NEW COMPTEL RESULTS ON PULSAR STUDIES AT MEV ENERGIES

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ABSTRACT

COMPTEL, aboard the Compton Gamma-Ray Observatory, has detected at MeV energies PSR B1951+32 and found indications for a signal from PSR B0656+14. In the combined COMPTEL – EGRET spectra it is apparent that the maximum luminosities of these objects are reached in the COMPTEL energy range, or at least spectral features/bumps are apparent. These spectra can be compared with those of four other pulsars for which the COMPTEL data provided evidence or indications of activity at MeV energies. Besides of the Crab pulsar, which follows approximately a power-law flux relation from keV to GeV energies, the spectral properties of the other five pulsars – Vela, Geminga, PSR B1509-58 and the above mentioned new detections – require breaks/bends at MeV energies. This behaviour at MeV energies may play a decisive role in discriminating between current gamma-ray emission models.

Keywords: radio pulsars; gamma rays; PSR B1951+32; PSR B0656+14.

1. INTRODUCTION

Since the launch of the Compton Gamma-Ray Observatory, with on board the four instruments BATSE, OSSE, COMPTEL and EGRET, the number of identified gamma-ray pulsars has increased from two (the Crab and Vela pulsars) to eight. EGRET measured high-energy gamma rays from five additional pulsars: Geminga (Bertsch et al. 1992), PSR B1706-44 (Thompson et al. 1992), PSR B1055-52 (Fierro et al. 1993), PSR B1951+32 (Ramanamurthy et al. 1995) and the most recent probable detection of PSR B0656+14 (Ramanamurthy et al. 1996). In addition, BATSE (Wilson et al. 1993), OSSE (Matz et al. 1994) and COMPTEL (Bennett et al. 1994) measured gamma rays up to ~ 1 MeV from PSR B1509-58. The diversities in light-curve shapes and spectral distributions, and e.g. the very large differences in the fraction of the spin-down power radiated at gamma-ray energies in this small sample of pulsars, pose important constraints to pulsar modelling. COMPTEL studied also the MeV emission from the Crab (most recently Much et al. 1995) and Vela (Hermsen et al. 1993) and found indications for Geminga (Kuiper et al. 1996). In this paper we summarize the results from a search in the COMPTEL data for MeV emission from the most recently discovered EGRET pulsars PSR B1951+32 and PSR B0656+14.

2. INSTRUMENT AND ANALYSIS TECHNIQUE

COMPTEL is the imaging Compton Telescope aboard CGRO and is sensitive for γ -ray photons with energies in the 0.75-30 MeV range. Its energy resolution is 5-10% FWHM and due to its large field of view of typically 1 steradian it is possible to monitor a large part of the sky simultaneously with a location resolution of $\sim 1°$. More detailed information about the instrument, its detection principle and performance can be found in Schönfelder et al. (1993). Events are sorted in a 3-dimensional data space spanned by the photon scatter direction (χ, ψ) and the calculated scatter angle $(\overline{\varphi})$ for a selected measured energy interval. The search for sources in this 3-d data space is performed by applying a maximum likelihood analysis at each position in the COMPTEL field of view, rendering quantitative information on the source detection significance, position and flux (see de Boer et al. 1992). The dominating instrumental background distribution has been determined from the data themselves using a smoothing method similar to that described in Bloemen et al. (1994). Extensive simulations have been performed to calibrate the likelihood method as used in the current analysis.

3. PSR B1951+32

PSR B1951+32 is a fast 39.5 ms pulsar in the core of the Galactic supernova remnant CTB 80. The derived age and surface field strength assuming spin-down by magnetic dipole radiation are 1.1×10^5 yr and 5×10^{11} Gauss, respectively. Its estimated distance based on both pulsar dispersion measure and estimates of the distance to the remnant is ~ 2 kpc. In the X-ray regime marginal detections of pulsed emission were claimed in the EXOSAT and *Einstein* data, but only recently a $\sim 99\%$ confidence level for detection of pulsed emission at the radio period could be reported from analysis of ROSAT PSPC and HRI data

