THE IMAGING PROPERTIES OF THE GAS PIXEL DETECTOR AS A FOCAL PLANE POLARIMETER

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Received 2013 August 9; accepted 2014 March 25; published 2014 June 3

ABSTRACT

X-rays are particularly suited to probing the physics of extreme objects. However, despite the enormous improvements of X-ray astronomy in imaging, spectroscopy, and timing, polarimetry remains largely unexplored. We propose the photoelectric polarimeter Gas Pixel Detector (GPD) as a candidate instrument to fill the gap created by more than 30 yr without measurements. The GPD, in the focus of a telescope, will increase the sensitivity of orders of magnitude. Moreover, since it can measure the energy, the position, the arrival time, and the polarization angle of every single photon, it allows us to perform polarimetry of subsets of data singled out from the spectrum, the light curve, or an image of the source. The GPD has an intrinsic, very fine imaging capability, and in this work we report on the calibration campaign carried out in 2012 at the PANTER X-ray testing facility of the Max-Planck-Institut f"ur extraterrestrische Physik of Garching (Germany) in which, for the first time, we coupled it with a JET-X optics module with a focal length of 3.5 m and an angular resolution of 18 arcsec at 4.5 keV. This configuration was proposed in 2012 aboard the X-ray Imaging Polarimetry Explorer (XIPE) in response to the ESA call for a small mission. We derived the imaging and polarimetric performance for extended sources like pulsar wind nebulae and supernova remnants as case studies for the XIPE configuration and also discuss possible improvements by coupling the detector with advanced optics that have a finer angular resolution and larger effective areas to study extended objects with more detail.

Key words: instrumentation: polarimeters – techniques: polarimetric – X-rays: general

Online-only material: color figures

1. INTRODUCTION

X-ray astronomy has so far obtained important results by using imaging, spectroscopy, and timing. New observational techniques are required to refine theoretical models and remove degeneracies by adding new observational parameters. X-ray polarimetry would allow for the introduction of the degree and the angle of polarization that closely relate to the emission mechanism and to the source geometry. However, despite the enormous improvements in X-ray astronomy, polarimetry has remained largely unexplored. The first detection of polarized X-rays from an astrophysical source was obtained for the Crab Nebula in 1971, by means of a sounding rocket experiment (Novick et al. 1972). The result was later confirmed and the polarization was precisely measured with a degree of (19.2\% ± 1.0\%) at 2.6 keV and (19.5\% ± 2.8\%) at 5.2 keV (Weisskopf et al. 1976, 1978) by the polarimeter on board the OSO-8 satellite. This result ultimately proved the synchrotron origin of the X-ray emission of the nebula and still remains the only precise non-zero result since the ’70s, while upper limits were measured by Hughes et al. (1984). The need to measure the polarization of high energy emissions of many other sources remains urgent, and new technological solutions are available today.

So far only a few measurements of non-imaging polarimetry, moreover, with a low significance, have been performed. Non-imaging polarimetry averages the polarization of all subsystems within the field of view (FOV). For extended sources, this can result in a substantial spoiling of the physical information. The reduction of measured polarization arises from the cancellation of the polarization vectors coming from regions with a different polarization state. This is crucial for extended sources such as pulsar wind nebulae (PWNe) and supernova remnants (SNRs). X-ray polarimeters with imaging capabilities would allow us to overcome this problem and to obtain polarization maps of extended sources. Moreover, imaging is useful for increasing the signal-to-noise ratio for polarimetry by developing analysis strategies aimed to reduce the contamination of the emission due to source regions or emission components different from the ones of interest (see in particular the study of the pulsar signal in PWNe of Section 7.1). This improvement is possible only with a detector that simultaneously has both polarimetric and imaging capabilities. The combination of an image detector and a non-imaging polarimeter would not be adequate to this aim.

The Gas Pixel Detector (GPD; Costa et al. 2001; Bellazzini et al. 2003) exploits the photoelectric effect to perform polarimetry and it is also able to simultaneously make spectral and timing measurements. The tracks of photoelectrons are produced in a gas with a charge content proportional to the photon energy. The polarimetric measurement is derived from their initial emission direction, while the image is obtained as a map of the photoionization locations. The GPD is the most advanced two-dimensional (2D) imaging polarimeter with high polarimetric sensitivity and spatial resolution with respect to other instruments. For example, CCDs were considered to perform polarimetry (Tsunemi et al. 1992; Buschhorn et al. 1994) by exploiting the border effect among neighbor pixels to detect.
Table 1

JET-X Telescope Characteristics (Spiga et al. 2014)

| Configuration | Wolter-I |
|---------------|----------|
| Focal length  | 3500 mm  |
| Diameter at entrance pupil (outer shell) | 300 mm |
| Diameter at entrance pupil (inner shell) | 191.1 mm |
| On-axis incid. angle at the intersection plane (outer shell) | 0◦/60 |
| On-axis incid. angle at the intersection plane (inner shell) | 0◦/39 |
| Mirror length (parabolic + hyperbolic) | 2 × 300 mm |
| Reflecting surface material | Gold |
| No. of shells | 12 |
| Eff. area at 1.5 keV | 147 cm² |
| Eff. area at 8 keV | 53 cm² |
| FOV – GPD+Telescope | 14.7 arcmin × 14.7 arcmin |

photoelectron polarization. However, this technique is heavily limited by systematics due to the small range of photoelectrons in silicon (only ≳1.5 μm at 10 keV) with respect to the pixel size. Another technique by Sakurai et al. (2004) exploits CCDs to detect the UV scintillation images of photoelectron tracks in a Capillary Gas Proportional Counter. The photoelectric effect in a gas is also exploited in time projection chambers for GEMS (Black et al. 2010). A high quantum efficiency is obtained at the expense of imaging, while its 1D imaging capability is very much blurred by inclined penetration (see Section 2), due to the expense of imaging, while its 1D imaging capability is very much blurred by inclined penetration (see Section 2), due to focusing, in astronomical implementations (Jahoda 2010) with a consequently much larger background. At higher energies, the Compton scattering polarimeter by Hayashida et al. (2012) has some imaging capability, with an angular resolution of a few arcminutes. In this case, the spatial resolution basically depends on the width (a few millimeters) of the scattering rods.

