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PULSAR STUDIES WITH COMPTEL

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ABSTRACT

The *Compton Gamma-Ray Observatory* (*C-GRO*) has completed a full-sky survey during which the number of known γ-ray pulsars has more than doubled. COMPTEL has observed the classical pulsars Crab and Vela on several occasions and has derived detailed pulse patterns and spectral parameters in the 0.7–30 MeV energy interval. The new *C-GRO* γ-ray pulsars have different properties in terms of energy spectra and light-curve shapes, and, in fact, only the Crab is seen by all four *C-GRO* instruments. This raises intriguing questions about the particle acceleration processes and beaming taking place in the neutron magnetosphere. We have examined the COMPTEL data to add information on these objects in the 0.7–30 MeV energy interval and present evidence for the detection of one of them, PSR B1509−58. We have also undertaken a search for candidate radio pulsars whose ephemerides are well defined. The results of these analyses are presented.

Subject headings: gamma rays: observations — pulsars: general

1. INTRODUCTION

Since the discovery of the γ-ray pulsars, Crab (PSR B0531+21) and Vela (PSR B0833−45), there have been great strides made in understanding the pulsed γ-ray production mechanisms. Be they based on a Polar-Cap (Daugherty & Harding 1982) or an Outer-Gap model (Cheng, Ho, & Ruderman 1986a, 1986b), it has been possible to test theories of accelerating the leptons which produce the γ-rays and explain the relative phase of the two γ-ray peaks of $\sim$0.4. The parameters of the system are highly dependent upon the period as this defines the size of the light cylinder and the compactness of the system. The spectrum and light curves of Geminga (Bertsch et al. 1992) are similar to those of Crab and Vela in the high-energy γ-regime of EGRET despite the periods differing by a factor of 3. The phase difference of the Geminga peaks was found to be 0.5. This was a favorite value in early models but was abandoned in the face of the Crab and Vela phase separations. With five γ-ray pulsars now established, the uniform yet complex model which suited Crab and Vela may have to be set aside, and as much complementary data as possible gleaned from the Compton Observatory to explain each pulsar in turn.

2. OBSERVATIONS OF THE "CLASSICAL" γ-RAY PULSARS

During the all-sky survey COMPTEL has viewed the Crab and Vela several times. With the benefit of contemporary ephemerides, phase folding has produced light curves for both pulsars as seen in Figures 1 and 2.

The pulsed signal-to-noise in COMPTEL is, as a result of the double-Compton detection technique, never better than 4%, and period-to-period variations in the pulsed shape reflect statistical variation in the signal plus backgrounds as demonstrated by Carramiñana et al. (1993). Nevertheless a glance at Figures 1 and 2 reveals several interesting features. For the Crab the total intrapulse emission is about equal to that of either peak. In no other energy range is this the case. The spectrum of the Vela pulsar is much harder than that of the Crab. This is reflected by the distinct light curve in the 10–30 MeV range, where, even for the combined data of six observations, there is no clear pulsed emission for the Crab. That the Crab is indeed pulsed in this interval is demonstrated by the presence of a point source in the sky-map in the phase intervals around the peaks.

An important parameter in the light curve of the "classical pulsars" is the pulse width. It is well established that the pulses are broader for the Crab than for Vela. In Figures 1 and 2 we make a simple illustration of this in the COMPTEL energy regime by showing the same light curve with double binning. The timing resolution of *C-GRO* is better than one-eighth ms, so the bin-to-bin variation is subject to counting statistics only. The surprising observation for Vela is that not only is the first peak merely 3.3% wide (compared with the Crab's $\approx$ 10%), but the second peak appears even sharper at 1% (Crab $\approx$ 6%). This narrow pulse is the sharpest that we have observed in all γ-ray light curves.

