THE PULSATION PERIOD AND POSSIBLE ORBIT OF 1E2259+586

G.G. Fahlman and P.C. Gregory
University of British Columbia
Vancouver, B.C. V6T 1W5 Canada

The currently known characteristics of the unique x-ray pulsar 1E2259+586 are briefly reviewed. The results from a recently completed analysis of the x-ray photon arrival times recorded by the Einstein Observatory are presented. The pulsar light curve has changed shape between two epochs separated by six months. The true pulse period is 6.978632 sec, double the previously reported value. In addition, there is evidence for orbital motion with a period close to 2300 sec. Some implications of this orbit are briefly discussed.

1. INTRODUCTION

The x-ray pulsar 1E2259+586 is unique in that it is located at the geometric center of curvature of a large semi-circular shell of diffuse x-ray emission (Gregory and Fahlman 1980, Fahlman and Gregory 1981). The shell has a radio counterpart and has been identified as a supernova remnant (SNR), designated by us as G109.1-1.0. Its distance and age are estimated as 3.6 ± 0.4 kpc and $\sim 10^4$ yrs. The compact x-ray source appears to be connected to the diffuse shell by a long curving arc of x-ray emission. This, together with its central location is compelling evidence that 1E2259+586 is the stellar remnant of the supernova explosion responsible for G109.1-1.0.

The x-ray spectrum of the compact source is harder than that of the diffuse emission. Acceptable fits to the output of the IPC pulse height analyser are obtained for thermal spectra with kT>1.0 kev and low energy absorption equivalent to a line of sight column density of $N_H \simeq 0.8 \times 10^{22}$ cm^{-2}. This column density is consistent with our estimate of the distance to the diffuse remnant and leads to a luminosity in the IPC band (0.5-4.0 kev) of $L_X \simeq 2 \times 10^{35}$ ergs S^{-1}. This luminosity is consistent with the object being a neutron star accreting mass.

The pulse period derived from an IPC observation in June 1980 was found to be 3.4890 sec (Fahlman and Gregory 1981). Subsequent observations, discussed below, indicate that the pulse period should be

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 445–453.

https://doi.org/10.1017/S0074180900034252 Published online by Cambridge University Press

double this value. In any event the period is long enough to indicate that the object is not a classical pulsar powered by the rotational energy of the neutron star. It appears to be an accretion powered pulsar and is probably a member of a binary star system.

We have spent considerable effort in a search for an optical counterpart and had suggested an identification with a faint, B $\approx$ 22 mag. star (Fahlman et al. 1982). On the basis of recent optical photometry, carried out at KPNO in Sept. 1982 by J. Middleditch and G. Fahlman, it appears that the counterpart is actually the even fainter star (B $\approx$ 23.5 mag.), located just 3 arc sec. SE of the earlier candidate (see Figure 1 of Fahlman et al. 1982). This work will be discussed in more detail elsewhere. The point to note here is that the optical counterpart is very faint and cannot be a massive star. Hence, the postulated binary containing 1E2259+586 is very dissimilar to the well known binary SS 433. The 1E2259+586 system apparently belongs to the group of low mass x-ray binary systems (see van Paradijs, 1981 for a discussion of their properties) and is the only such object associated with a diffuse remnant.

The existence of a compact interacting binary system at the center of a relatively young SNR is unexpected (van den Heuvel 1981 a,b; Tutukov 1981) and, clearly, the properties of this system are of more than usual interest because of this. Here we will present the main results from our analysis of the x-ray photon arrival times taken from observations made at two epochs with the Einstein Observatory.

2. Results from the Photon Arrival Time Analysis

The data discussed here is taken from the Einstein IPC observations described in Table 1. The photon arrival times were corrected for earth and satellite motion using the ephemeris program installed at the Harvard-Smithsonian Center for Astrophysics (R.F. Harnden, private communication).