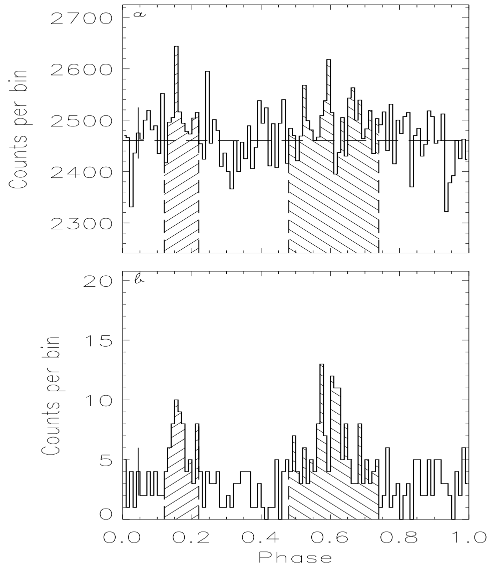

Figure 1: COMPTEL light curves for PSR B1951+32. a) COMPTEL 0.75-30 MeV light curve for Phase I data. Dashed line: background level determined from the "unpulsed" interval (not shaded); b) EGRET > 100 MeV lightcurve using the Phase I–III observations. The shaded phase intervals indicate the definitions for the first and second peaks by Ramanamurthy et al. (1995)

(Safi-Harb et al., 1995). In the EGRET data above 100 MeV Ramanamurthy et al. (1995) reported a firm detection of PSR B1951+32 with a lightcurve showing 2 peaks separated 0.44 in phase with the first peak lagging the radio peak by 0.16. In an earlier systematic search for pulsed γ-ray emission from radio pulsars in CGRO Phase I COMPTEL data ($0.75 - 30$ MeV) Carramiñana et al. (1995) found indications (random probability 0.62%) for a double-peak structure in the lightcurve, but had no information on the absolute phase. In this paper we summarize the detection of PSR B1951+32 by COMPTEL using more data and absolute timing, and the results are compared with those from simultaneous EGRET observations (for more details see Kuiper et al. 1997). All COMPTEL data have been used from observations between 30 May 1991 and 12 July 1994 in which the pulsar was less than $30°$ from the instrument z-axis.

3.1. Timing analysis

After selection of events which can originate from within a narrow region (acceptance angle $\leq 3.5°$) of the pulsar position, the arrival times of the selected events were transformed to arrival times at the Solar System Barycentre (SSB) using the known instantaneous spacecraft position, the source position and the solar system ephemeris. The used values of the radio ephemerides are listed by Kuiper et al. (1997). First, we repeated the analysis for the CGRO Phase I data for which Carramiñana et al. (1995) found an indication for a narrow and a broad peak in the COMPTEL lightcurve at unspecified phases. The new COMPTEL lightcurve for the total energy range 0.75-30 MeV is shown in Figure 1a, in which phase 0.0 is aligned with the radio peak. For Figure 1b we reproduced the EGRET light curve for energies above 100 MeV, using the same ephemerides. It can be seen that both histograms show two peaks nicely aligned in (absolute) phase.

The significance for a deviation from a statistically flat distribution was determined for the COMPTEL light curve using the bin free Z_n^2-test statistic (Buccheri et al. 1983). The pulsed source signal exceeds the 3σ level (3.1σ for n=2 harmonics, 3.4σ for n=3) with almost all power confined to energies below 10 MeV. The latter has been verified by producing light curves for the energy intervals 0.75-1 MeV, 1-3 MeV, 3-10 MeV and 10-30 MeV. Adding the data from Phase II slightly increases the significance for the 0.75-30 MeV lightcurve ($(3.9, 3.5)\sigma$ for n=(2,3)). Finally, adding data from the CGRO Phase III data does not yield an increase in significance ($(2.8, 2.4)\sigma$) for n=(2,3)). Given the weakness of the signal w.r.t. the dominating background (see e.g. the vertical scale in Fig. 1a) a relatively small background fluctuation can hide the signal. Spatial analysis, see below, gave evidence that the source was present during Phases I, II and III of the CGRO mission.

