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THE VARIABILITY OF EXTRAGALACTIC RADIO SOURCES

(Invited Talk)

Daniel R. Altschuler

Arecibo Observatory and
Depto. de Física, Fac. de Ciencias Naturales,
Universidad de Puerto Rico

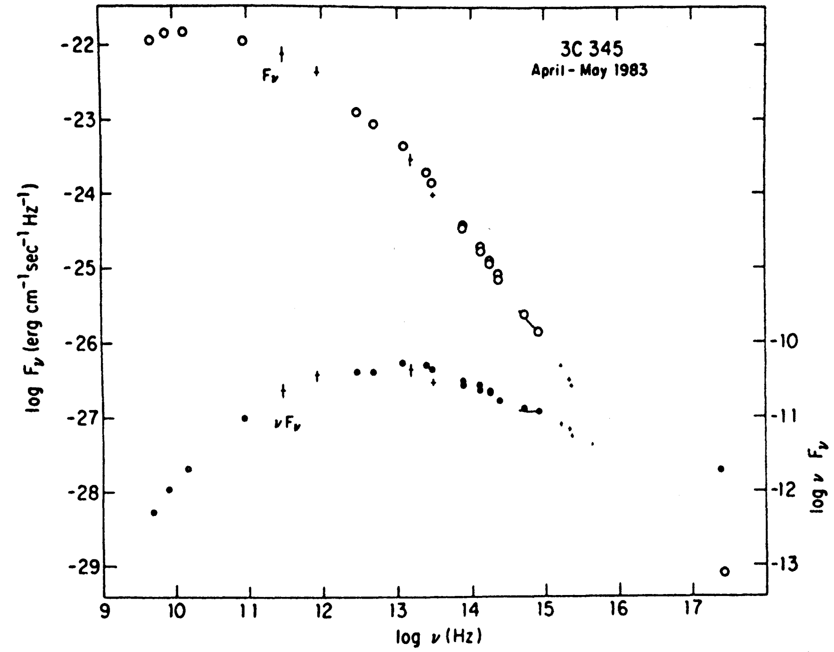
RESUMEN. Se presenta una discusión de las características básicas de la variabilidad de la densidad de flujo y la polarización de fuentes de radio extragalácticas. Las posibles causas de variabilidad a altas y bajas frecuencias son consideradas.

ABSTRACT. A discussion of the basic characteristics of the variability of the flux density and polarization of extragalactic radio sources is given. The possible causes for variability at high and low frequencies are considered.

Key words: GALAXIES-RADIO

. INTRODUCTION

The continuum radiation emitted by extragalactic radio sources has a very broad spectral istribution which for some objects has been measured from radio to X-ray frequencies (Figure 1). istant sources, if they emit isotropically, have integrated powers in excess of $L \sim 10^{45} ergs^{-1}$, (L $10^{12}L_{\odot}$). Anisotropic emission and relativistic beaming can reduce these numbers by several orders f magnitude.



igure 1. The flux density (top curve, left scale) and the flux per logarithmic frequency interval lower curve) for 3C345. Bregman *et al.* (1986).

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A complete specification of the incident radiation from a radio source is provided by fou functions (the Stokes parameters) $I(\nu,t,\alpha,\delta)$, $Q(\nu,t,\alpha,\delta)$, $U(\nu,t,\alpha,\delta)$ and $V(\nu,t,\alpha,\delta)$, giving th intensity and state of polarization of the radiation where the variables are frequency, time, an two sky coordinates respectively. The majority of measurements to date have been restricted t either $I(\nu)$ (spectra), $I(t)$ (time dependence of the flux density), or $I(\alpha,\delta)$ (brightnes distribution), sometimes at several frequencies and different epochs. Sometimes linea polarization has similarly been measured, but the fact that in general radio sources are weakl polarized, and that not all instruments are capable of measuring polarization, makes thes measurements more difficult. The situation is worse for circular polarization since this rarel exceeds 0.1%, (Weiler and de Pater, 1980) and is often ignored

The first evidence of variability in the radio radiation from an extragalactic source wa reported by Dent (1965) observing at a frequency of 8000 MHz (the QSO 3C273) and Sholomitski (1965) at a frequency of 940 MHz (the QSO CTA102). Polarization variability was first reporte by Aller and Haddock in 1967. At low frequencies (408 MHz) variability was reported by Hunstea in 1971. A review of the early work can be found in Kellermann and Pauliny-Toth (1968).

These results were quite unexpected since prior to 1965 it was thought that the radiatin region in extragalactic radio sources was very large and therefore would not show variations ove short times (months to years). The results of Hunstead were difficult to understand since by tha time the available models for active radio sources (ARS) indicated that at these frequencies larg amplitude variations would not be present.

The basic problem was brought about by the fact that if a source varies with characteristic timescale t_v (usually defined as $t_v = S\,(dS/dt)^{-1}$), it's diameter will be limited t $2ct_v/(1 + z)$, where z is the redshift of the source (accepted as cosmological), and no relativisti effects are considered. The small size implied by rapid variability imposed severe constraint on some of the models which had been proposed, often being inconsistent with the simplest form of these models, and requiring some form of relativistic motion or a more dramatic solution, suc as non-cosmological redshifts (Hoyle *et al.*, 1966; Rees, 1967; Jones and Burbidge, 1973; Burbidge 1979). In fact, variability in extragalactic radio sources was the first indication tha relativistic motion was important in these sources as suggested by Rees (1966). This fact has bee strengthened by the observation of apparent velocities larger than c (superluminal motion) whe very high resolution observations at several epochs are compared (Whitney *et al.*, 1971; Cohen *e al.*, 1971).

The study of the variability in extragalactic radio sources probes a region thought t be closely associated with the central energy source in these objects. Until the advent of Ver Long Baseline Interferometry (VLBI) with milliarcsecond (mas) resolution this was the only way t probe the pc-scale structure of ARS. Rapid variability still probes regions not yet resolved b mm or space VLBI. In this context I note that, until recently, all studies of variability have bee done with single-dish telescopes or short baseline interferometers, so that at a typical redshif $z = 1$ the best resolution (~1 arcsec) gives a linear size of about 10 kpc, very much larger tha the estimated size of the ARS (Figure 2).

Because of practical considerations, variability has been preferentially studies i objects of relatively high luminosity (and flux density) associated with unresolved object (typically QSOs and BL Lac objects), and much less work has been done on the low luminosity core of extended radio sources and the nuclei of galaxies.

Variability studies can be characterized by two complementary approaches:

(i) Study of the detailed behavior of known ARS with the goal of understanding the physic of the observed phenomena, and

(ii) Studies of well defined *complete samples* of radio sources to ascertain the statistic of variability with the goal of uncovering possible evolutionary trends and causative agents o activity, as well as finding new ARS.

