The Imaging X-ray Polarimetry Explorer 2.5 years later

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ABSTRACT

We have, at last, an observatory dedicated to X-ray polarimetry that has been operational since December 9th, 2021. The Imaging X-ray Polarimetry Explorer (IXPE) is a NASA SMEX mission, in partnership with ASI, based on three X-ray telescopes, each equipped with a polarization-sensitive detector in the focus. An extending boom was deployed in orbit, positioning the detectors at the optimal distance from the optics, which have a 4-meter focal length. The spacecraft is three-axis stabilized, providing power, attitude determination and control, transmission, and commanding capabilities.

After two and a half years of observation, IXPE has detected positive polarization from nearly all classes of celestial sources that emit X-rays. In this report, we describe the IXPE mission, detailing the performance of the scientific instrumentation after 2.5 years of operation. We also present the main astrophysical results and a few examples of scientific performance during flight.

Keywords: X-ray, Astrophysics, Optics, Polarimeters, Imaging X-ray Polarimetry Explorer

1. INTRODUCTION

The origin of polarization in celestial sources can be traced to various emission mechanisms including cyclotron radiation, synchrotron radiation, and non-thermal bremsstrahlung.[1–3] Even in cases where the radiation is thermal and initially unpolarized, polarization can arise through scattering in anisotropic plasma.[4,5] Moreover, X-ray polarimetry offers insights into phenomena such as vacuum polarization and X-ray birefringence.[6–8]

Although theoretical models have long predicted significant results from X-ray polarimetry, practical outcomes were limited until recently. The development of Gas Pixel Detectors (GPDs), which detect polarization via the photoelectric effect in gaseous media, revolutionized the field. These advanced detectors have paved the way for missions capable of performing sensitive measurements within the classical X-ray energy spectrum.[9–11] Tsinghua University pioneered the space-based application of GPDs for X-ray polarimetry with a collimated experiment onboard a CubeSat satellite.[12–16] An ingenious experiment, albeit with limited effectiveness. Achieving effective

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polarimetry necessitates the detection of a substantial number of photons, highlighting the importance of missions equipped with optical systems. The introduction of imaging polarimetry, particularly through the Imaging X-ray Polarimetry Explorer (IXPE),[17,18] has established X-ray polarimetry as a standard tool in X-ray astronomy.

2. MISSION OVERVIEW

The Imaging X-ray Polarimetry Explorer (IXPE) represents the 14^{th} mission in NASA's Small Explorer (SMEX) program, conducted in collaboration with the Italian Space Agency (ASI). Key institutions involved in IXPE's design, construction, testing, and operation are illustrated in Figure 1. NASA's Marshall Space Flight Center (MSFC) leads the mission, with the Italian National Institute for Astrophysics (INAF) and the National Institute for Nuclear Physics (INFN), alongside industrial partner OHB-Italy, managing the development, testing, and calibration of the four Detector Units (DUs), including one spare. These units incorporate the Gas Pixel Detectors (GPD) and the onboard filter and calibration systems. IXPE is on an equatorial orbit at 600 km altitude. Download and upload of data occurs during contacts with ground tracking station of Malindi, also contributed by ASI.

Figure 1. Institutions participating in IXPE's development and operation, detailing their roles. The lower section highlights the countries forming the Science Advisory Team (SAT), responsible for scientific data utilization in the mission's first two years.

Figure 2 depicts the IXPE mission after deployment.

3. THE PAYLOAD: EXPECTATIONS AND FACTS

IXPE's payload comprises three mirror modules, manufactured at NASA-MSFC with thermal shields provided by Nagoya University, and three detector units separated by a focal length of 4 meters. The spacecraft includes a Global Positioning System (GPS) for precise event timing, dual star trackers for image correction via photon-by-photon transmission to ground, and an X-ray shield combined with a stray-light collimator to block photons of the huge cosmic X-Ray background outside the field of view. An extensible boom, deployed in orbit, position the optics and the focal plane at the right distance. Thermal sock and shields completes the payload. Three longerons ensure the necessary rigidity for the telescopes and the correct positioning of the nested X-ray mirrors within each module. A tip/tilt/rotate mechanism compensates for any small misalignments after launch and deployment. All these features (and complications) derive from the fact that IXPE was originally designed for a Pegasus-XL launcher, IXPE was ultimately launched via Falcon-9 following a competitive selection process. But at the time of this swap the making of IXPE was so advanced that non major change was possible. Anyway we can state that IXPE as a whole is performing as expected. A minor bending of the boom according to a day/night thermal effect, was found but it has been very well calibrated and is corrected without any impact on the measurement accuracy or sensitivity. Detailed descriptions of IXPE's mirror design and performance, using thin electro-formed Nickel-Cobalt shells for minimal weight and optimal effective area, are found in.[17,19] The performance of the optics in space are consistent with the expectations, based on calibrations and modelling.

