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A solar flares X-ray polarimeter

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Abstract. The measurement of X-ray polarization from solar flares is a scientific challenge which did not give any exhaustive result so far. X-ray polarimetry would be a probe of the solar flares physics making possible to study directly the magnetic reconnection and particle acceleration in the solar atmosphere of active regions where flares take place. New instrumentation specifically developed to measure the polarization of X-ray is needed to obtain results with adequate significance. The photoelectric polarimeter Gas Pixel Detector (GPD), originally developed to observe astrophysical sources other then the Sun, can address also solar science. The recent development of a new detector prototype effective in the hard X-rays makes suitable this polarimeter to examine the solar flares spectral region in which typically the non-thermal bremsstrahlung emission, expected to be highly polarized, arises with respect to the thermal bremsstrahlung whose polarization is expected to be marginal. The GPD versatility and small size make such an instrument suitable to fly on board of small space missions.

Key words. Sun: flares – – Techniques: high angular resolution

1. Introduction

The Sun is an astrophysical source with a very intense emission in the X-ray band. The behaviour of the magnetic field of our star and the mechanism of acceleration of the solar wind can be understood by studying the energetic events, such as solar flares. They are produced by magnetic reconnection that causes the release of a huge energy in the solar atmosphere. The spectrum of solar flares in the X-ray energy band is characterized by the presence of two components. The Soft X-ray (SXR) component dominates the emission up to about 15–20 keV and it is strongly characterized by line emission up to about 7 keV (Doschek 2002). The Hard X-ray (HXR) component rises up with respect to the SXR from about 15–20 keV. While the continuum of the soft spectrum is produced by thermal bremsstrahlung which is due to hot plasma emission (Peres et al. 1987; Fludra et al. 1995; Battaglia et al. 2009), the hard component is interpreted as non-thermal bremsstrahlung produced by particles that slow down (Brown 1971; Hudson 1972; Lin & Hudson 1976) in the lower and dense layers of solar atmosphere (thick target

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model), but sometimes also in the reconnection site (thin target model). The SXR emission is therefore typically associated to the flare magnetic loop, while the HXRs are emitted from the regions where particles come to rest (the flare foot-points, but also from the loop-top). Such emission components evolve during the flare lifetime, making the solar flare an extremely dynamical source.

The polarization of X-rays depends on the beaming properties of accelerated particles that are strongly influenced by magnetic field geometry. There are in the literature numerous studies published about polarization predictions, for a wide range of solar flares models, but observations in the X-ray energy band have never been exhaustive. Zharkova et al. (2010) predict a polarization degree at 20 keV of the HXR non-thermal bremsstrahlung component up to 40% at the solar limb. A marginal polarization is expected to come from the thermal bremsstrahlung component (Emslie & Brown 1980) due to the anisotropic expansion of the hot plasma constrained by the magnetic field lines. At energy of about 20 keV radiation flux is still high, due to the power low shape of solar flares spectrum, and the emission becomes to be dominated by non-thermal bremsstrahlung whose polarization is expected to be significantly high. Therefore this energy region of the flare spectrum is suitable to be taken into account for polarimetric measurements.

2. The Gas Pixel Detector as an X-ray solar flare polarimeter

Polarimeters exploiting the photoelectric effect are among the most promising to measure the polarization of X-rays up to some tens of keV. The Gas Pixel Detector (GPD) is one of them (Costa et al. 2001; Bellazzini et al. 2006). This instrument has been developed in collaboration between the Italian research institutes INFN of Pisa and INAF-IAPS. The GPD is a gas filled detector that comprises an absorption gap, a Gas Electron Multiplier (GEM) and a read-out fine subdivided pixel plane (50μm of pitch). The instrument images the photoelectron tracks (see Fig. 1) produced in the absorption gap and allows to obtain the projection, onto the pixel plane, of the absorption points and the photoelectron emission directions that are statistically more probable along the direction of polarization of the absorbed photons. Therefore, if polarized radiation is detected, a modulation arises in the angular distribution of the azimuthal photoelectron emission directions. As a consequence, the GPD is capable to perform polarimetric measurements while doing the image of the source. Since the charge collected on each pixel that forms the track is proportional to the photon energy, also the photon spectrum can be obtained with a discrete energy resolution of about 20% at 5.9 keV. The detector has an active area of 1.5×1.5 cm^2 and a self-trigger capability that allows to download the collected charge only form the small pixel region interested by a track. By changing the pressure, the gas mixture and the depth of the absorption gap, it is possible to select properly the energy band of employment from 2 to some tens of keV.