Table 1
IPC Observation Summary

DESIGNATION	I8102	I9984	I9985	I9986
DATE (m/d/y)	7/7/80	1/23/81	1/24/81	1/25/81
DURATION (sec)	7864	4588	3318	5243
SOURCE ON TIME (sec)	5205	3079	3282	3217
Mean Count Rate	0.90	0.79	0.81	0.83

2.1. The Pulsar Light Curve

The second epoch observations (I9984, -5, -6) were combined to define the dominant pulse period via a fine grained folding analysis. The period derived in this way was P = 3.48931 ± 0.000007 sec; the same to within the error as the period derived from the first epoch data (I8102), P = 3.48932 ± 0.000015 sec. Unexpectedly, a power spectrum

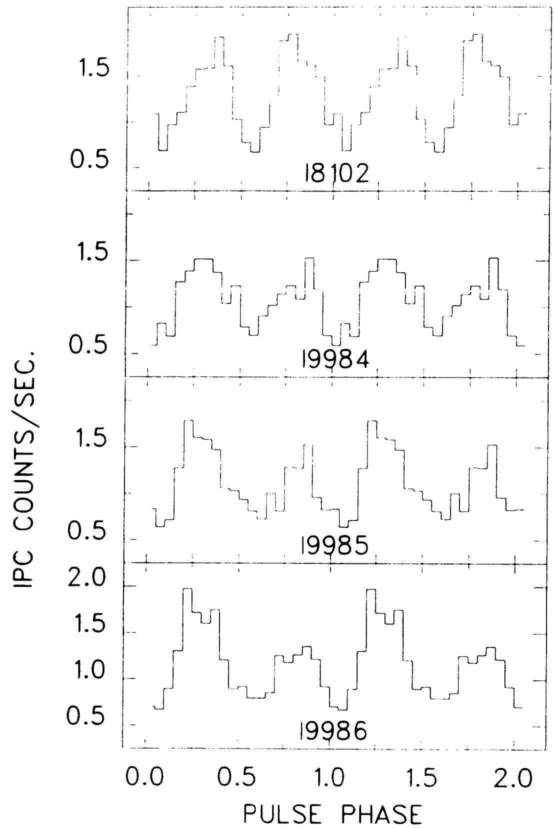

Figure 1: Pulsar light curves. Two cycles of the P = 6.978632 sec. pulse are shown with 20 bins per cycle. Zero phase is set arbitrarily but all four data sets have been aligned in phase. Note that the modulated signal is sitting on top of a constant flux of approximately 0.5 counts/sec. The data shown is that in a box with a length of 4 arc min. per side centered on the pulsar. The background from the diffuse source is expected to contribute no more than 0.05 counts/sec in this field.

of the continuous data in I9985 showed a significant peak at the frequency corresponding to double the best folding period, i.e., at 143.3 mHz (the fundamental). The power in the first harmonic (286.6 mHz) was almost an order of magnitude larger than that in the fundamental. A power spectrum of a comparable continuous data segment in the I8102 data did not show significant power at 143.3 mHz. At this epoch then, the two poles of the pulsar were statistically indistinguishable.

The light curves obtained by folding our data at a period of 6.978632 sec are shown in Figure 1. It is quite clear that a change in the observed character of the pulses has occurred and that the true pulsar period is 6.978632 sec.

Since pulsars in general are thought to be oblique rotators, the most direct way of accounting for the difference in the light curve is to postulate a change in the inclination angle of the rotation axis of the neutron star relative to our line of sight. In other words, the neutron star may be precessing.

The change in the pulsar light curve introduces some ambiguity in phasing the two epochs together. If we adopt the zero phase time and pulse period for the second epoch and count cycles back to the first epoch we find a phase discrepancy which has two possible values depending on which half of the 6.978632 sec period is used to match phases. The best fitting period for both epochs is either P = 6.97863313 or P = 6.97863173 with an error of $\pm$ 0.14 x 10^{-6} sec. Of course this period is strictly nominal because whole cycles lost between the two epochs would not be detectable. If we interpret the phase discrepancy as a period change then the pulsar is speeding up with an average $\dot{P} \simeq -7 \times 10^{-14}$ or slowing down with $\dot{P} \simeq 2 \times 10^{14}$. Following Rappaport and Joss (1977), we might have expected spin up to occur at a rate of $\dot{P} \sim -2 \times 10^{-12}$. The difference between the predicted and 'observed' $\dot{P}$ can be eliminated if some 5 cycles were lost in the six month interval. If we simply use the best period available at the two epochs, we can place an upper limit to the period change of $|\dot{P}| \lesssim 2 \times 10^{-11}$. Evidently third epoch x-ray data is needed to pin down any period change.

