VARIABLE RADIO SOURCES

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1. INTRODUCTION

Flux variations are a common feature of flat spectrum compact extragalactic radio sources. Detailed analysis and quantitative comparisons with theoretical models (e.g. van der Laan,1966) are difficult due to the complex characteristics of the flux variations,which generally appear to consist of different outbursts blended together in time. Nevertheless, the general consensus is that the basic process has been correctly identified and consists in an expansion of a synchrotron radiating plasma cloud of relativistic electrons and magnetic field partially opaque to its own radiation. The main differences between data and predictions of the theory are that the variations propagate too fast and with too large amplitude toward lower frequencies. This behaviour however may be indicative of continuous energy supply and consequent accelerated expansion.

At the moment the most troublesome problems are the flux variations at low frequencies (L.F.V.).After several years of doubts concerning their reality,in the past five years evidence has been accumulated on their reality (see e.g.: Cotton 1976;Mc Adam 1978,1979,1980;Condon et al.1979; Fanti et al.1979,1981;Fisher and Erickson 1981). So far there are more than 100 sources known or suspected to be low frequency variables.However,no definite explanation has been presented yet. First it seems that generally there is no correlation between the classical high frequency variability and that at low frequency. On the contrary,the two sets of events seem discontinuous,justifying the use of the terms "high frequency variability" ($\lambda<20$ cm.) and "low frequency variability" ($\lambda>20$ cm.).

A second crucial question is the source size. Since it is usually supposed that the time scale for variations cannot be less than the light travel time across the source,an upper limit on the linear dimensions of the variable region can be estimated. When combined with the distances calculated in the usual way from the red-shift,this generally indicates, for sources varying at low frequencies,angular dimensions which are so small that the inverse Compton limit for an incoherently radiating synchrotron source is exceeded.

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2. STATISTICS ON OCCURRENCE OF L.F.V.

The occurrence of L.F.V. in complete samples of radio sources has been examined by several authors,notably Cotton (1976),Condon et al. (1979),Mc Adam (1980),Fanti et al.(1981). The phenomenon appears very common in samples of flat spectrum sources (30% to 50% showing fractional flux changes $\Delta S/\overline{S} > 5\%-10\%$). It is important to realize that here by flat spectrum source we mean a source with spectral index $\alpha<.5$ around the frequency at which variability is searched for. This definition includes sources with a really flat spectrum over a broad frequency range and sources whose spectrum,flat around the search frequency,steepens at $\nu>1$ GHz,reaching the typical slope of a transparent synchrotron radiating radio source. There is no difference in the occurrence of L.F.V. between these two classes of sources. The best,at the moment,estimates of occurrence of L.F.V. among normal straight spectrum sources are those of Cotton (1976) and Mc Adam (1980). They indicate that fractional changes with $\Delta S/\overline{S} > 20\%$ are found with a probability of 2%-5%,or a factor > 4 less frequent than for flat spectrum sources.

In general quasars account for the largest fraction of the reported L.F.V. Four BL Lac objects (AO 0235+164,0735+178,OJ 287 and BL Lac itself) also show this behaviour. The situation is less clear for radio galaxies. At present there are $\sim$ 30 low frequency variables identified with galaxies. One of them is 3C 120. Also 3C 84 is a possible one. Most of the remaining ones are generally optically weak ($m > 18$) and little is known of their optical properties.

Finally we note that at least three sources (3C 120,3C 279,3C 345) out of the four reported to exhibit superluminal motions (Cohen et al. 1977) also show low frequency variability.

3. CHARACTERISTICS OF THE L.F.V.

Generally the pattern of the variations is similar to that seen at centimeter wavelengths. In a minority of cases the light curve can be described as a superimposition of one or more non overlapping outbursts, lasting several months,over a relatively stable flux level. In the majority of the sources,however,the variations are more complex,although they can still be described in terms of partly or totally overlapped outbursts. In these cases it is very difficult to establish the level of an eventual underlying stable component.

Typical time intervals from relative maxima to minima range from several months to a few years,although in some cases flux changes are seen to occur within 1 - 3 months. There seems to be a relative scarcity of flux variations lasting more than 2 - 3 years (Mc Adam 1978). The frequency of the outbursts,corrected to the source proper frame,is about 0.8 years^{-1},similar to that found at short wavelengths.

Besides the case of PKS 0736+01 (discussed by Mc Adam,1978),there are no other cases of flux variations such to suggest negative dips instead of positive outbursts.

