PROCEEDINGS OF SCIENCE

# An explosive year: first X-ray polarization detection of Supernova Remnants

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The study of young supernova remnants (SNRs) is pivotal in understanding non-thermal X-rays in our universe and the primary sources of Galactic cosmic rays. However, critical questions about the conditions at their shock fronts, including magnetic field orientation and turbulence, remain unanswered. The anticipation of polarized X-ray synchrotron emissions from these SNRs offers unique insights into magnetic field properties that are crucial for theories involving shock acceleration and magnetic field amplification in SNRs. The NASA/ASI Imaging X-ray Polarimetry Explorer (IXPE), launched in December 2021, is the first mission entirely dedicated to X-ray polarimetry. SNRs are a prime example of the novelties that IXPE brings to astrophysics, as its imaging-capable detectors allow us to perform spatially resolved X-ray polarimetry of extended sources with a spatial resolution of 30”. We report on the first results of the IXPE observation of the core-collapse SNR Cas A - that was the first target of the IXPE scientific campaign – and the I-a SNRs Tycho and SN 1006.

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## 1. Introduction

Supernova remnants (SNRs) are among the extended sources that the NASA-ASI Imaging X-ray Polarimetry Explorer [1] is uniquely equipped to observe and study thanks to its imaging capabilities, so that for the first time we can determine not only the X-ray polarimetric properties of these objects, but also how they change across different regions of interest. In its first year of operations since its launch in December 2021, IXPE observed three famous historical SNRs: Cas A, Tycho, and SN1006 shown in Fig.1 as a composite of Chandra and IXPE images. However, with IXPE, our goal is to obtain information on the morphology and turbulence of the magnetic fields at the shocks, and on the particle emission and acceleration processes, that the images alone cannot provide. The interest in polarization of SNRs comes from the fact they are thought to be the dominant source of Galactic Cosmic Rays (CRs), through the mechanism of diffusive shock acceleration mechanism (DSA, e.g. [2]). This involves particles scattering back and forth in the shocks thanks to turbulence in the background plasma and requires preexisting or self generated turbulence that can come from the streaming ions themselves. This efficient acceleration process requires a strong and turbulent magnetic field. Because in many SNRs we observe in the X-rays emission from thin filaments that we ascribe to synchrotron emission, this means that a population of relativistic electrons must exist that is accelerated very very close to the shocks. So, even if IXPE, with its 30 arcseconds angular resolution, cannot resolve these filaments like Chandra does, we know that the X-rays, and hence the polarized emission comes from close to the shocks. Moreover, the synchrotron emission is intrinsically polarized, so that the degree of polarization we observe provides us with information about the level of order, and hence turbulence, at such scales. On the other hand, the polarization direction gives us information on the magnetic field, being orthogonal to the magnetic field orientation.

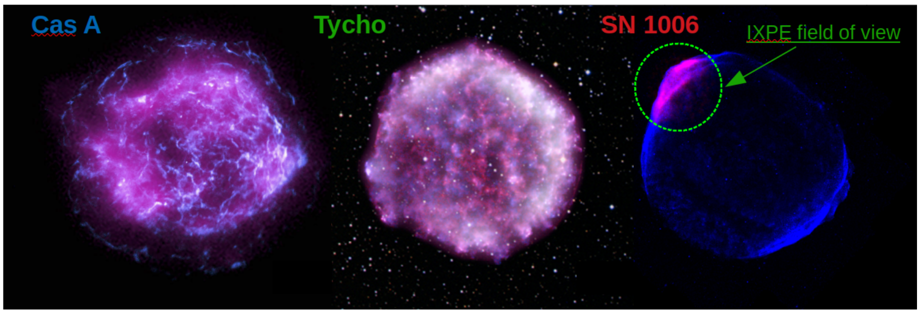


**Figure 1:** From left to right, composite Chandra (blue) and IXPE (purple) images of the SNRs Cas A, Tycho, and SN 1006. In the Tycho image, in white is also superimposed the Sloan Digital Sky-Survey image. The size of the objects in the images is not to-scale.

