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PULSE TIMING STUDIES OF X-RAY PULSARS

Final Report for NASA Grant NAG 8-695

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1. Introduction

The pulse-timing projects supported by NASA Grant NAG 8-695 were motivated in large part by our long-standing interest in the physics of rotating neutron stars and particularly the variations in rotation due to internal and external fluctuating torques. For accretion-powered pulsars, observed as compact galactic X-ray sources, our work has been motivated by questions regarding the physics of matter accretion, mass transfer and mass loss in these X-ray binary systems. For rotation-powered pulsars, using X-ray, optical and radio observations, we have examined the internal structure of neutron stars and mechanisms for secular spin-down. These issues are still central to the continuing process of understanding the complex behavior of these fascinating systems.

The work supported by this grant is based mainly on Ginga observations of three pulsating X-ray sources. We observed two of these sources (Her X-1 and SMC X-1) within the framework of a NASA-ISAS program for U.S.-Japan collaborations to obtain and analyze Ginga observations. In addition, we joined with members of the Ginga team to apply our pulse-timing methods to PSR 0540-69 data obtained as a collateral benefit of the regular monitoring by Ginga of SN 1987A.

In addition to these Ginga observations, there exist other relevant data on all three of these sources. The direction of our investigations has been affected by the necessity of including these supporting data in our analyses, and setting up the necessary collaborations has sometimes entailed extra work that was not anticipated in our proposals. Indeed, we have often taken the initiative in establishing these joint projects. Following is a brief summary of our efforts by individual sources.

2. SMC X-1

F-α correlations in SMC X-1. As a general principal, X-ray pulsars experience a torque due to matter accretion. The sign and magnitude of the torque depend on the accretion rate, the nature of the magnetosphere, and the character of the accretion flow exterior to the magnetosphere. Many aspects of the physics of this accretion process can be inferred from observations of fluctuations in torque manifest through both deterministic and statistical characterizations of the consequent changes in neutron star rotation rate (Ghosh and Lamb 1979a,b and references therein). These theoretical ideas guided the planning and analysis of a pulse-timing study of Vela X-1, placing a number of constraints on the accretion process in this slow rotator (Boynton et al. 1984, 1986).

One outgrowth of this study was the development of criteria for further investigations into the nature of correlations between changes in rotation rate and X-ray flux (Deeter et al. 1992). We concluded that the primary consideration in selecting a candidate source was that the fluctuations in rotation rate of the neutron star stand out above noise on the shortest possible time interval, thereby providing the largest number of correlation pairs (F_X,α) per unit observing time. The most promising candidate under this consideration is SMC X-1. We obtained almost six days of high-count rate Ginga data on this source during August and September, 1988. The analysis of these data, however, has been considerably slowed due to an instability in the clock on board Ginga that affected the accuracy of time assignment at the millisecond level (Deeter and Inoue 1990).

Even with this complication, we have finished a first-pass pulse-timing analysis of the SMC X-1 data. The parallel task of constructing the X-ray light curve has been started. Much of our data was taken in PC mode, with only two energy channels. To provide a basis for removing the effect of cold-matter absorption on the X-ray flux, we examined the X-ray spectrum to derive a relationship between the absorption column density and the hardness ratio of the PC low energy and high energy channels. This portion of the analysis is nearly completed.

In addition to our observations of SMC X-1 discussed above, a second project entailing Ginga pulse-timing observations of this source has been carried out by S. Rappaport and A. Levine (MIT). They obtained some 3.5 days of observations in July 1989, with the principal goal of redetermining the orbital parameters in order to measure the rate of change of the orbital period of SMC X-1. Moreover, the data obtained by the MIT group represents a 50% increase over that available from our initial observations in 1988, and it would be advantageous to include this new data into our study of correlations between F and α. We have arranged with Rappaport and Levine to include their data in our study.

Change in orbital period for SMC X-1. A first-pass pulse timing analysis was necessary to determine the orbital parameters at the current epoch, since the only reliable orbit is from a much earlier study based on SAS 3 data (Primini et al. 1977). Using our Ginga data, plus a short observation from the satellite check-out phase in May 1987, we discovered a significant secular decrease in the orbital period of SMC X-1 (Deeter and Boynton 1990), similar to that already seen in Cen X-3 (Kelley et al. 1983).

As with the F-α correlation study, the most effective use of Ginga data for a determination of the change in orbital period of SMC X-1 clearly requires a uniform analysis of all the available observations, including the MIT observations in 1989 and our own in 1988. In discussing this matter with Rappaport and Levine, we reached an agreement to combine all the relevant Ginga data and publish a joint paper on the orbital period change of SMC X-1, which is currently in preparation (Levine et al. 1992). The resulting improved orbital solution will enhance the reliability of the pulse-timing part of our original project to study correlations between X-ray flux and angular acceleration in SMC X-1.

3. Her X-1.

Decrease in orbital period for Her X-1. In collaboration with S. Miyamoto and S. Kitamoto (Osaka U.), we proposed an extensive series of Ginga observations of Her X-1, with the primary purpose of testing various models of the 35-day cycle by tracking the evolution of the pulse shape. We subsequently obtained data on twelve separate days during a 44-day span in April-June 1989, including two consecutive MAIN HIGH states and the intervening SHORT HIGH state.