A number of sources show long periods of stable flux level,lasting a few or several years. This is the case for 3C 454.3 during 1973-1974 and CTA 102 from 1975 to the present epoch. Note that while in its quiescent period CTA 102 was at its minimum flux density level for the last 15 years,3C 454.3 in its quasi stable flux level was definitely higher, by 2 - 3 Jy,than the well defined deepest minima observed in 1970 and 77.

4. FLUX DENSITY VARIABILITY AT DIFFERENT FREQUENCIES.

Although sources varying at centimeter wavelengths appear to have higher probability of varying also in the decimeter domain,this however does not mean that variability is due to the same event occurring at all frequencies with frequency dependent amplitude. The only case of this type known at present and conforming to the standard model of the opaque synchrotron emitting and expandind cloud is BL Lac. This source had three periods of strong activity from 1970 to 1980,during which a reasonable good flux monitoring was obtained in the range from 10 GHz to .4 GHz at several frequencies. In these three periods outbursts were first seen at very high frequency and subsequently drifted to lower frequencies,with somewhat reduced amplitude. In several other sources,however,the low frequency outbursts seem clearly unconnected with the higher frequency ones, as is often indicated by the quiescent level of the light curve at an intermediate frequency (e.g.:2.7 GHz) and by the lack of any preceding comparable amplitude event at higher frequencies. Furthermore,the evidence gained from studies of severall sources (see e.g.: Cotton and Spangler 1978;Fisher and Erickson 1981) shows that the low frequency variability extends over a broad band,confined to $\nu<2$ GHz and occurs roughly simultaneously at all frequencies,with amplitude decreasing,although in a not well known way,at increasing frequency.

In some sources a close coincidence in time has been noted of high frequency and low frequency maxima (Spangler and Cotton,1981),which however were disconnected throughout the frequency range.While it is difficult at present to evaluate the statistical significance of these coincidences,it is certainly important to pursue such a kind of search on a larger sample of sources over a longer period of time.

5. THE TIME SCALES OF VARIABILITY AND THE INVERSE COMPTON PROBLRM

The generally adopted definition for the time scale variability is:

$$\tau_{var} = (1+z)^{-1}(d \ln S(\nu)/dt)^{-1} \sim (1+z)^{-1}\Delta S_{max}\Delta t/\Delta S$$

where $\Delta S/\Delta t$ is the rate of change of the flux and ΔS_{max} the maximum flux of the varying component. There is considerable uncertainty on ΔS_{max}, depending on whether the emission of the varying source is seen super-

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imposed on an underlying stable component or not. In the first case ΔS_{max} can be obtained by subtracting the flux level of the stable component to the maximum observed flux S_{max}. The flux level of the stable component can be estimated tentatively from the deepest minima of the light curve, and $\Delta S_{max} \sim \Delta S$,the observed flux change. In the second case ΔS_{max} is taken equal to S_{max}. With the second assumption we obtain longer time scales,the ratio between the two estimates being $S_{max}/\Delta S$. In the following we adopt the second hypothesis,which minimizes the problems associated with fast variability,although we should keep in mind that the most realistic situation is certainly intermediate between the two cases. If more than one distinct burst is present in one source we consider a variability time scale for each of them. The distribution of τ_{var} for sources taken from the Bologna (Fanti et al. 1979,1981) and Molonglo programs (Mc Adam 1979),has a mean value around 2 - 3 years,although variations as fast as 1 - 3 months are seen (see,e.g., Fanti et al. 1979;Mc Adam 1979;Spangler and Cotton 1981). The observed time scale distribution is similar to the corresponding one at centimeter wavelengths.

If the variability is intrinsec to the source,on the basis of the "causality argument",we expect that the linear radius (Jones and Tobin 1977) r should be :

$$r/\delta < c\ \tau_{var} = r_{var}$$

(δ is a numerical factor of the order of few units,which describes the flux changing law : $S \propto t^{\delta}$; $\delta = 3$ for the standard expansion model). We take $\delta = 1$,since we have no clear information on the process producing the variability. The "variability diameters"computed in this way are not taken as representative of the whole source but only of the variable component seen at that particular epoch ($\pm\ \tau_{var}$).The angular diameter of the varying component ($q_o = 1$) is given by :

$$\theta < \theta_{var} = 2\ r_{var}/\text{distance} = 2\ r_{var}(1+z)^2 H(cz)^{-1}$$

Angular sizes computed in this way,using an Hubble constant H = 100 Km $s^{-1}Mpc^{-1}$ are mostly in the range of 0.1 to 1 m.a.s. These angular sizes can be used to compute the source brightness temperature T_b. Typical values are $\sim 10^{14} - 10^{15}$ ^oK,occasionally up to 10^{16} ^oK. These values exceed by 2 to 4 orders of magnitude the 10^{12} ^oK limit for incoherent synchrotron radiation.

