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Search for gamma-ray emission from the Lagrangian points of PSR 1957+20

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Abstract. — Compton Gamma Ray Observatory data of the COMPTEL and EGRET telescopes from 3 viewing periods have been used to search for gamma-ray emission from the Lagrangian points L_4 and L_5 of the binary system including the eclipsing pulsar PSR1957+20. The result was negative and the upper limits derived remain significantly below detections reported earlier.

Key words: gamma rays: observations — pulsars: individual: PSR 1957+20

1. Introduction

Brink et al. (1990) reported a possible gamma-ray flux in the 50 MeV to 1 TeV range, originating from the direction of the Lagrangian points L_4 and L_5 of the binary system which includes the 1.6 ms eclipsing pulsar PSR1957+20 (Fruchter et al. 1988). The radiation, coming from a region of 0.02 sr angular extent, equivalent to 14 min of the pulsar orbital phase, was explained as originating from the interaction of charged particles in the pulsar wind with the "Trojan matter" accumulated around L_4 and L_5 which, due to the very low mass (0.022 M_0) of the companion, are points of stable equilibrium of the system (Shapiro & Teukolski 1988). The indicated gamma-ray flux of 4.3 10^{-7} $E_{\rm GeV}^{-1}$ ph cm^{-2} s^{-1} was thought to be produced by π^0 decay formed in proton-proton collision following proton acceleration at a shock formed near the "Trojan matter" at the Lagrangian points. Such a flux would imply a column depth of at least 50 g cm^{-2}. Given the marginal statistical significance of the effects found, however, Brink et al. (1990) suggested follow-up observations by the Compton Gamma Ray Observatory, CGRO, in order to confirm the results, making use of the higher sensitivity of COMPTEL and EGRET, compared to the Max Planck Institute Double Compton telescope (Schönfelder et al. 1982) and COS-B (Scarsi et al. 1977), whose data were analyzed over the same orbital phase window by Brink et al. (1990).

We report on the analysis of COMPTEL (0.75 to 30 MeV) and EGRET (50 to 5000 MeV) data aiming to confirm the findings of Brink et al. (1990) at these energy ranges. At TeV energies no further information is available.

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2. Observations and data

Gamma-ray astronomy provides a powerful diagnostic tool for the study of high energy processes in the universe. The Compton Gamma-Ray Observatory was launched by NASA in April 1991 and completed the first all-sky survey in the range 10′s keV to 10′s GeV by November 1992. For the present study data from both the COMPTEL and EGRET instruments have been used. COMPTEL is an imaging Compton telescope (Schönfelder et al. 1993) which covers the range 0.75–30 MeV. Its location accuracy is better than one deg for sources like the Crab, its energy resolution is between 6% and 9% and it has a field of view of about 1 steradian.

The co-aligned EGRET spark-chamber instrument (Thompson et al. 1993) has a similar field of view to COMPTEL but covers the energy range 30 MeV to 10′s GeV. EGRET offers a position resolution of around 0.1 degree, an energy resolution of around 15% and an extremely low background.

The data-archive from all CGRO instruments is available for public access from the CGRO Science Support Centre (Shrader et al. 1992). In the present study we have made use of COMPTEL data and archival EGRET data from the 3 viewing periods (VP) listed in Table 1.

3. The data analysis

Two independent methods have been used to analyze the COMPTEL data. One, the timing approach, was based on the analysis of the binned orbital phase histogram and the other based on a spatial analysis of bin-free phase selected events. Both methods have systematic uncertainties in determining background distributions, however, these uncertainties are fully independent allowing for an internal consistency check. For EGRET only the timing approach was applied.

3.1. *Temporal analysis*

This was based on a direct comparison of the phase histograms built up using the times of the photons arriving from the pulsar direction (on-source data) and those arriving from regions away from the source (off-source data). The reason for using the off-source regions is the presence of large data gaps and e.g. variations in exposure due to rejection of all events from those parts of the field of view entered by the earth, resulting, after folding the photon arrival times with the orbital period of the pulsar, in a significant modulation of the residual phase histogram (see Fig. 1 and discussion below). In these conditions, the phase distribution in absence of signal is not flat and the usual techniques of searching for deviations from uniformity cannot be used. The off- source data are then needed as a term of reference for the analysis of the on-source data. The following procedure was used.

