985

N90-23301

RADIO PULSAR TIMING OBSERVATIONS FOR GRO

J. H. Taylor
Joseph Henry Laboratories and Physics Department
Princeton University
Princeton, New Jersey 08544

Abstract

Gamma rays probably provide the best diagnostic tool for probing the enigmatic physics of pulsar magnetospheres. At present, however, only two pulsars—the young, nearby ones in the Crab and Vela X supernova remnants—have been reliably detected at gamma-ray energies. With adequate radio observations to provide independent timing information, Gamma Ray Observatory should be able to detect a number of additional pulsars, and the results will be of great benefit in testing magnetospheric theories and models. Timing observations for this purpose have been started at a number of radio observatories around the world. In this paper I describe the general procedures being used, and I give a status report on the work by the Princeton group.

I. INTRODUCTION

The Crab and Vela pulsars have shown that gamma rays emitted by pulsars, and the associated electrodynamical processes, together account for a substantial fraction of a spinning neutron star's rotational energy losses. However, despite some early reports that proved premature, additional confirmed examples of gamma-ray/radio pulsars have not yet been found. For this reason we have very little statistical information on the range of parameters and distinguishing characteristics of gamma-emitting pulsars. The greatly increased sensitivity of instruments aboard Gamma Ray Observatory now gives us new reason for hope, and I believe we can be reasonably confident that GRO will succeed in detecting at least a few more examples of periodically pulsed gamma rays from radio pulsars.

With the planned schedule for pointing the GRO spacecraft, a number of radio pulsars will simultaneously lie in the field of view for periods of about two weeks. Even for the very bright Crab and Vela pulsars, the number of gamma photons detected in this time will be orders of magnitude less than the number of elapsed pulsar periods. This sparseness of data, together with the substantial background levels, will make it extremely difficult to search for unknown (or poorly known) periodicities in the gamma-ray data treated by itself. On the other hand, if accurate radio timing data are available it will be possible to phase-resolve the gamma-rays, in turn, for each of the pulsars in the field of view. Histograms of the calculated phases will then represent the pulsar's integrated waveform at gamma-ray energies, and it will be possible to average these coherently for the duration of the pointing session or even over several sessions. For this technique to be effective, the gamma photons must time-tagged at the time of observation with an accuracy of $\lesssim 1$ ms. This will be accomplished easily by the instrumentation aboard GRO.

Although a definitive model for the emission mechanism of radio pulsars does not yet exist, enough is known that one can make educated guesses about which ones might be good gamma-ray candidates. However, the incremental cost of making timing observations of a sizable list of radio pulsars is small enough to encourage making the observing lists rather long, thereby hedging all theoretical bets and minimizing the chances that interesting gamma-ray pulsars will be overlooked for want of the necessary radio data. In planning the appropriate observing strategies it is important to note that the young, fast pulsars thought most likely to show detectable gamma-ray emission have much poorer rotational stabilities than older pulsars. For this reason, it is desirable that the radio timing observations be contemporaneous with the collection of gamma-ray data, or nearly so.

Efforts toward providing concurrent radio support observations have been started by groups using the Arecibo, Green Bank, Jodrell Bank, and Parkes radio telescopes. An attempt has been made to coordinate the observing lists, taking advantage of the differing sensitivities and sky coverage of the telescopes to maximize the size of the total list, while keeping redundancies to a minimum. Approximately 125 pulsars are being observed at Arecibo, 140 at Green Bank, 130 at Jodrell Bank, and 100 at Parkes. The details of the observing lists may change as observing experience is accumulated over the next few months, but I do not expect any significant reduction in the total number of pulsars being timed. (In fact, the observing lists are probably more likely to grow than to shrink.) In Figure 1, I present a map in galactic coordinates of the pulsars currently on the observing lists at the four Observatories.

II. PULSAR TIMING METHODOLOGY

My group at Princeton is concentrating its GRO-related efforts at two of the NRAO[1] telescopes at Green Bank: a 26 m antenna operated for the United States Naval Observatory, and the 42 m telescope. The majority of pulsars on our list require the sensitivity of the 42 m telescope, and data-taking for them is scheduled in sessions of several days duration every two to three months. Most of the observations are made at frequencies near 400 MHz, with a few others near 1420 MHz. A total of 115 pulsars are being observed in this program. The data acquisition system is based on a digital, FFT-based "spectral processor" recently completed by the NRAO electronics division. In our mode of operation, this specialized hardware records, every 2 minutes and for each sense of circular polarization, a two-dimensional array of measured intensities as a function of observing frequency and pulse phase. An example of such a data array is presented as a gray-scale plot in Figure 2.

