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REMOTE SENSING OF ASTROPHYSICAL PLASMAS BY RADIO SCINTILLATION METHODS

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INTRODUCTION

The scattering of radiation by inhomogeneous media along the line of sight to a distant source degrades the image and leads to a loss of information in many observations. At the same time the fluctuations in phase and amplitude of the received signals in space, time and wave frequency can be used as a plasma-diagnostic to reveal some properties of the source and of the intervening media. Such methods can be particularly valuable in astrophysics where the media and the sources are usually inaccessible to more direct observations. Plasmas along the line of sight include the ionosphere, the heliosphere, the interstellar gas and the intergalactic medium. All these regions, save the latter, are known to modulate incoming signals and it is fortunate that the characteristic scales of the fluctuations in time, space and wave frequency are usually distinct so that effects due to the different media are not confused.

In this paper a broad outline is given of some applications of scintillation methods in astronomy and space research, with the emphasis on the extraction of useful information. Experience has shown that relatively unsophisticated theory is sufficient in many cases while some observed phenomena are not yet adequately treated theoretically.

In practice we are concerned with media that are extended along the line of sight but it is often a good approximation to assume that the irregularities are confined to a layer of negligible thickness (the thin screen case). The general characteristics of the scintillation pattern can then be summarised quite simply as illustrated in Figure 1. If the irregularities in the medium are typified by a scale-length $\underline{a}$, and produce a resultant rms phase deviation $\Delta\phi$ radians, there are four main regimes.

I, strong scattering-near field ($\Delta\phi > 1$, $Z < Z_f$); II, strong scattering-far field ($\Delta\phi > 1$, $Z > Z_f$); III, IV are the corresponding situations for weak scattering ($\Delta\phi < 1$). $Z_f \sim a^2/\lambda$ is the Fresnel distance where λ is the wavelength. Waves traversing the screen are scattered randomly through angles $\sim \theta_s$ and subsequently interfere to produce a diffraction pattern of characteristic scale ℓ having intensity variations ΔI. Disregarding small numerical factors, the important parameters of scintillation in the different regimes vary approximately as shown in Figure 1. It is sometimes helpful to consider the corresponding images of a point source at infinity when viewed through the screen and these are also shown.

Plasm irregularities normally include a range of scales and the resultant diffraction pattern is a combination of different regimes so that the focusing

