International Conference on Space Optics—ICSO 1997

Toulouse, France

2–4 December 1997

Edited by George Otrio

PIMACS (Polarimeter and improved modular anti-coincidence system): an effective instrument concept for x-, gamma-ray monitoring, and polarimetry measurements on the International Space Station

Timo Stuffler, Roland Graue, Antony J. Bird, Antony Dean, et al.

International Conference on Space Optics — ICSO 1997, edited by Georges Otrio, Proc. of SPIE Vol. 10570,
105700W · © 1997 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2326470

PIMACS (POLARIMETER AND IMPROVED MODULAR ANTI-COINCIDENCE SYSTEM) AN EFFECTIVE INSTRUMENT CONCEPT FOR X-, GAMMA-RAY MONITORING, AND POLARIMETRY MEASUREMENTS ON THE INTERNATIONAL SPACE STATION

Timo STUFFLER*, Roland GRAUE*, Antony BIRD , Anthony DEAN, Rüdiger STAUBERT^

**Kayser-Threde GmbH, Wolfratshauserstr. 48, 81379 Munchen, Germany*
University of Southampton, Dep. of Physics, Southampton, SO17 1BJ, United Kingdom
^*University of Tübingen, Inst. for Astronomy, Waldhäuserstr. 64, 72076 Tübingen, Germany*

Abstract - *This paper describes a mission to finalise the development of a modular anti-coincidence system with relevance across a wide range of space-borne hard X-ray and gamma-ray instrumentation. The addition of a small detector array based on the same technology constitutes an instrument which will be able to provide good quality spectroscopy and detect polarisation in astronomical gamma-ray emissions. Both primary detector and anti-coincidence system are based on a number of small, relatively low-cost CsI(Tl)-photodiode elements and some BGO-photodiode elements allowing a direct comparison between both crystal materials. CsI(Tl)-photodiode systems should offer both cost and performance benefits over the current standard BGO-PMT or CsI(Tl)-PMT systems*

1 - INTRODUCTION AND BACKGROUND

The performance of small (few cc) CsI(Tl)-photodiode detectors has been extensively evaluated and optimised over the past decade, particularly in connection with the imaging detectors for INTEGRAL [1]. Larger variants of these detectors are now being built for use in terrestrial nuclear physics experiments, but the design criteria are very different from those in space applications. Hence the design of larger-volume detectors which would be appropriate to the space anti-coincidence application has been largely unstudied.

The scientific performance of an anti-coincidence system based on this new technology can be at least as good as currently operating and proposed systems, while providing a number of technical advantages. The current standard anti-coincidence design is to use a scintillator combined with photomultipliers. in comparison, the CsI(Tl)-photodiode detectors offer

- reduced power consumption
- lower detector mass
- lower electronics mass
- lower cost
- simpler support structure as material is not brittle or hygroscopic
- high reliability due to high degree of shield segmentation
- higher reliability due to lack of HV supplies and use of proven radiation hard semiconductor technology
- possibility of spectroscopy with sufficient resolution
- reduced roll-off effects within the different crystals

We therefore propose to use the Space Station as an opportunity to study a number of novel detector configurations in operation in space over an extended period, and crucially to be able to fully characterize the materials on their return to Earth (postflight analysis). The key results from such a study would be:

- comparison of light collection methods in large crystals
- optimisation of crystal properties for space use (e.g. doping levels of Tl in the CsI)
- optimisation of electronics design to provide fast, accurate trigger capability
- precise measurement of the cosmic-ray induced radiation in the scintillator
  optimisation of photodiode structure and performance
- characterisation of radiation damage effects in scintillator, photodiode and electronics
  direct comparison with BGO crystal behaviour (inflight, postflight)

The outcome will therefore be a firm design for CsI(Tl)-photodiode anti-coincidence modules which can be used to reduce the cost of a number of forthcoming gamma-ray experiments significantly, while providing state-of-the-art performance and a proven reliability. As a useful by-product of this experiment, the radiation environment will be extensively studied during the course of the mission and will provide design input to future gamma-ray instrumentation for the Space Station.

