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Microstructure: A Review

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Abstract. Pulsar radio intensities contain a rich range of timescale variations ranging from months down to nanoseconds. The shortest of these fluctuations have been called *microstructure*. The observational properties of microstructure and the astrophysical value of microstructure are discussed.

1. Introduction

Among the first Arecibo pulsar observations, Craft *et al.* (1968) found that one of the original Cambridge pulsars, B0950+08, exhibited rapid intensity fluctuations with a time scale of about $200\,\mu s$ at 430 MHz. Shortly thereafter Ekers & Moffett (1968) observed similar intensity variations in B1133+33. These measurements set the stage for a continuing series of observations with higher and higher time resolution. The rapid intensity fluctuations have come to be known as *microstructure*. In this review I discuss the time resolution limits for microstructure observations, I review the history of unresolved microstructure, quasi-periodic microstructure, and its bandwidth. Then I review the only signal model that has thus far been developed, the Amplitude Modulated Noise (AMN) model, the shot-noise variation of this model, and its experimental verification. I then summarize the theoretical developments for the origin of microstructure and new simulations of the emission mechanisms. Throughout the review I mention what astrophysics we can learn from microstructure.

2. Limits to time resolution

There are several phenomena which limit the time resolution to which pulsar radio signals can be measured. We nearly always use a form of radiometer whose square-law detected output is proportional to the power of the received electric field. Since the pulsar signal is contaminated by receiver and sky noise, we try to use wide receiver bandwidths, $\Delta\nu$, and temporally smooth the output after square-law detection by $\Delta t_{\rm I}$ to improve the signal-to-noise ratio (S/N) as expressed by the radiometer equation, $T/\sigma_T = (\Delta\nu\,\Delta t_{\rm I})^{1/2}$, where T is the mean detector output power (expressed as a temperature) averaged over $\Delta t_{\rm I}$, and σ_T is its uncertainty. For the highest time resolution pulsar studies, we naturally assume that the post-detection smoothing time $\Delta t_{\rm I}$ is set to the minimum practical value.

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The received signals can vary no faster than the receiver rise-time, which we can assume is the reciprocal of the receiver bandwidth, $t_{\Delta\nu} = 1/\Delta\nu$. Dispersive propagation through the interstellar medium (ISM) smears the radio signals across $\Delta\nu$ by $t_{\rm DM} = \Delta\nu\,({\rm DM})/(1.205\times 10^{-16}\nu_0^3)$ seconds, where ν_0 is the receiver center frequency and DM is the dispersion measure in pc cm^{-3}. One can optimize the time resolution by adjusting $\Delta\nu$ so that $t_{\Delta\nu} = t_{\rm DM}$. Since minimizing $\Delta\nu$ to optimize time resolution is incompatible with maximizing $\Delta\nu$ to improve S/N, filter banks were used to split the receiver passband into many parts which are separately detected, smoothed, appropriately delayed to compensate for dispersion delay, then added to improve S/N, while maintaining the higher time resolution afforded by narrower $\Delta\nu$. But to cover the range of DM and ν over which pulsars are studied, requires at least 3 orders of magnitude range of filter bandwidths, clearly impractical to construct.

Interstellar scattering of pulsar signals by ISM electron density fluctuations further limits the attainable time resolution because of multipath propagation. Cordes (1994) has found an empirical relationship for the interstellar scattering broadening time,

$$\log t_{\rm ISS} = -6.8 + 0.65\log({\rm DM}) + 0.83(\log({\rm DM}))^2 - 4.4\nu_{\rm GHz}, \qquad (1)$$

where $\nu_{\rm GHz}$ is the receiver center frequency in GHz. For high dispersion pulsars, then one must observe at high frequencies to obtain high time resolution. For example, to keep $t_{\rm ISS} < 0.5\,\mu$s, at frequencies of 330, 430, or 1400 MHz, one must observe pulsars with DM < 9, 15, and 75 pc cm^{-3}, respectively.

Interstellar dispersion is a linear process, and its effects can be removed by passing the undetected received signal through a filter whose transfer function is the inverse of that of the ISM (Hankins 1971, 1974, Hankins & Rajkowski 1987). Using this technique I found unresolved structure in the 111.5 MHz signals from B0950+08 with a time resolution of $8\,\mu$s (Hankins 1972). In the same study I found that microstructure occurred in at least three forms; amorphous noisy bursts of several milliseconds duration; short, low-duty cycle random bursts between which the intensity returned abruptly to zero, and quasi-periodic bursts of a few to ~20 micropulses.