There are several excellent reviews about ARS and related topics too numerous to lis individually. Among specific reviews on ARS I note the ones by Kellermann and Pauliny-Toth (1968 1981), and the review on the theory of ARS by Begelman *et al.* (1985). An enlightening discussio

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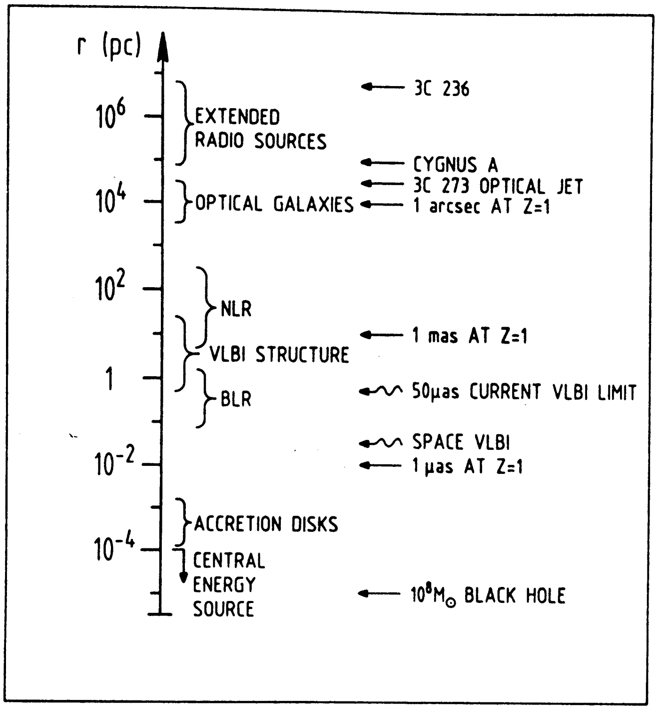

Figure 2. Relevant scales for ARS.

some issues relevant to ARS is given by Phinney (1985). The present review is an updated and ıdensed version of Altschuler 1989.

OPTICAL COUNTERPARTS

The first remark which has to be made is that most galaxies and QSOs (about 90%) are not :*ense* radio sources, so that the study of ARS associated with these objects provides information ›ut a small fraction of peculiar objects. Only in the so-called unified schemes, where intense lio emission is the result of beamed radiation toward the earth from randomly oriented parent ›ulation of sources, and where activity can be amplitied by Doppler boosting of the radiation, the study of ARS directly relevant to the radio quiet (misdirected beams) objects (Scheuer and ıdhead, 1979; Blandford and Koenigl, 1979; Orr and Browne, 1982). The nature of this parent ›ulation has not yet been answered satisfactorily.

The second remark that should be made is that the spectral *energy* emitted by ARS is quite when compared to that emitted in the IR and optical region as illustrated by the spectrum of 45 shown in Figure 1. It might therefore be misleading to base conclusions about the physics the energy generating region solely on the study of ARS. In spite of this, the physics of the io region by itself is of great interest and has given us a lot of insight into the possible ure of the ARS. In particular VLBI is currently the only technique routinely capable of liarcsecond (mas) resolution, 1000 times better than that achieved so-far in any other spectral ain.

ARS are found associated with different types of optical objects: *Seyfert Galaxies* irals with bright nuclei and broad emission lines), *Radio Galaxies* (ellipticals and related N, and cD galaxies), (Matthews *et al.*, 1964), BL *Lacertae objects* (BLOs), and *Quasi-stellar objects* Os).

BL Lacertae objects have been studied intensely because some of them exhibit the most reme behavior (large amplitude-short timescales) in variability of their flux density and arization (Altschuler and Wardle, 1975, 1977; Aller *et al.*, 1981; O'Dea *et al.*, 1983; Barvainis Predmore, 1984; Waltman *et al.*, 1986).

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Historically, BL Lac objects were defined as nearly stellar *radio* sources with featurel optical spectra, optical variability, and high optical polarization (Stein *et al.*, 1976). The d obtained from detailed optical studies of the nebulosities associated with those BLOs which be resolved ($z < 0.07$) is *consistent* with the interpretation that they are located in the nuc of giant elliptical galaxies (Miller *et al.*, 1978; Miller, 1981; Weistrop *et al.*, 1985). definition of what constitutes a BLO is complicated by the fact that the presence or absence spectral features for these optically variable sources is a time dependent property (Angel Stockman, 1980; Barbieri *et al.*, 1985), and except for this characteristic they seem to show fundamental difference with other ARS associated with QSOs.

The evidence obtained from photometric and spectroscopic studies of the nebulosit associated with low redshift QSOs ($z < 0.7$) supports the interpretation that these are also cent events in distant *galaxies*. These galaxies seem more luminous and larger on average than nor elliptical and spiral galaxies. There is some evidence that galaxies associated with radio qu QSOs are spirals whereas those associated with some radio QSOs are giant ellipticals but results are not conclusive (Gehren *et al.*, 1984; Hutchings *et al.*, 1984).

A large fraction (30%) of the QSOs studied with high resolution appear to be interact with a neighboring galaxy, suggesting that this interaction is important to the QSO phenome (Hutchings and Campbell, 1983; Heckman *et al.*, 1984). It is thus becoming clear that at all lev of activity associated with galaxies (Hummel, 1981a,b; Altschuler and Pantoja, 1984), thro Seyfert galaxies (Adams, 1977; Dahari, 1984), to QSOs the activity seems to be nurtured interactions. There are however active objects with no obvious companions, and interacting syst which show no activity so that there must be "more than meets the eye".

BLOs, OVVs [optically violently variable QSOs exhibiting changes larger than one magnit on a time scale of days or weeks; Penston and Cannon (1970)], and HPQ's [highly polarized QS showing variable and strong optical polarization greater than 3% sometimes reaching 30%; Moore Stockman (1984)], have been grouped together under the denomination of "*blazar*" (Angel Stockman, 1980), since they essentially show the same properties and are fairly well differentiat as a group from the rest of the QSO and radio source population.

In contrast, the optical output of the majority of QSOs and Seyfert galaxies varies by less t one magnitude over a time scale of months, and their degree of optical polarization is typica less than 1% (Moore and Stockman, 1984). These very active objects have proven to be extrem compact, most of the radio flux coming from an unresolved region, even when highest resolution V observations are made (Baath *et al.*, 1981; Jones *et al.*, 1984; Baath, 1984).

The extreme properties of blazars have led to the suggestion that in these objects we getting an unobstructed view of the core, (Altschuler and Wardle, 1975). A detailed study of t low brightness extended radio structure (arcsec scale) which surrounds the bright unresolved co of blazars shows that their properties are consistent with the hypothesis that they are nor extended extragalactic double radio sources viewed from one end (Browne, 1983; Wardle *et al.*, 19 Antonucci and Ulvestad, 1985). Their extreme properties would then be a consequence of our vi down one of the relativistic jets associated with the transport of energy from the central sou to the extended lobes. Relativistic boosting of the radiation of the intrinsically weak core a normal radio galaxy could lead to a strongly core dominated source as observed in blaza Barely detectable variability would similarly be boosted to levels typical of ARS.