2 - PIMACS OBJECTIVES

The key feature of the proposed new veto technology is to overcome some of the disadvantages which have delayed their use in space, and at the same time to provide a modular system which can be readily adapted to a number of applications, giving further potential benefits in terms of cost and flexibility of application.

2.1 - Technological Objectives

The technological objectives are aimed at optimising the modular anti-coincidence concept. The key requirements for an anti-coincidence system can be defined in terms of the following criteria:

i) detection efficiency
ii) low energy threshold
iii) spectral resolution
iv) maximum count rate
v) timing resolution for veto tag generation

(i)-(iii) are determined by the quantity of scintillation light generated in the crystal and the efficiency with which it is collected at the photodetector(s) and converted to an electrical signal. The latter two criteria are influenced primarily by the decay characteristics of the scintillator material and the readout electronics.

CsI(Tl) scintillators have an immediate intrinsic advantage in that they produce approximately eight times more optical photons for a given energy deposit than BGO does. However, in the past, CsI(Tl) scintillators have been coupled to photomultipliers with very poor performance in the ~580nm region where CsI(Tl) emits. The advantage of the very high scintillation yield of CsI(Tl) has therefore been almost completely lost in such systems. Use of photodiodes allows the scintillation photons to be converted to electronic signals with very high quantum efficiency, and so the number of signal carriers generaed is much higher; allowing for the first time a realistic possibility of providing moderate (~10% at 1 MeV) spectral resolution within a large CsI(Tl) veto counter.

However, the major difficulty associated with the use of photodiode readout is the very low level signals which must be dealt with. Unlike a photomultiplier a photodiode has no intrinsic gain, and so a 1 MeV energy deposit would lead to a signal of only ~35000 electrons. Thus the performance of the subsequent readout electronics chain is critical if the readout noise is not to dominate the overall detector performance. Recent improvements in both photodiode and preamplifier design have indicated that the electronics is indeed feasible in this respect, with prototype measurements at Kayser-Threde [2] showing the feasibility of using large volume CsI(Tl)-PD detectors with thresholds of ~100 keV. In addition, the decay time of CsI(Tl) is significantly longer than that for BGO or NaI(Tl), which has potential impact on the maximum rate at which any veto could operate.

The behavior of CsI(Tl) afterglow will be examined in the space radiation environment leading to a reconstruction and therefore better understanding of the activation process in space. Post flight characterizations of aging procedures on the crystal, coating, the glue etc after a long space exposure can be done extensively leading finally to an optimized H/W set-up. In addition, having different sizes of detectors allows the 'light bucket' effect observed in the SIGMA shield (CsI(Tl)+PMT) to be better scaled.

However, the concept of constructing a modular ACS offers two major advantages as compared to construction from large scintillator-PMT modules: the uniformity of performance within a single element is much better; and the impact of the loss of a single element is much less severe due to the high degree of segmentation.

The purpose of this experiment is to propose solutions to the problems associated with CsI(Tl)-photodiode systems, and demonstrate that they can be used successfully in the space environment.

2.2 - Scientific Objectives

The scientific objectives will be fulfilled by the use of the 76 small element CsI(Tl)-photodiode detector array mounted within the modular anti-coincidence and the spectroscopic data evaluation of the solar flares. As there will be no intrinsic imaging capability within the instrument, observations are necessarily limited to those based on time-extraction of the signal. The primary science objectives are therefore

- polarimetry of the Crab Pulsar
- burst detection, polarimetry and spectroscopy
- polarimetry and spectroscopy of solar flares

