

Chapter 1

Introduction

“...‘Blazar’ is a neologism invented in jest by Ed Spiegel who happened to be visiting Pittsburgh at the time of the 1978 meeting on BL Lac Objects. He failed to give a precise definition! Not surprisingly, a trail of taxonomic confusion has ensued.”

R.D. Blandford, 1996, *Blazar Continuum Variability* workshop summary (ASP Conf. Ser. 110, ed. Miller, Webb & Noble, p. 475)

1.1 Background

This section briefly reviews some fundamental aspects of what is known about extragalactic compact radio sources. Various aspects of these sources have been studied in all observable regions of the electromagnetic spectrum. Observations of radio variability, the focus of this thesis, have already contributed a great deal to the current understanding of Active Galactic Nuclei (AGN) and the “blazar” phenomenon (see Sections 1.1.5 and 1.2), and some important discoveries are briefly discussed in this context. For more complete, historical reviews of both observations and theory, see for example Kellermann & Pauliny-Toth (1968, 1981) and Begelman et al. (1984). *High Energy Astrophysics* by M.S. Longair (Second Edition, vol. 1, 1992 and vol. 2, 1994) is also a useful reference for detailed descriptions of physical processes such as synchrotron radiation and Inverse Compton scattering, which are believed to produce the continuum emission observed from blazars, as discussed below.

Radio frequencies are affected by scintillation in the interstellar medium (ISM), and this phenomenon is discussed in Section 1.3. There is now strong evidence that scintillation is the principal cause of centimetre wavelength intraday variability. The second half of this thesis consists of an investigation into the use of scintillation as a probe of source structure on microarcsecond scales.

1.1.1 Synchrotron emission

Alfvén & Herlofsen (1950) and Schklovsky (1953) proposed that the principal mechanism for radio continuum emission in cosmic radio sources is incoherent synchrotron

emission, produced by relativistic electrons gyrating in a magnetic field. This model has prevailed for 50 years, although it has at times been challenged by observed radio variability in some sources, apparently implying excessively high brightness temperatures (see Sections 1.1.3 and 1.3.6).

The *brightness temperature*, T_b , of a source of radiation is defined as (e.g. Longair, 1992):

$$T_b = \left(\frac{\lambda^2}{2k} \right) \left(\frac{S_\nu}{\Omega} \right), \quad (1.1)$$

where λ is the wavelength of the emitted radiation, corresponding to frequency ν , S_ν is the source flux density at that frequency, Ω is the solid angle subtended by the source at the observer, and k is Boltzmann's constant. For a source at cosmological redshift z , a factor of $(1+z)$ must be included in the right-hand side of Equation 1.1 to transform the quantities measured in the observer's frame to the source rest-frame brightness temperature at the emitted wavelength.

It is common to consider the synchrotron radiation of a power-law distribution of electron energies, since the observed energy spectra of cosmic rays and cosmic ray electrons can be approximated by power law distributions (Longair, 1992). Then the synchrotron radiation has a power-law spectrum, $S_\nu \propto \nu^\alpha$, where α is the *spectral index*. Note that some authors use the opposite sign convention (*i.e.* $S_\nu \propto \nu^{-\alpha}$) for the spectral index. $S_\nu \propto \nu^\alpha$ is the convention used throughout this thesis. If a power-law synchrotron source has the same physical size at all frequencies, then $T_b \propto \nu^{\alpha-2}$. Therefore, at low enough frequencies, the brightness temperature of synchrotron radiation may approach the kinetic temperature of the radiating electrons, in which case *synchrotron self-absorption* effects become important. The low frequency spectrum of a self-absorbed source behaves as $S_\nu \propto \nu^{5/2}$ (e.g. Longair, 1994).

Some compact extragalactic sources exhibit very “flat” radio spectra, with spectral index close to zero across a large range of frequencies. These flat spectra are usually explained as a superposition of self-absorbed components at different energies (Scheuer & Williams, 1968; Condon & Dressel, 1973; Marscher, 1977; Cook & Spangler, 1980).

Inverse Compton scattering

Inverse Compton scattering is the scattering of low energy photons by ultrarelativistic electrons. In this process, the energy is transferred from the high energy electrons to the low energy photons. The brightness temperature of a synchrotron source is limited to $\lesssim 10^{12}$ K by the onset of inverse Compton scattering (Kellermann & Pauliny-Toth, 1969), which leads to catastrophic energy losses by the relativistic electrons as they scatter the low-energy synchrotron photons to higher energies — the so-called “Inverse Compton Catastrophe”.

1.1.2 Observations of variability and inferred source sizes

The oldest recorded variability in compact extragalactic radio sources dates back over 100 years. Smith (1964) analysed historical photographic plates from Harvard Obser-

vatory, and found evidence for optical variability in the quasar 3C 273. At around the same time as these early data were published by Smith, radio variability observed in 3C 273, 3C 279, and 3C 345 (Dent, 1965) was used to infer source sizes. Based on causality arguments, a source which varies on a time-scale τ cannot have a diameter larger than the light travel-time distance, $2c\tau$.

Originally it was the inferred source sizes of light-months, combined with the implied high luminosities of these objects, which led to the hypothesis that AGN are powered by accretion onto a supermassive black hole ($10^6 - 10^9$ solar masses), since the energy released in the inferred volume could not be accounted for by ordinary stellar processes (see, e.g., Begelman et al., 1984). Perhaps the most direct evidence to date for the presence of a massive black hole in the centre of a galaxy comes from observations of the rotational velocities of water masers near the centre of NCG 4258 (Miyoshi et al., 1995). There is also strong evidence for a massive black hole at the centre of our own Galaxy (Genzel et al., 1997; Ghez et al., 1998).

Variability brightness temperature

From observed variability, assuming it is intrinsic to the source, a *variability brightness temperature*, T_b^{var} , of a source at cosmological redshift z , can be calculated using

$$T_b^{\text{var}} = 5.87 \times 10^{21} h^{-2} \frac{\lambda^2 S_{\text{max}}}{\tau_{\text{obs}}^2} (\sqrt{1+z} - 1)^2, \quad (1.2)$$

where λ is the observed wavelength in m, S_{max} is the maximum amplitude of an observed outburst in Jy, τ_{obs} is the observed variability time-scale in days, and the numerical factor corresponds to using $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$ and assuming that the source is a homogeneous sphere (Lähteenmäki & Valtaoja, 1999).

