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Upper Limits on the MeV Emission of Seyfert Galaxies

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Abstract. The gamma-ray emission of Seyfert galaxies has fallen far short of pre-CGRO expectations. From a sample of 26 X-ray bright Seyfert galaxies, we do not detect a single object of this class in the energy range 0.75-3 MeV in COMPTEL data. To derive a more stringent upper limit for the emission from these objects in the energy ranges 0.75-1 MeV and 1-3 MeV, we have summed a large number of COMPTEL observations acquired during Phase I of the CGRO mission. From a total of 50 observations of 26 individual X-ray selected Seyfert galaxies, we derive upper limits (2 σ) of 1.0×10^{-7} photons / (cm^2 s keV) in the 0.75-1 MeV band and 9.7×10^{-9} photons / (cm^2 s keV) in the 1-3 MeV band, two orders of magnitude below previously reported detections. Our observations show that if emission at the level previously reported for NGC 4151 and MCG 8-11-11 occurs as a transient phenomenon in Seyfert galaxies, it has a duty cycle of less than 5%.

Key words: Galaxies: active ; Gamma rays: observations

1. Introduction

Before the launch of the Compton Gamma Ray Observatory (CGRO), Seyfert galaxies were thought to be among the brightest known objects in the energy range of several MeV. Balloon observations of two Seyfert galaxies, NGC 4151 and MCG 8-11-11, indicated that fluxes at the level of 2×10^{-6} photons / (cm^2 s keV) may be common in these objects (Perotti et al. 1981a, 1981b).

The X-ray spectra of Seyfert galaxies were found to have a *canonical* shape, best described by a power law with photon index α = -1.7 (Rothschild et al. 1983, Turner & Pounds 1989), possibly extending to MeV energies. This shape indicates a non-thermal origin of the X-ray emission. Recent observations by Ginga, however, showed that this spectral shape is actually produced by the superposition of a steeper power law with $\alpha \approx$ -2.0 and a Compton reflected component (e.g. Nandra & Pounds 1994).

This was explained by a model proposed by Zdziarski et al. (1990) in which the direct component resulted from the injection of relativistic electrons into a compact source region. Subsequent reprocessing of the primary radiation by photon-photon pair production results in the steepening of the X-ray spectrum. Considerations of source compactness, deduced from observations of short timescale variability, imply that this effect should be important in Seyfert galaxies (see compilation in Done & Fabian 1989).

SIGMA and OSSE observations, on the other hand, showed a very different picture at energies above 50 keV. The brightest Seyfert galaxy, NGC 4151, showed a much steeper spectrum at energies $>$ 35 keV when observed by SIGMA (Jourdain et al. 1992). OSSE observed a thermal spectrum above 50 keV (Maisack et al. 1993), with no detectable emission above $\approx$ 0.5 MeV. This was confirmed for a larger sample of less bright Seyferts (Johnson et al. 1994). No individual Seyfert galaxy has been detected so far by the COMPTEL (0.75-30 MeV) and EGRET ($>$ 50 MeV) instruments on GRO (Steinle et al. 1993, Lin et al. 1993). To increase the sensitivity of the COMPTEL analysis, we have added 50 observations of 26 individual Seyfert galaxies obtained during the all-sky survey in Phase I of the CGRO mission (1991 May 16th – 1992 Nov 17th; for a log of the observations , see Gehrels et al. 1993) to measure the average emission from Seyfert galaxies as a class.

The remainder of the paper is organised as follows: in section 2, we describe the instrument, in section 3, we outline the data analysis methods, in section 4, we describe the source selection

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criteria and observations, in section 5, we summarize the results and discuss them in section 6.

2. Instrument

The COMPTEL instrument (Schönfelder et al. 1993), as part of CGRO, covers the energy range 0.75-30 MeV. It has an imaging capability of $\approx 1^o$ resolution and an energy resolution of 5-10% FWHM. Photons are detected if they deposit substantial parts of their initial energy by Compton scatterings in the upper layer of detectors (D1), and are subsequently absorbed in the lower detector layer (D2), and if they satisfy certain timing constraints in the process. D1 consists of seven elements of liquid scintillator material, D2 of fourteen cells of NaI. The energy deposited in the respective elements, the respective locations and scattering angle $\bar{\phi}$ yield information about the initial energy and direction of the incoming photon. The direction of each accepted photon lies on a circle which is centered on the direction between the locations of the two interactions with an opening angle defined as

$$cos\bar{\phi} = 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2} \tag{1}$$

where m_e is the electron rest mass, c is the speed of light, E_1 and E_2 are the energies deposited in the upper and lower detector layers, respectively. Background events are suppressed by an anticoincidence dome and considerations of light travel time between the two detector layers.