It is generally accepted that astronomical gamma-rays are produced via i) synchrotron emission; ii) Curvature radiation; iii) Cyclotron emission; iv) Bremsstrahlung radiation, v) Inverse Compton scattering, or by a combination of these mechanisms. Further, it has been shown that all these mechanisms operating in an environment, e.g. near a neutron star or black hole, will lead to highly polarised gamma-ray emission with little or no need for extra specialised source geometry or physical conditions [3]. As the polarisation signature of each production mechanism is distinct, polarimetric observations have the ability to provide a unique insight into astronomical objects where several models may fit the observed data equally well. By a successful identification of the correct emission mechanism, many models may be eliminated and valuable information can be gained about the emission geometry

Gamma-ray pulsars are excellent candidates for polarisation studies. There are currently two types of models for gamma-ray pulsars. Polar cap models assume that particles are accelerated along open field lines near the neutron star by strong parallel electric fields. The primary particle induced electromagnetic cascades through the creation of electron-positron pairs by either curvature radiation or inverse-Compton radiation gamma-rays. Outer-gap models assume that the primary particles are accelerated along open field lines in the outer magnetosphere, near the null charge surface, where the co-rotation charge changes sign, and where strong electric fields may develop. Since the magnetic fields in the outer gaps are too low to sustain one-photon pair production cascades, these models rely on photon-photon pair production of gamma-rays, interacting with either nonthermal X-rays from the gap or thermal X-rays from the neutron star surface, to initiate pair cascades. Both models predict highly polarised gamma-ray emission, up to 80%. Romani & Yadigaroglu [4] computed the polarisation angle variation for the Crab pulsar in frame work of the outer gap model and found the outcome is in good agreement with the polarisation sweep as observed at optical wavelengths. Confirmation of this in gamma-ray polarimetry studies will firmly locate the gamma-ray emission region in the outer magnetosphere.

The good spectral resolution of PIMACS around 0.5 MeV will enable the measurement of the shapes of the ^{7}Be ^{7}Li line complex (0.429, 0.478 MeV) resulting from non-thermal fusion reactions of accelerated alpha particles with photospheric ^{4}He. These line shapes are sensitive to the angular distribution of the energetic alpha particles and therefore reflect their acceleration and transport in flares. Investigations of this effect using SMM-GRS data [5] show the validity of this new approach to measure the directionality of high energy particles in flares. PIMACS will allow to continue these studies in the solar maximum.

The sensitivity to measure polarisation allows the search for polarised low energy gamma ray emissions from flares. In the visual range (H_alpha) polarisation has been observed during the impulsive phase of some flares. This has been explained as due to the impact of low energy protons (0.1-1MeV) on the cromosphere – it is therefore called 'impact polarisation'. In the photon energy range of several 100 keV (electron bremsstrahlung) one could expect to find similar polarisation effects. Such measurements have never been possible before.

After over 23 years of study, the origin of gamma-ray bursts (GRB) remains a mystery. The implied luminosity and the observed sub-millisecond scale variability suggest a neutron star (NS) or black hole (BH) origin. Old magnetised NS and the mergers in BH-NS, NS-NS close binary systems are suggested as possible source of GRB for the extended Galactic halo model and cosmological model respectively, while all above processes can be the underlying gamma-ray production mechanism. Shaviv & Dar [6] suggested the inverse Compton scattering of photons from transient jets of highly relativistic particles as a possible universal mechanism for production of GRB. One of the main prediction of this model is the high degree of polarisation of the burst photons, at maximum the gamma-rays are almost completely polarised.

In summary, the results of the experiment will lead to a better understanding of the physics underlying sources of polarized gamma-rays, that means

- geometry and production mechanisms relating to the Crab pulsar and neutron stars in general
- solar flare mechanisms, particle fluxes, evolution of the flare, particle containment, geometry of the system etc.

- geometry and production mechanisms relating to gamma-ray bursts and the way in which bursts evolve.

An additional scientific technical product of this mission will be an extensive characterisation of the background radiation environment on the Space Station. This will allow detailed models of the in-orbit performance of future gamma-ray instrumentation to be constructed and hence provide valuable design input.