Analysis of the data begins with the removal of obvious interference such as the several vertical and horizontal streaks in Figure 2 (which came from a distant thunderstorm and aircraft communications, respectively). The data are then "de-dispersed" by summing along sloping lines corresponding to the dispersion measure of the particular pulsar, and the resulting profile, similar to the one at the bottom of Figure 2, is matched with a standard profile to determine its phase at the accurately recorded time of observation. This procedure yields an equivalent pulse time of arrival, or TOA, with an accuracy that depends on the signal-to-noise ratio. Typical accuracies are around 10^{-3} to 10^{-4} periods.

[1]The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under an operating agreement with the National Science Foundation.

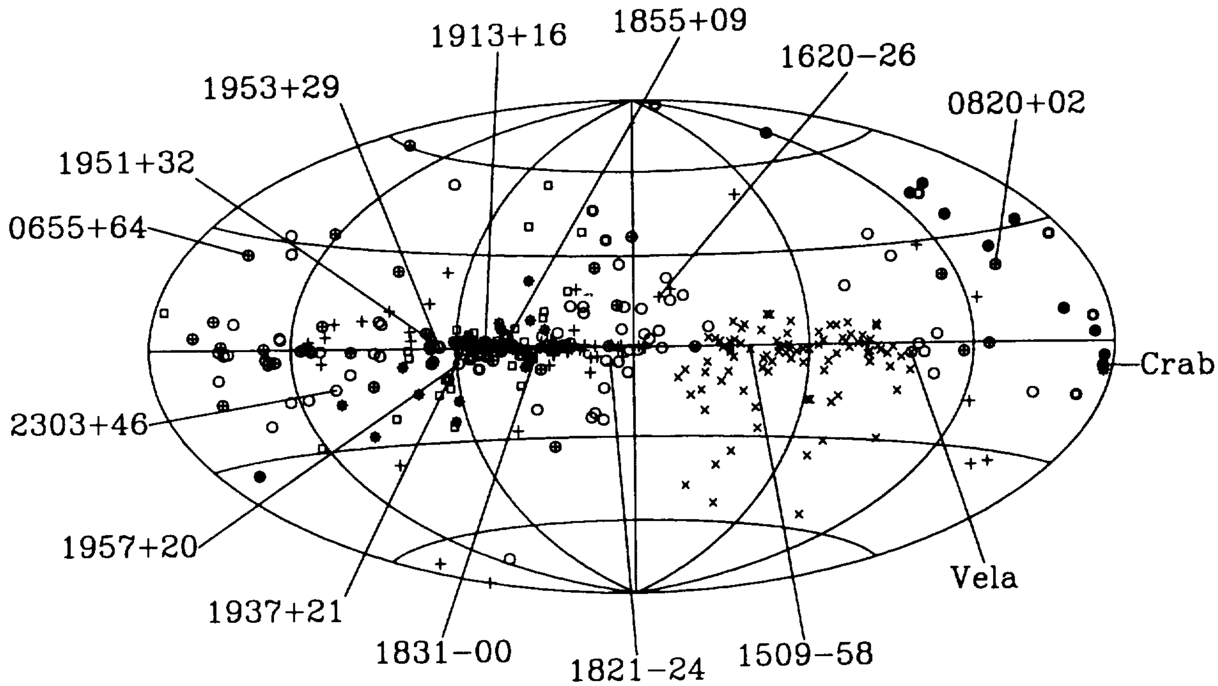

Figure 1: A map in galactic coordinates showing the radio pulsars being timed for GRO at four radio observatories: Arecibo (□), Green Bank (○), Jodrell Bank (+), and Parkes (×).

The strongest 35 pulsars being timed at Green Bank are observed much more often, using an automated system at the 26 m telescope. This antenna is used for VLBI observations (in connection with the timekeeping mission of the USNO) for 24 hours about every 5 days. For the remainder of the time it is dedicated to pulsar timing, using receivers built at NRAO for this purpose and a data acquisition and analysis system built at Princeton. The observations are made at a center frequency of 610 MHz, and profiles are recorded in 16 channels of 1 MHz bandwidth for each sense of circular polarization.

Telescope pointing and data acquisition chores are carried out by two 80286-class personal computers, loosely connected by a serial link carrying time and status messages every 10 seconds. The computers follow the same schedule, proceeding in sequence through a list of 35 pulsars and carrying out a 20- to 60-minute observation of each one. When an observation has been finished, the recorded data are sent over an Ethernet link to a minicomputer running UNIX, and stored there on disk. At 0200 local time every morning—when the minicomputer is generally not very busy—a background task awakens, processes any new pulsar timing data that it finds on its disk, and E-mails the new TOAs to Princeton. This system has been working reliably through most of 1989, and is now producing good TOAs for at least 29 pulsars, including several of the top prospects for detection by GRO.

