

# On the Making of IXPE

Martin C. Weisskopf \* and Brian Ramsey on behalf of the Entire IXPE Team

Marshall Space Flight Center, Huntsville, AL 35808, USA; brian.ramsey@nasa.gov

\* Correspondence: martin.c.weisskopf@nasa.gov; Tel.: +1-256-961-7798

**Abstract:** Drs. Weisskopf and Ramsey were the original Principal and Deputy Principal Investigators of the Imaging X-ray Polarimetry Explorer (IXPE). They outline the path to the development of IXPE and discuss the technical and programmatic history that led up to the mission, a partnership between the Italian Space Agency and NASA, and the first fully dedicated to imaging X-ray polarimetry in the 2–8 keV band. An admittedly biased, as seen through the eyes of the original and Deputy Principal Investigators, technical overview of the development of the historical and critical scientific instrumentation is provided. The outstanding, and often paradigm-shifting results are presented in the papers following this one.

**Keywords:** X-ray polarization; polarimetry; IXPE

## 1. Introduction

Opening a new field of study can be a lengthy process. For X-ray polarimetry, that process began more than 40 years ago on a short rocket flight where polarized X-rays were measured from the Crab Nebula and continued until the recent launch of IXPE. Along the way, many types of instruments were proposed, and new techniques developed. The challenge of X-ray polarimetry is that, unlike imaging or even spectroscopy, a very large number of photons must often be detected to provide statistically significant measurements at expected polarization levels. Thus, the field demands highly sensitive instruments and dedicated missions where large integration times are guaranteed.

In the following, we step through this journey, from first detections to the realization of IXPE, a dedicated X-ray polarimetry observatory.

## 2. The Early Days

The origins of IXPE can be traced to the early sounding rocket experiments performed by the group at the Columbia University Astrophysics Laboratory (CAL), under the direction and leadership of Professor Robert Novick. Bob, one of the pioneers of X-ray Astronomy, realized that polarimeters were missing from the tools needed to advance the young (at the time—the late 1960s and early 1970s) field of X-ray Astronomy. The future IXPE Principal Investigator (PI) was a member of the CAL where he, with Roger Angel, developed the use of mosaic crystals for X-ray polarimetry [1] and became infected with the desire to develop highly sensitive imaging X-ray polarimeters.

In early 1971, the group at CAL flew a sounding rocket with two types of X-ray polarimeters aboard—one based on Bragg reflection from mosaic graphite crystals, the other on the polarization dependence of the coherent and incoherent scattering of X-rays from blocks of lithium into surrounding proportional counters. Figure 1 shows the concept, and Figure 2 the scientists involved. The payload was very sophisticated for the time, involving four doors on the sides of the rocket which would open at altitude. Each door contained panels of graphite crystals which Bragg-reflected the source flux onto corresponding proportional counters. The rotation of the rocket would provide modulation of any polarized signal. This flight led to the first detection of the X-ray polarization of an extra-terrestrial X-ray source and found  $p = (15 \pm 5)\%$  at a position angle of  $(156 \pm 10)^\circ$



**Citation:** Weisskopf, M.C.; Ramsey, B., on behalf of the Entire IXPE Team. On the Making of IXPE. *Galaxies* **2024**, *12*, 38. <https://doi.org/10.3390/galaxies12040038>

Academic Editor: Bidzina Kapanadze

Received: 20 June 2024

Accepted: 9 July 2024

Published: 16 July 2024



**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

measured positive north by northeast. It is interesting to note that the doors and their electronics were built by Ball Aerospace which were to be the IXPE prime contractor.

