Pulsar Scintillation as a Physical Tool

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Pulsar scintillation as a physical tool

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The interstellar gas contains irregularities of electron density having a wide range of physical scales. Pulsar radiation propagating through this inhomogeneous medium suffers a random modulation of phase which causes the received intensity to scintillate on a variety of timescales. Observations of the radio frequency spectrum and temporal variation of scintillation give information on the form of the irregularity spectrum and the distribution of density structure across the Galaxy. The high spatial coherence of pulsar radiation leads to the formation of extremely fine-scale diffraction patterns which also provide information on the motion of sources across the line of sight and the size of pulsar emission regions. Some uses of scintillation as a means of probing the interstellar gas and elucidating the physical properties of pulsars will be discussed.

1. Introduction

The line of sight to a pulsar traverses three distinct plasma regions: the ionosphere and magnetosphere, the solar wind and the interstellar medium. Random variations of electron density in these media generate fluctuations of refractive index which scatter incoming radio waves, causing distant sources to scintillate. While scintillation due to the ionosphere and the solar wind may sometimes be confused, especially at lower radio frequencies, that due to the interstellar plasma is readily distinguished by its longer timescale and the much smaller radio bandwidth over which intensity fluctuations are correlated. It was Scheuer (1968) who pointed out that the intensity variations exhibited by the first pulsars on timescales of a few minutes to one hour, depending upon the radio frequency, were consistent with interstellar scintillation. Since then scintillation has been used to study variations of electron density in the interstellar gas over a wide range of physical scales and also to model the distribution of turbulence within the Galaxy.

In addition, because the transverse motion of pulsars across the line of sight is normally faster than bulk flows within the interstellar gas or the velocity of the Earth, the timescale of scintillation provides an estimate of pulsar speeds. When combined with estimates of the distances that pulsars have travelled from their birthplace in the galactic plane this gives information on pulsar ages, and in two instances for pulsars in binary orbits knowledge of the transverse velocity component has enabled the inclination of the orbits to be obtained.

Another aspect of interstellar scintillation concerns its potential for studying the physical size of the pulsar source at much higher resolution than is possible with very long baseline interferometry. This is because of the high spatial coherence of pulsar

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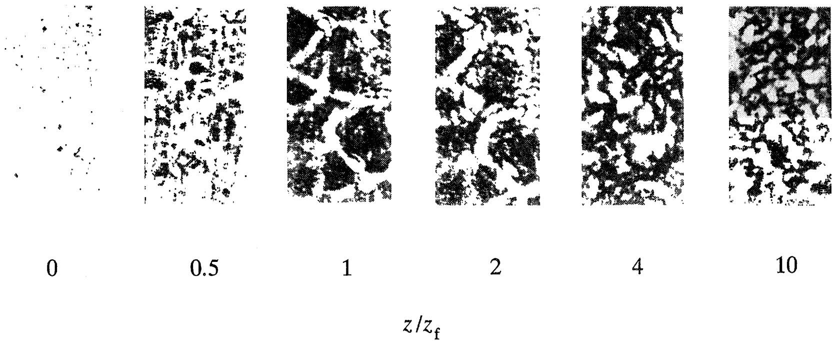


Figure 1. Fresnel diffraction patterns at increasing distances from a thin sheet producing irregular phase variations of about 3 rad on a scale of approximately 0.4 mm.

radiation which allows interference to be observed in wavefronts that have been scattered or refracted from regions separated by up to $\approx 10^8$ km transverse to the line of sight thus providing, in effect, an interferometer baseline of the same magnitude.

A very simple example of the kind of diffraction and refraction phenomena produced by an irregular transparent medium, in this case a thin layer containing irregularities having a roughly constant physical scale $a \approx 0.4$ mm and producing a root mean square phase modulation $\Delta\phi \approx 3$ rad, is illustrated by the optical simulation shown in figure 1. Plane wave illumination was provided by a He–Ne gas laser and the intensity across the wavefront was sampled at different distances z from the layer.

As z increases the pure phase modulation imposed by the layer causes intensity variations ΔI which build up steadily for $z < a^2/\lambda\Delta\phi$, where λ is the wavelength, and then saturate at a level $\Delta I/I \approx 1$ for $z > a^2/\lambda\Delta\phi$. Refractive focusing by individual features in the layer is evident at $z_{\mathrm{f}} \approx a^2/\lambda\Delta\phi$, while at larger distances the interference of waves scattered from several irregularities produces a random diffraction pattern consisting of 'speckles' having a characteristic scale $\approx \lambda/\theta_{\mathrm{S}}$, where θ_{S} is the average angle of scattering. At distances $z > z_{\mathrm{f}}$ the diffraction pattern is formed by waves from a scattering disc, of radius $\approx z\theta_{\mathrm{S}}$ at the layer, which contains about $(z\theta_{\mathrm{S}}/a)^2$ irregularities. The speckle pattern remains statistically similar for $z > z_{\mathrm{f}}$ but becomes decorrelated over successive intervals $\Delta z \approx z_{\mathrm{f}}$.

Inhomogeneous media such as the interstellar gas generally contain irregularities having a wide range of scales. These may be characterized by the power spectrum $g(k)$ in wavenumber so that the mean square variation of electron density N is $\langle \Delta N^2 \rangle = \int g(k)\,\mathrm{d}k$. For spatially homogeneous irregularities, such as simple turbulence, it is useful to consider a power law spectrum $g(k) \propto k^{-\alpha}$; for Kolmogorov turbulence $\alpha = \frac{11}{3}$. A physical picture of the irregularities may be obtained by considering clouds having some scale $a(k) = 2\pi/k$, where k is averaged over some constant logarithmic internal $\Delta(\ln k)$ of, say, one octave. Then if space is uniformly filled with clouds of any scale, so that the number per unit volume is proportional to a^{-3}, it is readily shown that the density variation ΔN in clouds of scale a is $\langle \Delta N^2(a) \rangle \propto a^{\alpha-3}$. For Kolmogorov turbulence we thus have $\langle \Delta N^2(a) \rangle \propto a^{\frac{2}{3}}$.