3. Data Analysis Methods

Among others, the following information is stored for each accepted event: the energy, defined as the sum $E_1 + E_2$, and the angular information, parameterized by the apparent direction in the sky where the scattered photon came from, represented by the angles ψ and χ, and the angle by which it was deflected in the upper layer, $\bar{\phi}$, according to equation (1). A maximum likelihood algorithm (de Boer et al. 1992), included in the standard COMPTEL data analysis package, was used to derive flux maps from this 3-dimensional data space for each individual Seyfert observation selected for this study. When a source has been observed repeatedly, one 3-dimensional dataspace can be produced for the sum of the individual observations. The likelihood algorithm is then applied to this summed dataspace. In order to search for a cumulative signal from a sample of Seyferts, one can generate 3-dimensional dataspaces centered on each Seyfert galaxy of the selected sample, and sum these, treating this as one very long observation of a single source.

4. Observations and Results

We selected a sample of Seyfert galaxies observed by COMPTEL that satisfied the following criteria:

- prominence in earlier high-energy Seyfert studies, such as the samples presented by Rothschild et al. (1983) and Turner & Pounds (1989).

- absence of other sources in a $5^o \times 5^o$ field which are likely or known to emit at MeV energies. This was achieved by checking the HEAO-A4 and HEAO-A2 Picciniotti catalogs in the HEASARC [1] database.

- at least one observation during which the source was within 25^o of the center of the field of view of COMPTEL (corresponding to a geometric efficiency greater than 0.5 during Phase I)

Only three of the Seyfert galaxies we selected have galactic latitudes smaller than $\pm 20^o$. Thus, we consider the contribution by emission from galactic gas as neglegible.

The list of Seyferts selected for this study and the respective Phase I viewing periods are listed in Table. 1.

5. Observations and Results

5.1. Individual Seyfert Galaxies

We do not detect a single Seyfert galaxy from our sample with a significance $> 3\sigma$. This is true for sources which were observed only once during Phase I, as well as for sources where several observation periods could be added. The upper limits (2σ) for the energy ranges 0.75-1 MeV and 1-3 MeV are listed in Table 1. Both the values for the individual COMPTEL observations and the limits on repeatedly observed sources are substantially lower than the flux values reported from the MISO observation of NGC 4151 and MCG 8-11-11, which were of the order of 2 $\times$ 10^{-6} photons/ (cm^2 s keV) between 1 and 3 MeV.

5.2. The cumulative signal

Adding all the individual observations and weighting them with the detector efficiency corresponds to a COMPTEL Z-axis observation with a net observation time of $\approx$ 70 days. We do not find a significant signal from the sum of 50 observations, nor from any sub-group selected by optical or X-ray brightness, off-axis angle or duration of the individual observation. The limits on the complete sample are 1.0×10^{-7} photons / (cm^2 s keV) for the 0.75-1 MeV band and 9.7×10^{-9} photons / (cm^2 s keV) in the 1-3 MeV band. These values roughly correspond to what is expected if the errors of the individual observations are propagated statistically. This implies that no systematic effects arise from our method of treating all the individual observations as a single observation of one putative "generic" Seyfert galaxy. The more interesting upper limit is the one in the 1-3 MeV band, since the effective area of the instrument is about a factor of $\approx$ 2 higher there than below 1 MeV. We find that the upper limits we derive here are 10-20% higher than those found in

[1] The HEASARC database is operated by NASA at Goddard Space Flight Center

Table 1. Individual upper limits for Seyfert galaxies observed by COMPTEL in Phase I

