Tycho SNR: ambient medium structure by analysis of the supernova remnant

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SNR images as diagnostic tools

A wealth of observational data on SNRs is available: fluxes, integral spectra, spatially-resolved *spectra, 1D profiles* of brightness, *maps* of the surface brightness and of the *polarization* parameters etc. However, not all the data available are exploited. In particular, spectra, local features on the brightness maps – the radial (e.g. Ballet 2006) or azimuthal profiles (Fulbright, Reynolds 1990), contact discontinuity-shock separation (Warren et al. 2005) or protrusions (Rakowski et al. 2011), the rapidly varying spots (Uchiyama et al. 2007) or the ordered stripes (Eriksen et al.2011) – attract attention while images of the overall SNR are much less used.

In general, there are two ways to deal with SNR images: (a) to model maps numerically starting from basic theoretical principles and (b) to process the observed maps with minimum assumptions.

(a) The method to simulate the synchrotron radio and X-ray images of spherical shell-like SNRs was developed and used for synchrotron maps by Reynolds (1998) and to gamma-ray images by Petruk et al. (2009b).

The simulation methodology was generalized to SNR evolving in ISM with *nonuniform* distributions of density and magnetic field: the asymmetries in the radio maps are studied by Orlando et al. (2007) and in X-rays and gamma-rays by Orlando et al. (2011).

(b) With observed maps in different bands and with the only use of properties of emission processes, it is possible, for example, to separate the thermal from nonthermal X-ray images out of the mixed observed one (Miceli et al. 2009), to predict gamma-ray images of SNRs (Petruk et al 2009a) or determine the magnetic field (MF) strength in the limbs of SNRs (Petruk et al. 2012).

Here, we report the application of the approach (b) to the Tycho SNR. It yields approximate evaluation of the ambient conditions around SNR which we use as input for 3D MHD simulations of Tycho SNR within the approach (a).

1

Tycho SNR: radio and X-ray maps

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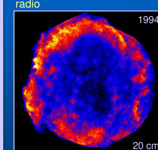
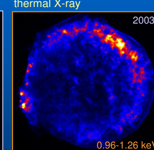


(Reynoso et al. 1997)



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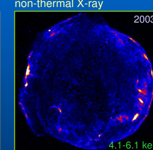

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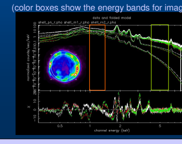
XMM spectrum from the rim: the nonthermal emission dominates in hard X-rays and the thermal one in soft X-rays

(color boxes show the energy bands for images)



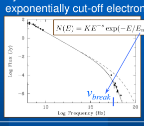
Simple procedures are applied to the maps in order to obtain spatial distributions of the synchrotron break frequency, gas density and magnetic field strength.

Images from different epochs are corrected for expansion and resampled to be of the same resolution.

Image processing

3

Synchrotron emission of the exponentially cut-off electron distribution



a Approximation of the numerically integrated synchrotron emissivity of the exponentially cut-off electron distribution (convolved with the full single-particle emissivity):

$$q_x = q_r\left(\frac{\nu_x}{\nu_r}\right)^{-(s-1)/2}\exp\left[-\beta_s\left(\frac{\nu_x}{\nu_{break}}\right)^{0.364}\right]$$

where $\beta_s = 1.46 + 0.15(2-s)$

radio and X-ray maps => ν_{break} map

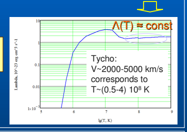
(Petruk et al. 2009a)

b Thermal X-ray emission

$$q_{th} \propto n^2\Lambda(T)$$

thermal X-ray map => density map

High V => High T



c Radio emission

$$q_r \propto nB^{(s+1)/2} \Rightarrow q_r^2 \propto q_{th}B^{s+1}$$

(assuming n_{acc}/n_{th} the same everywhere)

radio and thermal X-ray maps => MF map

Though approximate, the method gives hints about the actual situation

Map of ν_{break}

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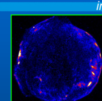
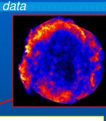
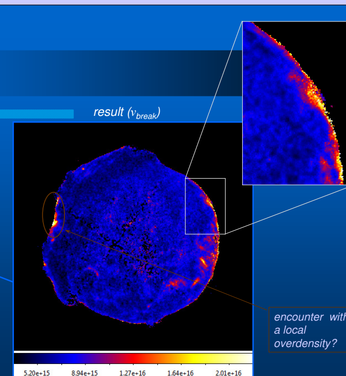
input data





$$q_x = q_r\left(\frac{\nu_x}{\nu_r}\right)^{-(s-1)/2}\exp\left[-\beta_s\left(\frac{\nu_x}{\nu_{break}}\right)^{0.364}\right]$$

result (ν_{break})



