Radio Emission Physics in the Crab Pulsar

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Summary for Impatient Readers

- We are carrying out ultra-high time resolution observations in order to understand the pulsar radio emission mechanism.

- We observed "giant" pulses from the Crab pulsar at the rotation phases of the main pulse and the interpulse.

- The main pulse consists of short-lived, relatively narrowband, nanoshots which are consistent with plasma emission from strong plasma turbulence.

- The interpulse is very different: its dynamic spectrum consists of emission bands which are proportionately spaced in frequency, from 6 to 10 GHz.

- Neither the characteristics of the interpulse, nor its differences from the main pulse, can be explained by any current model of pulsar radio emission.

Our goal: why do pulsars shine?

That is:

- What is the coherent emission mechanism?
- How does a relativistic, magnetized, pair plasma radiate at $T_B \sim 10^{36} - 10^{38}$K?

Three types of models have been proposed:

- coherent charge bunches;
- plasma masers;
- plasma turbulent emission.

Each mechanism has characteristic time and spectral and signatures; can we test these models with observations?

Our approach has been ...

- Carry out high time resolution observations;
- Compare the data to predictions of the models.

The Crab pulsar: two magnetic poles

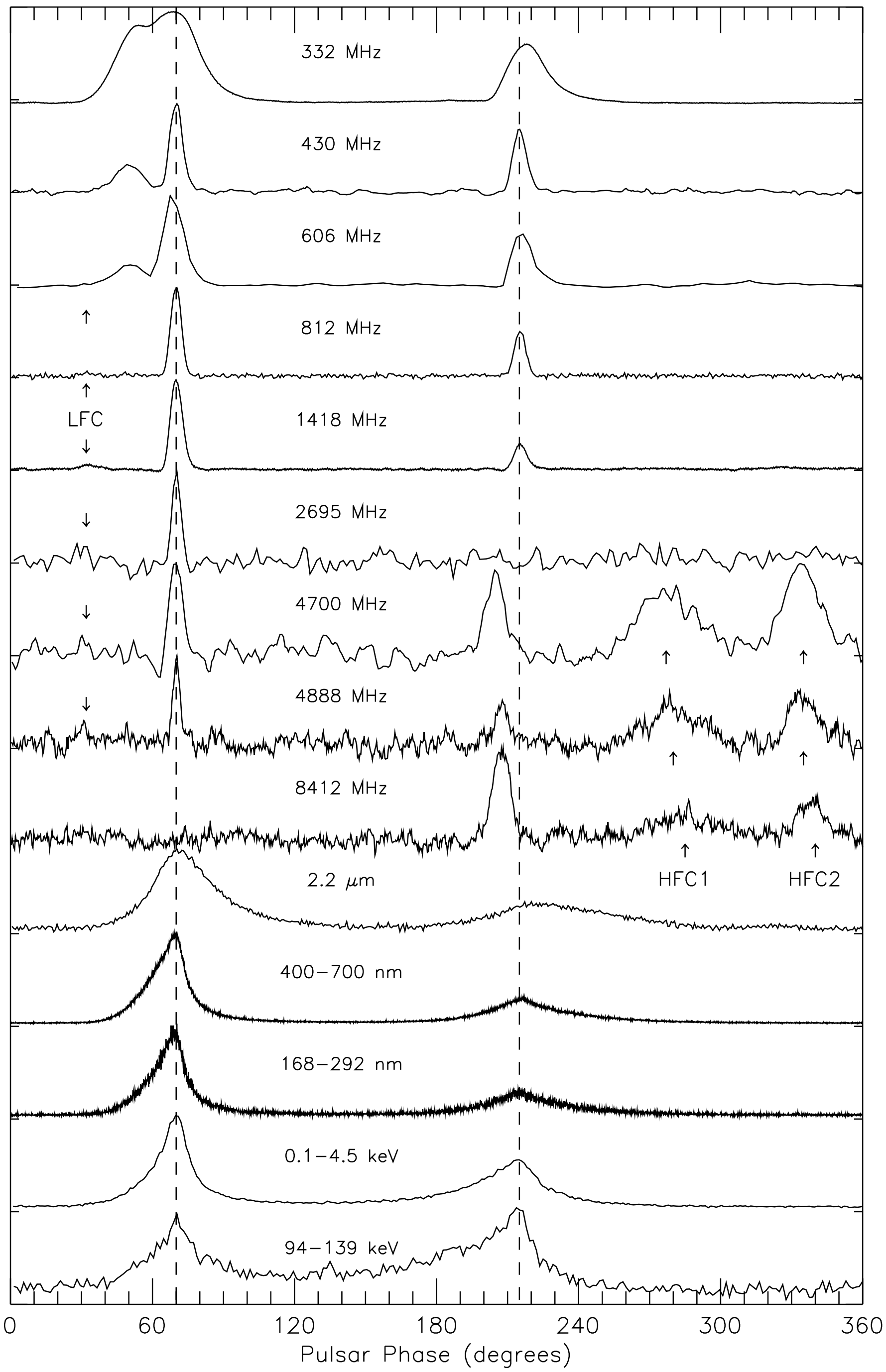
- We have studied the Crab pulsar because its occasional very strong “giant” pulses are ideally suited to our ultra-high time resolution observations.