As shown by Ulmer (1994), the pulsed Crab spectrum is

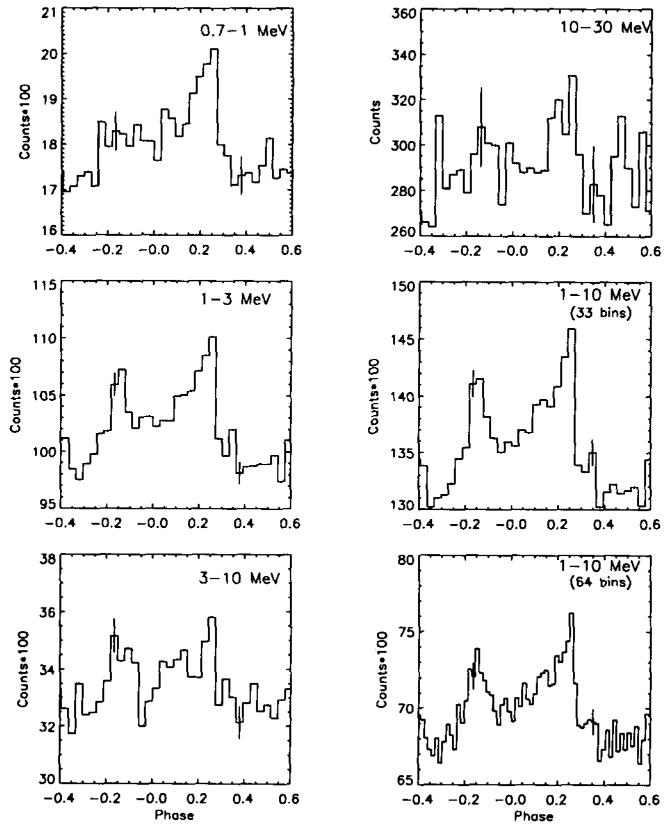

FIG. 1.—COMPTEL Crab light curves for the energy intervals indicated. The 1–10 MeV interval is shown for both 33 and for 64 phase bins.

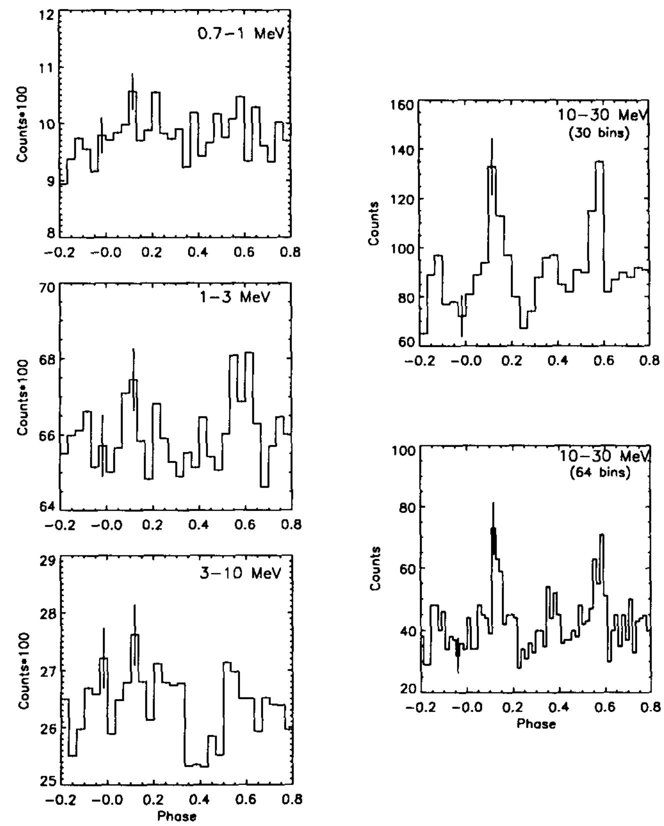

FIG. 2.—COMPTEL Vela light curves for the energy intervals indicated. The 10–30 MeV interval is shown for both 30 and 64 phase bins.

well behaved over seven decades of γ-ray energy covered by *C-GRO.* On the other hand the Vela spectrum breaks sharply around 70 MeV as seen in the combined data of OSSE, COMPTEL, and *COS B* shown in Figure 3.

The formerly perceived γ-ray similarity between Crab and Vela is already seen to be naive. Add to this the observed temporal variation of the pulses of Crab reported by *COS B* (Wills et al. 1982) and confirmed by EGRET (Nolan et al. 1993) together with the variation of the Vela pulses discovered by *COS B* (Grenier, Hermsen, & Clear 1988) and confirmed by EGRET (Kniffen et al. 1993) and the picture is starting to look very complicated. Spectral differences between peaks 1 and 2 and the intrapulse component means that the traditional presentation of the total pulsed spectrum of Crab and Vela is masking the details of the emission processes which should be unveiled as a result of the statistical precision offered by the combined Compton database.

While Crab and Vela are the *foundation* stones of pulsar astronomy, perhaps other pulsars are the *Rosetta* stones to the production mechanisms and COMPTEL data has been exploited to try to unearth more spectral detail on the new pulsars and on other likely pulsar candidates.