The intrinsic imaging capability of the GPD was already studied by Soffitta et al. (2013) who measured the spatial resolution of the detector alone (with a narrow, parallel X-ray beam). In our work we study the performance of a GPD combined with an X-ray telescope, and compare this with our predictions. From simulation studies (Fabiani et al. 2008; Lazzarotto et al. 2010) we expect that the GPD, if coupled with an X-ray optical module with an intrinsic angular response in the range of a fraction of an arcminute, should allow for imaging without a significant loss of performance, with respect to the intrinsic angular resolution of the telescope. In this work we report on this theory, by experimentally proving it for the first time. Even if this paper is focused on the analysis of the imaging properties, we also briefly discuss the relationship between polarization and grazing incidence reflection. This is useful to clarify what the expected limit is of spurious polarization induced by optics and why we have no concern about the feasibility of polarimetry by means of the GPD coupled with X-ray telescopes. The GPD was placed at the focal plane of the Flight Module No. 2 (FM2) of the JET-X telescope (Citterio et al. 1994; Spiga et al. 2014). We will show the results of the measurement campaign performed at the PANTER X-ray test facility carried out between 2012 November 27 and December 1. The JET-X telescope (see Table 1 for the characteristics) was originally built for the former SPECTRUM-X GAMMA mission.

Finally, we show the simulated response for two kinds of extended sources, namely PWNe and shell-like SNRs. The discussion is addressed with particular emphasis on the detector configuration proposed on board the small pathfinder mission XIPE (X-Ray Imaging Polarimetry Explorer; Soffitta & XIPE Collaboration 2013) which was presented, but not selected, to the 2012 ESA call for a small mission to be launched in 2017. Two GPDs, effective in the 2–10 keV energy band, were meant to be coupled with two JET-X optics modules to perform polarimetry for astrophysical sources.

In Section 2 the GPD polarimeter and the main properties of the JET-X telescope are introduced. In Section 3 the arrangement of the experimental set-up is explained. In Section 4 the on-axis angular resolution is studied, while the off-axis angular resolution is treated in Section 5. In Section 6 we briefly discuss the effects on the polarization of grazing incidence reflection of X-rays in the optics. In Section 7 the implications in terms of observational targets are discussed.

2. THE GPD AT THE FOCAL PLANE OF AN X-RAY TELESCOPE

2.1. The GPD Configuration and Operation

The GPD is a gas detector developed by the Italian research institutes INFN-Pisa and INAF/IAPS. It is designed to perform polarimetry in the X-ray energy band by exploiting the dependence of the photoelectric effect on the polarization of the radiation. When an X-ray photon, entering through a thin Be window, is absorbed in the detector gas cell, a photoelectron is ejected and ionizes the gas atoms until it stops and releases its larger fraction of energy in the Bragg peak. The electrons of the ionization track are drifted, multiplied by a Gas Electron Multiplier (GEM) (Sauli 1997; Tamagawa et al. 2009), and finally collected on a fine, subdivided pixel plane (50 μm of pitch). The analysis algorithm calculates the barycenter and the main axes of the projected charge distribution and finds the region of the track in which the projected absorption point (Impact Point–IP) is located (opposite of the site of the Bragg peak) by means of a skewness analysis. The IP and the direction of ejection of the photoelectron are finally calculated as the barycenter and the major axis of the initial portion of the track, properly weighting the charge content of the pixels (Pacciani et al. 2003; Bellazzini et al. 2003; Soffitta et al. 2013) due to the probable presence of the Auger electron.

The photoelectric differential cross section for a K-shell depends on the angular coordinates as follows:

$$\frac{d\sigma}{d\Omega} \propto \frac{\sin^2 \theta \cos^2 \phi}{(1 + \beta \cos \theta)^4}$$

(1)

where $\beta$ is the photoelectron speed in terms of light speed units, $\phi$ is the azimuthal component of the photoelectron ejection direction, and $\theta$ is the polar component. Therefore, when a polarized beam of radiation is observed, a $\cos^2 \phi$ modulation in the azimuthal distribution arises, since the photoelectrons are ejected with a higher probability parallel to the X-ray photon polarization vectors. The energy band of the detector depends on the gas mixture composition, pressure, and absorption gap thickness. It can be tuned in a range between 2 keV and tens of keV, with mixtures typically composed of DME$^5$ and helium, neon, or argon. The GPD collects the charge produced along the depth of the absorption gap because the charge signal is a readout from the pixel plane placed opposite of the Be entrance window. Therefore, photon tracks originating at different depths will suffer a different diffusion and a different recombination of the drifted ionization charge with the atoms of the gas.

The configuration operating in the 2–10 keV energy band, filled with a 20% He–80% DME gas mixture at 1 bar of pressure

$^5$ DME is dimethyl ether, C$_2$H$_6$O.
in a 1 cm thick absorption gap, equipped with a 50 μm thick Be window, was used for the characterization at the PANTER X-ray test facility (and proposed on board the XIPE mission). This detector configuration matches very well with the typical energy range of a classical grazing incidence X-ray telescope (as JET-X).

2.2. Imaging Properties

The angular resolution of an imaging system is limited by the blur introduced in the image of a point-like source. This property is summarized in the point-spread function (PSF) which, in our case, is given by the density distribution of the photon IPs on the detector image. We assumed that the PSF dependence was purely radial, as modeled by Moretti et al. (2004), for the on-the-detector image. We assumed that the PSF dependence was purely radial, as modeled by Moretti et al. (2004), for the on-the-detector image. We assumed that the PSF dependence was purely radial, as modeled by Moretti et al. (2004), for the on-the-detector image. We assumed that the PSF dependence was purely radial, as modeled by Moretti et al. (2004), for the on-the-detector image. We assumed that the PSF dependence was purely radial, as modeled by Moretti et al. (2004), for the on-the-detector image.

$$\text{PSF}(r) = W e^{-\frac{r^2}{2\sigma^2}} + N \left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-\eta}$$

