Simultaneous space and phase resolved X-ray polarimetry of the Crab pulsar and nebula

The Crab pulsar and its nebula are among the most studied astrophysical systems, and constitute one of the most promising environments where high-energy processes and particle acceleration can be investigated. They are the only objects for which significant X-ray polarization was detected in the past. Here we present the Imaging X-ray Polarimetry Explorer (IXPE) observation of the Crab pulsar and nebula. The total pulsar pulsed emission in the $[2–8]$ keV energy range is unpolarized. Significant polarization up to 15% is detected in the core of the main peak. The nebula has a total space integrated polarized degree of 20% and polarization angle of 145°. The polarized maps show a large variation in the local polarization, and regions with a polarized degree up to 45–50%. The polarization pattern suggests a predominantly toroidal magnetic field. Our findings for the pulsar are inconsistent with most inner magnetospheric models, and suggest emission is more likely to come from the wind region. For the nebula, the polarization map suggests a patchy distribution of turbulence, uncorrelated with the intensity, in contrast with simple expectations from numerical models.
frequencies and above, a bridge (B) of emission is observed between them. The total unabsorbed pulsed X-ray flux in the [2–10] keV band is roughly $2.7 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ (ref. 20), while the photon index in the energy band [1–100] keV is found to vary in phase between 1.4 and 2.2 (ref. 21–24). The photon index is phase dependent: the emission is harder for B than for the peaks, and slightly harder for P2 than P1. Optical and radio polarization have been measured since the PSR discovery. The PSR emission (in optical in the phase range 0.78–0.84) has a $P_D = 33\%$ and $PA = 130^\circ$ (ref. 25). After OP subtraction, the average PD of the pulses is found to be 5.5% and the average $PA$ is $96^\circ$ (ref. 25).

**Results**

The Imaging X-ray Polarimetry Explorer (IXPE), the first mission devoted to spatially resolved polarization measurements in the X-rays\(^{26,27}\), was successfully launched on 2 December 2021. IXPE observed the Crab PWN and PSR complex twice between 21 February and 7 March 2022 for a total on-source time of roughly 92 ks. Data were extracted and analysed according to standard procedures: HEASOFT v.6.30.1 (https://heasarc.gsfc.nasa.gov/docs/software/heasoft/) was used to perform a barycenter correction, with the BARYCORR FTOOL, using the most recent optical coordinates from the Gaia Data release 3, the DE421 JPL ephemeris and the ICRS reference frame (Supplementary Table 1). Xipeobssim v.26.3.2 was used to do energy calibration, detector World Coordinate System correction, aspect-solution corrections and all further (unweighted) analysis\(^{28,29}\), including phase folding at the derived ephemeris. We also performed a coeval observation of the Crab PWN with the CHANDRA Satellite (ObsID 23539; see Methods for further details).

In Fig. 1 (Table 1) we show the polarized properties of the Crab complex derived by spatially integrating all emission in a region within 2.5 arcmin from the PSR. Background contamination within this region is negligible. There is a significant change in the PA between the low [2–4] keV and high [4–8] keV energy band. The same trend is seen for the OP emission (whose phase range can be found in Supplementary Table 2), suggesting that it is of nebular origin. The change in PD is less significant, with the higher energy band being slightly more polarized. The OP phase emission is marginally more polarized than the total PWN and PSR emission, as already suggested by a similar analysis of the OSO-8 data\(^7\), while there is no evidence for even a marginal change in PA, suggesting that the PSR has a net low level of polarization, acting mostly to reduce the total level of polarization. The contribution of the PSR unpulsed (direct current) emission\(^{30}\) to the total OP emission, is estimated to be less than 1% and we can safely assume that the OP is mostly of nebular origin (we found no evidence for variations of the polarization properties in the OP; Supplementary Fig. 1). The OP PA is roughly $145^\circ$, larger by roughly $20^\circ$ with respect to the values reported in the literature for the PWN symmetry axis, derived from fitting the X-ray jet-torus intensity maps\(^{26,27}\). Its is also smaller by roughly $10^\circ$ than the previous OSO-8 measurements at a statistically significant level (Supplementary Fig. 2). Such discrepancies might simply reflect the variability of the PWN, where structures are known to change in shape and location over a typical time scale of a few years\(^3\).

In Fig. 2 we show an intensity map of the Crab PWN from the coeval CHANDRA ObsID 23539, the IXPE count map for the PWN and PSR complex in the [2–8] keV energy range, and the IXPE count map in the same energy range, but computed just for the OP emission.