Indeed the morphology of the magnetic field of SNRs is something we are very interested in, because of an open question coming about from our knowledge of radio polarization measurements: given a shock going through an initially random magnetic field, one would expect it to compress the field component that is perpendicular to the shock motion, as a result that component is enhanced, resulting in a mostly tangential magnetic field. In the radio band, this is exactly what it is observed in old ($\gtrsim$ 2000 years) such as the SNR CTB01 shown in Fig. 2. However, radio observations of younger SNRs, such as CasA, or Tycho, radio polarization implies a radial magnetic field [3, 4].

This dichotomy is illustrated in Fig. 2. The reason for the different morphology of the magnetic field of in young SNRs is still unknown, but many theories have been put forward and they mostly fall into two schools of thought. The first argues for hydro-dynamical instabilities such as Rayleigh-Taylor filaments that are strung along and stretch out so that the magnetic field is carried along in those directions and the particles are spiraling along that magnetic field and that's what is giving the radial orientation [5]. The second calls for a sort of selection effect due to a more efficient particle acceleration in regions where the shock velocity is parallel to the magnetic field [6]. Hence there is a clear interest in mapping the morphology of the magnetic field in the X-rays in order to understand what the morphology of the magnetic field is closer to the shocks.

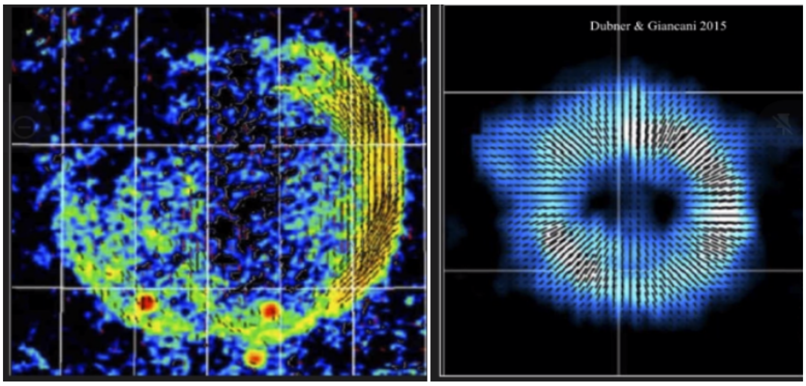


**Figure 2:** Left: magnetic field map in the radio band of the old SNR CTB01 showing a morphology that is parallel to the shock. Right: magnetic field map in the radio band of Cas A, a young SNR, whose field lines are instead radial. Figures adapted from [4].

## 2. IXPE observations of Cas A, Tycho, and SN 1006

### 2.1 Cas A

This brings us back to the IXPE observations of the three previously mentioned SNR. The SNR Cas A was the first target of the scientific campaign after the launch and commissioning, and it represented the benchmark for all the analysis techniques developed by the IXPE collaboration. Cas A is a bright and young ($\sim$ 350 years old) core-collapse SNR whose distance is 3.4 kpc [7]. In the radio band, Cas A is observed to have a radially oriented magnetic field[8, 9] and an average 5% polarization degree that arrives up to 8-10% in the outer rim [10]. The results of the IXPE observation of this source were presented in [11].

We started our analysis with a pixel-by pixel search of polarization signal. We considered spatial bins of size 42" and 84". Binning into larger pixel sizes improves the polarization statistics, but at the expense of potential depolarization due to the mixing of regions with different polarization angles. Shown in Fig. 3 for two values of spatial binning are the significance maps in the left panels which can be interpreted as $\chi^2$ for two DOF, and in the right panel the polarization degree maps where only the pixels with significance higher than $2\sigma$ are shown. The most significant pixels corresponds to a $\sim 3.5\sigma$ significance ranging from $\sim$ 3.5% in the inner region, using the 42" pixel size, to $\sim$ 15% in the outer rim, using the 84" pixel size. However, we do not have enough statistics

