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Lessons learnt from COMPTEL for Future Telescopes

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Abstract

After COMPTEL on NASA's Compton Gamma Ray Observatory has opened the 1 to 30 MeV range as a new window to astronomy, large world-wide efforts are now being undertaken to develop the next generation of Compton telescopes. The history of the Compton telescope development is reviewed and general guidelines for the design of new instruments are given with special emphasize to maximising the detection efficiency and minimising instrumental background radiation.

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1. Introduction

Large efforts are presently being made world-wide to develop the next generation of Compton telescopes. COMPTEL was the first successful Compton telescope put into space (Schönfelder et. al 2000). COMPTEL opened the MeV-range as a new window to astronomy. From COMPTEL we have learnt that the sky is rich in phenomena and objects that can be studied around 1 MeV. But it is also true that with COMPTEL we could only see the tip of the iceberg. The achieved COMPTEL sensitivity was still modest. This becomes clearly evident, if the COMPTEL sensitivity is compared to the sensitivities so far achieved in the neighbouring x-and high energy gamma-ray ranges. (Fig. 1). Also INTEGRAL will not be able to fill that gap. Integral's strength is its high spectral and spatial resolution. Its sensitivity is excellent only below-say 100 keV. Above that energy it is not better than that of OSSE or COMPTEL. It is now generally agreed that a next-generation low/medium-energy gamma-ray telescope should have a sensitivity which is at least comparable to that achieved by EGRET at higher energies. Finally, we must aim for an instrument comparable to the GLAST-sensitivity. There seems to be a world-wide agreement that such a step can only be obtained with an instrument, which is based on the Compton telescope principle. It is therefore extremely important to ask ourselves, what we have learnt from COMPTEL to build a next-generation Compton-telescope. Before doing so, let me briefly review the early history of Compton telescopes.

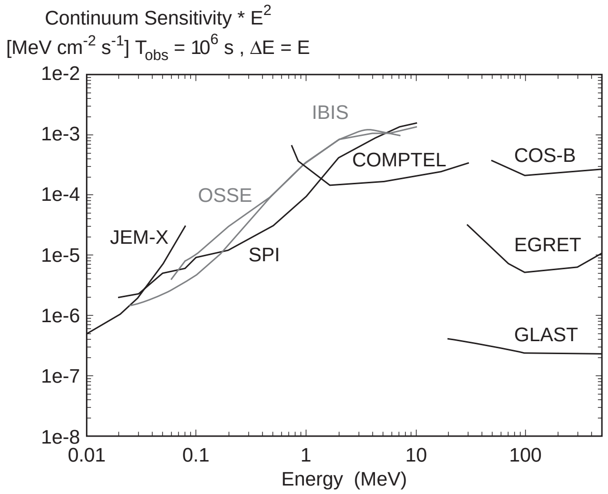


Fig. 1: Illustration of the existing sensitivity gap between-say 500 keV to 50 MeV.

2. History of Compton-Telescopes

The very first instrument which is described in the literature and which makes use of two subsequent Compton scatter processes was a spectrometer for accurate energy determination of incident gamma-rays, but it was not a telescope. It was published in 1950 by Hofstadter and McIntyre. It consisted of two scintillation detectors in backscatter arrangement. In 1961, Peterson and Howard (at that time at the University of Minnesota) for the first time describe a real double scatter Compton-telescope, which was designed to achieve directional collimation by using the kinematics of two Compton scatter processes. The directionality was achieved by postulating low energy losses in the first of two NaI-detectors, and high energy losses in the second one. No time-of-flight measuring technique was used. This instrument was flown on OSO-1 (launch: March 7, 1962), but was not successful. The difficulties with this instrument were summarised in a review article by Greisen (1966) as follows: "low efficiency for detection of gamma-rays (less than 1 %) combined with an increased sensitivity to secondary effects of the charged particle radiation arriving in all direction, and producing showers in the nearby vehical and instrumental material". Similar difficulties were mentioned for this technique in a review article by Fichtel in 1971. I think, the addition of a time-of-flight measurement would have improved the OSO-instrument considerably. In the early 1970's a re-birth of the Compton-telescope concept took place. In 1971 I myself had started building the first Compton-telescope at MPE (Schönfelder, Hirner and Schneider, 1973). In my Ph-D thesis in the late 1960's I had used a double scatter technique to determine the direction and energy of cosmic ray neutrons in the atmosphere. It was, therefore, a logical step to apply this method also to gamma-rays. The first Compton telescope was simple: it consisted of 2 plastic scintillator arrays. Downwards and upwards scattered events could be identified and separated by measuring the time-of-flight of the scattered gamma-rays. This first telescope was operated as a directional collimator only. The first balloon flights with this telescope in 1973 were very successful.

