion of 6% change detected in a comparison of 2 epochs. However, the present results show that some sources do have a slow and regular change in flux density.

The slowest confirmed variable is 0725+147 (3C181) which has decreased at a mean rate of 45 ± 12 mJy/yr corresponding to a time scale of 155 yr. The plot of flux density is given in Fig. 1. There are 99 scans spread between 33 sessions over the full decade. The decrease seems regular with very little short term flickering. The QSO has a steep spectral index α = -0.9 between 468 and 5009 MHz (Wills, 1975). It has been resolved by the NRAO interferometer at 2695 MHz (Hogg, 1969) into an equal double spaced 6" about the QSO position. The components are unresolved. The source diameter inferred from the light travel time is 20 pc and, at the redshift of z = 1.382, subtends an angle of 4 mas. The equivalent brightness temperature is 4×10^{12} K.

Another slow variable is 2223-052 (3C 446) which decreased by 7.7% between 1973 and 1978. The preliminary analysis of 134 scans in 37 sessions gives a time scale of ~ 70 yr. At a redshift of 1.404, the inferred diameter is 9 pc, the angular diameter ~ 2 mas and the equivalent brightness temperature ~ 4×10^{13} K.

This 408 MHz variability adds another characteristic to the extraordinary behaviour of 3C 446. It is a high frequency variable, has VLBI structure ~ 20 mas at λ 18 cm and an unresolved core < 0.4 mas at λ 6 cm. The optical emission is highly polarised (HPQ) with rapid changes in polarisation and luminosity (OVV): see the extensive discussion by Moore & Stockman (1981) and the references therein.

The flux density changes in both these QSOs are two orders of magnitude slower than those in active QSOs like 1504-166 and 0736+017. The derived brightness temperatures are close to the inverse Compton limit ~ 10^{12} K for the uniform van der Laan/Shklovsky model and it is possible that in each QSO we are observing the decay of a compact component created or re-energised by the QSO nucleus.

The calibration of data in the Molonglo archive is a recursive effort as more variable sources are recognised in the reference list. In addition to exploring the behaviour of the variables our aim is to identify a sufficient number of non-variable sources ($\Delta S/S$ < 5%) to give

a calibration for most sessions comparable with the gain stability of the telescope. I thank D.F. Crawford for the search analysis, and A.J. Turtle for help with the 11 000 scans in the monitoring Cycle observations. The Molonglo Cross was built with grants from the Nuclear Research Foundation within the University of Sydney and the National Science Foundation, U.S.A.

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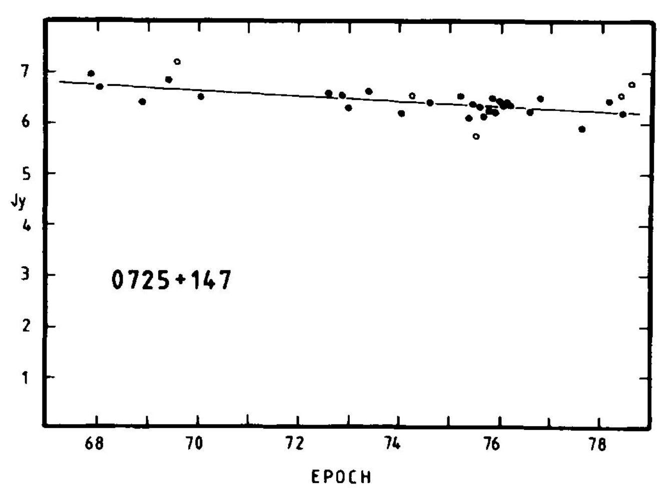
Figure Caption

Fig.1 Variations in the 408 MHz flux density of QSO 0725+147 (3C 181) measured with the Molonglo Cross Telescope. A filled circle shows the mean of 2-6 scans in a session: an open circle shows a value from a single scan. The line is a least-square regression, ignoring the single scans, and decreases at 45±12 mJy/yr.