3. THE NEW *C-GRO* PULSARS

3.1. *PSR B1509−58*

The plerion PSR B1509−58 was detected by BATSE (Wilson et al. 1991; Wilson et al. 1992), having been examined because of its high $\dot{E}/d^2$. This was observed earlier by *Ginga* in hard X-rays (Kawai et al. 1991). The light curve is broad with about a 50% duty cycle, and the spectrum is reported to be harder than the Crab, crossing over at about 10 MeV according to Figure 6 of Wilson et al. (1992). Combined with an early claim that PSR B1509−58 was observed in the BATSE integral energy channel > 1.8 MeV, this gave hope that this pulsar be observable by COMPTEL. Unfortunately, observations by *C-GRO* have not been optimal during phase 1 and none are

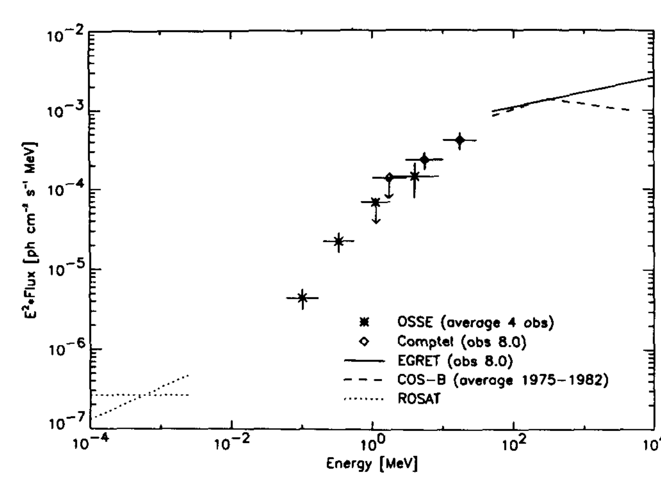

FIG. 3.—Vela pulsed energy spectrum

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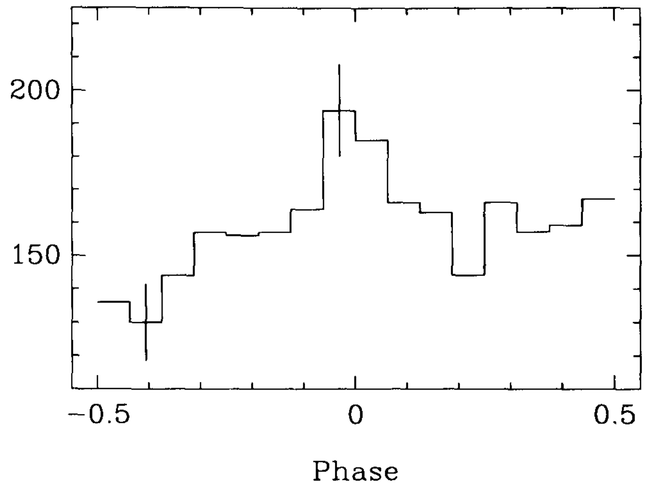

FIG. 4.—COMPTEL light curve for PSR B1509−58 observed in *C-GRO* observation 23.

planned in phase 2. The object was viewed at a large inclination angle of 25° in observation 12, at an optimum angle of 4°.5 in observation 23 and at 12°.5 in observation 27 which was a short observation. On the face of it, observation 23 was the most promising, but problems with data transmission seriously compromised the sensitivity. Nevertheless during that observation a light curve was obtained in the range 0.7–1 MeV (Fig. 4) which shows a 3 σ deviation from a flat distribution, with a peak at the expected maximum determined by OSSE. It has the broad shape reported by BATSE. Furthermore, in the same energy range the image of data selected in a phase interval around the peak shows evidence (3.9 σ) for localized emission at the position of the pulsar (see Fig. 5).

Supporting evidence from the other observations, for which the sensitivity was poorer, is somewhat confusing. Given the potential for secular variability, as seen in the classical pulsars, this may be understandable. Detailed analysis of all the observations continues.

3.2. *Geminga*

Although *C-GRO* phase 1 offered a large grasp on the Crab, Geminga, which is only ~15° from Crab, was relatively poorly covered in phase 1. Nevertheless we have folded the COMPTEL data to search for pulsation at the EGRET phases. No emission is so far detected at those phases. Preliminary upper limits (2 σ) were given by Strong et al. (1993) based on the total DC emission and these have been recalculated following analysis of the sky map derived from photons in the EGRET-defined phase interval to be:

3–10 MeV < 2.10^{-6} cm^{-2} s^{-1} MeV^{-1}
10–30 MeV < 3.10^{-7} cm^{-2} s^{-1} MeV^{-1}.

