A 2.14 ms Candidate Optical Pulsar in SN1987A

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Abstract.
We have monitored Supernova 1987A in optical/near-infrared bands from a few weeks following its birth until the present time in order to search for a pulsar remnant. We have found an apparent pattern of emission near the frequency of 467.5 Hz – a 2.14 ms pulsar candidate, first detected in data taken on the remnant at the Las Campanas Observatory (LCO) 2.5-m Dupont telescope during 14-16 Feb. 1992 UT. We detected further signals near the 2.14 ms period on numerous occasions over the next four years in data taken with a variety of telescopes, data systems and detectors, at a number of ground- and space-based observatories. The sequence of detections of this signal from Feb. '92 through August '93, prior to its apparent subsequent fading, is highly improbable ($< 10^{-10}$ for any noise source). We also find evidence for modulation of the 2.14 ms period with a $\sim 1,000$ s period which, when taken with the high spin-down of the source ($2-3 \times 10^{-10}$ Hz/s), is consistent with precession and spin-down via gravitational radiation of a neutron star with a non-axisymmetric oblateness of $\sim 10^{-6}$, and an implied gravitational luminosity exceeding that of the Crab Nebula pulsar by an order of magnitude.

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$^3$We lost our esteemed colleague, Dr. Kristian, in June 1996.
1. Introduction

We present evidence herein for the presence of an unique, 2.14-ms pulsar, which appears to precess and whose spindown is apparently dominated by gravitational radiation, but one which has also been very difficult to detect over the past three years due to its faintness and the complicated nature of its signal. A more detailed and exhaustive treatment of this candidate and upper limits for any other signal are given elsewhere (Middleditch et al. 2000).

2. Observations

The observations discussed in this work were made between Feb. ‘92 and Feb. ‘96, using the LCO 2.5-m, CTIO 4-m, U. Tasmania 1-m, and the ESO NTT (3.5-m) telescopes. In addition, archival data from the HST on SN1987A was also used. A GaAs tube with an 800 nm longpass filter were used for the first year (ibid.).

3. Discovery of the 2.14 ms Signal

3.1. LCO Feb. 14-16, 1992

We first detected the 2.14 ms periodicity in data taken at the LCO 2.5-m Dupont telescope during 1992 Feb. 14-16 UT. The 2nd harmonic phase was twice that of the fundamental, a sure sign of a “peaked” pulse profile, which turned out to have a noise probability of $\sim e^{-27.45}$ when actually computed. This profile is
3.2. LCO February 1993 – The Rosetta Stone

We continued to observe SN1987A with the 800 nm longpass filter in the year following the initial appearance of the 2.14-ms signal. A targeted search was made using the sum of the complex Fourier amplitudes, \( a(f) \), near the \( \sim 467.5 \) Hz fundamental frequency, \( f \), with those near the \( \sim 935 \) Hz second harmonic, \( a(2f) \), computed in the following way:

\[
a_{\text{sum}} = \frac{\|a(f)\| + e^{-i(\phi(2f)-2\phi(f))}\|a(2f)\|}{\sqrt{2}}
\]

where \( \phi(f) \) is the phase of \( a(f) \), and \( \phi(2f) \) is the phase of \( a(2f) \).

On the night of 6 Feb. UT 1993, in a run on the LCO 2.5-m which lasted \( \sim 80 \) minutes before high humidity forced an early termination (conditions were otherwise perfect), an unusual pattern of power appeared in the sum of the Fourier spectra from frequency regions encompassing 467.4843 Hz (close to the extrapolation of the Feb. ‘92 frequency) and twice this value (Fig. 2).

The three high peaks in the sum power spectrum are, to within errors, evenly spaced by 0.00214 Hz, modulo the 467.5 Hz fundamental frequency, and immediately suggest a periodic modulation in the phase/frequency and/or amplitude of the 2.14 ms signal with a period of \( \sim 467 \) s. The 467.48429 Hz frequency of the central peak (1/3 of the frequency of the top scale) also indicates a mean spindown for the pulsar implied by the 2.14 ms signal for the \( \sim 1 \) year interval between Feb. ‘92 and Feb. ‘93 of about \( -3\times10^{-10} \) Hz/s.
Figure 3. (Lower three frames) The Fourier power spectra for frequency regions near 467.48056 Hz and its first two higher harmonics (the 2nd near 935 Hz and the third near 1402.5 Hz) from data taken at the U. of Tasmania 1-m during July 26 UT, 1993. (Top frame) The sum spectrum of frequencies near the fundamental and 2nd harmonic. The peak in the sum spectrum near \(1402.4417/3 = 467.48056\) Hz is significant above the five sigma level (\(\sim 1:6,500,000\)).