3. VARIABILITY

The following discussion is divided into two frequency domains related to the possi mechanisms which produce the observed variability.

At frequencies above about 1 GHz the observed variability seems related to intrins evolution of the radio source.

It is generally assumed that the basic radiation mechanism operating in ARS is incoher synchrotron radiation from relativistic electrons spiralling in magnetic fields. A great deal our derived knowledge about ARS is based on this premise and several additional assumptions abo source geometry, often taken to be spherical and homogeneous, as a first approximation. The bas

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lel invoked to explain the observed variability (expanding sources) was formulated by Shklovskii)60), van der Laan (1966), and Pauliny-Toth and Kellermann (1966), and has been generalized by :scher and Gear (1985). Several modifications to this basic model, inspired by the fact that :en the data do not conform to it, have been developed. These modifications include relativistic :ions, which can reduce the very high brightness temperatures inferred from variability time-ıles, (Rees 1966, Vittello and Pacini 1978), non-uniform magnetic fields and particle densities ırscher 1977), prolonged (as opposed to instantaneous) particle injection, (Peterson and Dent '3, Aller *et al.* 1981), and departures from spherical symmetry (Vitello and Pacini 1977, Marscher l Gear 1985; O'Dell et al 1988), this latter geometry confirmed by the preponderance of observed 3I "jets" in most sources.

At frequencies below about 1 GHz the observed changes seem related to extrinsic causes, ıt is, to effects which occur during the passage of the radiation through a medium external to : source as suggested by Shapirovskaya (1978, 1982). Current theoretical and observational work licate that refraction by electron density inhomogeneities in the interstellar medium causes the ;erved variability in most sources (Sieber 1982, Rickett *et al.* 1984, Rickett 1986).

The radiation from a distant source will be alternatively focussed and defocussed so that : motion of the earth-sun system through the resultant pattern will cause the flux density to :y. The effect is expected to be large at low frequencies (proportional to λ^2) and for small ;ular sizes (proportional to Θ^{-1})

Nevertheless it is still debatable wether interstellar scintillation is wholy responsible : variability at low frequencies, there being examples where intrinsic variations seem to ıinate the observed variability (Spangler *et al.*, ; O'Dell *et al.* 1988). Intrinsic variability low frequencies leads to very high Brightness Temperatures ($T_b \sim \nu^{-2}$) and associated problems, .ess relativistic motion with very high Lorentz factors is invoked.

HIGH FREQUENCY VARIABILITY (HFV)

.1 The flux density

Figures 3 and 4 show the multifrequency behavior of *I(t)* for two representative ARS 35+164, and 1611+348 alias DA406) and Figure 5 shows the detailed high frequency behavior of '0+420 (alias BL Lacertae).

As can be appreciated from these examples the function *I(t)* shows in general irregular pattern, with large amplitude ($\Delta I/I$ > 50%) events occurring on time scales of months years often superimposed in time making it very difficult to separate the varying component from ' more slowly varying or constant emission that might be present.

At the highest radio frequencies (80 GHz) changes of large amplitude on a timescale of 's are sometimes observed (Epstein *et al.*, 1980; Barvainis and Predmore, 1984; Teraesranta *et* , 1987). Short timescale small amplitude changes (1 day, 2%) are also observed at cm-'elengths superimposed on the longer timescale variations (Heeschen, 1984; Witzel *et al.*, 1986). is not yet clear if this "flicker" is intrinsic to the ARS or due to a propagation effect ough a scattering medium.

Systematic variability on a time-scale of a few hours and amplitude up to 20% has been orted by Quirrenbach *et.al.* (1989), an example being shown in Figure 6.

For the majority of sources two general characteristics of the variability can be listed predicted qualitatively for an expanding source (Altschuler and Wardle, 1977; Andrew *et al.*, 8; Epstein *et al.*, 1982; O'Dea *et al.*, 1984; Aller *et al.*, 1985).

(i) The outbursts appear first at high frequencies and then propagate to lower quencies. There are cases where there seems to be no time delay between events at mm and cm 'elengths, and sometimes the events are not correlated between these two wavelength regions stein *et al.*, 1982; Ennis *et al.*, 1982). Furthermore, different time lags can be present in the .e source (Waltman *et al.*, 1986).

(ii) The maximum flux density decreases with decreasing frequency although this does not 'ays hold at mm wavelengths.

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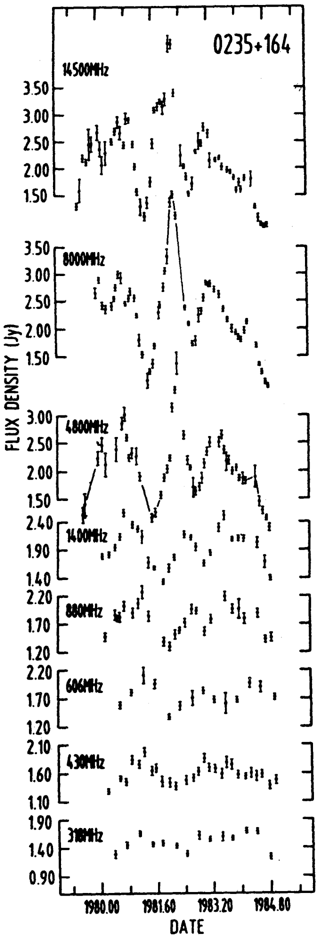

Figure 3. The multifrequency behaviour of *I*(t) for the source 0234+164. The data below 2 GHz are from the work of Altschuler *et al.* (1984), and above 2 GHz from the work of Aller *et al.* (1985).