The focal plane bench harbors, for each DU, an onboard calibration system.[20] that utilizes radioactive sources based on ^{55}Fe isotope, that decays emitting Mn K_α (5.89 keV) and K_β (6.49 keV) lines. These sources are mounted on a wheel and with a rotation can irradiate a detector for a pre-defined time interval. The calibration source A irradiates with photons monochromatic and polarized by Bragg diffraction on a mosaic graphite crystal, from the Mn K_α (5.89 keV) and AgL_I lines (2.98 keV), extracted from a thin silver target, and is aimed to monitor the stability of the polarimetric response of the detector. Source B irradiates with a high rate the center of the detector, where most of photons from point like sources are detected. This is good to monitor the gain and the resolution. Since K fluorescence photons are unpolarized by first principles this can also allow to detect spurious polarization. A second source of Mn K photons , named C, is irradiating a large field allowing to monitor large angular scale effect. A fourth source (D) is irradiating the large field with 1.74 keV photons of Si K_α (unpolarized as well). Beside complementing the measurements with 5.89 keV providing a second energy value for a linear fit, data from this last source are also the most sensitive to measure the spurious modulation, which is near to the maximum at this energy. Each DU is calibrated in-flight during the occultation by the Earth. Different measurements require very different integration times so they are not performed with the same frequency and duration. The procedure has been described in.[21] The results will be described in a forthcoming paper (Rankin2024 in preparation). Here we anticipate a few essential data useful to evaluate the performance of the IXPE DUs and to discuss the validity or the criticality of some major features of the design.

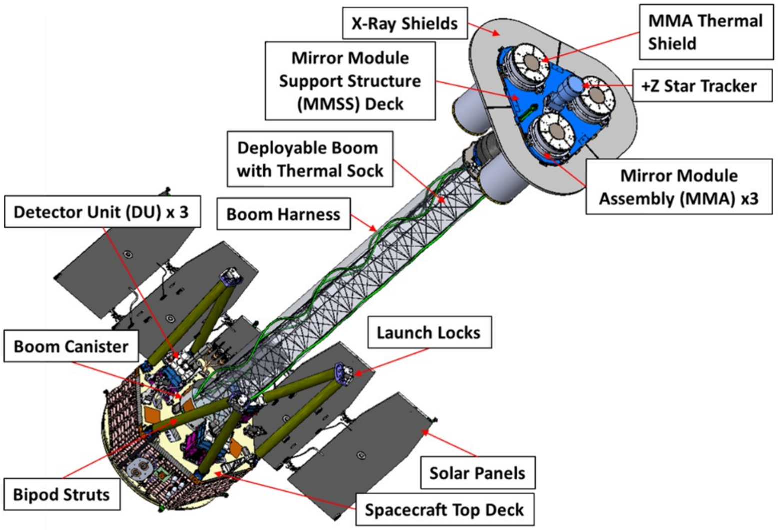


Figure 2. Deployment of IXPE with labeled main components

4. FLIGHT PERFORMANCES

We want first state that, after two years and half of continuous operation, following the long ground activity, the GEM/ASIC system resulted very robust . One single episode of sparking with the death of 7 pixels occurred to one of the 4 DUs during ground operations. No spark was detected during all the flight phase. The Detector Units

(DUs), detailed in,[18,22] have performed as expected from ground calibrations.[21,23] The absorption of dimethyl ether and the accompanying pressure reduction are studied from calibration data through the increasing trend of three parameters measured during the flight: the gain, the track length, and the modulation factor. Here we report (see figure 3) the trend of the gain of the three DUs. The jump in the gain in July 2023 is due to a trimming of the High Voltage to restore the nominal (pre-flight) value of gain. The difference in gain of the three DUs reflects the different pressure of the gas mixture inside each cell and the corresponding different efficiency. The increment of the modulation factor almost compensates for the decrement of the efficiency, providing only a slight loss of sensitivity. Such an efficiency time-drop is included in the response matrices by means of a public tool that calculates its value at the time of observation. The efficiency drop is quite small, being about 10 mbar each year. The latest response matrices available at the time of writing result in the same model normalization for the three Detector Units (DUs).