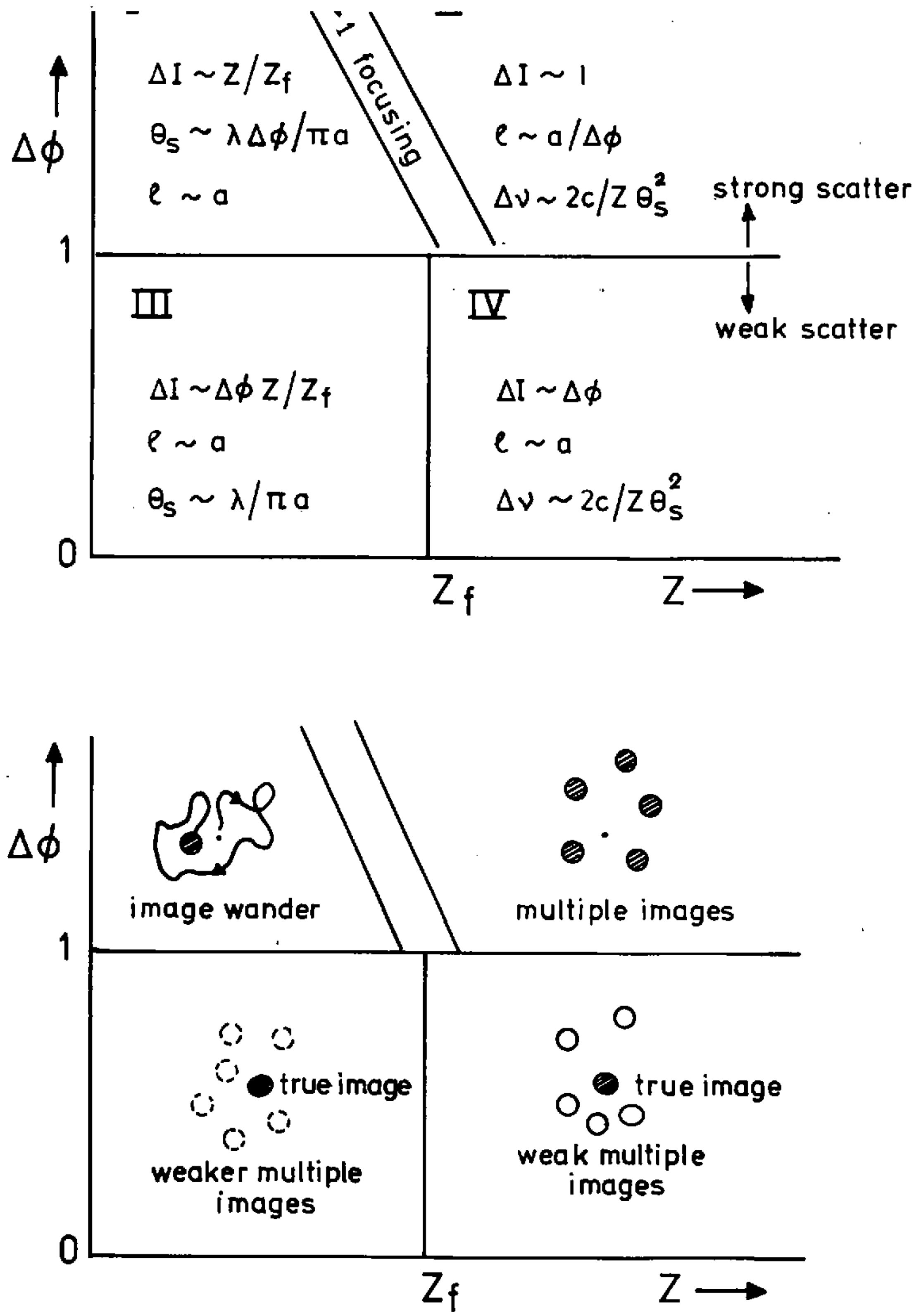

Figure 1. Schematic diagrams illustrating the characteristics of scintillation as a function of distance for a thin screen containing irregularities of scale a.

zone for strong scattering is smeared over a wide range of distance. Refraction by a few large irregularities can then be imposed upon far-field diffraction by many small irregularities leading to a systematic fringe modulation of random diffraction patterns. In this this case it is useful to consider refraction angles θ_r as a separate component of θ_s.

THE IONOSPHERE

An early application of scintillation was the remote sensing of ionospheric irregularities using radiation from celestial radio sources [1]. At metre wavelengths the situation corresponds to regime III. Since $\Delta\phi \propto \lambda$ for a plasma, observations of ΔI at different wavelengths could be used to derive Z and $\Delta\phi$ when ℓ had been measured. Thus it was possible to determine the height, scale (~km) and electron density of irregularities in the F-region. The drift motion of the diffraction pattern over the ground also gave the first measurements of ionospheric winds at these heights. More recently it has been found that density modulation on much larger scales gives refraction effects corresponding to regime I, where wandering of the image can be a major problem in the operation of radio telescopes.

THE INTERPLANETARY MEDIUM

The solar wind, which fills the heliosphere out to many times the Sun-Earth distance, causes scintillation of radio sources usually appropriate to regime IV. In this case θ_s is much smaller than for the ionosphere, being in the range of arcsecs as compared to arcmin, so that the diffraction pattern may be distinguished by its larger scale $\ell \sim 100$ km.

In spite of the larger scale the temporal variations are faster than those caused by the ionosphere, due to the much higher speed of the solar wind, and a good rejection of ionospheric scintillation is usually obtained by the simple means of a high-pass filter.

The degree of coherence of the incident radiation is important for interplanetary scintillation. Maximum visibility of the diffraction pattern requires transverse coherence over a distance $\sim \theta_s Z \geqslant 10^3$ km. Hence the angular extent of the source must be $\leqslant 0.2$ arcsec. Only the "hot-spots" in radio galaxies or quasars satisfy this condition. Interplanetary scintillation thus provides a useful means of measuring angular sizes. By a suitable choice of wavelength, and the fact that $\Delta\phi \propto \lambda\Delta N \propto \lambda/r^2$ where r is the distance from the sun, it can be arranged that lines of sight far from the Sun give regime IV while closer to the sun we have regime II. The increase of θ_s ($\propto \lambda/r^2$) for lines of sight nearer the sun provides, in effect, a method of measuring the coherence of the incident radiation. Curves of ΔI against solar elongation are analagous to those of fringe visibility for an interferometer of variable baseline and have provided much information on angular sizes, particularly at long wavelengths (see Figure 2).

