X-ray polarimetry towards high energy and solar science

S. Fabiani\textsuperscript{1,2}, R. Bellazzini\textsuperscript{3}, F. Berrilli\textsuperscript{1}, R. Campana\textsuperscript{2}, E. Costa\textsuperscript{2}, E. Del Monte\textsuperscript{2}, F. Muleri\textsuperscript{2}, A. Rubini\textsuperscript{2}, P. Soffitta\textsuperscript{2}

\textsuperscript{1}Universit`a degli studi di Roma “Tor Vergata”, via della Ricerca Scientifica 1, 000133 Rome, Italy
\textsuperscript{2}INAF-IAPS, via del Fosso del Cavaliere 100, 000133 Rome, Italy
\textsuperscript{3}INFN, Largo B. Pontecorvo 3, I-56127 Pisa, Italy

E-mail: sergio.fabiani@iaps.inaf.it

Abstract. In the history of X-ray astronomy the only polarimetric measurement obtained with high significance dates back to the late ’70s, when the Crab Pulsar Wind Nebula was observed. X-ray polarimetry remains a widely unexplored scientific field so far. The new 2–10 keV polarimetry era will be opened by GEMS satellite in the next future, while the extension to higher energies is still a challenging goal. The photoelectric polarimeter Gas Pixel Detector (GPD) could be employed with an Ar based gas mixture to measure the solar flares X-ray polarization up to about 35 keV, while coupling it with a Compton scattering polarimeter it would be possible to extend the energy range of measurements to higher energies.

1. Introduction
Polarimetry is an additional tool in the X-ray astronomy besides imaging, spectroscopy and timing which can be employed to study celestial sources. Polarimetric information can be useful to disentangle between source models which otherwise would not be distinguished depending on the other observational techniques. Historically the only polarimetric measurement obtained with high significance dates back to the late ’70s \cite{1, 2}. It gave the confirmation that the Crab Nebula X-ray emission was due to synchrotron radiation ranging from radio wave to X-rays. In the next future X-ray polarimetry will be performed by GEMS \cite{3, 4, 5} in the 2-10 keV energy band. This satellite mission will be equipped with two gas polarimeters based on the Time Projection Chamber (TPC) technology exploiting the dependence of the photoelectric cross section on the photons polarization. Recently many studies have been proposed to extend X-ray polarimetry towards higher energies. Photoelectric polarimeters can employ high Z gas mixtures \cite{6, 7}, while Compton scattering polarimeter are needed to measure polarization up to hundreds of keV \cite{8, 9, 6, 10, 11, 12}. The polarimetry extension up to the hard X-ray energy band allows to study the solar flares physics \cite{7, 13}. As for other sources the measurements of X-ray polarization from solar flares did not give exhaustive results so far \cite{14, 15, 16}. In this work we will show the possibility to employ the photoelectric polarimeter Gas Pixel Detector (GPD) to measure X-ray polarization from solar flares up to 35 keV exploiting also its imaging capabilities. To extend the energy band up to higher energy it is possible to couple the GPD with a Compton polarimeter.
2. Polarimetry Basics

A polarimeter can be thought as an analyser of angular directions coupled with a detector. The analyser allows to distinguish the angular directions of polarization and the detector allows to detect the signal for each angular direction. Therefore the instrument response will depend on the radiation preferential angular direction of polarization. If the detected radiation is unpolarized there are no preferential angular directions therefore the polarimeter response will be flat, being the same for each analysed angular direction (see figure 1a). If the detected radiation is polarized, the instrument will have a modulated response (see figure 1b). Both the photoelectric effect and the Compton scattering have differential cross sections dependent on a $\cos^2 \phi$ term that links the direction of polarization of the incoming photon to the photoelectron azimuthal emission direction in the first case and to the azimuthal direction of Compton scattering in the latter case. Therefore a modulated pattern arises in the detector response that can be fitted by the function:

$$N(\phi) = A_P + B_P \cos^2(\phi - \phi_0)$$  \hspace{1cm} (1)

where $P$ denotes the polarization degree. The modulation factor is defined for 100% polarized radiation as:

$$\mu = \frac{N_{\text{max}}^{100\%} - N_{\text{min}}^{100\%}}{N_{\text{max}}^{100\%} + N_{\text{min}}^{100\%}} = \frac{B_{100\%}}{2A_{100\%} + B_{100\%}}$$  \hspace{1cm} (2)

Such a term is a normalization factor needed to calculate the unknown degree of polarization in a generic case. The radiation whose degree of polarization must be measured will produce a modulated pattern response in the detector which will be fitted by the function of Eq. 1. From the modulation factor and the resulting fitted parameter the polarization degree is evaluated as:

$$P = \frac{1}{\mu} \frac{B_P}{2A_P + B_P}$$  \hspace{1cm} (3)

The sensitivity of a polarimeter is quantified by means of the Minimum Detectable Polarization (MDP) which is the minimum degree of polarization which can be detected within a certain
At the 99% of confidence level for a source dominated observation the MDP is given by:

\[ MDP(99\%) \simeq \frac{4.29}{\mu \sqrt{N_{ph}}} \text{ if } B \ll R_{source} \]  

(4)

where \( N_{ph} \) is the number of detected photons from the source, \( B \) is the background and \( R_{source} \) is the instrumental source counts rate and the factor 4.29 is derived assuming a Poissonian noise distribution. To achieve an MDP of 1%, with \( \mu = 0.5 \) the large number of about \( 7.36 \times 10^5 \) photons must be detected from the source.