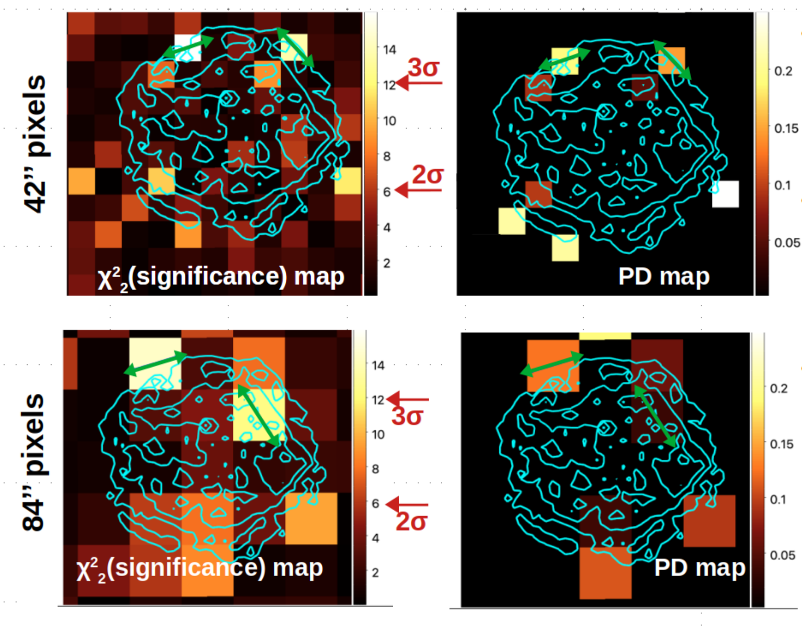


**Figure 3:** Figures adapted from [11]. Left column: significance maps in terms of two-degrees-of-freedom $\chi^2_2$ values for the polarization signal for the 3–6 keV band. Right column: the corresponding polarization degree maps. Only pixels with confidence levels larger than $2\sigma$ ($\chi^2_2 = 6.282$) are shown. For pixels with $\chi^2_2 > 11.82$ (corresponding to $3\sigma$ confidence level) the polarization angles are indicated with green arrows. The errors on these angles are $\sim 8$ degrees. Top row: maps with pixel sizes binned to 42". Peaks in the $\chi^2_2$ map are 15.9, 13.62 corresponding to polarization degrees of 19% and 14.5%, respectively. Bottom row: same plot, but with a larger pixel size of 84". Peaks in the $\chi^2_2$ map are 14.4, 12.32 corresponding to polarization degrees of 12.4% and 3.4%, respectively.

to claim a solid detection here: Cas A is covered by about 200 resolution elements and 3 sigma events should occur every 0.5 pixels so there is quite a good chance to detect two spurious pixels. Nonetheless, this result sill gives us important insights on the source polarization properties:

- the polarization degree must be low, no higher than about 4% in the inner region and 15 -20% in the outskirts;
- in the significant regions the direction of the polarization angle is tangential to the shock, suggesting a radial magnetic field the same as in the radio.

In order to determine how low the polarization degree actually is, and unveil the geometry of the magnetic field, we can resort to a data analysis technique that exploits the additivity properties of the Stokes parameters. From symmetry arguments, given the roughly spherical symmetry of Cas A itself, as well as from the radio observations, one would expect either a tangential or radial magnetic field orientation. By assigning to each event a reorientation of the reference frame from which the Stokes parameters are measured based on a template model for a radial or tangential magnetic field orientation, we can sum together the events in large regions, improve the statistics, and compare the observed polarization properties against the expectation of a model. The regions that we consider (see Figure 4) are the Outer Forward Shock containing the synchrotron filaments, the inner Reverse Shock that overlaps with the bright shell, but also the central region, and the very non-thermal western part of the reverse shock, as well as considering the whole remnant. Finally, we apply the observed polarization degree correction factors based on a full modeling of the expected IXPE data by folding the Chandra best-fit spectral models through the IXPE spectral and spatial response functions using ixpeobsim [12].