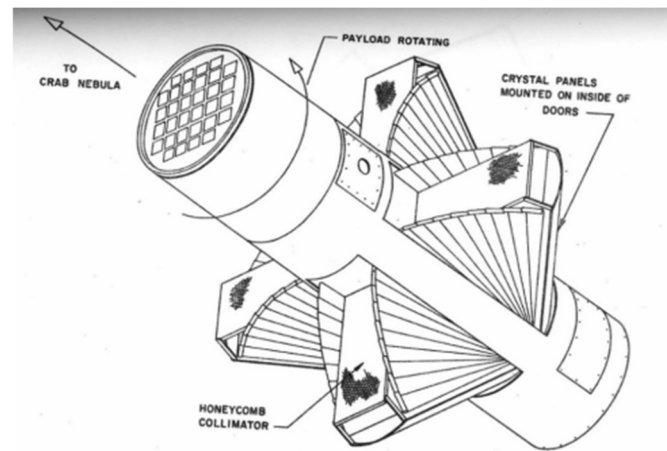


**Figure 1.** Schematic of Rocket 17.09 showing multiple lithium scattering polarimeters (square blocks) in the forward section of the payload and four doors that opened at altitude to reveal four Bragg-reflection graphite crystal polarimeters.



**Figure 2.** Left to right: Prof. R. Novick; Mr. G. Epstein; Asst. Prof. M. C. Weisskopf; Asst. Prof. R. Wolff; and Mr. Richard Linke.

This successful measurement enabled Novick to convince NASA to include a crystal polarimeter on the OSO-8 satellite for which Martin led the development. Observations of the Crab by this instrument produced a high-precision measurement of the nebular polarization finding  $p = (19 \pm 1)\%$  and a position angle of  $(156 \pm 2)^\circ$ . The sub-second time resolution of the OSO-8 polarimeter also provided the ability to perform pulse-phased polarimetry of the Crab pulsar. Unfortunately, only upper limits to the polarization of the pulsar at 99%-confidence were obtained [2] and one would have to await IXPE to perform this experiment. Because of the multi-instrument nature of OSO-8 only a handful of other bright sources were observed yielding upper limits and no solid detections.

### 3. The Stellar X-ray Polarimeter (SXP)

Novick managed to have an experiment, the Stellar X-ray Polarimeter (SXP), placed on the original Spectrum-X mission [3,4]. SXP involved more of what would become IXPE scientists, including the DPI and scientists from Italy. The SXP polarimeter was placed, together with other detectors, on a slide mechanism at the focus of the Soviet Danish Röntgen Telescope (SODART). A schematic of SXP is shown in Figure 3.