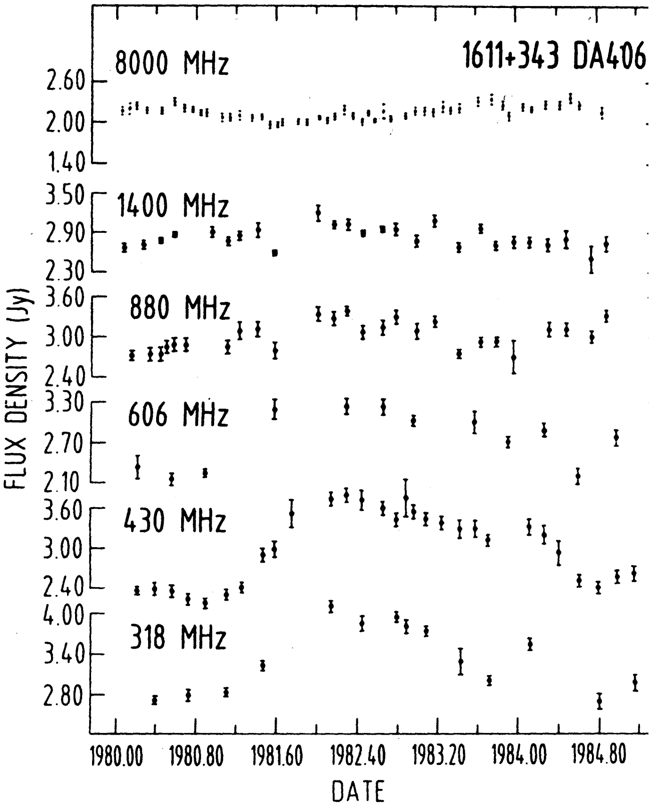

Figure 4. The multifrequency behaviour of *I*(t) for the source DA406. Data as in Figure 3

These characteristics are however not observed for all sources. In some sources t variations take on the form of sharp drops ("quenchings"), the flux density dropping by > 30% a time scale of days (Epstein *et al.*, 1982), and in others, long term (years) secular changes a observed (Altschuler and Wardle, 1977; Andrew *et al.*, 1978; Aller *et al.*, 1985; Forkert a Altschuler, 1987). As an example the flux density of 3C84 increased steadily from 10 to 60 Jy 7.9 GHz in a time interval of about 20 years as shown in Figure 7 (Aller *et al.*, 1985)

The behavior of BL Lac (Figure 5) shows that the degree of activity changes with tin between 1975 and 1979 BL Lac was not as active as in 1971 and 1981.
It is significant that the two periods of activity appear quite similar in structure suggesti that the activity is cyclic, possibly indicating that the repeating pattern reflects sc characteristic of the energy generation mechanism (Waltman *et al.*, 1986). In this context it mig be significant that the 1981 outburst of 0235+164 (Figure 3) resembles in form those in BL La If this characteristic can be confirmed by further detailed monitoring it will have significa consequences for our understanding of ARS.

In general the incidence of variability in a complete sample is higher at higt frequencies (Kesteven *et al.*, 1977; Seielstadt *et al.*, 1983), and over longer timescales t amplitude of variations increases (Rudnick and Jones, 1982).

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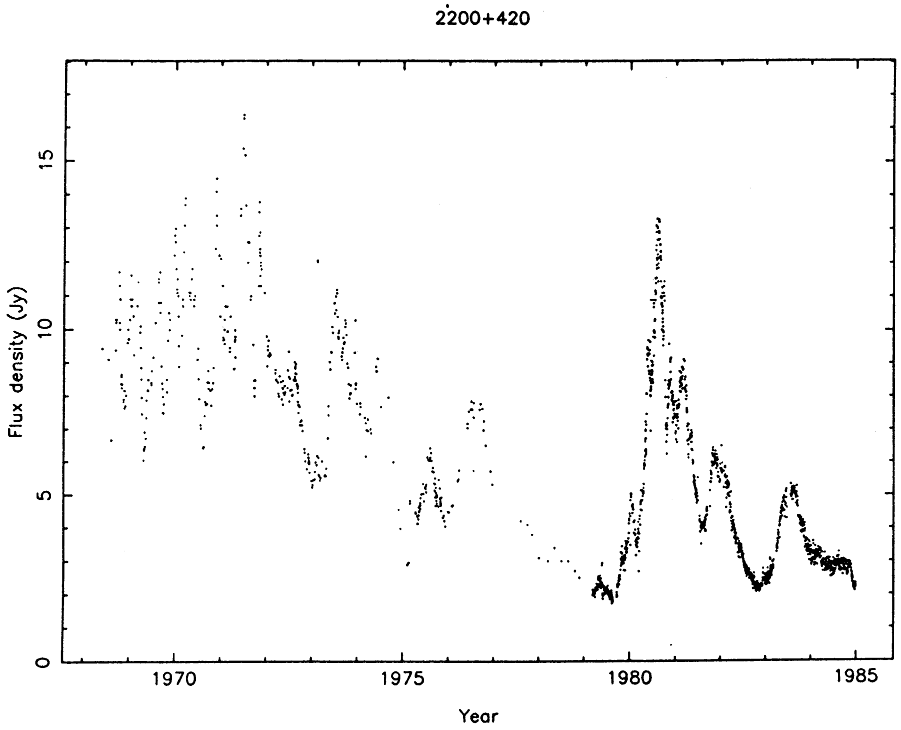
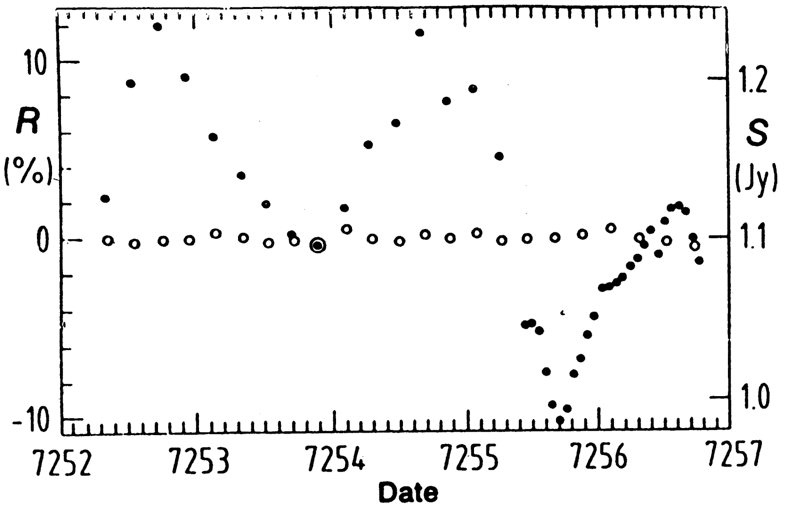


gure 5. The long term behaviour of $I(t)$ at 8085 MHz of BL Lac. The 1979-1983 data are from ltman *et al.* (1986). Data prior to 1979 are from Medd *et al.* (1971), and Aller *et al.* (1981).



gure 6. Rapid variability of the flux density of 0917+62 (filled circles) reported by Quirrenbach al. (1989). Open circles are for a reference source (0951+69). Data is at 2.7 GHz during March-ril 1988.

A different kind of phenomenon has been reported by Fiedler *et al.* (1987), who detected usual features in the flux density histories of various sources, an example being shown in Figure . This has been interpreted as due to occultation of the source by a compact ionized component the interstellar medium.