Practically at the same time independent work on Compton telescopes started also at other places: The Riverside group had already an existing double scatter neutron balloon experiment which used the time-of-flight technique to measure the energy of the scattered neutrons. In the first balloon flights with this instrument gamma-ray events were rejected as background. But in 1972 the interest in Riverside changed from neutrons to gamma-rays (White et al., 1973). From that time onwards their instrument was mainly operated as a Compton telescope. The Cosmic Ray Working Group at Leiden had performed independently studies about the Compton telescope technique at about the same time, which, however did not result in hardware developments. Studies were also made at Berkeley (Dauber and Smith, 1973) about a Compton camera using liquid xenon wire proportional counters.

In the years after 1973 the main activities with Compton telescopes took place at Garching and at Riverside. In 1975 we at Garching started building a new big balloon telescope which practically had already the size of COMPTEL. This telescope was flown three-times on balloons.

The COMPTEL-collaboration between the Max-Planck-Institute for Extraterrestrial Physics, the University of New Hampshire, the Space Research Organisation of Netherlands, and the Space Science Department of ESA was formed in 1977. From that time onwards it took then 13.5 years to get COMPTEL into space. The COMPTEL-era is now over, and we are now trying to design the best possible next-step telescope. The question which I now would like to address is: what have we learned from COMPTEL that should enter into the design of the next telescope.

3. Lessons learnt from COMPTEL

The most important parameters of any astronomical telescope are its angular resolution and its sensitivity. In case of COMPTEL the sensitivity was mainly determined by the background event rate within the angular resolution element. It had been clear from the beginning that the COMPTEL background should be composed of two different parts: a real cosmic gamma-ray background (mainly the diffuse cosmic background) and a background of non-cosmic origin which is produced locally in the material of the observatory or COMPTEL itself by cosmic-ray interactions. In the original COMPTEL-proposal to NASA the cosmic background was overestimated and the intensity level of locally produced background events was clearly underestimated. At that time I had estimated that the total event rate is by far dominated by cosmic gamma-ray events.

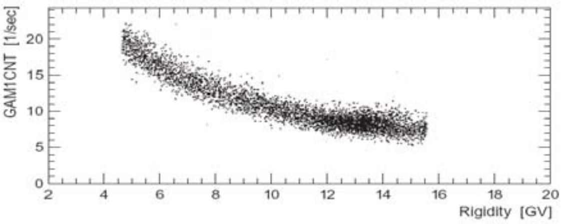


Fig.2: Dependence of the total COMPTEL background rate on the vertical cut-off rigidity

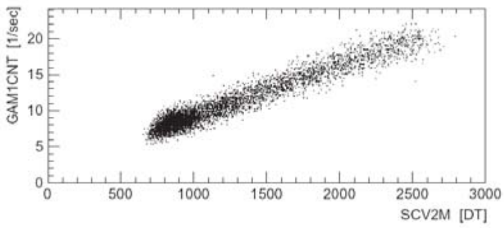


Fig.3: The correlation between the Gamma-1 event rate (GAM1CNT) and the V2 veto rate

Fig.2 and Fig. 3 from Weidenspointner et. al. (2001) prove, however, that most of the COMPTEL background actually must have been of local origin. Fig.2 illustrates that the COMPTEL background rate varies by a factor of 2.5 to 3.0 in the vertical cut-off rigidity-interval between 5 and 15.5 GV. If the background would consist of cosmic gamma-rays only, there should be no rigidity dependence at all. From Fig.3 we see that the gamma-ray background rate linearly increases with the charged particle background. If this curve is extrapolated to zero charged particle flux, then we see that the remaining rate (which then would be the real cosmic gamma-rate) is only of the order 10% to 20% of the total measured rate. Hence, most of the COMPTEL background is produced by charged particle interactions in and outside COMPTEL. Charged particle interactions with prompt gamma-ray emission are vetoed, if they are inside COMPTEL. Those with delayed emission cannot be vetoed. Charged particles very often also first produce neutrons - again inside or outside COMPTEL, and these neutrons are then an important source of secondary gamma-rays.

