# 2.10 TIMING OF OPTICAL PULSES FROM THE CRAB NEBULA PULSAR*

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**Abstract.** Timing the arrival of optical pulses from NP 0532 is a potentially important tool for studying the physics of this fascinating object. However, there are some difficulties in interpreting the data in terms of physical models. Some progress has been made on understanding the largest effect – the pulsar braking mechanism. The glitch of late September, 1969 can be interpreted as the speed-up, and subsequent relaxation, of the rotation of a neutron star crust. An alternate explanation is that of a planet in an eccentric orbit. Both models fit the rather meager data near the event. A small sinusoidal effect is indicated in a relatively quiet period of the data.

## 1. Introduction

The phase of pulses from the Crab Nebula pulsar has been followed for over a year now by radio and optical observers (Boynton *et al.*, 1969a; Richards *et al.*, 1970; Duthie and Murdin, 1970; Nelson *et al.*, 1970). This means, in effect, that the last $10^9$ or so pulses from NP 0532 have been counted, and that for some of these pulse arrival times have been measured with respect to precision atomic clocks.

Since arrival times can be easily determined to better than $10^{-3}$ cycles ($\sim 30\ \mu$s) in one night, the inherent precision of the measurement is better than 1 part in $10^{12}$ per year. However, in order to take full advantage of this precision, we must understand simultaneously (1) the pulsar clock mechanism, (2) any effects causing relative acceleration between the telescope and the pulsar, (3) possible effects on propagation of the pulses, and (4) relativistic effects on the clocks. The physics of (1) is poorly understood and could turn out to be very complicated at this level of precision. Most of the effects of interest in (2) are periodic, such as orbital displacements of the earth (taken out by an ephemeris) and of the pulsar (unknown). To fully utilize the current timing accuracy, we must understand those accelerations which change the Earth-pulsar distance by as little as a few kilometers.

Finally, to complicate matters still further, there was a 'sudden' decrease in the slowing-down rate of NP 0532 in late September, 1969 (Boynton *et al.*, 1969b; Richards *et al.*, 1969). Unfortunately, data is particularly sparse around that time, and progress toward understanding this 'glitch' has been slow and inconclusive to date.

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So, at the moment we are in the exciting, but frustrating, position of having data which appears to be considerably better than our understanding of the underlying physics. Putting it another way, there are still real effects buried in the timing data which must be recognized by their particular time dependence, and then removed. Therefore, we should not be surprised, or discouraged, if different observers present quite different interpretations of what, in the final analysis, is the same physical situation. We have different samples of a very complicated time series, and are using different approaches to understanding the data. Publishing and/or pooling raw timing data would probably lead to the resolution of most of these differences.

## 2. Data Analysis

At Princeton we have approached the data analysis as follows. (1) Telescope arrival times are transformed to the solar system barycenter, and known relativistic corrections (Hoffman, 1968) associated with the Earth's motion are removed. (2) A possible physical model is assumed and described by an equation involving time and some adjustable parameters. (3) The modeled phase is fitted to the measured phase by the method of least squares, giving best estimates of the model parameters and a goodness-of-fit estimate, $\chi^2$. (4) As the model improves, the value of $\chi^2$ approaches the number of degrees of freedom of the fit. This method of analysis assumes that the temporal behavior of the pulsar can be modeled and predicted, except for occasional small discontinuities in the rate. This assumption may be overly optimistic, but it does emphasize a physical, rather than a phenomenological, treatment of the data.

Our data span the dates March 15, 1969 to April 26, 1970 with a gap from May to August 1969, when the Crab was too near the Sun. Some of our analysis has also included data of the Arecibo radio timing groups which fills in the summertime gap. Here we will present only some qualitative results; details, including graphs of residuals and tables of data, are being prepared for publication elsewhere.

### A. POLYNOMIAL BRAKING

For some time it has been recognized that NP 0532 is secularly slowing down (Richards and Comella, 1969). One explanation (Gold, 1968; Pacini, 1967; Gunn and Ostriker, 1969) has a rotating neutron star (frequency $\nu$) losing angular momentum, with the pulsation frequency equal to the rotational frequency. We model this particular behavior either as a polynomial expansion of the phase

$$\varphi(t) = \varphi_0 + \nu_0 t + \tfrac{1}{2}\dot{\nu}_0 t^2 + \tfrac{1}{6}\ddot{\nu}_0 t^3 + \cdots, \qquad (1)$$

or as the more restrictive equation for $\varphi(t)$ which satisfies power-law radiation, $\dot{\nu} \propto \nu^n$. In the power-law fit, derivatives of $\varphi$ larger than $\ddot{\varphi}$ are constrained, and the results of fitting a cubic polynomial are essentially the same as those of a power-law fit. The parameter of most interest in these fits is $n$ – the braking index, because $n$

determines the braking mechanism ($n=3$ for magnetic dipole radiation, etc.). Depending on the particular piece of data fitted, we obtain values of $n$ anywhere from 2 to 5. A simple power-law fit to all of our data gives $n=2.5$, but this is a very poor fit, partly because of the glitch, but mostly due to a large quartic-looking residual. This residual is not understood; it is two orders of magnitude larger than the quartic term expected from a power-law expansion.

The apparent instability of $n$ may be real, if the braking mechanism is indeed complicated and time dependent, or it may be due to underlying transient or periodic effects which have not been removed from the data. This situation should become clearer as more data is obtained, and long term effects are evaluated. The braking effect is included in all of the following fits, either as a polynomial or a power-law.