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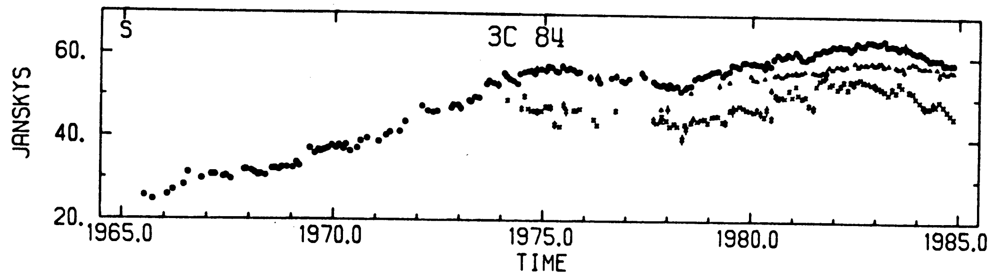

Figure 7. The long term behaviour of $I(t)$ for 3C84. Data at 4.8, 8.0, and 14.5 GHz are plotted triangles, circles, and crosses respectively. Aller *et al.* (1985).

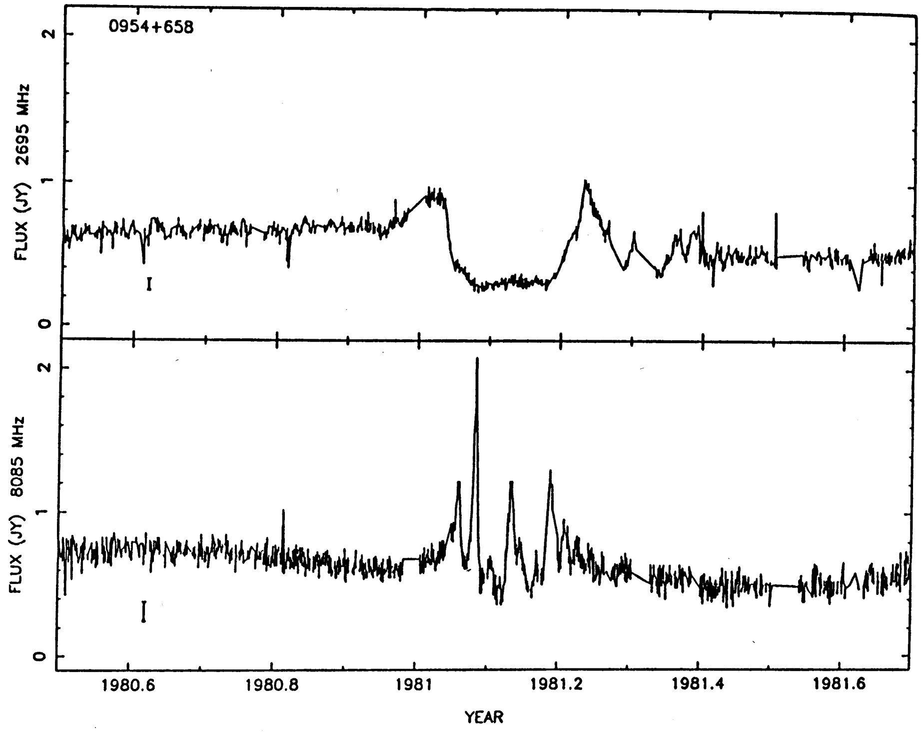

Figure 8. Occultation event discovered by Fiedler *et al.* (1987) in the light curve of 0954+658

3.1.2 Some Specific Results

The determination of statistical correlations and systematic behavior in the radiation from ARS is extremely important (and difficult) since these are likely related to the physics of the energy generation mechanism.

a) Timescales and wavelength dependence of outburst amplitude

Andrew *et al.*, (1978) established from their extensive monitoring of ARS that the outbursts occur in the average ARS about once every 1.5-2 years (corrected to the source frame). Although the range of timescales is fairly large this time scale must in some way reflect events at the energy source or its surroundings, and be a characteristic of the relevant physics. Furthermore the maximum flux density at a frequency λ (at cm wavelengths) is proportional to ν^{b} where $b = 0.4 \pm 0.2$. A similar analysis of the data of Altschuler and Wardle (1976) also gives the same value for b which is inconsistent with the simple expanding source model and has inspired some modifications.

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Noise character of the light curves

A power spectrum analysis of the light curves of some ARS by Cruise and Dodds (1985), owed that they are *consistent* with being the result of a series of randomly occuring identical ents (shot noise). This is what would be expected if the primary energy source is accretion onto collapsed massive object

Similarity of outburst shapes

Legg (1984) has found that the light curves for events in six different objects, though ffering in timescale and amplitude have profiles of the same shape (Figure 9). The profiles can fitted and a function of the form $t^n e^{-t/T}$ with $n > 3$ and $T \sim 1$ yr, showing the exponential decay the light curves. For a few cases (3C120, BL Lac) this characteristic decay can be followed th the same exponent through severeal successive outbursts of the source. The few observations the time dependence of the flux density of individual VLBI components also reveal exponential cays. It is however not yet established if this is a general feature for all sources at all equencies. Should this be the case it would have important implications for models of ARS.

Periodicity

The establishment of periodicities in ARS would severly constrain models based on black le accretion (Abramowicz and Nobili, 1982; Rees, 1985). Valtaoja *et al.*, (1985) reported a 15.7 nute periodicity in the 37 GHz flux density of 0J287(= 0851+202), and Kinzel *et al* ., (1988) port a possible 35 minute periodicity at 42.6 GHz. Periodicity in the optical was reported by rrasco *et al.* The reported periodicities are at a level of a few percent. Dreher *et al.*, 986), measured rapid fluctuations of the flux density of 0J287 ($t \sim 15$ min; $\Delta S/S \sim 0.5\%$) at 22 z but concluded that no periodicity with amplitude greater than 0.8% was present. It might well that periodicity, reflecting events associated with a spinning central object in this source ght only be detectable at the highest radio frequencies where the effects of opacity are nimized, and so a view of the inner source region becomes available. Because of their possible pact it is important to confirm these results.