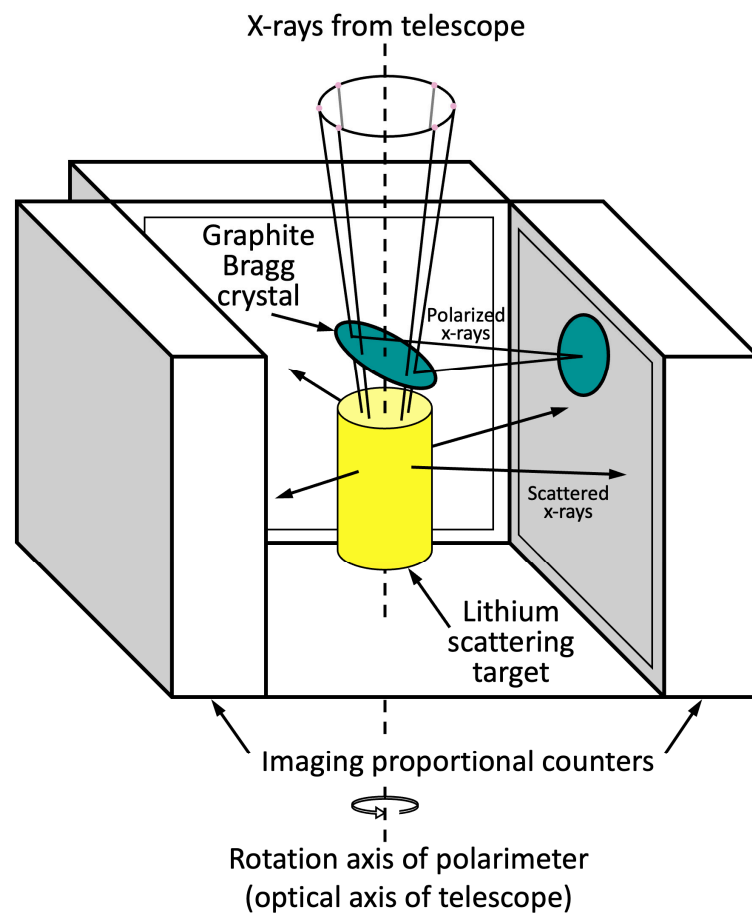


**Figure 3.** SXRP concept.

We became convinced that X-ray polarimetry would be best served by a dedicated satellite mission. Such a mission should have high sensitivity over a broad-enough energy band so that meaningful measurements could be performed, and one should be able to measure the polarization as function of energy and time. Most important is the necessity to perform spatially resolved polarimetry on physically meaningful angular scales. The Chandra images of the Crab emphasize this point—what is the polarization of the jet to the south-east of the Nebula and what does it tell us about the jet formation process?

#### 4. Progress in Detector Technology 1993

In the mid 1990s, an extremely important technical advance was made by the DPI [5] with the development of the first X-ray polarimeter that exploited the polarization dependence of the photoelectron. Figure 4 illustrates the concept. The light emitted by electron avalanches in a parallel plate proportional counter is used to image the tracks of photoelectrons initiated by the interaction of an incident X-ray with the gas filling the chamber. Of special relevance is the fact that the initial direction of the liberated photoelectron is determined by the polarization of the incident radiation. The developers built a small test chamber with which they imaged 54 keV-initiated photoelectron tracks with an intensified CCD camera and measured polarization. The successful demonstration showing one could image electron tracks implied that not only did one have a new polarimeter but one could also perform polarimetry on extended sources when such a detector is placed at a telescope's focus because the data could be used to produce an image. The challenge would then be to develop such devices to operate in the “standard” X-ray astronomy band, from  $\approx 2$ –10 keV, where photons are most plentiful.

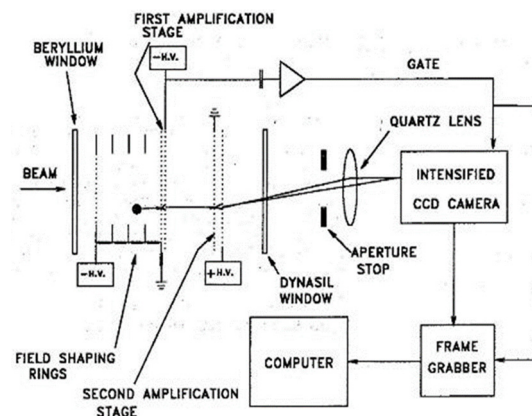


Figure 4. Concept of the first electron tracking polarimeter.

### 5. Proposals—The Beryllium Scattering Polarimeters

Under NASA, a dedicated mission would be best accomplished through the Small Explorer Program (SMEX) and possibly a Medium Explorer (MIDEX). Another possibility that sprung up once, also under the Explorer Program, was for a Student Explorer Demonstration Initiative (STEDI). We submitted proposals for what we called the X-ray Polarimetry Explorer (XPE) four times starting in 1994 and ending in 2003. All these polarimeters exploited the polarization dependence of Thompson scattering to determine the linear polarization of incident X-ray photons but were incapable of imaging.

The last polarimeter of this design consisted simply of a hollow beryllium-scattering cone, oriented with its axis parallel to the incident X-rays and azimuthally surrounded by a sealed gas proportional counter. X-rays from an astronomical source enter the instrument through a simple mechanical collimator—a plate with circular holes. These X-rays then scatter in a beryllium scatterer, in this case, a hollow beryllium cone, into the annular proportional-counter detector. The amplitude of the azimuthal variation of the detected signal determines the degree of linear polarization; the phase gives the position angle. To mitigate systematic effects that could produce false polarization detection, the instrument would be well-calibrated on the ground and the polarimeter/spacecraft combination would rotate about the line of sight to average out any residual systematic variations especially those that might arise after launch.

