X-ray emission of the shock of SN1006.
Constraints on electron kinetics

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SNRs and kinetics of electrons

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Supernova remnants (SNRs) are belived to be the main sources of galactic cosmic rays. The discovery of the nonthermal X-ray radiation from the shell SNR SN 1006 (Koyama et al., 1995), rise a new wave of numerous studies – theoretical and experimental – on galactic cosmic rays, acceleration processes and nonthermal emission of strong nonrelativistic shocks.

The X-ray spectrum of a region of SNR close to the shock is the most informative one. It is in general a mixture of (at least) two components: thermal and nonthermal emission. There are two key parameters which allow to separate these components: the level of electron-ion equilibration χ_s and the electron injection efficiency ζ.

The thermal X-ray spectrum is sensitive to the post-shock electron temperature T_{es}, while hydrodynamics deals with the mean post-shock temperature of the plasma T_s. The level of electron-ion equilibration defined as $\chi_s = T_{es}/T_s$ matches experimental data to theoretical model. The theoretically possible range is from $\chi_s \approx 10^{-3}$ in case of no equilibration to $\chi_s = 1$ in case of full equilibration. Experimental estimations narrow it to the range from $\chi_s \approx 0.03$ to $\chi_s = 1$ (e.g. Ghavamian et al. (2002); Vink et al. (2003)) that however remains to be wide to allow for a unique interpretation.

The normalization of the nonthermal spectrum strongly depends on the number density of accelerated electrons which is equal to ζn_{es}, where n_{es} is the post-shock number density of electrons. The value of the injection efficiency ζ, which can vary in a few orders of magnitude, is a free parameter in almost all models of nonthermal emission from SNRs.

A priori χ_s and ζ cannot be assumed to be constant in time. Namely, there are experimental evidences that at least χ_s is different for shocks with different Mach numbers (Schwartz et al., 1988; Ghavamian et al., 2001; Rakowski, 2005).

Understanding the factors which influence the fraction of accelerated particles, the level of electron-ion equilibration during the passage of the shock transition as well as energy partition between thermal and nonthermal particles is important both for the interpretation of experiments and the physics behind. In a situation when theory just undergoes development, any observational constraints are useful.

The goal of the present study is to trace the behaviour of the electron-ion equilibration level χ_s, the electron injection efficiency ζ, maximum energy of accelerated electrons E_{max} over the strong nonradiative shock in SNR.

For this puprose,

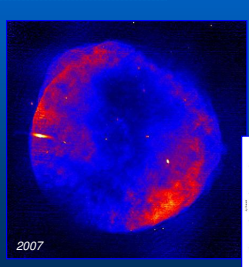
the *radio* and *X-ray* observations of SN1006 are used. These are the archive X-ray data from XMM-Newton observatory as well as newly processed Parkes and VLA radio observations including the data in AB configuration of VLA which provides highest angular resolution.

Radio observations

2

VLA

The best ever obtained radio image of SN1006 (synthesized beam 8"x5")

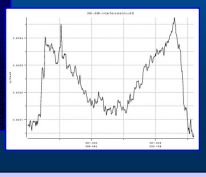


2007

Parkes

The image at 320 cm was produced on the basis of archival VLA data obtained in October 1991, February 1992 and July 1992 in the hybrid AB, BC and CD configurations, respectively. The observations in the AB configuration were carried out at 1370 and 1376 MHz, while the observations in the BC and CD arrays were performed at 1370 and 1665 MHz. The data corresponding to the more compact configurations of the VLA, BC and CD, were published as a part of an expansion study of SN 1006 (Moffett et al., 1993). The observations performed with the more extended antennae array, AB, which provide the highest angular resolution, however, were never presented before. The new interferometric image recovers emission from all spatial structures with angular scales between a few arcsec and 15 arcmin. To recover flux density contribution from structures on angular scales larger than 15 arcmin (which is important in this case since SN1006 is ~30 arcmin in diameter) we added single dish observations acquired in 2002 with the Parkes 64 m radiotelescope. The image has a synthesized beam of 7".7 × 6".8, position angle 9°.3, an rms noise of 1×10^{-4} *Jy*/beam, and the total recovered flux is S=14.9 Jy.