PIMACS is only a small prototype and will only study the polarization of the strongest solar flares and gamma-ray bursts, and the Crab after a long exposure. However, it will provide invaluable scientific and technical information which will allow the design of future astronomical gamma-ray polarimeters for missions in the next century and future gamma and hard x-ray missions on the Space Station.

3 - EXPERIMENTAL SET-UP

3.1 - The Spectroscopy and Polarimetry Array (SPA)

The polarimetry array consists of an approximately circular arrangement of 76 individual detector elements. The near-symmetrical arrangement is required in order to reduce systematic errors during the polarimetric measurements.

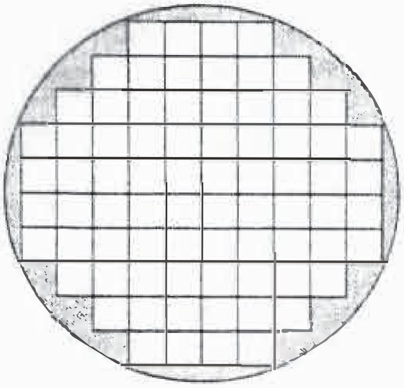

Figure 1: Pixel arrangement within the SPA array

The SPA detector elements are housed within a spark-eroded aluminium structure which holds the individual elements in a 10 mm pitch array (Figure 1), and also serves as a housing for the front-end electronics. The SPA housing is mounted within the well of the anti-coincidence system, which not only provides background rejection, but also defines the field of view of the SPA array. Each SPA detector element consists of a 9.5x9.5x25 mm^3 CsI(Tl) scintillator read out by a 6x6 mm^2 photodiode. The total active area of the SPA detectors is therefore 69 cm^2.

Small detectors of this type have been extensively optimised for the imaging detector arrays for the INTEGRAL mission. Each pixel consists of a small 9.5x9.5x25 mm^3 CsI(Tl) scintillator crystal polished on all surfaces, except the surface at the far end from the photodiode, which is roughened slightly. The crystal is completely enclosed in a Millipore paper wrapping which is extremely reflective and so minimises light losses during the transport of the scintillation photons to the photodiodes. The photodiodes used are selected low-noise devices with an active area of 6 x 6 mm^2 with dark current <0.5nA. The scintillation light is then coupled into the photodiode through a thin layer of optical adhesive selected to be chemically compatible with the CsI(Tl) material. Overall conversion efficiencies ~35 electrons/keV can be achieved in such a configuration.

The SPA detectors are coupled directly to the first stage preamplifiers within the front end electronics so as to minimise additional noise due to parasitic capacitance and inter-channel cross-talk. When coupled to electronics with a noise level of ~500 electrons (rms), typical performance for this type of detector is as follows:

Minimum energy threshold : <50 keV
Spectral resolution : 7% FWHM at 662 keV.

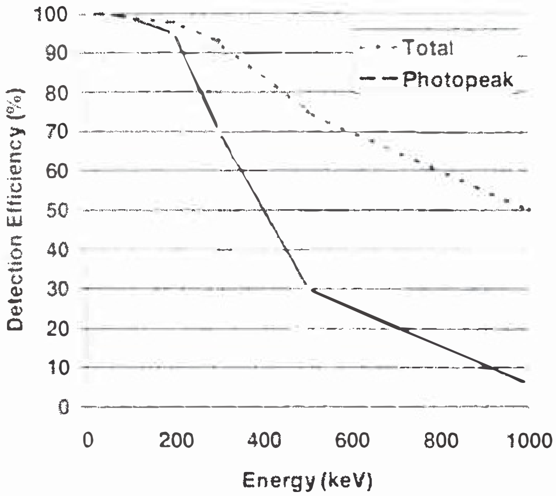

Figure2: Detection efficiency for SPA detectors

The SPA detectors can operate from ~50 keV to ~1 MeV in spectroscopy mode, the upper limit being simply dependent on the thickness of the scintillation crystals. The lower energy threshold will be commandable during flight. Since polarimetric measurement requires two energy deposits from a Compton scatter, the threshold for polarimetry is ~100 keV. The detection efficiency as a function of energy is shown in Figure 2.