L.3 The Polarization

The polarization of ARS is a signature of the magnetic field structure within the source, storted however by the effects of propagation through a magnetized plasma. The interpretation polarization is complicated by geometric and spectral effects, changing oppacities, and Faraday ation. In particular the superposition of several polarized variable components (some of which

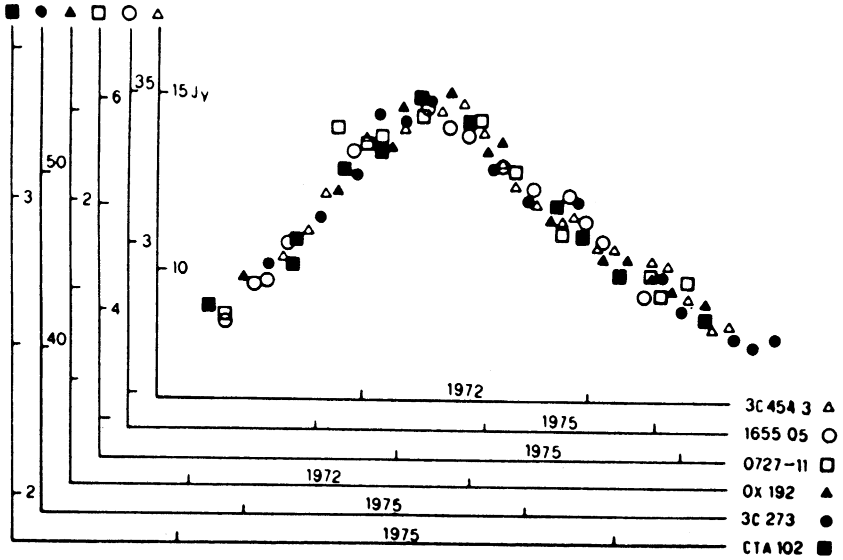

Figure 9. Similarity of outburst shapes of several ARS (Legg 1984).

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have been observed by polarization VLBI (Roberts et al. 1987, Wardle and Roberts 1988)) can lea to the very complex behaviour observed.

The average degree of integrated linear polarization of ARS at cm-wavelengths is abou 2.5% reaching as high as about 15% in some sources at some times (Altschuler and Wardle, 1977 Aller *et al.*, 1981; Rudnick and Jones, 1982). The observed variations in the polarization are ver complex and do not follow easily describable patters, so that little can be said whic characterizes these variations in general.

When analyzing polarization data, the problem of baseline subtraction to isolat individual events is even more difficult than for the flux density. Not only is the signal t noise ratio often rather poor, but we are now dealing with the vectorial superposition of th polarization of several components.

Figure 10 shows examples of the time dependence of the polarization vector for two ARS.

Note how for 3C120 the points cluster away from the origin, whereas for 0235+164 they ar spread out over the plane, an effect which is more evident at the shorter wavelength. The centroi of the points can be interpreted as the end point of a constant or slowly variable polarizatio vector, so that for 0235+164 the polarization seems to be mainly from the 4variable component specially at the shorter wavelength, whereas for 3C120 we see the effect of a constant polarize component.

These diagrams can be used to obtain an estimate of the average degree of polarizatio in the *variable* component as $m_v \Delta P/\Delta S$ where ΔP is the largest excursion from the centroid and ΔS $S_{max} - S_{min}$. The median value of the polarization of the variable components at cm wavelength i about 4%, there being little evidence for depolarization (Altschuler and Wardle, 1977; Jones e *al.*, 1985).

The fact that the polarization is generally observed to *vary* implies that the AR themselves are polarized. The changes in polarization occur often on a shorter timescale (weeks than the corresponding flux-density changes. A particularly interesting feature in some source are the remarkably large and rapid changes in polarization at times when the flux is essentiall

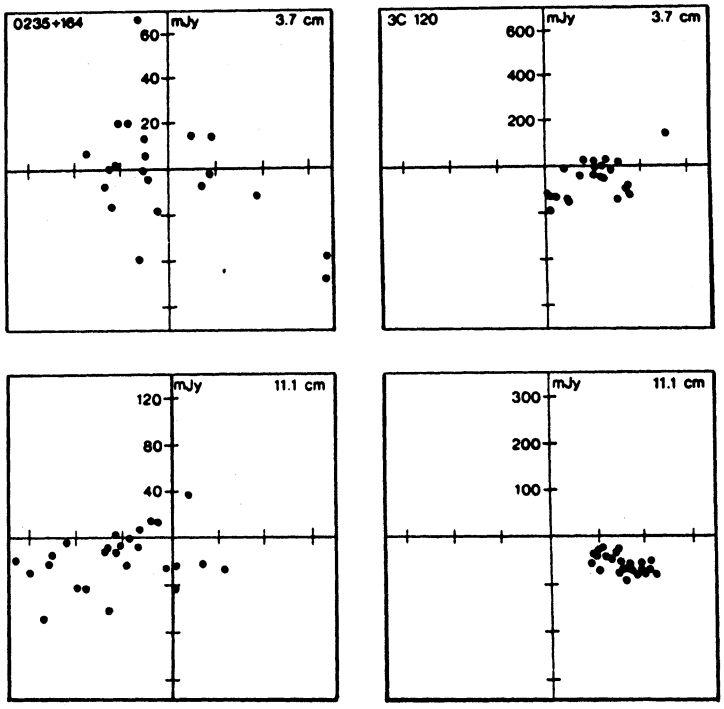

Figure 10. Polar diagrams of the polarization of 0234+164 and 3C120 at 2695 and 8085 MHz.

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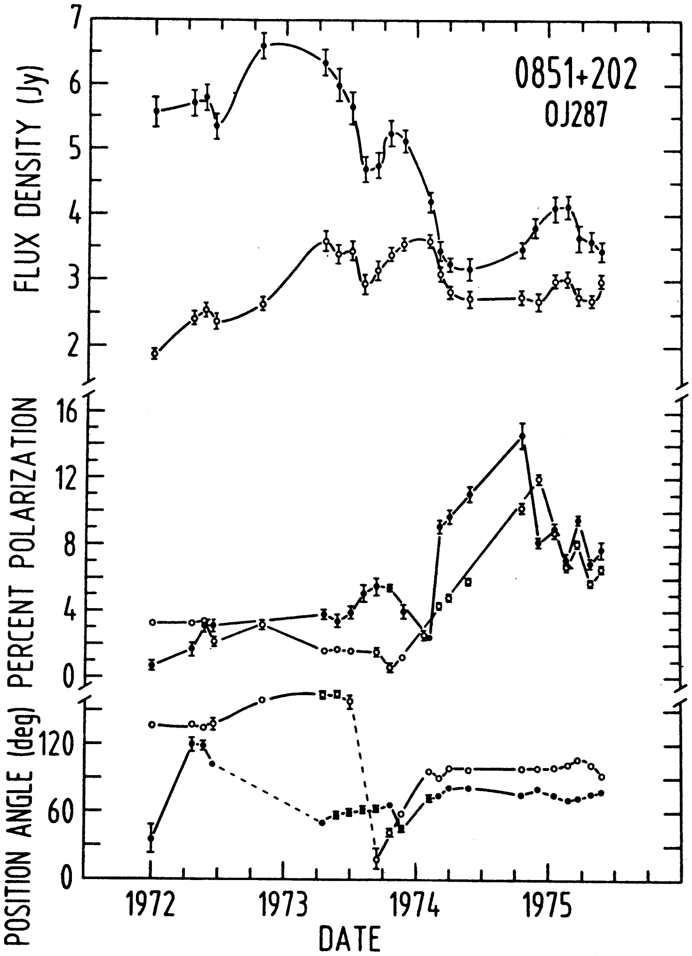
nstant (Altschuler and Wardle, 1976), while in other sources the polarization position angle nains constant throughout flux density outbursts even when the degree of polarization is varying ller *et al.*, 1981). In general the observed changes in polarization position angle are of nparable magnitude at different frequencies, showing that variable Faraday rotation is not sponsible for these changes.

