The weird Faraday screen in front of Cassiopeia A

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August 17, 2016

Background and Motivation

- Linearly polarized radiation, traversing magneto-ionic medium, undergoes rotation of its plane of polarization.
- This rotation χ is proportional to λ^2 – Faraday rotation

$$\chi \propto \lambda^2$$

$$\chi = RM \times \lambda^2$$

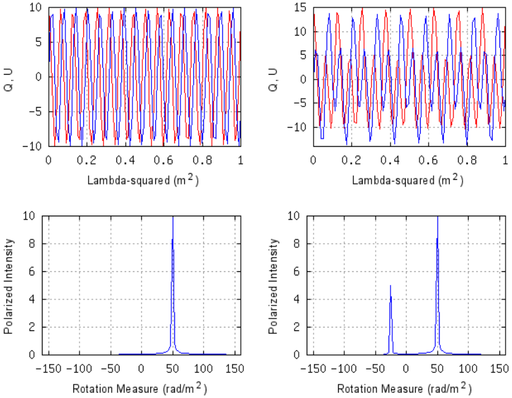
- The Constant of proportionality, known as the Rotation Measure (RM), carry information about the magneto-ionic medium through which the polarized radiation has propagated.

$$RM = \int_s n_e B_{||} ds$$

where n_e is the free-electron density of the medium, and $B_{||}$ is the component of the magnetic field parallel to the direction of propagation of the polarized radiation.

Background and motivation (contd...)

- In 1966, B. J. Burns demonstrated the technique of decomposing the spectra of the linearly polarized Stokes into their Fourier components *viz.* RMs – a technique now known as Faraday tomography or RM synthesis (Brentjens & de Bruyn, 2005).



Faraday tomography: A tool to study 3D-distribution of magneto-ionic matter

- The absolute RMs of polarized components along the sight-line contain information about the line-of-sight integrated $B_{||}$ in the foreground of the components.

- The sign of RM determines the orientation (parallel/anti-parallel) of $B_{||}$

- The strengths of components on the RM-axis contain information about $B_{\perp}$ at their Faraday-depths (or RMs).

- The Polarization Position Angle of components on the RM-axis contains information about the orientation of $B_{\perp}$ at their Faraday-depths.

Background and Motivation

- Cassiopeia A is one of the most widely studied objects in both total intensity and polarization.
- The non-thermal radio emission from Cas A is significantly polarized along the shell with near-circular morphology.
- Significant depolarization at low radio frequencies: polarization fraction drops from $\sim 5\%$ at 6 cm to about 0.3% at 20 cms (Downs & Thompson, 1972, Anderson et al., 1995).

Background and Motivation

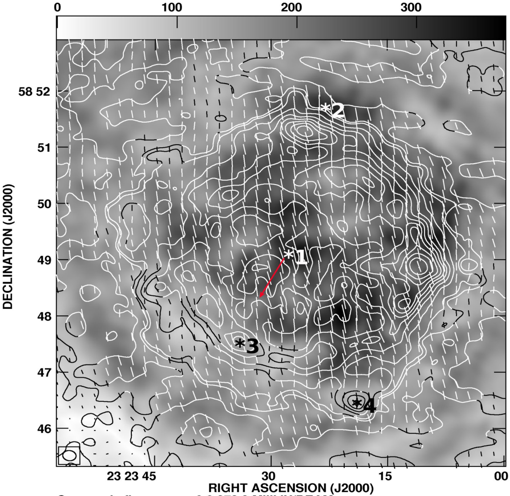
- The heavy depolarization is spatially correlated with soft X-radiation from the remnant (Anderson et al., 1995).
- The *apparent* RMs vary across the extent of the source and differently at the two wavelengths – 6 cm and 20 cm – as a manifestation of significant Faraday rotation internal to the source.
- This opens up the possibility as well as emphasizes the necessity of resolving the distribution of non-thermal emission along the sight-line as a function of the internal Faraday rotation measure (or Faraday depth).

The Observations

- Full synthesis at 327 MHz band of the GMRT
- Software Correlator: 16 MHz band-width, 256 spectral channels, 4 Stokes recorded.
- Angular resolution: $\sim 11'' \times 14''$
  Spectral resolution: $\sim 62.5 kHz$
  RM resolution: $\sim 40 rad/m^2$
  Unaliased RM range: $\sim \pm 5000 rad/m^2$

Key findings

- Despite the expected severe depolarization, our GMRT observation reveals detectable polarized emission from Cas A at 327 MHz.
- The RM of the dominant component in the Faraday tomographs is found to be $\sim 5 \pm 3 \text{ rad m}^{-2}$, along with weaker components at higher RMs.
- The dominant polarized emission component shows a nearly constant PA across the remnant, with the small dispersion ($\sim 5^{\circ}$) in the PA. This constancy of the PA is intriguing and is in direct contrast with the PA variation apparent in earlier studies of the remnant at higher frequencies.