- The dominant features of this star’s mean profile are a main pulse (MP) and an interpulse (IP), which can be identified from radio through Xray bands.

- Traditional radio-pulsar models ascribe MP/IP pairs to low-altitude emission above the star’s two magnetic poles. Alternatively, X-ray-pulsar models suggest higher emission altitudes (for instance the caustic model of Dyks & Harding).

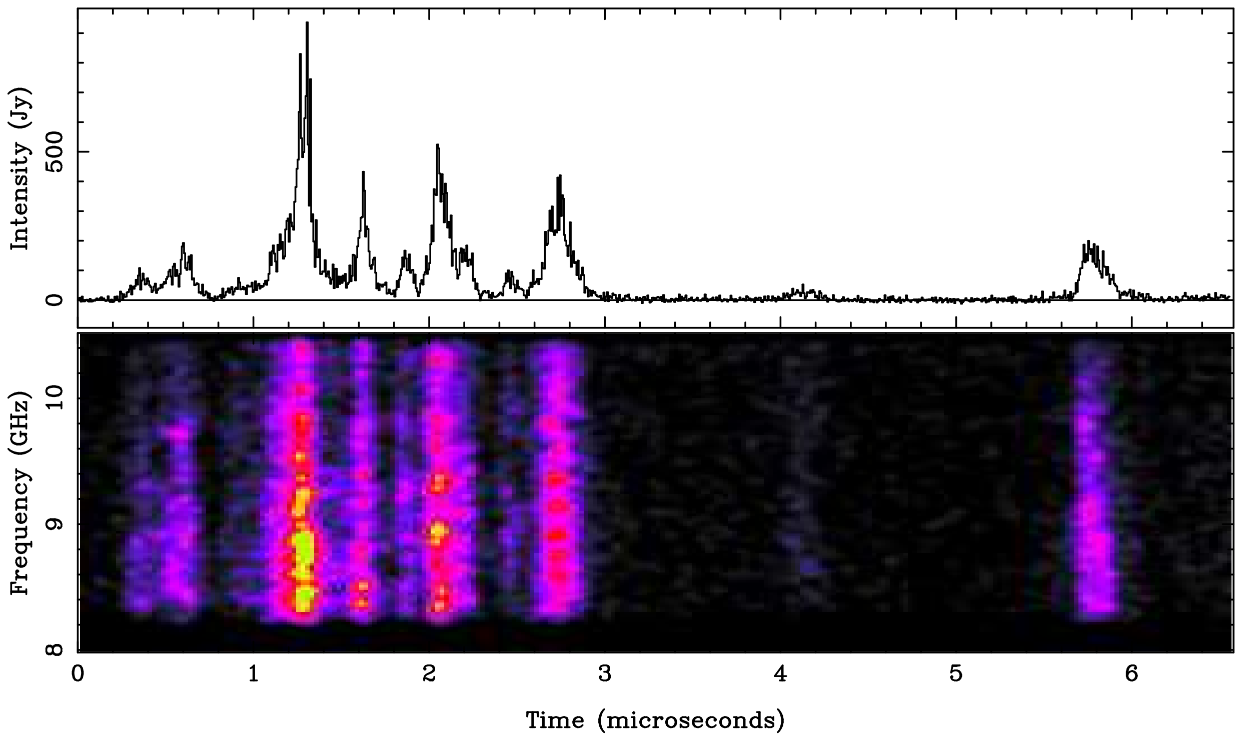
- Both of these models predict the MP and IP come from physically similar regions; the detailed radio emission physics should be the same for the MP and the IP. We were surprised to find this is not the case.