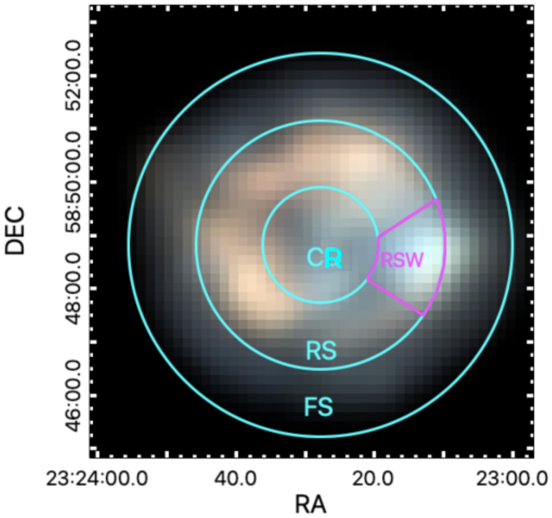


**Figure 4:** Figure adapted from [11]. IXPE three color Stokes I image, based on the 2–3 keV, 3–4 keV, and 4–6 keV bands, combined from the three detectors, with superimposed regions that were used to test for an overall radial or tangential polarization vector orientation. The regions of interest used for the Stokes parameter alignment analysis are tagged as Central Region (CR), Reverse Shock (RS), Reverse Shock West (RSW, in magenta), and Forward Shock (FS).

In Figure 5 are shown the polarization plots of the most significant results. We do find that the overall orientation of the magnetic field is radial, like in the radio, and not tangential as could have been expected from shock compression. This means that whatever the process that is responsible for the radial magnetic field observed in the radio, is already at work very close to the shock where particle are accelerated. Moreover, the measured polarization degree, after accounting for the dilution from unpolarized thermal plasma, is no higher than the value measured in radio. This could be indicative of a very high level of turbulence of the magnetic field at the shock, or that we are observing the reorienting of the magnetic field from tangential to radial

### 2.2 Tycho

The second SNR that IXPE observed was Tycho, during the Summer of 2022. The results of the IXPE observation of this source were reported in [13].

Differently from Cas A, believed to be a Core collapse remnant, Tycho is the result of a I-a explosion. A fascinating peculiarity of Tycho are striking stripe like structures, highlighted by Chandra observations [14] (see Figure 6) whose origin is not yet well understood but theoretical studies suggest that they can be highly polarized [15, 16, 17, 18]. We followed an analysis strategy similar to the one we used for Cas A, so we started with a pixel-by-pixel search of signal. However, Tycho is not as bright as Cas A, so the polarization map binned on a 1 arcminute scale shown in Figure 7 does not show highly significant detections. However, the most significant pixel highlighted in

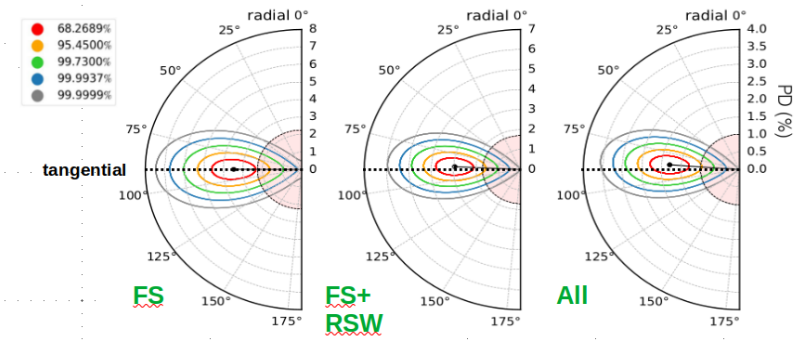


**Figure 5:** Figures adapted from [11]. Polar plots of the the measured polarization degree and angle with respect to circular symmetry as confidence contours for the Forward Shock (FS), combination of Forward Shock and Reverse Shock West (FS+RSW), and for the whole remnant (All). The radial coordinate indicates the polarization degree in percent. The pink shaded region corresponds to the MDP99 level. Values compatible with 90° correspond to an overall tangentially oriented polarization averaged over the region, while around 0° indicates on average a radially oriented polarization.