3.2. Spatial and spectral analysis

Spatial analysis of the sky region around PSR B1951+32 is complicated by the proximity (angular distance $\sim 2.6°$) of the black-hole X-ray binary Cyg X-1, which dominates the COMPTEL sky maps for energies below 3 MeV (e.g. McConnell et al. 1994). Above 3 MeV, however, maximum likelihood testing showed that the pulsar dominates Cyg X-1 in the sky map (Kuiper et al. 1997). In addition, selection of events in the pulsed phase interval (defined in Figure 1 by the shaded area) indicated that the source signal in the maps above 3 MeV is largely confined to the pulsed interval, strengthening the association with the pulsar. Selecting events in the pulsed phase interval, the source flux has been estimated in a spatial analysis for three energy intervals (0.75-3 MeV, 3-10 MeV and 10-30 MeV), treating Cyg X-1 and the Galactic diffuse gamma-ray emission as components in the underlying background. The summed evidence in the maps for pulsed emission between 0.75 and 10 MeV reaches a total significance of $\sim 3.3\sigma$. The resulting pulsar spectrum, including the EGRET (Fierro 1995), OSSE (Schroeder et al. 1995), BATSE (Wilson et al. 1992) and ROSAT results is presented in Figure 2. Note that the ROSAT fluxes represent the spectrum of the point-source, including "pulsed" and "unpulsed" components. Safi-Harb et al. (1995) estimated the pulsed fraction to be ~ 35 %, with a complex dependence on energy. The COMPTEL flux values might have a systematic uncertainty up to $\sim 25\%$; this has been added to the statistical 1σ errors.

The COMPTEL spectral points lie above the extrapolation of the EGRET spectrum, and a spectral break, or bump is required in the MeV region to be consistent with OSSE and BATSE upper limits.

4. PSR B0656+14

PSR B0656+14 is a relatively slow 385 ms pulsar which was identified with the *Einstein* supersoft X-ray source E0656+14 by Cordóva et al. (1989) with a significance for pulsed emission of $\sim 3.7\sigma$. X-ray studies using ROSAT (0.1-2.4 keV) confirmed the pulsed nature of the X-ray emission and allowed more detailed spectral analyses; most recently, Greiveldinger et al. (1996) used a combination of both ROSAT (0.1-2.4 keV) and ASCA (0.5-10 keV) data to study the spectrum over the 0.1-10 keV range, resulting in a best spectral description in

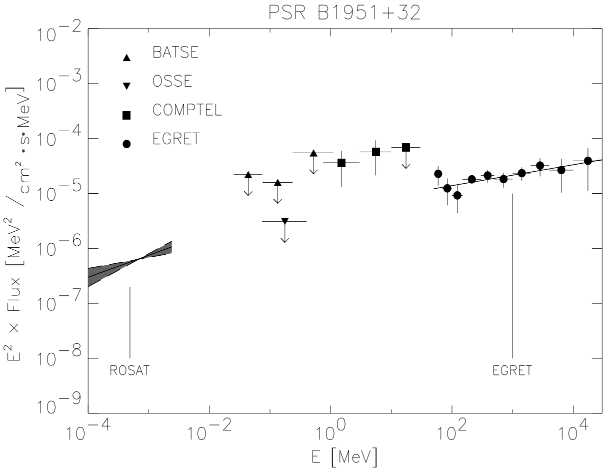

Figure 2: Spectrum of the pulsed emission from PSR B1951+32. For references see text. The COMPTEL error bars are 1σ statistical with an estimated 25% systematic uncertainty added, all upper limits are 2σ. The ROSAT point-source spectrum : "pulsed" plus "unpulsed" (see text).

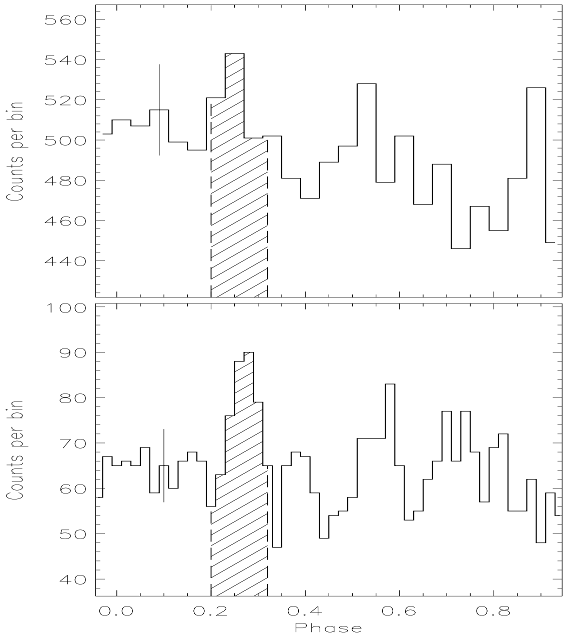

Figure 3: Light curves for PSR B0656+14. a) COMPTEL 10-30 MeV lightcurve for all observation up to and including Phase III. b) EGRET > 30 MeV lightcurve using all Phase I–III observations. The shaded phase intervals indicate the definition for the gamma-ray pulse by Ramanamurthy et al. (1996)