Unfortunately, none of these proposals was successful, the main limitation being the high background and the lack of imaging, both consequences of the non-focusing approach (see below).

### 6. Technical Progress 2000

A key breakthrough of direct relevance for IXPE was the paper by Costa et al. [6]. This exploited the photoelectron tracks produced when X-rays are absorbed in a gas-filled detector, as did the device reported in [5], but now, a direct charge readout method was used to image the tracks. Imaging was accomplished by using a gas-electron multiplier to amplify the charge, followed by a two-dimensional multi-pixel charge-readout plane with fine-enough pixels to ensure good track reconstruction. By careful choice of fill gas and very-fine readout pixels, the device could operate over the 2–10 keV band and could be placed at the focus of an X-ray telescope allowing for image-resolved polarimetry. This configuration also produces a significant enhancement in signal to noise as the background is reduced by orders of magnitude when compared with a non-focusing instrument. An enhanced version of this early device became the IXPE gas pixel detector (Figure 5).

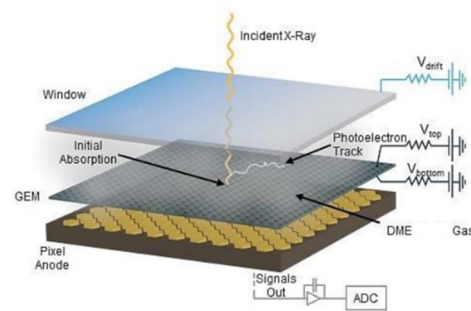


**Figure 5.** The gas pixel detector.

## 7. The First IXPE Proposal 2007

When the NASA call for proposals for SMEX missions arrived in 2007, we had decided that the time was ripe to propose an imaging polarimeter. We felt that MSFC had made sufficient progress in X-ray optics, and that sufficient work had been accomplished in Italy on Gas Pixel Detectors that a scientifically useful polarization-sensitive imaging system was conceivable. Accordingly, we contacted our Italian colleagues, many of whom we had worked with to foster polarimetry in the past, to see if they would join with us in a proposal where MSFC would build the X-ray optics and Italy would provide the polarization-sensitive X-ray detectors. This approach was welcomed in Italy, and we set out to write the Step 1 proposal—Explorer proposals involved two steps of competition before receiving authority to proceed.

An important NASA requirement was that proposers were to assume that the mission would be placed in orbit using the Pegasus launch system. This requirement had significant implications for the IXPE design. The most important of these was that it forced a need for a mechanism that would separate the optics and the detectors on-orbit as the Pegasus shroud could not accommodate the IXPE 4-m focal length. This was not as daunting as it sounded because another SMEX, NuStar, had been successfully launched on a Pegasus, and accommodated a 10 m focal length.

To our surprise, not only was our proposal not accepted, but another polarimeter, with less scientific capability in our opinion (e.g., only one-dimensional images), called the Gravity and Extreme Magnetism Small Explorer (GEMS), was. We were surprised as to this outcome as the principal weakness cited for our proposal was “the proposed science, while representing a significant advance beyond earlier studies of this type, is inherently limited in scope and potential impact by the SMEX-class mission envelope”. We simply could not see that this weakness did not apply equally well, if not more so, to the selected GEMS polarimeter.

## 8. NASA Cancels GEMS

On 7 June 2012, NASA officially announced that it would cancel the GEMS mission. The Small Explorer Program has a very-well-defined cost cap, and, as the GEMS mission entered its confirmation review, there was concern that, because of large and unexpected development costs already incurred, the program might not complete within its cost cap. Of course, as soon as we heard of the cancellation of GEMS, we started to plan for a new IXPE proposal to be submitted in response to the next SMEX Announcement of Opportunity (AO) in 2014. Activities that took place in preparation for the proposal included re-establishing contact with Ball Aerospace to be sure they were still on board to propose to be the prime contractor, a kickoff telecon with Enrico Costa and Ronaldo Bellazzini in Italy, and a subsequent first telecon with the IXPE-1 science collaborators on 30 January 2013, to discuss strategy and details.

