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PRECISION MEASUREMENT OF THE FREQUENCY DECAY OF THE CRAB NEBULA PULSAR, NP 0532*

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ABSTRACT

We are measuring the phase of optical pulses from NP 0532 against an atomic time standard. The first 6 weeks of observation give the pulsar frequency ν and its time derivatives $\nu_{,t}$ $(= d\nu/dt)$, and $\nu_{,tt}$ in agreement with earlier measurements, but with improved accuracy. We find $(\nu_{,tt}\nu/\nu_{,t}^2) = 4.76 \pm 0.65$. This preliminary result is consistent with angular-momentum loss by gravitational radiation.

INTRODUCTION

The pulsars have extended our horizon for precision time measurements to galactic distances. The possible applications of this new tool to the study of relativity have led us to undertake a program to measure the phase of the Crab Nebula pulsar over a long period of time. This Letter reports some preliminary results of the program, dealing with the physics of the pulsar itself.

We have obtained a tentative value for $\nu_{,tt}$, the second time derivative of the pulsation frequency of NP 0532. With only 6 weeks of useful data, we cannot be sure that all of the measured $\nu_{,tt}$ is due to secular effects on the clock mechanism. Long-term periodic effects (e.g., pulsar orbital motion) may become evident as measurements continue. Our current value for $\nu_{,tt}$ is consistent with braking due to gravitational radiation.

The precision of this work is traceable to our measurement of the phase of pulses over an extended period ($\sim 10^8$ pulses). Earlier workers (Richards and Comella 1969; Duthie *et al.* 1969; Goldwire and Michel 1969) were able to measure only the period of the pulsar as a function of time. Therefore, we will depart from convention and discuss our results in terms of pulse phase and its time derivatives, not pulse period. This has the advantage that the physics of the clock mechanism is more directly related to phase.

INSTRUMENTATION

We observed NP 0532 (Staelin and Reifenstein 1968; Cocke, Disney, and Taylor 1969) with the 36-inch telescope of the Princeton University Observatory from March 5 to April 26, 1969, when the pulsar was lost in evening twilight. Times of arrival of optical pulses were measured with precision of better than ± 150 μsec with 2 min of integration. This is about 10 times better precision than can be achieved with the radio pulses. More important for our purposes, optical measurements are less susceptible to systematic errors due to long-term changes in instrument band pass and pulse shape.

The instrumentation is sketched in Figure 1. These measurements were made with a 5″ aperture and an unfiltered FW130 photomultiplier (S20 response). The telescope was guided by the use of bright stars within 2′ of the pulsar. We were never able to see the source visually.

The electronics is similar to that used by Nather, Warner, and MacFarlane (1969). Pulses from the photomultiplier are counted into time bins by a computer of average

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transients (CAT). We used 400 time channels per sweep, each corresponding to 0.156 msec of time, so that nearly two pulsar cycles were stored in the memory per run. The CAT trigger is derived from a temperature-controlled crystal oscillator, giving a trigger-period stability of ± 20 nsec.

The only unique feature of our electronics is the provision for starting the CAT sweep at a precisely known time. The Epoch pulse in Figure 1 opens a gate, which has just been armed manually, and initiates the CAT sweep. The Epoch is a laboratory-generated 1-Hz pulse which has been brought into phase with the 1-Hz pulses from the Cape Fear Loran C transmitter. The phase difference between the two 1-Hz pulse trains is monitored with an oscilloscope. We record for each run the time, t_E, of the Loran C pulse which started the CAT. Pulses are identified to the nearest second by listening to station CHU (Canada).

The phase of the transmissions of the East Coast Loran C net is controlled by an atomic clock and is continuously monitored by the U.S. Naval Observatory against their

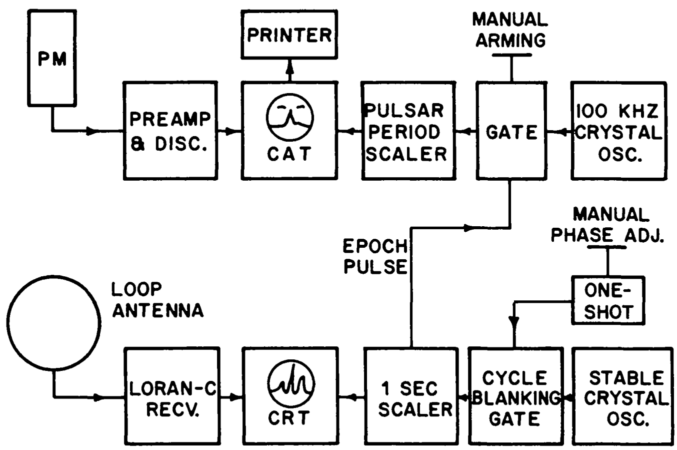

FIG. 1.—Instrumentation for pulsar timing. Coarse adjustments in the CAT trigger period are made with period-preset scaler; fine adjustments are made by pulling the 100-kHz oscillator.

bank of 16 cesium clocks. These clocks are our basic time standard. The Cape Fear transmitter phase drifted by less than 2 μsec during our observing period (U.S. Naval Observatory Time Service Announcements, Ser. 4, Nos. 111–117). Since we are able to receive the Cape Fear ground wave, changes in propagation delay are negligible.