A recent development of the GPD allows to measure polarization in the 6–35 keV energy band (Fabiani et al. 2012b) by means of a gas mixture composed by Ar 60%–DME 40% at the pressure of 3 bar in a 3 cm absorption gap. This new prototype was proposed to study the polarization of solar flares (Fabiani et al. 2012a,c).

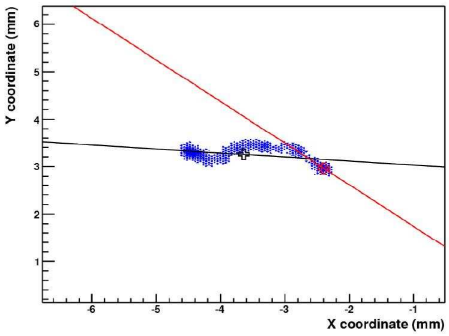

Fig. 1. Example of a photoelectron track imaged by the GPD filled with an Ar 70%–DME 30% gas mixture at the pressure of 2 bar. The black cross is the barycentre of the charge distribution, the black solid line is the main axis of the track, the red cross is the absorption point and the red solid line is the emission direction of the photoelectron.

3. The ESA call of 2012 for a small mission

A unique occasion to propose the GPD polarimeter to the science community was given by the ESA call of 2012 for a small mission opportunity for a launch in 2017. This call was addressed to instrumentation having a high technological readiness level such as the Gas Pixel Detector. The GPD was proposed on board two space missions: ADAHELI Plus and XIPE. The former is completely dedicated to solar observations and hosts also a payload operating in the visible–NIR energy band, the latter is a mission dedicated to the X-ray polarimetry both of solar and non-solar astrophysical sources. During the two years of nominal operational lifetime of the missions about 20 flares between the classes M5–X10 would be observable, even if the solar activity will be in the decreasing phase.

The polarimetric sensitivity of XIPE and ADAHELI Plus polarimeters were evaluated by means of the Minimum Detectable Polarization (MDP) which is the minimum degree of polarization that can be detected within a certain confidence level. At the 99% of confidence level the MDP is given by (Weisskopf et al. 2010):

$$\mathrm{MDP} = \frac{4.29}{\mu \cdot R} \cdot \sqrt{\frac{R+B}{T}} \tag{1}$$

where R is the detected source rate, B is the background rate and T is the observation time and μ is the modulation factor that represents the fraction of the modulated signal produced by completely polarized radiation over the total signal. The MDP expression for a source dominated observation (if B $\ll$ R_{source}), as an X-ray solar are observation, is:

$$MDP(99\%) \simeq \frac{4.29}{\mu\sqrt{TR_{\mathrm{source}}}} \tag{2}$$

We evaluate the GPD sensitivity by calculating the MDP for solar flares spectra available in the literature. A comprehensive list of solar flares spectra is given by Saint-Hilaire et al. (2008) that performed a statistical study on 53 flares exhibiting a double-footpoint structure. The authors reported the list of spectra in the supplementary material published on a web page[1]. The parameters of the power-low function fit performed on the flares spectra are listed in a table[2]. Each flare duration time is divided in sub-intervals whose integrated spectra produces a modulation factor μ that differs less then 1% between one interval to another, therefore an average value of μ can be considered for all the flare duration. Thus, the total MDP is:

$$MDP_{\mathrm{tot}}(99\%) \simeq \frac{4.29}{\mu_{\mathrm{avg}}\sqrt{\sum_i T_i R_i^{\mathrm{source}}}} \tag{3}$$

where the product $T_i R_i^{\mathrm{source}}$ is the number of counts collected during the sub-interval i and the sum is performed over the number of the flare sub-intervals, thus to obtain the total number of counts.

3.1. ADAHELI Plus

ADAHELI Plus (ADvanced Astronomy for HELIophysics Plus) is a proposed mission aimed to study the solar photosphere and the chromosphere and to monitor solar flare emission (see Fig. 2). ADAHELI Plus is based on the previous ADAHELI (Berrilli et al. 2010) design that completed a Phase-A feasibility study in December 2008, in the framework of Agenzia Spaziale Italiana (ASI) 2007 "Small Missions" Program. The ADAHELI Plus visible-NIR payload (see Fig. 2) comprises a 50 cm high-resolution telescope (ISODY) operating in the visible and the near-infrared band coupled to a Faby-Pérot interferometer, for fast cadence and high spatial, temporal and spectral resolution observations of the solar corona and chromosphere. The payload operating in the X-ray energy band comprises 4 photoelectric polarimeters based on the GPD technology, that are filled with an Ar60%–DME40% gas mixture at 3 bar of pressure in a 3 cm thick absorption gap. Only one

[1] http://sprg.ssl.berkeley.edu/~shilaire/FootPointProject/htmlsummaries/browser.html

[2] http://sprg.ssl.berkeley.edu/~shilaire/FootPointProject/htmlsummaries/_20/table1.html

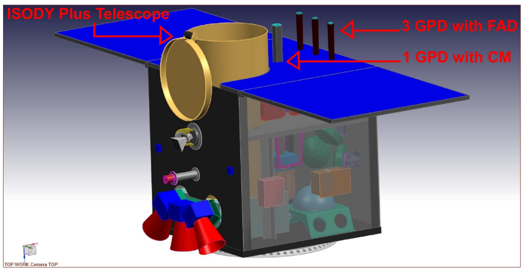

Fig. 2. ADAHELI Plus spacecraft.