We decoupled the two functions, where those of the original model linked by the normalization coefficient $N$ of the King function that was imposed equals 1-W. The PSF expressed as in Equation (2) is analytically integrable in $r dr$ and its integral profile is the encircled energy fraction (EEF):

$$\text{EEF}(r) = \int_0^r \text{PSF}(r) 2\pi r dr = \frac{\pi r^2 N}{1 - \eta} \left((1 + \left(\frac{r}{r_c}\right)^2)^{-\eta} - 1\right) + 2\pi W \sigma^2 \left(1 - e^{-\frac{r^2}{2\sigma^2}}\right)$$

so that the total flux of the source is analytically characterized as:

$$\text{EEF}(\infty) = 2\pi W \sigma^2 + \frac{\pi r_c^2 N}{\eta - 1}$$

Typically, the angular resolution is measured in terms of half-energy width (HEW), which is analytically defined as $\text{EEF(HEW/2)} = 0.5$ for monochromatic radiation. In our case it is easy to derive the HEW as the diameter, centered around the centroid of the PSF, containing half of the IPs of the image at a given photon energy. This allows us to summarize, with only one parameter, the imaging performance of an optical system in terms of angular resolution. However, accurate analysis of the PSF is needed to fully characterize the image quality, because the HEW does not take the PSF profile into account. The HEW was calculated by counting the IPs for each image of the point-like source one by one. The HEW is directly calculated in terms of spatial resolution on the detector plane and then the corresponding angular resolution is derived, taking into account the corrected focal length $f = 3.6\, m$, following the formula:

$$\text{HEW[ang. units]} = 2 \cdot \arctan\left(\frac{1}{2} \cdot \frac{\text{HEW[spat. units]}}{f}\right)$$

The $1-\sigma_{\text{HEW}}$ errors are also calculated, according to the binomial statistics. Since the HEW contains half of the counts of a PSF image, the probability of an IP to stay within the HEW is $p = 0.5$. Therefore, the binomial fluctuation associated with the number of events within the HEW is given by

$$\sigma_{ct} = \sqrt{\text{var}_{ct}} = \sqrt{n \cdot p(1-p)} = \frac{1}{2} \sqrt{n}$$

where $n$ is the total number of counts. The $\sigma_{\text{HEW}}$ is derived by calculating the HEW for the fluctuation of counts corresponding to $1/2n \pm \sigma_{ct}$. Therefore, the statistical fluctuation in terms of counts corresponds to a statistical fluctuation in terms of HEW.

The angular resolution of the system composed by the GPD and an X-ray telescope has three different contributions. The first contribution is due to the optics PSF and results in a spread of photons on the focal plane because rays in a gas deviate from the ideal focusing. The second contribution derives from the inclined penetration and absorption of photons through the thickness of the GPD absorption gap (Lazzarotto et al. 2010). In years past, this effect was given the ambiguous term “parallax” (Gabriel 1977; Lewis 1994). This effect causes a small PSF degradation (a few arcseconds) with respect to the intrinsic telescope angular resolution due to the fact that the penetration angle in gas, with respect to the mirror module focal axis, is small. It amounts to four times the angle of incidence of radiation on the mirror shells and varies from 0.60° for the most external shell, down to 0.39° for the innermost one. The third contribution to the angular resolution is given by the intrinsic spatial resolution of the detector which depends on the shape of the photoelectron tracks. This, in turn, depends on:

1. the scattering behavior of ejected photoelectrons,
2. diffusion properties of the ionization charge (gas mixture diffusion coefficient, pressure, drift length), and
3. detector pixel size (50 μm of pitch).

These effects impact the accuracy of the IP measurement performed by the track reconstruction algorithm. The contribution of the intrinsic spatial resolution of the GPD is shown in Figure 1, where we show a simulated photoelectron track produced by a photon of 8 keV of energy. In this figure, the hexagons...
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Figure 2. Measurement set-up in the vacuum chamber at PANTER.
(A color version of this figure is available in the online journal.)

represent the pixels and their size is proportional to the amount of charge collected. The empty crosses represent the barycenter of the charge distribution (blue), the projection onto the pixel plane of the true absorption point (green), and the reconstructed IP (red). Also, the projection of the true photoelectron ejection direction (green arrow) and the reconstructed one (red arrow) are shown. The capability to reconstruct the impact point (red cross) as close as possible to the true absorption point (green cross) depends on the spatial resolution of the intrinsic detector.

3. CONFIGURATION OF THE SET-UP

The PANTER X-ray test facility is described in Freyberg et al. (2005) and Burwitz et al. (2013). We installed the GPD in the test room (see Figure 2) and first searched for the best focus position after centering the X-ray spot on the detector active area. We shifted the X-ray mirror along its optical axis to find the position where we obtained the best angular resolution at an energy of 4.51 keV. This energy is about in the middle of the sensitive band and it is well-explored in our laboratory. For all measurements described in this work, the background is negligible and no subtraction to the source signal was needed. Figure 3 shows the HEW measured for different distances between the GPD and the telescope optics. By fitting a parabola on the points near the minimum, the position corresponding to the better on-axis angular resolution at 4.51 keV is obtained. The mirror module was shifted by steps of 2.25 μm of accuracy. Moving from left to right on the abscissa the detector/mirror separation increases.

(A color version of this figure is available in the online journal.)

Figure 3. Each point represents the HEW calculated for different distances between the GPD and the telescope optics. By fitting a parabola on the points near the minimum, the position corresponding to the better on-axis angular resolution at 4.51 keV is obtained. The mirror module was shifted by steps of 2.25 μm of accuracy. Moving from left to right on the abscissa the detector/mirror separation increases.

Figure 4. IP maps obtained for three different distances between the GPD and the telescope optics. The plots are normalized to the number of counts for each image. At the central position the image corresponding to the better angular resolution is shown. A narrower PSF core (white spot) with respect to the other images is present in this one.

(A color version of this figure is available in the online journal.)

Figure 4. IP maps obtained for three different distances between the GPD and the telescope optics. The plots are normalized to the number of counts for each image. At the central position the image corresponding to the better angular resolution is shown. A narrower PSF core (white spot) with respect to the other images is present in this one.

(A color version of this figure is available in the online journal.)

4. ON-AXIS ANGULAR RESOLUTION

The on-axis angular resolution was also measured at 2.98 and 8.05 keV with the detector in the position where the on-axis angular resolution at 4.51 keV was minimized. The profile of the overall PSF at 2.98, 4.51, and 8.05 keV of the optical system given by the JET-X FM2 plus the GPD is shown in the left panel
Figure 5. On the left: comparison of the PSF($r$) profiles of the 2.98, 4.51, and 8.05 keV radiation beams. The profiles are normalized to the total number of counts. At higher energies the wings’ contribution is larger. On the right: the corresponding EEF($r$) derived from the data. The contribution of the wings keeps the EEF well below unity even for large $r$ values, particularly at higher energies. (A color version of this figure is available in the online journal.)

