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The Imaging X-ray Polarimetry Explorer (IXPE) at last!

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ABSTRACT

IXPE, the first observatory dedicated to imaging X-ray polarimetry, was launched on Dec 9, 2021 and is operating successfully. A partnership between NASA and the Italian Space Agencey (ASI) IXPE features three X-ray telescopes each comprised of a mirror module assembly with a polarization sensitive detector at its focus. An extending boom was deployed on orbit to provide the necessary 4 m focal length. A 3-axis-stabilized spacecraft provides power, attitude determination and control, and commanding. After one year of observation IXPE has measured statistically-significant polarization from almost all the classes of celestial sources that emit X-rays. In the following we describe the IXPE mission, reporting on its performance after 1.5 year of operations. We show the main astrophysical results which are outstanding for a SMEX mission.

Keywords: X-ray, Astronomy, Polarimetry, Mirrors, Detectors

1. INTRODUCTION

Polarization from celestial sources may derive from the emission processes themselves, like cyclotron emission, synchrotron emission and non-thermal bremsstrahlung[1–3] . Even if the radiation has a thermal origin, and is intrinsically not polarized, it can assume a certain degree of polarization by scattering in aspherical plasmas like accretion disks, blobs and accreting columns, which are commonly found in astrophysical sources.[4,5] Further, vacuum polarization and X-ray birefringence can be studied by means of X-ray polarimetry.[6–8] Despite significant expectation from theories, X-ray polarimetry results were meager. With the advent of a new generation of X-ray detectors,[9–11] called Gas Pixel Detectors (GPD), which can measure polarization by exploiting the photoelectric effect in gas, we were able to devise an X-ray polarimetry mission capable of providing sensitive measurement in the classical energy band of X-ray Astronomy.

The first space implementation of the GPD for space X-ray polarimetry was done by Tsinghua University (Beijing, China) with a collimated experiment on-board of a CubeSat Satellite.[12–16] However, sensitive X-ray polarimetry is possible only if a large number of photons are available, and this requires use of X-ray mirrors. Only with the advent of the Imaging X-ray Polarimetry Explorer (IXPE)[17,18] was it possible to make X-ray polarimetry a common tool in Astrophysics.

2. THE MISSION IN A NUTSHELL

IXPE is NASA's 14th Small Explorer (SMEX) mission and was done in partnership with ASI. The scientific institutions and industrial partners involved in designing, building, testing and operating IXPE are shown in Figure 1. NASA-MSFC is the PI institution (Philip E. Kaaret, formerly Martin Weisskopf [Emeritus]) while INAF and INFN with their industrial partner OHB-Italia were responsible for devising, building, testing and calibrating four Detector Units (included one spare) and a detector service unit.

The IXPE observatory, [17,70] after on-orbit deployment is shown in Figure 2. The IXPE payload is composed of three mirror modules[19] fabricated and calibrated at NASA-MSFC with the contribution of Nagoya University (thermal shields), and an instrument composed of three detector units[18,20] separated from the mirror by a focal length of 4 meter set by an extensible boom.

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Figure 1. The main institutions involved in the IXPE mission development and operation with their respective roles. On the bottom the states which compose the Science Advisory Team (SAT), aimed at the scientific exploitation of IXPE observations in the first two years of operation, are indicated

IXPE is equipped with a global positioning system (GPS) for precise timing of the events, with two star-trackers (front and rear) used to correct dithered images thanks to the photon-by-photon transmission to ground, with an X-ray shield which, in combination with the stray-light collimator on top of the DUs, absorbs Cosmic Background photons arriving from outside the field of view. An ion-UV filter is also, located on-top of the DU.[21]

An on-board calibration system[22] inside each DU is based on ^{55}Fe isotopes which have a K_α line at 5.89 keV and a K_β line at 6.5 keV. Cal source A produces polarized X-rays at 3 keV (by means of a silver target, Ag L_α = 3 keV) and at 5.9 keV, through 45° Bragg reflection off a graphite mosaic crystal. Cal sources B and C produce unpolarized 5.9 keV and 6.5 keV X rays in a spot (3mm diameter) and flood (15 x 15 mm) configuration respectively. Cal source D utilizes a silicon target in front of the ^{55}Fe producing a large beam at 1.7 keV (Si K_α). During flight operation, each detector unit is calibrated during Earth occultation with Cal C and Cal D providing the final gain correction for event energy determination. As shown by[23] there is a residual mis-calibration of few (2-3) tens of eV which is irreducible, and most probably occurring due to gas gain reductions from surface charging of the Gas Electron Multiplier (GEM). This effect depends on the count rate and energy distribution and so there are small differences between flight calibrations and celestial source observations.[23]

IXPE mirror shells are fabricated using the classical technique of electro-formed Nickel-Cobalt replication. The individual mirror shells are quite thin, just 0.15 – 0.25 mm, to maximize effective area within the constraints of the launch vehicle lift capability. The design of the IXPE mission was based on a Pegasus-XL vehicle, then eventually a Falcon-9 launcher was selected after a competitive tender.

On orbit, the IXPE DU's are performing as expected from on-ground calibration (see[23]). We detected a slightly smaller efficiency from DU-2 and DU-3 with respect to DU-1. This may be related either to a slight overestimation of the mirror effective area and/or a lower quantum efficiency for the two DUs because the pressure inside the detectors is smaller.