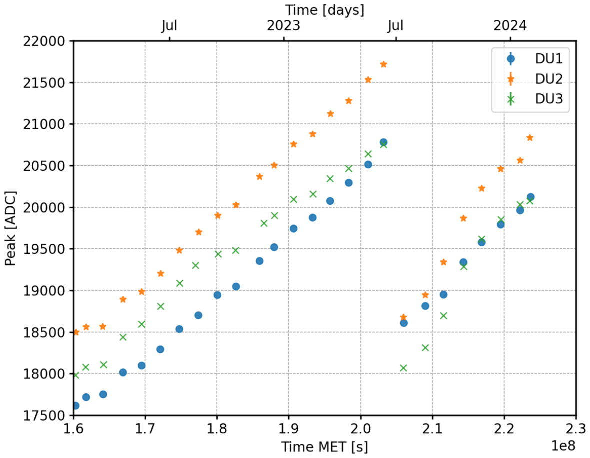


Figure 3. The time trend of the gain of the three DUs at 5.89 keV. The jump around July 2023 is evident and due to the adjustment of the gain down to the nominal value

Incidentally, we remind that IXPE data are public, except for very special cases where three-to-six-month proprietary data periods are granted to the P.I. Additionally, software for standard forward folding analysis based on XSPEC,[24] with weighted and unweighted capabilities for the event, is available to the public. The weighting capability, based on track morphology, enhances the sensitivity by 13%.[25] Standard models for forward folding are accompanied by an analysis of polarization trends (e.g., constant, increasing linearly with energy, etc.). The collaboration has also provided model-independent analysis software[26] for evaluating the polarization properties of the sources.

Another effect of this pressure drop is an increase of the gain. All these parameters were monitored with onboard calibration sources, during Earth occultations. In order to keep all the equipment stable around the nominal value fixed at the beginning, almost once every year we slightly reduced the High Voltage between the two sides of the GEM, that determines the multiplication.

Notwithstanding these changes, that are all interpreted as a change in the gas content of the cells, the energy resolution was stable in time and across the detectors. In Figure 4, we show the temporal trend of the energy resolution at 5.89 keV after gain equalization.[27] The energy resolution scatters around 18.2% due to the intrinsic systematic in the measurement, without showing a degradation in flight during the operative life of IXPE.

Pollution within the gas cell volume is therefore negligible and this confirms that there was no gas exchange between the inside and the outside of the gas cell during ground operation. We know that dimethyl ether is likely absorbed by the glue and possibly by the titanium frame glued to the aluminized beryllium window. Such internal absorption had been already found before the flight[22] and characterized by mechanical measurements at different temperatures. The cause of this unusual behavior was investigated through a dedicated experiment that measured the pressure drop within test boxes containing various materials used in constructing the detector

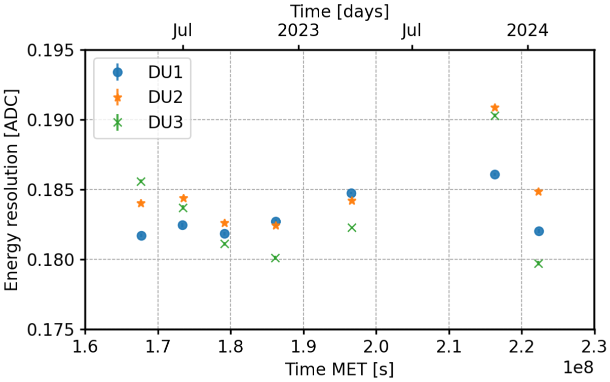


Figure 4. The energy resolution of the three DUs measured at 5.89 keV as a function of elapsed time

body. In conclusion we find that the gas does not show any contamination and the GEM does not show any degradation due to long term operation. This is a good performance and we remind that in the planning of IXPE we avoided any situation of stress. The GEM is operated at a low gain, thanks to the low noise of the analog chains of the ASIC. The High Voltages are decreased and increased again during each passage through the South Atlantic Anomaly (SAA) using a gradual procedure, to avoid dangerous transients. The dithering distributes the detected photons across a large surface of the detector. Additionally, IXPE benefits from a perfectly equatorial orbit, which provides a very moderate and constant radiation environment. On the other hand, we can state that IXPE is operating during a period of intense solar activity, characterized by flares and associated episodes of Coronal Mass Ejections. The major effect of these storms on IXPE is an increase in the extent of the SAA. Specifically, the increase in counts within the SAA begins a few seconds before the expected time and ends a few seconds after. While this effect is easily corrected, it necessitates considerable effort to ensure that solar activity does not affect observations of faint sources in the days following strong flares. The monitoring of the spurious modulation is much more demanding in terms of detected photons and thence in terms of calibration time. We are not able to monitor, as the gain and resolution, on the timescales of weeks, but we can confirm that on the timescale of 6 months, no change is present with respect to the on-ground calibrations. Therefore the relative correction can be still reliably applied. A paper on these monitoring activities is in an advanced preparation status (Rankin et al in preparation). The energy and space dependant spurious modulation is de-trended on an event-by-event basis, following a procedure described in[28] and based on calibration made at INAF-IAPS facilities.[29] However, we can check during flight the level and the time trend of the spurious modulation using the 1.74 keV and 5.89 keV unpolarized sources. We show this trend in Figure 5 plotted before the application of the removal procedure, which cannot be safely extrapolated down to 1.7 keV. Indeed the spurious modulation, which amplitude is inversely proportional to the photon energy, was calibrated down to 2.0 keV and no model is yet available to describe it with confidence for a safe extrapolation at 1.7 keV.