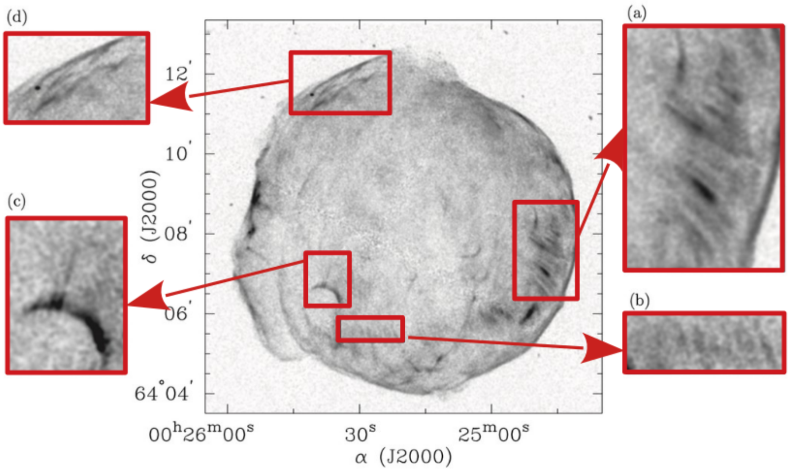


**Figure 6:** Figure adapted from [14]. Chandra X-ray 4.0–6.0 keV image of the Tycho SNR, showing various regions of striping in the nonthermal emission. Clockwise from the upper right: (a) the western stripes; (b) a fainter southern stripes; (c) arch of nonthermal emission; (d) north-eastern filaments.

cyan are located where there is a higher fraction of polarized synchrotron emission, especially in the western rim where the stripes are located (see Figure 8). Again, by observing the most significant pixels, this first inquiry suggests an overall tangential polarization and hence radial magnetic field.

By aligning and summing over the data from different regions of interest, such as the highest significant region in the west, the rim, but also the whole remnant, we do find highly significant detections of polarized signal, that confirms the radial morphology of the magnetic field, but also tells us that the degree of polarization is much higher than the one observed for Cas A, but also higher than the one observed in the radio that is about 12% in the rim in the X-rays, and about 7-8% in the radio in the same region. This could be indicative of a less turbulent magnetic field in Tycho than in Cas A,

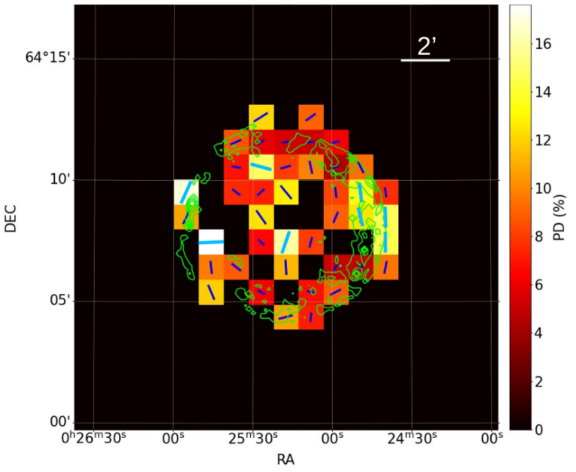


**Figure 7:** Figure adapted from [13]: polarization map in the 3–6 keV energy band with a 60" pixel size. Only the pixels with significance higher than $1\sigma$ are shown. The blue bars represent the polarization direction (that is, the direction of the electric vector polarization angle) and their length is proportional to the polarization degree. The thicker cyan bars mark the pixels with significance higher than $2\sigma$. The orientation of the magnetic-field is perpendicular to the polarization direction. Superimposed in green are the 4–6 keV Chandra contours.