III. STATUS REPORT

Some examples of standard profiles for pulsars observed with the 26 m telescope are

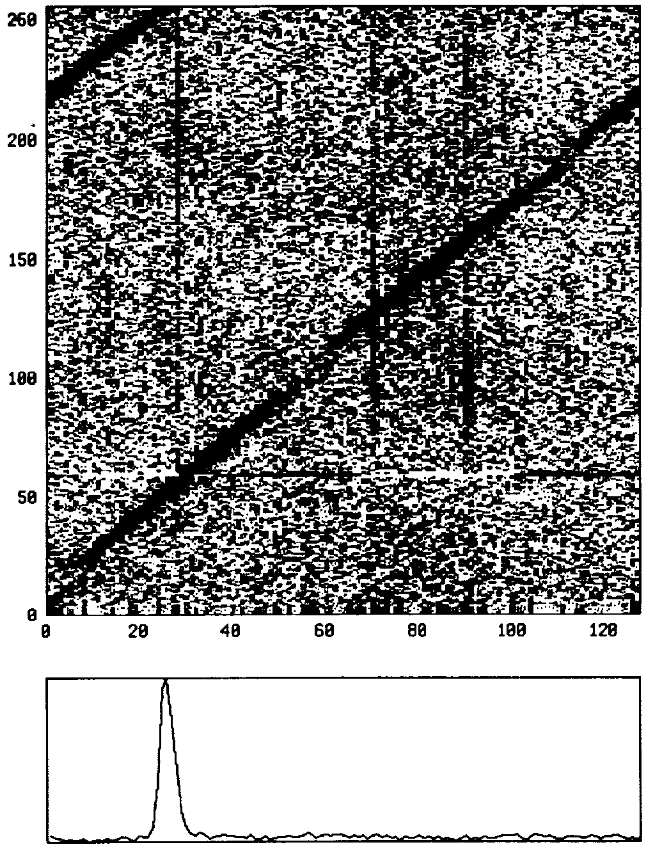

Figure 2: An example of data recorded using the NRAO Spectral Processor. The ordinate represents frequency channel number, in this case running from 400 MHz (bottom) to 380 MHz (top); the abscissa is pulsar phase over a full period. The de-dispersed average waveform of the pulsar is shown at the bottom.

shown in Figure 3. Similar profiles are now being produced from data recorded in the first three observing sessions with the 42 m telescope, in June, August, and October 1989, so that analysis of these data can proceed as well. After the standard profiles have been matched with observed profiles by a least-squares procedure, the resulting TOAs for each pulsar are accumulated in files from which they can be recalled and subjected to a multi-parameter solution for the relevant timing and astrometric parameters.

Post-fit residuals from the timing solutions are one of the best indicators of data quality, and they also yield interesting information on the amount of "timing noise" exhibited by a particular pulsar. Some representative plots of the residuals for PSRs 0329+54, 0740-28, and 1237+25 are presented in Figure 4. Parameters determined from these solutions are listed in Table 1, as an example of the information that the program will produce.

Table 1: Examples of Astrometric and Spin Parameters for Three Pulsars, from 1989 Data.

Parameter	PSR 0329+54	PSR 0740−28	PSR 1237+25
Right ascension (J2000) ...	03 32 59.44(4)	07 42 49.040(10)	12 39 40.43(9)
Declination (J2000)	+54 34 43.7(2)	−28 22 45.0(4)	+24 53 49.3(9)
Period (s)	0.714519923020(14)	0.166759979250(5)	1.38244920284(8)
Period derivative (10^{-15})...	2.079(15)	16.793(3)	0.96(8)
Epoch (JD−2440000)	7735.0	7735.0	7735.0

Figures in parentheses represent uncertainties in the last digits quoted.