From ground calibration we discovered that the efficiency of the detector slightly diminished with time, likely

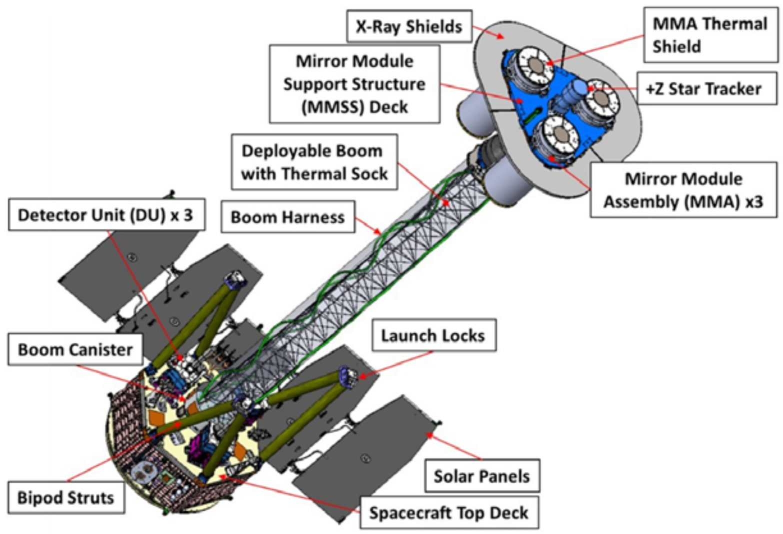
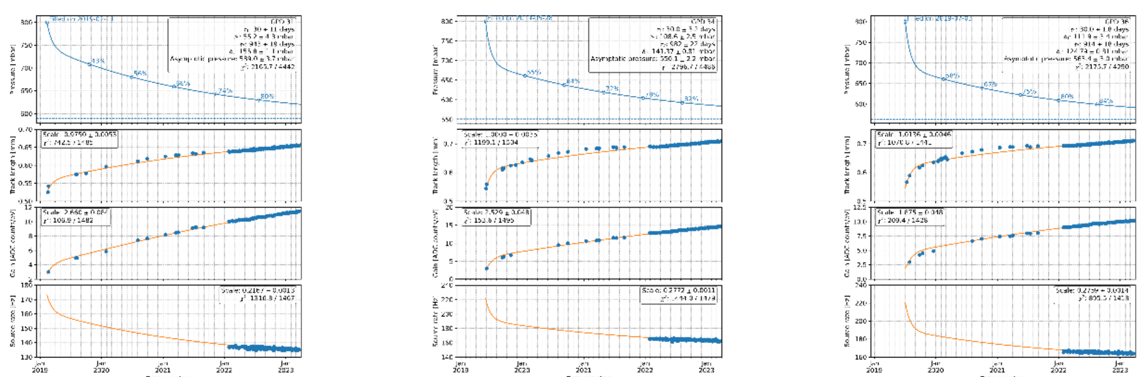


Figure 2. Key components of the IXPE Observatory

due to the absorption of Dimethyl-Ether by the epoxy used for sealing the detector body (Supreme 10HT, by Masterbond). Such absorption, and the consequent internal gas pressure drop, is expected to be asymptotic with a 2-3 years slow time constant and a one month fast time constant (for more details see [23]). The detectors measure polarization by determining the emission direction of photoelectrons, and this becomes slightly easier as the pressure drops due to longer photoelectron tracks. This improvement in polarization response effectively offsets the loss of quantum efficiency (see Figure 3), so polarization sensitivity overall is barely affected. A weighting approach based on the quality of the photoelectron tracks has been implemented[24] and this has been shown to improve polarization sensitivity. Weighted analysis is available to the general user by means of HEASARC (High Energy Astrophysics Science Archive Research Center) analysis tools. The expected improvements of a Neural Network weighted approach, currently under development [25–27], with respect to the weighted moment analysis is expected to be about 8%.[28]



(a) (b) (c)

Figure 3. Gain and track length increase, efficiency drop with respect to time(**a**) DU1. (**b**) DU2. (**c**). DU3

IXPE was designed to fit in a Pegasus-XL launcher and during the detailed design of the IXPE mission, it was decided to remove a boom metrology system to save power and weight. During flight we noted a thermally-

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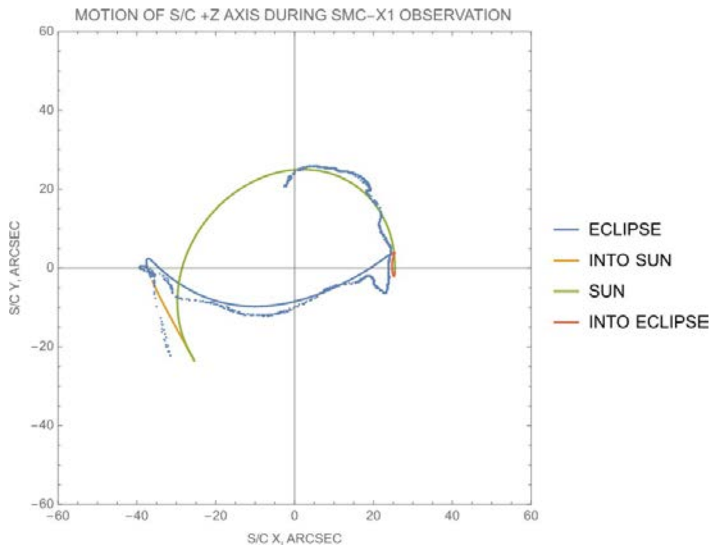


Figure 4. Example of thermally-induced boom motion around an orbit. The motion is accurately modelled and corrected in the data pipeline.

induced boom-motion when the satellite moved from the part of the orbit illuminated by the sun, to the shadowed one (see Figure 4). A careful modelling of the (~1 arcmin) displacement during the orbit, using front and rear star trackers and payload temperature sensors, enabled this displacement to be removed in the data pipeline before public release.