In these proceedings Grenier et al. (1994) present evidence for variability at several phases in the *COS B* light curve of Geminga, so given that the X-ray light curve also differs from the high-energy γ-ray one, the COMPTEL investigation might benefit from allowing the phase of the pulse to be a free parameter within the COMPTEL energy range. Results of this investigation are to be presented by Hermsen et al. (1993).

3.3. *PSR B1706−44*

This hard *COS B* source 2CG 342−02 (Swanenburg et al. 1981) is now seen by EGRET to be a pulsar with a particularly hard pulsed energy spectrum (Thompson et al. 1992). It is therefore not surprising, in view of the Vela light curves obtained, that COMPTEL does not see this source either in the pulsar timing or the sky maps. We have not yet ascertained an accurate upper limit, but COMPTEL's detection of Vela gives a rough estimate (2 σ) of ~30% of Vela in the 10–30 MeV interval.

4. SEARCH FOR NEW PULSARS

We have sorted the 550 or so pulsars presented in the Princeton Public Data-Base (Johnston et al. 1992a) plus the Australian Catalogue (Manchester 1992) in terms of $\dot{E}/d^2$ as a measure of detectability. Under the assumption of that $I = 0.57 \times 10^{45}$ g cm^2 for all pulsars and assuming 100% energy conversion we can order the pulsars in terms of the observed "flux" (F) of energy at Earth. From Table 1 which lists the 15 potentially most luminous objects we can see that the top of the list is populated by already detected γ-ray pulsars. Many others in the list have been seen by *ROSAT* at X-ray energies (Ögelman 1992). We are, therefore, confident that there is a good potential for detection within the top ranks of this list.

We are proceeding to work systematically through this list. The method we employ is to fold the Solar System Barycentre arrival times for events appearing to come from the source. We use the Z_n^2 (Buccheri & Sacco 1985) statistic as a measure of presence of peaks in the light curve. If we take as a threshold $Z_3^2 > 3\ \sigma$, we have thus far positive indications for only two objects: PSR B1951+32 and PSR B0740−28. We continue to refine these measurements by adding more data and image

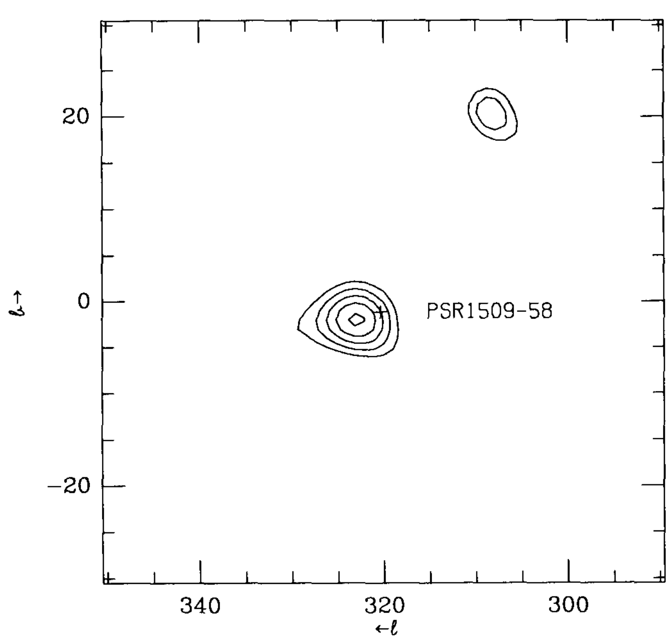

FIG. 5.—COMPTEL sky map for phase-selected events showing an image of PSR B1509−58 in *C-GRO* observation 23. The second excess seen in the figure is Cen A (Steinle et al. 1993).