Figure 6. Fit performed on the PSF at 4.51 keV with a Gaussian plus a King function. The fit is performed on the radial coordinate $\theta$ from 0 to 120 arcsec. See Table 2 for the fit results at the energy of 2.98, 4.51, and 8.05 keV. Each fit is performed on the radial coordinate $\theta$ from 0 to 120 arcsec and the IPs density distribution is normalized to the total number of counts.

of Figure 5. In the right panel the corresponding EEF profile is shown. In Figure 6, the fit with the PSF function of Equation (2) on the measured IP density distribution (normalized to the total number of counts) for radiation at 4.51 keV is shown. In Table 2 the fit parameters for the 2.98, 4.51, and 8.05 keV energies are listed. In Figure 7 the measured values of the HEW (top panel) are shown. They are also listed in Table 3.

As discussed in Section 2, the angular resolution of the GPD, coupled with the telescope optics, is affected by three blurring effects: the intrinsic PSF of the optics, the blurring induced by inclined penetration of photons in a gas, and the uncertainty in the determination of the photon IPs due to the intrinsic detector spatial resolution. While the first effect is an intrinsic property of the telescope optics alone, the second depends on both the optics and the detector parameters, and the third one depends on the detector parameters and on the analysis procedure. We are interested in decoupling each contribution with respect to the total angular resolution. The intrinsic telescope angular resolution in terms of HEW is shown in Figure 7 (second panel from the top). It was recently measured at the PANTER X-ray test facility (Spiga et al. 2014) at an energy of 1.49 (Al-K), 2.98, 4.51, 6.4 (Fe-K), and 8.05 keV. The measurement was performed with the TRoPIC CCD (Predehl et al. 2007) placed at the focal plane of the JET-X FM2. The area of the TRoPIC detector (1.96 cm x 1.96 cm) is nearly 4 cm$^2$, which is larger than that of the GPD (2.25 cm$^2$). Nevertheless, the FM2 PSF is so compact that its wings are almost entirely included in a 2 cm$^2$ region, at least in the range of measured X-ray energies, so the exact size of the GPD active region is not crucial. The GPD condition is therefore well-reproduced, adopting the HEW values computed over a 2 cm$^2$ area as done by Spiga et al. (2014).

The contribution of the inclined penetration of photons in a gas is evaluated by means of simulations (Lazzarotto et al. 2010), assuming that the photons propagate along ideal reflection paths, therefore neglecting the telescope PSF and the intrinsic GPD spatial resolution. In this simulation the radiation is assumed to come from infinity, therefore the nominal focal length of 3.5 m is assumed. In Figure 8 we show the simulation of the distribution of the absorption points. The 3D distribution is in the top left panel, whereas the marginal $zx$ and $xy$ planes are reported in the top right and bottom left panels, respectively. Eventually, the marginal distribution along the $x$ axis is reported in the bottom right panel. Due to the focusing and the absorption along the depth of the gas cell, the distribution of the absorption points on the readout plane is characterized by a narrow core and extended wings. The distribution of the absorption point on the $xy$ plane, that corresponds to the readout plane, is not Gaussian. The results of the simulations in terms of HEW are plotted in the third panel from the top of Figure 7. It is important to note that in the case of the GPD, having a 1 cm thick gas cell contributes for about 10 arcsec (in coupling with JET-X optics) to the total angular resolution. This term of the angular resolution is better for higher energies since high energy radiation is efficiently reflected by more internal mirror shells so that it penetrates with smaller inclination angles with respect to the optical axis.

Finally, the blurring due to the intrinsic spatial resolution of the detector is reported in terms of HEW in the bottom panel of Figure 7. This component was studied by Soffitta et al. (2013) who represented the impact point distribution with a bivariate Gaussian profile. Here we reanalyzed their results to
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Figure 7. HEW at 2.98, 4.51, and 8.05 keV for the on-axis configuration for the three different components that contribute to the overall PSF of the GPD/X-ray telescope optical system. In the top panel is the HEW measured at the PANTER X-ray test facility of the GPD coupled at the JET-X FM2 optical module. Plotted values are listed in Table 3. In the second panel (from the top), the intrinsic telescope HEW (Spiga et al. 2014) for a 2 cm² active area detector is shown. In the third panel is the HEW simulated for the inclined penetration of radiation in a gas by assuming the ideal optics case, therefore without the contribution of the intrinsic PSF of the optical module. Also, the effect of the intrinsic spatial resolution of the detector is not taken into account. This plot shows the contribution of the simple geometrical model of the optics to the overall PSF. Radiation is assumed to come from infinity, and therefore the simulated focal length is 3.5 m. In the bottom panel, the HEW for a zero-width vertical beam of radiation is shown both from simulations and from one measurement at 4.51 keV (red, data reanalyzed from Soffitta et al. 2013). The measurement result is obtained by quadratically subtracting the intrinsic beam HEW.

(A color version of this figure is available in the online journal.)

Table 2

| Energy (keV) | 2.98 keV | 4.51 keV | 8.05 keV |
|-------------|----------|----------|----------|
| $\chi^2$/ndf | 342.5/283 | 322.9/283 | 303.3/283 |
| $\chi^2$ Norm. | 1.21 | 1.14 | 1.07 |
| $W \pm \sigma_W$ (1/ sr) | $(3.87 \pm 0.027) \times 10^{-4}$ | $(2.79 \pm 0.21) \times 10^{-4}$ | $(5.5 \pm 1.4) \times 10^{-4}$ |
| $\sigma \pm \sigma_\sigma$ (arcsec) | $9.85 \pm 0.13$ | $10.61 \pm 0.16$ | $2.77 \pm 0.51$ |
| $N \pm \sigma_N$ (1/sr) | $(2.574 \pm 0.049) \times 10^{-3}$ | $(3.2890 \pm 0.0057) \times 10^{-3}$ | $(1.94 \pm 0.14) \times 10^{-3}$ |
| $r_\perp \pm \sigma_{r_\perp}$ (arcsec) | $7.57 \pm 0.18$ | $6.06 \pm 0.14$ | $9.57 \pm 0.39$ |
| $\eta \pm \sigma_\eta$ | $1.629 \pm 0.019$ | $1.481 \pm 0.014$ | $1.606 \pm 0.020$ |