The Crab pulsar: mean profiles

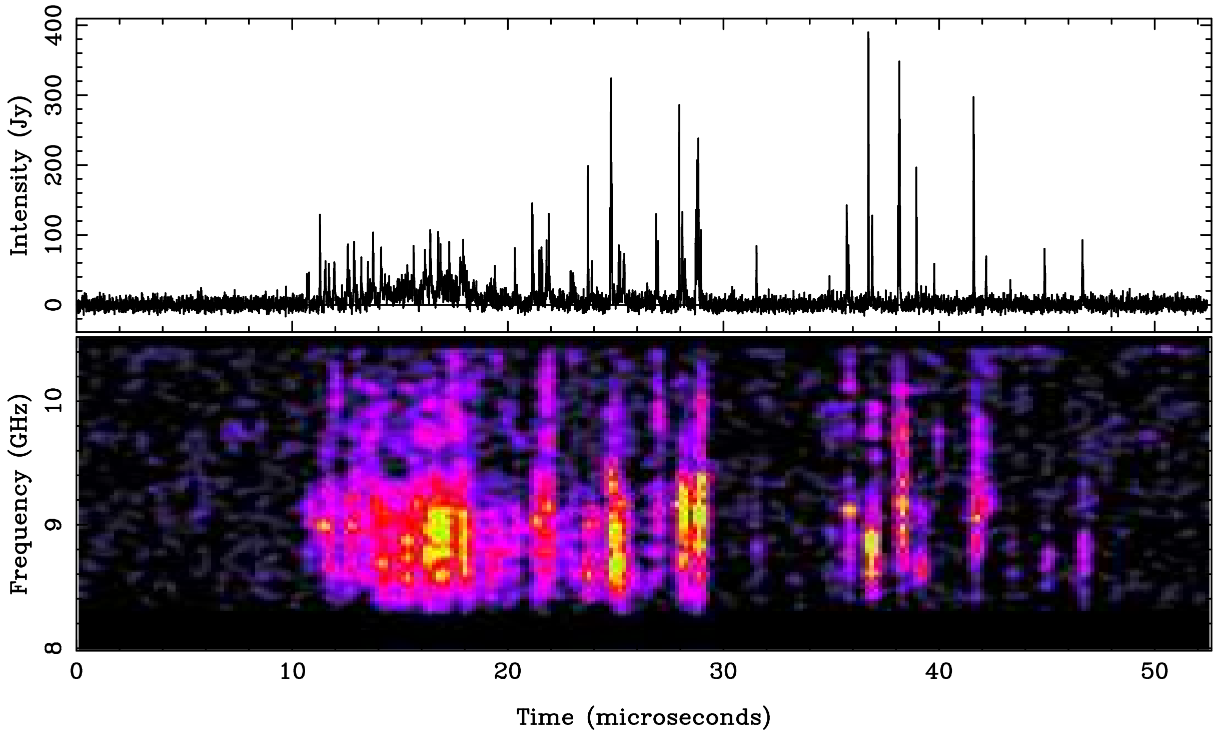


The mean profiles from the Crab pulsar show several frequency-dependent components. The Main Pulse and Interpulse are shown by the dashed lines at 70 and 215 degrees of rotation phase. They can be identified from low radio frequencies to hard X-rays. The Main Pulse becomes very weak and the Interpulse appears at a slightly different phase at high radio frequencies (Moffett Ph.D. thesis 1997).

