OBSERVATIONAL EVIDENCE FOR PERSISTENT MICROSTRUCTURE PERIODICITIES

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Abstract

By using Cross Spectral Density processing between high time resolution radio intensity observations of pulsars made simultaneously at two different receiver frequencies, several high frequency periodicities that are persistent over many pulses were discovered. A possible interpretation in terms of neutron star vibration models is discussed.

Introduction

Calculations of the pulsation modes and periods of neutron stars have been carried out since before their discovery. (*cf.* references in Chandrashekar 1969, Misner, Thorne, and Wheeler 1973, Thorne 1978, and McDermott, Van Horn, and Hansen 1988, hereafter MVHH. These papers have established expected the frequency ranges, energy requirements and decay times of neutron star oscillations. Many oscillation modes are excluded because they require enormous energies or they decay much too rapidly. Others are not readily observable within the time frames of the observations.

Boriakoff (1976) proposed that the quasi-periodicity in the pulsar microstructure was the observable evidence of neutron star free oscillations. The interpretation of these quasi-periodicities as neutron star oscillations, and subsequent results are still in doubt, perhaps best voiced by Cordes (1976). Additional possibilities have been brought to light by Cordes and Hankins (1977), Hankins and Boriakoff (1978), Ferguson and Seiradakis (1978, hereafter FS), Ramaty *et al.* (1980), Soglasnov and Popov (1983), and Kuz'min(1985).

Most of these studies have used auto- and cross-correlation processing as tools, typically analyzing individual, or consecutive pulses at a single frequency. FS as well as Rickett, Hankins, and Cordes (1975), and Kuz'min (1985) have made dual frequency analyses to a very limited extent. FS have also tried, with little success, the use of cross spectral densities (CSD). These studies have reported of many 'quasi-periods' of little enduring significance in this context because of their lack of persistence in time and resolution in frequency. FS have published a histogram of preferred periods, but overall the evidence for oscillations is not compelling. It is not known how large a physical displacement is required to be observed, given the uncertainties in the beam production mechanism(s), the coupling between the star and magnetosphere, and the magnetospheric structure, as well as the physical nature of the neutron star itself. Kuz'min (1985) shows that the coupling may be reasonably small.

We have chosen to examine our dual-frequency data using CSD techniques for several reasons: interference suppression, the specificity of the frequencies obtained, and the fact that a source-induced wideband periodic signal will have the same period at both frequencies unaffected by dispersion or pulse broadening. We have also chosen to look at samples of hundreds to thousands of consecutive two-frequency pulse pairs to enhance the detectability of threshold effects, and to concentrate on persistent and/or recurrent phenomena. While it is quite clear that there may be neutron star oscillations that decay in as little as one pulse period, (*cf.* MVHH), we feel that even very good single pulse evidence has done little to establish the existence of such oscillations. Long term or continually re-excited modes are more reasonable in this context. This assumes an underlying quality, be it an instability that continually excites the oscillation, or a much higher Q than previously quoted masked by a threshold effect. High Q values can be disguised as low Qs by beating and mode switching or by being only marginally visible in the noise of the emission process. According to MacDonald and Ness (1961), and Backus and Gilbert (1961) rotation causes coupling between transverse (T) and shear (S) modes as well as removing their zonal degeneracy, allowing both mode switching and beating.

Observations

We observed pulsars PSR 0950+08, PSR 1133+16, and PSR 2016+28 during several day sessions at intervals of a few months for several years. Individual

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sessions for each pulsar are limited to approximately two hours because of the limited tracking ability of the Arecibo telescope. The sampling of each pulsar was restricted to a synchronous pulse window to minimize tape consumption, and to allow dual frequency coverage. This resulted in 45 ms windows for PSR 0950+08, 80 ms for PSR 2016+28 and 100 ms windows for PSR 1133+16. The windows were sampled at 25 μs intervals yielding 1800, 3200, or 4000 samples per receiver frequency. Typically several thousand pulses per session were recorded. The data were then processed and examined in different length segments, as a whole, per session, and in sub-session segments.

The data were collected using the Arecibo Observatory 305-meter telescope in a linearly-polarized dual-frequency mode (318 and 196 MHz). Because of the dispersion delay in the interstellar medium the pulsar signals at the two-frequencies could be sampled sequentially, with no overlap. Separate receivers connected to coaxial antennas were used at each frequency. The signals were switched alternately, to a single 32 × 20 kHz filter bank controlled by an electronic switch synchronized to the pulsar period. The detected outputs of the filters were delayed by a time interval appropriate for dispersion delay compensation and then summed.