During the first two years of operation, the IXPE science team provides input for the observing plan. The science team is structured into topical working groups (TWGs), one for each class of X-ray emitting celestial source:

1. TWG1 Pulsar Wind Nebulae & Radio Pulsars Chair: Niccolò Bucciantini / INAF - Arcetri
2. TWG2 SuperNova Remnants Chair: Patrick Slane / Harvard–Smithsonian Center for Astrophysics
3. TWG3 Accreting stellar-mass Black Holes Chair: Michal Dovĉiak / Czech Academy of Sciences
4. TWG4 Accreting Wide Dwarfs and Neutron Stars Chair: Juri Poutanen / University of Turku, Finland
5. TWG5 Magnetars Chair: Roberto Turolla, University of Padova, Italy
6. TWG6 Radio-quiet Active Galactic Nuclei and Sgr A* Chair: Frèdèrik Marìn, University of Strasbourg, France
7. TWG7 Blazars and radio-galaxies Chair: Alan Marscher, Boston University

The IXPE collaboration (see Figure 5) consists of approximately 190 scientists from about 13 countries. The Science Advisory Team, which is chaired by Giorgio Matt (Università Roma Tre) and Roger Romani (Stanford Unversity), is responsible for the scientific integrity and the final version of the observing plan submitted to the PI during the first two years of IXPE Science operations. The distribution of collaborators among different nations is shown in Figure 5

In Table 1 we summarize the sources observed during the first year and half for each working group. As expected the largest group is for binary neutron stars and blazars science while for example the longest observations are for the magnetars and supernova remnants group. Due to the size of the on-board memory and the ground-link constraints of the S-band used at Malindi, bright sources are interleaved with dim sources to avoid overflow and this poses limitation on the eventual planning and on the maximum allowed source flux. In order to cope

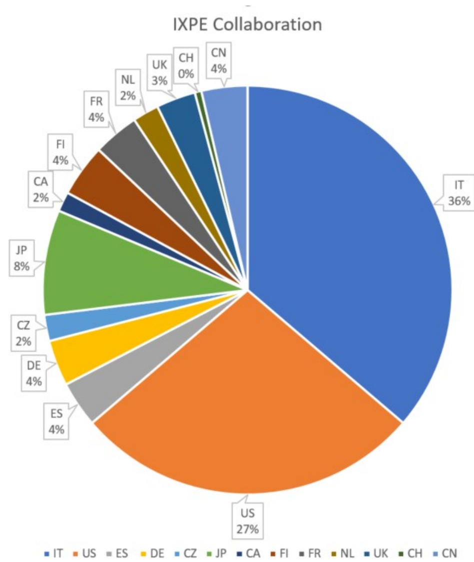


Figure 5. IXPE Science Team by country

Table 1. Celestial sources by IXPE during the first 1.5 years of operation

TWG	Sources observed
TWG1	Crab Nebula & pulsar, Vela PWN, MSH 15-52, PSR B0540-69
TWG2	Cas A, Tycho SNR, SN 1006 NE, RCW86
TWG3	Cyg X-1, 4U 1630-47, LMC X-1, Cyg X-3, 4U 1957+115, LMC X-3
TWG4	Cen X-3, Her X-1, GS 1826-238, Vela X-1, Cyg X-2, GX301-2, X Persei, XTE J1701-462, GX9+9, Swift J0243.6+6124, IC 4329A, GRO J1008-57,EXO 2030+37,LS V+44 17GX 5-1
TWG5	4U 0142+61, 1RXS J170849.0, SGR 1806-20
TWG6	Sgr A* Complex, MCG-05-23-16, Circinus galaxy, NGC 4151
TWG7	Mrk 501, S5 0716+714, 1ES 1959+650, Mrk 421, BL Lac, PG1553+113, 3C 273, 3C 279, 1ES 0229+20 S4 0954+65, 1E 2259+586, 3C 454.3

with very high flux sources an attenuating filter is available on each DU. We plan to use the attenuating filter during the observation of Sco X-1.

Table 2 shows the celestial sources for which X-ray polarization has been detected at greater than 6 σ significance by quick look analysis of the science data. This is a conservative list because the quick-look analysis doesn't allow for changes in polarization degree or angle with time, energy or position within extended soures. Also, no background rejection[29] or subtraction has been applied. Indeed, for a quite larger number of sources (about 70 %) we detected significant polarization by exploiting the capability of IXPE to resolve polarimetry in time/phase, energy and position, the latter with an angular resolution of $\sim$ 30 arcsec.