• For each of the 3 observations of Table 1, we selected the COMPTEL events whose event circles (Schönfelder et al. 1992) intersect a 3 degrees circular region around the pulsar direction and around two other off-source regions given in Table 1, Cols. 6 and 7. The whole COMPTEL energy range 0.75 to 30 MeV was considered. For EGRET, we selected a) the photons with energies between 50 and 5000 MeV recorded when the instrument was working in the "fully unocculted" mode (Thompson et al. 1993) and coming from an energy dependent acceptance cone in order to optimize the signal-to-noise ratio (Nolan et al. 1992) centered at the pulsar direction and b) the times of events coming from a 17 cone centered on the two "off-source" directions given in Table 1. This large angle was selected in order to define with good statistics the reference structure of the phase histogram in the same energy range.

• The photon arrival times of each data set were transformed to the Solar System Barycentre and then folded using the orbital ephemerides of the PSR1957+20 system, available from the Princeton catalogue (Arzoumanian et al. 1992):

$$\begin{aligned} P_{\rm orb} &= 33001.915785 \text{ s} \\ {\rm d}P/{\rm d}t &= -0.48\ 10^{-10} \text{ s/s} \\ T_0 &= 47699.506934 \text{ (TDB, MJD)} \end{aligned}$$

The residual phases obtained were then binned, into a 200-bin phase histogram in the case of COMPTEL and into a 40-bin phase histogram in the case of EGRET where the low statistics of data did not allow more detailed binning. Figure 1 shows, as an example, the folding results for the COMPTEL data of observation 20 both for "on-source" and "off- source" events. The positions of the Lagrangian points, given by

$$L_{4,5} = 0.25 \pm\ {\rm tg}^{-1}[(\sqrt{3}(1+q)/(1-q)]/2\pi$$

with q, the system mass ratio equal to 0.0157 in the case of PSR1957+20 (Shapiro & Teukolski 1988; Fruchter et al. 1988), are shown in the figure. The modulation observed in the figure is mainly due to gaps in the data arising from the switch-off of the satellite in the presence of the South Atlantic Anomaly.

• A statistical comparison was performed between "on-source" and "off-source" phase histograms. The comparison procedure included:

a) a normalization of the "off-source" phase histogram to the "on-source" phase histogram in the whole phase region, obviously excluding both the Lagrangian points L_4 and L_5 and the eclipse region, centered at phase 0.25 because a possible lack of photons in this phase interval could affect the comparison. The chosen regions to investigate for an excess or a lack of photons were defined to be 0.025 in phase (equivalent to 13.75 min of the orbital phase) around L_4 and L_5, placed at the central phase positions of 0.0822 and 0.4177, respectively. The eclipse region was defined to be 16 bins or 0.08 in phase, as indicated by Fruchter et al. (1990). By calling X_i and Y_i (i=1 to 40 or 200 for EGRET and COMPTEL, respectively) the bin contents of the on-source data and of the off-source data, respectively, the normalized off-source histogram was defined as $Z_i = (N_{\rm on}/N_{\rm off})Y_i$, with $N_{\rm on}$ and $N_{\rm off}$ being the total number of "on-source" and "off-source" photons within the normalization region, respectively.

b) the estimate of the excesses N_4 and N_5 in the "on-source" histogram at the Lagrangian points on the basis of the comparison between the "on-source" and the normalized "off-source" histograms. Following the definitions given in a), N_4 and N_5 are estimated as $N_L = X_L - Z_L$ with uncertainty given by $\sigma_L^2 = X_L + (N_{\rm on}/N_{\rm off})^2 Y_L$, with L = 4 or 5 labeling the phase of each of the 2 Lagrangian points. It is clear that larger samples of off- source data correspond to smaller σ and therefore to higher sensitivity of the method.

c) the derivation of the $\chi^2 = \Sigma_i (X_i - Z_i)^2/\sigma_i^2$ between the two phase histograms within the normalization region to test the validity of the comparison.