The combined effects of refraction and diffraction by an extended region containing irregularities having a range of scales is more complex than the simple example illustrated in figure 1 and has received considerable theoretical attention. For a

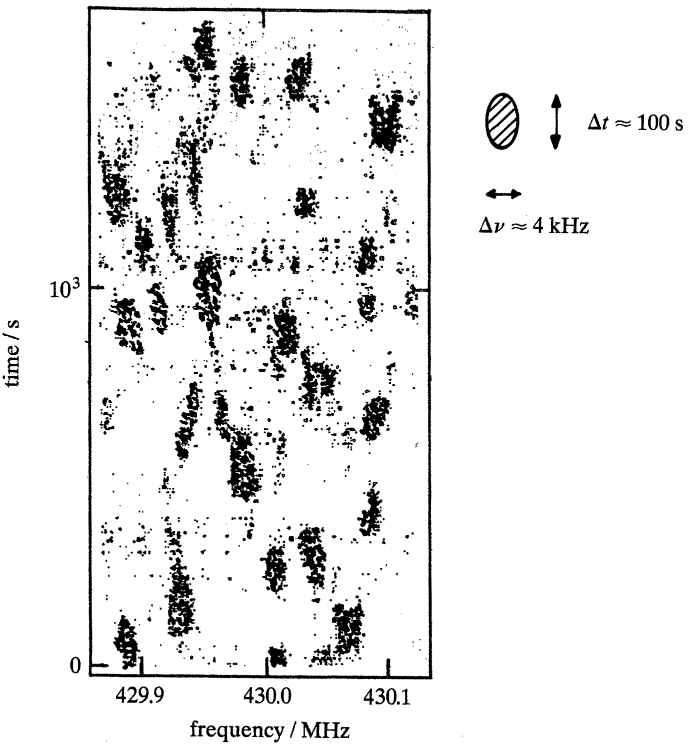


Figure 2. Dynamic spectrum of interstellar scintillation for the millisecond pulsar PSR 1937+214 (from Cordes *et al.* 1990).

review see Rickett (1990). The rich variety of scintillation phenomena displayed by pulsars has provided a fruitful source of new information on both their physical properties and the irregular structure of the interstellar gas.

2. Irregularities in the interstellar medium

(*a*) *Dynamic spectra of pulsar scintillation*

The general nature of pulsar scintillation is well illustrated by dynamic spectra in which the fluctuating intensity is plotted as a function of frequency and time as shown for PSR 1937+214 in figure 2. The characteristic scale of the pattern observed at 430 MHz is $\Delta\nu \approx 4$ kHz and $\Delta t \approx 100$ s (Cordes *et al.* 1990). The timescale is set by the relative motion of the speckle pattern past the Earth. Assuming that the pulsar has a typical speed of 50 km s^{-1} transverse to the line of sight (somewhat faster than the orbital velocity of the Earth) leads to a scale of about 5×10^3 km for the speckle pattern. This is comparable to the size of the Earth so that fluctuations observed at widely separated sites on the globe should exhibit significant spatial decorrelation, which has been confirmed (Rickett & Laing 1973).

(*b*) *The spectrum of electron density inhomogeneities*

The way in which the scales $\Delta\nu$ and Δt vary with radio frequency depends upon the structure of the irregularities. For a simple model in which the scattering medium is assumed to be a thin screen midway between the source and the observer we have

$\Delta\nu \approx c/z\theta_S^2$, where z is the distance to the layer and θ_S the average angle through which radiation is scattered, and $\Delta t \approx \lambda/\theta_S V$ where V is the relative drift speed of the speckle pattern. The thin screen model has been shown to be a reasonably good approximation to an extended medium for most purposes. For pulsars at large distances $\Delta\nu$ can be so small that it is hard to measure. In such cases $\Delta\nu$ may be deduced from the temporal broadening of pulses caused by pulse-smearing over a time δt, where $\delta t\,\Delta\nu \sim 1$.

For electron density fluctuations characterized by a single scale we have $\Delta\nu \propto \nu^4$ while for a range of scales having a Kolmogorov spectrum the relation is $\Delta\nu \propto \nu^{4.4}$. Observations over a range of frequencies yield a scaling index of 4.45 ± 0.15 in good agreement with the Kolmogorov model (Cordes *et al.* 1985). The steeper index, as compared with a single scale model, is due to dispersion in the medium which increases the scattering power of the smaller clouds at lower frequencies. For effective scattering the integrated phase modulation $\Delta\phi$ produced by clouds of any scale must satisfy the condition $\Delta\phi > 1$ rad (Hewish 1951). Since $\Delta\phi \propto an^{\frac{1}{2}}\nu^{-1}$, where n is the number of clouds along the line of sight, it follows that the overall contribution to θ_S extends to smaller values of a as ν decreases.

It is well known that the spatial scale l of the speckle pattern, given by $l \sim \lambda/\theta_S$, cannot in general be related to the scale of the irregularities in the medium without further information about $\Delta\phi$ (Hewish 1951). In the special case $\Delta\phi \lesssim 1$ there is a one-to-one correspondence and this can be applied to interstellar scintillation for a few of the nearest pulsars. The condition $\Delta\phi < 1$ corresponds to weak scattering in which only a fraction of the incident wave energy contributes to the speckle pattern. It is denoted both by the constancy of Δt with respect to ν and by reduced intensity variations as $\Delta I \propto \nu^{-1}$. Putting $\Delta t \approx l/V$ in these cases then yields a scale size for the clouds of $\approx 10^5$ km (Downs & Reichly 1971).