terms of a double backbody (T_{low} : $6.4 - 9.2 \times 10^5$ K; T_{high} : $1.3 - 1.7 \times 10^6$ K) and a power law component (photon PL-index : -1.5 ± 1.1) to explain the higher energy photons. At gamma-ray energies above 50 MeV possible evidence for pulsed emission was reported by Ramanamurthy et al. (1996) in the EGRET high-energy data using all contributing observations of the CGRO Phases I-III. Timing analysis selecting events with energies above 50 MeV resulted in a $\sim 3.6\sigma$ deviation from a statistically flat distribution with excess emission in the radio-phase interval 0.20–0.32. A spatial analysis for energies above 100 MeV, selecting events with pulse phases in the 0.20–0.32 range, yielded a $\sim$ 3-4σ source feature positionally consistent with the pulsar. Spectral properties had been determined crudely from the flux ratio F(50–100 MeV)/F(100–10000 MeV) and the resulting (very) soft nature of the pulsed emission (PL-photon index of -2.8 ± 0.3) made it a promising candidate for detection at MeV energies. In this paper we summarize the search for this soft gamma-ray pulsar in the COMPTEL window. More details will be presented by Kuiper et al. (in preparation for *A&A*).

4.1. Timing and spatial analysis

As described for the analysis for PSR B1951+32, the arrival times of photons which might arrive from PSR B0656+14 were transformed to arrival times at the SSB using an appropriate set of pulsar ephemeris parameters derived from the Princeton database. First we limited the analysis to all relevant observations up to and including CGRO Phase III (like in the reported EGRET search by Ramanamurthy et al. (1996)). We produced light curves in the standard COMPTEL energy ranges 0.75–1 MeV, 1–3 MeV, 3–10 MeV and 10–30 MeV. Only in the highest energy interval there was an indication for a detection. Depending on the used source acceptance angle, 2.5°, 3.0° or 3.5°, a $2.2 - 3.2\sigma$ deviation from a flat distribution was found, using again the bin free Z_n^2-test statistic (Buccheri et al. 1983) for n=5 (5 harmonics) (see Figure 3a). In order to enable comparisson in absolute phase we also produced the EGRET light curve for CGRO Phases I-III for the adjacent integral energy range above 30 MeV (see Figure 3b). The significance of this EGRET light curve amounts $\sim 3.8\sigma$, slightly higher than the value for the published histogram above 50 MeV. The bin-independent H-test, which considers the power in all harmonics (de Jager, Swanepoel & Raubenheimer, 1988) gives for the light curve above 30 MeV a probability of 6.6×10^{-4} for the null hypothesis, while the published light curve above 50 MeV (Ramanamurthy et al. 1996) reached 3.6×10^{-3}. This result strenghthens the EGRET detection, and shows in addition that the high-energy emission likely extends down to 30 MeV. It is worth noting that the highest peak in the EGRET light curve coincides in absolute phase with the maximum in the COMPTEL distribution.

Selecting the "pulsed" phase interval as defined by Ramanamurthy et al. 1996 (see Figure 3b) we produced "pulsed" maps in the standard COMPTEL energy ranges. Again, only in the highest energy window a weak indication at the 2.5σ level for the presence of a source was found.

We have also analysed CGRO Phase IV COMPTEL data independently, eventhough the exposure is lower, and produced phase histograms and skymaps for the four standard energy intervals. There was no significant evidence for pulsed emission, but there was a $\sim 3\sigma$ source-like feature consistent with the pulsar position in the map for 10–30 MeV, only.

