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LIMITS ON AN OPTICAL PULSAR IN SUPERNOVA 1987A

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ABSTRACT

Since 1987 March, we have searched the optical flux from supernova 1987A for periodic pulsations. As of 1988 August, after 38 separate observations, no pulsar has been detected. The typical upper limit we place on the pulsed fraction optical light from the supernova is 2×10^{-4}, for pulse frequencies in the range 0.03–5000 Hz. Our best limit on the pulsed fraction of supernova light is 7×10^{-6}, on 1988 January 22. On 1988 August 28, we reach our faintest limit for the magnitude of the pulsar, dimmer than 20th mag. These limits are based on Fourier transforms of up to 67 million points, covering a range of spindown rates. Our search is continuing.

Subject headings: pulsars — stars: supernovae

I. INTRODUCTION

Theoretical calculations and the neutrino detections at Kamiokande (Hirata *et al.* 1987) and by the IMB group (Bionte *et al.* 1987) strongly indicate that a neutron star was formed during the supernova explosion of SN 1987A. If conditions are favorable, a newly born neutron star may be emitting optical light inside the supernova. However, attempts to detect the pulsar by its optical light are complicated by several factors. Some theories indicate that even a small amount of material in the area of the neutron star can smother the pulsar emission mechanism (Woosley and Phillips 1988). Even if pulsar emission is present, the supernova envelope may not be sufficiently rarified, or sufficiently broken up, to allow the pulsations to escape. Further, the pulsar beam may not be aimed toward Earth.

The detection of cobalt gamma-ray lines may indicate that the optical depth of the photosphere has reached unity in some places (Matz *et al.* 1988). Also, TeV gamma-ray emission in 1988 January has been reported (Bond *et al.* 1988); Michel *et al.* (1987) point out that the gamma rays may be the first detectable signature of a pulsar. However, it can be inferred from Ho (1989) that the pulsar may not be discovered in gamma rays by the *Gamma-Ray Observatory* without a previous period measurement from optical observations.

In 1987 March, we began a program of monitoring the optical flux from the supernova and searching the data for periodic pulsations. We have used optical telescopes at Las Campanas Observatory, Cerro Tololo Inter-American Observatory (CTIO), and Mount Stromlo, Australia. This *Letter* reports upper limits on the fraction of light from the supernova that is pulsed.

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II. OBSERVATIONS AND HARDWARE

We report observations of the supernova during the period of 1987 March 17 through 1988 August 27. The data were acquired using photomultiplier tubes and a silicon photodiode detector. Because the photodiode has higher quantum efficiency and can tolerate higher count rates than a phototube, we have been able to set our best limits with it, in spite of its greater system noise. The data acquisition electronics writes to magnetic tape the number of counts received over a standard interval, typically 10^{-4} s. In the photodiode system, the integrated current over the standard interval is digitized through a voltage to frequency converter, whose output is counted and written to tape. The standard observation length is 1 hr.

The EMI specifications for the NS20 photomultiplier tube report an average quantum efficiency of 12% in the wavelength range 0.3–0.8 μm, with a peak of 0.36 μm and an approximately linear fall off toward the red. The quantum efficiency of the silicon photodiode, Hamamatsu model S1188-06, peaks at 70% at 0.6 μm, and is greater than 50% between 0.4 and 0.9 μm; it averages about 60%. The operating temperature for the diode is -30°C.

Various filters through the visible region were used in the earlier observations to reduce the count rate and possibly to improve the signal-to-noise ratio of the pulsar emission against the supernova background. Observations after 1987 October 8 were made with no filter. The typical aperture size was 0\'.5. Relevant technical data about each observation are presented elsewhere (Pennypacker *et al.* 1988).

Our data collection system and the follow-up analysis have been used extensively over the last decade. Among the results of such programs has been the discovery of another optical pulsar in the Large Magellanic Cloud (Middleditch and Pennypacker 1984). We verified that the system was behaving as expected by observing the Crab pulsar on 1988 January 23 using the Cerro Tololo 4 m telescope, and on two separate occasions using the 100 inch (2.5 m) telescope at Las Campanas. From the CTIO test, the Crab pulsar was detected at the 140 σ level in the second harmonic by analyzing 8 minutes of data. This observation is indicated separately in Figure 1.