Note. Each fit is performed on the radial coordinate $\theta$ from 0 to 120 arcsec.

determine the angular resolution in terms of HEW (not sigma as done by Soffitta et al. 2013). In the bottom panel of Figure 7 the simulated HEW (black diamonds) is evaluated considering photons impinging normally on the detector with a beam of intrinsic zero width. At an energy of 4.51 keV, the simulation is compared with the result of an experimental measurement with a real vertical beam with a finite (albeit small) size. To properly compare the simulation with the measurement, the intrinsic width of the radiation beam was measured in terms of $\sigma_x = 14.7 \mu$m and $\sigma_y = 8.7 \mu$m by scanning the beam with a SiPIN detector coupled with a slit (see Soffitta et al. 2013 for details). The average sigma was calculated by approximating the beam profile with a circularly symmetric Gaussian bivariate distribution: $f(r) = (1/2\pi\sigma^2)e^{-r^2/(2\sigma^2)}2\pi r$ with $\sigma = (14.7 + 8.7)/2 = 11.7 \mu$m. The corresponding $\text{HEW}_{\text{beam}} = 27.6 \mu$m was derived according to the formula

$$0.5 = \int_0^{r_0} f(r) dr = 1 - e^{-\frac{r_0^2}{2\sigma^2}} (7)$$

where 0.5 is the fraction of events inside a circle of radius $r_0 = (1/2)\text{HEW}_{\text{beam}}$. 
The corresponding HEW_{beam} of the beam was quadratically subtracted from the HEW_{gross} = 96.1 \, \mu m calculated from the measurement performed with the GPD to derive the intrinsic HEW of the detector that is 92.1 \, \mu m.

Some concern could arise, with respect to the measurement of polarization, from the small difference of the sigma of the Gaussian bivariate distribution that describes the intrinsic GPD response found by Soffitta et al. (2013). This is possibly due to the different X and Y sampling in a 50 \, \mu m pitch hexagonal pattern of pixels. One could speculate that this affects the determination of the ejection direction of photoelectrons because it is derived by means of a statistical analysis on the spatial distribution of charge. However, this difference is small, even smaller than the pixel pitch. Therefore, the effect on the polarimetric capability is negligible, if present, because the spurious polarization of the GPD alone (measured with unpolarized radiation) is (0.18 \pm 0.14)% (Bellazzini & Spandre 2010). This means that no evident spurious effects are detected depending on the honeycomb pattern of hexagonal pixels.

The vertical beam geometry reasonably approximates the case of radiation penetration with a small inclination with respect to the optics module axis. In fact, since photoelectrons are ejected with higher probability on the plane normal to the photon incident direction (see Equation (1)), if the radiation beam is inclined by a small angle (as in the case of the JET-X telescope) this plane is quite parallel to the pixel plane. In the case of narrower penetration angles, as for longer focal lengths and the same optics diameter, the energy band of the telescope would be extended to higher energies and the blurring due to inclined penetration of photons in gas would be reduced. On the other hand, with respect to the intrinsic spatial resolution of the GPD, the beam geometry would tend to approximate more closely the vertical beam condition for which the intrinsic GPD spatial resolution was simulated and measured (see bottom panel of Figure 7).

Looking at all panels of Figure 7, it turns out that the overall HEW increases with energy (top panel) and the larger contribution to this increase comes from the intrinsic PSF of the mirror module (second panel from the top). Since some blurring components do not follow a pure Gaussian statistic, the HEW of all components cannot be properly summed in quadrature. As the first approximation, the Gaussian statistics can only describe the core of the response of the detector to a vertical narrow beam (Soffitta et al. 2013).

Reported results confirm the GPD to be a high angular resolution focal plane instrument since the performance of the telescope is not compromised by coupling it with the 1 cm thick gas detector.

5. OFF-AXIS ANGULAR RESOLUTION

The angular resolution for radiation beams impinging off-axis on the telescope was measured at 2.98, 4.51, and 8.05 keV.
Figure 9. IP maps of the off-axis measurements at 2.98 (top panel) and 8.05 keV (bottom panel). The corresponding HEW values (also for 4.51 keV) are listed in Table 3 and shown in Figure 10. In the two panels, the zooms of the on-axis measurement (the FOV center is identified by a dashed cross) and of the larger off-axis measurement are shown.

(A color version of this figure is available in the online journal.)

This characterization is crucial to verify the telescope/detector response for extended sources, whose radiation also comes from directions different from the optical axis. The measurements were performed by tilting the mirror module in azimuth and polar angles to reproduce the effect of observing a point source in the different regions of the FOV. The radiation beam always impinged in the same central position on the detector plane, but the obtained PSF corresponded to offset images along the diagonal of the FOV in the third quadrant at 3.11 arcmin, 6.22 arcmin, and 9.33 arcmin from the central position (see Figure 9). The effect of the inclined penetration due to the off-axis angle is negligible with respect to the blurring induced by the inclined penetration due to beam focusing. In Table 3 the HEW values for the off-axis measurements are listed and in Figure 10 they are shown in the same plot.

The PSF deformation, due to the off-axis imaging, is small even for the 8.05 keV radiation beam at the larger off-axis angle sampled which is 9.33 arcmin. The off-axis measurements confirm the capability of the GPD to also perform imaging for extended sources like PWNe and SNRs.