Figure 11 illustrates several of these features for the ARS 0851+202 (alias 0J287): At GHz the degree of polarization rose from 2.5% to 9.1% in 33 days during early 1974 reaching 14% October, then dropping to 8.2% in November and remaining at about that level afterwards. At 7 GHz the behaviour was similar but less extreme. In early 1974, coinciding with the large crease in percent polarization the position angle (PA) at both frequencies settled down to a able value showing no deviations larger than 5° from the mean, suggesting that a highly polarized nponent dominated the flux density after 1974.

Rotation of polarization position angles

In several ARS (mostly BL Lacs) a linear change in the polarization position angle (PA) ring a flux density outburst has been observed (Ledden and Aller, 1979; Altschuler, 1980). The earest case for this rotation is shown by the 0235+164. This is the only case where during two nsecutive large amplitude outbursts the polarization PA of an ARS rotated at the same rate (-



ure 11. The flux density, percentage polarization, and polarization position angle for 0J287. n symbols: 2695 MHz, filled symbols 8085 MHz. Altschuler and Wardle (1976).

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3.2 deg/day). For the second outburst the rotation is the same at 8 and 14.5 GHz showing that th effect is not due to Faraday rotation.

It is significant that these rotations are associated with large amplitude outburs occurring at times when the total flux density is very low, suggesting that we are observing event occurring in one dominant component. The flux density of 0235+164 before the first rotation ever was the lowest in a ten year period.

Only the measurements of further such events will give confidence about the physica relevance of these rotations.

3.2 LOW FREQUENCY VARIABILITY (LFV)

A statistical investigation of LFV (318 MHz) over a ten year time span in complet samples of radio sources ($S > 2$ *Jy*) showed that about 40% of flat spectrum sources exhibi variability with amplitude > 8% whereas steep spectrum sources do not vary (Condon *et al.* 1979 Dennison *et al.* 1981).

The study of Gregorini *et al.*, (1986), found that in a complete sample ($S > 0.4$ Jy) nc selected for spectral characteristics about 4 % of the sources show variability with amplitude 20% over ten years at 408 MHz.

It is important to study the relation between low frequency variability and high frequenc variability since this will provide constraints on the possible mechanisms at work. This questic has been addressed by several investigations (Spangler and Cotton 1981; Fanti *et al.*, 1983 Dennison *et al.*, 1984; Altschuler *et al.*, 1984; Padrielli *et al.*, 1986) which have resulted in th determination of the following three categories.

(i) Sources for which the variations at high and low frequencies are not correlated, ar show a lack of activity around 1 GHz (intermediate frequency gap; (IFG)

(ii) Sources where the activity occurs mainly at frequencies below 1 GHz (e.g. DA4C Figure 4).

(iii) Sources where the variations follow high to low frequencies in a manner suggestiv of expanding sources, (diminished amplitudes and time delays) as can be seen in the behavior c 0235+164 (Figure 3; O'Dell *et al.*, 1988), and BL Lac (Fanti *et al.*, 1983)

The multifrequency studies of Fisher and Erickson (1980), Altschuler *et al.*, (1984), ar Padrielli *et al.*, (1986) demonstrated that the variability in the first two categories is such tha the events at low frequencies appear to be simultaneous (within the uncertainties due to sampling) and the amplitude of the LFV decreases as one approaches 1 GHz from below.

The few sources belonging to the third category (estimated to be 10 to 20% of LFV sources show however that intrinsic variability at low frequencies is observed in these sources.

A comparison of the detailed spectral evolution of 0235+164 and DA 406 clearly shows th different behavior of these sources (Figures 12 and 13).

An analysis of the 408 MHz data of Fanti *et al.* (1981) by Cawthorne and Rickett (1985 shows a decrease in the fraction of sources which exhibit fluctuations > 5% with increasir galactic latitude consistent with a $(\mathrm{cosec}\ b)^{1/2}$ dependence. Similarly the study of a complet sample of radio sources by Gregorini et al. (1986) at 408 MHz determined that about 4% show flu density variations larger than 20% and that the percentage of variables is significantly highe at low galactic latitude, suggesting that the observed variability is due to the Galaxy. Ther is some evidence suggesting that individual structures such as supernova remnants and the Nort Polar Spur are responsible for the observed variability in some sources (Hjellming and Naraya 1986).

Although the available evidence is consistent with a galactic cause for variability a low frequencies in many sources, there are good examples where the variations seem intrinsic t

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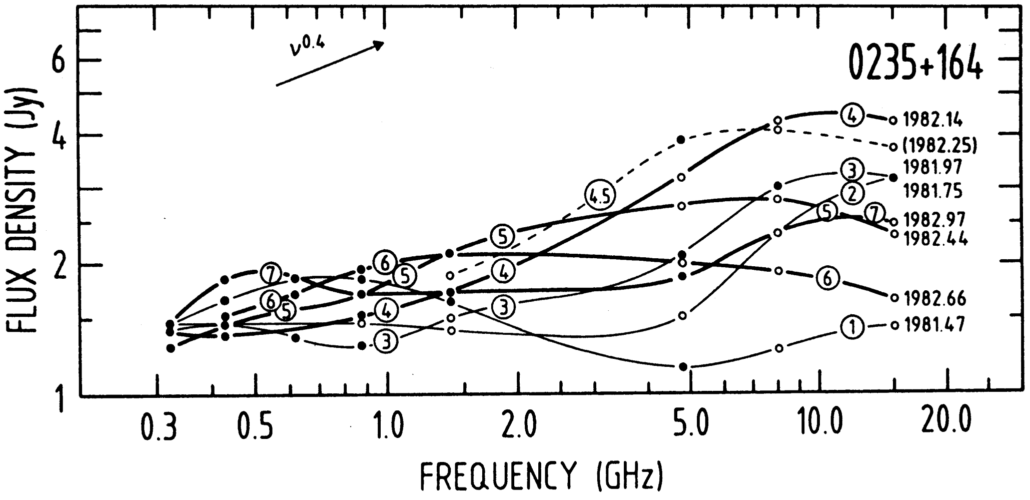

igure 12. Multiepoch spectra of 0235+164. The points represent simultaneous measurements of the lux density at eight frequencies. Data is from Aller *et al.* (1985), and Altschuler *et al.* (1984). illed symbols represent actual measurements whereas open symbols are linear interpolations between djacent dates. Spectra are labeled by circled numbers. At high frequencies the outbursts follow he sequence 1,2,3,4,5,6, peaking at 4. At lower frequencies the maximum flux is delayed in time. he arrow shows the trend derived from high frequency data.