### B. SMALL SINE WAVE

There is a relatively quiet stretch of data lasting for about 4 months between December and March. Simple power-law fits in this region leave periodic residuals and give $\chi^2=500$ for 28 deg of freedom. If a sine wave is included in the fit the following best-fit parameters are obtained:

$75 <$ Amplitude $< 150\ \mu$sec,
$50 <$ Period $< 60$ days,
13 Jan. $<$ Maximum $<$ 23 Jan. 1969.

Including the sine wave in the fit gives a $\chi^2$ of 50, for 25 deg of freedom. This improvement of $\chi^2$ by a factor of 10 is a strong indication that this effect is real. It should be noted that more than 2 cycles of the sine wave are included in this data string; fitting sine waves of fewer than 2 cycles can lead to serious interference from the cubic polynomial. Unfortunately, we have no other piece of data which is long enough and clean enough to look for this sine wave. If the effect persists with stable frequency and amplitude, a planetary interpretation is favored. However, if the period and amplitude are found to change, there are other more complicated models (Ruderman, 1970).

### C. TRANSIENT GLITCH FIT

As mentioned above there is a transient in pulse arrival times occurring in late September 1969, and lasting through early October. Qualitatively the feature is consistent with two-component neutron star models with sudden crust speed-up (Greenstein and Cameron, 1969; Baym *et al.*, 1969) followed by a period of decay back to steady state rotation. We have modeled this event as a sudden change in frequency $\Delta\nu$, followed by an exponential decay back to the original braking curve, except that provision is made for a permanent change in $\nu$ at the time of the glitch. This is to allow for a possible permanent change in the moment of inertia of the star.

The results of this fit are a function of the length of data included on either side of the glitch, again indicating that underlying effects are 'pulling' the results. For this particular model the fitted parameters usually fall within the following ranges:

0600 UT 28 Sept. < Glitch Time < 0600 UT, 29 Sept.

$$6 \times 10^{-9} < \frac{\Delta \nu}{\nu} < 8 \times 10^{-9}$$

$$0.4 \times 10^{-3} < \frac{\Delta \dot{\nu}}{\dot{\nu}} < 1.5 \times 10^{-3}$$

4 < Recovery Time Constant < 16 days,

$$-1 \times 10^{-9} < \text{Permanent } \frac{\Delta \nu}{\nu} < +1 \times 10^{-9}.$$

For the crust-cracking model (Ruderman, 1969) the values of $Q$ obtained from these fits range from 0.85 to 1.17, where a value greater than 1.0 rules out the model (Baym *et al.*, 1969). However, the larger values of $Q$ are obtained from longer pieces of data where the results may be more susceptible to distortion by other effects.

### D. ECCENTRIC PLANET GLITCH FIT

Another model that has been proposed (Michel, 1970; Hills, 1970) to explain the 'sudden' changes in pulsar frequencies is that of a planet in a highly eccentric orbit around the pulsar. We have attempted to fit the September 1969 glitch with such a model, with surprisingly good results. The best fits to the glitch are given by a planet which moves the pulsar in an orbit, with the following elements:

200 < Period < 220 days,
0.3 < Eccentricity < 0.8,
1000 < a sin $i$ < 2000 km
Oct. 1 < Periastron Passage < 10 Oct.,
170° < Longitude of Periastron < 210°.

Again the ranges are not formal fitting errors, which are much smaller, but estimates of the stability of the results for different fitting models and various pieces of the data.

It may seem surprising that the glitch data can be fit equally well by a transient model and by a relatively smooth elliptic orbit model. There are two reasons for this. First, the data are sparse; to our knowledge no one has data during the week preceding and the week following 29 September. So the detailed behavior near the glitch is not known. Secondly, the glitch in NP 0532 was small. A build-up of phase error over a period of several weeks was needed to see the effect; the total cumulative phase displacement caused by the glitch is only about 0.1 cycles (3 msec).

## 3. Conclusion

The high inherent precision of the Crab pulsar timing measurement is a mixed blessing at the moment, but if we are patient the rewards may be great. These include the possibility of examining (1) the pulsar clock mechanism, (2) possibly some details of the most interesting physics of neutron star interiors and crusts, or perhaps the orbits of a planetary system around a supernova remnant. Some things can already be said about this complicated system. Results to date on the slowing down rate favor a long-term average braking index between 2 and 2.5. If the glitch was caused by a sudden speed-up of the crust, it took the two components a week or two to relax back to steady state rotation, indicating a very weak coupling which points to a superfluid interior (Migdal, 1959; Ginzburg and Kirzhnits, 1964). Finally, there remains the possibility that the Crab glitch was caused by the close passage of a planet in an eccentric orbit. We should know about this within the next few months as more data allows us to explain and remove effects which are interfering with current models. Also, with the increased number of observers, data on the next glitch should be much better.

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## Discussion

*F. D. Drake:* Your two-planet model would predict that in April the Arecibo timing measurements would have shown a period discontinuity very similar to that seen in September 1969. Such an event did not occur.

*D. T. Wilkinson:* There are interactions of the two large 'planetary' effects which modify the shapes of discontinuity events. If this model makes any sense, the predicted April 1970 discontinuity could look quite different from the September 1969 one. We are currently trying to predict this shape.

Secondly it is possible to force a polynomial fit to partially smooth out a discontinuity event. It was nearly the end of October before the September discontinuity became apparent, and then only by fitting the data in a particular way. Before that it merely appeared that the data had become very noisy.

*N. Visvanathan:* There was a report in an *IAU Circular* in April this year indicating a change in period of the Crab Pulsar by Dr. Manchester. I understand it is now withdrawn.