The probability of noise producing three such peaks in the sum spectrum, each exceeding 10 times mean power, is less than \(10^{-5}\), even considering the rest of the data from Feb. ‘93 and Nov. ‘92 (Middleditch et al. 2000). Further modulation structure of the individual Fourier power peaks of the fundamental and 2nd harmonic lead to a further, very conservative, reduction in this probability by a factor of 100, in addition to the realization that the period of modulation was actually twice 467.5 s, or 935 s. Thus the probability fell to \(10^{-7}\).

The remainder of the data from LCO during 1992 and Feb. 1993 was searched for the 2.14 ms signal and \(\sim 1,000\) s modulation, and evidence was found for this signal and modulation in data taken on the other nights at LCO and CTIO (the 3rd, 5th, 7th, 11th, and 12th of Feb. ‘93) and in two of three nights during Nov. ‘92 (the 6th and 8th). In addition, a moderately strong and consistent 1430 s modulation was found in the data from Feb. ‘92.

4. Observations from Tasmania, 1993

By the time the pattern of the 2.14 ms signal was beginning to be discerned, the regular ‘92/’93 observing season was over. In order to continue observations during an interval in which the signal seemed reasonably consistent, observations had to be made from farther south. Thus the search continued (in the broad
Figure 4. The time histories of the $\sim 1,000$ s modulation period (lower), the $\sim 467.5$ Hz pulse frequency (middle), and the inferred I flux (upper) for points earlier than day 500, V + R + I composite for LCO and CTIO points afterward, and S20 band magnitude for HST, Galway/NTT, and U. Tas. points. The ‘v’ symbols are upper limits.

S20 band) with the 1-m telescope of the University of Tasmania, which was sufficiently far south to allow observations of SN1987A while under the pole (and through at most 2.7 airmasses).

A peak in the Fourier power spectrum at 467.481992 (5) Hz was found in the initial observation made from Tasmania on May 16, 1993 UT. The pulse profile had “flat” main and interpulses, both of which sharpened far more than would be expected from noise (which would have added only relatively “smooth” structure) when the obvious $\sim 1,000$ s phase modulation of the 2nd harmonic was incorporated into the pulse folding (see Middleditch et al. 2000).

The next observation, made on July 26, 1993, has over ten times mean power for a fundamental frequency near 467.48056(1) Hz, and a second harmonic with about half as much power at exactly twice this frequency, and stands out very clearly in the sum spectrum (Fig. 3). The pulse profile of this signal confirmed the Fourier spectral analysis, indicates a mean magnitude of 21.6 for the 320-750 nm S20 band, and is similar to that of the Feb. ‘92 observations (Fig. 1).

SN1987A was observed again four weeks later on 23 August ‘93. Analysis of this observation revealed a peak in the sum of the 2nd and third harmonics, and in addition, power in the fourth and fifth harmonics, when folded at 467.479874(4) Hz. Unusually high numbers (0.67±0.073 and ±0.095, where 0.5 is expected – Middleditch et al. 1993) for the centroids of harmonics 2 and 5 (3 and 4 were still > 0.5) led to the discovery that most of the contribution to the main pulse occurred during the last hour of the observation. The pulse profile
The spindowns of the 2.14 ms pulsations are scattered against the reciprocal of the squares of their ∼1,000 s periods.

for this hour, a single sharp pulse, is less probable still than that of the July 26 data (2.44×10⁻⁷), and the peak in the sum spectrum produced by the 2nd and third harmonics for this run is even higher than that shown in Fig. 3.

Observations of SN1987A and detections of the 2.14 ms signal continued on the big telescopes, in spite of the fading of the signal after Sep. ’93 (Fig. 4). The data from all telescopes, large and small, remain consistent.

If the apparent precession is a result of the same non-axisymmetric oblateness (relative to the axis of rotation) which drives the apparent spindown, then \( \Omega_{\text{prec}} \propto \frac{\delta I}{I} \omega_{\text{spin}} \) and \( \frac{\partial \omega_{\text{spin}}}{\partial t} \propto (\delta I)^2 \), where \( \omega_{\text{spin}} \) is the rotational frequency of the pulsar, \( \Omega_{\text{prec}} \) is the precession frequency, \( I \) is the moment of inertia of the (precessing part of) the neutron star, \( \delta I \) is the non-axisymmetric contribution to \( I \), and \( \frac{\partial \omega_{\text{spin}}}{\partial t} \) is the spindown. Combining these gives, \( \frac{\partial \omega_{\text{spin}}}{\partial t} \propto \Omega_{\text{prec}}^2 \) (Fig. 5).

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