3. SELECTED SCIENCE RESULTS

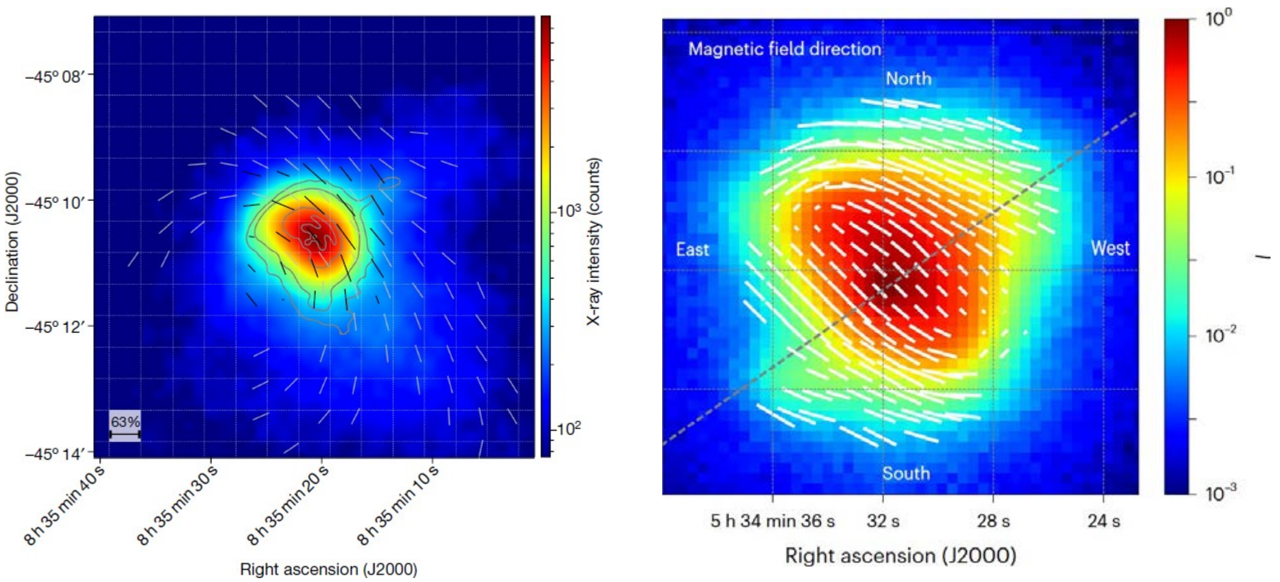
3.1 Pulsar Wind Nebulae & Radio Pulsars

Pulsar wind nebulae (PWNe) are bubbles of plasma and magnetic fields produced by a spinning neutron star which is the remnant of a Supernova explosion. The interaction of this flux with the interstellar medium, and

Table 2. The sources for which a Quick Look Analysis provided measured polarization at a significance larger than 6σ.
* Cas A, Tycho SNR and SN 1006 show significant polarization when spatially resolved.
† NGC4151 and Circinus galaxy show significant polarization when when background and energy selection are correctly taken into account.

TWG	**Celestial Sources**
TWG1	Crab Nebula & pulsar, Vela PWN, MSH 15-52
TWG2	none*
TWG3	Cyg X-1, 4U 1630-47, Cyg X-3, LMC-X3
TWG4	Cen X-3, Her X-1, XTE J1701-462, Swift J0243.6+6124 GRO J1008-57,LSV 44-17, GX 5-1
TWG5	4U 0142+61, 1RXS J170849.0, SGR 1806-20
TWG6	none†
TWG7	Mrk 501, Mrk 421, 1ES1959+650

the possible proper motion of the neutron star, are responsible for the complex morphologies seen in X-rays which are synchrotron radiation produced by electron beams accelerated up to 10-100 TeV. The Crab Nebula was the only source for which polarized radiation was detected in the 70ies[30] (by OSO-8 via its collimated Bragg-diffraction polarimeter) and, more recently, re-detected by Polarlight.[12, 13] At the time of writing, spatially-resolved polarimetry was published already for Vela PWN[31] and Crab Nebula and pulsar[32] while the analysis of the other PWNe are still in progress. The polarization maps obtained by IXPE for these two PWNe are shown in Figure 6.



(a) (b)

Figure 6. (**a**). IXPE polarization map for the Vela PWN. (**a**). IXPE Polarization Map for the Crab Nebula.

The high level of polarization measured in both the Vela PWNe (up to 67-72 %) and the Crab PWNe (up to 45-50 %) and the direction of the magnetic field, show that the Crab magnetic field is mostly ordered and toroidal and that the turbulence is much less effective than expected. The IXPE image of Vela PWN shows that the polarization structure is symmetric about the projected pulsar spin axis which corresponds to its proper motion direction. For Crab PWN the integrated polarization degree is 20 % and the polarization angle is about 145°. While the polarization degree is consistent with that measured by OSO-8 the polarization angle has a small but statistically significant difference value (145 vs 154° [30]). Such difference could be due to the morphology of the inner structure of the Crab nebula changing with time.

IXPE also investigated the polarization properties of the Crab pulsar, facilitated by the imaging and timing capabilities of IXPE. After subtracting the residual nebular component under the pulsar point spread function (PSF), the phase-resolved polarization properties showed positive detection, 15% polarization at an angle of 105°, only at the center of the main (P1) pulse. The phase-integrated polarization of the Crab pulsar is measured to be $2.6^{+2.7}_{-2.6}$ much smaller than expected from most of the current PSR models[33, 34].