Observations of the solar wind speed derived from the motion of the

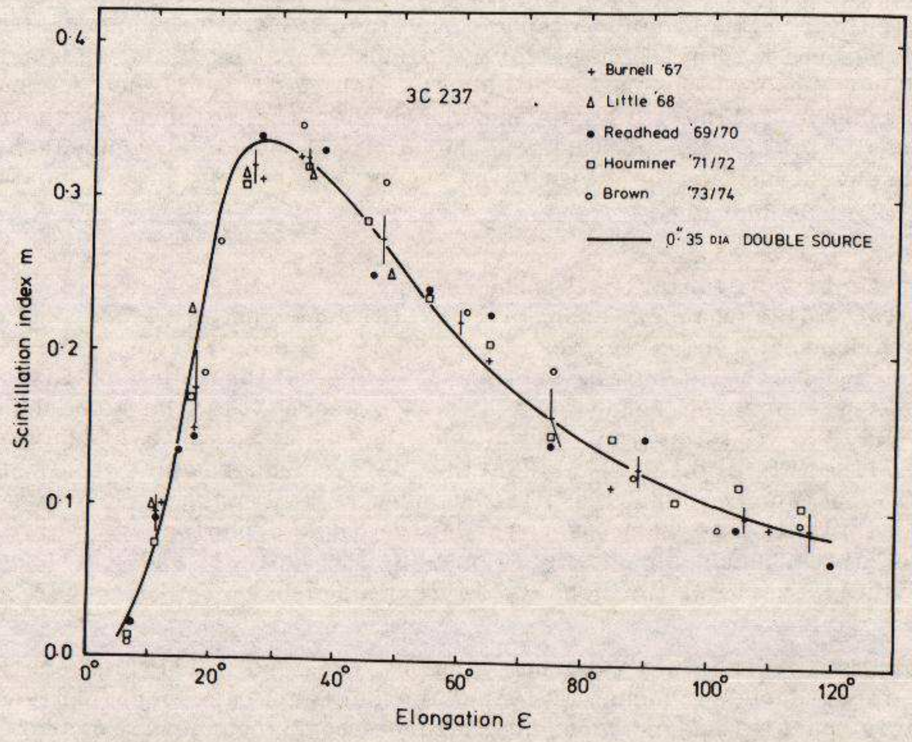

Figure 2. The use of interplanetary scintillation observed at different solar elongations to measure the angular size of a radio source.

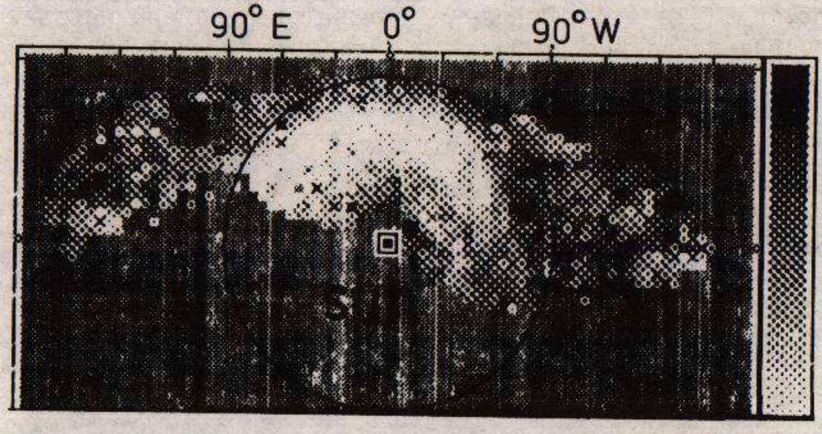

Figure 3. A map of enhanced scintillation showing a large disturbance leaving the Sun. The map was constructed from observations of 900 sources.

diffraction pattern, using a cross-correlation analysis to measure time displacements in the temporal variations of ΔI observed at three sites, have been particularly important in space physics. As yet, spacecraft have been confined to orbits in the ecliptic plane and in situ measurements have therefore not probed the solar wind at high heliolatitudes. Scintillation measurements have filled this gap and shown that the solar wind above the Sun's pole is substantially faster than in the ecliptic plane at sunspot minimum [2]. Routine observations of the solar wind using scintillation are now carried out in the USA, Japan and India.