INTENSITY CHANGES AT 408 MHz FOR 9 QSOs

W.B. McAdam

The flux density changes in low frequency variables between November 1967 and August 1978 have been investigated by searching through data in the Molonglo archive. This paper presents results for 9 active QSOs selected on the basis of their variability during Molonglo observations. The intensity curves show a variety of behaviour. Most have a rapid flickering that determines a median time scale of 2 yr but 3 QSOs also have a slow change in base level with a time scale $\gtrsim$ 20 yr.

Introduction

Changes in radio, optical or X-ray emission occur in many QSOs and the complex activity is thought to give information about the energy processes in the compact parts of the source - the nucleus, jets or hot spots. Correlation of the time, amplitude and shape of the fluctuations is required over the wide range of frequencies. The general interpretation of the QSO emission in terms of opaque synchrotron components requires that variations in radio flux density are slower at the longer wavelengths. A single homogeneous outburst should also have the peak intensity at long λ occurring later and with lower amplitude than the short λ. The first intensity curves for 3C 120 at $\lambda\lambda$40 to 2.8 cm supported this model, but other QSOs had a diversity of behaviour that required considerable changes to the model (Kellermann & Pauliny-Toth, 1981). Observations at λ > 30 cm over intervals of 2-6 yr found many low frequency variables (LFVs) that had flux density changes apparently unrelated to changes at shorter λ. Intensity curves at 408 MHz and 365/380 MHz have been published for 41 LFVs (Hunstead, 1972; Cotton, 1976; Fanti et al., 1979) and their general characteristics have been summarised by Fanti et al., (1981).

The most active QSOs have changes $\gtrsim$ 30% in a few weeks and these provide the strongest challenge to theories of emission. A few events seem to occur simultaneously at a range of wavelengths and there have been attempts to follow the changing spectrum of the bursts. (Spangler & Cotton, 1981.) The flux density of any underlying stable component should be subtracted for this exercise but the level is difficult to determine when the time scale of the variation is comparable with the total period of monitoring. In addition, the rates of rise or fall are similar so that it is still not clear whether activity represents outbursts or downbursts (or both) from a quiescent base level.

The data from Molonglo Cross observations allow intensity curves of ~ 300 sources to be followed over a 10 yr interval using a retrospective search through our data archive (McAdam, companion paper I). This paper presents the intensity curves for 9 QSOs that are already well known for activity at optical and cm wavelengths.

Selection of the Sources

The selection of the 9 QSOs was based solely on the 408 MHz flux density changes observed at Molonglo.

The monitoring of extragalactic sources was most intensive during the year from March 1975 when the cycle of sources was observed in sessions of 2-4 days every 4 weeks. There was one further cycle session in October 1976. The Hunstead (1972) observations in 1968/69 provide an equivalent session (but with a different source list. Two measures of variability were obtained from these sessions.

a) Short term activity: the mean flux density S and the standard deviation sd were found for the N scans in each session as well as the mean S_{75} for the whole cycle. There was a similar stability for all sources over the 3 or 4 days in a session and for non-variable sources over the year with sd ~ 1.6% (McAdam, 1980).

Using only 'reliable' sessions for which $N \geq 3$ and $sd < 3\%$ the % Range was found:-

$$\text{Range} = (S_{max} - S_{min})/S_{75}$$

b) Long term activity: the change in flux density between 1968/69 and 1975/76 was found using the mean:-

$$\text{Change} = (S_{75} - S_{69})/S_{69}$$

The Molonglo criteria for variability is that either change or range must be ≥ 6% and $\Delta S \geq 300$ mJy (and $N_{69} \geq 3$ if applicable). The greater activity of long term change or Range during 1975/76 was then ranked for 229 strong sources (with $S_{75} > 1$ Jy) in the cycle. In general, QSOs rank before galaxies or unidentified sources. Of 39 known QSOs in the cycle, 8 rank in the 1st 10 places, which were:-

1.	0833-45	6.	2251+158
2.	1510-089	7.	1036-697
3.	1504-166	8.	1055+018
4.	0736+017	9.	1148-001
5.	0537-441	10.	1524-136

Meanwhile, among calibrators used for the second Molonglo Deep Survey, another variable, 2345-167, was recognised that had a greater change than 1510-089 (McAdam & White, 1982). Except for the vela pulsar 0833-45 and 1036-69 (thought to be a 20^m galaxy) all these LFVs are QSOs. and the 9 form a convenient sample for this initial report.

