EGRET GAMMA-RAY OBSERVATIONS OF THE CRAB P2/P1 RATIO

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ABSTRACT

Recent observations of the Crab pulsar by the Energetic Gamma-Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory show that the high-energy gamma-ray light curve has changed little over the lifetime of the instrument. Previous data collected by SAS 2 and COS B in the years 1972–1982, along with earlier EGRET data, suggested a 14 yr sinusoidal variation in the flux ratio between the first and second peaks. The new data from EGRET indicate that the flux ratio is constant.

Subject headings: gamma rays: observations — pulsars: individual (Crab)

1. INTRODUCTION

High-energy gamma-ray emission from the Crab pulsar was observed by satellite-borne telescopes for 15 years: in 1972–1973 by SAS 2 (Kniffen et al. 1974), from 1975 to 1982 by COS B (Clear et al. 1987), and since 1991 by EGRET (Nolan et al. 1993; Ramanamurthy et al. 1995). Early observations showed possible sinusoidal variation in the relative intensities of the two peaks (Wills et al. 1982) with a timescale of ~14 yr, and it was suggested that this variation might be due to the precession or free nutation of the neutron star (Kanbach 1990; Özel 1991). An apparent confirmation of the sinusoidal signal was seen in the low-energy gamma-ray emission (Ulmer et al. 1994), which matched the high-energy results in phase and period, but with a smaller amplitude. EGRET data from 1991 through early 1994 were consistent with the expected variation (Nolan et al. 1993; Ramanamurthy et al. 1995), although these observations spanned a time when the ratio of the peaks was predicted to be fairly constant, near the minimum of the sinusoid.

EGRET observations have now extended the available data by over 2 years. The most recent data were expected to be 4–6 $\sigma$ from the average of the previous values if the sinusoidal model is correct.

2. OBSERVATIONS AND ANALYSIS

The EGRET instrument is a spark chamber gamma-ray telescope with an energy range of 30 MeV–30 GeV. Details of the instrument design, calibration, and standard analysis software are given in Thompson et al. (1993).

All viewing periods during which EGRET was pointed within 20° of the Crab were analyzed, with the exception of viewing period 0021 (1991 July 8–15), in which there was a large solar flare. CGRO viewing period numbers and dates for these observations are shown in Table 1. The eight viewings numbered 4120–5280 (1995 February–1996 August) have been completed since the time of the previous work of Ramanamurthy et al. (1995).

All photons with measured energy above 50 MeV that were within an energy-dependent cone of half-angle $\theta_{\text{max}}$ were used in this analysis. The angle $\theta_{\text{max}}$, chosen such that 68% of the photons originating from the pulsar are within the acceptance cone, is given by (Thompson et al. 1993)

$$
\theta_{\text{max}} = 5.85(E/100 \text{ MeV})^{-0.534}.
$$

(1)

The arrival time of each detected photon was transformed to solar system barycentric time using the DE200 ephemeris, and then binned according to the pulsar phase at that time, determined from the Princeton Pulsar Timing Database (Arzoumanian, Nice, & Taylor 1992). This analysis was performed using the PULSAR program (Fierro 1995).

As seen in Figure 1, the light curve was divided into several sections, including peak 1 (phase 0.94–0.4), peak 2 (phase 0.32–0.46), and the off-pulse background (phase 0.46–0.94). These definitions follow those used in the COS B analysis (Wills et al. 1982) and are similar to those used by Nolan et al. (1993) and Ramanamurthy et al. (1995). The background (from the Crab Nebula, nearby sources, and the diffuse Galactic radiation) was assumed constant as a function of pulsar phase. The off-pulse count rate was then used to find the background-subtracted counts estimates of the two peaks (P1 and P2). In order to avoid any effects from changes in instrument performance, the evolution of the ratio P2/P1 was examined (as in previous analyses).

The two peaks have slightly different energy spectra (Nolan et al. 1993), and the EGRET response at different energies has changed at different rates (Esposito et al. 1997). Thus, the ratio P2/P1 is affected by the changes in instrument performance over time. Calculations of this effect, however, indicate that it is an order of magnitude smaller than the errors in P2/P1 due to Poisson fluctuations.

The differences in the energy responses of the SAS 2, COS B, and EGRET instruments are larger than the variation in the EGRET response. However, statistical errors in the previous instruments' data are larger as well; thus the value of P2/P1 obtained from EGRET data should be comparable to that obtained with SAS 2 and COS B.

3. RESULTS

The values of P2/P1 obtained, together with the 1 $\sigma$ errors, are shown in Table 1. A reduced data set, in which nearby points are joined for clarity, is shown in Figure 2.
The data were fitted with a constant, yielding \( P2/P1 = 0.54 \pm 0.03 \), with \( \chi^2 = 6.01 \) with 20 degrees of freedom (dof). Such a low value of \( \chi^2 \) might imply that the errors in the data were overestimated. In this case, however, the errors arise purely from statistical Poisson fluctuations, and the low value must occur purely by chance. The data are very consistent with a constant value of \( P2/P1 \).

The data were also fitted with a straight line (\( \chi^2 = 5.96 \) with 19 dof), and a quadratic (\( \chi^2 = 5.92 \) with 18 dof). Neither result gives a significantly better fit: the EGRET data are most consistent with no variation.