A more recent development is the mapping and tracking of large scale interplanetary disturbances associated with geomagnetic storms at the Earth. Major disturbances typically take the form of compression zones bounded by shock fronts at their outer surfaces. By calibration against spacecraft observations it has been found that $\Delta I \propto N^{1/2}$, where N is the mean density of the solar plasma, so that scintillation can be used to obtain the mean density along the line of sight [3]. Routine daily measurement of ΔI for several thousand radio sources enables disturbances to be mapped across the sky and simple model-fitting is then used to derive the morphology in three dimensions [4]. The disturbance shown in Figure 3 is typical and corresponds to an expanding shell in which the density is increased by a factor of 3.

Studies of "interplanetary weather" using this scintillation method are of practical importance. Shocks arriving at the Earth are accompanied by showers of energetic particles and present hazards to astronauts, distort satellite orbits, and cause geomagnetic storms which disrupt radio communications and electrical power systems.

No reliable prediction of these events has yet been achieved because their solar origin is obscure. It is widely beleived that they are caused by solar flares and filament eruptions. Scintillation mapping enables disturbances to be projected back to the Sun and it has been found that the sources are regions of open magnetic field lines known as coronal holes, and not solar flares [5]. This new knowledge, and the ability to detect transients at more than one day's travel time from the Earth, should lead to vastly improved predictions.

Intensity fluctuations cannot, of course, provide information on plasma irregularities that are much larger than the Fresnel scale $a \sim (\lambda Z)^{1/2}$. Refraction by large irregularities can, however, be revealed by the transverse shear of the diffraction pattern obtained from intensity measurements at different frequencies. This method has been used to gain information on the wavenumber spectrum of density variations in the solar wind [6]. In terms of the angle of refraction θ_r, we have a time lag $\Delta t_{12} = (\nu_1 - \nu_2) 2Z\theta_r / V\nu$ where V is the transverse velocity of the intensity pattern. Measurements of Δt_{12} give θ_r when V is known.

An interesting use of interplanetary scintillation in zone I is the Doppler scintillation of spacecraft tracking signals [7]. Doppler, rather then phase measurements, comprise the radio tracking data that are routinely collected, and "Doppler noise" provides a measure of density fluctuations along the line of sight if the solar wind speed is known. Use of this technique has demonstrated that the power spectrum of density variations in the solar wind follows a Kolmogorov law except at the smallest scales. which lie close to the proton gyroradius.

THE INTERSTELLAR PLASMA

Scintillation phenomena that became well-understood through interplanetary scintillation were recognised again for the interstellar plasma via observations of pulsars. In this case ΔI fluctuates on a timescale of 10 minutes and a spatial scale $\ell \sim 10^5$ km. Only pulsars irradiate the plasma with sufficient coherence (source size $< 10^{-7}$ arcsec) to generate high-visibility diffraction patterns and timescales are determined by transverse motion of the source, rather than by the medium. This has provided information on the space velocities of neutron stars of relevance to the evolution of neutron star progenitors. One example of particular interest was the discovery [8] of periodic variations in $\Delta t \sim \ell/V$. showing clearly that the pulsar was in a binary orbit about a companion star and enabling the inclination of the orbit to be derived (see Fig 4).

Pulsar scintillation. except at the highest radio frequencies. corresponds to regime II where the coherence bandwidth is $\Delta\nu \sim 2c/Z\ \theta_s^2$ with $\Delta\nu/\nu << 1$. The shape of the autocovariance function in frequency depends upon the form of the irregularity spectrum and has been used [9] to show that the spectrum is Kolmogorov rather than Gaussian (single scale length). However. it is clear that a simple Kolomogorov spectrum cannot extend over a wide range of scales because of refraction effects on timescales of days- months which indicate that $\theta_r > \theta_s$ at the largest scales. For a power law spectrum this requires a slope exceeding 4, which is inconsistent with the Kolmogorov value of 3.6.

The presence of refraction such that $\theta_r > \theta_s$ is immediately revealed when the large irregularities generate effects appropriate to regime I or the I-II boundary (focusing zone). Then we have systematic gradients in the dynamic spectra, or interference fringes within the random fluctuations caused by the small-scale irregularities [10]. Emsemble-averaged parameters naturally smear out the interference effects and this is where a more appropriate theory should be developed. Elementary considerations show that an approximate value of θ_r/θ_s is given by the number of fringes that appear in one coherence area $\Delta\nu\ \Delta t$ of the dynamic spectrum. A more detailed theory of combined refraction and diffraction effects has been given [11]. Examples of patterns that could occur are shown schematically in Figure 5. where the close resemblance to an observed dynamic spectrum is apparent.