Intensity Curves

The Molonglo flux densities are shown in Fig. 1 as intensity curves over the decade from Nov. 1967 to Aug. 1978. A linear scale is used without suppression of the zero axis because the relative changes as well as the waveforms are important. Error bars are omitted for clarity. During the cycle observations of 1975/76 the session means have an error $\sigma_m \sim 0.9\%$ ($N \geq 3$) which is smaller than the filled circle. In other years the sessions have $\sigma_m \sim 2\%$. The open circles represent less reliable single scans - usually with sd ~ 6% (Paper I) and these are joined by dashed lines. Hunstead (1972) has already presented the curves up to 1972 for the three QSOs, 1504-166, 1524-136 and 2251+158 but a few additional scans were found in the archive. The intensity curves show a range of behaviour for the QSOs and I distinguish two patterns.

1) Rapid flickering about a base level. There is usually inadequate sample to follow these changes. They may be large (20-40% as in 1504-166), small (5-10% as in 1055+019 and 1148-001) or absent (1510-089).

2) Slow changes in base level continuing for several years as in 2345-167, 1510-089 and, probably, 0537-441, 2251+158.

The time scale has been defined as $S_{max}/(\Delta S/\Delta t)_{max}$ or almost equivalently $\Delta t/\Delta(\log S)$. The histogram of time scales has a peak at ~ 2 yr determined by the flickering pattern (McAdam, 1978). The slow changes give time scales in the range 20-150 yr when flickering is negligible. All flux densities in Fig. 1 are based on the Wyllie scale (Paper I) and the uncertainty of ~ 6% in the absolute scale is not relevant. However, there are further data from Bologna on 5 QSOs from 1975-77 and a merging of these with Molonglo values must consider both absolute scales and possible confusion effects from the differing beam shapes. In general, the overlap in 1975/76 is in excellent agreement but 1504-166 needs an offset of 900 mJy because of the confusion from the nearby QSO 1504-164, (McAdam, 1979).

QSO Characteristics

Some parameters for the 9 QSOs are collected in Table 1. The redshifts and optical magnitudes are from standard lists except for 1524-136 and 2345-167 (R.W. Hunstead, Private Communication). The radio spectral index between 2700 and 5000 MHz is derived from the flux densities in the Parkes Catalogue: for variable sources the index cannot be precise. Column 5 indicates when the source was first recognised as a variable: RWH refers to 1968/70 (Hunstead 1972); Cycle - 1975/76; GLW - 1978 by G.L. White in the Second Molonglo Deep Survey (in preparation). Columns 6-8 summarise the Molonglo data. S_{max} is the highest flux density in a reliable session. The change and range were found from the cycle observations and used in the selection of this sample as outlined above. The time scale is an observed value. The intrinsic time scale in the QSO frame then gives the inferred source diameter and, assuming a cosmological distance, the equivalent brightness temperature.

As a group the 9 QSOs are extremely active at optical and radio frequencies. There have been intense optical flares in 0537-441 (Eggen, 1973) 1510=089 (Liller & Liller, 1975) and 2345-167 (Folsom et al, 1970) that place them among the most luminous QSOs. Both 2251+158 and 2345-167 are optically violent variables in the list of 20 OVVs monitored at Rosemary Hill Observatory (Pollock et al. 1979). The same two sources, with 0736+017 and 1510-089, are in the list of highly polarised QSOs (HPQ) discussed by Moore & Stockman (1981). The association of low frequency variations with optical polarisation suggested by Moore & Stockman is strongly supported by my results. Including 2223-052 (Paper I) and 2345-167 there are now 7 LFVs recognised in the 9 HPQs that have been monitored for variability: definite if 1510-089, "almost certainly" a definite HPQ, is added, the ratio becomes 8/10.