As technology improved, so did the observer's time resolution. Using a system with $0.8\,\mu$s resolution Hankins & Boriakoff (1978) found unresolved submicrosecond pulses whose peak flux exceeded 1000 Jy from the main pulse (MP) of B0950+08 and weaker microstructure from this pulsar's interpulse (IP). The statistics of the microstructure of the MP and IP, as characterized by the microstructure autocorrelation function scale size, τ_μ (see section 3.), are similar, indicating that the emission mechanism and conditions for the MP and IP must be similar (Hankins & Boriakoff 1981).

Recently Dave Moffett and I (1996) have made observations of the 'giant' pulses from the Crab pulsar at 4.8 GHz which show unresolved structure with 10 ns time resolution and peak fluxes over 10^4 Jy, (figure 1). If one makes the conventional interpretation that the size of the emitting region cannot be any larger than the distance light can travel in the emitted pulse duration, then the emitting entity can be no larger than about 3 m in extent, the smallest entity ever detected outside the Solar system. If radiating isotropically the equivalent brightness temperature for this 3-m source exceeds 10^{37} K; the emission mechanism must be coherent.

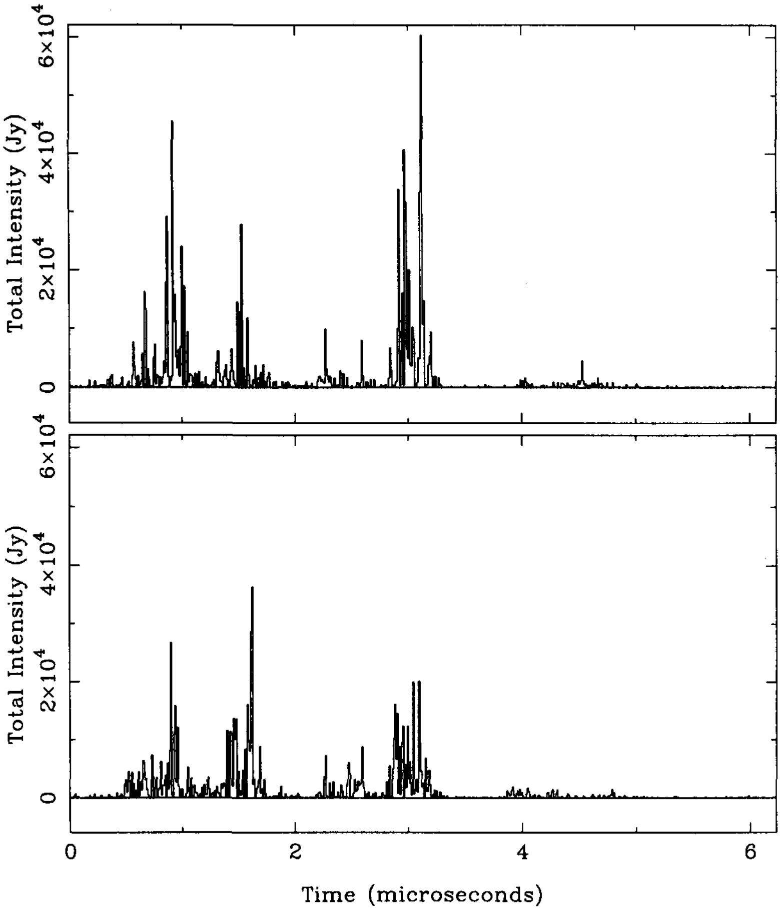

Figure 1. Right and left hand circular polarized intensities of a 'giant' pulse from the Crab pulsar are shown. The VLA observing frequency was 4.885 GHz, and bandwidth was 50 MHz. Dispersion smearing was removed using the coherent dedispersion method. The pulse is shown with 10 ns time resolution.

In figure 2 several 'giant' pulses from the Crab pulsar are shown. One sees here similar behaviour to B0950+08 at lower frequencies, but with much shorter time scales. There are quasi-periodic bursts, longer 'noisy' pulses, and occasionally very short intense spikes. It appears that the shortest pulses are the strongest ones, though this has not been formally tested.