For the phase resolved analysis of the PSR we take events in the range [2–8] keV and within 20 arcsec from the PSR itself to limit the PWN contamination. The Stokes parameters of the OP emission have been subtracted (see Supplementary Material for the exact definition of the OP in terms of pulse phase, as well as the other phase bins). In Fig. 3 we plot the OP-subtracted light curve, in 200 equally spaced phase bins. For the polarization analysis of the PSR emission we opted for a variable phase binning, focusing on the peaks and bridge, to get a finer sampling near P1 and P2. Figure 3 shows PSR normalized Stokes parameters $U$/$I$ and $Q$/$I$, for the phase bins of interest (see Supplementary Table 2 for further details). The OP emission in the PSR aperture has $Q/I = -0.0106 \pm 0.008$, $U/I = -0.241 \pm 0.008$, corresponding to $PD = 24.1 \pm 0.8\%$ and $PA = 133.6 \pm 1.0^\circ$. This is significantly more polarized than the OP emission for the entire PWN, and the PA is roughly $10^\circ$ smaller, indicative of a spatial variation of the polarization properties. The only phase bin showing a polarization above the $3\sigma$ confidence level is the centre of P1 in the phase range [0.12,0.14], where the OP-subtracted emission has $Q/I = -0.132 \pm 0.025$, $U/I = -0.079 \pm 0.025$, corresponding to $PD = 15.4 \pm 2.5\%$ and $PA = 105 \pm 18^\circ$. There is no significant change of the polarization properties of this phase bin with energy. Rapid PA variation might suppress the polarization in these bins. The total PSR normalized Stokes parameters are $Q/I = -0.018 \pm 0.019$ and $U/I = -0.019 \pm 0.019$, confirming that the integrated PSR contribution serves only to reduce the polarization of the entire complex.

In Fig. 4 we show the total PWN and PSR map of $PD$ in the [2–8] keV energy range, obtained by smoothing the maps of Stokes parameters with a Gaussian kernel (5 arcsec width) and cut at the $5\sigma$ significance level (Supplementary Figs. 2 and 3), together with an intensity map where we have overlaid the polarized magnetic field direction (by definition perpendicular to direction of the electric field). We are able to map the magnetic field structure in the inner nebula. The overall polarization pattern confirms long-held general expectations for PWNe based on the paradigm that the synchrotron emission takes place in the (mostly) toroidal magnetic field, originating from the PSR wind and compressed in the nebula, which sets the symmetry axis of the jet torus structure. The observed polarization and emission patterns arise from the interplay of the magnetic field geometry and bulk motion of the relativistic plasma within the nebula itself, also depending on the inclination of the nebular axis with respect to the line of sight. It is indeed the presence of bulk motions directed towards and away from the observer that creates the various bright arc-like features and makes the front side of the torus brighter than the back. The results shown in Fig. 4 agree with this picture, assuming a symmetry axis inclined in the plane of the sky as derived from X-rays\(^8\). The direction of the inferred magnetic field broadly follows the shape of the emission torus (which extends also on the back but is fainter due to Doppler de-boosting). There are two unpolarized regions

![Fig. 1 | Global polarization properties of the Crab PWN + PSR complex.](image-url)

Emission is integrated over a region of 2.5 radius centred on the PSR. Normalized Stokes parameters are shown for the total emission, the emission in the [2–4] keV and [4–8] keV energy bands (mean values plus error bars representing the $1\sigma$ standard deviation) and for the OP only, together with contours of polarized degree (in %) and angle.
at the north-east and south-west edges of the main torus, where the polarized direction varies rapidly within the point spread function. The overall PD map shows a far stronger level of asymmetry with respect to the PWN axis than the total intensity map, indicating possibly large variations in the amount of magnetic turbulence within the PWN, or major distortions of the magnetic field structure in the fainter outer regions. The more polarized regions are not found in the centre of the PWN, where there is a marginal contribution from the PSR that lowers the PD, but north and south of the main torus, in regions that do not correspond to any bright feature in X-ray. On the basis of smoothed maps the peak PD in the Northern region is found to be 46%, with a PA of 163°, at 25σ significance, while the peak in the southern region has PD of 51%, with a PA 156° at 20σ significance (Supplementary Fig. 3).

Table 1 | Global polarization properties of the PSR + PWN complex

| Selection       | \(Q/I\)          | \(U/I\)          | PD (%) | PA (degrees) | Significance |
|-----------------|------------------|------------------|--------|--------------|--------------|
| PSR + PWN [2–8] keV | 0.177(0.0019)    | 0.068(0.0019)    | 19.0(0.19) | 145.5(0.29) | 99           |
| PSR + PWN [2–4] keV | 0.168(0.0019)    | 0.081(0.0019)    | 18.7(0.19) | 147.8(0.29) | 100          |
| PSR + PWN [4–8] keV | 0.199(0.0038)    | 0.037(0.0039)    | 20.2(0.38) | 140.2(0.55) | 53           |
| PWN (OP)        | 0.189(0.0036)    | 0.073(0.0036)    | 20.2(0.36) | 145.6(0.51) | 57           |