1.1.3 Relativistic beaming

Observed variability presents a problem where the implied brightness temperature exceeds the inverse Compton limit of $\sim 10^{12}$ K. To reconcile this problem, Rees (1967) postulated that the variability occurs in source components moving relativistically at a small angle to the line of sight. This relativistic motion causes the observer to underestimate the size of the source, because the observed time-scale of variability is decreased, with respect to the intrinsic time-scale, by a factor $(1 - \beta \cos \theta)$, where $\beta = v/c$ is the speed of the component relative to the speed of light and θ is the angle between the direction of motion and the line of sight.

Furthermore, radiation emitted isotropically by such a relativistic component, with spectral index α , is enhanced in the observer's frame by a *Doppler boosting factor* $\delta^{3-\alpha}$, where $\delta = \gamma^{-1}(1 - \beta \cos \theta)^{-1}$ is the Doppler shift due to the motion of the source, and $\gamma = (1 - \beta^2)^{-1/2}$ is the *Lorentz factor*. If the relativistic motion is in the form of a continuous flow rather than discrete components, then the Doppler boosting factor is $\delta^{2-\alpha}$ (e.g. Kellermann & Owen, 1988).

The variability brightness temperature, T_b^{var} , as defined above, is then related to the intrinsic source brightness temperature, T_b^{int} , by $T_b^{\text{var}} \sim \delta^3 T_b^{\text{int}}$. Where the angular size of a source can be measured directly with VLBI, or inferred from scintillation observations, then the inferred brightness temperature T_b^{VLBI} , corrected for cosmological redshift z , is related to the intrinsic source rest-frame brightness temperature by $T_b^{\text{VLBI}} \sim \delta T_b^{\text{int}}$ (see, e.g., Marscher, 1998).

A consequence of relativistic beaming, which is directly observable for many sources with VLBI, is *apparent superluminal motion*, where VLBI components appear to separate with speed

$$\beta_{\text{app}} = \frac{\beta \sin \theta}{1 - \beta \cos \theta}$$

faster than the speed of light. From observations of β_{app} it is usually possible to place some constraints on both δ and θ .

1.1.4 Mechanisms for radio variability

Begelman et al. (1984) review early proposed models for variability of compact radio sources. Models of adiabatically expanding spherical clouds of electrons (e.g. van der Laan, 1966) were able to explain some observed variations, most notably those of the quasar 3C 120 (Kellermann & Pauliny-Toth, 1968), however this model did not generally fit observed variability. More recently, models based on particle reacceleration at shock fronts (e.g. Hughes et al., 1989) have successfully accounted for much of the variability observed at cm wavelengths on time-scales of months to years (e.g. Aller et al., 1996). Furthermore, “outbursts” can sometimes be associated with the ejection of new VLBI components, supposedly corresponding to shocks propagating outwards along the jet (e.g. Valtaoja, 1996).

At cm wavelengths and below, scattering of the radio waves in the local Galactic ISM also plays an important role in observed variability of compact sources, as discussed in Section 1.3.

1.1.5 AGN classification and unification

Historically, classification of sources has been based on observational properties. In the case of AGN this has led to an inherently orientation-biased, not to mention wavelength-biased, taxonomy. This is because the appearance of AGN depends strongly on viewing angle, as can be seen from Figure 1.1 which shows a schematic diagram of the prevailing model of a radio-loud AGN, from the review of Urry & Padovani (1995). In this picture, an AGN is powered by the gravitational potential energy of a central supermassive black hole, surrounded by an accretion disk which glows brightly at ultraviolet and soft X-ray wavelengths. Hard X-ray emission may be produced in a hot corona. Clouds orbiting above the disk, shown as dark blobs in Figure 1.1, typically out to a distance of $\lesssim 0.1$ pc, produce broad emission lines. A thick, dusty torus obscures the broad-line region from transverse lines of sight. Beyond this, at pc-scale distances from the central engine, slower moving clouds produce narrow emission lines

(grey blobs in Figure 1.1). Outflows of energetic particles occur along the poles of the disk, which form collimated radio-emitting jets, streaming outwards initially at relativistic speeds. Some radio jets have been observed to extend out to large distances, up to Mpc from the core.

Urry & Padovani (1995) review “unified schemes” for radio-loud AGN, which attempt to explain how different classes of AGN are related to one another. Another aspect of AGN unification is seeking to explain why only a small fraction, $\sim 10\%$, of AGN are “radio-loud”. A typical “radio-loud” quasar has $\log R > 2$, where R is the ratio of radio to optical flux, $R = f(5\text{ GHz})/f(B)$ (e.g. Kellermann et al., 1989; Stocke et al., 1992). Most AGN have much weaker radio emission, typically $\log R < 0.5$. The dividing line is usually set close to $\log R \sim 1$. It has been proposed that radio loudness may be related to host galaxy type (Smith et al., 1986) or to black hole spin (Blandford et al., 1990; Wilson & Colbert, 1995), which might in some way enable the formation of powerful relativistic jets. Although there are still many unanswered questions relating to AGN unification, proposed models usually invoke some combination of different viewing angles, intrinsic jet powers, and host galaxy environments (see Urry & Padovani, 1995, and references therein). Studies of different classes/orientations of AGN provide information on different aspects of their physics.

There exists a large array of names for radio-loud AGN, which reflect various observational properties. A single source often fits into several categories. Rather than discuss AGN nomenclature in great detail here, the reader is referred to the review of Urry & Padovani (1995).

What are “blazars”?

Presumably a contraction of ‘BL Lac’ and ‘quasar’, the term “blazar” has become widely used to define an observational phenomenon which is believed to arise when the jet of a radio-loud AGN is directed towards the observer. Most authors group flat spectrum, radio-loud quasars (FSRQ) and BL Lacertae objects together under the heading of “blazars”. The essential difference between these two types of object is that quasars display strong, broad emission lines in their optical spectra, while BL Lac objects exhibit a smooth, featureless optical spectrum with a marked absence of broad emission lines (see Section 1.2 for further discussion). Some authors do not like the term “blazar” since it is somewhat of a catch-all; quite different objects are apparently lumped together in the blazar category. In particular, the unbeamed “parent” population of FSRQ is believed to be the Fanoff-Riley Class II (FR II) radio galaxies, while BL Lac objects are thought to be the beamed population of Fanoff-Riley Class I (FR I) radio sources, which have less powerful jets. However the distinction is not always clear, as some BL Lac objects have extended radio luminosities more consistent with the FR II population (Rector & Stocke, 2001), and furthermore, occasionally show broad emission lines in their optical spectra which would lead them to be classed as quasars (e.g. Nilsson et al., 1996). It is important to remember that “blazar” describes an observational phenomenon rather than a physically distinct and well-defined class of object.