3.2 Supernova Remnants

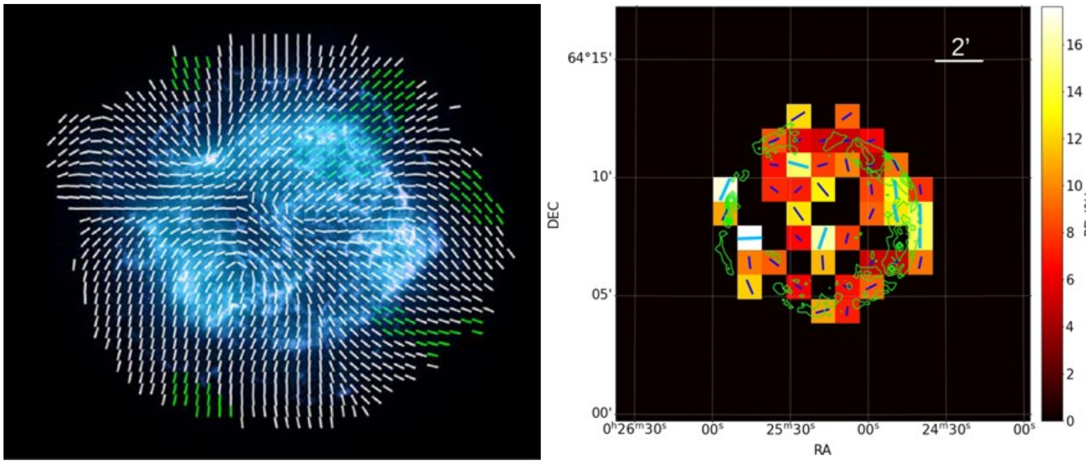
To date IXPE has observed four Supernova Remnants: Cas A, Tycho SNR, SN 1006 North East rim and RCW86. In order to measure the polarization of Cas A[35] and Tycho SNR[36] we first selected an energy range between the Calcium/Argon and Iron line where the thermal emission is expected to be minimum. We then analyzed them on a pixel-by-pixel basis (see Figure 7), but the results were inconclusive. So, we adopted a different technique: assuming a circular symmetry for the polarization direction, we recalculated the Stokes parameter for each event[37], taking the center of the SNR as the origin. This procedure resulted in new values for the Stokes parameters to provide the tangential and radial Q and U Stokes parameter in each region. For every annular or circular region selected we found that the polarization was tangential. Since polarization is certainly due to synchrotron emission, and therefore the polarization is perpendicular to the magnetic field direction, we discovered that for both Cas A and Tycho SNR the magnetic field is globally oriented radially, as in radio wavelength. But X-rays are emitted close to the accelerating shock fronts and the 10-100 TeV electrons responsible for this emission have a short life-time, due to cooling. Further the interstellar magnetic fields in the outer shock (and in the reverse shock in Cas A, too) are compressed tangentially, an instability mechanism should be present fast realigning the magnetic field in radial direction.

For the entire Cas A SNR, the tangential polarization degree is 1.8% +/- 0.3%, which is smaller than in the radio band. The corresponding average polarization degree for the synchrotron emission alone is 2.5 % and 5 % considering the external shock rim. For Tycho SNR, the global tangential polarization degree is 3.5% +/-0.7% corresponding to 9.1% +/-2.0% for the synchrotron component. The X-ray polarization of the external synchrotron rim is 11.9%+/-2.2%. For Tycho, the levels of polarization are larger than those in the radio band. It is worth noting[36] that in the Tycho SNR, the west non-circular region containing the stripes and, possibly, indicating the presence of non-linear diffusive shock acceleration,[38] shows an expected high polarization (~ 23%).

3.3 Accreting stellar-mass Black-Holes

The first black-hole observed by IXPE was Cyg X-1.[39] During this first pointing, while Cyg X-1 was in a low-hard state, the polarization results were surprising, in that the polarization degree was much larger (4%) than expected on the basis of the orbital inclination. This suggests an accretion disk, at least its innermost part, observed more edge-on than expected, as for a warped disk. A hint of an increase of polarization with energy was also found in these data (see Figure 8(a)). The other important result is that the polarization angle is found to be parallel to the radio jet (see Figure 8(b)). As it is assumed that, in the low-hard state, most of the X-ray emission is due to the corona, the polarization direction is inconsistent with a lamp-post geometry model (see Figure 8(c)) in which the polarization angle should have been perpendicular to the radio jet. The corona geometry that fits the X-ray polarization results, is a wedge-shaped corona sandwiching the disk. So, since the the polarization can be either parallel or perpendicular to the disk and the jet cannot be parallel to the disk, this demonstrates that the normal to the disk is parallel to the jet direction.

Other black holes were observed as indicated in Table 1. The most puzzling were 4U1630-47[40, 41] and Cyg X-3.[42] 4U1630-47 was observed at two different levels of luminosity in a high soft state. Its complex behavior challenges a simple geometrically thin and optically thick disk model. Cyg X-3 shows a polarization perpendicular to the



(a) (b)

Figure 7. (**a**). IXPE magnetic field map for the Cas A SNR (Image credit: NASA / CXC / SAO / NASA / MSFC / Vink et al) In green the region with a higher confidence measurement. The magnetic field is mostly radial(**b**). IXPE Polarization map for Tycho SNR. The polarization directions show a mostly radial magnetic field

radio ejection, thought to be due to reflection from circum-nuclear material and a polarization degree as high as $\sim$ 25 %.

3.4 Accreting White Dwarfs and Neutron Stars

During the first year and half we observed both low-magnetized neutron stars and X-ray binary pulsars. Generally, we find that X-ray pulsars are more polarized than low mass X-ray binaries. This is not unexpected because the magnetic field in pulsars is much larger (few 10^{12} Gauss) and photon scattering and opacity are anisotropic with respect to the magnetic field direction. In low-mass X-ray binaries, instead, the residual polarization may derive from scattering of primary radiation either from: the accretion disk that extends down to the neutron star surface; a layer of accreting material on the neutron star surface which is approximately perpendicular to the accretion disk; or from the boundary layer, which is the parallel layer between the truncated disk. So far, we have observed Cyg X-2,[43] XTE J1702-462 and [44] GX5-1. These are called 'Z-sources' because of their characteristic 'Z' shape in the color-color diagram. A nother class of sources, termed 'Atoll' source, were observed including GS 1826-238,[45] GX 9+9[46] and 4U1830-303.[47]