The Main Pulse: Microbursts

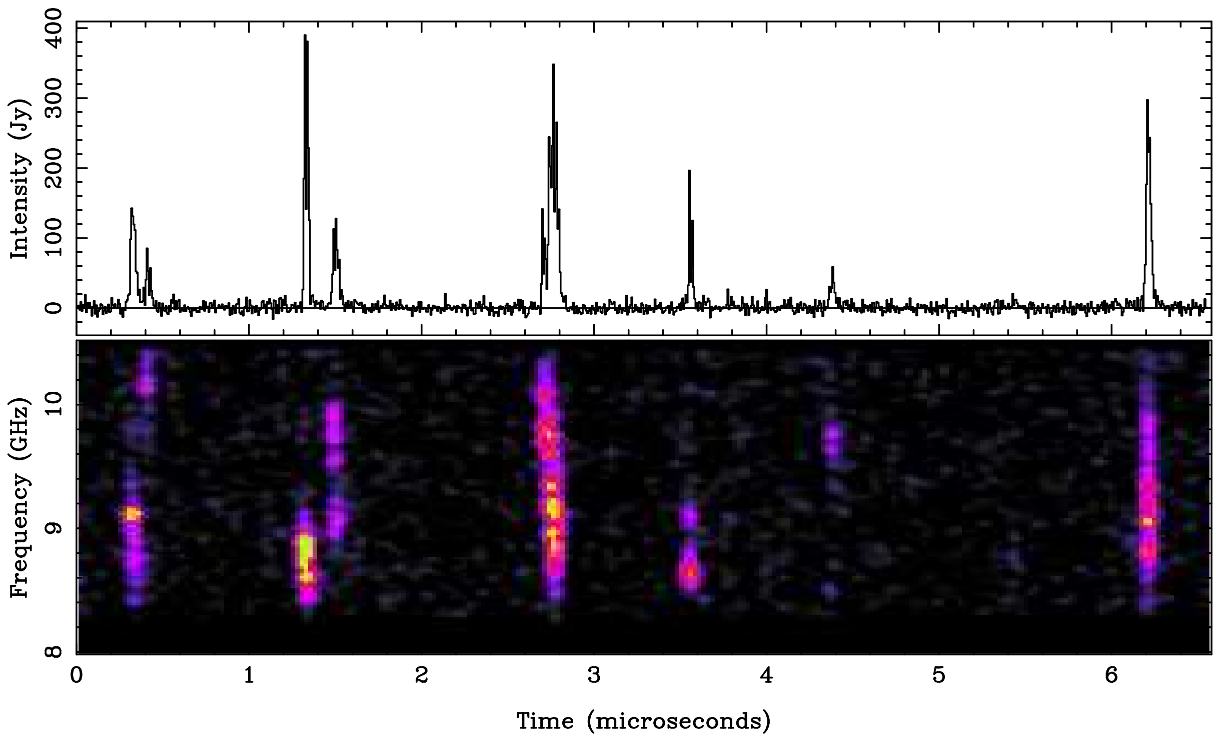


Most giant MPs consist of several microbursts, as shown here. The total intensity is plotted with time resolution 6.4 ns; the dynamic spectrum is plotted with 19.5 MHz spectral resolution and 51 ns time resolution. This and all data shown were observed at Arecibo and coherently dedispersed.