6. POLARIZATION AND GRAZING INCIDENCE IN X-RAY TELESCOPES

The assessment of the polarization introduced by the optics is an important point when dealing with detectors that measure the polarization. We know by theory (Chipman et al. 1992, 1993; Sanchez Almeida & Martinez Pillet 1993) that the grazing incidence reflection of X-rays on classical (perfect reflection)
optics based on Wolter-I configuration, as far as described by Fresnel equations, does not introduce a spurious polarization larger than 0.1%. Moreover, Katsuta et al. (2009) demonstrated experimentally that the reflection on multilayer (Bragg reflection) optics induces a negligible spurious polarization. They performed a reflectance measurement on a multilayer mirror sector finding no more than 0.8% of polarization. On the contrary, by using a complete mirror module (as we did with a classical mirror) an even lower spurious polarization would be expected owing to the axial symmetry that nearly (on-axis, even completely) cancel out the artificial polarization term. This consideration also ensures future employment of the GPD for hard X-rays, coupled with multilayer optics. During our measurement campaign at PANTER it was not possible to verify the level of absence of spurious polarization induced by optics because this measurement requires a rigorous control of the set-up, especially concerning the Bremsstrahlung radiation source (which this measurement requires a rigorous control of the set-up, especially concerning the Bremsstrahlung radiation source (which functions as a source of spurious polarization). We expect this to be at a negligible level for our observation.

Undoubtedly concerning the Bremsstrahlung radiation source (which this measurement requires a rigorous control of the set-up, especially concerning the Bremsstrahlung radiation source (which functions as a source of spurious polarization). We expect this to be at a negligible level for our observation. Nevertheless, it is crucial to note that any artificial polarization related to this effect should be averaged out to much less than 0.1%. Artificial polarization can also derive from profile errors of the optics in the axial direction.

Inhomogeneities of the optics can artificially induce a polarization, but we expect this to be at a negligible level for our observations. A source of spurious polarization is the non-uniformity of reflectivity. We did not perform a pencil-beam scan on the surfaces of the mirror, but no apparent asymmetry was seen in the focal spot (Spiga et al. 2014), and also the process of polishing mandrels from which the mirrors were replicated should rule out axial asymmetries in reflectivity performance. Even in the worst case, indeed, the reflectivity would change by only a few percent, and it would for sure not exhibit a bipolar distribution. Hence, any artificial polarization related to this effect should be averaged out to much less than 0.1%. Artificial polarization can also derive from profile errors of the optics in the axial direction. Such errors degrade also the angular resolution. They directly affect the incidence/reflection angles at which the X-rays strike on the mirror, so in principle they locally change the polarization of the reflected radiation. Nevertheless, the intrinsic angular resolution of the JET-X FM2 implies slope errors in the range of 10 arcsec or so. Even at the largest nominal incidence angle in the JET-X FM2 module (0.67 deg, corrected for the finite distance at PANTER), the maximum polarization introduced would be less than 0.4% in the band 0.5–10 keV. In addition, a variation of the incidence angle, as mentioned above, locally increases the polarized term by less than one part over $10^4$. The effect of roundness errors is even smaller, by a factor of 50 or more. Therefore, to the level of sensitivity of the GPD, the expected polarizing effect of the JET-X optics is negligible ($<0.5\%$).

Another source of degradation of the polarimetric response of the GPD, coupled with an optics module of an X-ray telescope depends on scattering from roughness and from the telescope structure that may contaminate the observation of faint sources when close to bright sources. However, the fine imaging capabilities of the GPD allow the additional contribution to the image to be taken into account, if any.

7. SCIENCE GOALS OF IMAGING POLARIMETRY

In this section we show two examples for which X-ray polarimetry resolved in space can contribute in modeling the sources, by simulating images of the Crab PWN and Cas A SNR convoluted with the PSF of the optics coupled with the GPD. We also simulated polarimetry by using the XIPE detector configuration. Some regions of interest of the sources are taken as an example to verify the polarimetric capability of this small mission. The polarimetric simulation assumes the performance of the GPD as simulated by means of a Monte Carlo software, whose predictions were confirmed by experimental measurements performed in our laboratory (Muleri et al. 2008). The uncertainties of the degree and angle of polarization of the simulated measurements are derived by convolving the response of the polarimeter with the degree of polarization expected by models and applying the Poisson statistic to the count rate of the expected signal (Dovčiak et al. 2011).

7.1. Pulsar Wind Nebulae

PWNe originate from the interaction of the relativistic particles of the pulsar wind with the interstellar medium and they are sources of non-thermal emission, ranging from radio to $\gamma$-rays, due to synchrotron and inverse Compton processes. The prototype of this class of sources is the Crab Nebula for which the first positive detection of integrated polarization in the X-rays was performed in 1971 during a sounding rocket experiment (Novick et al. 1972).

Even from the first images of the Einstein Observatory (Harnen & Seward 1984) and ROSAT (Hester et al. 1995), the Crab PWN appeared as a structured source. This was confirmed by the high resolution X-ray images of Chandra that also showed the presence of small-scale features (Weisskopf et al. 2000). The complexity of the structure of PWNe depends on their nature. They host a neutron star surrounded by a bright axisymmetric nebula that comprises jets, a structure of equatorial bright rings and a torus (Helfand et al. 2001; Gaensler 2002) with wisps. These features are generated by the activity of the inner neutron star whose relativistic wind interacts with the interstellar medium, which is modeled by many MHD simulations (Komissarov & Lyubarsky 2003, 2004; Del Zanna et al. 2004). Due to the complexity of such astrophysical targets, polarimetry integrated in a wide field is no longer sufficient for providing information about all the observed features. PWNe are very structured in X-rays that are well-suited to studying the magnetic field configuration from the pulsar up to the external torus and the jets. Imaging polarimetry, if combined with synthetic polarization maps derived from relativistic MHD simulations, would be a powerful tool for the diagnostics of synchrotron polarization features in PWNe (Bucciantini et al. 2005). In particular, it would allow us to infer the inner bulk flow structure (Volpi et al. 2009) and turbulence (Shibata et al. 2003).

The GPD at the focus of a suitable telescope could address these issues. In fact, two detectors were proposed at the focal plane of two JET-X optics modules in the framework of the XIPE mission proposal (Soffitta & XIPE collaboration 2013) to the 2012 ESA Call for a launch of a small mission in 2017. In Figure 11 (top panel) we blurred the Chandra image of the Crab PWN with the PSF of XIPE. The original high resolution image is convoluted with the on-axis PSF at 4.51 keV of the XIPE polarimeter which is shown in Figure 6 (see Table 2 for the PSF parameters). Even if the smaller features are not resolved, the torus region is separated by the jets and the polarization across the image can be studied for different regions as shown in Figure 11 (bottom panel). We simulated an observation by assuming a polarization degree of 19% (Weisskopf et al. 1978) in the energy range 2–10 keV for a 100 ks observation. We chose the average polarization measured by Weisskopf et al. (1978) to be conservative. The blurred image of the source has been subdivided into 13 regions, and for each one the $1 \pm \sigma$ errors of the degree and angle of polarization have been evaluated by simulation and reported in Table 4, together with...
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Figure 11. Top panel: the Chandra high resolution image of the Crab PWN as it would appear at the JET-X telescope coupled with the GPD. The image is convoluted with the on-axis PSF at 4.51 keV of the XIPE polarimeter (see Figure 6 for the function profile and Table 2 for the function parameters). The field of view of XIPE is much larger (see Table 1). The torus region is clearly separated by the jets. Bottom panel: selected region of the Crab image for which the polarization measurement was simulated. Results are shown in Table 4

(Credit: NASA/CXC/MSFC/M. Weisskopf et al.