Normalized Stokes parameters, polarized degree and angle for various energy and phase ranges (in brackets the 1σ errors). The OP is in the [2–8] keV range. The significance is given as the ratio of PD over its 1σ error (Fig. 1).
The magenta curves represent the range of optical data over P1 and P2, energy band, normalized and rescaled to the range of the horizontal bar is the bin width), overlaid with the phase bins of interest: OP and based on numerical magnetospheric solutions, have shown that models, focused on emission in the wind and outer magnetosphere in B, but also predict a fully unpolarized P1 (ref. 34). However, recent striped-wind emission models suggest possible lower polarization PD must vary across P1, and be intrinsically higher in the core. Analytical trend as shown in Fig. 3. Hence the Q/I optical range. Intrinsic depolarization is most probably required. This PA swing (at a constant rate over P1) does not seem capable by itself of caustics are typically depolarized by means of rapid PA sweeps. By reported. The low average polarization is in contrast with most of the σ differences are below the 3σ range is not fast enough to match the X-ray trend. Note, however, that the more recent PolarLight narrow band [3–4.5] keV measures are consistent with our findings that the PSR emission is probably unpolarized. A strong decrease in the PD of the total pulsed emission, from the optical to the soft X-ray (with a possible recovery to large PD in the hard X-ray) is not expected in existing modelling, which primarily relies on geometry of the emission zone to determine the polarization (for example, ref. 36); as noted above, additional physical effects will be required to accommodate the IXPE data. We were able to map the large scale PWN polarization pattern confirming the general expectation of a predominantly toroidal magnetic field, extending well beyond the observed location of the X-ray torus. Indeed, earlier spatially resolved optical polarization measurements did not show unambiguously the presence of toroidal magnetic field. For synchrotron radiation, this is consistent with general expectation from magnetohydrodynamic modelling of this source. We found, however, that the mostly symmetric PA (that is, magnetic field) pattern is associated with large asymmetries in the PD, probably indicating variations in the level of turbulence inside the PWN. Such a level of asymmetry is similar to, but stronger than, that seen in the intensity maps, and reflects a similar trend found in optical polarization images. The magnetic axis of the PWN, derived by taking the symmetry axis of the magnetic field pattern, is found to be roughly 140°, about 15° further out than estimates based on fitting axisymmetric structure to the torus intensity. It is also possible to estimate the inclination of the magnetic axis with respect to the plane of the sky: we found it to be roughly 60°, in agreement with previous estimates. While the average PD roughly 20% agrees with previous measures, the PA differs in a statistically significant way from other estimates, reflecting the spatial variation of the PD, or possible temporal variability. The spatially resolved PD reaches a maximum of roughly 46–50%. This is about two times larger than expected from simple predictions based on synchrotron turbulent modelling of the Crab Torus and Inner Ring luminosity profiles, calibrated on the OSO-8 results. More sophisticated 3D models (lacking, however, micro-turbulence) can give PD values close to the theoretical maximum of roughly 70% (ref. 40), with higher values typically in the south-west region, but in general the prediction is for polarized patterns symmetric with respect to the nebular axis, unlike what was found. This suggests that the level and development of turbulence within the nebula is not as strong as predicted and much patchier in its spatial distribution. While the lower level of polarization close to the centre of the PWN is easily explained by summed emission from a wide range of PA in the central resolution elements, the increase of the PD with distance at the rim of the torus suggests the presence of a highly ordered magnetic layer at the edge of the torus itself (the ratio of southern region has Q/I = 0.30 ± 0.02, U/I = −0.37 ± 0.02, corresponding to PD 47 ± 2% and PA = 154 ± 1°, at 27σ significance with a MDP of 0.05. These regions are far enough from the PSR that its depolarizing contribution is negligible.