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Peak contour flux = 4.5919E+01 JY/BEAM
Levs = 4.592E+00 * (0.030, 0.700, 1, 2, 3, 4, 5,
6, 7, 8, 9, 10)
Pol line 1 arcsec = 2.0000E-02 JY/BEAM
Rotated by 30.0 degrees

The usual suspect!

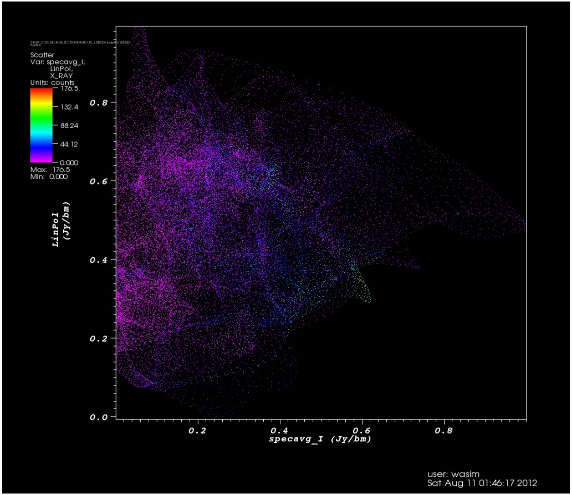
- Degree of Polarization LOW – Severe depolarization apparent.
- Is this polarized radiation indeed from Cassiopeia A ?
  OR,
  Is it an artifact of any residual instrumental polarization?

The trial...

- Is the polarized intensity correlated with Stokes-I?
- Does the degree of polarization show spatial anti-correlation with the depolarizing soft X-radiation as would be expected if intrinsic?
  (a critical Independent verification)

Conviction difficult...

- Polarized intensity is un-correlated with Stokes-I



- Is the polarized intensity also spatially anti-correlated with the depolarizing soft X-radiation?

Acquittal not easy...

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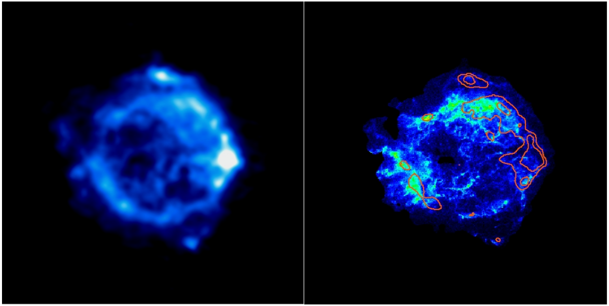
- Stokes-I and X-ray are spatially correlated.

- 

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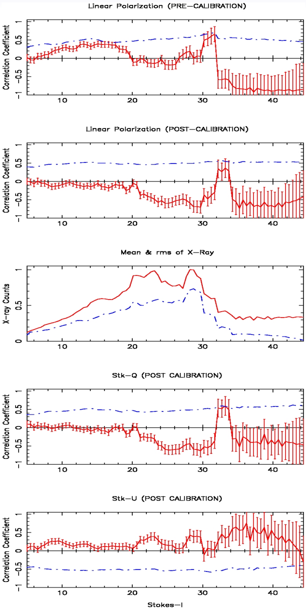
- Stokes-I and X-ray are spatially correlated.
- Instrumental leakage is proportional to Stokes-I.
- Hence, in the presence of the I-dependent leakage, the expected anti-corelation between linearly polarized intensity and X-radiation, would be corrupted.

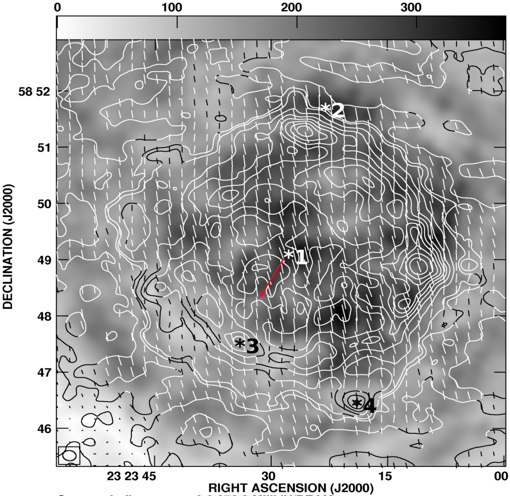
The way out: Assessing correlations in narrow I-bins

- Perform the X-ray-LinPol Correlations within ultra-narrow Stk-I bins.
- Estimated correlation NOT sensitive to any mean polarization.