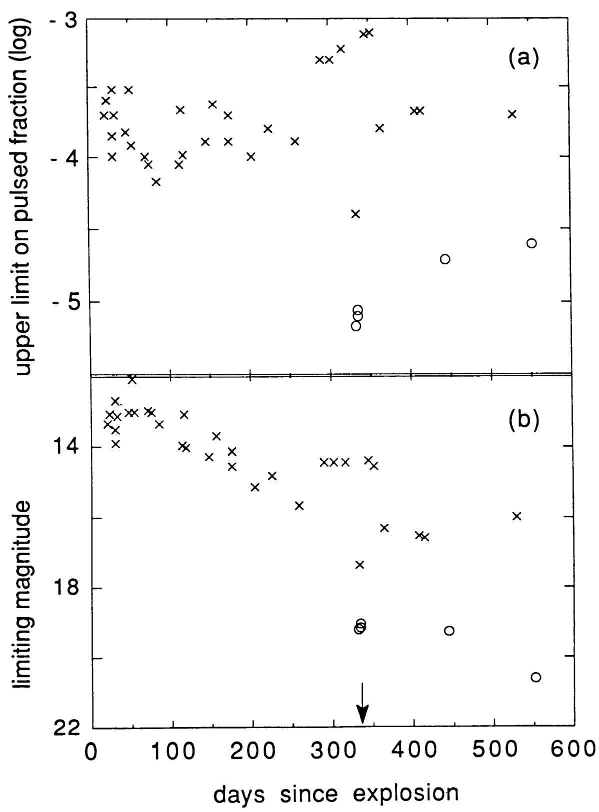

FIG. 1.—(*a*) Upper limit (90% confidence level) of pulsed fraction of total supernova light vs. time since explosion date. Crosses are phototube measurements; circles indicate Si-photodiode measurements. The arrow indicates the date of our CTIO calibration test. (*b*) Upper limit on magnitude of pulsed light escaping the supernova.

III. DATA ANALYSIS AND RESULTS

The analysis of the data follows that of Middleditch and Kristian (1984). Data sets of up to 67 million points are analyzed on a Cray XMP-416 at the Los Alamos National Laboratory Integrated Computing Network. We use a modified Fourier analysis, which differs from the standard Fourier transform by allowing the period of the expected signal to change with time, since the frequency of a pulsar may change significantly during an observation. The analysis covers a range of frequency and derivative space, and the upper limits we quote reflect the appropriate confidence level given the size of the region of phase space searched. We search in frequency from 0.03 Hz to the Nyquist limit of 0.5 of our sampling frequency. The limits on the derivative space searched are set at each frequency by the ratio of this frequency to its time derivative, $f/\dot{f}$, and the time since the explosion. Standard theory predicts a lower bound of this ratio to be 2 times the lifetime of the pulsar, if the primary energy loss mechanism is magnetic dipole radiation, or 4 times the lifetime if gravitational quadrupole radiation is dominant (Manchester and Taylor 1977). We search from the lower bound of this ratio to an upper limit of infinity, typically in 100 steps of $\dot{f}$.

Because it has become increasingly clear that a high rate of energy loss from the pulsar is not yet required to power any of the observed emission from the supernova, since 1987 August we have searched in frequency derivative space for energy loss rates down to a rate corresponding to gravitational quadrupole radiation.

The sensitivity limits we calculate are based on the flux received over the entire instrument bandpass (or relevant filter). The peak of the sensitivity curve places the photomultiplier tube near the standard U bandpass, while the photodiode is between V and R. The magnitude limits we quote are scaled from the visual magnitude of the supernova at the time of the observation (from Phillips *et al.* 1988).

Scintillation of the supernova light by the atmosphere reduces our sensitivity at frequencies below 50 Hz. For this low-frequency region, the combined effects of scintillation, clouds, and poor atmospheric transmission reduce sensitivity by a factor of 2–3, depending on the night. Also, there is some noise in the photodiode system centered about 545 Hz which we attribute to the voltage-to-frequency converter chip. We do not see any similar noise in the data obtained with the photomultiplier tubes. All of these effects are reflected in the limits shown in Figure 1.