Ionized regions of the interstellar gas occur in warm plasma ($\approx 10^4$ K) associated with molecular clouds and sites of star formation, and also in hotter zones ($\approx 10^6$ K) which are more diffuse and widespread and which are probably heated by blast waves from supernovae or stellar winds. It is hardly to be expected that the irregularities of density in such a complex medium should be described by a single Kolmogorov spectrum over too wide a range of scales. For the Kolmogorov model it is readily shown that the magnitude of phase gradients imposed by the medium is weighted slightly towards the smallest scales (Hewish *et al.* 1985), so that the observed variation of $\Delta\nu$ with ν supporting this model is related mostly to scales near 10^5 km. Evidence on the larger scales can be drawn from refractive phenomena which are manifested in a variety of ways.

One characteristic feature which can be seen in many dynamic spectra is a slanting pattern, as exemplified in figure 3. This indicates the presence of large-scale phase gradients which persists for several days producing angular tilts θ_r across the wavefront and shifting the speckle pattern transversely to the line of sight. Dispersion in the medium causes the systematic displacements to vary inversely with frequency resulting in slants of magnitude $\mathrm{d}\nu/\mathrm{d}t \approx V\nu/z\theta_r$ where V is the component of drift speed of the pattern parallel to the displacement (Hewish 1980). This effect can be used to estimate the angle of refraction θ_r caused by large-scale irregularities for which the observer is well inside the focal distance $z \approx a/\theta_r$.

The comparison of θ_r, and θ_S (obtained from $\Delta\nu$), provides a test of the Kolmogorov model which predicts $\theta_r < \theta_S$. The limiting case $\theta_r \approx \theta_S$ occurs when the power law index $\alpha = 4$. Some observations of slanted dynamic spectra on timescales

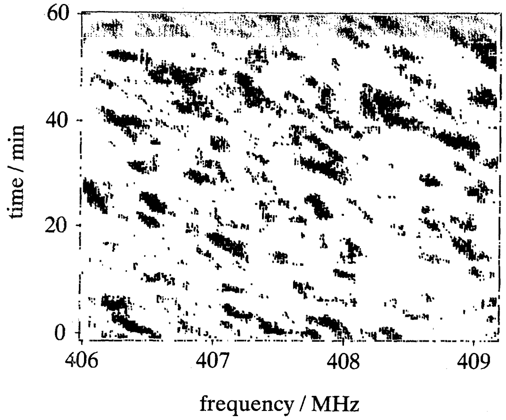


Figure 3. Dynamic spectrum of PSR 1642-03 showing a typical slanting pattern (from Rickett 1990).

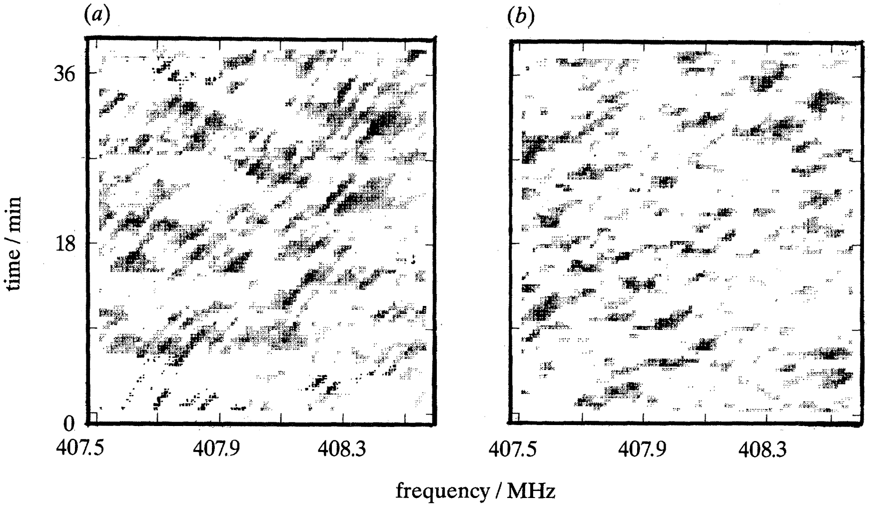


Figure 4. Quasi-periodic structure in the dynamic spectrum of PSR 1642-03 (from Hewish *et al.* 1985).

of several days, corresponding to scales *ca.* 10^7 km, do indicate $\theta_r > \theta_S$ (Hewish 1980) although other data (Smith & Wright 1985) are consistent with a Kolmogorov spectrum.

Another interesting feature of dynamic spectra is the occurrence of quasi-periodic bands as illustrated in figure 4. Periodicities denote interference between superposed tilted wavefronts which could occur beyond the focal distance of large-scale irregularities. Since smaller irregularities are always present, the resultant speckle pattern in this case is due to the superposition of two or more individual speckle patterns, each having its own systematic phase gradient on a scale much larger than that of the speckles. If the characteristic timescale and bandwidth of interference bands in dynamic spectra are Δt_i and $\Delta \nu_i$ it has been shown by Hewish *et al.* (1985) that $\theta_r/\theta_S \approx \Delta t/\Delta t_i \approx (\Delta\nu/\Delta\nu_i)^{\frac{1}{2}}$. A simple count of the number of interference bands within each 'speckle' therefore gives a measure of θ_r/θ_S. Note that the interference bands are expected to maintain constant phase only across one speckle.

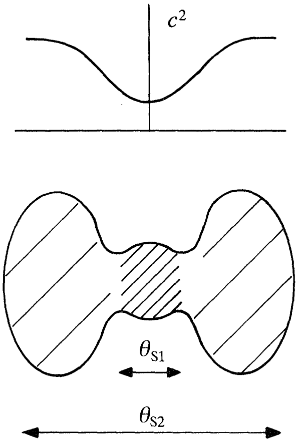


Figure 5. Schematic diagram showing how variations in the strength of scattering transverse to the line of sight can lead to a complex scattered image of enhanced intensity.