Source Name	l	b	Viewing Periods	Upper Limit 0.75-1 MeV[a]	Upper Limit 1-3 MeV[a]
NGC 7314	26.44	-59.17	42	108.8	11.7
NGC 6814	29.15	-16.01	7.5, 13, 43	49.0	4.7
NGC 5548	31.94	70.49	24	140.0	15.0
MRK 509	35.97	-29.85	7.5, 13, 19, 43	40.4	5.5
3C 445	61.87	-46.71	19	50.0	5.0
MCG -2-58-22	64.08	-58.76	19	37.5	7.5
NGC 7469	83.09	-45.46	19, 28, 37	32.4	7.2
III ZW 2	106.97	-50.63	28, 37	57.6	8.0
MRK 335	108.76	-41.42	28, 37	106.8	12.4
NGC 4051	150.12	69.71	4	39.6	4.8
NGC 4151	155.05	75.06	4	15.8	4.8
3C 111	161.67	-8.81	15, 31, 36, 39	22.8	3.0
MCG +8-11-11	165.72	10.40	30, 36, 39	58.2	8.8
NGC 1068	172.10	-51.93	21	51.0	7.0
3C 120	190.37	-27.39	1, 2.5	27.3	3.8
MCG +5-23-16	200.82	46.46	40	42.1	5.5
ARK 120	201.69	-21.12	1, 2.5	50.9	6.6
NGC 3227	217.01	55.44	40	40.6	9.4
NGC 3783	287.45	22.94	12, 14, 32	22.2	3.3
FAIRALL 9	295.07	-57.82	10	45.2	5.9
NGC 4593	297.47	57.40	3, 11	71.4	3.3
IC 4329 A	317.49	30.92	12	50.5	6.1
ESO 141-55	338.18	-26.71	35, 38	83.2	16.0
MCG -6-30-15	338.46	44.53	12	85.5	10.6
NGC 5506	339.14	53.80	3, 11, 24, 25	30.5	5.2
NGC 7582	348.07	-65.69	9, 42	122.2	9.9

[a] in 10^{-8} photons / (cm^2 s keV)

a preliminary analysis (Maisack et al. 1994a). This increase is due to an revised background filtering and more accurate error calculation. The background models used here are determined by applying a filter technique to the 3-dimensional dataspace, which smoothes the photon distribution and eliminates source signatures in first-order approximation. This technique is described by Bloemen et al. (1994), although we applied here an improved algorithm. The slight overestimate of source significances that was inherent in this technique is now avoided.

The upper limits we derive for the average flux from Seyfert galaxies are two orders of magnitude below the fluxes reported by the MISO experiment for the Seyfert galaxies NGC 4151 and MCG 8-11-11, and about an order of magnitude below the preliminary values of the flux of the quasar 3C 273 (Hermsen et al. 1993). They are also a factor of 2 below the limits at MeV energies derived by Johnson et al. (1994) for a sample of relatively faint Seyferts observed by OSSE.

It is not possible to directly compare the fluxes and upper limits from various X-ray samples and the MeV data, since they are neither simultaneous nor do they contain the same individual objects. Even the OSSE average Seyfert spectrum (Johnson et al. 1994), which contains many Seyferts also observed by COMPTEL, does not provide simultaneity, since the two instruments usually observe different targets. It is therefore not possible to derive stringent constraints on the broad-band spectral shape of Seyfert galaxies between 10 keV and several MeV. Keeping in mind those caveats, we compare our upper limits to measurements of Seyfert galaxies in the X-ray range. OSSE observations (Johnson et al. 1994) have shown that the average Seyfert spectrum falls below the extrapolations of the canonical α=-1.7 or α=-2.0 spectra found below $\approx$ 20 keV. In Fig. 1, we show our upper limits together with the average Seyfert X-ray spectra measured by HEAO-A4 (Rothschild et al. 1983), EXOSAT (Turner & Pounds 1989) and a sample of