Therefore we plotted the raw time trend for both sources. The spurious modulation is found not increasing with time, so we are confident that the application of the ground calibration spurious modulation map obtained at the time of the ground calibration are still valid today. Further, since the calibration sources used have a little divergence photons impinging at large incidence angles provide some additional residual modulation[30] that is largely compensated by the azimuth symmetry. The spurious modulation obtained by adding the calibration data on the whole detector is an unbiased value..

^{55}Fe has a half-life of 2.74 years, resulting in the calibration rate from the onboard sources now being almost halved. We are currently working on an updated calibration schedule. Due to the smooth and regular evolution of the detector parameters, we believe this issue can be managed without significant loss of observing time.

Another parameter monitored through onboard sources is the charging effect, which refers to the decrease in gain in certain regions of the detector following significant localized radiation. The models that accurately fit the ground-collected data do not adequately describe the in-flight behavior, likely due to the different radiation environment and continuous operation. We have had to adjust the fit parameters, and some work is still in

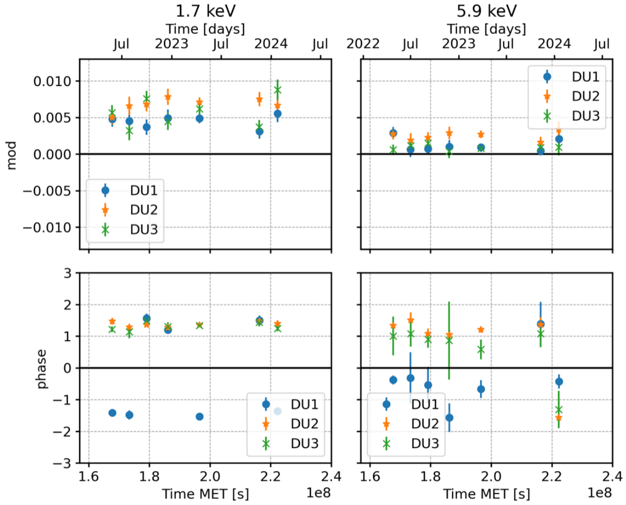


Figure 5. The time trend of the spurious modulation for the three Detector Units before subtraction by the IXPE pipeline. The phase of DU1 is just 180° from DU2 and DU3 so it corresponds to the same polarization angle

progress. Despite the generally positive evaluation of the in-flight performance of the GEM, this feature requires significant effort for improvement.

5. A WALK-THROUGH THE SAA

IXPE's orbit is at 600 km equatorial. In this way, it is not affected by trapped particles in the magnetosphere unless it crosses, once per orbit for a total time of approximately 10 minutes, SAA. The detector unit high-voltages are usually stepped down during that portion of the orbit by a time-tag command (called SAA mode). This is a precaution set to prevent not probable but possible harm to the detector due to interaction with such trapped charged particles (mostly protons and electrons). On 25^{th} April 2024 at 11:58 UT, due to an interplay in loading the weekly plan and the time-tag command, IXPE crossed the SAA with HV on, and the ratemeters registered an increase in the rate as shown in Figure 6.