Furthermore it was found during the course of the mission that the background rate below 4.2 MeV steadily increased as is illustrated in Fig.4. A deeper analysis (Weidenspointner et. al, 2001) led to the conclusion that the reason of the increase was due to the build-up of radio-active isotopes, such as ^{22}Na, ^{24} Na, and others. These isotopes are gamma-ray emitters, but none of them above 4.2 MeV.

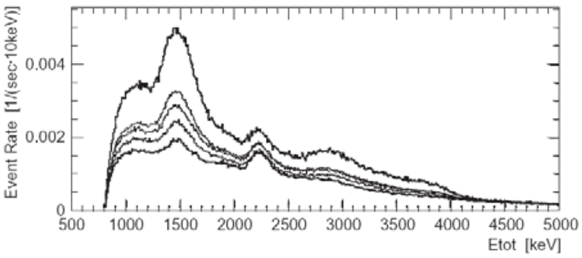


Fig.4 COMPTEL background spectrum measured at different times of the GRO mission: lowest spectrum: May 1991 to Nov 1993, intermediate spectra taken between November 1993 (time of first reboots) and May 1997, highest spectrum: after re-boost of the observatory to 517 km altitude in May 1997.

For the design of future instruments it is essential to understand how and where these background production processes occur. The most imported processes are summarized in Fig. 5. The first type of background events are real gamma-ray events which are produced within the COMPTEL field -of-view inside or around D1 of COMPTEL (labelled as "type A" and "type B"-events in Fig.5). If the material is inside the veto-domes, prompt gamma-ray production can only occur via secondary neutrons that were produced somewhere inside the 15 tons spacecraft. If the material is outside COMPTEL's veto shields (e.g. OSSE or EGRET instruments) then gamma-rays may be produced by either cosmic rays-mainly protons-directly, or again by secondary neutrons (type–B events in Fig.5). The second important category of background events are " cascade events". These are produced by nuclear interactions which lead to the simultaneous emission of at least two gamma-rays: one of them hits D1, the other one D2 (type "C" and "D"-events in Fig.5). Quite a fraction of these events are suppressed by means of time-of-flight measurements. Finally, cosmic ray showers in the neighbouring experiments and materials can produce several gamma-rays which are spatially uncorrelated but timely correlated (type "F" events). Again, the time-of flight measurement helps to suppress significant fractions of these events.

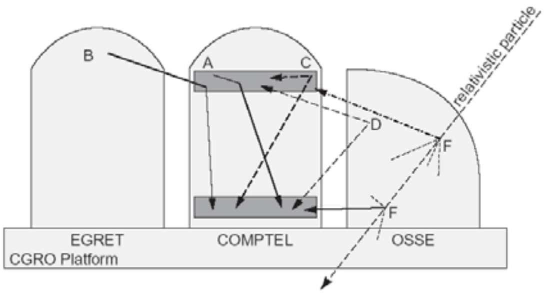
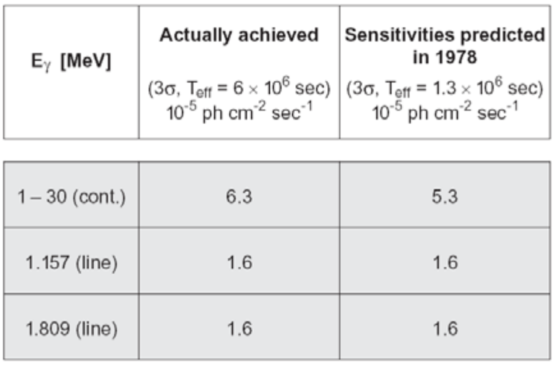


Fig.5 Schematics to illustrate COMPTEL instrumental background events.

The effect of the higher-than-expected background rate on the COMPTEL sensitivity is illustrated by Table 1. The last column lists the originally expected sensitivity for continuum and line emission for an effective observation time of 1.3• 10^6 sec (roughly 1.5 months actual observing time). This exposure time was assumed to be appropriate in order to complete an all-sky survey within 2 years (the announced nominal mission life time of GRO). Actually, however, we were extremely lucky! The actual mission life time of the Compton Observatory was not 2, but 9 years. Thus the loss in sensitivity due to the higher background was compensated by the 4.5 times higher observation time (see second columns of table 1). In the end, we got what we had expected. The final COMPTEL sensitivities have to be improved by at last the factor of 10, mentioned above, by any future gamma-ray mission in the 0.5 to 50 MeV energy band.