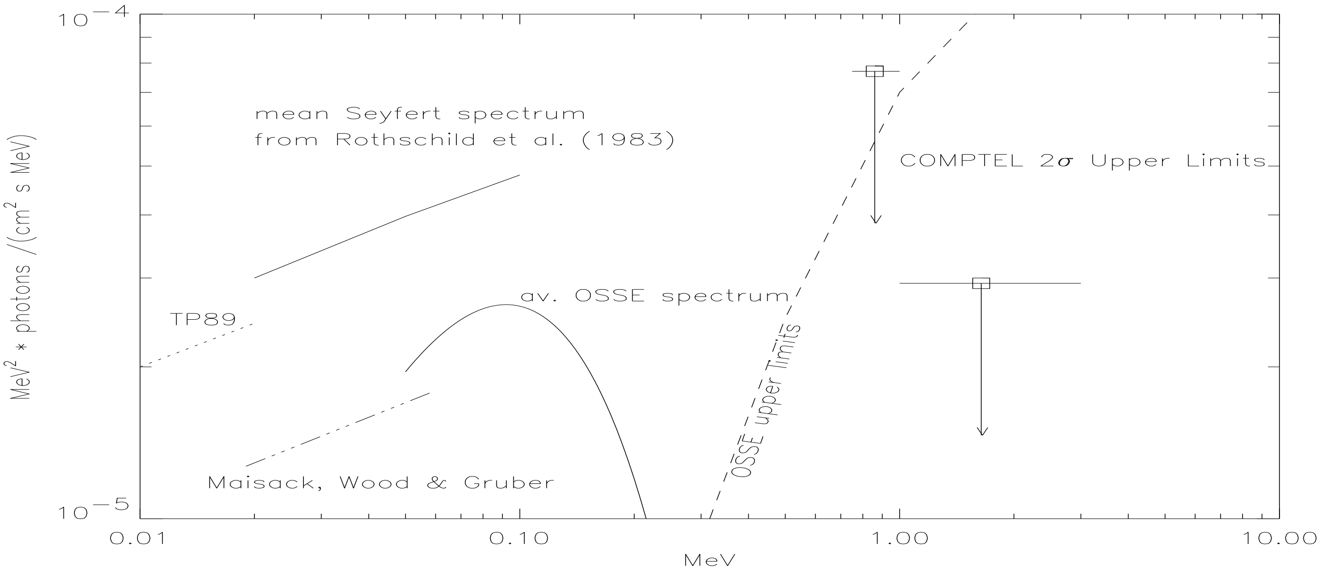

Fig. 1. COMPTEL Upper Limits Compared to X-Ray Samples

less bright Seyfert galaxies (Maisack et al. 1994b). All of these samples follow the canonical α=-1.7 slope. The intensity of the OSSE spectrum comes close to that of the Maisack et al. (1994b) sample. Johnson et al. (1994) have excluded the brightest objects as observed by OSSE, but did also exclude less bright Seyferts which were not detected. We conclude that our data should be compared to the Turner & Pounds or the OSSE sample, rather than to the spectrum of Rothschild et al. which was derived from the brightest sources only. We find that our upper limit in the 1-3 MeV band lies below the extrapolation of each of the three X-ray samples assuming α=-1.7. A more recent model for Seyfert galaxies explains the X-ray spectra by a superposition of a power law with a steeper photon index of up to α=-2.0 and a Compton reflected component (Zdziarski et al. 1990). This model is compatible with the COMPTEL upper limits, but not with the OSSE spectra of the brightest Seyfert galaxy, NGC 4151 (Maisack et al. 1993).

The maximum of the emission of Seyferts in the X-ray and γ-ray range seems to occur at several tens of keV. Other than in blazars, the MeV and GeV emission does not dominate the multi-frequency spectrum.

5.3. Variability

Considerations of source variability were not taken into account in the determination of this upper limit. However, we ran simulations under the assumption of a generic average variability of Seyferts as a class.

It is possible that MeV emission from Seyfert galaxies is a transient phenomenon, and we have just been unlucky in our observations such as to catch each of these sources in a low state of emission. We have therefore computed probabilities for this assumption, depending on the "duty cycle", i.e. the average time between two potential "high states", and the duration of such an event. First, we take a look at the 10 keV emission measured by EXOSAT (Turner & Pounds 1989). We find that the intensities of the sources in our sample at this energy have a dynamic range of $\approx$ 10, excluding the brightest source NGC 4151. The COMPTEL upper limits for individual observations are below the MISO flux for MCG 8-11-11 by more than a factor of 10. Assuming that some canonical spectral shape exists for Seyfert galaxies not only at X-rays, but continues through to MeV energies, we conclude that each Seyfert in our sample would have been detected if its MeV emission was at the same level as observed for MCG 8-11-11 by MISO, relative to its X-ray flux, for a duration of $\gtrsim$ 1 day.