The SPA detector will by default be concurrently operated as both a spectrometer and a polarimeter. The detector will be able to operate in a Photon-by-photon mode. The advantages of photon-by-photon mode are:

- concurrent spectroscopy (256-channel pulse-height spectrum for each pixel) and polarimetry
- polarimetry possible for whole of source pass through FOV
- all corrections can be carried out on ground
- simpler implementation of burst spectroscopy (no requirement for pre-burst buffering of histograms)

The storage of a global event spectrum is possible through an on-board energy correction requiring regular uploads of pixel gain correction tables to the instrument. A fast-clear facility will be used to empty all histograms in the event of a burst detection to prevent contamination with pre-burst data, although this may result in loss of data during the early part of the burst.

Within the polarimetry mode, the pixellated detector array allows the angle through which a photon is Compton scattered to be coarsely measured. The pixels of the SPA are made fairly small so that the range of the scattered photon is quite large (a few pixels), and so the angular determination is then somewhat better than if only nearest neighbours are involved in the scatter. Two polarimetry-only data acquisition modes are possible: if a stable orientation towards the source is maintained, then onboard histogramming of the calculated scatter angles is possible. This allows for very efficient storage and transmission of the polarimetric data. However, the default mode of operation of to carry out long observations as the source sweeps across the large SPA field of view. In this case, then the scatter angle (in instrument co-ordinates) and space station orientation information must be sent to ground so that the true scatter distribution can be reconstructed.

Some of the corner elements of the SPA detector will be equipped with Si-drift-diodes. This diode type promise measurements with superior performance [7] and thus a direct comparison with the measurements of the scintillators using Pin-diodes can be made. Further, for a detection of the charged particles within the FOV of PIMACS a plastic scintillator based on APD (Avalance Photodiode) readout will be mounted on top of the whole instrumentation.

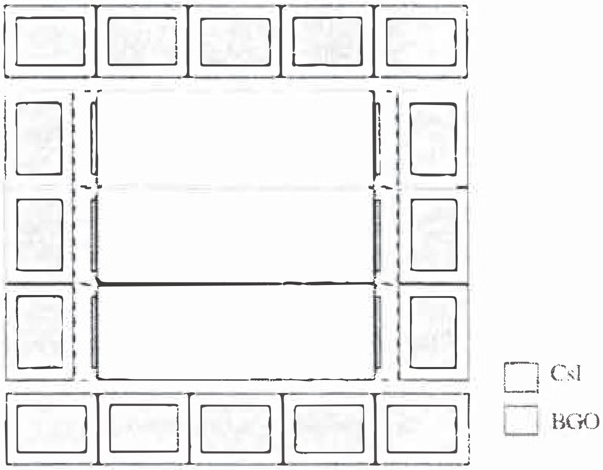

Figure 3: Rear view showing construction of ACS - the four corner elements are made from BGO

3.2 - The Anti-Coincidence System (ACS)

The Anti-Coincidence System is built up from 16 single-diode detector modules which make up the sides of the veto, and three larger volume two-diode variants which form the rear shield (see Figure 3). The four corner elements of the side veto are made from BGO, while all the other veto elements use CsI(Tl). This symmetrical arrangement has again been designed to minimise the systematic effects within the polarimetry array.

The three rear veto elements each comprise 30x40x120mm^3 CsI(Tl) scintillator crystals read out by a 25x35mm^2 photodiode mounted centrally on each of the small ends of the crystal. For each of these rear modules, the signals from the two photodiodes are summed before discrimination to form the veto signal. The side veto elements each comprise a smaller 30x40x80mm scintillator crystal, read out by a single 25x35mm photodiode on one of the small crystal end surfaces.