Observed dynamic spectra for a sample of 30 pulsars show that quasi-periodic bands indicating $\theta_r > \theta_S$ are not uncommon, although good determinations of the timescales over which they occur are not yet available (Cordes & Wolszczan 1986). Clearly a simple Kolmogorov spectrum is but a first approximation to the irregularity spectrum and there is evidence for greater density variations at scales exceeding 10^7 km along many lines of sight.

Further information on the largest scales can be obtained from the level of intensity modulation which remains when the small-scale speckle pattern has been averaged out, for example by observing with a bandwidth considerably larger than $\Delta\nu$. It has been found that the residual modulation, which has a level of typically 10–40% of the mean intensity, has a timescale which increases from a few days for the nearest pulsars to more than 100 days for more distant sources. This is consistent with refractive focusing caused by the larger irregularities. To focus effectively the irregularity scale must exceed the diameter of the scattering disc $\approx z\theta_S$, which increases as $z^{1.6}$ for a Kolmogorov spectrum. The rather long timescale demands extended observations for accurate measurements but systematic studies for over one year are in fairly good agreement with theory regarding the timescale and the magnitude of the intensity variations (Kaspi & Stinebring 1992). In some cases the intensity modulation is greater than that predicted for a Kolmogorov spectrum providing further evidence that some large-scale irregularities have higher than predicted densities. It should be noted, however, that truncation of a Kolmogorov spectrum at an inner scale $\approx 10^6$ km can lead to enhanced scintillation (Coles *et al.* 1987).

Long-term intensity modulation on a timescale which increases with z could also arise if the small-scale irregularities are not uniformly distributed perpendicular to the line of sight. If the degree of turbulence varies over distances comparable with $z\theta_S$, the roughly gaussian distribution of intensity across the scattering disc could be either truncated, or extended, leading to reduced or increased intensity respectively as shown schematically in figure 5. This mechanism does not require large-scale irregularities and has been proposed in connection with rare events observed on extragalactic sources by Fiedler *et al.* (1987) suggesting extremely large scattering.

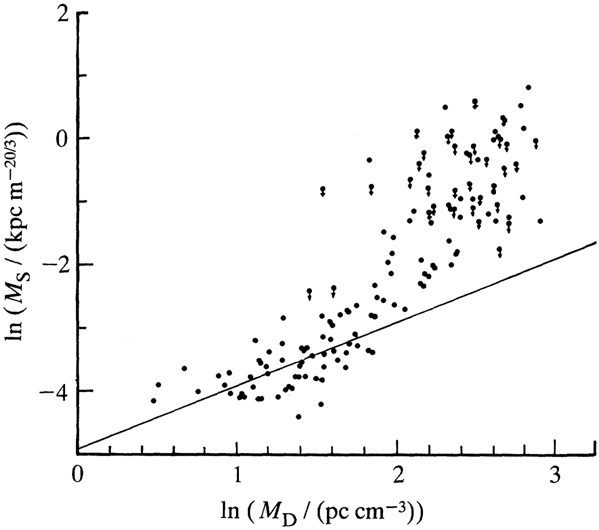


Figure 6. Values of scattering measure M_S plotted against dispersion measure M_D for a large sample of pulsars (from Cordes *et al.* 1991).

It seems more likely to occur when the scattering is dominated by some local region along the line of sight, rather than by the integrated effect of many irregularities distributed over a large range of distance.

(*c*) *The distribution of ionized gas within the Galaxy*

The existence of ionized gas far above the galactic plane is not well understood and little is known about its distribution in the inner region of the Galaxy. By combining evidence from pulsar scintillation with other data taken along many lines of sight it is possible to derive an overall model for both the distribution of mean plasma density and the degree of turbulence within it (Cordes *et al.* 1991). Adopting a Kolmogorov spectrum $g(k) = c^2 k^{-\frac{11}{3}}$ as a reasonable approximation, we may obtain values for the scattering measure

$$M_S = \int_0^D c^2 \, \mathrm{d}s,$$

and the dispersion measure

$$M_D = \int_0^D N \, \mathrm{d}s,$$

where ds is an element of path towards a pulsar at distance D. M_S is derived from the scintillation bandwidth $\Delta\nu$ while M_D is obtained from the differential arrival time of pulses at different frequencies. In a medium where c^2 and N are constant, then $M_S \propto M_D$ and this relation is obeyed for nearby pulsars. However, at large values of M_D, corresponding to greater distances, M_S increases far above the linear relationship as shown in figure 6. Hence the degree of turbulence c^2 must be far greater for the more distant pulsars which are seen mainly in directions towards the galactic centre.

Combining all the data on M_S and M_D, and including a number of pulsars whose distances have been estimated independently from parallax, *HI* absorption or association with other objects, Cordes *et al.* (1991) derived a model for the scattering material consisting of two discs, each characterized by a scale height H and radius R. In terms of distance r from the Galactic centre, and height h above the Galactic plane, the electron density in the discs was of the form

$$N(r, h) = N_0 \exp(-|h|/H) \exp[-(r/R_0)^2].$$

For the larger disc $H \approx 1$ kpc and $R_0 \approx 20$ kpc, and for the smaller inner disc $H \approx 0.1$ kpc and $R_0 \approx 4$ kpc. The turbulence specified by c^2 was about 10^3 times stronger in the inner disc and this region also contained some localized clouds where the turbulence was several orders of magnitude greater.

3. Velocity measurements

The relations $\Delta\nu \approx c/z\theta_s^2$ and $\Delta t \approx \lambda/\theta_s V$ (see §2*a*) for the speckle pattern allow V to be estimated, provided that the speckle pattern does not change significantly due to temporal rearrangement of turbulence along the line of sight in a time Δt. While V, in general, depends upon the combined motion of the Earth, the medium and the pulsar, it has been found that it is the transverse velocity of the source that normally dominates. In a study of 20 pulsars whose transverse velocity was obtained independently from measurements of proper motion, Lyne & Smith (1982) found a reasonable correlation between the two velocity estimates, although the scintillation velocity was usually lower.