As a first step in the treatment of these data, we performed a pulse-timing analysis to determine local orbital parameters and establish the behavior of the pulse frequency for subsequent aspects of this investigation. The results of this initial analysis, combined with all available historical data indicate a significant ($\sim 10\sigma$) change in orbital period over the interval 1971--1989. This change is substantially larger than expected from simple models of mass transfer and/or loss, suggesting a more complicated mechanism such as a magnetically channelled wind from the surface of the companion star. This analysis also provides improved constraints on the ''slaved disk'' mechanism for the 35-day clock in this system. In this model, the forced precession of an obliquely rotating stellar companion results in a compensating precession of the orbital plane, producing a potentially detectable 35-day periodic change in the orbital parameters (Deeter and Boynton 1976). The results of this study have now been published (Deeter et al. 1991).

Models for HIGH-LOW cycle in Her X-1. We have finished the pulse-timing phase of the analysis of the Ginga data on Her X-1, and are currently engaged in an analysis of the 35-day evolution of the pulse profile. The ultimate goal of this project is to test models of the 35-day cycle, such free precession of the neutron star (Trümper et al. 1986), and the precessing disk model (Petterson 1975, 1977). This study is now under way as part of the doctoral thesis research of M. Scott (U. Washington), and concurrently we are preparing a paper for publication (Miyamoto et al. 1992).

Cyclotron feature in Her X-1. A portion of the 1989 Ginga observations of Her X-1 were performed with an extended high-energy cutoff, enabling improved detection of a cyclotron resonance feature at about 34 keV and providing a relatively high precision measure of the magnetic field, B = $3.0 \pm 0.3 \times 10^{12}$ G (Mihara et al. 1990). Pulse phase sampling and differencing were employed to reduce the uncertainty in background subtraction.

4. PSR 0540-69

J. Deeter, F. Nagase (ISAS), and other members of the Ginga team have analyzed extensive Ginga pulse-timing observations of PSR 0540-69 (a Crab-like, 50 ms pulsar in the LMC). They have determined a remarkably precise value for the braking index ($n = 2.01 \pm 0.01$) from just one year of data (Nagase et al. 1990). Braking indexes have been measured for only two other pulsars, this one exhibiting the most significant departure from $n = 3$, the value appropriate to braking from magnetic dipole radiation.

Because pulsations of PSR 0540-69 are not detectable in the radio band and are very weak in the optical, the Ginga X-ray observations constitute the largest existing data set for studying this pulsar. It is therefore critical that our pulse-timing analysis of the first part of the Ginga observations be extended to the entire data set. The field including SN 1987A and PSR 0540-69 has continued to be monitored about every six weeks since October 1988 (the cut-off date for data included in the study by Nagase et al. 1990), and useful observations have been obtained up to demise of Ginga in November 1991.

An analysis of the entire data set should give not only an more precise value for the braking index, but it will also provide additional valuable information. For instance, we will be able to determine an improved value for the celestial position of PSR 0540-69, which was not possible over the 16 month span covered by the current analysis. Furthermore, we should be able to detect or place strong limits on glitching behavior or other irregularities in pulsar rotation.

During the period covered by Grant NAG 8-695, we have set up two new collaborations to pursue pulse timing studies into behavior of this interesting pulsar. One project involves a joint analysis of Ginga observations of PSR 0540-69 and overlapping optical data obtained by Manchester and Peterson (1989), and the other entails combining more recent Ginga observations and Rosat and optical data obtained by Gouiffes, Finley, and Ögelman (1992). The goal of these studies is to extend coherent pulse timing over the longest possible time span (Deeter 1991a), and to compare the relative phase of optical and X-ray pulse profiles (Deeter 1991b).

5. Summary

The research supported by Grant NAG 8-695 comprised three projects based primarily on Ginga observations. All were initiated as collaborations with scientists in Japan working in the field of high-energy astrophysics, arranged through an NASA-ISAS program established for that purpose. We proposed and carried out much of the Ginga observations for the Her X-1 and SMC X-1 projects, and became involved with the Ginga team in the PSR 0540-69 program as a natural application of our pulse-timing methods.

This research has resulted in three papers published in refereed journals, which present our results on the braking index for PSR 0540-69 (Nagase et al. 1990), on a cyclotron feature in the spectrum of Her X-1 (Mihara et al. 1990), on the detection of a decrease in the orbital period for Her X-1 (Deeter et al. 1991). We are currently preparing two papers for publication, one on orbital decay in SMC X-1 (Levine et al. 1992), and a second on the 35-day evolution of the pulse profile in Her X-1 (Miyamoto et al. 1992). In addition, we have published two papers informally, one dealing with on the stability of the Ginga clock (Deeter and Inoue 1990), and second based on a talk given at the Izu conference on Ginga results (Deeter 1989). We have also written three reports intended for limited circulation, primarily among our collaborators: one which attempts to resolve apparent inconsistencies among published pulse-timing results for PSR 0540-69 (Deeter 1991a), a second which compares the phases of optical and X-ray pulse profiles in PSR 0540-69 (Deeter 1991b), and a third which gives a preliminary value for the change in orbital period for SMC X-1 (Deeter and Boynton 1990). Abstracts of these papers and reports are given in the Appendix.

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