4.2. Spectral analysis

The timing and spatial analysis summarized above hint at a detection of PSR B0656+14 in the 10-30 MeV band. Admittedly, the signal is weak but not unexpected since this energy window is adjacent to the EGRET band in

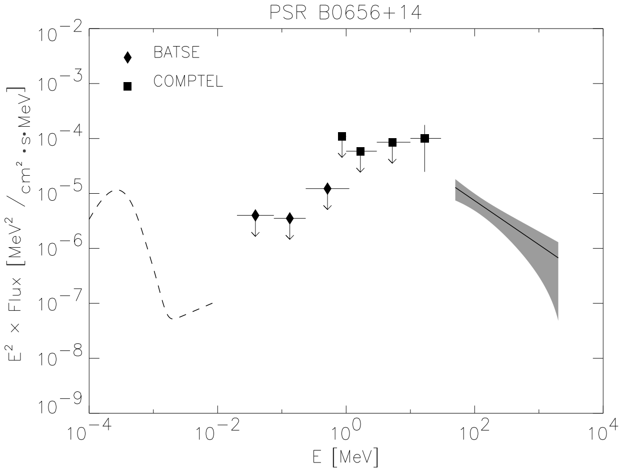

Figure 4: Spectrum of the emission from PSR B0656+14. For references see text. The COMPTEL error bars are 1σ statistical plus an estimated 25% systematic uncertainty added, all upper limits are 2σ. The ROSAT/ASCA point-source spectrum : "pulsed" plus "unpulsed" (see text).

which a very soft signal was reported. In order to verify the spectral consistency, we combined all available COMPTEL data from CGRO Phases I-IV for spatial analysis in the standard energy intervals. The resulting flux value above 10 MeV and the upper limits below 10 MeV are shown in Figure 4 together with the EGRET power-law fit and the ROSAT X-ray spectrum. The latter spectrum represents the total emission (pulsed and unpulsed). For the high-energy power-law tail the statistics are insufficient to determine a pulsed fraction (Greiveldinger et al. 1996). To the COMPTEL statistical errors a 25% systematic uncertainty has been added again. The COMPTEL flux between 10 and 30 MeV appears consistent with an extrapolation of the EGRET fit. This spectrum must break below 10 MeV, however, otherwise the pulsar would become a very strong MeV source, easily detectable by COMPTEL.

We consider the (possible) detection by EGRET of PSR B0656+14 above 30 MeV and the consistent COMPTEL indications in the neighbouring energy interval 10-30 MeV, as evidence for the detection of this pulsar. Then the luminosity spectrum exhibits a maximum in the 10-30 MeV range, more pronounced than seen sofar in any other gamma-ray pulsar.

5. DISCUSSION

The combined results from COMPTEL and EGRET on PSR B1951+32 and PSR B0656+14 as shown in the spectra in Figures 2 and 4 indicate that their spectra exhibit pronounced spectral features in the form of breaks or bumps in the COMPTEL 1-30 MeV window. We can compare this to the four additional pulsars for which COMPTEL provided evidence or indications of activity at MeV energies. Firstly, the Crab pulsar (see e.g. Much et al. 1995) behaves differently: Its total pulsed spectrum extrapolates over the COMPTEL range with a power-law index ~ -2.2 from high-energy gamma rays to X-rays. More importantly, strong spectral variations with pulse phase are seen. The latter is also the case for the Vela pulsar, which has been firmly detected by COMPTEL, and its total pulsed spectrum shows a break or bend at MeV energies (see e.g. Strickman et al. 1996). The Geminga gamma-ray pulsar most likely has a spectral break in the COMPTEL range, although a power-law extrapolation (index ~ -1.5) from the EGRET range cannot be excluded yet. COMPTEL found only weak signals from this source (Kuiper et al. 1996), which has a very much harder spectrum than the Crab. Finally, PSR B1509-58, has been detected by COMPTEL only during one observation (Bennett et al. 1994). The combined CGRO results on this source, particularly the EGRET upper limits, indicate that also this pulsar reaches its maximum luminosity at MeV energies; The spectral break could be as sharp as seen in Figure 4 for PSR B0656+14. In conclusion, with the exception of the Crab, all five pulsars for which there are detections or indications in the COMPTEL range show spectral features in this energy window. Only recently there are theoretical attempts to explain such characteristic spectral features (e.g. Harding, Baring and Gonthier, 1997; Romani, 1996).

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