We have attempted to express pulse times of arrival in absolute time (U.T.C.) by determining all system time delays. We list these below.

1. Loran C propagation delay, $t_D = 2524$ μsec. (Kindly computed for us by the U.S. Naval Observatory Time Service Division.)
2. Loran C receiver delay, <1 μsec.
3. Delay from Epoch pulse trigger to center of first CAT channel, $t_T = 23$ μsec.
4. Delay from light pulse in telescope to signal pulse into CAT, <2 μsec.

(Note that our results are not affected by the above time delays, as long as they remain constant.)

5. Time interval between Epoch pulse and Loran C pulse, t_C (typically 20 ± 10 μsec).
6. Time between CAT channel 1 and some fiducial point on first pulse stored, t_P (explained below).

The time of arrival (U.T.C.) of a pulse at Princeton is given by $t = (t_E + t_D + t_C + t_T + t_P)$.

DATA ANALYSIS

After each 2-minute run the CAT memory was read into a printer that recorded the channel number and the number of counts in each channel. Typical runs have 200 counts near the main-pulse peak and 100 counts of noise. The position of a fiducial point (*P* in Fig. 2) of each pulse was located to within about half a channel width by the following procedure. A "master" pulse shape was determined by cross-correlating and averaging 14 of our best pulses. The resulting pulse shape (Fig. 2) agrees with those of Warner, Nather, and MacFarlane (1969) and Wampler, Scargle, and Miller (1969). Each run was then convolved with the master pulse, the maximum of the convolution giving the channel position of the fiducial point of the pulse for that run. The error in channel position was determined from the width of the convolution and the noise in the pulse.

At least three errors were made in the course of collecting these data. (1) An early electronics problem caused noise to be superimposed on our data printout. All data from March 5 through March 14, when the problem was corrected, have been thrown out. (2) CAT trigger-period settings were not calculated accurately enough, and no correction

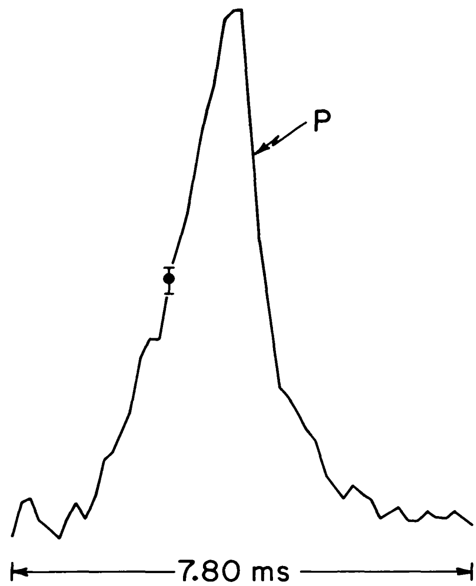

FIG. 2.—Master pulse shape. *P* is used as the fiducial point for arrival-time measurements

was made for diurnal drift. However, the CAT trigger period was accurately measured, and the amount of phase slippage has been calculated for each 2-minute run. Arrival-time corrections of the order of 100 μsec, with an uncertainty of ± 30 μsec, have been made to correct this error. (3) The frequency of the CAT sweep oscillator was not monitored, and it was temperature-dependent. This affected the time per channel calibration (nominally 156 μsec per channel). Fortunately, most runs contained two main pulses, so that their separation could be used to determine the sweep calibration to an accuracy of about ± 0.3 μsec per channel. This leads to an uncertainty in t_P that depends on the channel location of the pulse but does not exceed ± 100 μsec for the first pulse.

The possible systematic errors from the second and third sources of error listed above have been added by quadrature to the error in determining the channel number for each run. This total error, our best estimate of the standard deviation in t_P, varies greatly from run to run but is typically less than ± 150 μsec.

The pulse arrival times were converted to Ephemeris Time and transformed from Princeton to the solar-system barycenter. This correction is the light travel time from Princeton to a plane normal to the direction of NP 0532 and containing the barycenter. This computation was made with ephemeris tapes kindly supplied to us by the Jet Propulsion Laboratory. The 1950.0 coordinates of the star were taken as $\alpha = 5^h31^m31\overset{s}{.}46$,

$\delta = 21°58'54''.8$. The uncertainties in the ephemeris correction are negligible compared to our timing errors.