The 90% confidence limits are based on the lack of any peaks in the power spectrum above 27.3 times the average local power level; typically the highest peaks actually observed were 20 times the average power level.[9] The range of these limits is due to the observation conditions and to the noise at particular frequencies, discussed above. Our best limit on the fraction of light from the supernova that is pulsed to the total light is 7×10^{-6}, on 1988 January 22.

The pulse profile determines the amount of power appearing in each harmonic of the fundamental frequency. The limits shown in Figure 1 are thus only for a *single* harmonic; they can be interpreted as the limit for a pure sine wave pulsar signal. If the pulse shape more nearly resembles a delta function, the detectable limit becomes fainter by a factor of 2. This is because the amplitude of the fundamental for a periodic delta function is twice as strong as the amplitude of the fundamental for a sine wave with the same number of photons. For an intermediate example, consider the Crab pulsar. It has a double-peaked signal, for which most of the power goes into the second harmonic. The fact that the two peaks are more like delta functions than sine waves makes the amplitude of the second harmonic about 1.4 times (0.35 mag) stronger than a sine wave with the same number of photons.

We performed two additional statistical tests on about 200 of the most significant peaks in the power spectrum from each observation (those more significant than $\approx 4.5\ \sigma$), using algorithms more sensitive to nonsinusoidal periodic signals. The more stringent limits from those two tests are not included in the limits of Figure 1*a*. For the first test, the emitted power is summed for the frequencies corresponding to the integer and half-integer harmonics up to and including the third harmonic of the significant peaks (Middleditch and Córdova 1982, Appendix).[10] No such sum was found exceeding a level with an

[9] The distribution of a power spectrum for random noise is exponential. The probability of a frequency bin with a power level of 20 times the local average is $e^{-20} \approx 2 \times 10^{-9}$, about as probable as a 6 σ event from a Gaussian distribution. Multiplying this probability per bin times the number of frequency bins searched and by the number of spindown-rate bins searched gives a result of order unity, confirming the fact that we should be seeing a peak this size.

The distribution of a power spectrum for a signal of strength P_0 is approximately Gaussian, with $\sigma \approx \sqrt{2P_0}$. The exact probability of a signal, with an expectation mean power of $P_0 = 27.3$ times the average fluctuating down to 20 times the average power level, is 10%. Thus we have a 90% confidence limit in Fig. 1.

[10] The exponent of eq. (A1) of this paper should be negative, and the left-hand side of the equation should read $df/dt \times T_{\rm fft}{}^2$.

equivalent Gaussian distribution probability of a 7 σ event. This test is particularly sensitive to double-peaked signals, where the second harmonic is dominant. For a Crab pulsar–shaped signal, this test gives a limit 1.7 times more sensitive than is shown in Figure 1*a*.

For the second test, the emitted power is summed for the integer harmonics up to and including the sixth harmonic of the significant peaks. Again, no sum exceeded a 7 σ level. This test is particularly sensitive to single-peaked delta function signal shapes, such as have been found for radio pulsars (e.g., the radio pulsar in M15, Wlszczan *et al.* 1989). For these signal shapes, this test gives a limit 3.5 times lower than shown in Figure 1*a*.

If the envelope is optically thin, then we can calculate the measured limits of optical flux beamed toward Earth, by multiplying the limit on the pulsed fraction for a given measurement by the brightness of the supernova at that time. The limiting magnitudes from this calculation are shown in Figure 1*b*. Our faintest apparent magnitude limit is from 1988 August 28, which resulted in a magnitude limit of 20.6.

In the results quoted here, the sensitivity of the system is limited by the light from the supernova itself. As the supernova dims, we will eventually reach a maximum sensitivity set by the background light from the LMC and our instrumental noise. The background sources sum to about 18th mag, counting some nebular emission from a supernova remnant, unresolved stars in the LMC, and stray light from a 17th mag star which is 1″7 from the supernova. The instrumental noise is slightly less. With these sources of noise, we should in time be able to detect a pulsar as faint as a broad-band magnitude of 25.