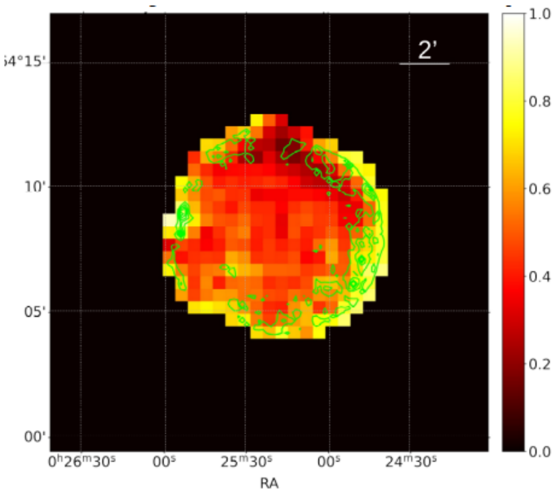
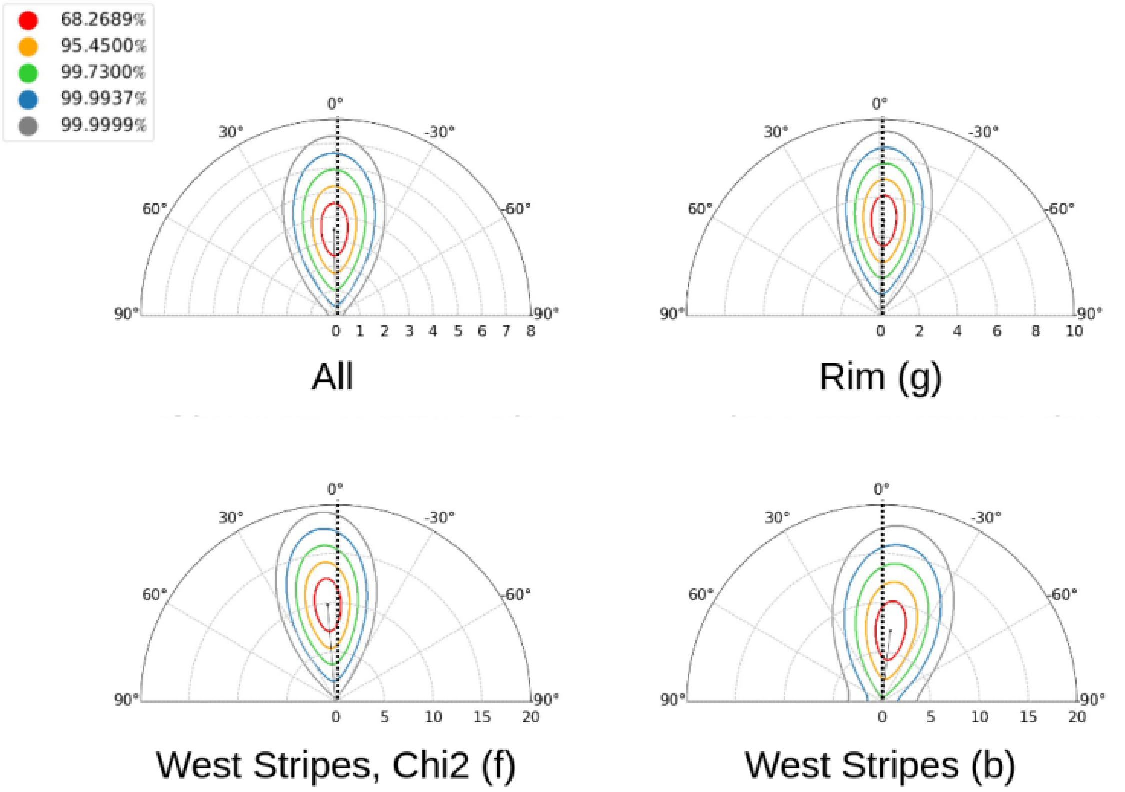


**Figure 8:** Figure adapted from [13]: simulated Tycho synchrotron fraction map in the 3–6 keV binned on a pixel size of 30" with (in green) the Chandra contours of the 4–6 keV emission overlayed.

or a longer maximum turbulence scale. These results are shown as polarization plots in Figure 9. Moreover, the magnetic field amplification inferred from the observed polarization degree is much smaller than the expected values from the acceleration models, implying that either we are in the presence of highly anisotropic magnetic field turbulence (and indeed our results would be compatible with turbulence produced by an anisotropic cascade of a radial magnetic field near the shock as proposed by [18]), or that the emitting electrons favor regions of lower turbulence or accumulate preferentially in radial magnetic field regions.



All

Rim (g)

West Stripes, Chi2 (f)

West Stripes (b)

**Figure 9:** Figure adapted from [13]: polar plots for the most significant Tycho regions of interest. Each diagram depicts the measured polarization degree, and direction with respect to circular symmetry with respect to the geometrical center of the remnant, as confidence contours. The confidence levels are given color-coded in the legend. The radial coordinate indicates the polarization degree in percent. Values more consistent with a polarization direction of 0° correspond to an overall tangentially oriented polarization averaged over the region.