The VLBI network at λ 13 cm has found compact structure on the scale of ~ milliarc sec (mas) in 7 of the sources (Kellermann et al, 1979) and a large part of the flux density is from unresolved components at λ 6 cm for 1055+018, 1510-089, 2251+158 and 2345-167 (Kellermann et al, 1971). The slow change in 408 MHz base level in the latter 3 sources infers a compact of ~ mas size and brightness temperature ~ 10^{13} K close to the inverse Compton limit for synchrotron emission. It seems likely that the slow changes with time scale $\gtrsim$ 20 yr are associated with the component expansion while the flickering activity with equivalent brightness temperature ~ 10^{16} is associated with the optical or X-ray activity in cores of HPQ.

At high radio frequencies, most of the 9 QSOs have flat or inverted spectra and are variable although, surprisingly, neither 0736+017 nor 1148-001 was found to change at 2.7 GHz (Wardle et al., 1981).

Monitoring of these active sources at 843 MHz has begun and their future history will be followed with interest.

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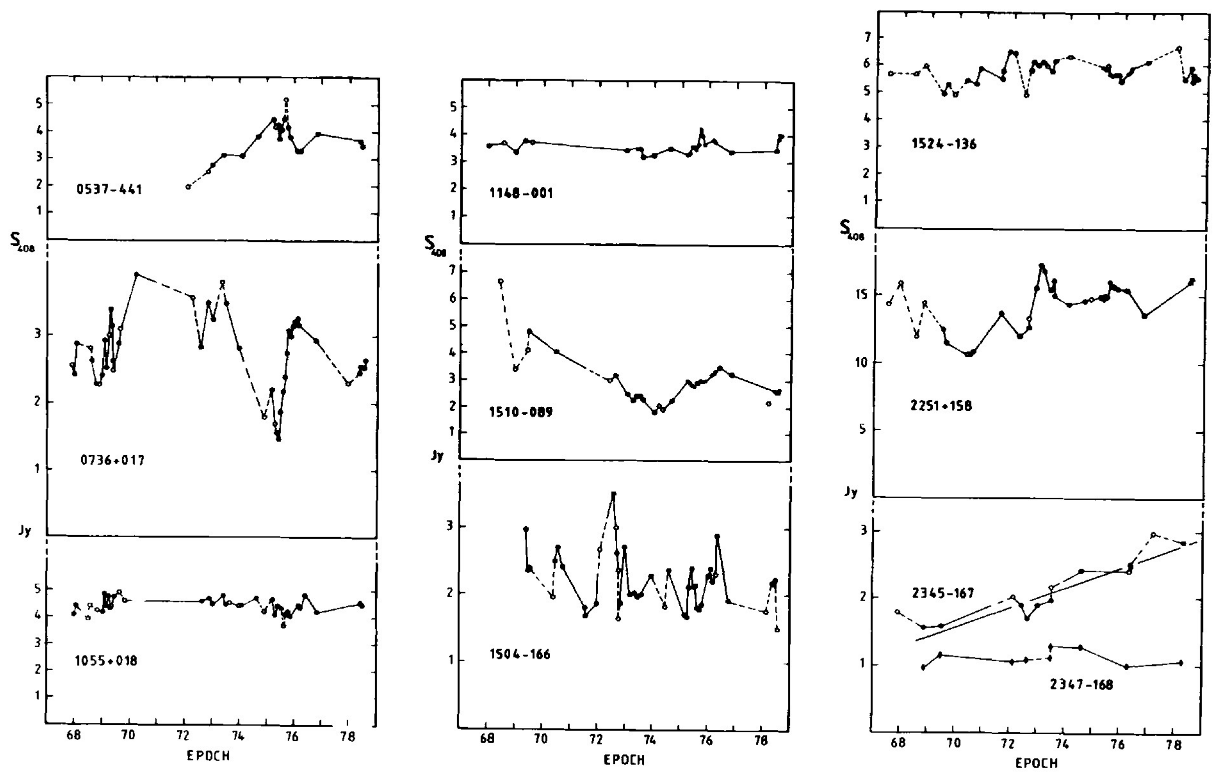
Fig. 1 Variations in the 408 MHz flux density of the most-active QSOs observed at Molonglo. All plots have linear scales with zero baselines to emphasise the extent of the variations. Filled circles show the mean of 2 or more scans in a session: open circles are single scans.