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TABLE 1

COMPTEL PULSAR SEARCH PRIORITY LIST

Pulsar	l	b	P (ms)	$\dot{P}$	D_{dm} (kpc)	log ($\dot{E}_{rot}$)	log (F_{max})
0531+21[a,b]γ[a]ρ[b]	184.56	−5.78	33.342	4.212×10^{-13}	2.00	38.41	−6.27
0833−45[a,b]	263.55	−2.79	89.286	1.243×10^{-13}	0.50	36.60	−6.88
Geminga[a,b]	195.13	4.65	237.097	1.098×10^{-14}	(0.10)[c]	34.27	−7.82
1706−44[a,b]	343.10	−2.69	102.442	9.304×10^{-14}	1.46	36.29	−8.12
1259−63	304.18	−0.99	47.762	1.850×10^{-14}	2.34	36.58	−8.23
1509−58[a,b]	320.32	−1.16	150.652	1.537×10^{-12}	4.40	37.01	−8.36
1929+10[b]	47.38	−3.88	226.517	1.157×10^{-15}	0.08	33.35	−4.48
1951+32[b]	68.77	2.82	39.530	5.849×10^{-15}	2.50	36.33	−8.54
1046−58	287.43	0.58	123.646	9.593×10^{-14}	2.60	36.06	−8.85
1823−13	18.00	−0.69	101.441	7.522×10^{-14}	3.98	36.21	−9.07
1800−21	8.40	0.15	133.588	1.341×10^{-13}	3.90	36.10	−9.16
1758−24	5.25	−0.88	124.874	1.278×10^{-13}	4.35	36.17	−9.18
0740−28	243.78	−2.45	166.752	1.683×10^{-14}	1.10	34.91	−9.25
1937+21	57.51	−0.29	1.558	1.051×10^{-19}	3.72	35.80	−9.42
1821−24	7.80	−5.58	3.054	1.618×10^{-18}	5.50	36.11	−9.45

[a] γ-ray pulsars already detected by *C-GRO*.

[b] X-ray pulsars already detected by *ROSAT*.

[c] The assumed distance to Geminga is within the range of Bertsch et al. 1992.

phase-selected events. In the case of PSR B1259−63, being an unusual and exotic binary system (Johnston et al. 1992b), the ephemeris is as yet too uncertain to make a 14 day coherent observation. This is the minimum interval required for COMPTEL to observe a pulsar of about the strength of Vela. In addition, the parameters for PSR B1821−24 are not contemporary, having been taken from the Australian Catalogue, which still leaves the possibility for detection open if another ephemeris should become available.

5. SUMMARY

Detailed energy-dependent light curves for Crab and Vela are emerging from the COMPTEL experiment. These represent a unique data set in the 0.7–30 MeV energy interval. New spectral timing features are being revealed. Given that determination of the γ-ray emission processes in pulsars demands knowledge of the light curve and energy spectrum over the entire *C-GRO* energy band, it is incumbent upon COMPTEL to search for pulsations from all possible candidates. This work has made a promising start: there is a positive detection of PSR B1509−58, and the first traces of emission have been detected for two other objects. These will be followed up by deep observations in later phases of the *C-GRO* mission.

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REFERENCES

Bertsch, D., et al. 1992, Nature, 357, 221
Buccheri, R., & Sacco, B. 1985, Data Analysis in Astronomy II (New York: Plenum Press)
Carramiñana, A., et al. 1993, Proc. Compton Science Symposium, AIP Conf. Series, in press
Cheng, K. S., Ho, C., & Ruderman, M. 1986a, ApJ, 300, 500
———. 1986b, ApJ, 300, 522
Daugherty, J. K., & Harding, A. K. 1982, ApJ, 252, 337
Grenier, I. A., Bennett, K., Buccheri, R., Henriksen, R. N., Hermsen, W., Kanbach, G., & Sacco, B. 1994, ApJS, 90, 813
Grenier, I. A., Hermsen, W., & Clear, J. 1988, A&A, 204, 117
Hermsen, W., et al. 1993, Proc. Integral Symposium, Les Diablerets, 1993
Johnston, S., et al. 1992a, C-GRO/radio timing data base, Princeton University
Johnston, S., Manchester, R. N., Lyne, A. G., Bailes, M., Kaspi, V. M., Guojun, Q., & D'Amico, N. 1992b, ApJ, 387, L37
Kawai, N., Okayasu, R., Brinkmann, W., Manchester, R., Lyne, A. G., & D'Amico, N. 1991, ApJ, 383, 645
Kniffen, D. K., et al. 1993 Proc. Compton Science Symposium, AIP Conf. Series, in press
Manchester, R. 1992, private communication
Nolan, P. L., et al. 1993, ApJ, in press
Ögelman, H. 1992, private communication
Steinle, H., et al. 1993, Adv. Space Research, in press
Strong, A. W., et al. 1993, A&AS, 97, 133
Swanenburg, B. N., et al. 1981, ApJ, 243, L69
Thompson, D. J., et al. 1992, Nature, 359, 615
Ulmer, M. 1994, ApJS, 90, 789
Wills, R. D., et al. 1982, Nature, 296, 723
Wilson, R., et al. 1991, BAAS, 23 (4), 1440
———. 1992, Proc. Los Alamos Workshop, Physics of Isolated Pulsars, ed. K. Van Riper & C. Ho, in press