3. Solar flares X-ray emission

Solar flares are huge releases of energy into the solar atmosphere originating from magnetic reconnection. As a consequence heating of coronal plasma and acceleration of particles take place. Particles precipitate downwards to the lower solar atmosphere, while depositing their energy [18, 19, 20]. Electrons slowing down emit via bremsstrahlung the non-thermal Hard X-Ray (HXR) emission. Some times the Soft X-Ray (SHR) emission produced by thermal heating from the magnetic reconnection site is not negligible contradicting the model according to which the atmospheric heating is due simply to particles slowdown [21, 22, 23]. Therefore solar flares emission is characterized by thermal emission from hot plasma below about 10–15 keV, where there is also a strong emission due to lines up to about 7 keV [24], and non-thermal bremsstrahlung from accelerated electrons above about 15–20 keV. The soft emission comes typically from the flare loop, whereas the hard one arises from the loop foot-points and sometimes also from the magnetic reconnection site. Polarized radiation is expected from flares models of non-thermal emission due to the anisotropic distributions of electrons that are accelerated in ordered magnetic fields [25, 26, 27, 28, 29, 30]. Thermal radiation is not expected to be highly polarized, only a few per cent is expected due to possible anisotropies in the electron distribution function [31]. The backscattered radiation by the low solar atmosphere can induce and modify the polarization properties of reflected photons [32, 33].

4. The Gas Pixel Detector

The Gas Pixel Detector (GPD) has been developed by the INFN and the INAF-IAPS Italian research institutes. It exploit the dependence of the photoelectric differential cross section to the polarization of the absorbed photon. In figure 2a the scheme of the polarimeter is shown. When an X-ray photon is absorbed in the gas a photoelectron is emitted with higher probability in the direction of oscillation of the electric field of the absorbed photon (\( \phi = 0 \)). It propagates ionizing gas atoms, therefore losing its energy. Electron-ion pairs that are produced along the photoelectron path are drifted and amplified by the Gas Electron Multiplier (GEM) and eventually projected on a fine sub-divided pixel detector located to the opposite site of the entrance window (see figure 2b). The GEM is composed by two metal layers to which a difference of potential is applied for charge multiplication. They are separated by a thin insulator, etched with a regular hexagonal pattern of holes. Low Z He-DME based gas mixtures are suitable to measure polarization in the 2–10 keV energy range, while high Z Ar based ones can extend the energy range of employment up to about 35 keV. The analysis of the projected charge distribution statistical momenta allows to evaluate the projection on the pixel plane of the absorption point (useful to obtain the image of the celestial source) and of the photoelectron emission direction (needed to obtain the modulation curve when many photons are detected). For such an instrument the role of the analyser is played by the gas, while the detector is the pixel plane used to readout the charge signal. Thanks to the imaging capability of the GPD it can be couple with coded mask aperture or X-ray grazing incidence telescope to obtain the image of the source, allowing to get its X-ray polarization map. Sensitivity estimates have been evaluated [13] for this polarimeter coupled with a coded mask aperture assuming an open area.
Figure 2. On the left (a): Scheme of the Gas Pixel Detector. On the right (b): 4.5 keV photoelectron charge distribution projected on the pixel plane. The gas mixture is 100% DME at 0.8 bar of pressure.

of 1 cm$^2$ with respect to the X1.9 flare of 30 August 2002 [34]. An MDP of 5% in the energy band 15–20 keV and 12% in the energy band 20–35 keV were estimated during the peak burst event lasting for 16 s.

5. Compton polarimeter
To measure X-ray polarization at higher energies with respect to the energy range at which the photoelectric absorption is effective, the Compton scattering must be taken into account. Following the Klein-Nishina cross section the scattered photon has a higher probability to be scattered orthogonally to the direction of oscillation of the incoming photon electric vector ($\phi = 90^\circ$). A double phase instrument given by a scatterer made of a low Z material (to have a large scattering efficiency) coupled with a high Z would allow to reduce instrument background taking advantage of the coincidence signals of the scintillation scatterer and the absorber. Therefore it is possible to reduce the low energy threshold down to about 20 keV, where Compton scattering probability in organic scintillators equals the photoelectric absorption. At the present work is in progress and further studies are needed to optimize such an instrument design for solar flares observations.

6. Conclusions
The extension of polarimetry to the hard X-ray energy band allows to study the physics of solar flares. The photoelectric polarimeter Gas Pixel Detector equipped with an Ar based high Z gas mixture can be used to measure the polarization up to about 35 keV. Such an instrument has imaging capabilities and can be coupled with a coded mask aperture or a grazing incidence X-ray telescope to obtain the image of the source. A Compton scattering polarimeter can extend upwards the possibility to measure X-ray polarization to higher energy. If a low energy threshold configuration is chosen, for example by applying coincidence between scatterer and absorber, it is possible to overlap the energy range of this instrument with the GPD Ar based in the energy band 20–35 keV.

References
[1] Weisskopf M C, Cohen G G, Kestenbaum H L, Long K S, Novick R and Wolff R S 1976 ApJ 208 L125
[2] Weisskopf M C, Silver E H, Kestenbaum H L, Long K S and Novick R 1978 ApJ 220 L117
