Density and magnetic field gradients in Tycho SNR

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Introduction

- Remnant of SN1572, size $8'$, distance 2.3 kpc
- Expansion into inhomogeneous ISM [1, 2]
- Interaction with dense clouds on East and NW [3, 4]
- Presence of a large scale density gradient [5, 6]
- **What is the direction of the density gradient?**
- **What about the magnetic field distribution?**

Utilizing the pixel-to-pixel analysis of the radio and X-ray images of Tycho SNR as well as theoretical properties of emission, we obtained the images for the post-shock density and magnetic field strength over the remnant.

By using these maps, we further derived the spatial distributions of both the cut-off frequency and the maximum energy of electrons and commented on gamma-ray emission from Tycho SNR.

Observations

- VLA radio map (q_r), 2014, 1.4 GHz, resolution $1.91''$ [2]
- LOFAR radio index map (α), 2013-2016, 48-1400 MHz, resolution $40''$ [7]
- Chandra X-ray map (q_x), 2015, 1.2-4.0 keV, resolution $0.492''$
- Chandra X-ray map (q_{xs}), 2015, 4.0-6.0 keV, resolution $0.492''$
- All images were reprojected to the same pixel grid to allow for the pixel-to-pixel analysis.

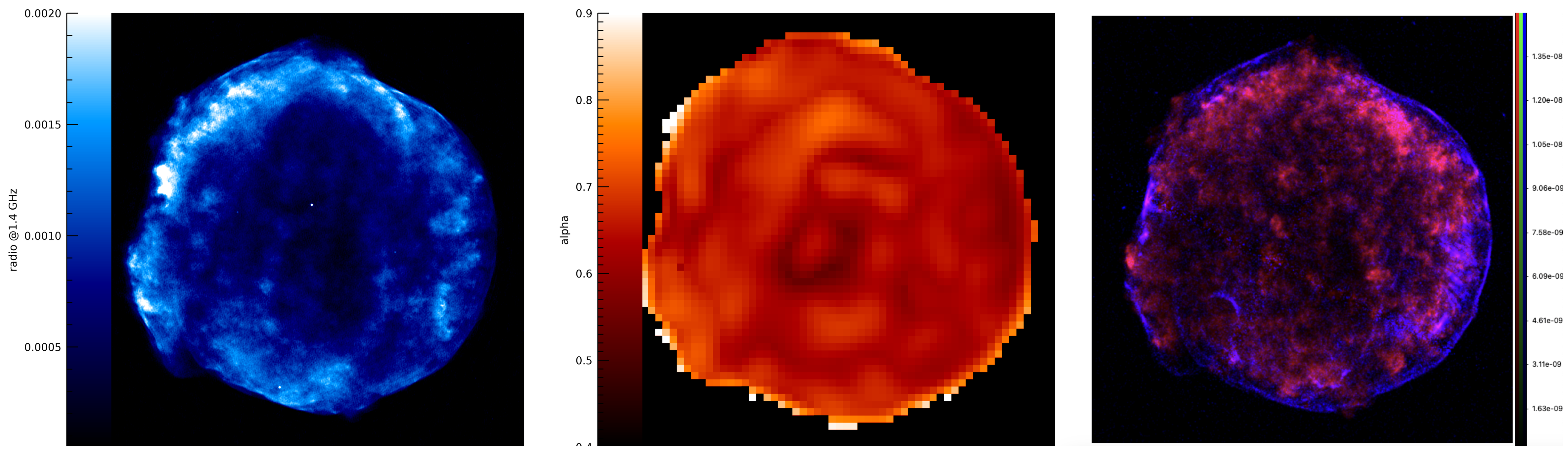

Figure 1: Radio *(left)*, radio index *(center)* and X-ray *(right)* images of Tycho SNR. X-ray colors: 1.2-4.0 keV (red), 4.1-6.0 keV (blue).