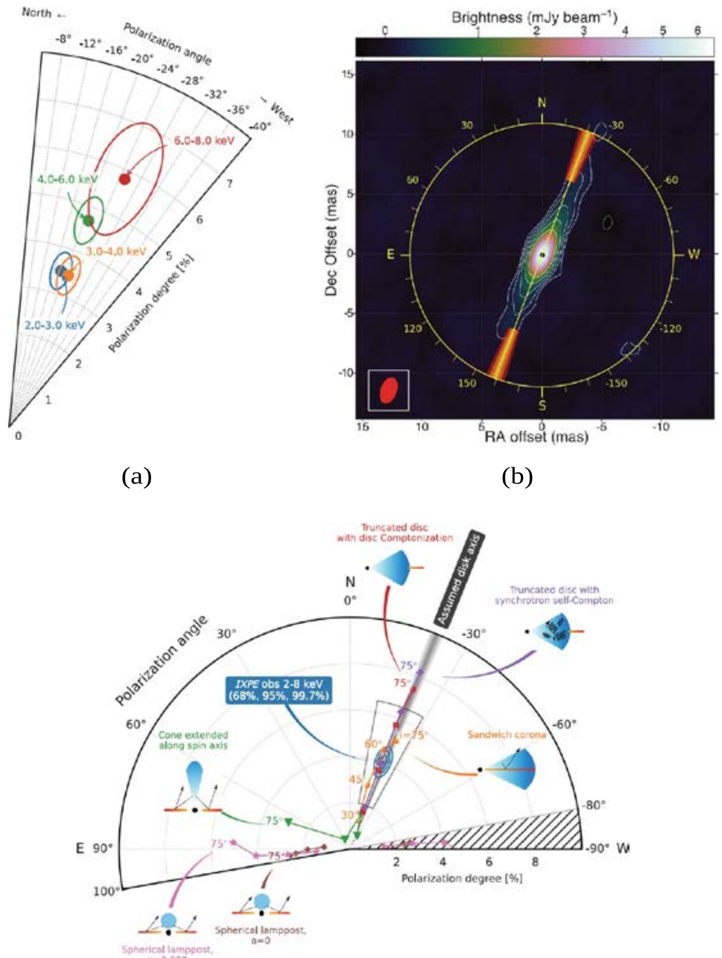
Although X-ray pulsars are found to have higher degrees of polarization than low mass X-ray binaries their measured values ($\sim$ 10-15 %) were much smaller than those expected (60-80 %) from then current theories.[5, 48, 49]

The hypothesis is that the polarization measured is the result of a much more complicated reprocessing-geometry[50] than with the simple 'fan' or 'pencil' models which involved, respectively, only simple columns and hot spots at the poles. This is outlined[50] in Figure 9. In addition, the low polarization degree found[51]

IXPE measurements of binary pulsars offer the promise of disentagling the physics of a source from its geometry. Indeed, it is now possible, thanks to phase resolved polarimetry and the rotating vector model derived from radio-polarimetry, to directly measure for the first time the magnetic obliquity which is the angle between the magnetic dipole axis and the projected spin axis on the sky. Interestingly, in one case an orthogonal rotator (with magnetic obliquity close to 90°) was found[52] by IXPE.

3.5 Magnetars

Magnetars are isolated neutron stars powered by an extremely large magnetic field ranging 10^{14}-10^{15}Gauss. They are very interesting laboratories to study photon propagation in highly magnetized atmospheres and magnetospheres. IXPE



(a) (b)

(c)

Figure 8. (**a**) The polarization degree shows a hint of increasing with energy. (**b**). The polarization angle is parallel to the radio jet. Such a discovery: (1) establishes that the disk axis is parallel to the jet; (2) establishes that the corona geometry cannot be the lamp-post geometry model. (**c**). The different expected polarization degrees and angles for different corona models