2.2. Orbital Motion

The three consecutive observations in January 1981 were used in a modified pulse arrival time delay analysis to look for evidence of orbital motion. The procedure used was as follows:

(i) assume a trial orbital period P_o,

(ii) bin the photon arrival times according to orbital phase,

(iii) fold in each orbital bin at the dominant pulse period (3.489316 sec),

(iv) cross-correlate these pulses with a suitable template and determine the position of the maximum in the cross-correlation function,

(v) the variation on the position of the maximum of the cross-correlation function measures the time delay in the pulse arrival relative to a fixed epoch; it is examined for evidence of Keplerian motion (essen-

https://doi.org/10.1017/S0074180900034252 Published online by Cambridge University Press

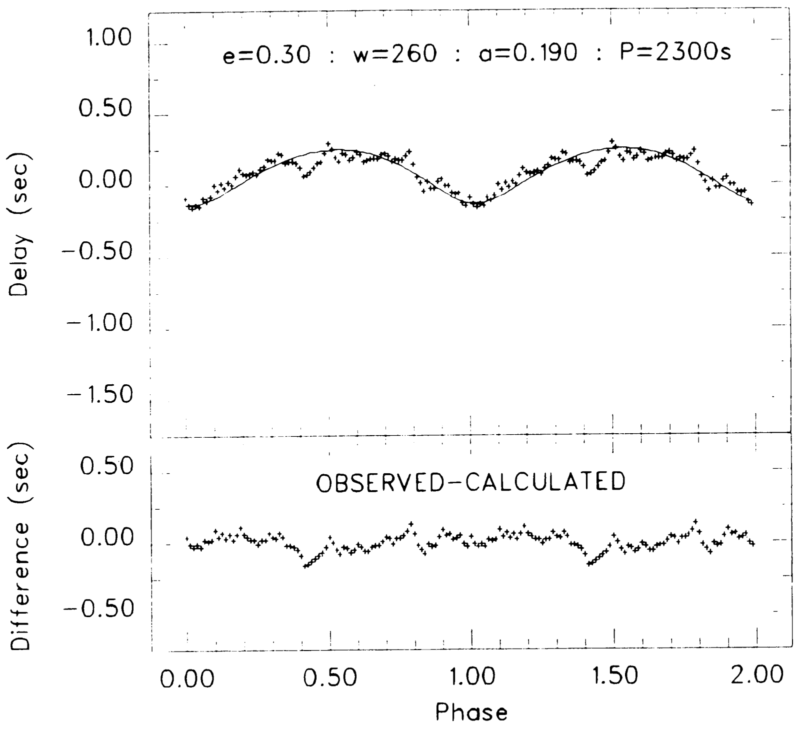

Figure 2: Orbital Motion. The upper panel shows the time delay points determined by the method described in the text. The solid line is the model with the parameters shown: e is the eccentricity, w is the argument of periastron, a is the projected semi-major axis of the pulsar orbit around the center of mass of the system measured in light seconds. Two complete cycles of the orbit are shown. The lower panel shows the residuals from the model fit on the same scale as the upper panel. It is apparent that the residuals are dominated by a distinct minima centered at phase ~0.4. This may well be an artifact of the method and should not be considered significant at this time.

https://doi.org/10.1017/S0074180900034252 Published online by Cambridge University Press

tially one looks for a smooth variation with orbital phase).

A systematic search for orbital periods between 1000 and 10,000 sec was made. The large gaps in the data prevented all independent periods in this range from being checked and generally complicated the interpretation of the results obtained from an automated search program. Moreover, to achieve adequate resolution, we settled on a minimum number of bins (orbital + pulse) of 80 which resulted in an effective (modulated) signal to noise ratio in each bin of between 3:1 and 5:1.