We make use of:
- *Brightness profiles*
- *Fluxes for X-ray analysis*
- *Detailed map for comparison with X-ray images*



X-ray observations with XMM

3

SN1006 was oserved by XMM
8 times in period 2000-2005.
Total cleaned exposure is 122 ksec

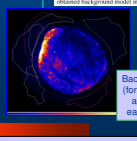
Exposure map

Two different methods are used for analysis of X-ray spectra
the main difference is the way of background substraction

ESAS

In the first approach, we use the Extended Source Analysis Software package (XMM-ESAS) for analysis of a set of observations from the EPIC-MOS cameras.

We have proposed a procedure which is similar to the "double background subtraction" technique (Read & Ponman, 2003). In this procedure, the instrumental background is subtracted applying the method of Snowden & Kuntz (2008), with the use of data from the unexposed sky corners of the EPIC-MOS detectors; then the cosmic background are modelled. To model the cosmic and soft proton background, we choose the background regions, close to the SN1006 (figure), and model the obtained "cosmic-background" spectra in Xspec. After rescaling of model components, we substitute the obtained background model into source regions.



Background regions (for ESAS analysis) are different for each observations

MOS

In the second approach we use the Science Analysis System (SAS). We derive the contribution of the background from high signal-to-noise blank fields and we subtract it taking into account the inhomogeneous response of the instruments across the field of view. The fittings were performed simultaneously on both MOS and pn spectra.

XSPEC

The spectra from source regions are modeled using XSPEC and considering a thermal VPSHOCK component with variable abundances (O, Ne, Mg, Si) plus a non-thermal SRCUT component with two free parameters (i.e. spectral index, α, and break, Δ, the normalization being derived from the radio-data). Since in the non-thermal limbs of SN 1006 it is difficult to constraint the parameters of the thermal component, for each limb we frozen these parameters to the mean values obtained in the adjacent thermal regions (where they are quite uniform). We also find an entanglement between the best fit values of α and b in the thermal regions, which we solved using the α value derived in adjacent non-thermal regions (where it is quite uniform).

This allow us to obtain relatively low values of the reduced χ^2 ($\chi^2 = 0.9 - 1.7$) and robust results across the whole rim.

Results of the spectral fitting in these two approaches are compared. In both approaches, parameters characterizing thermal and nonthermal components in the X-ray spectra are quite close in each source region.

X-ray mosaic images

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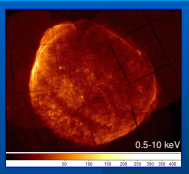
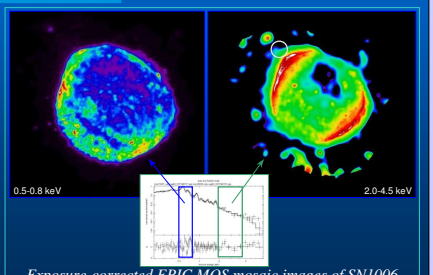


0.5-10 keV

EPIC MOS mosaic of SN1006
used for spectral analysis

After running *mos-filter*, additional exclusion of soft proton flaring periods from the event files with the help of *xmm-light*, *clean.csh* is done. This produced cleaned MOS images which used to obtain the mosaic image (with SAS tool *emosaic*). The mosaic image is neither smoothed nor exposure corrected. The reason for that is to determine the goodness of spectra, produced from selected regions, which is proportional to event number rather than event rate.



0.5-0.8 keV

2.0-4.5 keV

Exposure-corrected EPIC MOS mosaic images of SN1006

Source regions and spectra

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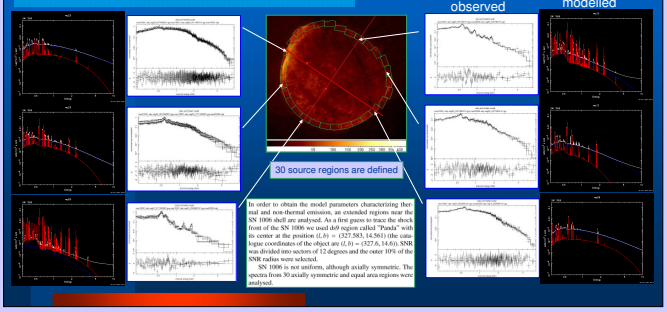

observed

modelled

30 source regions are defined

In order to obtain the model parameters characterizing thermal and non-thermal emission, an extended regions near the SN 1006 shell are analysed. As a first guess to trace the shock front of the SN 1006 we used *ds9* region called "Panda" with its center at the position (*l*, *b*) = (327.583, 14.581) (the catalogue coordinates of the object are (*l*, *b*) = (327.6, 14.6)). SNR was divided into sectors of 12 degrees and the outer 10% of the SNR radius were selected.