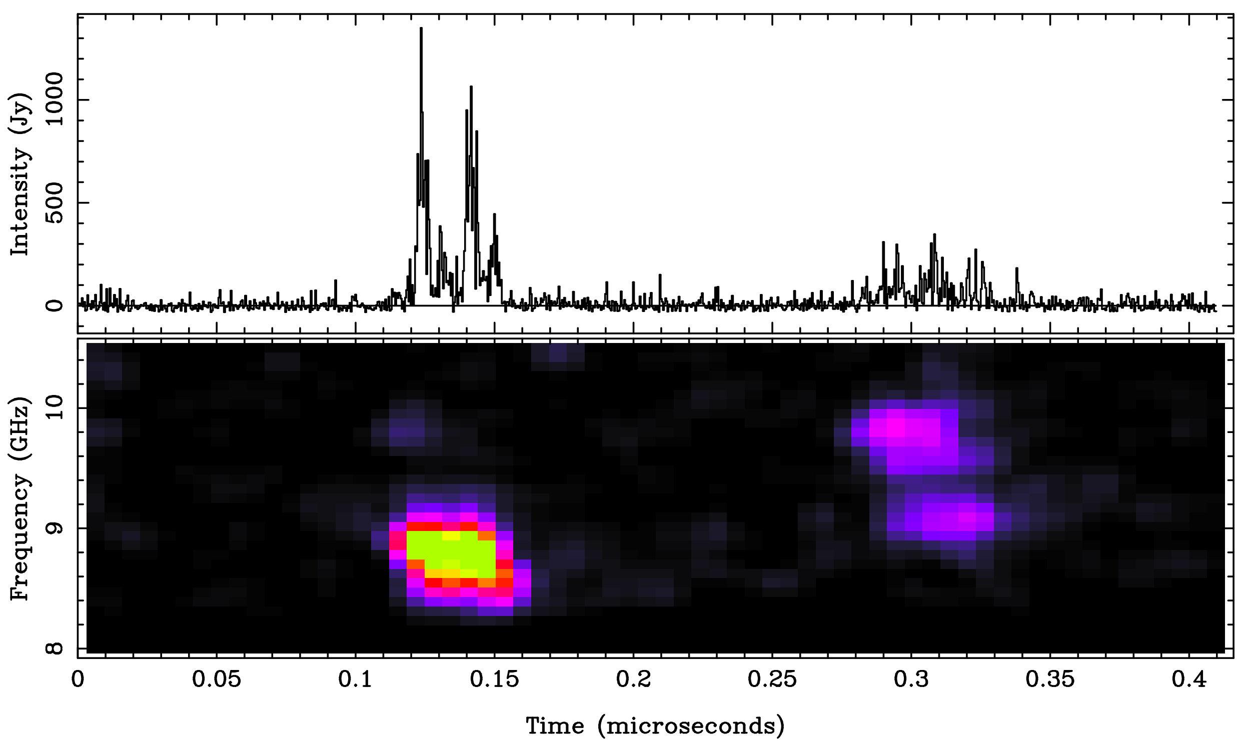


An occasional giant MP, however, consists of many short-lived nanoshots, which are well separated enough to be individually resolved. Time resolution 6.4 ns; dynamic spectral resolution 19.5 MHz and 406 ns. This pulse is shown at higher resolution in the next figures.

The Main Pulse: Nanoshots



Blowing up the $35.5 - 42\mu$s region of the "sparse" MP shown in the previous figure. Some individual "shots" are apparent, and the relatively narrow-band spectrum ($\delta\nu/\nu \sim 0.1$) of individual shots can be seen. Time resolution 6.4 ns; dynamic spectral resolution 19.5 MHz and 51 ns.



Blowing up the $1.2 - 1.6\mu$s region of the MP shown above, at our maximum time resolution, to reveal the temporal and spectral signature of individual nanoshots. Time resolution 0.4 ns; dynamic spectral resolution 78 MHz and 6.4 ns.

Characteristics of the Main Pulse

- Most giant MPs consist of several microbursts, each $\lesssim 1\mu$s long at $\sim 8 - 10$GHz, with bandwidth $\gtrsim 2$GHz.

- The microburst width increases at lower frequencies, $\tau \propto 1/\nu^2$. This is too flat to be due to interstellar broadening (which dominates at even lower frequencies); is it due to turbulence in the local plasma?