Linear Polarization (PRE—CALIBRATION)
Correlation Coefficient
Linear Polarization (POST—CALIBRATION)
Correlation Coefficient
Mean & rms of X—Ray
X—ray Counts
Stk—Q (POST CALIBRATION)
Correlation Coefficient
Stk—U (POST CALIBRATION)
Correlation Coefficient
Stokes—I

Results



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Conclusions

- It is clear that the depolarization at the lower frequencies is due to wavelength-dependent Faraday rotation within the source.
- Non-thermal emission from inner radii is likely to be almost completely depolarized, possibly erasing any memory of the internal field structure.
- The PA constancy as well as the constancy of RM across the source suggests that the observed polarized emission at 327 MHz originates from the outer regions of the source.

Modeling 3D distribution of emission components of Cas A

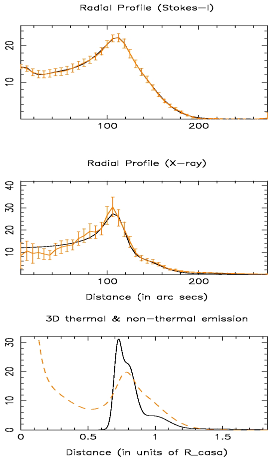
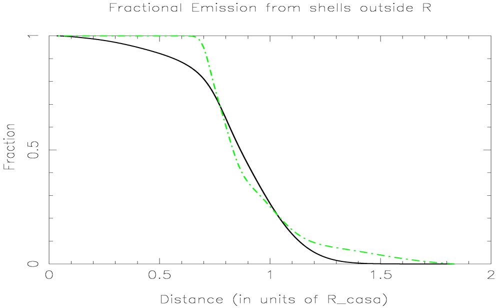


Figure: 3D models of thermal and non-thermal emissivities from Cas A.

Cumulative emissivity from regions outside a given radius



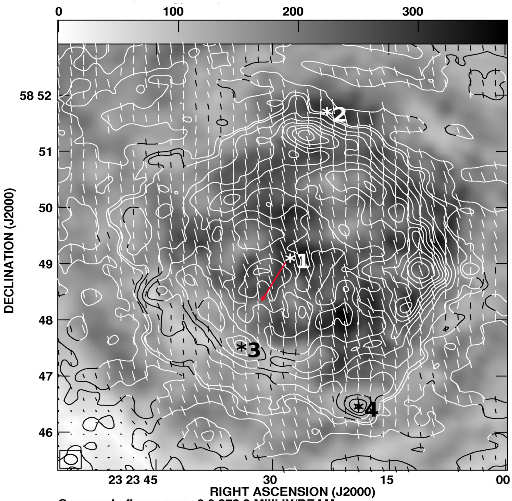
It can be seen that a considerable fraction ($\sim 25\%$) of both the thermal and the non-thermal emission comes from shells of radius greater than $150''$, which is also the nominal radius of Cas A.

Some unusual suspects

1. The near constancy of the PA associated with the polarized emission could be a manifestation of the compressed ambient uniform magnetic field as a result of an expanding spherical shell (van der Laan, 1962).
2. Could we be witnessing a Pulsar Wind Nebula (PWN) in the making?

- Rotation of the compact star, would lead to a resultant configuration of the magnetic field (carried along with the particle flow) that is toroidal well outside the light-cylinder. This would naturally imply significant uniformity in PA associated with the polarized emission expected from such a nebula driven by the wind from the compact object.

- The polarized intensity is significantly spatially offset from Stokes-I emission at 327 MHz in approximately North-West direction.
- The polarized intensity distribution is also roughly symmetric about this direction.
- The morphology of observed polarization is strikingly reminiscent of shapes and structures associated with PWN [Rees and Gunn (1974);Radhakrishnan and Deshpande (2001); Dodson et al., (2003)].



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- If the polarized emission in Cas A is indeed due to a forming PWN the projection of rotation axis of the associated pulsar on the sky plane must align with the axis of symmetry in the spatial distribution of the polarized emission, i.e., along NW-SE direction.
- Interestingly, the proper motion (kick-direction) of the central compact object in Cas A happens to be aligned along SE. Young pulsars are found to have proper motions in the direction of the rotation axis.
- The observed uniformity in PA implies suitably large inclination of the rotation axis with our sight-line.

While these expectations offer attractive and consistent model for the observed polarized emission, we have no confirmation of such a PWN in Cas A, and neither of a pulsar.
Future observations at higher frequencies will help resolve some of these intriguing issues.

Future: Continue to seek new evidence for a verdict...