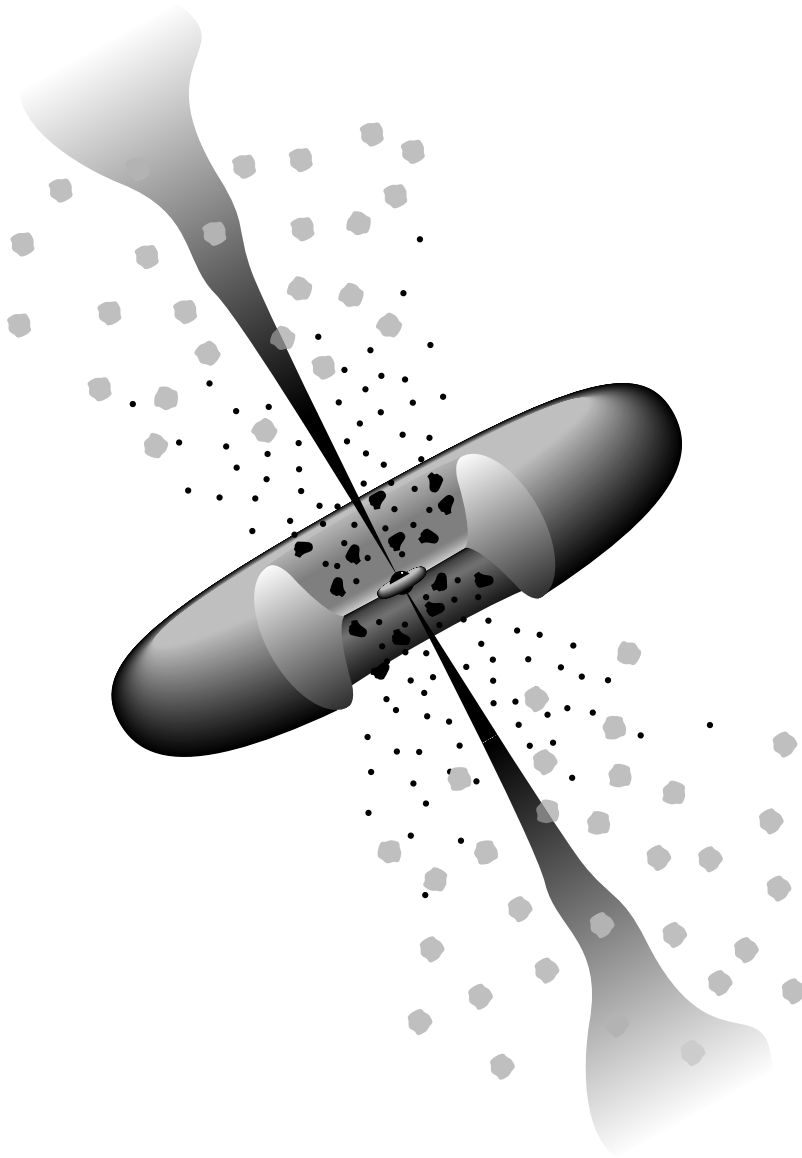


Figure 1.1: A schematic diagram (not to scale) of the prevailing model for radio-loud AGN, from Urry & Padovani (1995). See Section 1.1.5 for explanation.

Properties of blazars were first reviewed by Angel & Stockman (1980). Their commonly observed characteristics include high, and often variable, polarization in optical emission, violent variability, a compact, flat-spectrum radio source, which on milli-arcsecond and smaller scales can often be resolved into components showing apparent superluminal separation, and broad-band continuum emission extending from radio to X-ray or γ -ray energies. It seems plausible that a common process of energy release is responsible for the observed properties of blazars. The major goal in studying blazar emission is to understand the structure and physical state of the plasma in the jet, i.e. the geometry, acceleration and radiation processes.

1.2 Multiwavelength properties of blazars

Figure 1.2 shows a schematic diagram of the typical broadband spectral energy distributions (SED) observed for blazars, from the review of Ulrich et al. (1997). In this figure, $\log \nu f_\nu$ is plotted against $\log \nu$, where f_ν is the observed flux at frequency ν . Plotted in this way, blazar SEDs have a characteristic “double-humped” shape. There is strong evidence that the lower energy component is synchrotron emission (see Ulrich et al., 1997). In most models the higher energy component is produced by Inverse Compton emission, as a result of the high energy electrons scattering photons to higher energies. The low energy “seed photons” could be either the synchrotron photons produced by the relativistic electrons themselves (the *synchrotron self-Compton* mechanism), or photons external to the jet, perhaps from the accretion disk (the *external Inverse Compton* mechanism). In an alternative model (e.g. Mücke & Protheroe, 2001), the high energy component of the SED is due to synchrotron radiation from accelerated protons.

The dashed line in Figure 1.2 shows a typical SED for flat-spectrum radio-loud quasars (FSRQ) and low-energy peaked BL Lac objects (LBL), sometimes also called “red” blazars. These objects are by definition bright at radio wavelengths, so they tend to be selected by radio surveys. The dotted line in Figure 1.2 shows a typical SED for high-energy peaked BL Lac objects (HBL) or “blue” blazars, which are X-ray bright and tend to be selected by X-ray surveys. Recently, searches which use positional coincidence methods, and follow-up optical spectroscopy, to find “blazar” objects from both radio and X-ray catalogs with lower flux density limits than previous surveys, have found evidence that there are in fact many “intermediate”-type BL Lac objects, and the previously evident dichotomy is a result of selection effects (e.g. Perlman et al., 1998; Caccianiga et al., 1999; Laurent-Muehleisen et al., 1999; Landt et al., 2001). In the *Conference Highlights* summary from *Blazar Demographics and Physics*, Padovani & Urry (2001) argue that the continuity of blazar properties is consistent with the continuity in observed radio powers and host galaxy magnitudes of the “parent population” of blazars, FR I and FR II radio galaxies. Böttcher & Dermer (2002) propose an evolutionary model for the unification of quasars and BL Lac objects.