One might have thought that the preparation of the proposal would have required little effort as the previous proposal clearly served as a high-quality first draft. Nevertheless, having the extra time to further develop the technical design, review and respond to NASA requirements, and evolve and sharpen the proposed interactions amongst the various

organizations and institutions was extremely worthwhile. Moreover, the second SMEX call now explicitly allowed for payload contributions from non-USA entities. The role of the Italian contribution could, therefore, grow accordingly. The ASI endorsement was much stronger for this proposal and additional items were included in the Italian contributions such as the complete detector system and the flight and ground detector calibration system.

## 9. Preliminary Selection

In July of 2015 the Step 1 proposal was accepted! Three proposals were selected to move into a formal study phase: IXPE, an infrared survey mission known as SPHEREx, and an updated version of GEMS, now known as PRAXyS. Thus, we won the opportunity to prepare, in our case, a 1249-page concept study report, undergo a site visit, and present a briefing to the Associate Administrator.

The site visit which took place on 17 November 2016, is a major element of the selection process. A successful outcome of the site visit might not guarantee selection but a poor one could easily lead to failure. The site visit process and ground rules were fully described in advance by NASA. Each site visit would take place in one day, which could include no more than 7 h of presentations/discussions and up to one additional hour for optional tour/demonstrations. The site visit would end precisely after the allotted time and all written materials needed to be provided at that time.

Exactly eight days before the site visit, we received a list of 41 questions and instructions as to how and where to address them. The 8 days leading up to the site visit were very busy!

The most important element of our site visit was two live demonstrations of prototypes of the most critical technical elements of IXPE: a 50% scale model of the IXPE boom and a live demonstration of a prototype polarization-sensitive proportional counter with both polarized and unpolarized X-ray sources. Viewers could watch as the direction of each photon's position angle was measured and then azimuthally binned, which demonstrated either a modulated curve, indicating a polarized beam, or a flat curve, indicating an unpolarized beam.

The briefing to the NASA Associate Administrator (Thomas Zurbuchen) and his Science Management Council took place on December 6, 2016. The briefings were very structured and were based on 45 min presentations in response to a list of questions such as: "What is the most important science result expected from your mission?"; "In your opinion, what are your top risk areas (technical, management, etc.)"; and "How do you propose to address them?" Only five persons were allowed to represent each proposal: for IXPE, these were Martin Weisskopf, Brian Ramsey, Paolo Soffitta (who was now the P.I. for the Italian contribution), Enrico Costa, and Rich Dissly, the Ball Study Manager.

After the briefing, we all thought it had gone extremely well and that Martin and Enrico had been very effective in conveying the scientific wonders of the IXPE mission, the technical readiness, and the strength of the Italian commitment. Brian, Paolo, and Rich were also called upon by Martin to deal with certain questions that arose during the briefing, and they handled themselves very well.

## 10. Final Selection

Early in the morning of 3 January 2017, Martin received a phone call from T. Zurbuchen informing him that IXPE had been selected for development under the condition that there would be no proprietary data. The offer was accepted and the condition on the data was the motivation behind the creation of IXPE's Science Advisory Team.

We naturally felt as if IXPE had been selected for flight. Of course, all we had been selected for was the opportunity to move into the next phase of development. There would be several obstacles to overcome to accomplish the mission. Examples of these were as follows: an early significant lowering of the NASA funds available, forcing a replan of the program including a five-month launch delay; an apparent estimated shortfall in the amount of reserve just prior to one of NASA's Key Decision Point reviews; the COVID

pandemic; unanticipated, yet calibratable, changes in the properties of the detectors; and a five-week furlough of Civil Servants at MSFC. Despite these obstacles, and, after having successfully undergone numerous programmatic and technical reviews in Italy and the United States, IXPE was approved for flight.