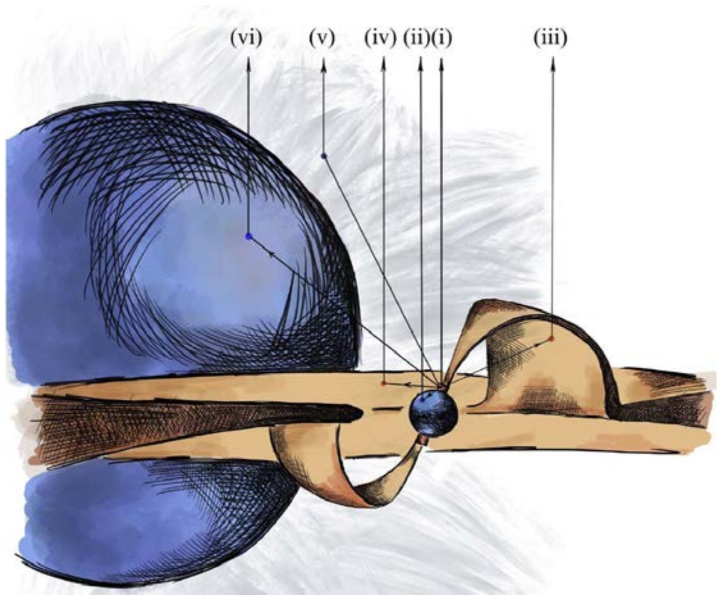
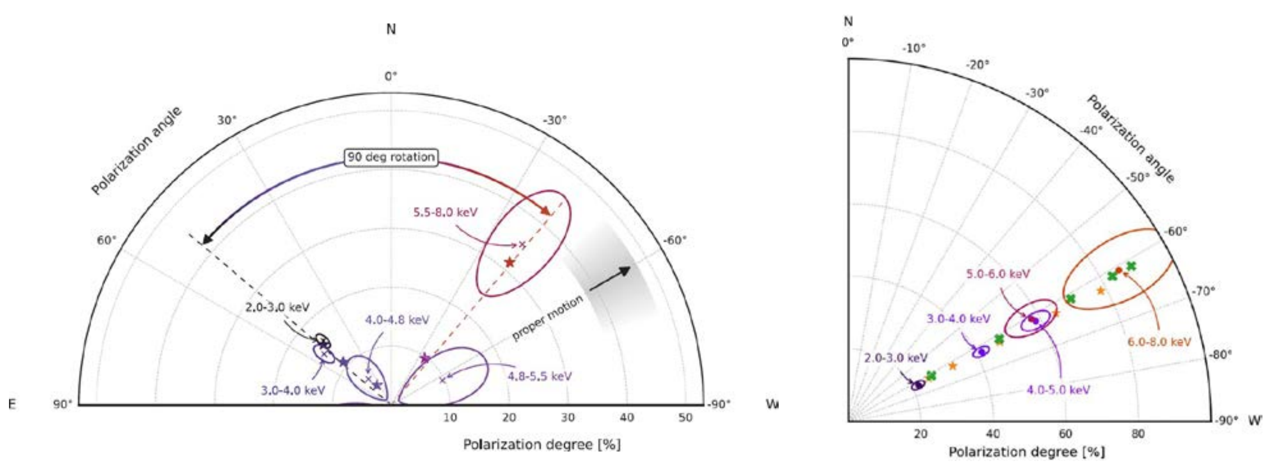


Figure 9. Schematic view of possible different reflection components of the primary emission: (i) primary hot spot or column polarization, (ii) reflection from the NS surface, (iii) reflection from the curtain (iv) accretion, (v) stellar wind reflection, (vi) optical companion reflection.

observed three magnetars (see Table 1) exploring the behavior of polarization both as a function of energy and phase for each. A very different behavior was found between magnetar 4U0142+61[53] and magnetar 1RXS J170849.0[54] in terms of energy resolved polarization (see Figure 10).



(a) (b)

Figure 10. (**a**). The measured values are indicated with crosses. Contours enclose the 68.3% confidence level. Equatorial belt condensed-surface RCS model are indicated by the stars. The gray shaded area and the black arrow indicate the direction of its proper motion and its uncertainty (**b**). Spectro-polarimetry of 1RXS J1708. 50% confidence regions for joint measurement of the polarization degree and angle. Green crosses and orange stars show the prediction of the two different possible emission region structure

This difference (the jump of polarization angle by 90 degrees at higher energies) is explained by the different kinds of geometry and physical conditions of the surface emitting regions. Although some of the effects are consistent with vacuum birefringence, which is incorporated in the models, the sizes of the emitting regions are not extended enough to unambiguously require these quantum electrodynamical effects. A large extended region, as determined by a small pulsed fraction, and a high polarization degree is necessary for securing vacuum birefringence at work for these systems. A third magnetar SGR 1806-20, was observed to be similar to 4U0142+61 albeit with a much smaller significance.[55]

3.6 Radio-quiet AGN and Sgr A*

Radio quiet AGN's accretion disk is different from accreting black galactic holes because its emission is mostly in the UV-optical energy band and the primary X-ray emission is thought to be due to inverse Compton in a hot corona that surrounds the colder accretion disk.[56] Such geometry can produce polarized radiation[57] and from the degree of polarization is possible to derive information on the geometry of the corona which in turn is connected to its origin (an aborted jet for a lamp-post corona along the disk axis, or disk instabilities for a corona sandwiching the accretion disk). An angle of polarization parallel to the disk axis, which is defined by the direction of the, often present, weakly emitting extended radio emission, is the signature of a corona sandwiching the disk, because the average last scattering before reaching the observer is by photons propagating along the disk surface. Indeed, for NGC4151 this is the case and the polarization measured (4.9 +/-1.1) % is thought to be entirely due to reflection from the accretion disk. Only upper limits[58] were found for NGC-5-23-16. Interestingly, for IXPE observations of the Circinus galaxy, a Compton-thick AGN which is observed almost edge-on with respect to its symmetry axis confirms by polarization[46] (28 7)% the presence of a thick obscuring torus as neutral reflector. For this AGN, the polarization direction is normal to the, weak, radio jet (see Figure 11).

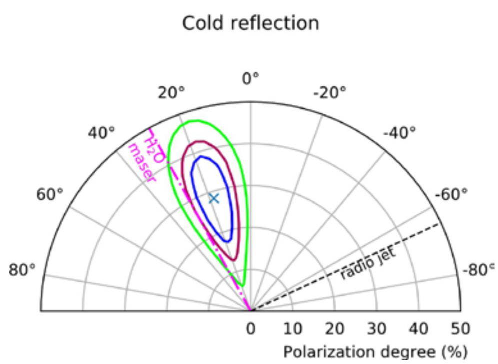


Figure 11. Polarization angle of Circinus Galaxy is directed along the accretion disk traced by the H_2O maser: this is the signature of the presence of an accretion disk responsible for the observed polarization. From comparing simulation with the observed polarization the aperture of the torus is 45°-55°