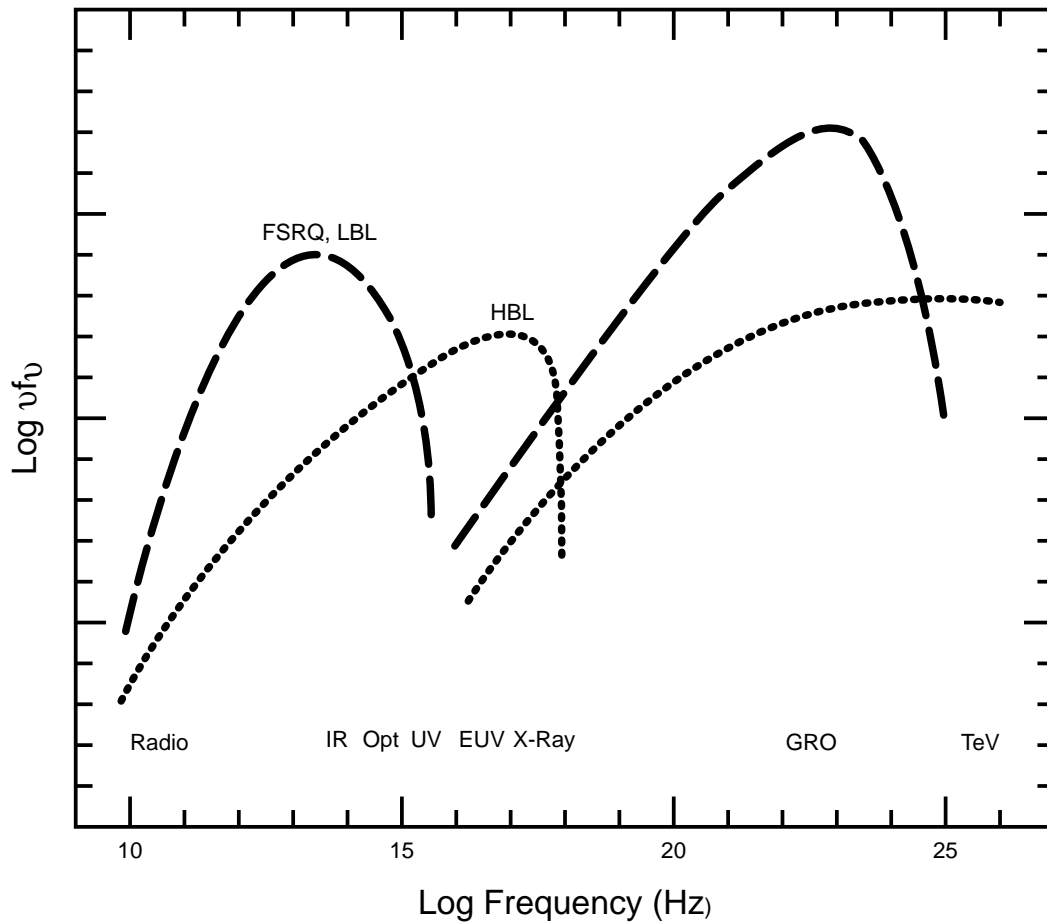


Figure 1.2: Characteristic double-peaked spectral energy distributions of blazars. The low-energy component, due to synchrotron radiation, peaks in the infrared–optical for flat spectrum radio-loud quasars (FSRQ) and low-energy peaked BL Lac objects (LBL), and at UV–X-ray energies for high-energy peaked BL Lac objects (HBL). The corresponding high-energy components, which may be due to inverse Compton scattering of soft photons, peak at GeV or TeV energies, respectively. From Ulrich et al. (1997).

1.2.1 Jet models and the importance of variability studies

Variability in blazar emission is observed across the entire electromagnetic spectrum from radio to high-energy gamma rays. Connecting emission at different wavelengths is an important test of various models for the emission processes and geometry of the jet. In principle, multiwavelength observations of variability should help to test and distinguish between a number of models, for example accelerating (Georganopoulos & Marscher, 1996) and decelerating (Melia & Konigl, 1989) jet models, and synchrotron self-Compton or external inverse Compton models for the high-energy component of the blazar SED (e.g. Ghisellini et al., 1996).

Most “outbursts” observed at multiple frequencies are consistent with shock-in-jet models (see, e.g., Marscher, 1996; Valtaoja, 1996, and references therein). This thesis presents observations at radio frequencies < 10 GHz. According to most models, the inner regions of blazar jets should be optically thick at these frequencies, and cm-wavelength observations will detect only the “tail-end” of activity occurring in the inner jets. Intraday variability at cm-wavelengths, if interpreted as being intrinsic to the source, poses problems for the models - in fact, the highest implied brightness temperatures (10^{21} K; Kedziora-Chudczer et al. 1997) conflict squarely with the interpretation of the low-energy component of blazar SEDs as synchrotron emission. However, there is now strong evidence that interstellar scintillation (ISS) in the local Galactic ISM is the principal cause of cm wavelength IDV, as outlined below in Section 1.3.6. Since cm wavelengths are so affected by ISS, it is important to understand this process in order to interpret observations of variability at cm wavelengths.

1.3 Interstellar scintillation and radio variability

1.3.1 A very brief history of radio source scintillation studies

As early as the 1950s, ionospheric scintillation was noted for some radio sources, and the theory investigated (Smith, 1950; Hewish, 1952; Ratcliffe, 1956; Wild & Roberts, 1956). It was soon recognised that scintillation is a signature of compact sources, since the diffraction pattern is smeared out by a sufficiently extended source. Before the advent of VLBI, *interplanetary* scintillation of compact radio sources in the solar wind was a powerful tool to investigate the sub-arcsecond-scale angular sizes of distant radio sources (e.g. Little & Hewish, 1966; Cohen et al., 1967).

Shortly after the discovery of radio pulsars, Scheuer (1968) explained pulsar variability in terms of scattering in the ionized Galactic interstellar medium (ISM). Much of what is known about the ionized ISM comes from studies of pulsar scintillation in the regime of strong scattering (see Section 1.3.2). Rickett et al. (1984) suggested that refractive interstellar scintillation (RISS) is the cause of low-frequency ($\lesssim 1$ GHz) variability observed in compact, extragalactic radio sources (Hunstead, 1972). More recently, the importance of both weak and refractive interstellar scintillation for cm-wavelength variability, typically in the frequency range 2–10 GHz, has been under investigation. This section summarises the relevant results of scintillation theory and

recent observations which have highlighted the importance of ISS for radio emission from compact AGN.

