CHAPTER ONE

Introduction to Interstellar Scintillation

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RADIO SOURCES AND SCINTILLATION

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Abstract. A review is given of the interplay between studies of compact radio sources and the scattering and scintillations that occur as the signals travel through the irregular refractive index of the interstellar and interplanetary plasmas.

Keywords: scattering, scintillation, AGN, pulsar

1. Historical Perspective

The interplay between radio scintillation and sources dates back nearly fifty years to when ionospheric scintillation was noticed for some but not all radio sources. This difference was recognised as due to the influence of source size. Since the diffraction pattern is smeared by an extended source, scintillation was recognised as a signature of the more compact radio sources. This simple principle has been a recurrent theme in much of the research on scatttering in radio astronomy in subsequent decades. In the ionosphere the critical source diameter that quenches the scintillation is on the order of arcminutes, while it ranges down to arcseconds for interplanetary scintillation (IPS) and milli- to micro-arcseconds for various regimes of interstellar scintillation (ISS).

The evolution of the study of sources and scintillation is illustrated in Figure 1. The early observations of ionospheric scintillation were the trigger that stimulated theories for propagation through random phase-changing media. The idealization of a phase screen still provides essential insight into scattering phenomena. The basic phenomenon of interplanetary angular broadening was recognized in the 1960s, as the increase in a source diameter when it is viewed through the outer solar corona. This was interpreted as due to inhomogeneity in the solar wind plasma as it flows out from the Sun. The accompanying phenomenon of IPS was first seen by Margaret Clarke and vigorously pursued at Cambridge (Hewish, Scott and Wills, 1964), where it was recognised that quasars showing IPS must be very compact at 80 MHz.

Hewish had the insight and drive to go after both the use of IPS as a tool to study the solar wind and also the use of IPS to explore compact radio sources at a resolution of 0.2 arcseconds at 80 MHz, a resolution far beyond that available by interferometry. For the former he built secondary spaced antennas and, by measuring the time offset in the scintillation pattern, estimated the solar wind velocity. This

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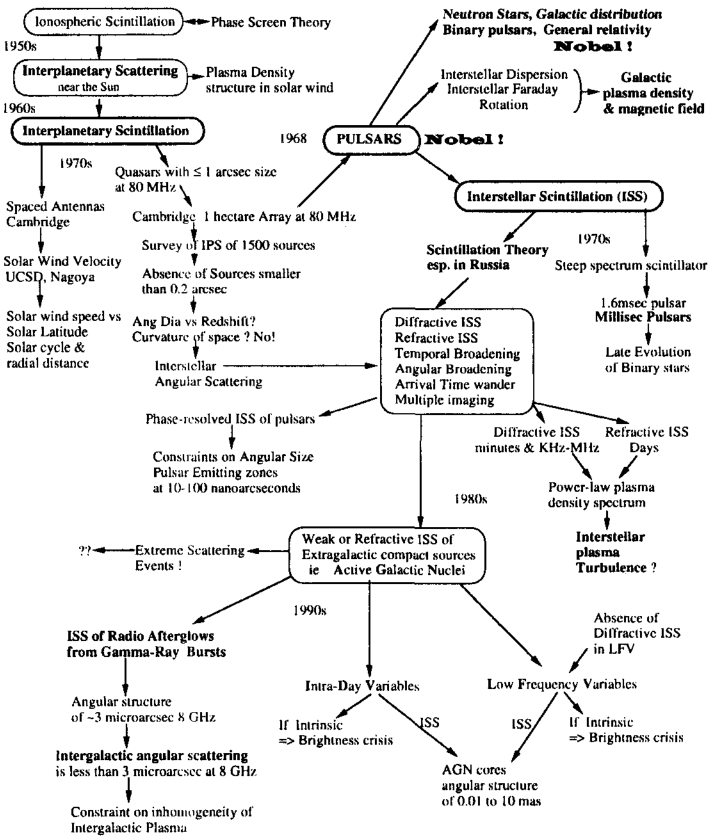

Figure 1. Sources and Scintillation: a 'flow chart'

technique was subsequently developed by several groups and has led to valuable studies of the solar wind speed versus solar latitude, longitude and distance and its solar cycle evolution.