Refractive intensity variations in regime I require less stringent coherence conditions than for diffraction in the far field and may be obtained when θ(source) $< \theta_r$. Slow (weeks-months) intensity variations of pulsars, once thought to be intrinsic to the source, are now recognised to be caused in this way [12]. Sufficient coherence might be obtained for compact sources outside the galaxy and there is evidence that some otherwise puzzling intensity variations may be similarly explained.

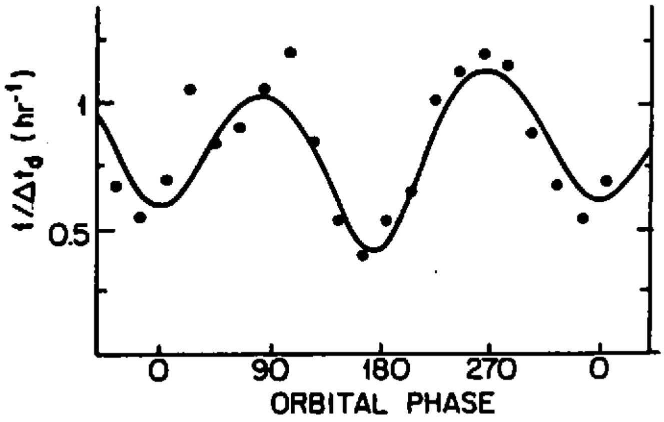

Figure 4. Periodic variations in the timescale of interstellar scintillation for a pulsar. This shows that the pulsar is in a binary orbit.

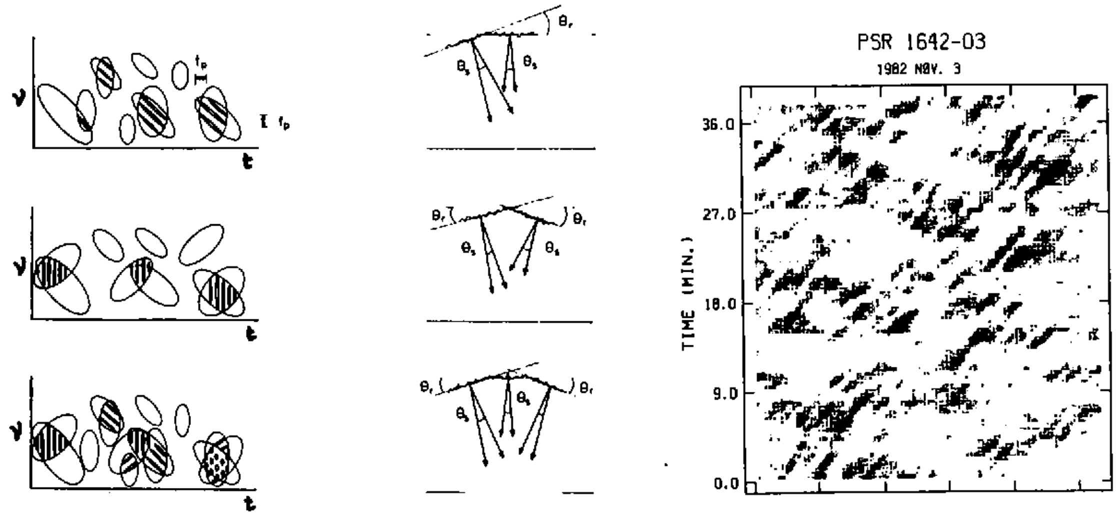

Figure 5. Schematic diagram of dynamic spectra expected for a medium containing both large and small irregularities. An observed dynamic spectrum is shown on the right.

The high angular resolving power of interstellar scintillation has also been utilised to obtain some information on the location of the emitting regions in the magnetosphere of the pulsar PSR 0525+21. This source emits a double-peaked pulse and each component exhibits identical fluctuations, from which it may be deduced that the emitting zone must be within 10^3 km of the neutron star.

From the many examples outlined in this paper it is clear that scintillation provides a powerful technique for remote sensing and some of the methods used in astronomy may have applications to other disciplines when propagation through inhomogeneous media is involved.

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