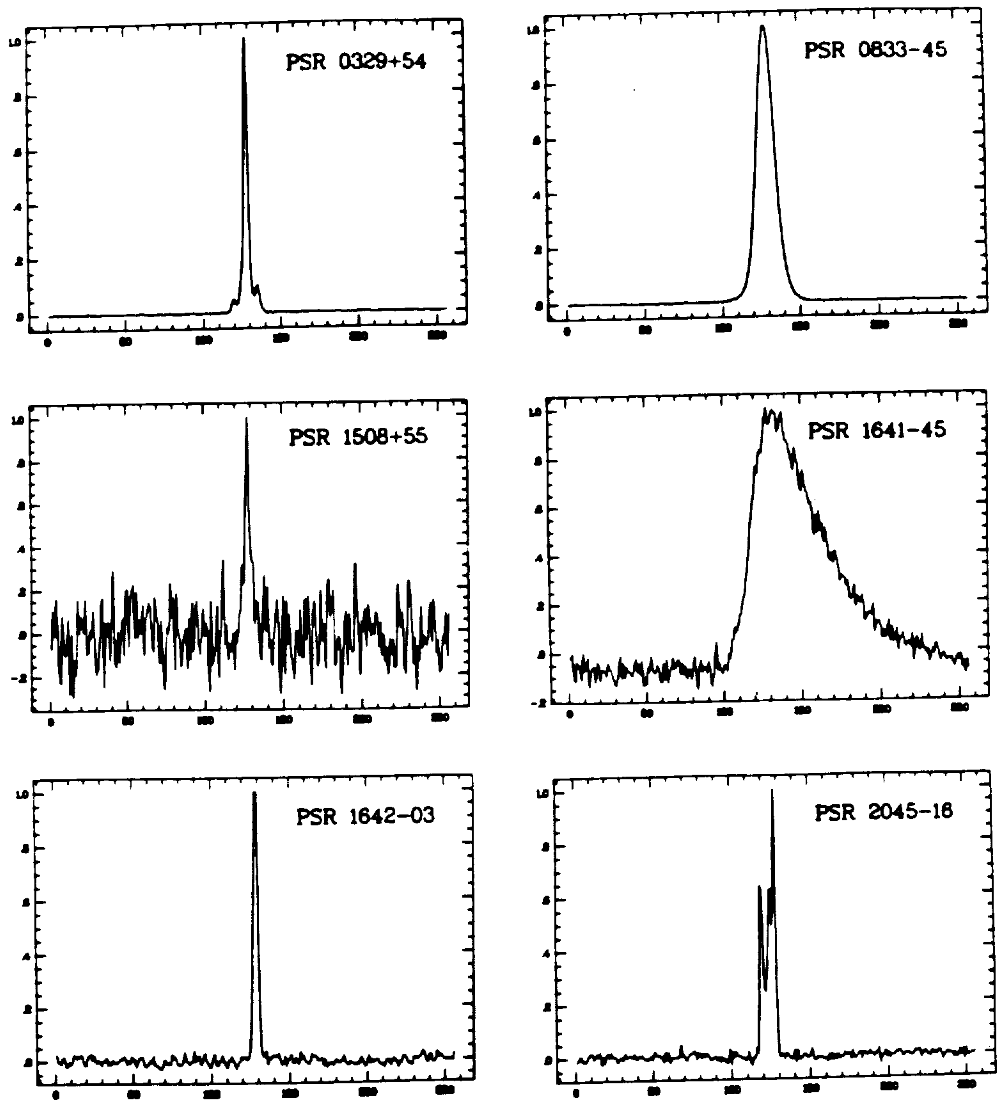

Figure 3: Standard profiles for nine pulsars being observed with the NRAO 26 m telescope at 610 MHz.