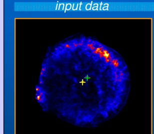
ν_{break}=3.5e15 – 2.1e16 Hz

- *The largest ν_{break} is in the very thin outer shell.*
- *It increases toward the edge, like in the spatially resolved spectral analysis of SN1006 (Katsuda et al. 2010).*
- *The largest ν_{break} are registered mostly at the western part of Tycho SNR.*

encounter with a local overdensity?

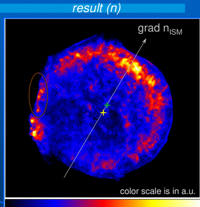
Density map

input data



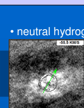
$$q_{th} \propto n^2\Lambda(T)$$

result (n)



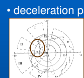
- *There is evidence for large-scale ISM density gradient.*
- *The explosion center (green cross) is shifted from the geometrical center (yellow cross) along the gradient toward NW, as shown by Xue & Schaefer (2015).*

- neutral hydrogen 21 cm line (Reynoso et al. 1997)



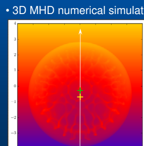
evidence? for the dense medium at NW; the density gradient

- deceleration parameter (Reynoso et al. 1997)



deceleration of the shock: most prominent in the eastern region: encounter with a local overdensity? (cf. ellipses on density and ν_{break} maps)

- 3D MHD numerical simulations: n_{ISM}~exp(y/H_n)



log density (sum along LoS)

- the denser ISM the denser the ejecta;
- ejecta are closer to the shock where density is larger

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Magnetic field map

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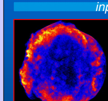
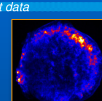
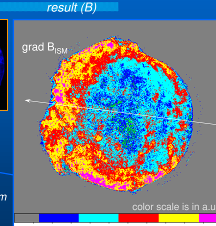
input data





$$q_r^2 \propto q_{th}B^{s+1}$$

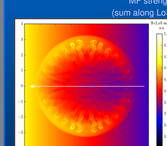
result (B)



- *The azimuthal variation of B along the rim B_{max} / B_{min} ~ 4.*
- *There is an evidence for a large-scale gradient of ambient MF.*
- *MF is smaller where ν_{break} is larger (acceleration is more efficient at parallel shocks).*

- 3D MHD numerical simulations: B_{ISM}~ exp(-x/H_B)

MF strength (sum along LoS)



- converging "MF limbs"
- grad B is not large

MF and density around Tycho SNR

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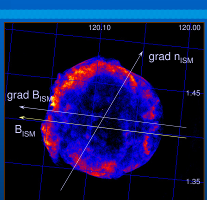
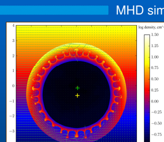
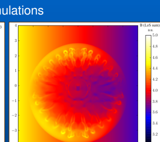


- *The ambient MF gradient is along the Galactic plane while the density gradient is (almost) in the perpendicular direction.*
- *MF is along the Galactic plane.*
- *i.e., MF limbs are around perpendicular shock: Tycho SNR is barrel-like, no polar caps.*

MHD simulations

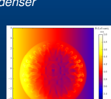


log density, MF vectors (cross section)



MF strength (sum along LoS)

- *Asymmetry in density – North is denser*
- *Asymmetry in magnetic field – i) MF limbs converge to East; ii) SE limb is thicker and enchansed*



- *Alternative orientation of MF (perpendicular to grad B) is not likely*

B_{ISM} ↑

Conclusions and References

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- rather simple handling of images in various bands gives hints about conditions around SNR (*B, grad B, grad ρ*)
- results may be used as input for numerical simulations
- gradients of MF and density are almost perpendicular around Tycho SNR
- MF is along the Galactic plane and the MF limbs are around the perpendicular shock: Tycho SNR seems to be barrel-like
- MF is larger at perpendicular shock and ν_{break} is larger at the parallel shock: i) acceleration is more efficient around parallel shock; ii) MF is compressed at perpendicular shock rather than amplified at parallel

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