(A color version of this figure is available in the online journal.)

We refer to the synthetic polarization maps of PWNe by Volpi et al. (2009) derived by means of relativistic MHD simulations. They assumed a purely toroidal magnetic field of the torus, thus the polarization vector is parallel to its symmetry axis and rotated by increasing the angular distance from this axis up to become orthogonal. The angular position at which the 90° rotation is completed is a function of the pulsar wind flow velocity for a given inclination angle of the torus. For lower bulk flow velocity, this turning point is further away from the symmetry axis. Such a swing of the polarization vector could be easily detected by XIPE by looking at regions No. 5, 6, 7, 8, 9, and 10 of Figure 11 (bottom panel). Polarization is expected to be very high (up to 70%) at the center (regions 7 and 8) and to decrease moving to the edges (regions 5 and 10, respectively). The higher the bulk velocity is, the sharper the polarization decrease is. The net effect of such a blurring is to sum the signals coming from slightly different positions and this obviously implies a certain depolarization if, as expected from current models, the polarization is different for each feature of the source. On the one hand, the angle of polarization should change, smoothly passing from one region to another, and major rotations should occur on an angular scale larger than our PSF. Moreover, the high degree of polarization measured with OSO-8 (Weisskopf et al. 1978) by averaging the signal from the entire source points to the fact that, if a rotation of the angle of polarization does exist, it is not very large, or, alternatively, the polarization degree from some bright region is much higher than that from the others so that a net polarization “survives.” Therefore, we expect that the contamination of the polarization signal from neighboring regions does not significantly affect our sensitivity estimates reported in Table 4.

Table 4

| Region No. | σdegree (%) | σangle (deg) | MDP (%) |
|------------|-------------|--------------|---------|
| 1          | 0.7         | 1.1          | 2.2     |
| 2          | 0.5         | 0.8          | 1.5     |
| 3          | 0.8         | 1.3          | 2.5     |
| 4          | 1.0         | 1.6          | 3.2     |
| 5          | 0.7         | 1.1          | 2.2     |
| 6          | 0.5         | 0.9          | 1.7     |
| 7          | 0.5         | 0.8          | 1.6     |
| 8          | 0.5         | 0.8          | 1.6     |
| 9          | 0.5         | 0.9          | 1.7     |
| 10         | 0.7         | 1.1          | 2.2     |
| 11         | 0.6         | 1.0          | 1.9     |
| 12         | 0.6         | 1.0          | 1.9     |
| 13         | 0.7         | 1.1          | 2.2     |

Notes. The source is subdivided in 13 regions as shown in Figure 11 (bottom panel). The uncertainties of the degree and angle of polarization are listed, assuming a polarization degree of 19% (Weisskopf et al. 1978) in the energy range 2–10 keV for a 100 ks observation.

Imaging capability of the GPD is, moreover, a powerful tool for the measurement of the polarization of the pulsar emission alone. The pulsed signal from the inner neutron star (corresponding to a pulsed fraction of about 15% at 2.6 keV and 11% at 5.2 keV, Weisskopf et al. 1978) can be studied by means of a phase-resolved analysis and, thanks to imaging, the contribution of the nebular emission can be reduced by only selecting the region where the pulsar is located. The nebular emission acts like a background and by reducing its contribution with respect to the pulsar signal, it is possible to improve the sensitivity of the measurement. Elsner et al. (2012) addressed this issue by performing a detailed statistical analysis and considering the specific case of the Crab pulsar.

As seen in Sections 4 and 5, the image quality depends largely on the telescope’s intrinsic PSF. Therefore, future availability of telescopes with a better angular resolution (a few arcseconds), and possibly large effective area, would allow a more detailed study of extended sources such as PWNe. For example, with IXO/ATHENA-like optics (5 arcsec of intrinsic angular resolution; Collon et al. 2011; Ghigo et al. 2012), small features such as the bright knots would be singularly observable and detailed polarization maps could be obtained. For IXO, due to the long focal length (20 m) and very narrow penetration angles, the
blurring for inclined absorption in a gas would be negligible and the GPD would totally preserve the telescope performance in terms of image resolution (Lazzarotto et al. 2010). A small worsening is expected for ATHENA+\(^7\) due to the larger penetration angles that are a consequence of the shorter focal length (12 m) and the optimization for a softer energy band. However, as demonstrated for JET-X, this worsening gives an angular resolution only a few arcseconds larger than that of the telescope, up to the grazing incidence angle of the order of the degree. Therefore, it is reasonable to expect that the total angular resolution would not be worse than 7 arcsec–8 arcsec.

At present, 54 PWNe are known and many present interesting features like the Crab PWN (Kargaltsev & Pavlov 2008). Among them Jellysh, Vela, G0.9+0.1/G0.87+0.08, and MSH 1162/G291.020.11 (No. 7, 13, 41, and 48 in Kargaltsev & Pavlov 2008) are mCrab sources having sizes comparable to the Crab PWN. For these sources, an uncertainty on the polarization angle of about 10\(^\circ\) (instead of about 1\(^\circ\) of the Crab) could be reached if observed for 500 ks each and if the number of regions was divided in half with respect to the Crab example (to double the flux for each region). This is due to the fact that such an uncertainty scales as the root square of the number of counts (Weisskopf et al. 2010; Strohmayer & Kallman 2013), and therefore of the integration time (or of the intensity or the effective area). This measurement has so far never been performed and is compatible with the science objective of a pathfinder mission like XIPE.