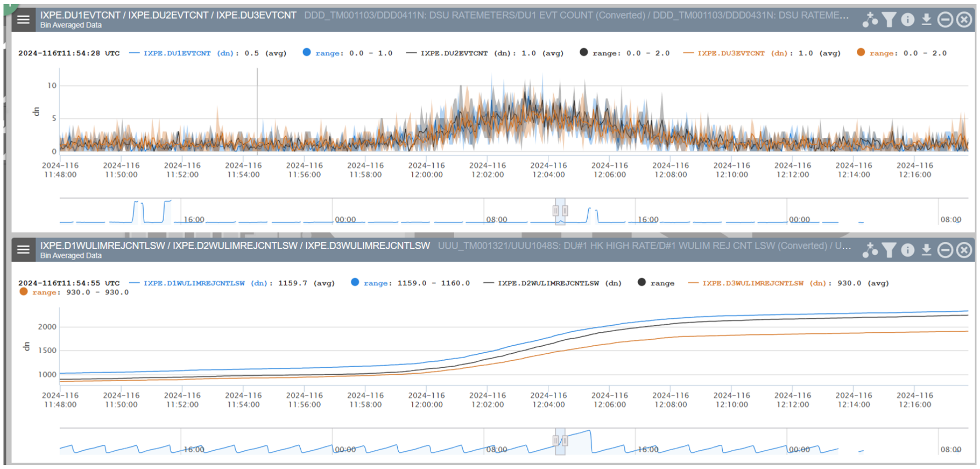


Figure 6. (Top) Counting rate (dn,counts/s) observed during the portion of the orbit characterized by the passage through the SAA. The ratemeters for each DU are shown. (Bottom) Integral counts for each DU detected during the portion of the orbit characterized by the passage through the SAA with High Voltage on.

The total number of counts collected during the passage of the SAA was about 1000 for each DU, with an average of about 1 count/s and a peak rate of about 6 counts/s. In Figure 7, we show the charge map accumulated in one minute of observation with tracks collected during the passage through the SAA. Although very long tracks are rejected in hardware and therefore not shown, the plot clearly indicates the presence of larger-than-average tracks, while most events are still short tracks, possibly from low-energy photoelectrons.

The low counting rate during such SAA passage can be puzzling but it is expected. An investigation with SPENVIS software using the AP8 Radiation Belt Model showed an expected peak flux of protons with energy above 30 MeV of about 1.7 events $\text{cm}^{-2}\ \text{s}^{-1}$ at IXPE's orbit (height and inclination) during solar maximum. Only protons above this energy can cross the aluminum side of the DUs and the MACOR frame, while only protons above 2 MeV can cross the beryllium window (with a rate of about 2.5 $\text{cm}^{-2}\ \text{s}^{-1}$). These rough estimates show that indeed the expected counting rate at the orbit chosen for IXPE is small.

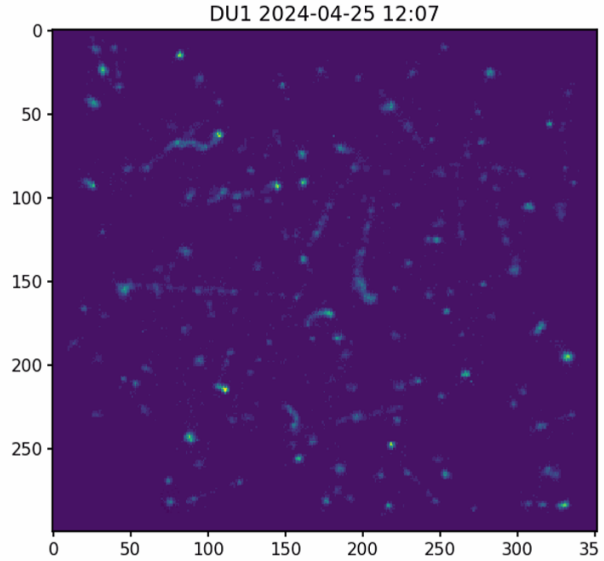


Figure 7. Map of the charge accumulated in one minute during the SAA passage. The presence of long tracks, derived from the interaction of high-energy protons and electrons trapped in the SAA and detected by IXPE, is evident.

A precautionary measure was incorporated into the flight software, which transitions the payload into SAA mode if the accumulated number of counts exceeds a specified threshold. This mode is activated in the presence of accumulated events prior to entering the SAA (referred to as pre-SAA) due to the presence of charged particles originating from the Sun, such as those from a coronal mass ejection, as precedently antiipated. As a result, a few minutes are added to the SAA times for each orbit when these events occur.

6. ASTROPHYSICS, AT LAST

During IXPE's first two years, the collaboration oversees the observing plan, organized into specialized topical working groups (TWGs)

1. WG1 Pulsar Wind Nebulae & Radio Pulsars Chair: Niccolò Bucciantini
2. WG2 SuperNova Remnants Chair: Patrick Slane
3. WG3 Accreting stellar-mass Black Holes Chair: Michal Dovĉiak
4. WG4 Accreting Wide Dwarfs and Neutron Stars Chair: Juri Poutanen
5. WG5 Magnetars Chair: Roberto Turolla

6. WG6 Radio-quiet Active Galactic Nuclei and Sgr A* Chair: Frèdèrik Marìn
7. WG7 Blazars and radio-galaxies Chair: Alan Marscher

The IXPE collaboration involves approximately 190 scientists from 13 countries. The Science Advisory Team, (Università) Roma Tre and Roger Romani (Stanford Unversity), is responsible for scientific data exploitation and observing plan proposals for the mission's first three years. Tables 1 and 2 summarize the celestial sources observed by IXPE during the first 1.5 years and those with significant X-ray polarization detection, respectively.