1.3.2 Scattering regimes

Narayan (1992) discusses the basic physics of scattering in a turbulent medium. Rickett (1990) reviews radio propagation through the turbulent ISM, and the interplay between observations and scattering theory up to 1990. As radio waves propagate through a turbulent medium, random phase fluctuations are introduced into the wavefront. These fluctuations generally occur on a range of spatial scales, the statistics of the which can be described by a power spectrum, or a *phase structure function*. In many cases in astronomy, phase fluctuations are assumed to arise from Kolmogorov turbulence in the scattering medium. It is common to make the simplifying assumption that the turbulent medium between the source and the observer is replaced by an equivalent thin phase changing screen at distance L from the observer. The description of scattering in an extended medium is more difficult, but the effect has been investigated in several studies (e.g. Rickett et al., 2002). At distance L from the screen, the mutual interference of the different components in the angular spectrum converts the phase modulation to an observable amplitude modulation, known as scintillation.

There are two physically distinct regimes of scattering, which are set by the *Fresnel scale*, $r_F = \sqrt{\lambda L/2\pi}$, where λ is the wavelength of the radiation, and the *diffractive* length scale, r_{diff} , which represents the transverse separation for which the root mean square (rms) phase difference is equal to 1 radian. *Weak scattering* occurs when $r_{\text{diff}} > r_F$, implying that the medium introduces a phase change < 1 radian across the first Fresnel zone. Thus, scintillation is weak at high frequencies and for nearby scattering material. *Strong scattering* occurs when $r_{\text{diff}} < r_F$, and in this regime, there are two distinct branches of scintillation. *Diffractive scintillation* corresponds to interference effects, which produce narrow-band flux variations with typical length scales r_{diff} . *Refractive scintillation* is the result of lens-like phenomena which produce slow, broad-band variations on length scales $r_{\text{ref}} = r_F^2/r_{\text{diff}}$.

1.3.3 Source angular size limits

When the source angular radius, projected onto the diffraction pattern at distance L , becomes comparable to the spatial scale of the scintillations, the pattern becomes “blurred” due to the superposition of diffraction patterns from independently emitting regions. Thus there are angular size cut-offs for each of the three regimes of scintillation: $\theta_{\text{weak}} = r_F/L$, $\theta_{\text{diff}} = r_{\text{diff}}/L$, and $\theta_{\text{ref}} = r_{\text{ref}}/L$ (Rickett, 1990). Scintillations will be suppressed for sources which exceed the corresponding angular size limit. So far, there is no firm evidence of diffractive scintillation being observed for any quasar or BL Lac object. Most AGN far exceed the angular size cutoff for diffractive scintillations. However, refractive ISS is important for milliarcsecond-scale sources at frequencies below ~ 1 GHz, and weak ISS is important for sources with microarcsecond-scale components, as discussed below in Section 1.3.6.

1.3.4 Scintillation time-scales

Figure 1.3, from Rickett (2001b), summarises typical time-scales for source variations due to ISS at different frequencies and in different scattering regimes. The actual value of the scintillation time-scale depends on both the scintillation length scale and the speed at which the pattern moves past the observer (see Section 1.3.7 for further discussion). Also indicated in Figure 1.3 are time-scales for intrinsic synchrotron bursts in blazars, typically months–years at frequencies of $\sim 3 - 10$ GHz, and shorter at higher frequencies. The three straight lines on the plot correspond to the different scattering regimes. Below the transition frequency, in the strong scattering regime, diffractive scintillation time-scales are represented by the line labelled t_d which goes to shorter time-scales at lower frequencies. Diffractive scintillations are generally not observed in AGN. Refractive scintillation time-scales increase towards lower frequencies, represented by the line t_{ref} . In the refractive scintillation regime, low frequency variability (LFV) occurs at frequencies below ~ 1 GHz on typical time-scales of months to years, while “flicker” occurs on time-scales of days. Above the transition frequency the diffractive and refractive branches merge into one, with the time-scale t_{weak} slowly decreasing towards higher frequencies in the regime of weak scattering. For a source size θ_S exceeding the angular size cut-offs in each regime as given in Section 1.3.3 above, the scintillation time-scale is simply increased by a factor $\theta_S/\theta_{\text{weak}}$ in weak scattering, or $\theta_S/\theta_{\text{ref}}$ in the case of refractive scattering.

1.3.5 Modulation index for scintillation

The *modulation index* of variability is usually defined as the root mean square (rms) amplitude of the flux density variations, normalised by the average flux density. At the transition frequency ν_0 , the modulation index for a point source is equal to unity. In the regime of weak scattering, the modulation index scales with frequency ν as $(\nu_0/\nu)^{17/12}$. For refractive scintillations, the modulation index scales as $(\nu/\nu_0)^{17/30}$ (Walker, 1998). When the source size θ_S exceeds the corresponding angular size cut-off θ_{lim} , the modulation index is reduced by a factor $(\theta_{\text{lim}}/\theta_S)^{7/6}$ (Narayan, 1992; Walker, 1998). The exponents arise from assuming Kolmogorov turbulence. For a different spectrum of turbulence, the exponents in the above formulae may differ, as would also be the case if there was anisotropy in the medium.

1.3.6 Recent advances in understanding radio intraday variability

Wagner & Witzel (1995; hereafter WW95) review much of the historical background on IDV across the electromagnetic (EM) spectrum. They consider both intrinsic and extrinsic mechanisms for IDV. The authors conclude that although interstellar scintillation (ISS), due to density inhomogeneities of electrons in the interstellar medium (ISM), is likely to make some contribution to variability at radio wavelengths, the fact that IDV is such a broad-band phenomenon, occurring from radio all the way to

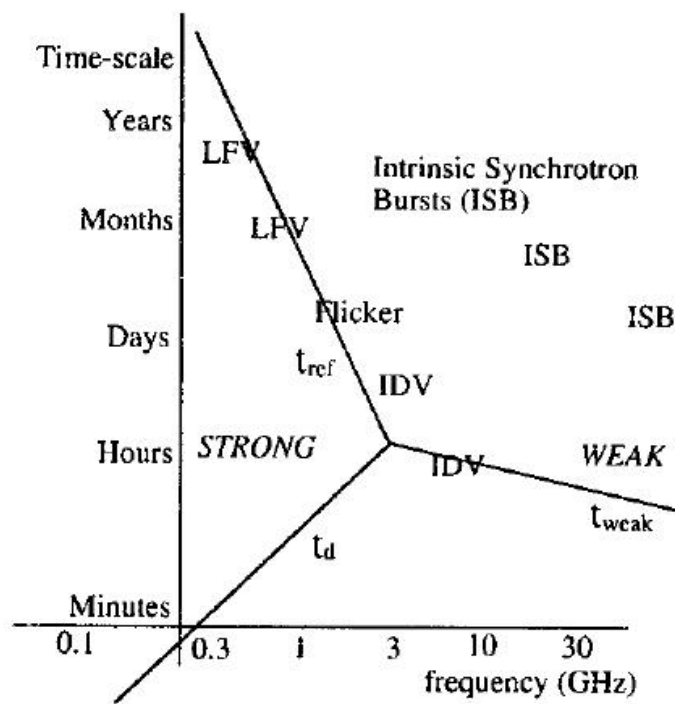


Figure 1.3: Logarithmic plot of typical time-scales for source variations in different scattering regimes, from Rickett (2001b). See Section 1.3.4 for explanation.