Table 1. Solar Flares MDP achievable with ADAHELI Plus. Spectral data are taken from Saint-Hilaire et al. (2008) by summing the flux from two footpoints since the polarimeter configuration used is not able to separate spatially their emission.

Flare Class	MDP (%)	Integration Time (s)
X10	0.5	748
X5.1	1.0	989
X1.2	3.7	239
M5.2	5.0	489
M1	35.5	128

Table 2. Solar Flares MDP achievable with XIPE. Spectra from Saint-Hilaire et al. (2008)

Flare Class	MDP (%)	Integration Time (s)
X10	0.6	748
X5.1	1.3	989
X1.2	4.8	239
M5.2	6.6	489
M1	46.4	128

GPD is coupled with a tungsten Coded Mask Aperture (CMA) that allows to localize solar flares on the solar disc that is always within the $70' \times 70'$ fully coded FOV (the solar diameter is about $30'$) during observations. The coded mask aperture is capable to localize solar flares onto the solar disc with an angular resolution of at least $1'$. This detector/mask configuration is the only one that allows to exploit the GPD imaging capability by ensuring a minimal impact on the mission profile. The three other GPDs are coupled with simple field angular delimiters. Since at energies below 15 keV the solar flux is too high for the detector functionality and moreover the polarization is expected to be very marginal, a fix multilayer gray filter (as a baseline, 5μm copper foil + 200 μm titanium + 200 μm aluminum) will be place in front of the beryllium window to remove low energy photons which otherwise would completely overwhelm the hard X-ray component. Therefore the polarimeter configuration chosen is effective in the 15–35 keV energy band.

In Table 1 the sensitivity of the photoelectric polarimeter on board ADAHELI Plus in terms of MDP is reported. Spectral data are taken from Saint-Hilaire et al. (2008) by summing the flux from two footpoints since the polarimeter configuration used is not able to separate spatially their emission.

The ADAHELI Plus fits very well in single or shared configuration with the VEGA and PSLV launchers that are capable to put the spacecraft in a Sun-Synchronous orbit at 800 km. It allows to perform continuous, long duration (4-h), daily acquisitions, with the possibility of extending them up to 24 h. This kind of orbit allows ADAHELI Plus to point constantly the Sun except during manoeuvres, eclipses or contingencies. Such an orbit is optimized for Doppler shift, important for the visible and near infrared observations, and limits the duration of eclipse phases. It gives about 10 months per year without eclipse.

3.2. XIPE

XIPE (X-ray Imaging Polarimetry Explorer) is a mission based on the concept of the POLARIX mission (Costa et al. 2010) that passed a phase A study in the framework of the Announcement of Opportunity for small missions issue by ASI.

In Fig. 3 the XIPE spacecraft is shown. The extra-solar payload of XIPE consists of two identical X-ray photoelectric polarimeters filled with low-Z gas mixture He20%–DME80% at 1 bar of pressure in 1 cm of ab-