Table 1. Celestial sources observed by IXPE during the first 2.5 years of operations

Topical Working Group	**Observed Sources**
WG1	Crab Nebula & pulsar, Vela PWN, MSH 15-52, PSR B0540-69, GX 21.5
WG2	Cas A, Tycho SNR, SN 1006 NE, RCW86, RX J1713.7-3946, Vela Jr, SN1006SW
WG3	Cyg X-1, 4U 1630-472, Cyg X-3, LMC X-1, SS433, 4U 1957-115, SS 433 Lobes, LMC X-3, SWIFT J1727.8-1613, 4U 1957+115, Swift J0243.6+6124, Swift J1727.8-1613, GX 339-4, SWIFT J151857.0-572
WG4	Cen X-3, Her X-1, GS1826-67, Vela X-1, Cyg X-2, GX 301-2, Xpersei, GX 9-9, 4U 1820, GRO J1008-57, XTE 1701-46, EXO 2030+375, LS V+44 17, GX 5-1, 4U 1624-49, Sco X-1, Cir X1, GX13+1, SMC X-1, SRGA J144459.2-604207, 4U 1538-52, V395 CAR, PSR J1023+00
WG5	4U 0142+61, 1RXS J170849, SGR 1806-20, 1E 2259+586
WG6	MCG 5-23-16, Circinus Galaxy, NGC 4151, IC 4329 A, Sgr A* Complex, NGC 1068
WG7	Cen A, S5-0716-714, 1ES 19-59-650, Mrk 421, BL Lac, 3C 454, 3C 273, 3C 279, Mrk 501,1ES 1959-650, BL-Lac, 1ES 0229-200, PG 1553 -113, S4 0954+65, 1E 2259+586, RGB J0710+591, H 1426+428

Table 2. Sources with X-ray polarimetry significance larger than 6σ from the Quick Look Analysis. Note: * Significant polarization detected in Cas A, Tycho SNR, SN 1006 and RX J1713.7 when spatially resolved. †Significant positive polarization detected in NGC 4151, Circinus galaxy and NGC 1068 with proper background handling and careful energy selection.

Topical Working Group	**Celestial Sources**
WG1	Crab Nebula & pulsar, Vela PWN, MSH 15-52, G21.5 - 0.9
WG2	None*
WG3	Cyg X-1, 4U 1630-47, Cyg X-3, LMC X-3, SWIFT J1727
WG4	Cen X-3, Her X-1, GX 301-2, X Persei, XTE J1701-462, GX 9+9, Swift J0243.6+6124, GRO J1008-57, LS V+44 17, GX 5-1, Sco X1, j0243, GX 13+1, GX 340+1
WG5	4U 0142+61, 1RXS J170849.0-400910, SGR 1806-20
WG6	None†
WG7	Mrk 501, Mrk 421, 1ES 0229+200, 1E 2259+586, 3C 454.3, 1ES 1959650

7. ASTROPHYSICS HIGHLIGHTS

We present some key highlights not included in,[31] characterizing the past year.

IXPE observed and the collaboration published[32] spatially resolved polarimetry of the Pulsar Wind Nebula (PWN) MSH 15-52 and its pulsar. A significant polarization of approximately 70% was found in the outer arc, thumb, and end of the jet, with the magnetic field generally aligned with the filamentary structure. Similar to observations of the Crab PWN[33] and Vela PWN,[34] the high polarization degree, close to the synchrotron limit, indicates very low turbulence. This suggests that the 10-100 TeV electrons responsible for the observed X-ray radiation may be accelerated by mechanisms that require a well-ordered magnetic field, such as magnetic reconnection.

Non-plerionic Supernovae, like SN1006,[35] exhibited a turbulent magnetic field with a general direction perpendicular to the shock front, similar to Cas A[36] and Tycho SNR,[37] as seen in radio wavelengths but now even at sub-parsec scales. Conversely, a magnetic field parallel to the shock front was observed in the NE rim of RX 1713.7,[38] possibly related to its status as the oldest among the four SNRs.