gamma-ray wavelengths, implies that “intraday variability in general cannot be due to extrinsic mechanisms” (p 191, “Conclusions and prospects”, paragraph 1). ISS is strongly wavelength dependent (Narayan 1992, see Section 1.3.2), and does not affect frequencies above the radio regime. An important consideration for radio IDV, however, is that for the very small source sizes required if the IDV is intrinsic to the source, extremely high brightness temperatures are implied, often many orders of magnitude higher than the Inverse Compton limit for synchrotron radiation (see Section 1.1.1).

Despite the foregoing conclusions of WW95, the role of ISS in the short-timescale radio variability observed in compact extragalactic objects has been extensively re-examined in recent years.

To a large extent, further investigation of ISS in extra-galactic sources was prompted by the discovery of extremely rapid, large-amplitude IDV in PKS 0405–385 (Kedziora-Chudczer et al., 1997), which, if intrinsic to the source, implied an unacceptably high brightness temperature, T_b , of 10^{21} K. This requires a Doppler factor in excess of 10^3 if the radio emission is incoherent synchrotron radiation, which is far higher than any observed or theoretically expected Doppler factors (Begelman et al., 1994). The authors therefore investigated a model of interstellar scintillation for this source, which was able to fit very satisfactorily the observed frequency dependence of the IDV. The observed time-scales of variability were longer at 1.4 and 2.5 GHz than at 4.8 and 8.6 GHz, while the modulation index (rms fractional variation) peaked near 4.8 GHz. This was found to be quantitatively consistent with 15% of the source flux density being in a scintillating component, with 1.4 and 2.5 GHz variability due to refractive scintillation, and 4.8 and 8.6 GHz being in the weak scattering regime. A similar frequency dependence is often found for other IDV sources (e.g. Rickett et al., 1995; Macquart et al., 2000; Dennett-Thorpe & de Bruyn, 2000).

The role of interstellar scintillation in short-term variability of extragalactic radio sources is discussed by Walker (1998), who emphasises that provided a source is sufficiently small in angular diameter, the largest intensity modulations will be observed at frequencies close to the transition between weak and strong scattering. The transition frequency is often close to commonly observed frequencies of several GHz. Another important consideration is that if a source were small enough to display intrinsic variations on time-scales of the order of a day, then it would be sufficiently small in angular size that ISS would surely be important.

IAU Colloquium 182, ‘Sources and scintillations: refraction and scattering in radio astronomy’, held in Guiyang, China, in April 2000, provided a forum for many new results and ideas to be promoted within the radio astronomy community, and for outstanding problems to be discussed. Some presentations relevant to AGN variability are briefly highlighted below, with their corresponding references in the conference proceedings (ed. R. Strom et al. 2001, reprinted from AP&SS, 278).

- An overview of scintillation of radio sources was presented by B. Rickett (p. 5), who also showed in a separate paper that ISS could quantitatively explain the rapid variations in total and polarized flux density observed in PKS 0405–385, concluding that “there is no evidence in support of an intrinsic component in the

IDV” (p. 129, Abstract).

- S. Wagner reviewed studies of intrinsic IDV across the EM spectrum, acknowledging that radio frequencies are affected by ISS, so “it is important to assess different contributions and decompose intrinsic from scintillation effects wherever both are important on the same time scales” (p. 105, Section 1).
- Results showing an annual cycle in the characteristic time-scale of the extreme variable J1819+3845 were first presented at this meeting by Dennett-Thorpe & de Bruyn (p. 101). This annual cycle was explained by the relative change in the observed velocity of the scintillation pattern due to the Earth’s orbital motion (see section 1.3.7 for a detailed explanation), and shows unequivocally that the rapid IDV in this source is due to interstellar scintillation.
- Results of the ATCA IDV Survey were presented by Kedziora-Chudczer et al. (p. 113), who concluded that the observed variability could be best explained as scintillation.
- Results on strong ($> 1\%$) and variable circular polarization in PKS 1519–273 were presented by Macquart et al. (p. 135). The characteristics and frequency dependence of the IDV in PKS 1519–273 are consistent with interstellar scintillation, however the origin of the circular polarization is unclear, and the implied brightness temperature, $T_B > 5 \times 10^{13} K$, is difficult to account for. These and other problems remaining to be solved for IDV radio sources were outlined by Jauncey et al. (p. 87).
- Several presentations focussed on Extreme Scattering Events (ESEs; Fiedler et al. 1987). Properties of ESEs were reviewed by M. Walker (p. 149) and J. Lazio et al. (p. 155). These events are sometimes manifest in the light-curves of compact radio quasars at frequencies of a few GHz, usually as dramatic decreases in flux density lasting several weeks-months, bracketed by substantial increases. Although it is generally agreed that they are due to refraction by intervening, ionised, Galactic gas, little is known about the structures, or “lenses” responsible. Lazio et al. discussed current observational constraints on these structures. Walker presented an overview of models which have been proposed, as well as ideas for future observational tests.
- It is clear that much remains to be understood about the structure of the Galactic interstellar medium (ISM). A number of papers discussed recent results relating to the ISM, e.g. Bhat et al. investigated the distribution of scattering plasma in the Local Interstellar Medium, using pulsar scintillation measurements. This work may have important implications for investigation of scintillation of extragalactic sources, as nearby scattering plasma has the greatest influence on rapid variations in these sources (e.g. Dennett-Thorpe & de Bruyn, 2002).