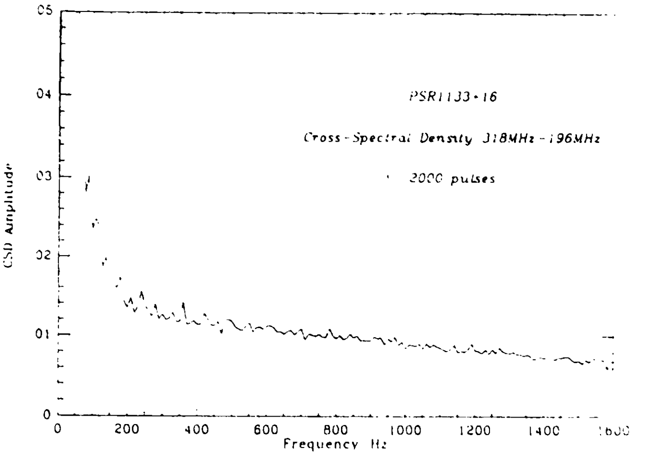

Figure 1 A typical average Cross Spectral Density of 2000 pulses from PSR 1133+16.

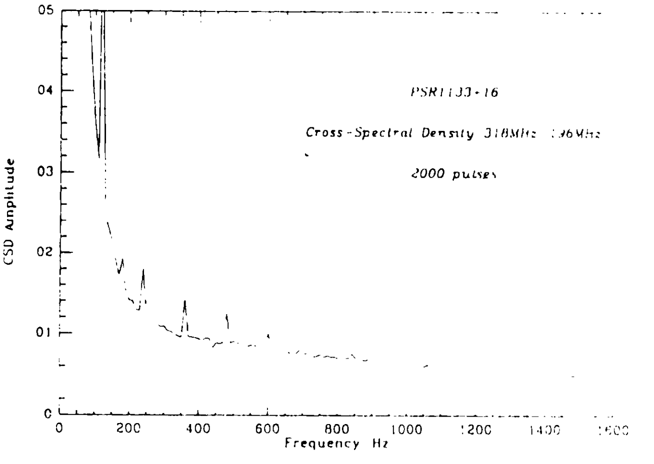

Figure 2 Highly structured 60 Hz interference average cross spectral density of 2000 pulses from PSR 1133+16.

Results and discussion

The result of each analysis session is a normalized average cross-spectrum of all of the included pulses. The pulses included in any analysis were chosen in various ways, but most commonly, all of the two-frequency pulse pairs from one or more observing sessions were processed with no intensity selection criteria. That is, we simply summed all of the individual cross spectral densities (power spectra). Figure 1 shows a typical spectrum with many individual 'lines' of varying strength. Some spectra are highly structured, as in figure 2, and are found to contain mostly 60 Hz harmonic interference.

Occasionally very interesting spectra are obtained as in figures 3 and 4. They represent 20 and 8 minutes of data respectively, and while the signals seen in these average spectra are not seen in every individual spectrum that make them up, they are seen in every 500-pulse subset that we have checked.

While spectra 3 and 4 are spectacular, the typical spectra also contain possible microstructure period candidates. Figure 5 is a histogram of the lines present in about 35 spectra, selected in various ways from PSR 0950+08 data, approximately 13 of which are chosen to represent a weak background. Many of the lines are clearly 60 Hz harmonics, but others are not and therefore represent serious candidates for source periodicities in the microstructure.

To be a serious candidate for a periodic microstructure signal it must: i) not be coincident

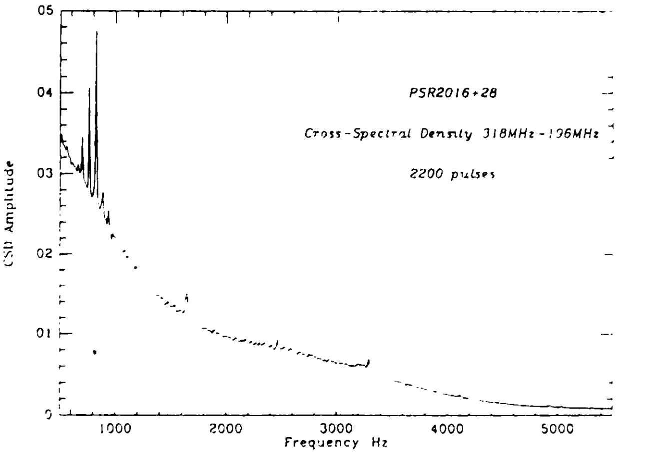

Figure 3 Average Cross Spectral Density of 2200 pulses from PSR 2016+28 displaying microstructure periodicities and beating with 60 Hz interference.