6. DIRECT MEASURES OF ANGULAR SIZES OF LOW FREQUENCY VARIABLES

VLBI observations at relatively low frequencies (Readhead et al.1977 at 50 cm.;Romney et al.1981,at 18 cm.) all show that low frequency variables are generally resolved,often with jet-like morphology with overall sizes of few m.a.s. to several tens of m.a.s. The components are often partially resolved as well with sizes of 1 - 2 m.a.s. They show that a substantial fraction of the flux originates in regions of brightness temperature $T_b < 10^{12}$ ^oK,although we cannot exclude the existence of much smaller subcomponents with sizes comparable with that implied by the time scale variability.

A much higher resolution (10^{-4} - 10^{-3} m.a.s.) is achievable by means of interstellar scintillation studies. A number of low frequency variables have been studied by means of this technique (e.g. Dennison and Condon 1981),always with negative results. For several of these sources the upper limits to the interstellar scintillation index have been considered an evidence against the existence of high brightness radio components. However a choice of conservative values of H and q_o,as those we have taken,or of the interstellar scintillation angular scale,or invoking intergalactic angular size broadening,leaves some margin for the existence of high brightness components. Furthermore,the lack of interstellar scintillation does not necessarily apply to the rapidly variable fraction of the flux (actually the one which needs to be small),since the scintillation measures generally do not coincide with major outbursts. Even with our conservative assumptions on τ_{var},the sources for which the interstellar scintillation measurements coincide,within τ_{var},with an outburst,are half a dozen at most. For each of these the choice of conservative parameters allows for the presence of high brightness components. If we were to have taken the other less conservative assumption for τ_{var},only for DA 406 would there have been a coincidence between an outburst and the observation of interstellar scintillation (august 1977). In this case the less conservative assumption on τ_{var} would imply $\theta_{var} \sim 7\ 10^{-5}$arcsec against the lower limit,from absence of interstellar scintillation,of $6\ 10^{-5}$ arcsec,and the presence of a high brightness component would be just marginally possible.

7. X RAY OBSERVATIONS OF LOW FREQUENCY VARIABLES

If the low frequency variables are as small as implied by their τ_{var} and if they radiate at radio frequencies by incoherent synchrotron process,the large brightness temperatures implied would require an enormous inverse Compton flux during a radio outburst. Evidence that this is not the case is obtained from the X ray literature data (e.g. HEAO-A observations in the band 3 to 17 kev of several radio sources during active phases,reported by Marscher et al.1979). No X ray flux was detected.The deduced brightness temperatures are generally $< 5\ 10^{11}$ °K.

8. DISCUSSION

There are essentially two ways to solve the inverse Compton problem which arises in the case of L.F.V. One way is to look for alternative radiation mechanisms allowing higher brightness temperatures. The other is to invoke explanations which,assuming the ordinary synchrotron process, are nevertheless able to reconcile big sizes and fast variations. To this second class belong models based on relativistic expansion or models involving phase effects. The explanations should also account for other characteristics of the variability,namely the spectral behaviour,the statistics on the occurrence of L.F.V.,the source structure,etc..

A third possibility would be to consider the variations as due not to changes in the emission region,but rather to some kind of modulation of a constant source by variable scattering (scintillation) or absorption in an intervening medium. However considerations based on time scales and correlation bandwidth indicate that ionospheric,interplanetary,interstellar and intergalactic scintillation are unlike processes. The suggestion by Shaperovskaya (1978) that L.F.V. are due to scintillation in the weak focusing regime,occurring in nearby galactic structures (loops,spurs,ridges,..) is no longer supported by the sky distribution of the known or suspected variables. Absorption models can work only if phase effects are present and therefore will be considered in the class of phase models.

The inverse Compton problem is solved if small pitch angle synchrotron radiation or coherent processes are assumed to be responsible for the variation (e.g.: Cocke and Pacholczyk 1975; Cocke et al.1978). Of course only the varying flux needs to be explained by these processes, while the more stable underlying component could still be due to the ordinary synchrotron process. For instance,the sources with a normal high frequency spectrum flattening at low frequencies,where variability is seen,have the typical characteristics of a synchrotron radiating source. The variations would be due to a distinct component radiating by a different process at low frequencies only and responsible for the variation. In this hypothesis one would not expect a one-to-one correspondence between high and low frquency events,with the former evolving continuously into the latter;but a correlation between levels of activity in the two radio domains would be possible if the ultimate engine is the same. Also there would be no difficulties in understanding simultaneous high and low frequency variations. The evidence against this class of models lies essentially in the absence of interstellar scintillation,which however still leaves some marginal possibilities for them. Furthermore it would be difficult to understand the correlation between occurrence of L.F.V. and the shape of the radio spectrum near the frequency of variability.