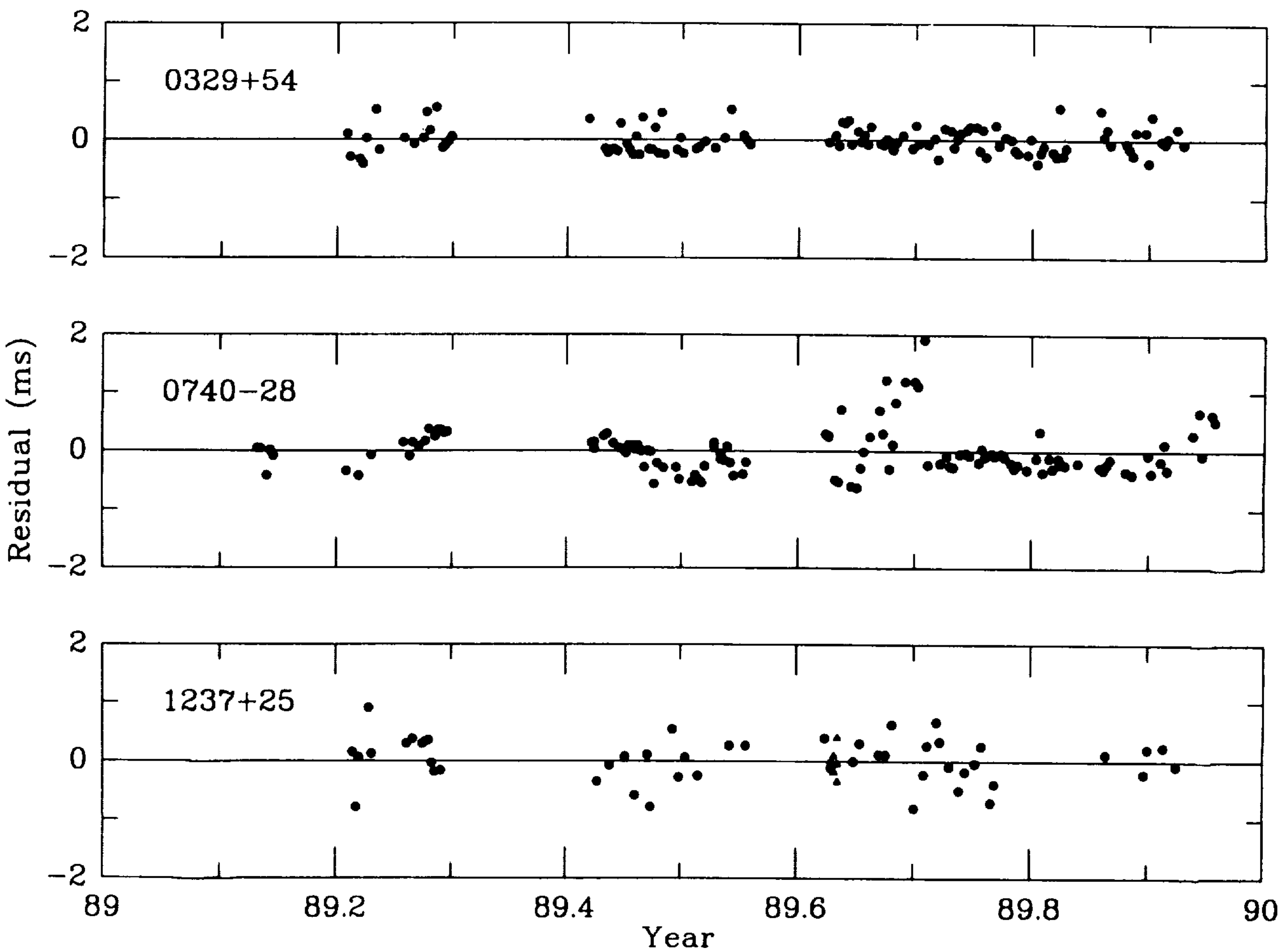

Figure 4: Post-fit residuals for timing observations of PSRs 0329+54, 0740-28, and 1237+25. The data have been averaged to a single equivalent arrival time per day. Filled triangles in the plot for PSR 1237+25 represent data taken with the 42 m telescope and the NRAO Spectral Processor; all other measurements were made with the 26 m telescope and the automated observing system described in the text.

I wish to acknowledge the essential contributions made to this project by D. R. Stinebring and especially D. J. Nice, who is responsible for much of the non-automated observing and the data analysis. F. Ghigo of the NRAO staff has been of great help in keeping the automated system on the 26 m telescope operational. Funding for the receiver and feed system on this telescope, and for some of the support services, was provided by the US Naval Observatory. I thank J. M. Cordes, A. G. Lyne, and R. N. Manchester, for keeping me informed about the parallel efforts being undertaken at the Arecibo, Jodrell Bank, and Parkes Observatories, and for furnishing their current observing lists.

DISCUSSION

R. Buccheri:

You have shown that for some pulsar the residuals are not randomly distributed around zero but show trends whose time scale may be of the order of the GRO observing time (2 weeks). A fit of radio pulses limited to the time interval where the trend is observed, could result in a value for period significantly different from that derived by radio measurements done once every three months?

Joe Taylor:

Although in a few extreme cases it is true that pulsar "timing noise" can be seen over time scales as short as a few weeks, the total phase variation over such an interval is a very small fraction of a period. Barring an actual "glitch" during a GRO pointing session, there should be no problem in assigning accurate pulsar phases to GRO gamma rays.

Jane MacGibbon:

Can you update us on the status of the limits on $G\mu$ in cosmic string theory from changes in the pulsar periods?

Joe Taylor:

High precision timing of millisecond pulsars at Arecibo shows phase fluctuations of no more than a microsecond or so over as much as seven years. This result implies an upper limit of $\Omega_g < 10^{-7}$ for the fractional energy density (relative to closure density) in a stochastic background of gravitational waves with periods around several years.