### Discussion

We report here a simultaneous phase and space-resolved soft X-ray polarized observation of the Crab PSR and PWN. Our results show that the total polarization of the pulsed signal is negligible. As can be seen from Fig. 3, the consistency with optical polarization measure is marginal. Deviations are prominent for Q/I in the left wings of both P1 and P2. U/I on the other hand is in very good agreement. The discrepancy for P1 is an indication that the polarization swing observed in the optical range is not fast enough to match the X-ray trend. Note, however, that differences are below the 3σ uncertainty. Only the core of the main peak was found to be significantly polarized. This represents a statistically significant detection of an X-ray polarized signal from the Crab PSR. Marginal evidence for polarization, below 3σ, in other phase bins is also reported. The low average polarization is in contrast with most of the existing PSR models, that typically predict polarization fraction in the pulsed emission of 40–80%. The model polarization is generally especially high in the B phase bin. The peaks that are believed to be caustics are typically depolarized by means of rapid PA sweeps. By contrast, we find our highest PD in the core of P1. Moreover, a simple PA swing (at a constant rate over P1) does not seem capable by itself of explaining the presence of a highly polarized core in P1 surrounded by low polarization wings, unless the PA swings much faster than in the optical range. Intrinsic depolarization is most probably responsible. This is easily seen by comparing the Q/I trend as shown in Fig. 3. Hence the PD must vary across P1, and be intrinsically higher in the core. Analytical stripped-wind emission models suggest possible lower polarization in B, but also predict a fully unpolarized P1 (ref. 34). However, recent models, focused on emission in the wind and outer magnetosphere and based on numerical magnetospheric solutions, have shown that the polarization signatures are highly sensitive to the location and geometry of the emission region. Low integrated polarization suggests that the emission region should be close to or beyond the Light Cylinder. However, none of the current models includes important physical ingredients: micro-turbulence, which is probably present in the wind current sheet and could lead to significant depolarization; short time-scale variability that manifests as timing noise and could lead to potential depolarization for long time integration. A detailed comparison with previous measures, typically in higher energy ranges, or with optical data would benefit from better statistics, and would require further modelling/extrapolation (to account for changes in the pulse shape with energy) and goes beyond the scope of this work. Thus we have chosen to avoid any discussion or comparison with earlier polarization measurements with statistical significance less than 3σ. Due to their large error bars, previous results are compatible with our measures (Supplementary Fig. 1). The best estimates for the polarized fraction of the hard X-ray integrated PSR emission have typical values of roughly 20–30% (with low significance and and with some inconsistency among different observations). Given the low MDP (high sensitivity) of our measurement, we can confidently state that the PSR emission in the [2–8] keV must have an integrated polarized fraction of less than 20%. Note, however, that the more recent PolarLight narrow band [3–4.5] keV measures are consistent with our findings that the PSR emission is probably unpolarized. A strong decrease in the PD of the total pulsed emission, from the optical to the soft X-ray (with a possible recovery to large PD in the hard X-ray) is not expected in existing modelling, which primarily relies on geometry of the emission zone to determine the polarization (for example, ref. 36); as noted above, additional physical effects will be required to accommodate the IXPE data.

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The magnetic axis of the PWN, derived by taking the symmetry axis of the magnetic field pattern, is found to be roughly 140°, about 15° further out than estimates based on fitting axisymmetric structure to the torus intensity. It is also possible to estimate the inclination of the magnetic axis with respect to the plane of the sky: we found it to be roughly 60°, in agreement with previous estimates. While the average PD roughly 20% agrees with previous measures, the PA differs in a statistically significant way from other estimates, reflecting the spatial variation of the PD, or possible temporal variability. The spatially resolved PD reaches a maximum of roughly 46–50%. This is about two times larger than expected from simple predictions based on synchrotron turbulent modelling of the Crab Torus and Inner Ring luminosity profiles, calibrated on the OSO-8 results. More sophisticated 3D models (lacking, however, micro-turbulence) can give PD values close to the theoretical maximum of roughly 70% (ref. 40), with higher values typically in the south-west region, but in general the prediction is for polarized patterns symmetric with respect to the nebular axis, unlike what was found. This suggests that the level and development of turbulence within the nebula is not as strong as predicted and much patchier in its spatial distribution. While the lower level of polarization close to the centre of the PWN is easily explained by summed emission from a wide range of PA in the central resolution elements, the increase of the PD with distance at the rim of the torus suggests the presence of a highly ordered magnetic layer at the edge of the torus itself (the ratio of...
the energy in the turbulent versus ordered magnetic field components should be about a factor of two smaller than in the core of the torus\(^3\). This differs from what is seen in optical where higher polarization is found in a few selected inner features\(^18\), suggesting that optical and X-ray emitting particles might be accelerated in different locations and sample different regions of the nebula as previously claimed\(^18\).

Note, however, that the X-ray inner ring, which supposedly traces the wind termination shock, at the same distance of the optical wisps (smaller than the IXPE resolution), is strongly subdominant with respect to the torus (and the PSR), such that, even if highly polarized, it would not give a significant signal. The fact that the PD (which depends on the ratio of magnetic energy in the turbulent to ordered components) is far more asymmetric, with respect to the nebular axis, than the intensity (which depends on the total turbulent plus ordered magnetic energy density) suggests that the level of turbulence anticorrelates with the strength of the ordered component of the magnetic field. This is what one would expect if turbulence was driven by the growth of instabilities, such as Rayleigh–Taylor, which are suppressed by stronger fields\(^44\).

