BRAKING INDEX OF GEMINGA PULSAR

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ABSTRACT

The pulsar Geminga, also known as 2CG195+04, IE0630+178 and the faint star G'', is a remarkable object in the sense that its energy output is almost all in high energy gamma rays. The braking index,

$$n = f \times \ddot{f}/(\dot{f})^2$$

as obtained from the elements given by *any one* group of authors (Hermsen *et al.*; Bertsch *et al.*) based on their own data set appears to be too high or has a very large upper limit compared with 3, the value expected for magnetic dipole radiation.

Rather than fitting a polynomial in elapsed time to the event phases over different data sets, we have taken a different approach to determine $\ddot{f}$. Hermsen *et al.* (1992) and Mattox *et al.* (1994) have determined f and $\dot{f}$ from *COS-B* and *EGRET* data respectively at two widely separated epochs. Assuming that there were no glitches, we obtained $\ddot{f}$ by dividing the difference in $\dot{f}$ values at the two epochs by the time difference between the two epochs; the resulting value of $\ddot{f}$ is $(3.85 \pm 1.19) \times 10^{-26}\ s^{-3}$. Combining this with the f and $\dot{f}$ values we obtained a value of (4.3 ± 1.3) for the braking index. This value agrees well with the expected.

1. Introduction

High Energy Gamma Rays (HEGR) with energies $\geq 50\ MeV$ from celestial sources were observed by a series of satellite-borne detectors — $SAS-2$[1], $COS-B$[2] and $EGRET$[3] — with progressively increasing sensitivity. Based on the results [Fichtel *et al.*[4]] from the latest and most sensitive detector ($EGRET$), one can characterise the HEGR sky as consisting of a strong diffuse radiation by the Galactic center and disk, emission from 5 pulsars, atleast 21 AGNs and 16 unidentified sources. If marginal detections with $\geq 4\sigma$ are included, these numbers increase further. Geminga is one of the 5 HEGR pulsars detected so far, the others being the Crab and the Vela pulsars and PSR1055-52 and PSR1706-44.

Geminga was discovered by Fichtel *et al.*[5] with the $SAS-2$ detector. It is now known that the objects variously referred to in the literature as Geminga, 2CG195+04, the X-ray object 1E0630+178 and, most probably, the faint blue star G'' all refer to the same object with the $J2000$ co-ordinates of $R.A = 6h\ 33m\ 54.02s$ and $\delta = +17^\circ\ 46'\ 11''.5$ and located at a distance of $\sim$ 100 *to* 1000 *pc* from Solar system. During the seventies and eighties there were several erroneous claims for a periodicity $\sim 59\ s$ in X-ray, HEGR and TeV gamma ray emissions. Recently Halpern and Holt[6], using a deep $ROSAT$ X-ray observation have convincingly demonstrated that the true period of Geminga pulsar is $\sim 237\ msec$. Soon Bertsch *et al.*[7] found the same periodicity in HEGR from the $EGRET$ data and further concluded that Geminga is a rotating magnetised ($B \sim 1.6 \times 10^{12}$ G) neutron star, with a slow-down energy loss rate of $\sim 3.5 \times 10^{34}\ erg.s^{-1}$ and a characteristic age of $\sim 3.2 \times 10^5\ yr$. Searches of the $COS-B$ and $SAS-2$ archival data have also confirmed[8–10] the 237 msec periodicity. Bignami *et al.*[11] measured the proper motion of G'' to be $\sim 0''.17\ yr^{-1}$. A search for radio pulsations, however, did not find[12] any 237 msec pulsations at $\geq$ 1 mJy. In the TeV energy range, there were two claims[13,14] of detection and one[15] of non-detection of pulsations at 237 msec periodicity.

It is clear that Geminga is a unique object shining brightest in HEGR, with luminosity ratios of $L_{HEGR}/L_{X-rays} \sim 10^3$, $L_{HEGR}/L_{opt} \sim 2 \times 10^6$ and $L_{HEGR}/L_{TeV\gamma} \geq 150$. Geminga can truly be called a high energy gamma ray pulsar.

2. Braking Index

A rotating non-aligned magnetic neutron star loses energy by emission of electromagnetic radiation and it is expected theoretically

$$\dot{\Omega} = -k \times \Omega^n \qquad (1)$$

where Ω is the angular velocity of rotation of the neutron star, $\dot{\Omega}$ its first time derivative and n, the braking index. From (1) it follows

$$n = \Omega\ddot{\Omega}/\dot{\Omega}^2 = f\ddot{f}/\dot{f}^2 \tag{2}$$

Here f is the rotation frequency (cycles/sec) of the pulsar. For an ideal rotating magnetic dipole, the theoretical value for the braking index is 3. In reality the braking index could differ from this value; for example, the Crab pulsar, PSR0540-69 and PSR1509-58 exhibit braking indices of 2.50 ± 0.01, 2.04 ± 0.02 and 2.80 ± 0.01 respectively. Glitches, timing noise and moving crust of the neutron star might be responsible for the discrepancy. To estimate the braking index to within an error of, say, 1%, one has to obtain f, $\dot{f}$ and $\ddot{f}$ to accuracies better than 1 %.