Other sources like Kes 75, Mouse, and G54.10+0.27 (No. 12, 22, and 10 in Kargaltsev & Pavlov 2008) are also mCrab sources, but their extension is less than about 1/3 of the Crab. Therefore, they can be easily studied by means of IXO/ATHENA-like optics having an effective area 100 times larger than XIPE, and an angular resolution more than 3 times better. Moreover, many other faint but extended sources, down to about 0.01 mCrab, would be accessible with these advanced optics (for example, some of them are G21.500.89, 3C 58, G106.65+2.96, G332.500.28, G11.180.35, and IC 443/G189.23+2.90 corresponding to No.4, 5, 6, 8, 14, and 47 in Kargaltsev & Pavlov 2008).

### 7.2. Shell-like Supernova Remnants

In shell-like SNRs, environment electrons are accelerated up to 10–100 TeV by shocks and they radiate via synchrotron emission up to X-rays (Reynolds & Chevalier 1981). Therefore, polarization maps would give information about the particle acceleration processes and the magnetic field behavior in this turbulent environment (Bykov et al. 2009). Above 10 keV the thermal component (bremsstrahlung and lines) is superseded by a power-law extending up to hundreds of keV (Vink 2005; Helder & Vink 2008) that originates hard tails in shell-like SNRs (including Cas A), possibly due to synchrotron emission (Allen et al. 1997; Allen 1999).

However, the non-thermal fraction of the spectrum can also be highlighted by means of polarimetry at a lower energy, if regions with a minor line emission are identified in the images. In these cases it would be possible to study the non-thermal component by more than just means of spectral analysis. The polarized non-thermal emission would come primarily from structures such as filaments and clumps, and the capability to perform imaging polarimetry would allow us to resolve the emission coming from different structural features. Particularly

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7. http://athena2.irap.omp.eu/IMG/pdf/sp_14.pdf

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Figure 12. Top panel: the *Chandra* high resolution 4–6 keV image of the Cassiopeia A SNR as it would appear at the JET-X telescope coupled with the GPD. The image is convoluted with the on-axis PSF at 4.51 keV of the XIPE polarimeter (see Figure 6 for the function profile and Table 2 for the function parameters). The SNR is clearly resolved and its features can be studied separately. The entire source fits in the field of view of the polarimeter (see Table 1). Bottom panel: selected region of the Cassiopeia A SNR for which the polarization measurement was simulated. Results are shown in Table 5 Credit: NASA/CXC/MSFC/M.Weisskopf et al.

(A color version of this figure is available in the online journal.)

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suited for this kind of study are the young SNRs like Cas-A, Tycho, and Kepler that efficiently accelerate electrons and show the X-ray emissions from well-confined, narrow regions (Araya et al. 2010). Such non-thermal emitting regions were observed by *Chandra* at the edges of the Cas-A shell-like SNR. In the images they are particularly evident in the 4–6 keV continuum-dominated band (Vink 2005) and spatially coincide with the radio emitting region (Gotthelf et al. 2001). The absence of line emission in this spectral region is evidence for a synchrotron origin of the radiation (Vink & Laming 2003). Similar features were also found in other shell-like young SNRs such as SN 1006, Tycho, and Kepler (Bamba et al. 2003; Hwang et al. 2002; Cassam-Chenaì et al. 2004). In Figure 12 (top panel) we blurred the *Chandra* image of Cas A (4–6 keV)
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Table 5
Simulation of a Polarization Measurement for Cas-A

| Region No. | $\sigma_{\text{degree}}$ | $\sigma_{\text{angle}}$ | MDP |
|------------|------------------------|----------------------|-----|
| 1          | 2.4                    | 6.6                  | 7.7 |
| 2          | 2.7                    | 8.3                  | 8.8 |
| 3          | 2.1                    | 5.9                  | 6.7 |
| 4          | 2.9                    | 7.8                  | 9.5 |
| 5          | 1.9                    | 5.3                  | 6.1 |
| 6          | 3.5                    | 11.0                 | 11.1|
| 7          | 3.6                    | 11.0                 | 11.6|

Notes. The source is subdivided in 7 regions as shown in Figure 12 (bottom panel). The uncertainties of the degree and angle of polarization are listed, assuming a polarization degree of 11% in the energy range 4–6 keV for a 2 Ms observation. Regions 4, 6, and 7 are probably dominated by the non-thermal component, therefore the polarization arising from their emission should be higher with respect to regions 1, 2, 3, and 5 in which the thermal component is dominant.

The GPD is a photoelectric polarimeter with an intrinsic imaging capability that makes it suitable to be used as a focal plane instrument to produce image the source while performing polarimetry in the X-rays. So far, the imaging performance of the GPD coupled with X-ray telescopes was only studied by means of Monte Carlo simulations, and for the first time we demonstrated its feasibility by means of experimental measurements.

We measured the PSF of the GPD placed at the focus of the JET-X X-ray telescope in the 2–10 keV energy band, both for on-axis and off-axis radiation beams. This detector/optics system is the configuration proposed for the pathfinder mission XIPE in response to the ESA small mission call of 2012. We measured the angular resolution in terms of HEW, that is, 22.7 arcsec at 2.98 keV, 23.2 arcsec at 4.51 keV, and 28.9 arcsec at 8.05 keV for on-axis radiation. In this work we showed that a detector/optics configuration typical of a pathfinder mission is able to obtain important results, also opening the field of imaging polarimetry in the X-rays. PWNes and SNRs were considered as case studies and the relation between the polarized emission and the source geometry and the magnetic field configuration were analyzed.

We demonstrated experimentally that the image quality of the optical system given by the GPD coupled with an X-ray mirror module depends mainly on the telescope intrinsic PSF. We showed that even with a small mission like XIPE, bright SNRs and PWNe can be studied by imaging polarimetry. The availability of optics with better angular resolution (a few arcseconds) and a large effective area would allow GPD to obtain even more detailed images while performing sensitive polarimetry for many extended sources. Therefore, with IVO/ATHENA-like optics, smaller and fainter features of a larger population of sources would be accessible.

S. Fabiani and F. Muleri acknowledge the STSM (Short Term Scientific Mission) program of the COST (European Cooperation in Science and Technology) Action MP1104: “Polarization as a tool to study the solar system and beyond” which financially supported the measurement campaign at the PANTER facility.

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