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with a 60 Hz harmonic, or if coincident with a 60 Hz harmonic, not consistent with the normal sequence observed in other spectra and stronger than surrounding harmonics; ii) be present fairly often; iii) be unusually strong, or persistent; iv) not be a beat frequency of known interference; and, for this particular study, v) be present over at least 500 pulse periods. Several 'lines' have been detected that fulfill criteria (i), (ii), and (v), a few for (iii), and almost all, so far, (iv). However, it is difficult to identify all sources of interference. Only occasionally, as is the case with 60 Hz harmonics, is the source obvious. Figure 3 is an average of 2200 consecutive spectra from PSR 2016+28. The normal low frequency peak, a secondary peak at 60 Hz and discernible signals at 120, 180, and 240 Hz, all obviously interference, have been truncated in order to emphasize smaller lines of interest.

The five-line sequence seen in the left side of figure 3 is the result of the strong central line at 825 Hz mixing with the 60 Hz interference. There are at least 6 higher order harmonics of the 825-Hz line. There is a broad line just before the fourth harmonic centered near 3200 Hz, a sharp line near the sixth harmonic at 5037.5 Hz, as well as a very broad feature from the second to fifth harmonic detectable as a change in the general trend in the background spectrum that, in addition to the 825-Hz line, are serious candidates for microstructure periodicities. Examination of the spectrum under higher vertical amplification than in this figure yields additional sharp, broad, and very broad candidates similar to those above. Evidence of some 60 Hz mixing around the third harmonic is also present.

The PSR 0950+08 spectra of figure 4 are particularly interesting when considered as a temporal sequence from (a) to (c). In figures 4*a* and 4*b* we see two overlapping sequences; one is almost certainly a 120-Hz harmonic train, while the other is well modeled by a 160-Hz harmonic series. It is easy to see both trains in each figure, and it is equally easy to see the change in their relative intensities. Figure 4*c* is several thousand pulses later, both frequency trains are absent.

We often see 60-Hz harmonic trains and they prove very useful in verifying the analysis technique as well as giving us some confidence in the identification of lines only slightly above the background. The fact that we do not see such clear spectra all of the time places some severe constraints on the emission and/or production mechanism(s), and must tell us something about the stability of the neutron star to perturbations, *i.e.* internal instabilities that can generate these decaying signals. If we wish to identify the source of these periodicities as the star, itself, then, after having assured ourselves that we have excluded all other reasonable explana-

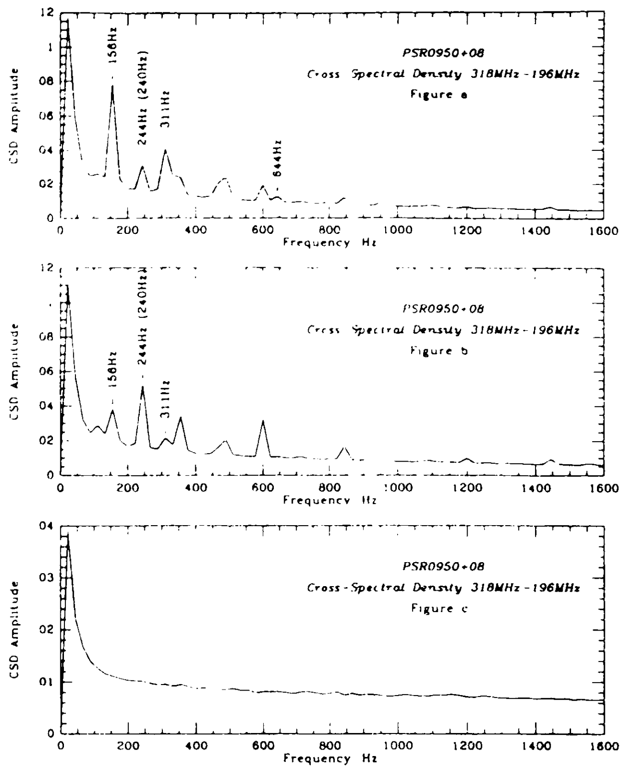

Figure 4 *a.* Average Cross Spectral Density of 2000 pulses from PSR 0950+08 with 2 harmonic trains, 120 Hz and 160 Hz, the 120 series is probably interference.
b. Average CSD of the next 2000 pulses from PSR 0950+08 showing a change in the relative intensities of the two harmonic trains above.
c. Average CSD of 2000 pulses from PSR 0950+08 taken much later than (*b*), when both trains have disappeared.

tions with a high degree of confidence, we must also consider any theoretical constraints. Many studies of neutron star free oscillations have been carried, such as those of MVHH and included references; but, they are, as yet, not able to exclude many of the candidates that have passed the observational tests listed here.