The publication of Kraus et al. (1999b), “A change in the variability properties of the intraday variable quasar 0917+624”, prompted a number of people independently to re-examine historical data on 0917+624. In 2001, three papers were published independently on the annual modulation in the IDV timescale of 0917+624, by Rickett et al. (2001), Jauncey & Macquart (2001), and Qian & Zhang (2001). Jauncey & Macquart (2001) searched the literature back to the first detailed observations of 0917+624, at 2.7 GHz in 1985 with the Bonn 100m telescope (Witzel et al., 1986; Heeschen et al., 1987). Heeschen et al. (1987) published data from August 1985, which, until the observation in September 1998, was the only lengthy observation of the source during its expected “slow-down” period. The source was observed then to be varying slowly with only a monotonic change over 4 days, similar to its behaviour in September 1998. The fact that such a slow-down was observed in these two datasets separated by 13 years, while for all other observations before 2000 it was showing strong and rapid variability, strongly supports the case that these periods of very slow variability were due to the low relative velocity between the Earth and the scattering material at this time of the year.

However, frequent monitoring of 0917+614 since September 2000, reported by Fuhrmann et al. (2002) at the workshop ‘AGN variability across the Electromagnetic Spectrum’ held in Sydney in June 2001, showed that the character of its IDV has significantly changed, with the source showing no return to its “usual”, large-amplitude IDV since September 2000. Observations with the VLA in early 2002 (Lovell et al., 2002, 2003) confirm that the source is still not showing IDV.

Whether this change in the IDV behaviour was due to a change in the scattering medium, e.g. an ionized “cloud” or other structure drifting out of the line-of-sight, or in the source itself, e.g. expansion of a compact component which became too large to scintillate, it is not unexpected that both the source and the material in the line-of-sight may change on time-scales of years or less. From a comparison of the long-term flux density history of 0917+624 from 1994–1999, presented by Peng et al. (2000), with the more recent data, there are no dramatic variations evident in the long-term average flux density of this source. The most extreme IDV source yet observed, PKS 0405–385 (Kedziora-Chudczer et al., 1997), is another source which has shown remarkable changes in its IDV behaviour. PKS 0405–385 has shown only two short-lived episodes of extreme IDV, each lasting a few months. Much remains to be understood about the phenomenon of scintillation-induced variability.

In addition to new observational results, recent theoretical work has examined how information on microarcsecond-scale source structure can be extracted from observations of scintillation-induced variability (Macquart & Jauncey, 2002; Rickett et al., 2002). This necessarily also involves modelling properties of the ISM. Observations of annual cycles in the characteristic timescale of variability not only prove that the variability is due to interstellar scintillation; they also yield information on properties of the ISM in the line-of-sight to these sources, and, more importantly from the point of view of investigating the blazar phenomenon, yield information on source structure on scales of a few to a few tens of microarcseconds (μas). Not even space VLBI can yet match this resolution.

1.3.7 Annual cycles in variability time-scales and Earth Orbit Synthesis

The Earth’s velocity relative to the interstellar medium (ISM), and thus to a scintillation pattern, \mathbf{v}_{ISS} , changes with an annual cycle as it orbits the Sun (see Figure 1.4). The velocity of the ISM with respect to the heliocentre, \mathbf{v}_{ISM} , and the orbital velocity of the Earth, \mathbf{v}_{\oplus} , add vectorially to give the transverse scintillation velocity, \mathbf{v}_{ISS} . Both the magnitude and the direction of \mathbf{v}_{ISS} potentially influence the time-scale of variability, t_{ISS} , observed due to a scintillation pattern moving past the observer. If the scintillation pattern is isotropic, then only changes in the magnitude of \mathbf{v}_{ISS} will cause changes in t_{ISS} ($t_{\text{ISS}} \propto 1/|\mathbf{v}_{\text{ISS}}|$). However, in general, the direction of \mathbf{v}_{ISS} also influences t_{ISS} , as the length scale of the scintillation pattern can change with orientation. This can occur due to μas -scale source structure, which broadens the scintillation pattern along the long-axis of the source, and/or ultra-fine magnetic field structure in the ISM which produces anisotropy in the scintillation pattern itself.

Observation of an annual cycle in t_{ISS} can be used to constrain the velocity of the scattering medium, which may or may not be moving with the *local standard of rest* (LSR). The LSR refers to the motion of the Sun relative to other stars in the solar neighbourhood, obtained by averaging the velocities of nearby stars (e.g. Kerr & Lynden-Bell, 1986). The shape of the annual cycle also constrains the two-dimensional scale of the scintillation pattern. This in turn can be used to constrain both the screen distance and source angular size, using the relations given in Sections 1.3.3, 1.3.4 and 1.3.5 above. Fitting to the t_{ISS} annual cycle can yield source structure on a μas -scale, provided it is possible to also solve for the velocity and anisotropy in the ISM. This technique is analogous in many ways to Earth rotation synthesis, and has therefore been dubbed “Earth Orbit Synthesis” (Macquart & Jauncey 2002). There are a number of free parameters involved in such modelling, and there is often some non-uniqueness in the derived model. Often, the greatest uncertainties arise because of the limited number of independent samples of the scintillation pattern, or “scintels”, which can be obtained in a typical observing session.

A comparison of the scintillation of different Stokes parameters may help to constrain source structure. For example, the strong correlation between variations in Stokes I and V for PKS 1519–273 shows that both the unpolarized and the circularly polarized scintillating components are coincident and have the same size (Macquart et al., 2000). The observed scintillation in polarized flux density is often different to that in total intensity, indicating polarized substructure in the source (Rickett et al., 1995; Macquart & Jauncey, 2002; Rickett et al., 2002). Anisotropy in the ISM may also be constrained from the autocorrelation functions of the light curves (Rickett et al., 2002).

For very rapid (intra-hour) variables, it is possible to independently constrain the ISM velocity and the shape of the scintillation pattern by measuring the time delay in pattern arrival times between widely separated telescopes (Jauncey et al., 2000a; Dennett-Thorpe & de Bruyn, 2002, and see Section 6.3).