In this way, ninety-five barycentric arrival times (E.T.) over a 6-week period were obtained. These were fitted by the method of least squares to a cubic equation for the phase,

$$\phi = \nu(t - t_0) + \frac{\nu_{,t}}{2}(t - t_0)^2 + \frac{\nu_{,tt}}{6}(t - t_0)^3 , \qquad (1)$$

where ϕ is in cycles and ν in hertz. The quantities ν, $\nu_{,t}$, and $\nu_{,tt}$ are the pulsar frequency and its time derivatives at the instant $t = t_0$. The parameters t_0, ν, $\nu_{,t}$, and $\nu_{,tt}$ are adjusted so that the weighted sum of the squares of the differences between ϕ and the nearest integer is minimized. The fitting is done with progressively larger pieces of data, to be certain that no error in cycle counting occurred. The fit gives

$$\nu = 30.2155298589 \pm 0.0000000034 \text{ Hz} , \qquad (2a)$$

$$d\nu/dt = -(3.859294 \pm 0.000053) \times 10^{-10} \text{ Hz sec}^{-1} , \qquad (2b)$$

$$d^2\nu/dt^2 = (2.34 \pm 0.32) \times 10^{-20} \text{ Hz sec}^{-2} , \qquad (2c)$$

$$t_0 = \text{J.D. } 2440297.50904 , \qquad (2d)$$

where the errors are standard deviations derived from the arrival-time errors.

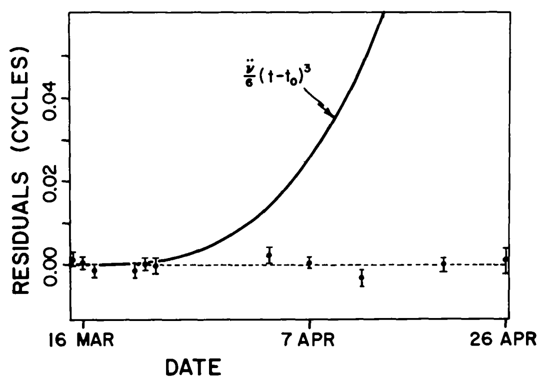

FIG. 3.—Residuals in the time-of-arrival data after subtraction of ephemeris corrections and fitted cubic equation. Each point is the average of results for one night; error flags are standard deviations. Curve is the cubic term found by the fit.

The residuals in phase for each night's data are shown in Figure 3. Each point and its error were obtained by combining all the times of arrival for that night. The χ^2 for the least-squares fit to these eleven points is 6.8, in agreement with the expected value of 7. On the other hand, if only t_0, ν, and $\nu_{,t}$ are fitted to the data, $\chi^2 = 70$, indicating a great improvement in the fit if the $\nu_{,tt}$ term is included. Also shown in Figure 3 is the fitted value of the cubic term in equation (1). Clearly this term is needed to minimize the residuals.

A term was included in the above fit to account for phase shift due to relativistic effects arising from the eccentricity of the Earth's orbit (Hoffman 1968; Keswani 1968). Because our data span only about 0.1 year and the change in phase shift was near a minimum, the relativistic effects cannot be seen in these data.

In terms of period P and its time derivatives, we find, for $t = t_0$,

$$P = 33.0955639268 \pm 0.0000000037 \text{ msec} , \qquad (3a)$$

$$dP/dt = 36.52256 \pm 0.00050 \text{ nsec day}^{-1} , \qquad (3b)$$

$$d^2P/dt^2 = -0.0404 \pm 0.0095 \text{ nsec day}^{-1} \text{ year}^{-1} . \qquad (3c)$$

DISCUSSION

The results described above have interesting implications for the braking mechanism in the rotating-neutron-star model of Gold (1968). If one writes

$$d\nu/dt = -K\nu^n , \tag{4}$$

then, for simple models in which K and n are constant,

$$n = \frac{\nu_{,tt}\nu}{\nu_{,t}^2} = 4.76 \pm 0.65 , \tag{5}$$

the second equation being a result of this work. This result is in good agreement with $n = 5 \pm 3$, obtained by Goldwire and Michel (1969) from a careful analysis of X-ray data.

Current theoretical models for the braking mechanism predict $n = 1$ for a relativistic "solar" wind (Michel and Tucker 1969); $n = 3$ for magnetic-dipole radiation (Pacini 1967); $n = 3$ to 3.03 if the dipole moment is decaying (Gunn and Ostriker 1969; Ostriker and Gunn 1969); and $n = 5$ for gravitational radiation. At the time of these observations our result seems consistent only with braking due to gravitational radiation.

We would like to thank the Princeton Observatory for granting us time on the 36-inch telescope. The ephemeris supplied to us by Dr. J. Derral Mulholland and the Jet Propulsion Laboratory was essential to the completion of this work; we are indebted to them. Discussions with Dr. R. Ruffini were most helpful in the interpretation of these results.

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