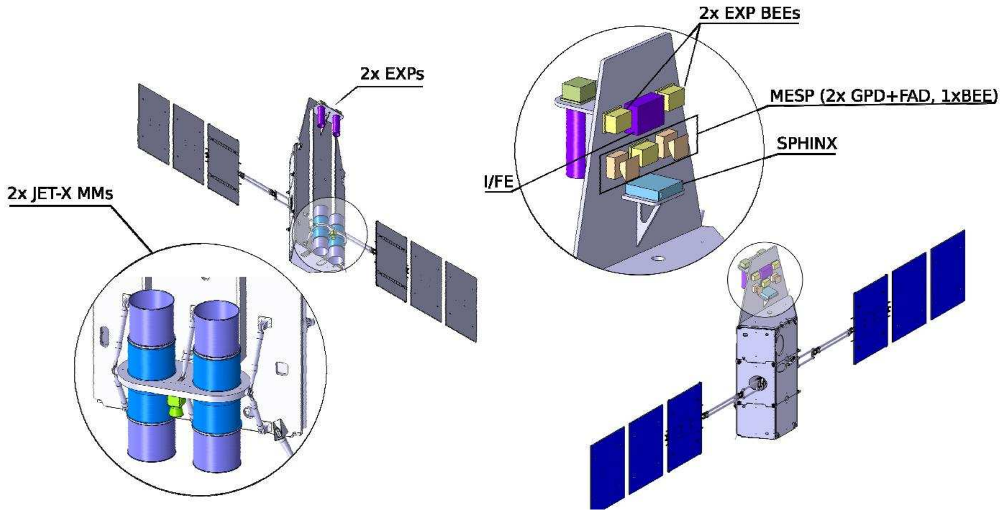

Fig. 3. XIPE spacecraft. The EXP (Efficient X-ray Photoelectric Polarimeters) units are the GPDs for polarimetry of non-solar sources, the MESP (Medium Energy Solar Polarimeter) units are the GPDs for solar flares observations.

sorption gap effective in the 2–10 keV energy band coupled with 2 modules of the JET-X X-ray telescope (Wells et al. 1997). The payload for solar observations comprises two identical photoelectric polarimeters filled with Ar60%–DME40% gas mixture at 3 bar of pressure in a 3 cm thick absorption gap effective in the 15–35 keV energy band thanks to the multi-graded gray filter as for ADAHELI Plus and an X-ray solar spectrophotometer (SphinX) effective in the 0.5–15 keV energy band that is a recurrent of the CORONAS-Photon mission (Sylwester et al. 2008). The XIPE solar polarimeter is equipped only with a field of view angular delimiter.

In Table 2 the sensitivity of the solar photoelectric polarimeter on board XIPE in terms of MDP is reported. Spectral data are taken from Saint-Hilaire et al. (2008) by summing the flux from two footpoints since the polarimeter configuration used is not able to separate spatially their emission.

The mission profile is based on a launch with a VEGA or DNEPR launcher into a LEO type orbit at 600 km of altitude with 5° of inclination.

4. ADAHELI Plus and XIPE: two different approaches

Two different configurations were chosen for the solar flares polarimeter on board XIPE and ADAHELI Plus. The former mission hosts two detector units that do not exploit the imaging capability of the GPD, while the latter is equipped with four GPDs, one of which is capable to localize the flare on the solar disc by means of a coded mask aperture, that on the other hand reduces by a factor of 50% the detectable source flux due to mask shadowing. The sensitive area of the solar flares polarimeter on board ADAHELI Plus is therefore 1.75 times the XIPE sensitive area, that corresponds to an increase of polarimetric sensitivity by a factor of 30%, since the MDP scales as the root square of the effective collecting area. This polarimeteric sensitivity difference explains the difference in terms of MDP reported in Tab. 1 and 2 for ADAHELI Plus and XIPE respectively.

The other important difference between two solar polarimeters regards the field of view. Since ADAHELI Plus is planned to perform observations of sources located on the solar disc, pointing angle does not exceed ±30′ with respect to the solar disc center. Therefore, a fully coded field of view for the coded mask aperture of $70' \times 70'$ was chosen. The same aperture corresponds to the flat top of the field of view angular delimiters for the other three detectors. Instead, XIPE must be free to point sources all over the sky, limited only by the angle of the solar array with respect to the Sun ($< 30°$). Therefore, a $30° \times 30°$ flat top of the field angular delimiter for two detector units was chosen. Besides, ADAHELI Plus is placed on a Sun synchronous orbit that allows to reduce at minimum the Sun obscuration due to Earth eclipses. Therefore the mission payload is always observing the Sun excepted during manoeuvres or contingencies. On the other hand, XIPE is placed on a LEO equatorial orbit, thus for the half of the orbit time the solar flares polarimeter is obscured by Earth and moreover the orientation with respect to the Sun depends primarily on the observation plan for extra-solar sources.

5. Conclusions

Solar flares X-ray emission is expected to be polarized due to the emission of accelerated beamed particles in the magnetic field of the solar atmosphere. The measurements of the polarization in terms of polarization degree and angle is useful to disentangle among different flares models. Measurements performed so far have not been exhaustive. In this work we present the Gas Pixel Detector photoelectric polarimeter as an instrument to measure the polarization of solar flares X-ray emission. This instrument was presented to the ESA call of 2012 for a small mission opportunity for a launch in 2017, in two configurations, on board the XIPE and ADAHELI Plus missions. The former hosts two detector units that do not exploit the imaging capability of the GPD, while the latter is equipped with four GPDs, one of which is capable to localize the flares on the solar disc by means of a coded mask aperture. During the two years of nominal operational lifetime of the missions about 20 flares between the classes M5–X10 would be observable, even if the solar activity will be in the decreasing phase.

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