The EGRET data were also analyzed in conjunction with the SAS 2 (Kanbach 1990) and COS B (Clear et al. 1987) data. The best-fit sinusoid to the previous instruments’ data,

\[
P2/P1 = 0.85 - 0.56 \sin [2\pi(T - 1975.67)/13.3],
\]

where \( T \) is the year of the observation, and to the combined data set,

\[
P2/P1 = 0.544 - 0.060 \sin [2\pi(T - 1976.48)/11.55],
\]

are shown together with the data and the average value of \( P2/P1 \) in Figure 3. As can be seen, the most recent EGRET observations (the last data point) are much less consistent with the large-amplitude sinusoid. The constant value of \( 0.528 \pm 0.027 \) gives \( \chi^2 = 24.0 \) (with 27 dof), indicating a good fit. The sinusoid fit to the combined data gives a period of 11.6 yr with \( \chi^2 = 21.2 \) (with 24 dof), which does not represent a significant improvement. Thus, using the combined data sets, the data are most consistent with no variation in \( P2/P1 \).

The light curves obtained from phase 1 data (1991 April–1991 September) and from phases 4 and 5 (1995 February–1996 August) are shown in Figure 1. The overall shape seems to have changed little, in contrast with the expected change if the 14 yr cycle were correct. A \( \chi^2 \) test was performed to compare the two light curves in a quantitative way. In order to filter out possible systematic effects, both an additive offset and a multiplicative factor for the second light curve were fitted to the data. The resulting \( \chi^2 = 58.5 \) (with 48 dof) is consistent with no change in the light curve. Without the offset, \( \chi^2 = 87.9 \) (with 49 dof) was obtained, indicating an inconsistency at the 99.95% confidence level. That an offset is required indicates a lower background level in the later observations. This could be due to a change

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**TABLE 1**

| Viewing Period | Dates          | \( P2/P1 \) |
|----------------|----------------|------------|
| 0002           | 1991 Apr 22–28 | 0.57 ± 0.11|
| 0003           | 1991 Apr 28–May 1 | 0.54 ± 0.15|
| 0004           | 1991 May 1–4    | 0.65 ± 0.18|
| 0005           | 1991 May 4–7    | 0.55 ± 0.14|
| 0010           | 1991 May 16–30  | 0.52 ± 0.07|
| 0360           | 1992 Aug 11–12  | 0.66 ± 0.34|
| 0365           | 1992 Aug 12–20  | 0.37 ± 0.15|
| 0390           | 1992 Sep 1–7    | 0.65 ± 0.17|
| 2130           | 1993 May 23–29  | 0.45 ± 0.19|
| 2210           | 1993 May 13–24  | 0.49 ± 0.12|
| 3100           | 1993 Dec 1–13   | 0.55 ± 0.16|
| 3211           | 1994 Feb 8–15   | 0.59 ± 0.11|
| 3215           | 1994 Feb 15–17  | 0.61 ± 0.31|
| 4120           | 1995 Feb 28–Mar 7 | 0.52 ± 0.15|
| 4130           | 1995 Mar 7–21   | 0.58 ± 0.12|
| 4200           | 1995 May 23–Jun 6 | 0.45 ± 0.15|
| 4260           | 1995 Aug 8–22   | 0.50 ± 0.20|
| 5020           | 1995 Oct 17–31  | 0.73 ± 0.14|
| 5260           | 1996 Jul 30–Aug 13 | 0.50 ± 0.12|
| 5270           | 1996 Aug 13–20  | 0.69 ± 0.21|
| 5280           | 1996 Aug 20–27  | 0.48 ± 0.22|

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**FIG. 1.**—Gamma-ray phase histograms of photons with \( E > 50 \) MeV for EGRET observations of the Crab in (a) 1991–1992 and (b) 1995–1996. Vertical dashed lines indicate phase boundaries used in the peak height analysis. Horizontal dashed lines indicate the background level as determined from the data.

**FIG. 2.**—Variation in the ratio of the two peaks in the Crab light curve for \( E > 50 \) MeV (from Table 1). For clarity, the 21 observations are grouped into six data points, where each point represents the average of several nearby observations. Error bars are \( 1 \sigma \). The dashed line is the average of all EGRET observations.

**FIG. 3.**—Variation in the ratio of the two peaks in the Crab light curve from SAS 2 (1973), COS B (1975–1983), and EGRET (1991–1996), where the EGRET data set has been reduced as in Fig 2. The dotted line is the best-fit sinusoid to the pre-EGRET data. The solid line is the best-fit sinusoid to all the data. The dashed line is the average of all the data.
in the nebular emission (de Jager et al. 1996), or it could be an effect of changes in the performance of EGRET. As the gas in the spark chamber ages, the sensitive area at low energies decreases, which decreases the width of the average point-spread function. This effect might lower the background in the later observations.

4. SUMMARY AND CONCLUSION

Recent observations with EGRET have provided data relevant to the reported variation in the $P_2/P_1$ ratio of the Crab pulsar. Data from $SAS \ 2$ and $COS \ B$ suggested a sinusoidal variation in this ratio. The EGRET data, whether taken alone or in conjunction with the data from previous instruments, are most consistent with a constant value of $P_2/P_1$. Examination of the light curves from early and later observations shows no distinct changes in the pulsar’s light curve. The EGRET data cannot, of course, rule out past variability in the $P_2/P_1$ ratio. Future observations by EGRET and its successors may allow a more precise characterization of the long-term behavior of the Crab’s light curve.

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