We have tentatively identified many lines, such as those discussed in figures 3 and 4, and the starred histogram bars in figure 5 indicate serious candidates for the microstructure expression of neutron star free oscillations. While individual identifications are difficult at this time because of model-dependent differences in the frequencies, an examination of tables 5 and 6 in MVHH reveals several reasonable possibilities, especially low order T and S modes.

Summary and conclusions

Through the use of the CSD technique and the summing of many individual cross spectra we have found several candidates for neutron star free oscillations in our dual-frequency data. Using

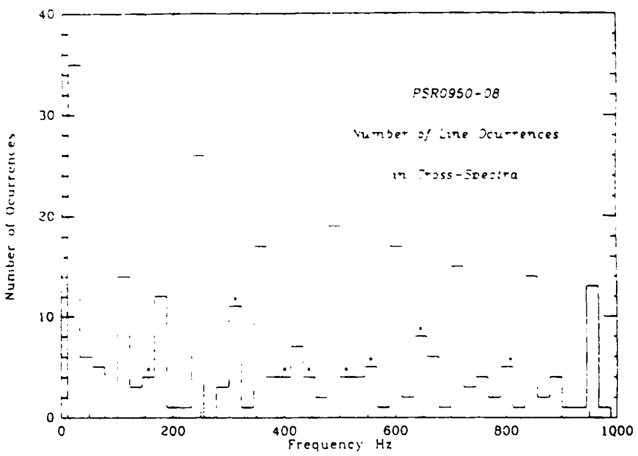

Figure 5 Histogram of line occurrence in 35 different analysis runs from PSR 0950+08. Each run included a different subset of the data, and various selection criteria. Marked with a star are candidates for pulsar-generated frequencies.

two widely-separated frequencies eliminates most sources (except 60 Hz) of local interference while taking advantage of the broadband character of the microstructure (Boriakoff and Ferguson 1981). We have established the persistence of our signals by looking only at long data trains, and examining interior subsets of them for identical signals. There is still uncertainty as to the source of our signals and we continue to investigate possibilities of a nonpulsar origin. The source may be unrelated to free oscillations, *e.g.* preferred electromagnetic breakdown periods in the spark gap of the pulsar, but it is unlikely that the persistent signals we have found are shot noise as described by Cordes (1976a).

How can the emission mechanism be affected by physical oscillations and translated into periodicities in the microstructure? The most logical intermediary is the magnetic field frozen into the structure of the neutron star. Any oscillation of the neutron star surface will be translated into the magnetosphere *via* the field. Horizontal oscillations will propagate as waves in the field and periodically change the direction of the tangent to the field lines contributing to emission in the line of sight. A change of a few degrees should be observable (Kuz'min 1985). McDermott *et al.* (1984), and MVHH state that relatively little energy in some modes produces very large surface displacements. Vertical oscillations can change the frequency of the horizontal oscillations by periodically Doppler shifting them and change, also periodically, the rotation rate by changing the moment of inertia. They can also change the size of the spark gap. MacDonald and Ness (1961), (and references therein), point out that rotation will couple T and S modes, so that initially purely horizontal motion will develop a vertical component; and that the rotation will also cause the local motion of particles to change their orientation, changing, in the case of a neutron star, the influence of the motion on the magnetic field periodically in time.

We would like to conclude with an observational caution. MVHH calculate that the period of the $_{2}T_0$ mode is very nearly the same in many neutron star models, 17.3–19.1 ms in their table 6, or at a frequency of 53–58 Hz. This is very close to 60 Hz and with resolutions similar to ours, 10–22 Hz, may well be indistinguishable from electronic interference. If the situation above were true the entire spectrum for model NS13T8 in tables 5 and 6 in MVHH would be accommodated with a little adjustment to a slightly lower mass by our data in figure 3 and the 5-line sequence in figure 3 might then be a result of an interaction of the 825-Hz line with the $_{2}T_0$ line. (It should be noted that Carroll *et al.* have determined that a strong neutron star magnetic field can significantly affect the periods and lifetimes of some of these modes.) In a similar vein spectral lines with periods near 2 ms may suffer the same fate in being lumped with a 480-Hz interference line, and so forth. Other low frequency lines of frequencies less than about 40 Hz may be blended in the low frequency peak in the CSD.

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