- Occasionally, however, a giant MP reveals a more sparse distribution of nanoshots – narrow bursts, δt $\lesssim$ 1ns at 8-10 HGz – which also have narrower bandwidth ($\delta\nu/\nu \sim 0.1$).

- We infer that every giant MP is a "cloud of nanoshots" – usually overlapping and unresolved, but occasionally sparse and resolved.

The Main pulse: plasma turbulent emission

How do the nanobursts compare to the predictions of the three coherent emission mechanisms?

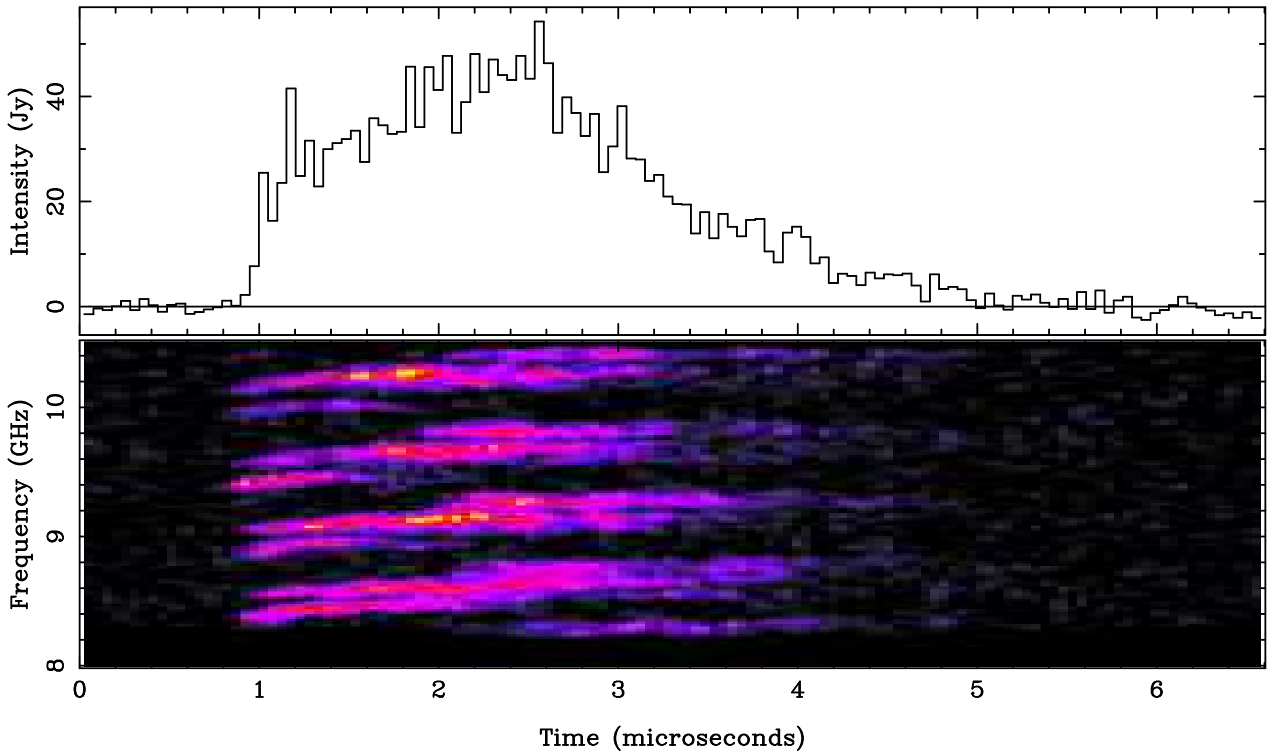
The different models predict different characteristic times (which we estimate at $\nu \sim 5$ GHz from their saturation mechanisms):