If this is correct, we should expect that more highly polarized PWNe (less turbulent systems) should show a stronger toroidal pattern with smaller degree of Rayleigh–Taylor induced patchy depolarization and intensity enhancement.

The IXPE polarization results indicate that present modelling lacks physical ingredients needed to explain the low PSR polarization seen at most phases. The substantial spatial variation of the PD in the nebula also indicates that effects are missing even in the most advanced 3D relativistic magneto-hydrodynamical models; magnetohydrodynamic turbulence seems likely to be important in both cases.

**Methods**

**Observations and data analysis**

The IXPE is a National Aeronautics and Space Administration (NASA) mission in partnership with the Italian Space Agency (ASI) launched in 9 December 2021. As described in detail elsewhere (refs. 26, 27 and references therein), the IXPE Observatory includes three identical X-ray telescopes (DUs), each comprising a Wolter-I X-ray mirror assembly (NASA-provided) with angular resolution (half-power diameter) of 19 (DU1), 26 (DU2), 28 (DU3) arcsec, respectively, and a polarization-sensitive pixilated detector (gas pixel detector (GPD), ASI-provided), with a typical energy-dependent dead time of roughly 1.1 ms. This allows one to measure the energy, arrival direction, arrival time and linear polarization of the detected X-ray signal, which are all reconstructed from the photo-electron track shape using moment analysis. The IXPE energy range is the [2–8] keV band, with a total effective area of 590 cm\(^2\) at 4.5 keV. The modulation factor (the amplitude of the modulation of the reconstructed photo-electrons angle distribution for a 100% polarized source) ranges from roughly 15% at 2 keV up to around 60% at 8 keV (ref. 27).

The Crab PWN and PSR were observed twice: the first time from 21 February 2022 UTC 16:13:32 to 22 February 2022 UTC 18:46:37, the second from 7 March 2022 UTC 00:14:20 to 8 March 2022 UTC 02:40:02, for a total of 92,363 s of ONTIME exposure (the total exposure as obtained from the sum of the good time intervals) and 85,062 s of total LIVETIME (the total amount of time in which the charge-coupled device was actively observing a source; this excludes the time it takes to transfer charge from the image region to the frame store region).

We carried out the polarization analysis on publicly available level 2 event list files. These were corrected to account for the following calibration issues that have emerged during flight operations. The World Coordinate System was corrected to account for the small offset among the various units, registering the pointing solution to centre the intensity peak of each unit on the PSR position at right ascension $= 5\, h 34\, m 31.86\, s$, declination $= 22°\, 00′\, 51.3″$. The time dependent charge-to-energy conversion was reconstructed for each units using the two onboard calibration sources at 1.7 keV (Si-Ka) and 5.9 keV ($^{56}$Fe $\rightarrow$ $^{56}$Mg with following Kα emission)\(^45\). Spurious offsets in the pointing solution (aspect solution), associated with the switch between different star trackers during orbit, were identified looking at the time variations of the count rate in a set of background sky regions and later filtered out by removing the affected time intervals. This results in a loss of counts smaller than 2% and an effective new on-source time of roughly 91 ks. At the time of the Crab observation, the optical axis of the mirror system relative to the star trackers had not yet been accurately determined and was not yet compensated (by offset pointing). Consequently, the Crab PSR was about 2.8 arcmin off axis with respect to the mirror system. This precluded accurate computation of image response functions—energy-dependent vignetting and energy-dependent exposure maps—necessary for a correct spectral analysis (the mirror-system–star-tracker offset has now been accurately determined and compensated, such that future observations will place the image close to the mirror-system optical axis. Furthermore, it may be possible, in the future, to recalibrate the image response functions) and for computing correct count rates. However, this should not affect polarization measures that come from flux ratios among Stokes parameters.
**Timing analysis**

We initially used the Jodrell Bank Crab PSR Monthly ephemeris (http://www.jb.man.ac.uk/pulsar/crab.html) to calculate the pulse phase of each photon. However, the time span of the two IXPE observations requires two separate JB solutions, and the alignment between the arrival time of the pulse in the two observations using these ephemerides is visibly off (roughly 0.02 in phase). Therefore, we determined a new ephemeris by using the X-ray data alone, as follows. As a starting point, we used the JB monthly ephemeris of February in CGRO format (https://www.jb.man.ac.uk/-pulsar/crab/CGRO_format.html), but modifying the frequency and derivatives for them to refer to an epoch between the two observations:

\[ v_{\text{new}} = v_{\text{old}} + 0.5v_{\text{old}}(T_{\text{new}} - T_{\text{old}})^2 \]  

\[ \dot{v}_{\text{new}} = \dot{v}_{\text{old}}(T_{\text{new}} - T_{\text{old}}) \]

where \( v_{\text{old}}, \dot{v}_{\text{old}} \) and \( v_{\text{new}}, \dot{v}_{\text{new}} \) are the frequency, its first and second time derivative at \( T_{\text{old}} \). While \( v_{\text{new}} \) and \( \dot{v}_{\text{new}} \) are the frequency and its first time derivative at \( T_{\text{new}} \).