Many scans of QSO 2345-167 extended sufficiently to include the neighbouring non-variable source 2347-168 shown as diamonds.



Low Frequency Variations: Where are we Ten Years Later

T.W. Jones
University of Minnesota

This workshop has served the very useful purpose of bringing out most of the known facts on the phenomenon we have called for ten years "low frequency variability" (LFV). The many excellent observational data such as those presented by Drs. Padrielli, McAdam, Payne and Simon make LFV very clearly real. Although none of us at this meeting have questioned that fact, others have, especially theorists.

Yet the salient question which is still unanswered in my view is "Is LFV a distinct phenomenon to be reckoned with?" By that I mean to ask whether or not it really has special characteristics or difficulties which must be dealt with outside of the phenomena observed at higher frequencies. When Geoff Burbidge and I wrote in 1973 what I believe was the first theoretical paper about LFV (1) we considered a variety of possible explanations and concluded that the fewest difficulties were encountered if one was dealing with a relativistic jet or noncosmological redshifts. The latter would be excluded by most of us today, but the former is now the standard explanation for much of what is seen at high frequencies. From what has been said here it is the clear favorite for LFV, as well. Other explanations are not yet excluded, but they seem to me largely unnecessary. I will elaborate more later on that point.

I) Observational Constraints on LFV

To put things in perspective let me summarize current observational constraints (mostly these are borrowed from papers given at this workshop and references therein):

1) Variations in the decimeter fluxes of extragalactic radio sources are common on a timescale $\tau \lesssim 2$ years (corrected to the source proper frame). For a 1 Jy source at a redshift $Z \gtrsim 1$ a source radius $\lesssim 2$ light years would

imply a brightness temperature $\gtrsim 10^{16}$ K (400 MHz). The canonical synchrotron self-Compton theory (2,3) limits the brightness to $\lesssim 10^{12}$ K.

2) There is a strong association between sources which undergo LFV and sources which show other "interesting" characteristics. For example, there is a good correspondence with optically violent variables (OVV's), highly polarized quasars (HPQ's) and flat spectrum, centimetric variables (CV's). However, some of the LFV sources have steep radio spectra, all of which are apparently invisible in the Palomar Sky Survey.

3) Limited VLBI data show that all LFV sources have structures visible on transcontinental baselines at decimetric wavelengths and that flux changes take place in structures at least partly unresolved. We cannot yet tell if the LFV are actually cospatial with the high frequency variable cores.

4) A simple-minded interpretation of limits to interstellar scintillation (ISS) on several LFV sources gives upper limits on the brightness temperatures often one or more orders of magnitude below those calculated from variations (4). This would be a very important limit, for (because of constraint 1) it would establish the basic need to invoke relativistic motions. However, the interpretation of the ISS is difficult because we don't understand the scattering medium very well and cannot be certain that the source images have not been subjected to angular broadening, i.e., that the seeing is bad. We may consequently, never be able to believe the relevance of the brightness limits.

5) The bandwidth of LFV is of the order of a decade or possibly more. There may in some cases be a sharp high frequency cutoff to the variations. Many LFV sources are also CV sources, but the direct association of decimetric and centimetric variations is ambiguous. A mid-frequency gap around 1000 MHz has been suggested by some data but in other cases it is violated (see discussions by Spangler, Cotton and Payne). It is clear, however, that LFV

events are generally not a pure extrapolation of events observed at high frequencies. There is a hint that some details of the LFV are different from CV. For example, the analyses by Payne, Dennison and Cotton seem to show more nearly simultaneous variations at different decimetric wavelengths than is typical at centimetric wavelengths.