Hewish and colleagues pursued the IPS study of radio sources by building a 2-hectare array also at 80 MHz to find sources showing IPS during the Sun's annual trajectory. This was published as a catalog of 1500 compact sources (Readhead and Hewish, 1974), in which there appeared to be a cut-off in the distribution of source diameters smaller than 0.2 as. Though this was initially thought to be of cosmological origin, it was later found to be limited by angular broadening due to density inhomogeneities in the *interstellar* medium (ISM). Another unexpected spin-off from this project was the discovery of pulsars by Jocelyn Bell-Burnell (Hewish *et al.*, 1968). Not long after they were discovered, the deep fluctuation in their signal strength on times of a few minutes was identified as yet another form of scintillation, due to the same inhomogeneities in the ISM that cause the

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angular broadening. This interstellar scintillation has a fascinating set of associated phenomena which opened up a broad range of studies of both sources and the ISM.

In the 1980's a second branch of ISS was recognised as the cause of slow (days to months) flux variations of pulsars (Rickett, Coles and Bourgois, 1984). This branch only occurs in strong scintillation conditions and, though it had been recognized in the theoretical wave propagation studies in Russia (e.g. Prokhorov *et al.*, 1975) it had not been observed before in the radio regime. Now referred to as refractive ISS it turns out to provide evidence for inhomogeneities on scales as large as several AU, while normal (now called diffractive) ISS probes scales as small as the Earth's radius. Together these two regimes show the density spectrum to follow the Kolmogorov form in the local ISM (Armstrong, Rickett and Spangler, 1995). In the next section I give a brief explanation of these scattering phenomena and in the following section continue the story of ISS as applied to extra-galactic sources.

2. Basic Theory of Scintillation

Consider waves that pass through a thin region that disturbs their phase (a phase screen). The waves are scattered into an angular spectrum of width θ_{scatt}, which is a very small angle in radio astronomical observations. At some distance L from the screen the mutual interference of the differing components in the angular spectrum converts the phase modulation to an amplitude modulation (i.e. scintillation). A critical scale that governs the process is the field coherence scale $s_d = 1/(k\theta_{\text{scatt}})$ where k is the radio wavenumber. The scintillation remains weak (rms intensity less than mean intensity) when $s_d > r_f$, where $r_f = \sqrt{L/k}$ is the Fresnel scale. Thus the scintillation is weak near the scattering medium and at high frequencies (in ISS, distances $\lesssim$500 pc and frequencies above about 3 GHz). Then the Fresnel scale sets the temporal scale by:

$$t_{\text{weak}} \sim r_f/V = \sqrt{L/k}/V,$$

where V is the velocity of the scintillation pattern past the observer.

Strong scintillations occur at the other extreme when $s_d < r_f$, in which case the diffraction pattern develops two scales referred to as diffractive and refractive. The flux variation shows peaks on a scale of s_d typically separated by a few times their width, but grouped loosely into 'clumps' on a scale $s_r \sim L\theta_{\text{scatt}}$. The smaller diffractive scale (s_d) results from interference between components of the angular spectrum; the larger refractive scale (s_r) corresponds to the size of the scattering disc, the region above an observer that influences the observed flux at any instant. For a medium with a wide range of scales, the scattering disc determines the largest scale that can influence the amplitude, since still larger scales simply cause tilts in the wavefront – a wander in the angle of arrival. When mapped into time by the same pattern velocity V the two time scales are:

$$t_d \sim 1/(Vk\theta_{\rm scatt}) \quad t_r \sim L\theta_{\rm scatt}/V$$

In the ISS of pulsars below 1 GHz the diffractive time is on the order of minutes and the refractive time is on the order of days. The relations highlight the important fact that the two scales depend in opposite ways on the scattering angle. As this angle decreases the two scales converge and merge into one at the Fresnel scale when the scintillation is weak (Rickett, 1990).

These phenomena are particularly evident in pulsars because they are effectively point sources. There is a wide range of pulsar scattering phenomena, of which the most direct is temporal broadening caused by the extra path delay for waves scattered through an angle $\theta_{\rm scatt}$. This causes a blurring of the intrinsic pulse shape by a function that is close to a one-sided exponential with a time constant $\delta t_d \sim L\theta^2_{\rm scatt}/2c$. When considered in the frequency domain this phenomenon is seen as a deep modulation of the diffractive scintillations over a narrow frequency range $\delta\nu_d \sim (2\pi\delta t_d)^{-1}$. Thus diffractive scintillation is studied in high resolution dynamic spectra, which have become a workhorse of ISS observations for investigating the inhomogeneous interstellar plasma density. These have been added to the information gained from pulsar dispersion measures and built into a widely used model of the Galactic plasma distribution (Taylor and Cordes, 1993).