### 11. IXPE Launches!

IXPE was launched on 9 December 2022, in a Falcon 9 (SpaceX was selected by NASA over Orbital to provide the launch vehicle) and successfully placed in an equatorial orbit to minimize passage through the radiation belts, and thereby reduce the detector background. The IXPE configuration, after on-orbit deployment, is shown in Figure 6. The payload consists of three identical telescopes, each comprising a mirror module assembly with a polarization-sensitive detector unit at its focus. The focal length of the IXPE telescopes is 4 m, and the overall observatory length is 5.2 m. Tables 1 and 2 summarize the properties of the X-ray optics and the polarization-sensitive imaging detectors. The X-ray shields, together with collimators placed in front of each detector, are used to prevent non-source X-rays from being detected. A more complete description of IXPE may be found in [7].

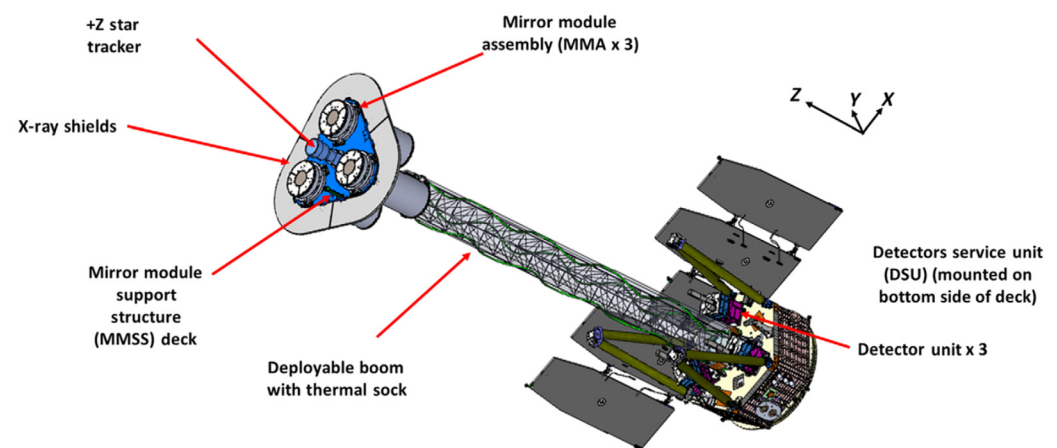


Figure 6. IXPE deployed.

Table 1. X-ray optics parameters.

| Parameter                  | Value                                                           |
|----------------------------|-----------------------------------------------------------------|
| Number of modules          | 3                                                               |
| Shells per module          | 24                                                              |
| Focal length               | 4 m                                                             |
| Total shell length         | 600 mm                                                          |
| Range of shell diameters   | 162–272 mm                                                      |
| Range of shell thicknesses | 0.18–0.25 mm                                                    |
| Shell material             | Nickel-Cobalt alloy                                             |
| Effective area per module  | 166 cm <sup>2</sup> , 2.3 keV<br>>175 cm <sup>2</sup> , 3–6 keV |
| Angular resolution (HPD)   | <28 arcsec                                                      |
| Detector limited FOV       | 12.9 arcmin square                                              |

**Table 2.** IXPE detector parameters.

| Parameter                  | Value            |
|----------------------------|------------------|
| Sensitive area             | 15 mm × 15 mm    |
| Fill gas                   | DME              |
| Asymptotic pressure        | 0.656 atm        |
| Window material            | 50 µm beryllium  |
| Absorption and drift depth | 10 mm            |
| Spatial resolution (FWHM)  | <124 µm @ 2 keV  |
| Energy resolution (FWHM)   | 0.57 keV @ 2 keV |
| Useful energy range        | 2–8 keV          |

## 12. The Science

After a few years of operation, IXPE has completed its baseline science mission and is now in a General Observer phase. During this time, IXPE has made many scientifically successful observations of various categories of X-ray sources. These include weakly magnetized neutron stars, pulsar wind nebulae and supernova remnants, magnetars, accreting stellar mass black holes, jets from stellar mass black holes, and blazars and radio loud active galactic nuclei. In most cases, linear X-ray polarization was detected, and, in many of these cases, the results were unexpected in that they did not necessarily conform to our current theoretical understanding. You will hear and see the fascinating details during the Symposium and in the accompany papers.