IV. DISCUSSION

By comparing the light curve of SN 1987A to the decay curve of ^{56}Co, Woosley (1987) sets an upper limit of approximately 2×10^{38} ergs s^{-1} on the absolute energy output of a putative pulsar. If a pulsar were currently supplying this much total energy, our measurements limit the fraction in pulsed visible radiation to be less than 4×10^{-5}. This is comparable to ratio of pulsed optical light to the total energy emitted by the Crab pulsar (Manchester and Taylor 1977).

A number of estimates have been given for the probability of a pulsar being observable for SN 1987A (Michel *et al.* 1987; Ho 1989). We address here some of the relevant questions for this search.

Probability of a pulsar from a new neutron star.—Several authors have considered whether the magnetic field strength and spin period of a newborn neutron star will be sufficient to activate the pulsar mechanism. Blandford *et al.* (1983) have modeled the magnetic field turn-on for pulsars and find that it might occur only after 10^4 yr and reach full strength after 10^5 yr. In support of this scenario, Radhakrishnan (1982) argues that half or more of all pulsars do not begin emitting before this time. The example of the Crab pulsar shows that at least some pulsars turn on in a much shorter time.

Luminosity of a pulsar.—Most predictions of the SN 1987A pulsar's luminosity are based on the Crab pulsar. A recent analysis by Ho (1989), using the model of Cheng *et al.* (1986*a*, *b*), finds an intrinsic optical luminosity of about one-half the Crab pulsar, for a pulsar with a magnetic moment equal to that of the Crab pulsar, and a 15 ms period. This would give it a visual magnitude of 23 at 55 kpc in the absence of extinction. However, Ho notes that, for the Crab pulsar, this model agrees with observations least well in the optical, where it overestimates the luminosity by a factor of 10.

Ho predicts the extinction in the supernova envelope due to electron scattering to reach an optical depth of unity 40 months after the explosion, while Woosley (1987) predicts this to occur at 20 months. With 1 mag of extinction, the hypothesized pulsar would be 24th mag. Dwek (1988) argues that dust formation in the supernova mantle could add many magnitudes of extinction for at least 5 yr after the explosion.

Our faintest limit to date is at $m = 20.6$, but as the supernova fades subsequent measurements can set fainter limits. If the supernova continues to dim at its present rate, we could expect to see to 24th mag around 27 months after the explosion. This estimate assumes that we take longer integrations as the flux of photons goes down, to keep the statistical sensitivity to pulsed light at 10^{-5} of the unpulsed light. However, the LMC will be in an unfavorable observing position at 27 months; a continuous 6 hr observation may not be possible until several months later.

Luminosity-period uncertainties.—Narayan (1987) and Chevalier and Emmering (1986) examined the period distribution of known pulsars and concludes that many pulsars are "born slow," with initial periods between 100 and 500 ms. The three known optical pulsars, the Crab, Vela, and PSR 0540−693, have shorter periods of 33, 89, and 50 ms. The luminosity of a young pulsar is expected to be coupled to its spin period. Pacini and Salvati (1987) have argued on dimensional grounds that the optical luminosity of a pulsar depends on about the tenth power of the frequency. For magnetic dipole radiation, the energy loss is proportional to the fourth power of the frequency. Although these luminosity-period relations have been debated (Lyne, Manchester, and Taylor 1985; Pacini and Salvati 1987; Middleditch and Pennypacker 1984), it is clear that luminosity falls rapidly with increasing period. Thus, only a pulsar as fast as the known optical pulsars should be detectable.

Pulsar beaming direction.—A pulsar in supernova 1987A could be undetectable simply because its optical pulsed emission is beamed away from us. Various estimates have been made for the beam width of radio pulsars, predicting the fraction visible at Earth, the beaming factor, to be 0.2 for all pulsars to 1.0 for fast pulsars (Narayan 1987; Manchester and Taylor 1977; Barnard 1986). The relationship of the radio beaming factor to the optical beaming factor is uncertain. The duty cycle of the known optical pulsars is longer than that in the radio by a factor of 3–5. If the beaming factor scales with duty cycle, then an optical pulsar would probably not be missed because of beaming.

We are continuing to make observations. We hope to obtain data monthly from telescopes at Las Campanas, Chile, including the 2.5 m, 1 m, and University of Toronto 61 cm, and the 16 cm at Mount Stromlo and 2.3 m at Siding Spring, and occasional observations with the 4 m at CTIO. We will continue to report on the results of our program.

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