E_γ [MeV]	Actually achieved (3σ, $T_{eff} = 6 \times 10^6$ sec) 10^{-5} ph cm^{-2} sec^{-1}	Sensitivities predicted in 1978 (3σ, $T_{eff} = 1.3 \times 10^6$ sec) 10^{-5} ph cm^{-2} sec^{-1}
1 – 30 (cont.)	6.3	5.3
1.157 (line)	1.6	1.6
1.809 (line)	1.6	1.6

Table1: COMPTEL point source sensitivity.

4. Guidelines for the next Generation of Compton-Telescopes

It is not the intention of this paper to make suggestions for a specific next generation instrument but instead to establish some general guidelines. In order to gain the required increase in sensitivity, the sensitive area of the telescope has to be increased and the background has to be minimised. The increase of the sensitive area does not necessarily mean that the instrument has to be bigger and heavier than COMPTEl. COMPTEL's detection efficiency was only of the order of 1%. An increase of the efficiency by about a factor of 5 to 10 is possible, if large solid angles (e.g. 2π steradian) for the Compton scattered gamma-ray are allowed. (In case of COMPTEL, this solid angle was only of order 0.5 steradian).The most sensitive tool to increase the sensitivity is to reduce the instrumental background rate. There are different possibilities:

(1) To improve the detectability of point sources, it is most effective to have the best possible angular resolution (to minimize the angular resolution elements). The angular resolution is determined by the spatial resolution of the detectors (localisation of gamma-ray interactions) and the energy resolution.

(2) The most effective general background rejection tool in case of COMPTEL was the time-of flight

measurement. On average, there were about 10-times more up-scattered (bad) events than downwards scattered (good) events (Fig.6). For some pairs of (E1,E2)-values the ratio was even of the order of 100:1. All new instruments which are now being developed or investigated do not foresee this background rejection tool. Therefore it seems to be essential to me that these instruments must have other comparable tools (like the "direction of motion" parameter which determines the sequence of interactions from consistency checks of the Compton kinematics or from measuring the direction of motion of the Compton electron).

(3) A very significant background reduction can be achieved by localising the arrival direction on the event circle. This is possible, if the track of the Compton electron is measured. By this means the background per angular resolution element can be suppressed typically by a factor of 10 (energy dependent).

4) To minimise the production of secondary gamma-rays (the main background source of COMPTEL), it is existential to have as little passive material around the instrument as possible, and to have no neighbouring instruments.

(5) Optimisation of φ-selection windows and windows for scatter angle directions is another important and sensitive tool to reduce the background. In case of COMPTEL the suppression of Earth albedo gamma-rays was achieved in this way. In addition, φ- restrictions also reduce the fraction of so-called masquerading events (these are events in which the interaction in D2 is not triggered by the Compton-scattered gamma-ray but by a bremsstrahlung gamma-ray of the Compton electron or by secondary gamma-ray emission from an initial pair production process in D1). See Weidenpointner (1999), Kappadath (1998) and v. Dijk (1996).

(6) The choice of the satellite orbit has a huge effect on the overall background. Remember, that for the case of COMPTEL the background varied already by a factor of 3 between geographical latitudes of 0° and 28°. The increase of the orbit from 450 km to 517 km added another factor of 2 to the background rate.

(7) The coincidence window between D1 and D2 has to be narrow enough to keep the accidental coincidences below ~ 10 % of the total event rate.

During this workshop more than half a dozen of new suggestions for advanced Compton telescopes are presented. I recommend that the above seven aspects be checked, when designing the next mission.

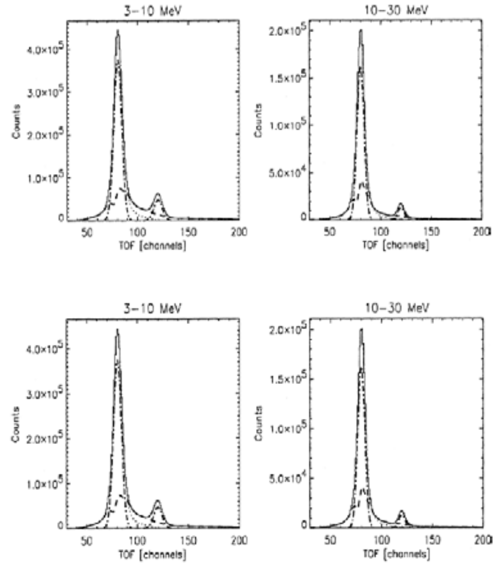


Fig.6 Time-of –flight distributions measured by COMPTEL in four energy intervals.

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