## 13. Conclusions

Thus, approximately 50 years after the initial Crab polarization measurement, a dedicated high-sensitivity X-ray polarimetry mission is finally in orbit, opening a new window on the X-ray sky!

The authors give heartfelt thanks to the very large number of people who have contributed to IXPE in numerous ways and who, through their efforts, have made its success possible.

**Funding:** The Imaging X-ray Polarimetry Explorer (IXPE) is a joint US and Italian mission. The US contribution is supported by the National Aeronautics and Space Administration (NASA) and led and managed by its Marshall Space Flight Center (MSFC), with industry partner Ball Aerospace (contract NNM15AA18C). The Italian contribution is supported by the Italian Space Agency (Agenzia Spaziale Italiana, ASI) through contract ASI-OHBI-2022-13-I.0, agreements ASI-INAF-2022-19-HH.0 and ASI-INFN-2017.13-H.0, and its Space Science Data Center (SSDC) with agreements ASI-INAF-2022-14-HH.0 and ASI-INFN 2021-43-HH.0, and by the Istituto Nazionale di Astrofisica (INAF) and the Istituto Nazionale di Fisica Nucleare (INFN) in Italy.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Angel, J.R.P.; Weisskopf, M.C. Use of Highly Reflecting Crystals for Spectroscopy and Polarimetry in X-ray Astronomy. *Astron. J.* **1970**, *75*, 231. [[CrossRef](#)]
2. Silver, E.H.; Kestenbaum, H.L.; Long, K.S.; Novick, R.; Wolff, R.S.; Weisskopf, M.C. Search for X-ray polarization in the Crab pulsar. *Astrophys. J.* **1978**, *225*, 221–225. [[CrossRef](#)]
3. Costa, E.; Piro, L.; Soffitta, P.; Massaro, E.; Matt, G.; Perola, G.C.; Giarrusso, S.; La Rosa, G.; Manzo, G.; Santangelo, A.; et al. SXP: An X-ray polarimeter for the SPECTRUM-X-Gamma mission. *Il Nuovo C. C* **1992**, *15*, 791–799. [[CrossRef](#)]
4. Meszaros, P.; Novick, R.; Szentgyorgyi, A.; Chanan, G.A.; Weisskopf, M.C. Astrophysical Implications and Observational Prospects of X-ray Polarimetry. *Astrophys. J.* **1988**, *324*, 1056. [[CrossRef](#)]
5. Austin, R.A.; Ramsey, B.D. Optical imaging chamber for X-ray astronomy. *Opt. Eng.* **1993**, *32*, 1990–1994. [[CrossRef](#)]

6. Costa, E.; Soffitta, P.; Bellazzini, R.; Brez, A.; Lumb, N.; Spandre, G. An efficient photoelectric X-ray polarimeter for the study of black holes and neutron stars. *Nature* **2001**, *411*, 662–665. [[CrossRef](#)] [[PubMed](#)]
7. Weisskopf, M.C.; Soffitta, P.; Baldini, L.; Ramsey, B.D.; O'dell, S.L.; Romani, R.W.; Matt, G.; Deinger, W.D.; Baumgartner, W.H.; Bellazzini, R.; et al. Imaging X-ray Polarimetry Explorer: Prelaunch. *J. Astron. Telesc. Instrum. Syst.* **2022**, *8*, 026002. [[CrossRef](#)]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.