The two different ACS module sizes have been arranged so as to provide a 3cm thick ACS wall surrounding the SPA detectors on all sides. Any gaps between modules have been arranged so as to avoid a direct path through the ACS onto any of the SPA detectors. The performance of the ACS detector configurations has been extensively modelled using optical Monte-Carlo techniques. The air-gap method clearly provides the most uniform light collection, which is important for the overall detector performance.

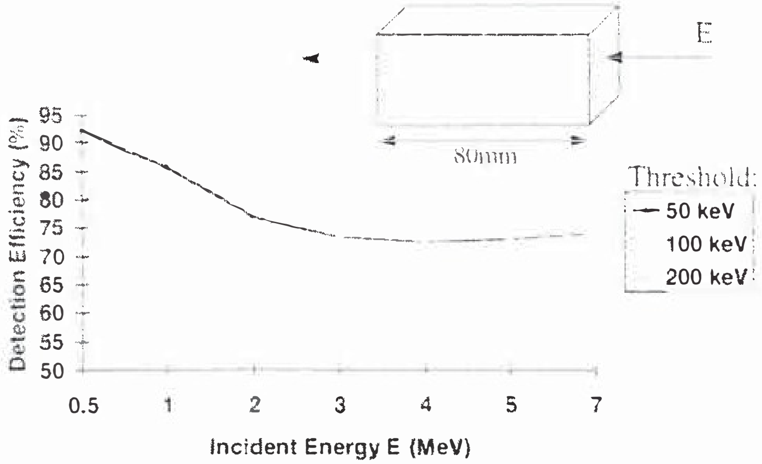

Figure 4: Veto efficiency as function of minimum threshold

A common configuration is used for all the veto elements, as in every case the same requirements of maximum and uniform light collection are of paramount importance. A comparison of the veto efficiency as a function of the minimum energy threshold is shown in Figure 4. All crystal surfaces are polished to a high degree, and then each scintillation crystal is wrapped by a highly reflective white paper coating. The porous or fibrous nature of the paper ensures that a small gap is maintained around the crystal even under vacuum conditions, which maximises total internal reflection of the scintillation light. If the scintillation light does escape from the crystal then the white paper coating is ~98% reflecting so as to minimise the light losses. The photodiodes are coupled to the crystals using an optically transparent glue which is also inert when placed in contact with CsI(Tl). In order to carry out one of the principal materials studies, the different sections of the ACS walls will be constructed with CsI(Tl) with different thallium doping levels.

The operating low energy threshold for the ACS modules will be individually commandable during the flight. In addition, the individual veto readout channels will be commandable on/off so as to:

- provide protection against noisy channels
- investigate the effect of one or more 'dead' veto elements on the SPA background
- enable specific tests on the ACS modules (see section on calibration system)

The ACS signals will also be taken for spectroscopic data evaluations. A typical performance of the ACS detectors is:

Minimum energy threshold: < 100 keV
Spectral resolution: 18 % FWHM at 662 keV.

3.3 - Calibration Measurements

In order to provide frequent accurate monitoring of the performance of both the SPA and ACS detectors, the 511 keV background line will be measured for a calibration providing very clear diagnostic signatures. The SPA calibration will be a continuous process, carried out by inspection of the pixel energy spectra, from which gain correction tables will be derived. The ACS calibration will be carried out on a regular basis (once per week) so as to monitor any changes in the ACS module performances. A 256-channel pulse-height spectrum from each detector, accumulated over a period of several orbits will be transmitted to ground for analysis, primarily to detect any overall gain changes.

For the characterisation of the SPA gamma-ray detector array on ground, a polarised gamma-ray source described in the following will be set-up. Certain nuclei emit naturally polarised gamma-rays; in some cases two photons may be emitted and the angle between their directions can be used to infer the polarisation of the photons. The calibration configuration is then to detect one of the two photons in a external coincidence detector which subtends a small solid angle to the source, and to calibrate only on photons in coincidence with this external counter. A Co-60 source has been used successfully in this way to produce a beam of 1.173 and or 1.332 MeV photons with well-defined polarisation angle and a degree of linear polarisation of ~17%.