An interesting application of this technique by Lyne (1984) was a study of the binary pulsar PSR 0655+64. Pulse timing gave an accurate value of 87.5 km s^{-1} for the orbital velocity component along the line of sight so that the full orbital velocity was $(87.5/\sin i)$ km s^{-1}, where i is the angle at which the orbit is inclined to the plane of the sky. The transverse velocity obtained from scintillation was strongly modulated at one half the orbital period of 24.7 h (see figure 7) from which it was possible to solve for both the inclination and an assumed steady motion of the binary system transverse to the line of sight. A residual ambiguity between the two solutions $i = 62°$ or $84°$ could have been resolved by further observations at a different time of year, making use of the known orbital velocity of the Earth. Similar observations on another binary pulsar were made by Dewey *et al.* (1988). The importance of these observations is that they allow a more accurate determination of the mass of the pulsar companion through the mass function of the binary system.

4. Scintillation and source size

On the thin screen model of the interstellar medium two independent sources at the same distance, but slightly displaced transverse to the line of sight, will produce identical speckle patterns correspondingly displaced in the opposite sense. When the displacements are significant in relation to the scale of the pattern, simultaneous observations of dynamic spectra will begin to exhibit decorrelation. For a pattern with a typical scale of 10^5 km a displacement of $\approx 10^3$ km might be just detectable. This is smaller than the radius of most pulsar magnetospheres and raises the possibility of gaining information on the physical size of emission regions.

The scale of the speckle pattern is $\approx \lambda/\theta_s$, or the smaller value $\approx \lambda/\theta_r$ when interference bands are evident in dynamic spectra. It follows that the latter occasions offer the best hope of resolving the source. Wolszczan & Cordes (1987) observed remarkable interference effects for PSR 1237+25 lasting for a few days and used

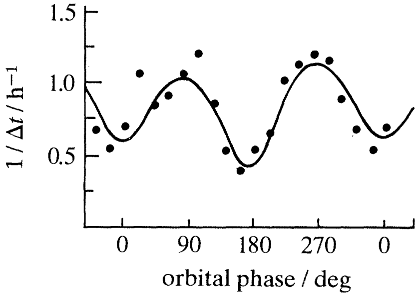


Figure 7. Periodic variation in the rate of scintillation for the binary pulsar PSR 0655+64 (from Lyne 1984).

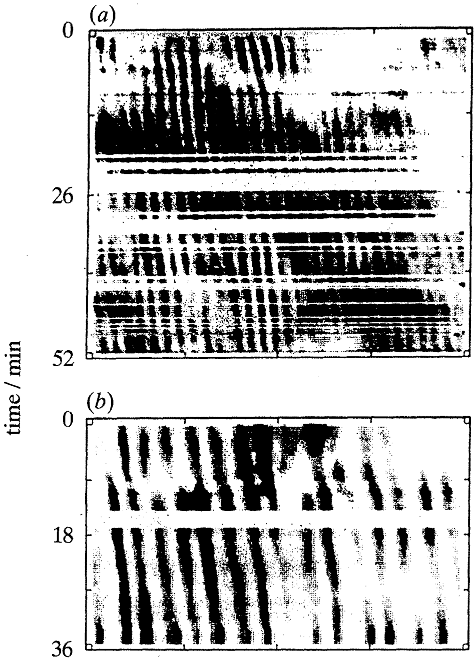


Figure 8. Dynamic spectra for PSR 1237+25 showing pronounced interference bands (from Wolszczan & Cordes 1987). (*a*) 9 December 1986; (*b*) 22 December 1986.

them for this purpose. Dynamic spectra observed at 430 MHz in December 1986 are shown in figure 8. The relative phase of the fringes was compared at several points across the pulse, corresponding to longitudes separated by 2.8° over a range of 19° in the rotating magnetosphere, and a significant phase difference of about 0.4 rad between the leading and trailing edges of the pulse was obtained. This corresponds to a transverse displacement of $\approx 10^3$ km at the source.

The interpretation of this result is problematic. If radiation is beamed along the magnetic field in accordance with the polar cap emission theory, and if a simple dipole magnetic field is assumed, an emission region extending for $\approx 10^3$ km would be obtained only near the velocity of light cylinder, which occurs at a radial distance of about 10^5 km for this pulsar. Unfortunately this is contrary to other evidence from pulse shapes and polarization which suggests that the emission zone is located well inside the radius of the velocity of light cylinder.

It may, of course, be incorrect to assume that the large-scale phase gradients required to explain the dynamic spectrum are imposed roughly midway between the source and the observer. If the large-scale irregularities responsible were located much nearer the pulsar the separation of emitting regions necessary to explain the observed decorrelation would be reduced. Alternatively the dipole assumption for the magnetic field may be incorrect. In either case it is evident that the extremely high spatial resolving power provided by interstellar scintillation is beginning to yield important information on the size of pulsar emission zones. Earlier observations by Cordes *et al*. (1983) on PSR 0525+21 and PSR 1133+16, using dynamic spectra not dominated by refractive interference, showed no decorrelation across the pulse, thus providing upper limits of *ca*. 10^3 km for the source size in these cases.

References

Coles, W. A., Frelich, R. G., Rickett, B. J. & Codona, J. L. 1987 Refractive scintillation in the interstellar medium. *Astrophys. J.* **315**, 666–674.

Cordes, J. M., Weisberg, J. M. & Boriakoff, V. 1985 Small scale density turbulence in the interstellar medium. *Astrophys. J.* **288**, 221–247.

Cordes, J. M. & Wolszczan, A. 1986 Multiple imaging of pulsars by refraction in the interstellar medium. *Astrophys. J. Lett.* **307**, L27–L31.

Cordes, J. M., Wolszczan, A., Dewey, R. J., Blaskiewicz, M. & Stinebring, D. R. 1990 Timing and scintillations of the millisecond pulsar PSR 1937+214. *Astrophys. J.* **349**, 245–261.