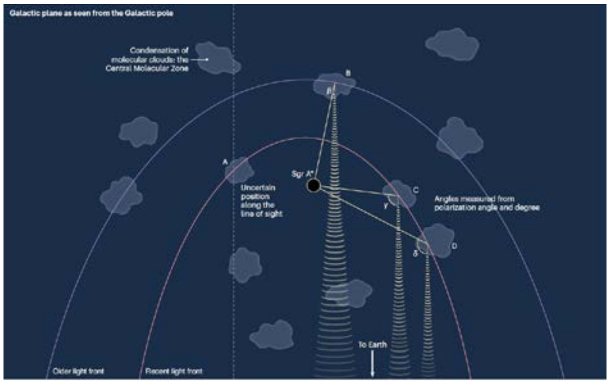
Much closer to us, our galactic super-massive black hole is currently a very dim X-ray source with occasional fast flares. This was not always the case and the presence of cold molecular clouds near to Sgr A* that are shining in X-ray are indicative of reflected[59] photons from a formerly active Sgr A*. If this is the case the observed radiation should be polarized[60] with the polarization vector pinpointing Sgr A* as the origin of the radiation. This, indeed, is what IXPE has (see Figure 12) established.[61]

3.7 Blazars and Radio Galaxies

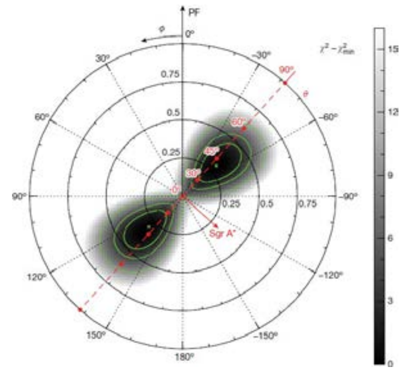
IXPE is particulary well suited for studying blazars, either the High Synchrotron Peaked (HSP) ones with X-rays in the synchrotron peak and the Low Synchrotron Peaked (LSP) ones with X-rays in the Inverse Compton peak. At the present time, only HSP blazars were found to be polarized.[63–65] Other LSP blazars like BL Lac were found unpolarized[66] albeit with upper-limits still too high to probe current hadronic versus leptonic models as origin of the peaks.[67] This was not totally unexpected given their lower fluxes which limits polarization sensitivity. Interestingly, an observation of BL Lac (LSP) during a flare showed a statistically-significant polarization detection with X-rays moved into the synchrotron peak.[68]

For HSP blazars the situation is much different. Mrk 501 observation[63] showed a polarization degree of about 10%, twice as much as in the optical band, and a polarization angle directed along the jet. Together with a modest polarization variability, these characteristic features are considered the signature of an energy stratified shock acceleration process.

When IXPE first observed Mrk 421 the polarization vector was not coincident with the jet direction[64] while the polarization degree $(15\pm2)\%$ was $\sim$ 3 times larger than in optical-infrared-mm. However a successive



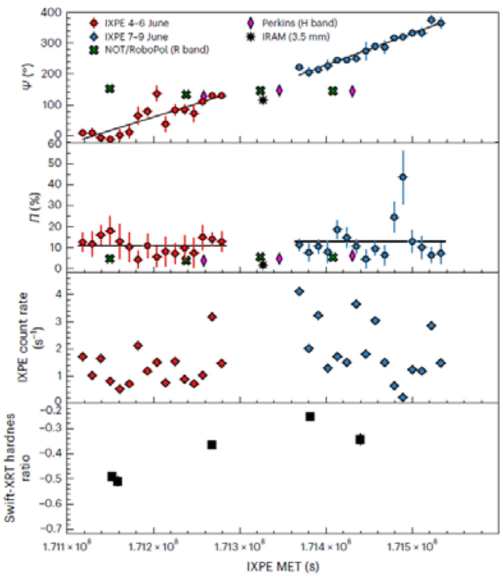
(a)



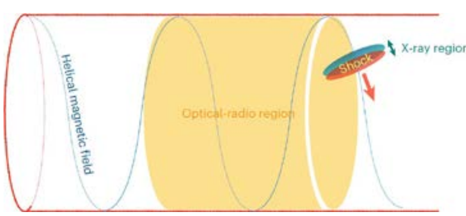
(b)

Figure 12. (**a**). Polarimetry map of the molecular clouds in the vicinity of the galactic center region.[62] The mapping would allow for reconstructing the past X-ray flare history of the galactic center by the polarization degree and angle(**b**). IXPE[61] measurements showed that Sgr A* was 10^6 times brighter in X-rays some 200 years ago. Mapping of a few different molecular clouds at different distances from Sgr A would allow the flare history to be determined.

observation showed a polarization angle fast rotating with time[65] (see Figure 13(a)) indicating the presence of a helicoidal magnetic (see Figure 13(b)) field along which the energy stratified shock acceleration was propagating.



(a)



(b)

Figure 13. (**a**). The rotation of the polarization angle measured in X-rays in Mrk 421 is much faster (80°-90°/day) than in past measurements in the optical band[69] (8°-9°/day) for this source (**b**). The energy stratified shock acceleration is active in an environment embedded with a helicoidal magnetic field.

4. CONCLUSION

IXPE is now on orbit and successfully operating. The first dedicated imaging X-ray polarimetry mission. IXPE is discovering and explaining new physical phenomena in previously known X-ray sources, while helping to disentangle geometry from physics, thus finally realizing the promise of the first rocket launches and the early discoveries of OSO-8. With the IXPE mission completeing its baseline mission in 2024 January, it will then enter a general observer phase. At last, the dream of the scientsists who advocated such a mission over the past 4-5 decades has been fulfilled.

5. ACKNOWLEDGMENTS

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