Table 1. CGRO viewing periods (VP) used in this analysis. The source aspect angle w.r.t. to the pointing directions and the two off-source positions used in the temporal analysis are also given

VP n.	Start date (TJD)	End date (TJD)	Aspect angle	Pointing (RA, D)	Off-1 (RA, D)	Off-2 (RA, D)
2.0	30.05.1991 (8406)	08.06.1991 (8415)	15.83°	301.4, 36.6	300.0, 52.0	303.0, 21.0
7.0	08.08.1991 (8476)	15.08.1991 (8483)	11.74°	310.1, 28.1	321.6, 34.5	300.0, 36.0
20.0	06.02.1992 (8658)	20.02.1992 (8672)	20.23°	285.3, 6.4	270.0, 20.0	300.0, - 8.0

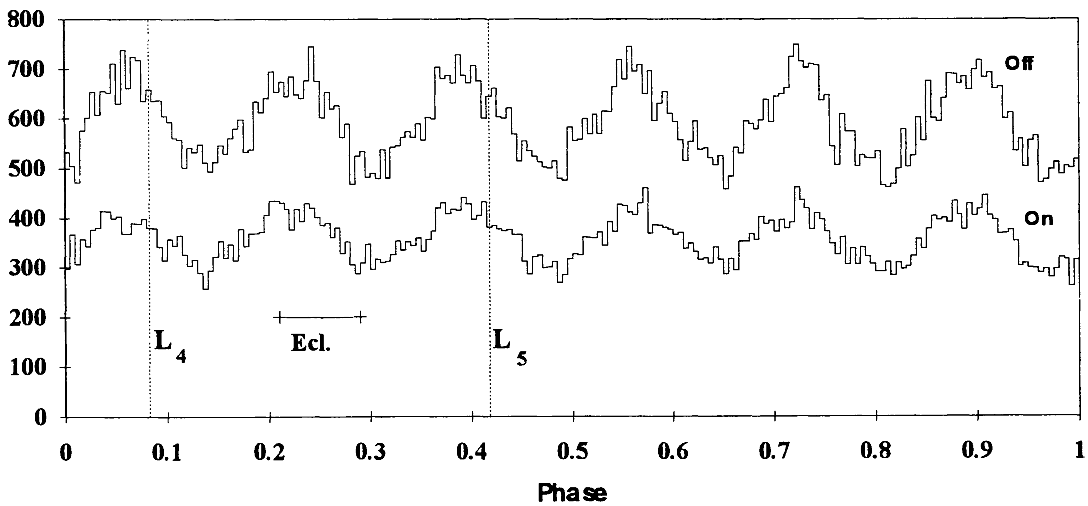

Fig. 1. On-source and off-source phase distributions of the COMPTEL arrival times from VP 20. Positions of L_4, L_5 and eclipse are shown

3.2. *Spatial analysis*

In the method described below, adopted in the case of COMPTEL, we employ the imaging capabilities of the experiment.

• Using the measured event parameters E_1 (energy deposit in the upper detector), E_2 (energy deposit in the lower detector) and the interaction locations in both detectors, it is possible to bin the COMPTEL events in a three dimensional dataspace constructed by 3 angles; two angles specifying the direction of the scattered photon (χ, ψ) and the third being the Compton scatter angle $\varphi = \arccos\{1 - m_0c^2(1/E_1 - 1/E_t)\}$ with $E_t = E_1 + E_2$ and m_0c^2 the electron rest energy.

• Events with timetags within the orbital phase windows corresponding to L_4, L_5 or $L_4 + L_5$ are sorted in the binned 3-d dataspace. In addition, events in the radio eclipse phase interval of the pulsar are used to construct a background model $B(\chi, \psi, \varphi)$. This model is then used to test at the position of PSR1957+20 (χ_0, ψ_0) whether a source signature is present in the 3-d data space by applying a maximum likelihood analysis. The expected number of counts N in each pixel (χ, ψ, φ) is given by:

$$N(\chi, \psi, \varphi) = \alpha\ P\ (\chi, \psi, \varphi | \chi_0, \psi_0)\ G\ (\chi, \psi, \varphi) + \beta\ B(\chi, \psi, \varphi)$$

with $P(\chi, \psi, \varphi|\chi_0, \varphi_0)$ being the instrumental point-spread function and $G(\chi, \psi, \varphi)$ a geometry function which takes into account the effective exposure of each bin in the 3-d dataspace. α and β are scaling factors for the source and background intensity, respectively. For the generation of P a power law source spectrum with index -2 has been assumed.

• Quantitative information on the detection significance, source strength α and source position can be derived simultaneously by determining a maximum likelihood ratio of 2 alternative hypotheses. In the zero hypothesis the likelihood is maximized for the case that the data are described by a background distribution alone (source contribution α fixed at 0), while in the alternative hypothesis the likelihood is maximized for a data description in terms of a background distribution (with scale factor β) and a point-source distribution being the product of the instrumental point-spread function P and the geometry function G. The detection significance is derived from the quantity $-2 \ln \lambda$ (where λ represents the ratio of the maximum likelihood under zero hypothesis and the maximum likelihood under alternative hypothesis) behaving like a χ^2 distribution for large sample sizes (de Boer et al. 1992). From the maximized scale parameter $\alpha_{\max}$ one can then determine the source flux or the upper limit on it.