Cordes, J. M., Weisberg, J. M., Frail, D. M., Spangler, S. R. & Ryan, M. R. 1991 The galactic distribution of free electrons. *Nature, Lond.* **354**, 121–125.

Dewey, R. J., Cordes, J. M., Wolszczan, A. & Weisberg, J. M. 1988 Inclination of the orbit of the binary pulsar PSR 1855+09. In *Radio wave scattering in the interstellar medium* (ed. J. M. Cordes, B. J. Rickett & D. C. Backer), pp. 217–221. UC San Diego.

Downs, G. S. & Reichly, P. E. 1971 Observations of interstellar scintillation of pulsar signals at 2388 MHz. *Astrophys. J. Lett.* **163**, L11–L16.

Hewish, A. 1951 The diffraction of radio waves in passing through a phase changing ionosphere. *Proc. R. Soc. Lond.* A **209**, 81–96.

Hewish, A. 1980 Frequency-time structure of pulsar scintillation. *Mon. Not. R. astr. Soc.* **192**, 799–804.

Hewish, A., Wolszczan, A. & Graham, D. A. 1985 Quasi-periodic scintillation patterns of the pulsars PSR 1133+16 and PSR 1642-03. *Mon. Not. R. astr. Soc.* **213**, 167–179.

Kaspi, V. M. & Stinebring, D. R. 1992 Long term pulsar flux monitoring and refractive interstellar scintillation. *Astrophys. J.* (In the press.)

Lyne, A. G. & Smith, F. G. 1982 Interstellar scintillation and pulsar velocities. *Nature, Lond.* **298**, 825–827.

Lyne, A. G. 1984 Orbital inclination and mass of the binary pulsar PSR 0655+64. *Nature, Lond.* **310**, 300–302.

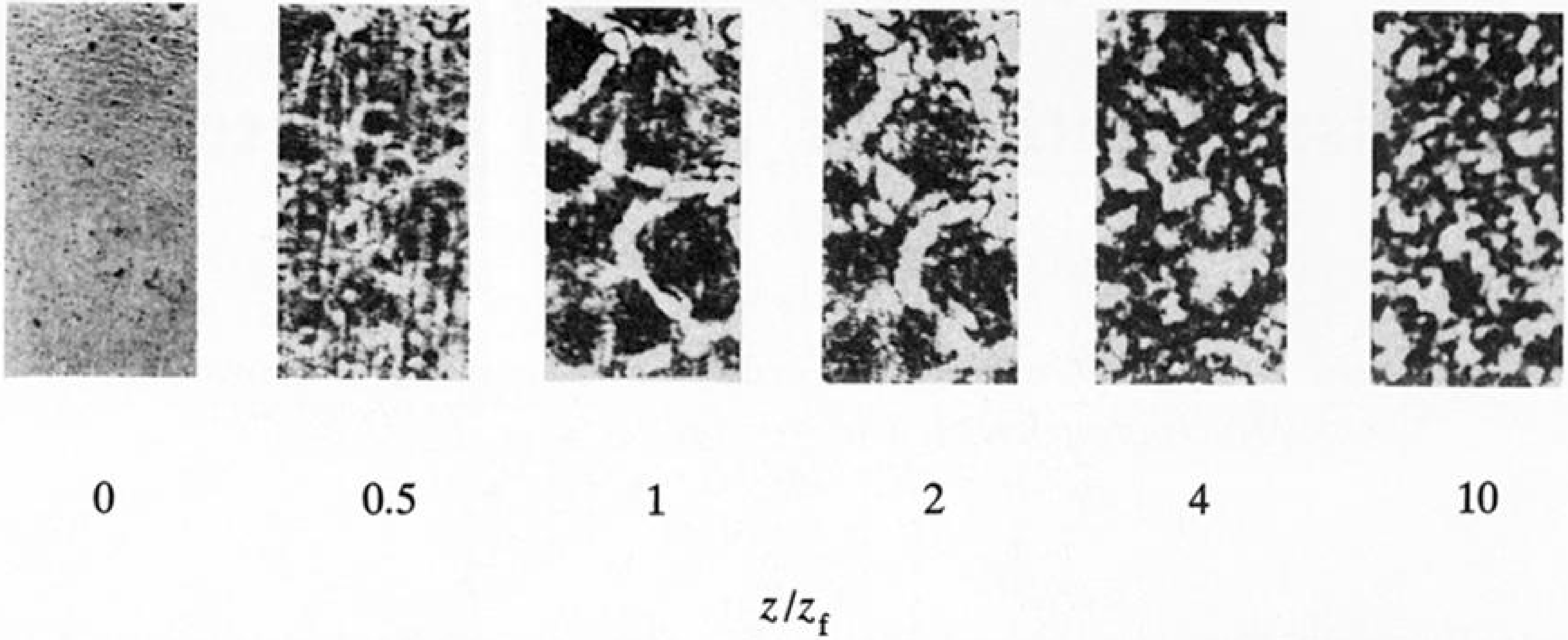
Rickett, B. J. & Lang, K. R. 1973 Two-station observations of the interstellar scintillation from pulsars. *Astrophys. J.* **185**, 945–950.

Rickett, B. J. 1990 Radio propagation through the turbulent interstellar plasma. *A. Rev. Astr. Astrophys.* **28**, 561–605.

Scheuer, P. A. G. 1968 Amplitude variations in pulsed radio sources. *Nature, Lond.* **218**, 920–922.

Smith, F. G. & Wright, W. C. 1985 Frequency drift in pulsar scintillation. *Mon. Not. R. astr. Soc.* **214**, 97–107.

Wolszczan, A. & Cordes, J. M. 1987 Interstellar interferometry of the pulsar 1237+25. *Astrophys. J. Lett.* **320**, L35–L39.