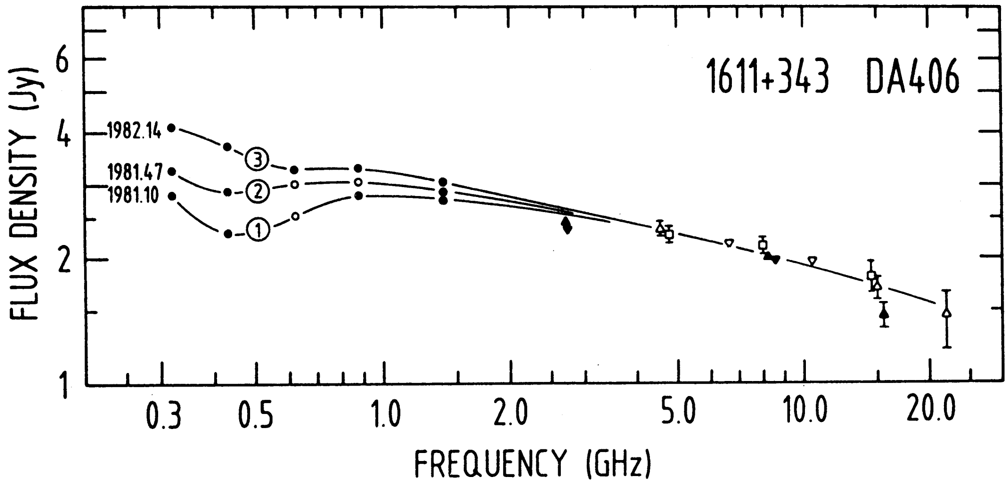

Figure 13. Multiepoch spectra of DA406. Symbols are as in Figure 12.

ne source over the entire observed frequency range. The flux density of the QSO 2345-167 ncreased linearly from 1.6 to 2.8 Jy at 408 MHz between 1968 and 1978 (McAdam and White 1983). n optical flare 1.8 magnitudes in amplitude was observed to conincide with the start of the radio ariation. The correlation between the optical and radio activity, although not conclusive, would le out a local galactic mechanism for the variations. The flux density of the QSO 1055+018 ncreased by factors of 2 and 3 at 160 MHz and 80 MHz respectively during the first seven months f 1983 (Slee 1984). A detailed study of the structure of this source shows that the component ariations necessary to account for the observed flux density changes are very unlikely to be due o interstellar scintillation (Gopal-Krishna et al. 1984). The best example is provided by 235+164 (a source which is the "best" example for many things), whose detailed spectral evolution ring a high frequency outburst is shown in Figure 12. The outburst peaking about 1982.14 at high requency is seen to peak at lower frequencies at progressively later times as indicated by the

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circled numbers. The amplitude of the variations increases roughly as $\nu^{0.4}$ as indicated by the solid arrow, in accord with the empirical result obtained by Andrew et al. (1978) from high frequency data. The correlation of the high and low-frequency activity in this source indicates that the variability at all frequencies is due to the same cause. Essentially all the variability can be understood in terms of adiabatically evolving structures in a relativistic jet. The radiating plasma travels at relativistic speeds with a Lorenz factor $\Gamma > 25$, close to the line of sight (O'Dell *et al.*, 1988).

Quite different behaviour can be observed for the QSO DA406 as shown in Figure 13 where the variations occur only at low frequencies, with comparable amplitudes at the three lowest frequencies. The high frequency data for DA406 were taken from the literature without regard for the precise epoch of observation and illustrate the long term stability of it's flux density. The low-frequency outburst is the second one observed, the first one peaking in 1977 showing a similar light curve (Cotton and Spangler 1978; Padrielli *et al.* 1986). There is no significant difference in the light curves observed at 318, 430, and 606 MHz, variations being simultaneous to within the sampling uncertainty, and of equal amplitude.

4. SUMMARY

The observed variability of the flux density, polarization, (and strucutre) of ARS is complex, and it has often been the case that the measurement programs undertaken have suffered from insufficient sampling, frequency coverage, and angular resolution as well as a lack of polarization information. This has often limited the usefulness of many investigations.

Although the basic physical processes involved seem understood, we are far from having a definite model for ARS, there being different mechanisms possibly operating at different wavelengths. The basic scenario consists of a central energy source in the form of a massive rotating object (black hole) which accretes matter, providing energy to relativistic particles which are accelerated along two collimated beams. These jets are the channels through which energy and particles are transported to the outer lobes of the radio sources. The interaction of the particles with the medium and with the ambient magnetic field produces the radiation which is observed in the form of synchrotron emission and inverse Compton scattering. The initial acceleration and collimation over very large distances of astrophyscial jets remains a major unsolved problem.

Unified schemes have been devised which try to explain the diversity observed in radio sources as due to geometric effects related to relativistic beaming. This might also be part of the reason why some sources are extremely variable while others are not. It is quite clear however that there are intrinsic differences among ARS which cannot be ignored.

A determination of the detailed behaviour of variable flux density, polarization, and structure over a wide range of frequencies to be confronted with various possible models is not yet available. In particular the variations often seen at low radio frequencies might be due to scattering in the interstellar medium and therefore not reflect intrinsic behaviour, although for some sources they seem intrinsic.

Except for a few statements that can be made about the general characteristics of the behaviour of the emergent radio radiation in ARS very little evidence for systematic phenomena (such as periodicity) has been found, the claimed examples often being of limited statistical significance. At some level such behaviour should be a reflection of the physical mechanism causing the observed activity (the "engine"), but it is clear that we are looking at effects which are spatially and temporally quite removed from it, and that several effects will act to distort or completely destroy any relation between the observed phenomena and the central energy source. It should be noted that if this central energy source has a characteristic dimension of 10^{-4} pc (as would be the case for a massive black hole), then our best achieved spatial resolution (VLBI) is still several orders of magnitude larger.

One important thing that has been learned from the large amount of data gathered so far is that future progress towards understanding the complex phenomena occurring in ARS will come about through a coordinated effort to obtain multifrequency (from radio to x-ray), very high resolution, well sampled data.

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Carefully defined complete samples should be studied to obtain statistical information out the general conditions necessary for the ocurrence of activity and it's association with her characteristics of the population studied.

The space telescope, new technology large ground based telescopes, optical interferometers entually achieving angular resolution in the nanoarcsecond range, and space based high energy servatories will all contribute significantly to our understanding of these enigmatic objects.

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niel R. Altschuler: Arecibo Observatory, P.O. Box 995, Arecibo, Puerto Rico 00613, and Depto. de Física, Fac. de Ciencias Naturales, Universidad de Puerto Rico, Rio Piedras, Puerto Rico 00931.

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