Table 2. Results from timing analysis

Viewing period		0.75 - 30 MeV	0.05 - 50 GeV
VP 2.0	N_4	104.91 ± 52.97	-0.67 ± 4.44
	N_5	-69.39 ± 46.54	1.81± 4.51
	χ^2	167.53	29.40
VP 7.0	N_4	-85.03 ± 43.98	2.79 ± 2.98
	N_5	-22.66 ± 40.70	4.42 ± 2.93
	χ^2	141.00	53.49
VP 20	N_4	-112.48 ± 62.27	-4.77 ± 4.99
	N_5	-83.50 ± 63.12	-9.63 ± 4.60
	χ^2	179.02	42.93
All Obs.	N_4	-133.99 ± 92.57	-1.87 ± 7.32
	N_5	-76.28 ± 88.36	-0.36 ± 7.00
	χ^2	164.71	27.81

4. Results

Table 2 gives the results of the temporal analysis both for the COMPTEL and EGRET data samples for each of the viewing periods considered. The estimates for N_4 and N_5 and their uncertainties are shown together with the χ^2 between the "on-source" and "off-source" phase histograms within the normalization region. The values of the χ^2 in the normalization region, shown in Table 2, fall reasonably around the expected value of 174 for COMPTEL and of 35 for EGRET data, which shows that the "on-source" and the "off-source" histograms are statistically equivalent to each other within the normalization region and therefore that the results of the analysis are reliable. Figure 2 shows the phase histogram of $N_\sigma = (X - Z)/\sigma$ for the full sample of COMPTEL data. The values of N_4 and N_5 given in Table 2 show that no positive signal was detected from any of the two Lagrangian points both in the COMPTEL and EGRET data.

To determine upper limits from the lightcurves derived using the temporal analysis, an accurate estimate of the exposure is needed. Taking for COMPTEL the applied data selection into account, a modelled instrument response was used to determine the effective exposures when converting the 2σ upper limits on the excess photons N_4 and N_5 into photon fluxes. The derived exposure values are 10.87 10^6, 10.86 10^6 and 10.89 10^6 cm^2 s for the energy ranges 0.75–3 MeV, 3–30 MeV and 0.75–30 MeV, respectively.

The 2σ upper limits on the gamma-ray fluxes from the Lagrangian points L_4 and L_5 (averaged over the binary orbit) were therefore calculated, using the COMPTEL exposures described above and the EGRET exposure of 3.48 10^8 cm^2 s, corresponding to an effective area of 607.5 cm^2 averaged over the 3 viewing periods. For COMPTEL, the upper limits on the flux values (energy range 0.75–30 MeV), averaged over the whole orbit, turns out to be 1.70 10^{-5} and 1.62 10^{-5} ph cm^{-2} s^{-1} for L_4 and L_5, respectively. In the case of EGRET we obtain a 2σ upper limit flux of 4.21 10^{-8} and 4.02 10^{-8} ph cm−2 s^{-1} for L_4 and L_5, respectively.

Table 3 shows the results of the spatial analysis applied on the COMPTEL data. The derived counts with their errors show again that no signal significant has been detected from the two Lagrangian points and that the upper limits on their emission for the total energy interval 0.75–30 MeV are consistent with the limits from the temporal analysis.

Table 3. Results from spatial analysis of COMPTEL data (VP 2.0 + 7.0 + 20)

Energy range	Orbital phase	Max. lik. counts	2σ upper limit flux (ph cm^{-2} s^{-1})
0.75 - 3 MeV	L_4	-126.9 ± 95.3	1.6 10^{-5}
	L_5	77.3 ± 89.4	1.8 10^{-5}
	$L_4 + L_5$	-39.0 ± 129.8	1.8 10^{-5}
3 - 30 MeV	L_4	-14.2 ± 40.9	0.52 10^{-5}
	L_5	-0.3 ± 37.6	0.67 10^{-5}
	$L_4 + L_5$	-19.9 ± 54.9	0.76 10^{-5}
0.75 - 30 MeV	L_4	-136.2 ± 104.2	1.3 10^{-5}
	L_5	260.0 ± 97.2	3.2 10^{-5}
	$L_4 + L_5$	-59.8 ± 139.5	1.9 10^{-5}

5. Conclusions

The upper limit values for L_4, derived from spatial analysis for COMPTEL and from temporal analysis for EGRET, are shown in Fig. 3 together with the findings of Brink et al. (1990). It is evident that the upper limits from the present analysis are significantly lower than the upper limit from MPE balloon data and the detection claimed for COS-B.