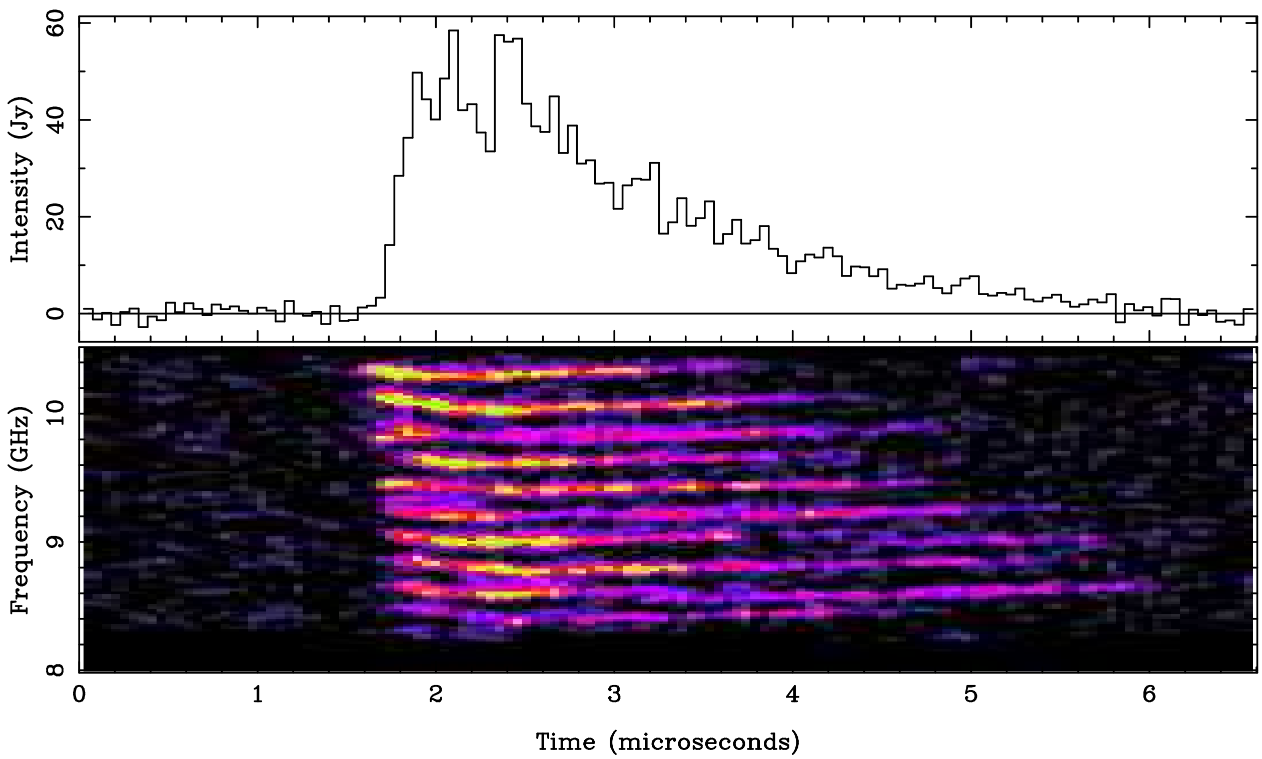
- **Strong plasma turbulence (saturation by soliton collapse): $\lesssim$ 1ns**
- **Coherent curvature emission (beam trapping): $\sim 0.01 - 1\mu$s**
- **Plasma maser (quasilinear diffusion): $\sim 0.1\mu$s.**

Simulations of strong plasma turbulence (Weatherall 1998) find narrow-band spectrum, $\delta\nu/\nu \sim 0.1$, centered at the co-moving plasma frequency.

Thus, only one of these models – strong plasma turbulence – can explain our observations of giant main pulses.

The Interpulse: Emission Bands





Two typical giant interpulses. The dynamic spectrum of the interpulse contains several sets of emission bands, each of which lasts $\sim$ a few μs. These bands appear in *every* giant IP, but not in giant MPs observed at the same time; thus they are neither instrumental nor interstellar. Time resolution 6.4 ns; dynamic spectral resolution 19.5 MHz and 52 ns.