Gradients of density n and magnetic field strength B

- Radio $q_{\rm r} \propto \eta_{\rm r} n B^{\alpha+1}$
- Thermal X-ray $q_{\rm x} \propto \eta_{\rm x} n^2 \Lambda$
- Band where $\Lambda(T,\tau) \approx$ const
- Geometric factors $\eta_{\rm r}$, $\eta_{\rm x}$ account for the internal structure along LoS
- $n \propto \left(\dfrac{q_{\rm x}}{\eta_{\rm x}}\right)^{(1/2)}$
- $B \propto \left(\dfrac{q_{\rm r}^2}{q_{\rm x}}\dfrac{\eta_{\rm x}}{\eta_{\rm r}^2}\right)^{1/(2\alpha+2)}$

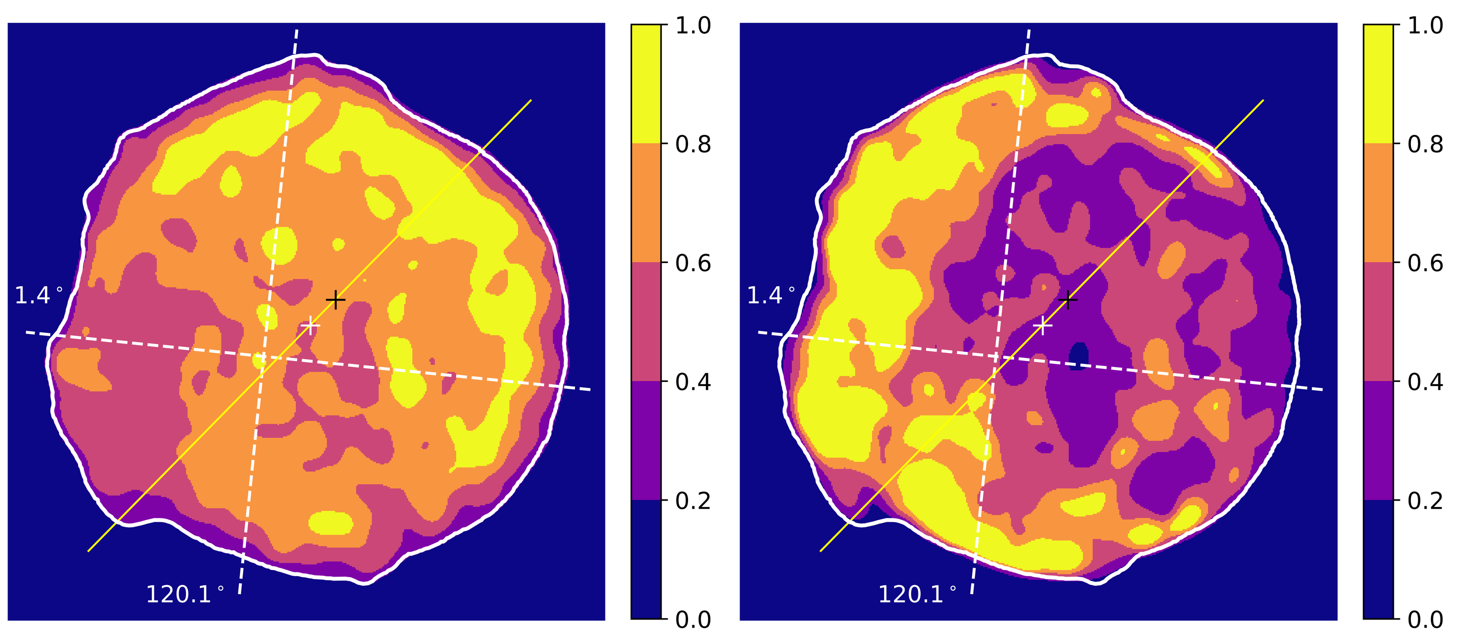

Figure 2: Maps of n *(left)* and B *(right)*. Geometric center (white cross) and explosion site (black cross) are also shown.

Conclusions: gradients

- Density gradient is in the North-West direction.
- Yellow line passes through the two centers. Coincides with grad(n). Independent confirmation of the explosion location.
- Density enchancements pre-shock at East and NW [1, 6]. Our results: a large scale grad(n) is toward NW, while the shock hit a local overdensity at East just recently.
- Gradient of magnetic field strength points toward the East.
- grad(B) is parallel to the Galactic plane.