Some of the Crab 'giant' pulses at cm wavelengths appear to be scattered; *e.g.*, they appear to have fast risetimes and slower exponential decays (FREDs). But the exponential time constant is much longer than predicted by using equation (1) to extrapolate the low-frequency measured ISS broadening up to 1.4, 5, and 8 GHz. This is interpreted as scattering in the pulsar magnetosphere, which

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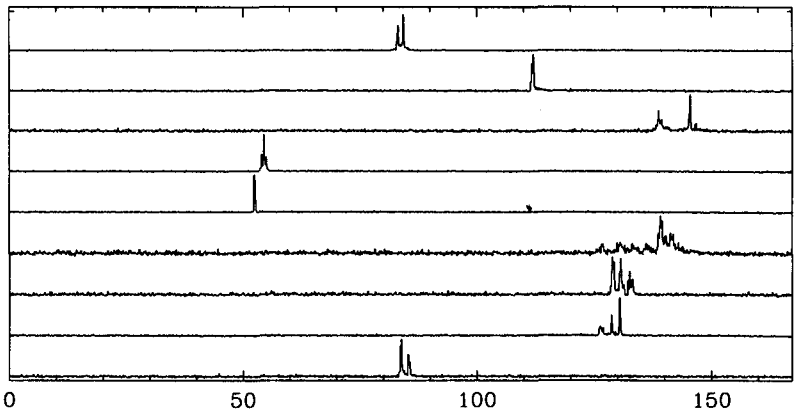

Figure 2. Several 'giant' pulses from the Crab are plotted with 160-ns time resolution. These are not consecutive periods, but rather those pulses which exceeded a certain threshold on the output of a conventional square-law detector. The pulses are aligned precisely with the average period of the pulsar, and their heights are all normalized to the same value. The time of arrival jitter is intrinsic to the pulsar.

shows a shallower frequency dependence of the time constant than for the ISM (Eilek, Hankins & Moffett 1996).

3. Signal model: The Amplitude Modulated Noise model

Rickett (1975) developed a model for the pulsar signal where the emitted electric field, $x(t) = a(t)n(t)$, where $a(t)$ is a slowly varying amplitude envelope modulation of a Gaussian noise process, $n(t)$. He showed that with the proper correction for receiver noise the autocorrelation function (ACF) of (unsmoothed) $x^2(t)$ should be an unresolved spike of width $1/\Delta\nu$ containing 1/2 the power at ACF lag $\tau = 0$, plus a wider function characteristic of the modulation function $a(t)$. Cordes (1976b) expanded this model by showing that $n(t)$ could be represented as the ensemble of a large number of nanosecond 'shot pulses' which are postulated to be the fundamental emitting entities. He also showed that one may only resolve individual shot pulses if dispersion, scattering and receiver time resolution limits are extremely small. Then only if there are only a small number of shot pulses in one's time resolution interval, may one see deviations from the modulation index predicted by the AMN model.

Calculations of pulsar signal ACFs have verified the AMN model (*e.g.*, Cordes 1976a) by showing that the zero-lag spike does contain 1/2 the ACF amplitude to within the estimation errors for a dozen pulsars at several frequencies. Data with a wide range of time resolutions from my original 7-μs observations (Hankins 1972) to my recent 10-ns Crab 'giant' pulse studies are consistent with the AMN model. We found what we call the microstructure feature in the ACF,

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a break-point in the ACF slope at ACF lag $\tau_\mu \approx 0.0005\,P$ for a typical pulsar. The ACF also shows the average subpulse width. There are, however, several pulsars (*e.g.*, B0525+25 and B1237+25) which show clear microstructure in individual periods, but whose ACF shows no microstructure feature. For three pulsars either there is no preferred value for τ_μ or the subpulse intensity is only weakly modulated by micropulses (Cordes *et al.* 1990). By computing ACFs of the Stokes' parameters, Cordes & Hankins (1977) found that micropulses tend to be more highly polarized than both the subpulses that contain them and the average pulse profiles. The polarization state tends to be constant across a micropulse, though for B1133+16 we found that there are frequent 90° position angle flips near the edges of micropulses and that these are often coincident with circular polarization sign changes; the orthogonal polarization modes are antipodal on the Poincaré sphere.

4. Quasiperiodic microstructure

A number of pulsars are strong enough to allow detailed studies of individual pulses. In my first microstructure paper (Hankins 1971) I reported that about 0.5% of the 111.5-MHz pulses from B0950+08 showed from 9 to 20 regularly spaced micropulses with periods of 300 to 700 μs. Backer (1973), Boriakoff (1976) and Cordes (1976a) have shown that B2016+28 has quasi-periodic microstructure with a dominant period of 0.9 ms, but ranging from 0.6 to 1.1 ms. In another detailed study Cordes *et al.* (1990) found three pulsars (B0809+77, B1944+17 and B2016+16) with drifting subpulses that show clear periodic microstructure. We also noted that the strength of microstructure in these objects decreases roughly as ν^{-3}. In general it appears that the pulsars with the richest microstructure are those with drifting subpulses or are otherwise classified as 'conal' objects by Rankin. We found that there is a tendency for pulsars with rich quasiperiodic microstructure to have smaller period derivatives than a similar set of pulsars for which no 430-MHz microstructure feature has been seen.