A puzzling and intriguing black-hole binary observed by IXPE, in a recently accepted paper,[39] is Cyg X-3. IXPE observed it three times: once as part of the observing program decided by the Topical Working Groups of IXPE (Main), and twice as a result of two Target of Opportunities (ToOs) observation. The analysis of the third observation is ongoing while writing these proceedings. In the main observation, Cyg X-3 exhibited a hard spectrum with a polarization degree of 20% and an East-West polarization angle, perpendicular to the direction of ejection of the plasmoids (North-South). When observed at a higher flux (in the first ToO) and transitioning to the soft state, the polarization degree halved while maintaining the same polarization direction. The large polarization degree in the Main observation was explained as resulting from the scattering of radiation produced near the black hole from the internal surface of a funnel. In the ToO observation, the funnel may have modified its geometry and opacity, allowing some radiation to escape across its volume with a larger contribution from direct radiation (unpolarized or polarized but rotated 90°), explaining the smaller polarization.

A black-hole binary in the soft state, which is generally characterized by a photon power-law spectrum with an index smaller than 2 and describable by multi-temperature thermal emission, that provided a big surprise is 4U1830-303.[40] Analysis of the energy-resolved polarization degree and angle revealed that the standard Chandrasekhar disk model, as described by[41] for a relativistic disk, does not fit the data. Currently, a partially ionized disk with mildly relativistic wind outflow and low to intermediate black-hole spin is considered a better fit for the IXPE data.

IXPE was fortunate to observe the black-hole binary Swift J1727.8-1613[42–45] in both the hard state (high and low intensity) and the soft state (low intensity). Unfortunately, the complete transitioning events were not observable. The most compelling result is the decrease in the polarization degree over time in the hard and intermediate states (high flux), while the polarization angle remained the same during the initial transition to the soft state. Furthermore, in the soft state, the polarization degree dropped below the significance level but returned to previous values (both degree and angle) after transitioning back to the hard state (low intensity).

IXPE continued to observe binary systems with neutron stars in accretion. For pulsating binaries (magnetic field $\sim 10^{12}$ Gauss), the swing of the polarization angle is well described by the rotating vector model, as in radio for isolated pulsars, providing and constraining geometric parameters (spin inclination, obliquity between the spin and the dipole axis, and the projection on the sky of the spin axis). Two pulsars, GRO J1008-57[46] and X Persei,[47] showed orthogonal obliquity, while LSV +44 17 was observed in both super-critical (accretion column on the poles) and sub-critical regimes (accretion hot-spot on the poles). To explain the polarization data of the latter,[48] an additional phase-independent component is added to the data. The correlation between the phase-dependent polarization degree and intensity does not follow the expectation[5] for a hot-spot in the sub-critical regime.

Low magnetized neutron stars are subdivided into two broad groups depending on their behavior in the color-color diagram or in the color-intensity diagram. Both *Atoll* sources and *Z* sources have a smaller magnetic field ($< 10^{10}$ gauss) and a complex structure with an accretion disk and a boundary/spreading layer in the vicinity of or on the surface of the neutron star. Both types are characterized by a small polarization degree, usually less than a few percent, which typically increases with energy.

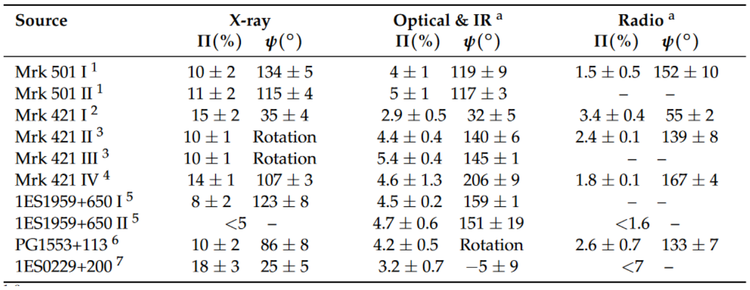
Z sources show a larger polarization in the horizontal branch[49] than in the normal branch[50] or flaring branch.[51] While the polarization angle of Cyg X-2 was found to be parallel to the jet, Sco X-1 shows a different polarization angle orientation that needs to be investigated with future multi-wavelength observations.