Apparent violation of the causality argument occurs if the emitting regions have bulk motions at speed close to the speed of light. In this case the intrinsecally long history of the source is compressed into a small parcel of the observer's time. This class of models was proposed a long time ago (Rees 1967) just to explain the fast variations known at that time and somewhat later has been used to explain apparent superluminal motions found by VLBI observations. Many variants have been proposed (see,e.g.,Blanford and Mc Kee,1977;Salvati,1979;Blanford and Konigl 1979,and references therein) and we examine only a few difficulties. Relativistic motions could be of two types : i) relativistic isotropic expansion of one component; ii) relativistic collimated expansion (or beamed ejection). In both cases apparent brightness temperatures deduced from time scales are $\sim \Gamma^3$ larger than the values measured in the source frame (Γ is the Lorentz factor of the expansion). Typical Lorentz factors needed are around 10 (18 for 3C 454.3 in the 1978 outburst;27 for PKS 1524-13 in the 1977 outburst;21 for PKS 1504-16 in 1975). In the first case (isotropic expansion) one would naturally explain the large occurrence of L.F.V. in samples of flat spectrum radio sources since no preferred orientation between source and observer is necessary. Difficulties are essentially due to the energetics implied, which is generally > 10^{58} ergs and in some cases exceeds 10^{60} ergs. The energetics can be reduced by a factor Γ^2 if the expansion is beamed (case ii). Such a model would also fit the generally accepted schemes for superluminal motions (Blanford and Konigl 1979). However in this case one requires a preferred orientation between the source and the observer's line of sight, at variance with the large fraction of sources showing variability in complete samples, and the same explanations should be invoked as for superluminal motions (Scheuer and Readhead 1979). In this class of models, which maintain the synchrotron process as that responsible for radiation, the spectral characteristics of the varying component and the simultaneity at the various frequencies would indicate that the emitting regions are transparents and the variations would be due, for instance, to an increase in the number of radiating particles, followed by rapid expansion. The typical linear sizes would be of the order of 10 pc (case ii) or 100 pc (case i) and might be also situated at large distances from the core of the source.

Phase effects have been discussed in connection with flux variability in Fanti and Salvati (1980). The merit of these models resides in reducing the energetics involved in the phenomena, compared with the relativistic models. They may also be coupled with relativistic expansion models, but require more moderate values of Γ. However, if associated with jet-like source morphology they still require the same preferred orientation as for beamed relativistic motion.

The phase models class includes also absorption models where a suitable screen orthogonal to the line of sight changes opacity when impinged on by a signal coming from a distant center. The most discussed model of this type is that of Mc Adam (see Marscher 1979 and Condon et al. 1979) where the screen is a neutral hydrogen layer which is ionized by the signal and becomes opaque. This model would naturally produce superluminal "negative" outbursts, whereas the general situation is more complex. Furthermore this model has difficulties in explaining the simultaneity of high frequency and low frequency events. An absorption model capable of producing positive outbursts instead of negative ones can be envisaged if the screen is usually partially opaque and the triggering signal makes it more transparent, followed by a reincrease of opacity. In case of simultaneity of high frequency and of low frequency events, the high frequency one would be closely connected with the triggering signal. A model of this type, where the screen is a partially ionized hydrogen layer, has been suggested by Spangler and Cotton (1981). This version of the absorption model is strongly suggested by the finding that the L.F.V. occur at a frequency where the radio spectrum flattens, a clear indication of the presence of an absorption process. Since the low frequency flattening is generally believed to be due to synchrotron self absorption, we are led to think that the varying absorber should be looked for more in the relativistic particles - magnetic field system

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DISCUSSION

O'DELL: I have two relevant remarks based upon recent work by J. J. Broderick, J. J. Condon, B. K. Dennison, J. E. Ledden and myself: (1) Using our three-epoch observations at 318 MHz, we also find that the typical duration of events appears to be $<$ 5 years in low-frequency variables. (2) Regarding the association of low-frequency variability with variability at other frequencies, we have found a statistically significant (> 99% confidence) correlation of low-frequency variability with optically violent variability as phenomena (not event-to-event correlation). In particular, of 24 quasars common to our complete sample and the sample monitored, by the Florida group, for optical variability, we find the following results:

	Not Opt. Var.	Opt. Var.	Opt. Violent Var.
Low-freq. var.	0	2	6
Possible low-freq. var.	1	0	1
Not low-freq. var.	7	7	2

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