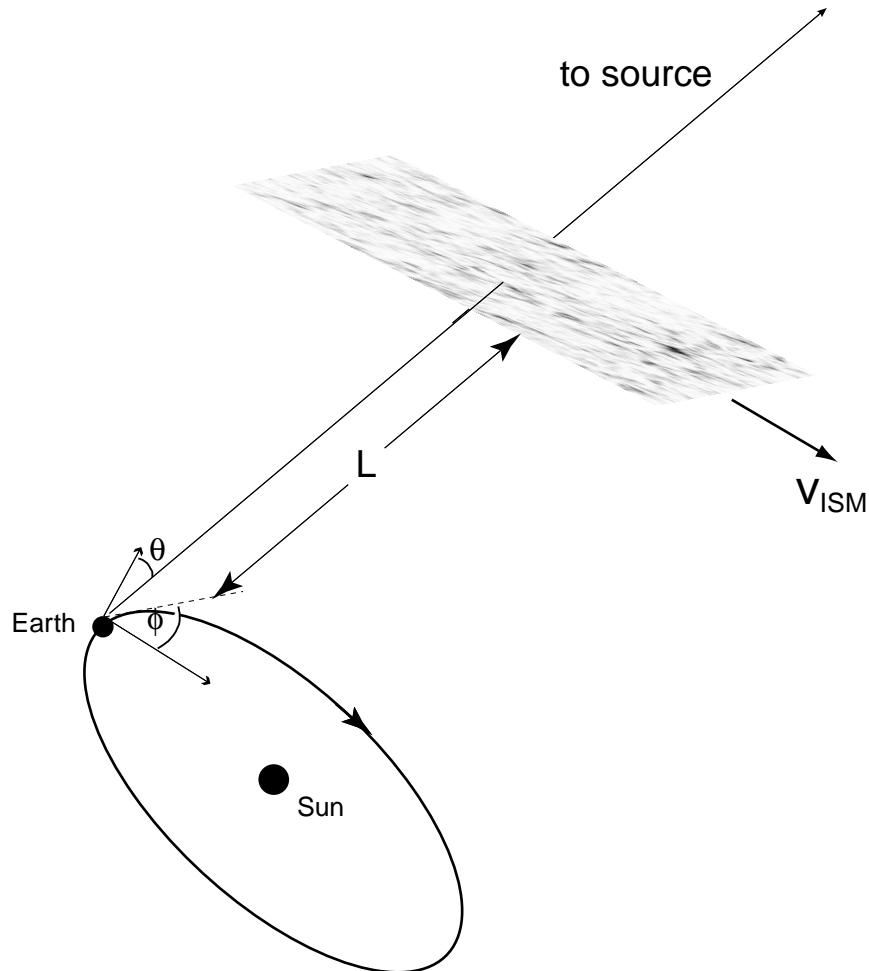


Figure 1.4: The geometry of the scattering model for Earth Orbital Synthesis, from Macquart & Jauncey (2002). The scattering screen at distance L moves with speed V_{ISM} relative to the heliocentre and tangential to the line-of-sight to a source with ecliptic coordinates (ϕ, θ) . The Earth's orbital velocity contributes a component to the velocity of the scintillation pattern observed from Earth, which varies over the course of a year. The shape of the resulting *annual cycle* depends on the ecliptic latitude, θ , of the source.

1.4 Summary of thesis

This thesis presents several observational studies of blazar radio variability and interstellar scintillation. Chapter 2 describes the telescopes used. Most of the observations were done with the Australia Telescope Compact Array (ATCA) and the Australia Telescope Long Baseline Array (LBA). Some of the work presented also involved the use of the NRAO's Very Large Array (VLA) and Very Long Baseline Array (VLBA). Chapter 2 discusses the important steps involved in obtaining accurate flux density measurements for studies of variability. Most of the data reduction procedures used are standard, however some further development was undertaken during this project; in particular to correct the gain-elevation dependence found in ATCA 3 cm data, and to apply amplitude calibration to the LBA data.

Chapters 3 and 4 present the results and analysis of a long-term (3 year) study of blazar radio variability with the ATCA and the LBA. This project was originally intended to be part of a multi-wavelength study of blazars observed with the BeppoSAX X-ray satellite. The sample was not well-defined but rather representative of different types of "blazar" sources; the main aim was to study in detail the multiwavelength variability of a number of individual sources of interest, rather than measure statistics of a large, complete sample. However, one of the original aims of the program, to cross-correlate radio and X-ray flux density measurements, proved to be not possible for most sources in the sample, due to the lack of repeated X-ray observations over the same time frame as the radio monitoring. The radio data alone are of value for studying the blazar phenomenon, and can be compared with (mostly) non-simultaneous data at other wavelengths. The majority of sources in the sample were detected at γ -ray energies with the EGRET instrument on board the CGRO satellite (e.g. Fichtel et al., 1994). Several of the southern-most sources had not previously been studied in detail at radio wavelengths. For the stronger, more northern sources in the sample, many have been observed in other, longer-term radio monitoring programs (e.g. Aller et al., 1985).

An advantage of the ATCA compared to single dish telescopes is that its high sensitivity and accurate flux density measurements allow studies of intra-day variability (IDV), in both total and polarized flux density. A new IDV source, PKS 1622–253, was discovered as a result of the above monitoring program. At the time that the work for this thesis was being undertaken, there was a great deal of interest in understanding radio IDV. If such variability is intrinsic to the source, this severely challenges one of the most fundamental aspects of the current AGN paradigm, i.e. the interpretation of the low energy continuum emission as incoherent synchrotron radiation. On the other hand, if IDV is a result of interstellar scintillation, then a number of questions arise, such as what does this tell us about the Galactic ISM, and about the sources themselves?

Chapters 5 and 6 present the first results of a study which aims to help answer these questions. A number of IDV sources were observed over the course of a year, to look for annual cycles in the time-scale of variability. One of these sources, PKS 1257–326, another serendipitously discovered IDV source, showed extremely rapid, intra-hour

variability, and proved to be extremely important in aiding our understanding of IDV and interstellar scintillation (ISS) of extragalactic radio sources. Chapter 6 is devoted to a detailed study of this source. The presence of a clear *annual cycle* in the time-scale of variability, as well as a time delay between the IDV pattern arrival times at the VLA and the ATCA, show unequivocally that ISS is the cause of the rapid variations observed in this source. PKS 1257–326, and the two previously discovered rapid scintillators, PKS 0405–385 (Kedziora-Chudczer et al., 1997) and J1819+3845 (Dennett-Thorpe & de Bruyn, 2000), have proved crucial in making the shift to the ISS paradigm, and in showing that ISS is a powerful probe of both the local ISM, and the microarcsecond-scale structure of radio sources. The relationship between intrinsic and scintillation-induced variability is another topic investigated in this thesis.

It is notable that two of the three known extremely fast scintillators were discovered serendipitously, and are relatively weak (< 0.5 Jy) radio sources. This was one of the major factors prompting a large-scale survey of the northern sky, to search for IDV in a large, well-defined sample of flat spectrum radio sources, including weaker sources than had not previously been included in IDV surveys (Lovell et al., 2002, 2003, and see Chapter 7). Modern interferometers allow highly sensitive and accurate measurements of the full set of Stokes parameters, and there are many possibilities for using scintillation-induced variability as a probe of physical conditions in sources and in the local ISM, which are really just beginning to be explored.