We simulated a sample of 26 objects which emit at a level comparable to that measured by MISO with a certain duty cycle and for a certain duration, allowing various forms of scatter around the average values (e.g. Gaussian, normal of square root). We then randomly picked two of these sources for 26 simulated observations (roughly corresponding to 1.5 years of CGRO observations) and counted those which happened to be in the "high state" during that "year". This random procedure was repeated 100.000 times to determine the probabilities for not detecting any of the simulated sources in their "high state" for certain combinations of duty-cycle and duration of the "high state". We find that the results are independent of the assumed scattering. The result of this simulation is shown in Fig. 2. The combinations of duty cycle and duration of high state to the left of the lines in the diagram can be excluded at the 90 and 99% confidence level, respectively. One can see that the COMPTEL data restrict the general duty cycle to a value greater than 150 days (at the 99% confidence level), and the fraction of time

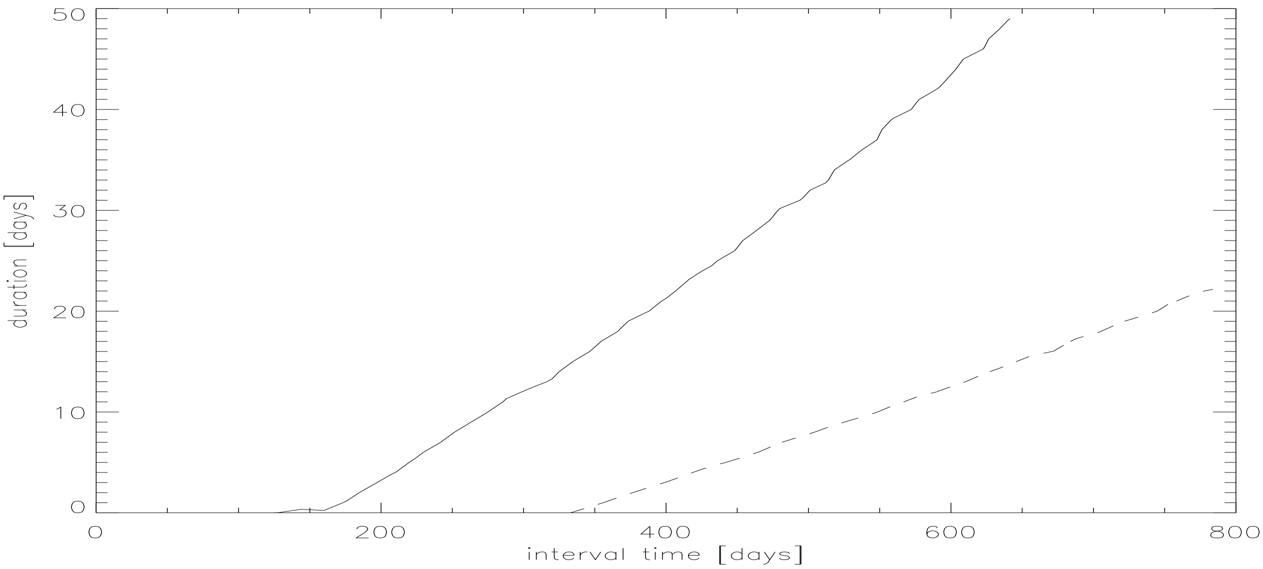

Fig. 2. Duration vs. duty cycle of a transient event. Combinations to the left of the solid line are excluded at the 99% confidence level, to the left of the dashed line at the 90% level

during which Seyfert galaxies in general can be in a "MISO-like high state", represented by the duration over the duty cycle, to approximately 5%.

6. Summary

The COMPTEL instrument on CGRO has not detected a single Seyfert galaxy after one year of observations. The upper limit derived from superposition of the signals of a sample of 50 observations of X-ray bright Seyferts is two orders of magnitude below previously measured fluxes. We find that emission at previously expected levels occurs, if at all, with a duty cycle of less than 5% .

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