II. Are LFV a Special Problem?

The nature of compact radio sources and particularly the causes of variations are of considerable current interest. For that reason alone LFV are worth studying. However, that is not why we are here. The original excitement about LFV was generated by constraint 1), (the brightness temperature crisis) since it clearly requires some modification of the canonical theory. It was through LFV that the need for such modification was faced head-on. But in the past few years the brightness temperature crisis has appeared at a comparable level in CV. In addition, centimetric VLB observations of "superluminal" motions and X-ray observations placing constraints on the amount of synchrotron self-Compton radiation have strongly indicated the need for similar modifications in the canonical model. Therefore, the brightness temperature crisis is not sufficient reason to isolate LFV for special study. In fact most theorists have avoided providing such attention. From a theorist's point of view LFV are not yet a unique and well defined problem.

For the moment then, LFV remains largely an observational problem. The basic character of the phenomenon must be better defined (constraints 2-5). It must be established if the form of the LFV are qualitatively the same or different from CV (when proper account is taken of expected length scale differences). Is there really a meaningful mid-frequency gap. What connection really exists between outbursts at high frequencies and at low frequencies and are these connections different for example from what one would establish between millimeter and centimeter behaviors? What are the special characteristics of the steep-spectrum LFV sources? Are there distinctive structural features seen through decimetric VLBI? Is the association with OVV's and HPQ's special or merely representative of the condition that "active objects are active?" For good measure I should encourage someone to explore the decimeter polarization characteristics of LFV sources, particularly if we are to entertain serious models involving coherent radiation. That obviously will involve some care, however.

III. Theoretical Status

Finally let me return briefly to the theoretical efforts so far. Most of the papers written to date have focussed almost entirely on the brightness temperature crisis. A few have tried to deal with the mid-frequency gap (5) or similarly the appearance of a sharp high frequency cutoff to the variations (6).

The methods of dealing with the brightness temperature crisis are largely the ones that were immediately obvious (1) and for the most part the same as those which have been applied to CV sources (see e.g. 7). They can be categorized as extrinsic and intrinsic. Extrinsic effects include absorption by intervening clouds, for example. Although some individual events might be explained in this fashion, there is really no evidence that a stable upper flux limit exists for the variable sources, as one might expect. The most popular and in my view the most plausible intrinsic effect is bulk relativistic motion. Such motions increase the apparent brightness temperature by the Doppler factor, δ, and compress the timescale of events by a like factor. Measured in terms of my earlier discussion of brightness temperatures implied by variability, the implied brightness temperature, therefore is amplified by $\sim\delta^3$. The most extreme examples of the brightness temperature crisis are resolved with $\delta \sim 20$ and most with Doppler factors of only a few. Similar Doppler factors seem to be indicated by some VLBI measurements of structural changes at centimeter wavelengths (i.e., superluminal motions). The most commonly invoked alternative is some kind of coherent emission process (e.g. 8). Since pulsars have been so successfully explained through coherent mechanisms at these wavelengths, they seem to be good candidate processes. However, my main argument against them at this point is that they are superfluous to the brightness temperature crisis, since almost every coherent mechanism so far suggested requires relativistically streaming particles (and this solves the crisis by itself). There is no evidence really pointing to coherence (such as extremely large linear or circular polarization - but the data are scarce). Coherent processes might be a natural way of accounting for a relatively sharp high frequency cutoff, however, if that turns out to be a general characteristic of LFV.

It seems to me that any major theoretical advances toward understanding LFV are likely to await a clearer picture from the observers. That is not to say, of course, that clever theorists should ignore the extant data set, but rather that until clear evidence to the contrary is available LFV should be viewed as one end of the general radio variability spectrum. Examples of possibly fruitful theoretical explorations would involve such questions as why no clear connection exists between CV and LFV and, (perhaps related) what is really the basic energy transport process. If relativistic jets are the answer then the key questions involve how such jets are produced and how they behave in nuclear environments.

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