3. ISS of Extra-Galactic Sources

The influence of ISS on extra-galactic radio sources is largely suppressed by the smoothing, that comes from the super-position of diffraction patterns from independently emitting regions extended over the core of the galaxy or quasar. In the context of a screen model, relations can be written down simply for the critical source radius that suppresses each regime of scintillation. The source angular radius projected onto the diffraction pattern (at distance L) blurs the pattern over a scale $L\theta_{\rm source}$; when this becomes comparable to the spatial scale of the scintillations they are partially suppressed and the fluctuation time is determined by $L\theta_{\rm source}/V$. As a consequence there are effective cut-off diameters for the three regimes of scintillation: $\theta_{\rm weak} = r_f/L$, $\theta_{\rm d} = s_d/L$ and $\theta_{\rm r} = s_r/L = \theta_{\rm scatt}$. When $\theta_{\rm source}$ exceeds these limits the corresponding scintillations decrease inversely with $\theta_{\rm source}$.

Even the smallest diameter nucleus of an active galaxy (AGN) has an angular extent greater than that of pulsars and so blurs out the diffractive ISS. However, refractive ISS has a less stringent limit since it comes from larger scale inhomogeneities and so causes several forms of flux variability. It is now recognised that ISS is responsible for many variations previously thought to be intrinsic to the sources: low-frequency variations (LFV) over months (Fanti *et al.*, 1981), flicker over days

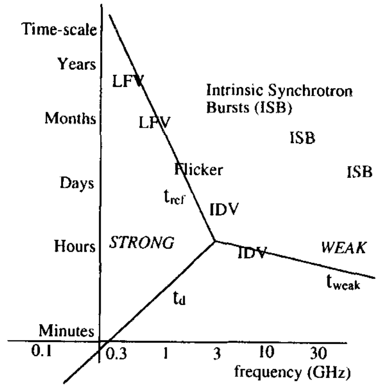

Figure 2. Logarithmic plot of typical time scales for source variations

and intraday variations (IDV) at a few GHz (Quirrenbach *et al.,* 1989) (some debate continues over whether ISS can account for all of the IDV observed at cm-wavelengths). Figure 2 shows typical time scales for the various types of ISS for extra-galactic sources observed at a mid Galactic latitude. Whereas pulsars show all three branches of ISS, AGNs only show refractive and weak ISS as indicated.

Of course, it should be noted that intrinsic synchrotron bursts (ISB) which have typical time scales of months remain a major phenomenon that, first seen in the 60s, led to the discovery of apparent super-luminal motion and the highly successful jet model for cm-wave emission from AGNs. Using classic light-travel time arguments variations are interpreted as due to extremely compact sources, with implied brightness temperatures increasing as the inverse square of the variability-time and the square of the wavelength. Month-long variabilty at cm-wavelengths gives brightness temperatures as much as a hundred times the inverse Compton limit for incoherently emitting electrons. These have been successfully explained as the Doppler boosting in relativistic jets. The same argument applied to LFV and IDV gives brightnesses very many orders of magnitude above the inverse Compton limit. With an ISS explanation for the variations such extreme brightness temperatures are no longer necessary, and most source structures can now be fitted into the scenario of emission from relativistic jets with Doppler factors consistent with observed 'super-luminal' motion. Possible exceptions exist for the very rapid IDV sources 0405-385 and 1819+385 discussed in this meeting, though here the brightness temperature is greatly decreased in models where the distance to the scattering is reduced from hundreds to tens of parsecs.

The extraordinary discovery of gamma ray bursts and their radio afterglows shining across cosmological distances has opened yet another stage for scintillation and scattering. Radio observers have been able to explain the rapid flux variabilty from an afterglow as due to ISS, and hence obtained a three microarcsecond estimate for its 8 GHz angular diameter at a time one month after the gamma ray burst (Frail *et al.*, 1997). This measurement in turn sets an interesting upper limit on the angular broadening that must take place in the highly ionized clouds of *inter-galactic* space.

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