4 - USE OF PIMACS ON THE INTERNATIONAL SPACE STATION

An Express Pallet Adapter on the ISS forms the optimum accommodation for the PIMACS instrumentation in that it provides a combination of a long observation time of order three years in combination with the possibility of post flight analysis of the H W at the end of the mission. Through the observation times of three years, the proof for a use of the technology on e.g. a free flyer satellite mission with expected living times between 2 - 5 years will therefore be given.

In terms of the technology aspects of the instrumentation, the behavior of the scintillation crystals being exposed to the mixed gamma-ray and charged particle fluxes in the space environment is very different to that from the radiation of gamma-ray sources on the ground. The use of a novel and not flight proven CsI(Tl) based scintillation technology on a satellite would increase uncertainty due to the necessary optimization of different crystal and detector parameters, and the likelihood of a failure or at least an early degradation of the scintillation detector elements.

In-flight analysis will lead to an optimized scintillation detector set-up in combination with the analyzed weekly condition test cycles for both the Anti-Coincidence-Shield and the polarization detector. However, this is only a measurement of the global changes in detector performance. The possibility of a post flight analysis of the scintillation crystals allows damage effects on the PD's, glue areas, crystal coating etc. to be examined extensively and the respective components analysed in isolation. Thus, the causes of any long-term changes can be determined with far greater certainty.

Looking at the scientific aspects of the experiment, due to the rather long term observation of three years practical gamma-ray polarization measurements will be performed with what is, after all, a small prototype. Here, for the Crab observations the averaging and comparison of multiple measurements leading to an improved statistics can be carried out. For the gamma-ray burst and solar flare detection, a three years observation time raises the probability of detection of strong events significantly and thus also the possibility to detect the polarization of the measured gamma ray bursts and solar flares. The PIMACS results will be combined with the Southampton radiation modelling methods to provide a comprehensive and well-calibrated background model.

5-SUMMARY

The PIMACS mission represents a joint scientific and technological test-bed which uses a novel modular anti-coincidence system to shield a small gamma-ray detector array capable of a small number of well-targeted astronomical observations. Specific solar flare and polarimetry investigations can be executed leading to measurements that have never been possible before. Further, a possible comparison of the measurement results with the results from INTEGRAL can be of great scientific value.

The Anti-Coincidence Shield will make use of an very innovative combination of materials, photosensitive detector elements and new readout techniques to provide a flexible, low cost system having very good background rejection performance. The availability of a proven high-performance and high-reliability instrumentation would have a considerable impact on the design of future space missions in the hard X-ray and gamma-ray energy range.

6 - ACKNOWLEDGEMENTS

We would like to express special thanks to Dr. Kanbach and Dr. Rieger, Max-Planck-Institute for Extraterrestic for their expertise of solar flare detections.

7 - REFERENCES

[1] C. Labanti et al., *PICsIT: the high energy detection plane of the IBIS instrument onboard INTEGRAL*, SPIE Proceedings 2806, 1996.
[2] R. Graue, T. Stuffler, T. Göbel, K. Schwenkenbecher, *High-Resolution-Gamma Ray Detector System for INTEGRAL*, Proceedings AAAF, Paris, 1996.
[3] Lei F., Hills G.L., Dean A.J., *Compton Polarimetry in Gamma-Ray Astronomy*, Space Science Reviews, in press
[4] Romani & Yadigaroglu, Ap.J. 438, p314 (1995)
[5] Share, Murphy, Ap.J. 485, p409 (1997)
[6] Shaviv & Dar, Ap.J. 447, p863 (1995)
[7] C. Fiorini et al., *First experimental results of a new gamma-ray detector based on a Silicon Drift Chamber coupled to a scintillator*, Nuclear Instruments and Methods, to be published soon.