SN 1006 is not uniform, although axially symmetric. The spectra from 30 axially symmetric and equal area regions were analysed.

Parameters of interest

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The goal is to estimate:

- *electron thermalization level* χ_s,
- *electron injection efficiency* ζ,
- *energy partition between thermal and nonthermal electrons* E_{nth}/E_{th},
- *maximum energy of accelerated electrons* E_{max}
- *their dependence on the shock velocity V and*
- *on the shock obliquity*

Observations yield:
T_{es}, n_{es}, R, F_ν, s, ν_{max}

Level of electron thermalization

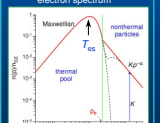
$$\chi_s = T_{es}/T_s$$

$$T_s = \frac{\sigma - 1}{\sigma^2}\frac{\mu m_p}{k}V^2$$

$$V = \frac{2}{5}\left(\frac{E_{SN}}{\sigma A_R \rho_0 (kR)}\right)^{1/2} R^{-3/2}$$

$$\chi_s = \frac{25\sigma A_R k \mu\sigma}{4\beta_e(\sigma-1)}\frac{T_{es} n_{es} R^3}{E_{SN}}$$

electron spectrum



Injection efficiency of electrons

The synchrotron flux of relativistic electrons at some radio frequency ν is $F_\nu = P_\nu V/4\pi d^2$ where V is the volume of emitting region, d the distance to SNR, $P_\nu = C_4(s)KB^{(s+1)/2}$ is the emissivity, $C_4(s)$ the known constant. Thus, for our regions

$$F_\nu = \frac{C_4 V}{4\pi d^2} K_e R^{(s+1)/2} \quad (7)$$

The normalization K_e is related to the injection efficiency, defined as the fraction of nonthermal electrons

$$\zeta = \frac{1}{n_{es}}\int_{p_{th}}^{\infty} K_e p^{-s} dp = \frac{K_e p_{th}^{1-s}}{(s-1)n_{es}} \quad (8)$$

The break momentum p_b, the momentum where Maxwellian electron distribution matches the nonthermal power-law distribution of accelerated electrons is

$$p_b \approx 3.7 p_{th} \approx \sqrt{27 m_e k T_{es}} \quad (9)$$

It is important to note that the coefficient $p_b/p_{th} \approx 3.7$ is able to change in 10-20% only for wide range of $\zeta \sim 10^{-6} \div 10^{-2}$. Substitution (8) with (9) and K_e from (7) gives

$$\zeta = \frac{4\pi d^2 (27 m_e k)^{(1-s)/2}}{C_4 V(s-1)} \frac{F_\nu}{\mu^{-(s+1)/2} n_{es} R^{(s+1)/2}} \quad (10)$$

Thermal and nonthermal electrons

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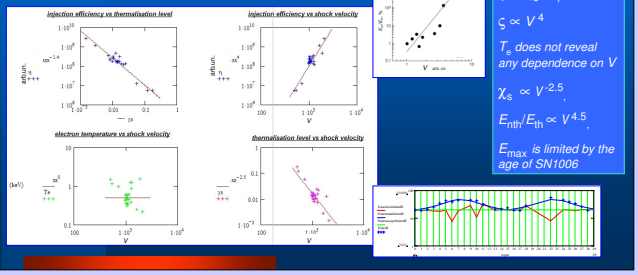
in the source regions around the shock in SN1006



Trends (preliminary)

$\zeta \propto \chi_s^{-1.4}$,

$\zeta \propto V^4$

T_s *does not reveal any dependence on V*

$\chi_s \propto V^{-2.5}$,

$E_{nth}/E_{th} \propto V^{4.5}$,

E_{max} *is limited by the age of SN1006*

Conclusions

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Electrons around the shock in SN1006 reveal the following properties
(preliminary results)

E_{max} *is within 20-60 TeV*
E_{max} *is limited by the age of SN1006, not by the radiative losses*

The higher electron-proton equilibration the smaller injection efficiency: $\zeta \propto \chi_s^{-1.4}$ *, in agreement with model of Petruk & Bandiera (2006).*

T_s *does not reveal any dependence on the shock velocity V, in agreement with model of Ghavamian et al. (2007).*
Since $T_s \propto V^2$ *then the expected dependence of thermalization level on V is* $\chi_s \propto V^{-2}$*. This is close to our preliminary trend* $\chi_s \propto V^{-2.5}$

E_{nth}/E_{th} *increases with V, due to decrease of the electron thermalisation level and increase of the electron injection efficiency*