Then, we calculated times of arrival (TOAs) of the pulse using the HENphaseogram tool distributed with HENDRICS (https://hendrics.stingray.science). This tool folds the data in small fractions of the observation, creating a series of pulse profiles. Next, it calculates the misalignment between each of these profiles and a smoothed version of the folded profile from the whole observation, and transforms this misalignment into a TOA. The TOA refers to the maximum of the reference profile. As an output, the tool produces a parameter file and a TOA file in Tempo2 format. We loaded these approximate parameters and TOAs in the pintk graphical interface to PINT (https://nanograv-pint.readthedocs.io), and fitted a new spin-down solution that aligned the TOAs of the two observations. Then, we went back and calculated new TOAs, this time using the improved timing solution and, consequently, the better resolved total pulse profile that the solution provided, and fitted these TOAs again with PINT. We stopped this iterative procedure when the improvement in the fitting through PINT was smaller than the uncertainties. Finally, we calculated the closest TOA to the epoch chosen for the timing solution, and referred the frequency and derivatives to this time, using the above equation, to have a single number for the reference TOA and the PEPOCH of the timing solution for convenience. The new ephemeris is reported in Supplementary Table 1. Note that, having chosen the reference time in between the February and March observations, the determination of the second time derivative of the period is highly uncertain, but on the other hand the correction due to the second time derivative is not significant, and can potentially be neglected. Note, moreover, that the absolute time alignment of the pulse profile is not necessary for the analysis in this paper. However, we did verify that the X-ray pulse leads the radio pulse (as provided by the JB ephemeris) by roughly 300 \( \mu \)s, consistent with past observations from other missions. The Crab PSR is a young one and its timing can be noisy, to the point that ephemeris cannot be extended beyond their range of validity.

**Polarization analysis**

The polarization analysis of both the PWN and the PSR was performed using the IXPE collaboration software ixpeobssim v.26.3.2. ixpeobssim has been designed to act both as a simulation software and for data reduction. We opted for a more robust and established unweighted analysis, limited to the [2–8] keV energy range. Phase folding was performed with xpphase, while event selection was done using the xpselect tool. Polarization was computed with the xpsbin tool and PCUBE and PMAPCUBE methods.

Given the additive nature of Stokes parameters, to get the polarization properties of a spatial region and/or phase range of interest, we just need to take the sum of \( I \) and \( Q \) of each event (calibrated for the known spurious modulation of the instrument and corrected for the modulation factor) within the same region and/or phase range. ixpeobssim can compute all polarization relevant quantities including their error and the significance. Deformation of the phase resolved light curve (pulse shape) due to dead time, with respect to the dead-time corrected one, is estimated to be less than 3% (the difference between the dead-time correction when the count rate is at maximum (P1) and the one when the count rate is at minimum (OP)), and was thus ignored. The net PSR’s Stokes parameters in a given phase bin are obtained as follows: for a generic Stokes parameter \( X = I, U, Q \) of phase bin \( i \) we have \( X_{\text{OP}} = X_{\text{OP}} - X_{\text{OP}}(\Delta_{\text{phase}}/\Delta_{\text{phase,OP}}) \), where \( \Delta_{\text{phase}} \) is the phase width of phase bin \( i \) and \( \Delta_{\text{phase,OP}} \) is the phase width of OP bin (0.3). Supplementary Fig. 4 shows the maps of normalized Stokes parameters, of the total PWN plus PSR emission. The contribution of the lowly polarized PSR is hardly visible. We verified that the pattern, apart from counting noise, is the same if one considers just the emission in the OP phase range. Whereas the \( U/I \) map shows a high level of symmetry with respect to the direction of the nebular axis inferred from the intensity maps, the one for \( Q/I \) is far more asymmetric (its symmetry axis is more aligned with the north–south direction). The inclination of the magnetic axis of the nebula was derived by fitting ellipses to the internal magnetic field structure as shown in Fig. 4.

Owing to the brightness of the Crab Complex, all the IXPE field of view (FoV) contains events from the PSR and PWN; however, for space integrated measures, we have verified that polarization properties do not change once one selects a circular region centred on the PSR and with radius of more than 2 arcmin (we selected 2.5 arcmin). Supplementary Fig. 5 shows that roughly 98% of counts are within 2 arcmin. For the PSR analysis, we have verified, using a large set of mocked observations, that the optimal region size, to reduce the errors of the OP-subtracted polarization measures, ranges between 15 and 25 arcsec. We opted for 20 arcsec (Supplementary Fig. 5).