Within the range searched, the only reasonably coherent variation was found for orbital periods near 2300 sec. In Figure 2, we show a typical solution for the variation seen at P_o = 2300 sec. Similar phase modulations are seen for the trial orbital periods within about 30 sec of this value but, in view of the gaps in the data the real uncertainty in the period is perhaps two or three times greater. To obtain the data points shown in Figure 2, overlapping orbital phase bins were used; there are actually only eight completely independent orbital phase points.

The Keplerian orbit fitted to the data points requires the specification of four parameters: ω, the argument of periastron; e the eccentricity; a_x sini (designated simply as a on the plot), the projected semi-major axis measured in light seconds and ϕ_o, a parameter to determine the epoch of periastron. Given trial values of e and ω, a_x sini and ϕ_o were found by fitting a normalized model curve to the data; the best fit being determined by a least squares criterion. Provision was made for some manual adjustment of these latter two parameters because the residuals are dominated by systematic effects. The complexity of projected Keplerian motion allows virtually any reasonably smooth curve to be fitted with some combination of parameters. The particular fit shown is representative of the best solutions obtained. Similar results are obtained for a fairly wide range of parameters:

$$0.16 \lesssim a_x \sin i \lesssim 0.21; \; 200^\circ \lesssim \omega \lesssim 280^\circ; \; 0.15 \lesssim e \lesssim 0.55 \qquad (1.)$$

In the case of the eccentricity, a wide range gives formally acceptable fits but values below about 0.2 generally show objectionable (even by the standards used here!) systematic departures from the data.

From a purely statistical point of view, none of the fits is particularly impressive - the rms residual after fitting a finite amplitude model are typically only a little more than a factor of two better than 'fitting' a zero amplitude model. The I8102 data covers slightly more than three of these orbits but a similar analysis of that data set did not reveal orbital phase modulation. However, for this data set the signal to noise in a given phase bin is so low (~3:1 on average) that any small amplitude phase modulation is expected to be hidden by the errors in determining the pulse phase.

It should be evident from the forgoing remarks that the results suggesting orbital motion must be regarded with caution. Nevertheless, the 2300 sec orbit is consistent with the 1 mHz downshift (at the 3.5 sec period) in the infrared observations noted in Fahlman et al. (1982) and discussed more thoroughly by Middleditch, Pennypacker and Burns (1982, preprint). A similar downshift was noted by Middleditch and Fahlman in their optical observations mentioned earlier. The available x-ray data has been all but exhausted and further progress in studying the binary nature of the source will undoubtably come by pursuing the optical and infrared observations already initiated.

3. Comments on the Nature and Origin of the Binary System

The spectroscopic mass function obtained from the orbital solutions discussed here is

$$m_2^3 \sin^3 i \,/\, (m_x + m_2)^2 = 0.008 \pm 0.0002\ M_\odot \quad . \qquad (2.)$$

For a reasonable pulsar mass $m_x = 1.0\text{-}1.4\ M_\odot$, the mass of the secondary is $m_2 \gtrsim 0.2\ M_\odot$. If the companion is a normal main sequence star, its radius would exceed the characteristic radius of its Roche lobe by a factor of at least two. The relatively low x-ray luminosity is inconsistent with a high rate of mass transfer and the extreme faintness of the companion shows that an optically bright accretion disk is absent. Consequently, the companion is unlikely to be filling its Roche lobe (except perhaps near periastron) let alone exceeding it by a factor of two or more. We are forced to conclude that the companion is not a normal low mass main sequence star. The possibility that it is a degenerate star can be entertained. Here, the difficulty is just the opposite - a normal degenerate star with the minimum mass of 0.2 $M_\odot$ and hence the largest radius, would underfill its Roche lobe by a factor of about 5, even at periastron (for $e \simeq 0.3$). The system would be fully detached and presumably quiescent. It would be possible to induce some mass flow if the eccentricity is sufficiently high, $e \gtrsim 0.8$. Such high values are outside the range of the good fits to our data but cannot be totally ruled out since our analytic method would tend to underestimate the true eccentricity of such nearly rectilinear orbits. Further study on this point is needed. Continued observations of the infrared and optical pulses from the system will likely put better constraints on the secondary than the x-ray data.