### 2.3 SN 1006

During the Summer of 2022, IXPE observed SN 1006, also another type I-a SNR. At the time of this writing, the results have not yet been published, but the expectations for this target can be stated. First of all, this remnant has a large angular extension, and indeed the IXPE field of view can cover only one limb of SN 1006. However, this allows us to probe even smaller linear scales with respect to Cas A or Tycho, with the possibility of investigating spatial variations of the polarization direction and the acceleration efficiency. Moreover, differently form the previous targets, the SN 1006 spectrum is fully non thermal, so that we do not have dilution of the signal due to unpolarized thermal components, and its polarization, based on radio data, is also expected to be higher with respect to Cas A and Tycho. On the other hand, is the faintest of the three, so that background has a larger impact on the detectability.

## 3. Conclusions

The observation of SNRs has been the perfect showcase of the IXPE capabilities and allowed us to learn about the turbulence and magnetic field morphology of these objects at unprecedented scales. Both the observations of Cas A and Tycho led to significant detections of X-ray polarization and many surprises, such as the radial morphology of the magnetic field at sub parsec scales and the wildly different polarization degrees among the two objects, confirming that they have indeed different personalities. The observation of SN 1006, thanks to its extension and non-thermal spectrum, will tell us even more about possible small scales variability of the magnetic field turbulence and morphology. Future SNR observation by IXPE include RCW86, RX J1713.7-3946, and Vela Jr.

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## DISCUSSION

**MATTEO BACHETTI:** Cas A has a messy matter distribution. Does it interfere with the radial symmetry you use in your modeling?

**RICCARDO FERRAZZOLI:** It is mostly the unpolarized thermal emission that is "clumpy". Its distribution does not affect the Stokes parameter reference frame rotation that we use and its depolarization effects are factored-in when estimating the intrisic polarization degree.

**SALVATORE ORLANDO:** Did you try to analyze data for Cas A considering separately the western and eastern side? In fact, some line of evidence suggest interaction of the remnant with an inhomogeneity of the circumstellar matter in the western side. It could be interesting to check any difference between result form the West and East side.ous

**RICCARDO FERRAZZOLI:** With the collected data it is difficult to establish any difference in polarization degree between the west and east halves of the remnant. Using the same version of analysis tools as that in the paper, the significance of polarized emission from the west and east halves are 4.7$\sigma$ and 2.2$\sigma$, respectively. It is in good agreement with the fact that the region, FS+RSW (see Table 1 from Vink et al. 2022 [11]), is detected at a high significance. The measured polarization degree corresponding to the west half is $2.2 \pm 0.4\%$, while the 2$\sigma$ upper limit on the polarization degree corresponding to the east half is <2.5%. Recently new instrument response functions became available and allow a refined analysis. The refined analysis shows that the polarized emissions from the west and east halves are detected at 5$\sigma$ and 3$\sigma$, respectively. Therefore, the polarization degree for the east half is obtained more precisely than before. The measured polarization degrees are $2.2 \pm 0.4\%$ for the west half and $1.7 \pm 0.5\%$ for the east half. These values are compatible within 1$\sigma$ uncertainty. Thus, no difference in polarization degree is found. To obtain the (corrected) polarization degree for the synchrotron component, the values above should be multiplied by factors of 1.5 and 1.6 for the west and east halves, respectively. After multiplications, the polarization degrees remain compatible.

**JORDAN EAGLE:** You quote a shock compression ratio (SCR) of $3.3 \pm 0.4$ but then say it is not consistent with shock compression needing to be $10-20$, but many works (e.g. 2011Castro, 2003Vink) assume SCR of $\sim 4$, so to me your estimate is plausible for DSA.

**RICCARDO FERRAZZOLI:** In our case, the evidence is for a radial reorienting of the magnetic field downstream of the shock. The tangential anisotropy due to shock compression is almost immediately lost, and in the bulk of the downstream field it makes sense to assume an uniform turbulence on top of a mostly radial magnetic field. So, in order to achieve a 200$\mu$G total magnetic field in the downstream, the upstream turbulent component needs to be already amplified up to about 60-70$\mu$G, that corresponds to a $(\delta B/B)_{upstream} \sim 10-20$, assuming an average interstellar matter magnetic field of $3-6\mu$G. However, with our observed polarization degrees, in the downstream we have $\delta B/B \sim$ 3-4! This implies that it is even lower in the upstream ($\sim$ 1 since Landau damping is not effective downstream). Thus, it is challenging to achieve the 200$\mu$G starting from 3-6$\mu$G.