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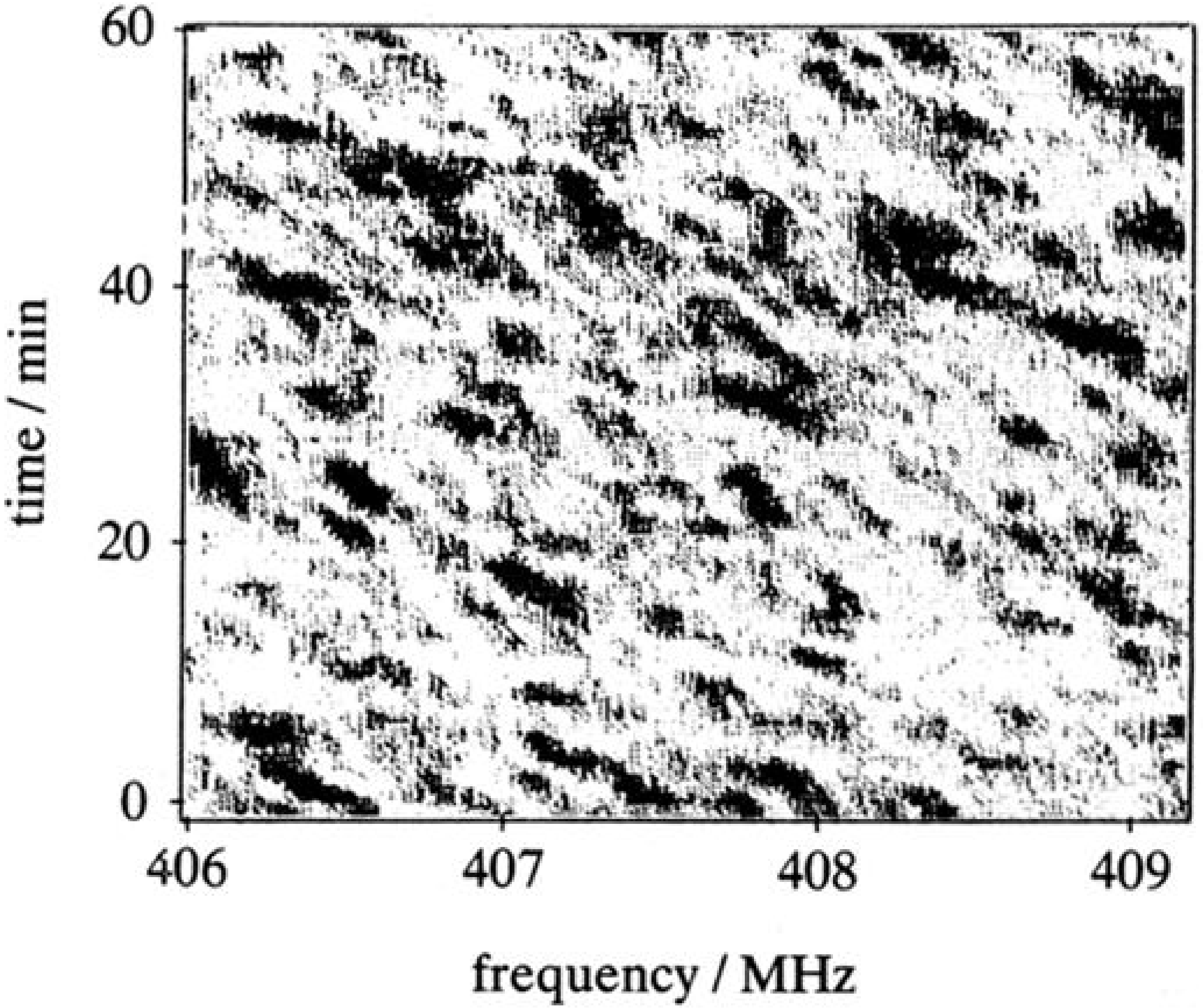