3. Determination of f, $\dot{f}$ and $\ddot{f}$

First one reduces the observed event times of gamma rays to solar system barycenter to correct for the earth's orbital motion and rotation. One, then, expresses the number of rotations of the pulsar upto i^{th} event time by

$$m_{rot} = f \times T_i + \frac{1}{2} \times \dot{f} \times T_i^2 + \frac{1}{6} \times \ddot{f} \times T_i^3 \tag{3}$$

where $T_i = t_i - t_0$. Here t_0 is an arbitrary epoch at which the phase of the pulsar equals 0. The difference between m_{rot} and its nearest integer is called residual. One minimizes the residuals to obtain the best fit for f, $\dot{f}$ and $\ddot{f}$. While f can be obtained reasonably accurately in a relatively short data span, the other two terms $\dot{f}$ and $\ddot{f}$ require rather long duration data spans. One requires data time streams of durations of $\sqrt{2 \times \delta m/\delta\dot{f}}$ and $\sqrt[3]{6 \times \delta m/\delta\ddot{f}}$ to obtain $\dot{f}$ and $\ddot{f}$ to within errors of $\delta\dot{f}$ and $\delta\ddot{f}$ respectively. As an example, for $\delta m = 0.03$, $\delta\dot{f}/\dot{f} \approx 0.01$ and $\delta\ddot{f}/\ddot{f} \approx 0.01$, one needs, in the case of Geminga, data streams of $63\,d$ and $27\,yr$ respectively. The data streams of $COS-B$ and of $EGRET$ (upto now) are only of approximately 7 and 2.8 years long. This is the major reason why Hermsen *et al.*[8] could determine $\ddot{f}$ only to an accuracy of 60%.

As examples we reproduce below two of the published ephemerides of the Geminga pulsar: the first set by Hermsen *et al.*[8]

$$\begin{aligned} t_0 &= JD\,2443946.5 \\ f &= 4.21775012277(24)\,s^{-1} \\ \dot{f} &= -0.1952379(24) \times 10^{-12}\,s^{-2} \\ \ddot{f} &= (0.28 \pm 0.16) \times 10^{-24}\,s^{-3} \end{aligned} \tag{4}$$

and the second set by Mattox *et al.*[16]

$$\begin{aligned} t_0 &= JD\,2448750.5 \\ f &= 4.21766909413(5)\,s^{-1} \\ \dot{f} &= -0.195221(8) \times 10^{-12}\,s^{-2} \\ \ddot{f} &\leq 3 \times 10^{-24}\,s^{-3} \end{aligned} \qquad (5)$$

Using these ephemerides one obtains, using formula (2), values of (31.1 ± 17.8) and < 332 respectively for the braking index, n, of the Geminga pulsar. It may be pointed out that the rather large errors in n are due to the correspondingly large errors in $\ddot{f}$. Though the derived values of n, with their large errors, are not seriously in conflict with the expected value 3, there have been a few suggestions in the literature to explain these 'high values' of braking index in terms of glitches[17] and of pulsar proper motion[18].

4. Our method to determine $\ddot{f}$

The errors in $\ddot{f}$ in the ephemerides (4) and (5) preclude joining the $COS-B$ and $EGRET$ data sets into a *single* data set of $18\,yr$ long lever-arm allowing one to determine $\ddot{f}$ more accurately. Instead, we adapted a simple method to obtain $\ddot{f}$. Since Geminga did not show any evidence for any glitch in its observed history, we have divided the difference in the $\dot{f}$ values by the difference in the epochs given by the two ephemerides (4) and (5); see Figure 1. The resulting $\ddot{f}$ value is given by $\ddot{f} = (4.1 \pm 2.0) \times 10^{-26}\,s^{-3}$, leading to the value for braking index $n = (4.5 \pm 2.3)$. There has been one more observation on Geminga by $EGRET$ in December, 1993. If we include these data and reanalyse the $EGRET$ data, we obtain a more accurate value $\dot{f} = -0.1952219(43) \times 10^{-12}\,s^{-2}$. When we combine this value with the ephemerides (4), we obtain $\ddot{f} = (3.85 \pm 1.19) \times 10^{-26}\,s^{-3}$. This leads to a value $n = (4.3 \pm 1.3)$.

5. Conclusions

We conclude that, while neither the $COS-B$ data nor the $EGRET$ data stream is long enough to determine $\ddot{f}$ accurately, one can obtain a reasonably accurate value for $\ddot{f}$ from the $\dot{f}$ values given by the two groups. The newly determined value of $\ddot{f}$ leads to a value for the braking index of Geminga pulsar of $n = (4.3 \pm 1.3)$. This value is in agreement, within errors, with the theoretical value, 3, for a rotating non-aligned magnetic dipole, obviating any need to look for explanations for a 'large' braking index.

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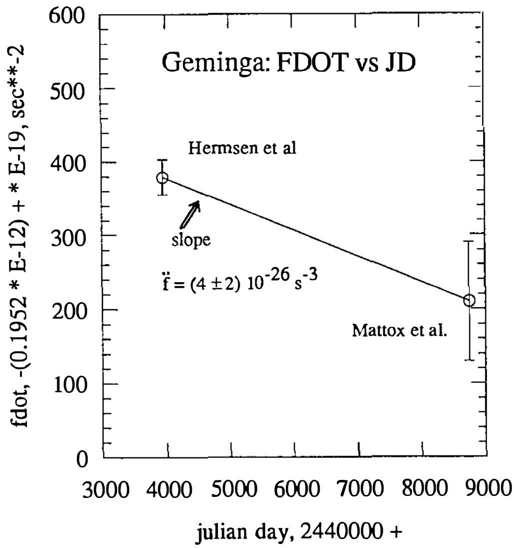

Fig.1: Time derivative of Geminga pulsar frequency vs time in Julian Days. The data points are from the ephemerides given by Hermsen *et al.* and Mattox *et al.*. The slope of the line joining the two points is a measure of the second time derivative of frequency of the pulsar.

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