The supernova configuration must have been even more massive and compact than the current system. Assuming an initially circular orbit and adopting a current eccentricity of 0.3, we can estimate the mass ejected by the explosion (Wheeler, Lecar and McKee, 1975). Ignoring the possible momentum transfer to the companion from incident ejecta (Fryxell and Arnett, 1981), we estimate an ejected mass of ~0.2-0.3 $M_\odot$ which implies that the original orbit was some 30% smaller than the observed now. Such a system would be much more compact than any of the known cataclysmic variables which might otherwise be considered as plausible precursors to 1E2259+586. In effect, this is also an

https://doi.org/10.1017/S0074180900034252 Published online by Cambridge University Press

argument against the companion being a non-degenerate dwarf.

An alternate possibility is that the precursor consisted of two degenerate dwarfs. Two spectacular examples of twin degenerate interacting binaries are HZ 29 (Patterson et al. 1979) and G61-29 (Nather, Robinson and Stover, 1981). Since both of these systems are thought to have extremely small mass ratios, they are probably not examples of the immediate percursor to 1E2259+586. Rather it is some variant of the parent to those systems which might be imagined as the precursor to 1E2259+586. An interesting discussion of the evolutionary paths leading to twin degenerate systems is given by Nather, Robinson and Stover (1981). One difficulty with this picture is that the mechanism which triggered the supernova is not clear. The obvious possibility is catastrophic mass loss from the smaller to the larger star but, given a companion mass of ~0.2-0.3 $M_\odot$ and the assumption that it must fill its Roche lobe, this would imply such a small initial orbit that the current orbit would be unattainable through impulsive mass loss associated with the supernova explosion.

Until the nature of the secondary is known, i.e., whether it is degenerate or not, one has little basis for further speculation on the precursor system. If the secondary is degenerate then one might hope to observe the relativistic periastron advance of the orbit (Will, 1975):

$$\dot{\omega}_R = 6\pi \frac{(GM)}{C^2} \left[P_o \; a(1 - e^2)\right]^{-1} \qquad (3.)$$

For reasonable system parameters, $a_x \sin i$ = 0.175 light-seconds and e = 0.3, we find $\dot{\omega}_R \simeq 100^\circ \; (M/M_\odot)^{4/3} \; yr^{-1}$, where M is the total mass of the system. If the companion is not degenerate, then a large quadruple component to the periastron shift will be added to this value. Hence, an observation of the periastron shift, could provide an important constraint on the secondary. Further optical/infrared studies could provide this data.

ACKNOWLEDGEMENT

Our work is supported through grants from the Natural Sciences and Engineering Research Council of Canada. We are very grateful to the staff at the Einstein Observatory data center, in particular Rick Harnden, for their assistance.

REFERENCES

Fahlman, G.G. and Gregory, P.: 1981, Nature 293, 202.
Fahlman, G.G., Hickson, P., Richer, H.B. and Middleditch, J.: 1982, Astrophys. J. 261, L1.
Fryxell, B.A. and Arnett, W.D.: 1981, Astrophys. J. 243, 994.

Gregory, P.C. and Fahlman, G.G.: 1980, Nature 287, 805.
van den Heuvel, E.P.J.: 1981a, in "Fundamental Problems in the Theory of Stellar Evolution" (D. Sugimoto, D.Q. Lamb and D.N. Schramm, eds.), Reidel: Dordrecht, pp. 155-175.
van den Heuvel, E.P.J.: 1981b, Space Sci. Rev. 30, 623.
van den Paradijs, J.: 1981, Astron. Astrophys. 103, 140.
Patterson, J., Nather, R.E., Robinson, E.L. and Handler, F.: 1979, Astrophys. J. 232, 819.
Rappaport, S. and Joss, P.C.: 1977, Nature 266, 683.
Tutukov, A.V.: 1981, in "Fundamental Problems in the Theory of Stellar Evolution" (D. Sugimoto, D.Q. Lamb and D.N. Schramm, eds.), Reidel: Dordrecht, pp. 137-154.
Wheeler, J.C., Lecar, M., and McKee, C.F.: 1975, Astrophys. J. 200, 145.
Will, C.M.: 1975, Astrophys. J. 196, L3.