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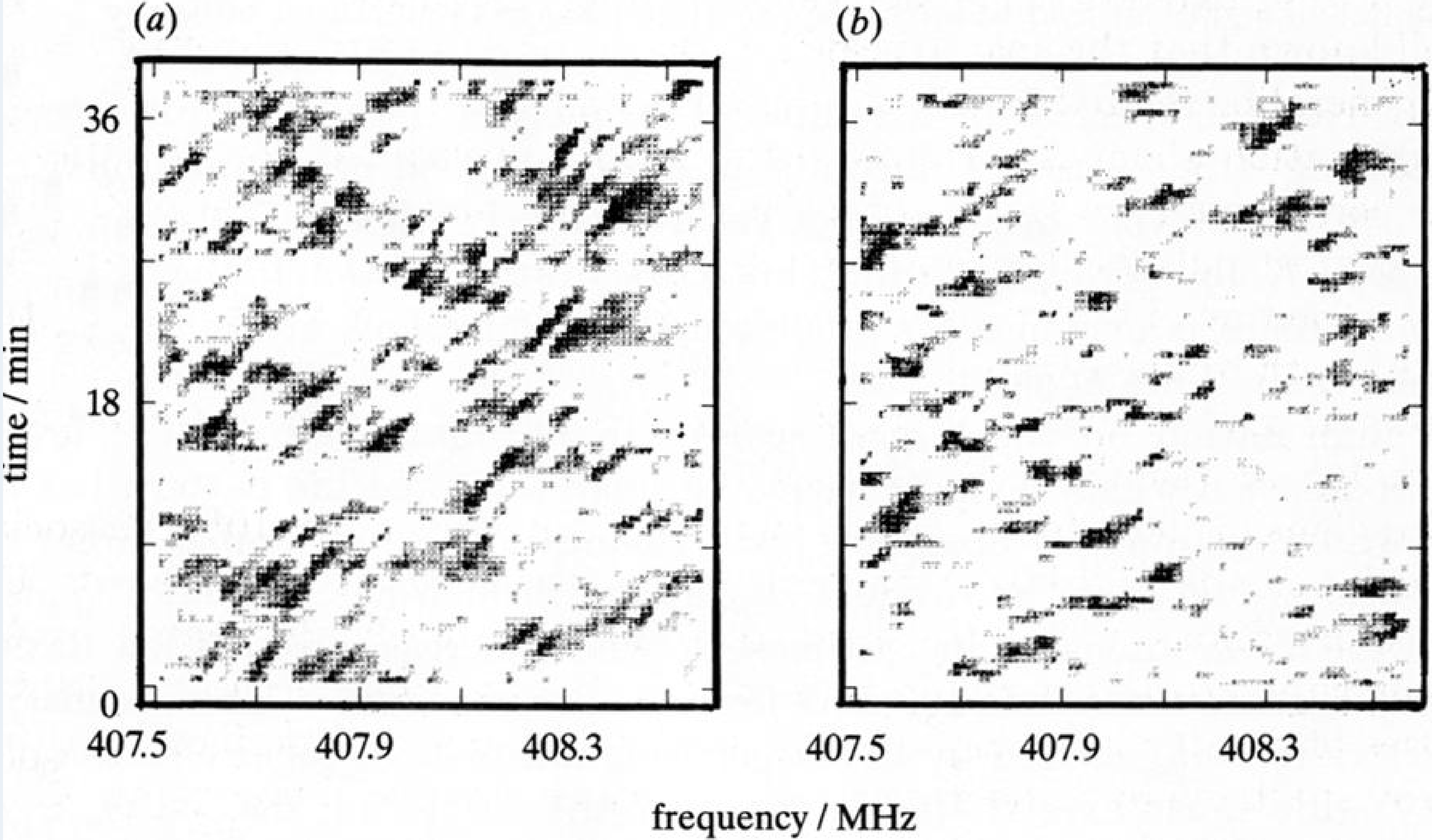
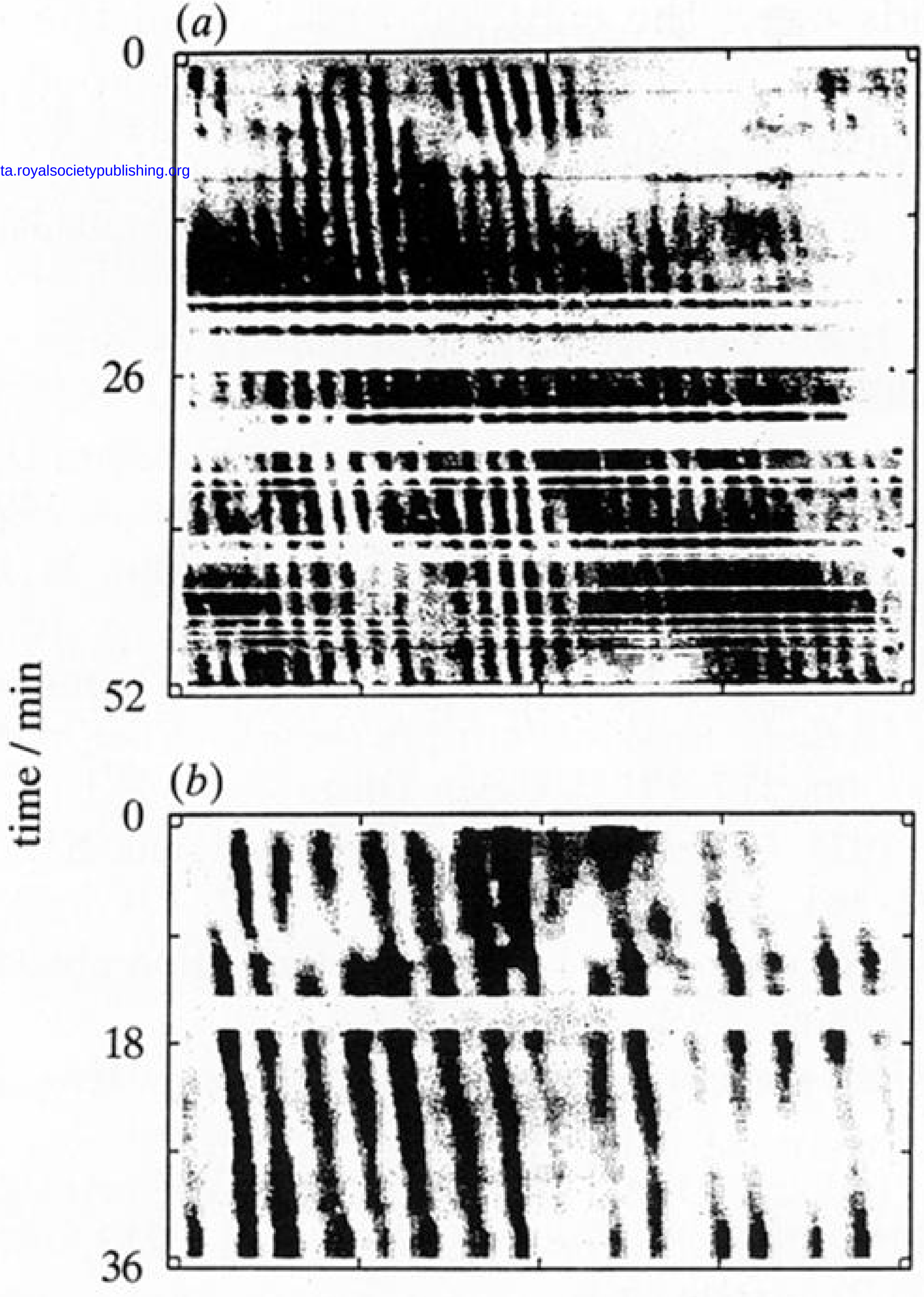


Figure 4. Quasi-periodic structure in the dynamic spectrum of PSR 1642-03 (from Hewish *et al.* 1985).



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