Among *Atoll* sources, IXPE has shown different behaviors. For instance, 4U 1820-303[23] provided a hint of a 90° rotation with energy, which may be due to different emitting regions, while GX 9+9 did not show such a rotation.[52]

Four magnetars were observed by IXPE.[53–56] They exhibited very different behaviors in terms of polarization degree and angle, both in energy and phase-resolved analyses. This indicates that much work remains to be done to understand the geometry and physical state of the X-ray emitting regions, as they all showed distinct characteristics. Furthermore, IXPE was not able to unambiguously prove the vacuum polarization mentioned in Section 1. This is because the observed magnetars have a relatively large pulsed fraction, indicating that only a small portion of the neutron star is involved in the emission. To detect vacuum polarization and birefringence unambiguously, a very large emitting region is required. This region should result in an initial small polarization due to the diverse magnetic field orientations but a large detected polarization caused solely by the QED effect.

Observed radio-quiet Active Galactic Nuclei (AGN), such as Seyfert-1 galaxies, all showed a polarization angle parallel to the radio jet,[57–60] implying a corona (wedge or slab) on the same plane as the optical-UV emitting accretion disk. Polarization from Seyfert-2 galaxies like Circinus[61] or NGC 1068[62] was found to be compatible with scattering from a molecular torus with a similar aperture (45° - 55°) as determined by the observed polarization and information on inclination.

IXPE continues to observe Radio-Loud AGNs such as blazars, which can probe both synchrotron-dominated blazars (X-rays in the synchrotron peak) and inverse Compton-dominated blazars (X-rays in the inverse Compton peak). While synchrotron-dominated blazars are clearly detected by IXPE with polarization levels 2-3 times larger than at longer wavelengths (see Figure 8(a)), corroborating the mechanism of energy-stratified shock acceleration, only upper limits are yet available for inverse Compton-dominated blazars (see Figure 8(b)).



Source	X-ray		Optical & IR [a]		Radio [a]	
	$\Pi(\%)$	$\psi(°)$	$\Pi(\%)$	$\psi(°)$	$\Pi(\%)$	$\psi(°)$
Mrk 501 I [1]	10 ± 2	134 ± 5	4 ± 1	119 ± 9	1.5 ± 0.5	152 ± 10
Mrk 501 II [1]	11 ± 2	115 ± 4	5 ± 1	117 ± 3	–	–
Mrk 421 I [2]	15 ± 2	35 ± 4	2.9 ± 0.5	32 ± 5	3.4 ± 0.4	55 ± 2
Mrk 421 II [3]	10 ± 1	Rotation	4.4 ± 0.4	140 ± 6	2.4 ± 0.1	139 ± 8
Mrk 421 III [3]	10 ± 1	Rotation	5.4 ± 0.4	145 ± 1	–	–
Mrk 421 IV [4]	14 ± 1	107 ± 3	4.6 ± 1.3	206 ± 9	1.8 ± 0.1	167 ± 4
1ES1959+650 I [5]	8 ± 2	123 ± 8	4.5 ± 0.2	159 ± 1	–	–
1ES1959+650 II [5]	<5	–	4.7 ± 0.6	151 ± 19	<1.6	–
PG1553+113 [6]	10 ± 2	86 ± 8	4.2 ± 0.5	Rotation	2.6 ± 0.7	133 ± 7
1ES0229+200 [7]	18 ± 3	25 ± 5	3.2 ± 0.7	-5 ± 9	<7	–

(a)

Source	Instrument	Observation ID	MJD range	Exposure (ks)[a]	Π_X[b]
3C 273	IXPE	01005901	59732.37 - 59734.45	95.28	$< 9.0\%$
3C 279	IXPE	01005701	59743.02 - 59748.85	264.42	$< 12.7\%$
3C 454.3	IXPE	01005401	59730.19 - 59732.34	98.12	$< 28\%$
S5 0716+714	IXPE	01005301	59669.43 - 59674.80	358.68	$< 26\%$

(b)

Figure 8. (**a**). List of results[63] from High Synchrotron Peak blazars observed by IXPE and other ground facilities. In this table, [a] represents median polarization properties during the IXPE observation. Especially for optical and IR polarization, only corrected polarization values, accounting for the dilution of polarization by unpolarized starlight from the host galaxy, were considered for calculation. The sources of this information are indicated in.[63] (**b**) List of upper limits[64] at 99% confidence level from Inverse Compton Dominated blazars. [a] indicates that the average exposure of the three Detector Units (DUs) was used. [b] indicates that a 99% confidence level was used to set the upper limits. To achieve the best (smallest) upper limit, the unbinned, event-based likelihood method was used (see[64] for reference).

It is interesting to note that, while IXPE detected a relatively fast rotation of the polarization angle in X-rays for Mrk 421, this rotation was absent at longer wavelengths. In contrast, for PG 1553+113, such rotation is absent in X-rays but present at longer wavelengths. This observation supports models that propose different geometrical configurations of the magnetic fields for particles emitting high-energy and low-energy emitting photons.

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