We caution the reader that due to error in the reconstruction of the photons absorption point in the GPD, polarization leakage can contaminate the Stokes maps. The effect of polarization leakage arises specifically from correlations between the reconstructed PA and the photon absorption point in the GPD. This leads to false polarization patterns (this has no effect on integrated or OP-subtracted values), even for unpolarized sources. Preliminary estimates based on Monte Carlo simulations of the GPD response indicate that this effect can at most be as high as 10% in the outer regions of the PWN, and does not alter significantly our overall findings. A more detailed discussion and treatment of this effect will be presented in a forthcoming publication.

**CHANDRA observation**

The Crab PWN was observed by CHANDRA (ObsID 23539) starting on 15 March 2022 at 13:32:23 UTC and ending on 15 March 2022 at 15:14:17 UTC, for a total of roughly 10 \( ^{+} \) s; due to telemetry saturation from the bright source, the effective exposure time was 1,331 s. Data were processed with the CIAO package v.4.14 using CALDB v.4.9.7, with the chandra repro mode=‘h tool using default settings, and the [2–8] keV image was done with the fluximage tool, and later smoothed with a gaussian kernel using aconvolve kernelspec={lib:gauss,(2.5,1.1,1)}.

**Data availability**

Data from the Crab PSR and nebula observation are available in the HEASARC IXPE Data Archive (https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/). Additional data are available in the Supplementary Information and from figshare at https://doi.org/10.6084/m9.figshare.22203163. Source data are provided with this paper.

**Code availability**

The ixpeobssim software and documentation can be downloaded at https://github.com/lucabaldini/ixpeobssim. Other information supporting the findings of this study, and specific data-reduction pipelines, are available from the corresponding author upon request.
Acknowledgements

The IXPE is a joint US and Italian mission. The US contribution is supported by NASA and led and managed by its Marshall Space Flight Center (MSFC), with industry partner Ball Aerospace (contract no. NNM15AA18C). The Italian contribution is supported by the Italian Space Agency (Agenzia Spaziale Italiana, ASI) through contract no. ASI-OHBI-2017-12-I.0, agreement nos. ASI-INAF-2017-12-H0 and ASI-INAF-2017-13-H0, and its Space Science Data Center (SSDC) with agreement nos. ASI-INAF-2022-14-H0 and ASI-INAF-2021-43-H0, and by the Istituto Nazionale di Astrofisica (INAF) and the Istituto Nazionale di Fisica Nucleare (INFN) in Italy. This research used data products provided by the IXPE Team (MSFC, SSDC, INAF and INFN) and distributed with additional software tools by the High-Energy Astrophysics Science Archive Research Center (HEASARC), at NASA Goddard Space Flight Center (GSFC). The research at Boston University was supported in part by National Science Foundation grant no. AST-2108822. Part of the French contributions is supported by the Scientific Research National Center (CNRS) and the French spatial agency (CNES). I.A. acknowledges financial support from the Spanish ‘Ministerio de Ciencia e Innovación’ (grant no. MCIN/AEI/10.13039/501100011033) through the Centro of Excellence Severo Ochoa award for the Instituto de Astrofisica de Andalucia-CSIC (grant no. CEX2021-001131-S), and through grant nos. PID2019-107847RB-C44 and PID2022-139117NB-C44. C.-Y.N. is supported by a GRF grant from the Hong Kong Government under no. HKU 17305419. N.B. was supported by the INAF MiniGrant ‘PWNnumpol - Numerical Studies of Pulsar Wind Nebulae in The Light of IXPE’. J.H. acknowledges support from the Natural Sciences and Engineering Research Council of Canada through a Discovery Grant, the Canadian Space Agency through the co-investigator grant programme, and computational resources and services provided by Compute Canada, Advanced Research Computing at the University of British Columbia, and the SciServer science platform. S.G. and E.W. were supported by grant nos. JSPS KAKENHI JP 19H00696 and 22K14068.

Author contributions

N.B. led the data analysis and the writing of the paper. R.F., M.B., J.R., L.P. and F.M. contributed to data analysis and data calibration. N.D.L., C.S., N.O., T.K., T.M., S.G. and E.W. contributed to data analysis and results interpretation. M.C.W., M.N., S.S., E.D.O.W., F.X., J.H., R.W.R., P.T., A.P. and H.L.M. contributed to text revision and data interpretation. L.B. and M.P.-R. contributed to software development. The remaining members of the IXPE collaboration contributed to the design of the mission, to the calibration of the instrument, to defining its science case and to the planning of the observations. All authors provided inputs and comments on the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary material The online version contains supplementary material available at https://doi.org/10.1038/s41550-023-01936-8.