Considering that the observations used here span several weeks, in the context of the scenario in which a strong, stable wind is continuously flowing out of the companion of the pulsar, it is difficult to reconcile our results with the Brink et al. (1990) indications in terms of time variability of the "Trojan matter". We rather derive that the agglomeration of matter around the Lagrangian points of the system is much less important than it was thought, possibly due to the dispersing pressure of the evaporation wind (Phinney et al. 1988).

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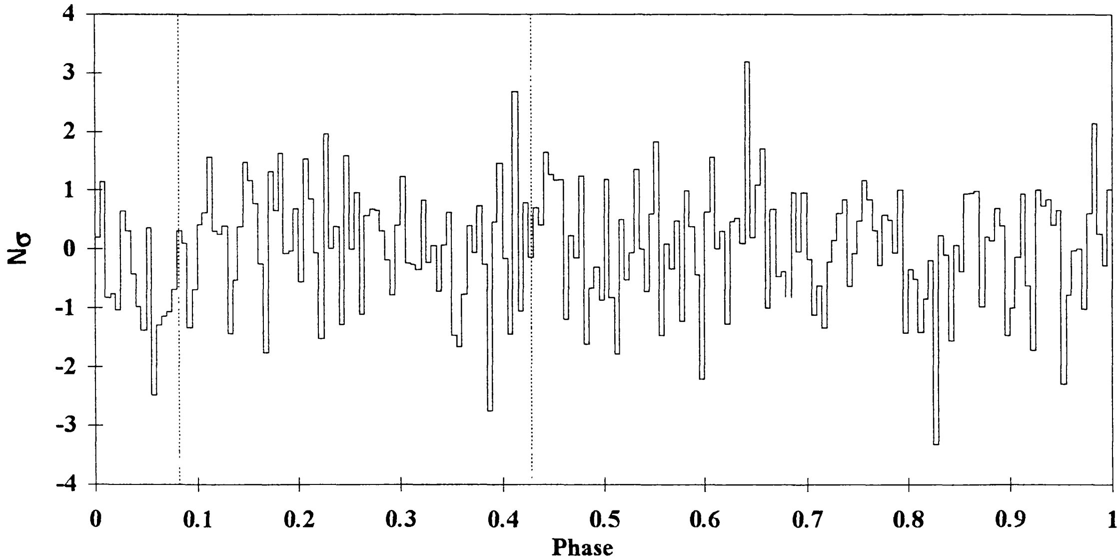

Fig. 2. Phase histogram of $(X - Z)/s$ for the full sample of COMPTEL data. Dashed lines indicate the positions of L_4 and L_5

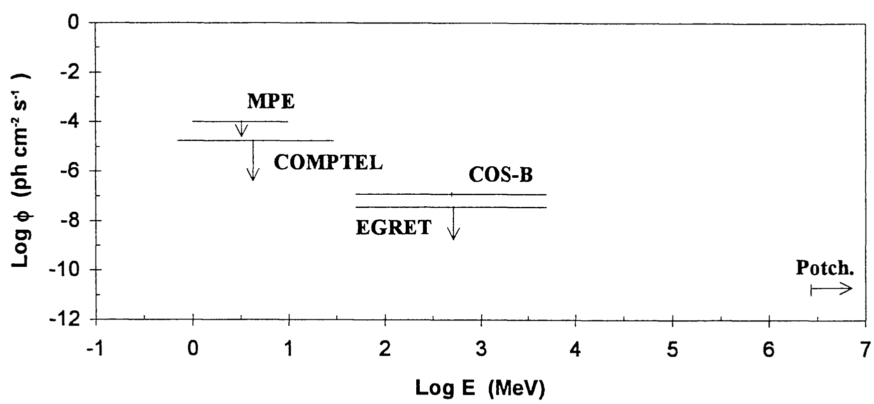

Fig. 3. COMPTEL and EGRET 2σ upper limits of the flux from Lagrangian point L_4 in comparison with the earlier upper limits from MPE balloon data and the COS-B detection claimed by Brink et al. (1990)

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