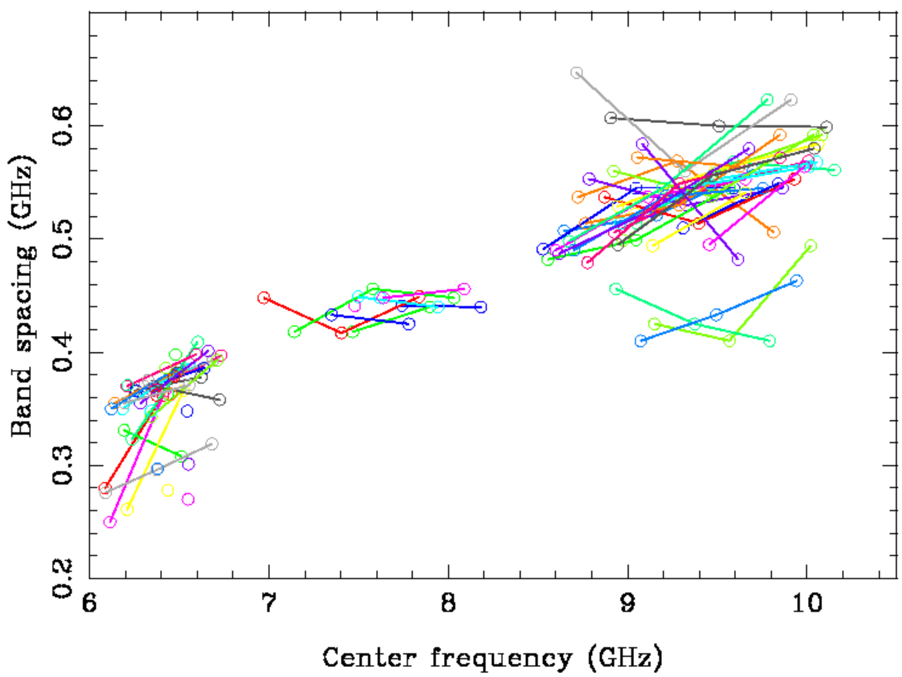
Characteristics of the interpulse

The dynamic spectrum contains sets of emission bands:

- each lasts a few μs;
- more than one band set can be identified in most GIPs.

The bands appear in *every* IP; they do *not* appear in MPs observed at the same time. Thus they are neither interstellar nor instrumental.

The band spacing depends on frequency: $\Delta\nu/\nu \sim 0.06$.



Separation of adjacent emission bands, plotted against center frequency. Lines connect band sets within a single giant pulse. The scatter reflects intensity variations within a band and errors in manual estimation of the centroid frequency of a band; the trend $\Delta\nu \propto \nu$ is nonetheless apparent.

The Interpulse $\neq$ the Main Pulse

We are very struck by the fact that the IP and MP do not have the same radio emission properties.

- **The IP shows emission bands, and a broad profile in time; the MP contains narrow band nanoshots.**
- **Giant IPs are slightly more dispersed than giant MPs measured at the same time.**
- **Giant IPs are strongly linearly polarized, while giant MPs are only weakly polarized, when measured at μs time resolution.**

Neither the emission properties of the IP, nor the differences between the IP and the MP, are predicted by any of the models.

The Interpulse: simple models

The emission bands are not anticipated by any current model; in addition their proportional spacing presents a challenge for any new models. We are exploring (and all too often rejecting) possible models for the interpulse.

At this point we are considering three types of models:

- **Strong plasma oscillations?**

  The bands might come from trapped particles in long-lived plasma oscillations (*e.g.* free electron lasers or linear acceleration emission). The time signature of the oscillations in numerical simulations may be consistent with the observed band spacing.

- **Plasma stratification?**

  The bands are reminiscent of – but more complex than – type II solar flares. Plasma emission from a multiply stratified region (with many steps in $\sqrt{\gamma \mathrm{n}}$, for instance from a series of shocks) might give what we see.

- **Interference fringes?**

  The bands could be fringes, if two coherent optical paths exist in a plasma with a ν-dependent index of refraction, and if a *broadband radiation source* (perhaps a double layer) illuminates them.

All of these models are very preliminary; we remain perplexed by the emission physics of the interpulse.