A number of hypotheses have been proposed to explain periodic microstructure, including oscillations of the ion to positron ratio in the emission region, neutron star vibrations, and interference effects associated with index of refraction gradients in the magnetosphere (Cordes *et al.* 1990, Strohmayer *et al.* 1992). For the first of these, the relevant emission region thermal parameters are so uncertain that the oscillation periods can not be predicted to several orders of magnitude. The excitation and damping times of neutron star oscillations are difficult to reconcile with the observations. The wide bandwidth of quasiperiodic microstructure and the frequency independence of its periods limits the explanations based on interference effects. to explain the wide bandwidth of quasiperiodicities. It is clear that a consistent explanation of quasiperiodic microstructure is yet forthcoming.

5. Bandwidth of microstructure

Microstructure, at least as characterized by its modulation index and the presence of the ACF breakpoint at τ_μ, is strongest at meter wavelengths, and for some of the few slow pulsars for which it has been measured, effectively disappears for $\nu > 1\,\mathrm{GHz}$ (Cordes 1976b, Cordes *et al.* 1990). However, Ferguson & Seiradakis (1978) found a number of examples of individual micropulses at 18 and 11 cm wavelengths, and the Crab 'giant' pulses have extremely short structure for $\lambda < 30\,\mathrm{cm}$.

An analysis of microstructure in the frequency domain (Cordes & Hankins 1979) has shown that the observed frequency structure of micropulses is fully consistent with the AMN model predictions. Within a narrow receiver passband micropulses appear to be strongly modulated (Rickett, Hankins & Cordes 1975, Smirnova 1988, Novikov & Soglasnov 1992), but microstructure is fundamentally a wideband phenomenon. Popov, Smirnova & Soglasnov (1987) suggested that for three pulsars two kinds of microstructure exist; 'small scale' which does not correlate over $\Delta\nu \approx 20\,\mathrm{MHz}$, and 'large scale', which does correlate well at different frequencies and whose delay follows the expected cold plasma dispersion of the ISM.

By crosscorrelating dedispersed signals recorded simultaneously at three frequencies from 67.5 to 102.55 MHz, Kardashev *et al.* (1982) found correlated microstructure. Rickett *et al.* (1975) also found that microstructure is correlated over the 3:1 frequency range, 318 to 111.5 MHz. The ACF microstructure feature appears in the crosscorrelation function (CCF) as well, but displaced by the amount expected from dispersion delay. Stinebring, Thorsett & Kaspi (1992) used this property to make precision dispersion measurements of B1133+16. They found that the dispersion measure of B1133+16 has fluctuated over about $0.005\,\mathrm{pc\text{-}cm^{-3}}$ with a 10-year time scale.

Boriakoff (1983) found similar CCF results for 196.5/318 MHz, and concluded that microstructure does not follow the emission radius-to-frequency pulse phase spreading that one sees in the frequency dependent average profiles, particularly in conal components. He confirmed this conclusion with a simultaneous observation of a single quasi-periodic pulse from B0950+08 in which the microstructure is highly correlated between 430 and 1406 MHz (Boriakoff, Ferguson & Slater 1981).

6. Theoretical developments

Virtually all of the plausible emission models are based on the standard model of a highly magnetized rotating neutron star whose magnetic moment is oriented obliquely to the rotation axis; a pair plasma ($e^+ - e^-$) is formed by a strong electric field above the magnetic polar cap; and collective behavior is required for coherent emission. There are several candidates for the emission mechanism, which could be classified as emission by bunches, plasma instabilities, or maser action (Melrose 1992). Each of these predict time signatures in the 10–1000 ns range (*e.g.* see Asseo, Pelletier & Sol 1990, Asseo 1993, 1994 and references therein). One of the most promising of these, plasma turbulence produced by growing modes in a two-stream instability with subsequent soliton collapse and escape of radio radiation is discussed by Weatherall in this volume. His preliminary numerical simulations mimic the nanosecond-resolution observations of the Crab giant pulses such as those in figures 1 and 2.

Observed microstructure has been characterized by ACF statistical tests, and by low-dimensional deterministic chaos (Zhuravlev & Popov 1992) but formal statistical comparisons of observations with numerical simulations have yet to be developed.

7. Conclusions

The ultra-high time resolutions measurements of microstructure and the numerical simulations of non-linear plasma processes that have recently been developed may provide us with a method of closing the loop on the question of the origin of microstructure.

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