Cut-off frequency $\nu_{\rm cr}$ and maximum energy $E_{\rm max}$ of electrons

- B on Fig. 2 is in arbitrary units. Convert to physical: set $\langle B\rangle = 120\ \mu G$. This provides $B \approx 200\ \mu G$ around the rim [8].
- Cut-off frequency $\nu_{\rm cr}$ for electrons with energy $E_{\rm max}$ is calculated by fitting, for each pixel, the synchrotron spectrum from radio ($q_{\rm r}$) to X-rays ($q_{\rm xs}$) and assuming the electron momentum distribution as a power-law (α) with an exponential cut-off.
- $E_{\rm max} = \left(\dfrac{\nu_{\rm cr}}{c_1 B}\right)^{1/2}$

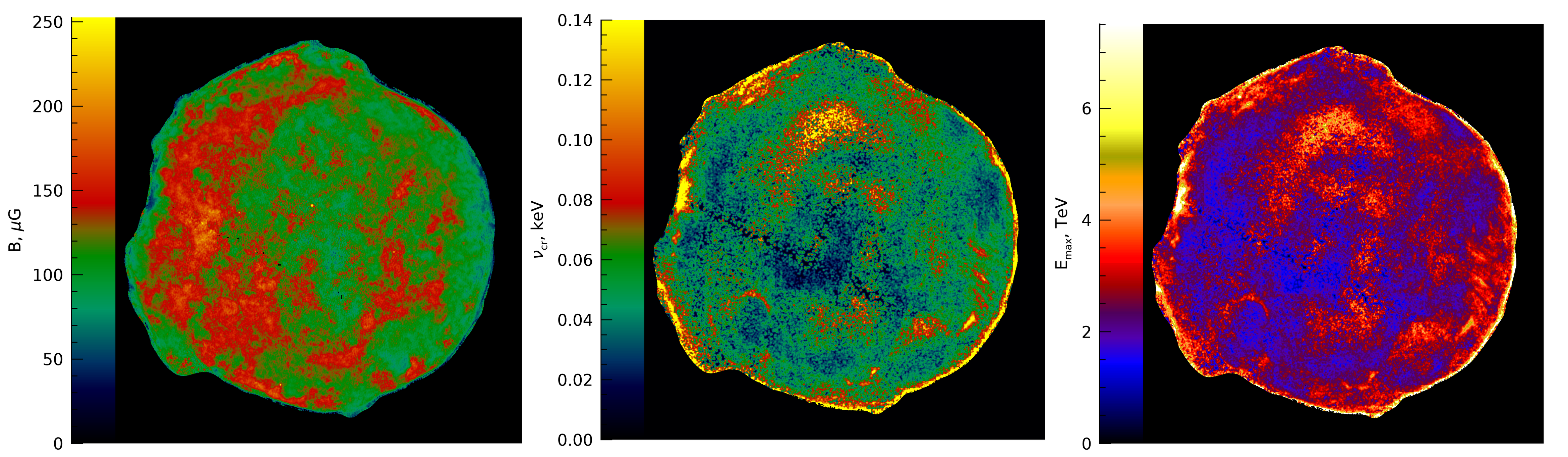

Figure 3: Maps of B *(left)*, cut-off energy $\nu_{\rm cr}$ *(center)*, maximum energy of electrons $E_{\rm max}$ *(right)*

Conclusions: Emax

- X-ray emitting electrons lose energy quickly $\Rightarrow$ thin rims for $\nu_{\rm cr}$ and $E_{\rm max}$.
- $E_{\rm max}$ is in the range $5-7$ TeV around the rim. This is in agreement with [9].
- $E_{\rm max} \simeq 11$ TeV is greatest at East where the shock encountered the local overdensity recently.
- Higher $E_{\rm max}$ also around the stripes at West and the arch at South-East.

Discussion: γ-rays

- GeV and TeV γ-rays are detected from Tycho SNR [10, 11].
- Two preferable locations for γ-rays, with enhanched ambient density: @East, @NW
- The shock speed $V \approx 2000$ and 3400 km/s at East and NW. Efficient acceleration and γ-rays @NW?
- Our analysis: East is preferable (V has decreased recently, $E_{\rm max}$ is the highest).

References

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