Correspondence and requests for materials should be addressed to Niccolò Bucciantini.

Peer review information Nature Astronomy thanks Santosh Vadawale and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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Simonetta Puccetti23, Brian D. Ramsey13, Ajay Ratheesh4, Oliver J. Roberts28, Paolo Soffitta4, Gloria Spandre7, Doug Swartz28, Toru Tamagawa6, Fabrizio Tavecchio47, Roberto Taverna48, Yuzuru Tawara52, Allyn F. Tennant15, Nicolas E. Thomas13, Francesco Tombesi44,49, Alessio Trois5, Sergey Tsygankov46, Roberto Turolla48,50, Jaccio Vink51, Kinwah Wu50 & Silvia Zane50

1INAF Osservatorio Astrofisico di Arcetri, Florence, Italy. 2Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Sesto Fiorentino, Italy. 3Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, Sesto Fiorentino, Italy. 4INAF Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy. 5INAF Osservatorio Astronomico di Cagliari, Selargius, Italy. 6Department of Physics and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA, USA. 7Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Pisa, Italy. 8RIKEN Cluster for Pioneering Research, Wako, Japan. 9Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Japan. 10Yamagata University, Yamagata-shi, Japan. 11Dipartimento di Fisica, Università di Pisa, Pisa, Italy. 12Center for Astrophysics, Harvard Smithsonian, Cambridge, MA, USA. 13NASA Marshall Space Flight Center, Huntsville, AL, USA. 14MIT Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA, USA. 15Center for Research and Exploration in Space Science and Technology, NASA/OSSFC, Greenbelt, MD, USA. 16NASA Goddard Space Flight Center, Greenbelt, MD, USA. 17Department of Astronomy, University of Maryland, Maryland, MD, USA. 18Deutsches Elektronen-Synchrotron (DESY), Zeuthen, Germany. 19Guangxi Key Laboratory for Relativistic Astrophysics, School of Physical Science and Technology, Guangxi University, Nanning, China. 20University of British Columbia, Vancouver, British Columbia, Canada. 21Instituto de Astrofísica de Andalucía, IAA-CSIC, Glorieta de la Astronomía s/n, Granada, Spain. 22INAF Osservatorio Astronomico di Roma, Monte Porzio Catone, Italy. 23Space Science Data Center, Agenzia Spaziale Italiana, Rome, Italy. 24Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, Rome, Italy. 25Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Turin, Italy. 26Dipartimento di Fisica, Università degli Studi di Torino, Turin, Italy. 27ASI, Agenzia Spaziale Italiana, Rome, Italy. 28Science and Technology Institute, Universities Space Research Association, Huntsville, AL, USA. 29Istituto Nazionale di Fisica Nucleare, Sezione di Roma Tor Vergata, Rome, Italy. 30Institut für Astronomie und Astrophysik, Universität Tübingen, Tübingen, Germany. 31Astronomical Institute of the Czech Academy of Sciences, Prague 4, Czech Republic. 32Department of Physics and Astronomy and Space Science Center, University of New Hampshire, Durham, NH, USA. 33California Institute of Technology, Pasadena, CA, USA. 34Osaka University, Suita, Japan. 35International Center for Hadron Astrophysics, Chiba University, Chiba, Japan. 36Institute for Astrophysical Research, Boston University, Boston, MA, USA. 37Department of Astrophysics, St. Petersburg State University, Petrodvoretz, Russia. 38Department of Physics and Astronomy, University of Iowa, Iowa City, IA, USA. 39Physics Department and McDonnell Center for the Space Sciences, Washington University in St. Louis, St. Louis, MO, USA. 40Finnish Centre for Astronomy with ESO, University of Turku, Turku, Finland. 41Université de Strasbourg, CNRS, Observatoire Astronomique de Strasbourg, Strasbourg, France. 42Graduate School of Science, Division of Particle and Astrophysical Science, Nagoya University, Nagoya, Japan. 43Department of Physics, The University of Hong Kong, Pokfulam, Hong Kong. 44Department of Astronomy and Astrophysics, Pennsylvania State University, Pennsylvania, PA, USA. 45Université Grenoble Alpes, CNRS, IPAG, Grenoble, France. 46Department of Physics and Astronomy, University of Turku, Turku, Finland. 47INAF Osservatorio Astronomico di Brera, Merate, Italy. 48Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Padua, Italy. 49Dipartimento di Fisica, Università degli Studi di Roma Tor Vergata, Rome, Italy. 50Mullard Space Science Laboratory, University College London Holmbury St. Mary, Dorking, UK. 51Anton Pannekoek Institute for Astronomy and GRAPPA, University of Amsterdam, Amsterdam, the Netherlands. e-mail: niccolo.bucciantini@inaf.it