Particle acceleration in SN 1006

Anne DE COURCHELLE, Service d’Astrophysique/AIM, IRFU
CEA Saclay, France

First results from an XMM-Newton LP on SN 1006


see also next talk by F. Bocchino
Origin of Galactic Cosmic rays

**Supernova remnants:** likely the birth places of Galactic CRs up to $\sim 3 \times 10^{15}$ eV
- 10% of their kinetic energy: to maintain the pool of Galactic Cosmic rays
- High mach number shocks: 1st order Fermi mechanism through diffusive shock acceleration (1949)

**Radiative signatures at their shock:**
- **Radio synchrotron** $\Rightarrow$ electrons accelerated to GeV energies (1954)
- **X-ray synchrotron** $\Rightarrow$ electrons up to TeV energies in SN 1006 (Koyama et al. 1995, Nature)
- **TeV gamma-ray emission** $\Rightarrow$ particles accelerated to TeV energies (Aharonian et al. 2004, Nature)
Evidence for ion acceleration? Fraction of shock energy tapped by cosmic rays?

- Curvature of the particle spectra (Berezhko & Ellison 99, Ellison & Reynolds 91, Allen et al. 08)
- Lower post-shock temperature (Ellison et al. 00, Decourchelle et al. 00)
- Shrinking of the post-shock region (Decourchelle et al. 00, Cassam-Chenaï et al. 08, Miceli et al. 09)

Where particle acceleration occurs? Polar caps vs equatorial belt (Berezhko et al. 02, Rothenflug et al. 04)

What is the maximum energy $E_{\text{max}}$ of accelerated particles?
Electrons are a few % of cosmic rays but can reveal a lot on the mechanism of diffusive shock acceleration $\Rightarrow$ accelerated like protons, so their spectrum is expected to be the same.

How does $E_{\text{max}}$ and hence particle acceleration vary with ambient $B$ orientation?
High latitude SNRs evolving in a uniform interstellar magnetic field, like SN 1006, offer the possibility to investigate this dependence (Völk et al. 03)
SN 1006

- Historical type Ia SNR
- Dual nature in X-rays with a bipolar non-thermal morphology like in radio, superposed on a fainter extended thermal emission

First evidence of electrons up to TeV energies in SN 1006 (Koyama et al. 1995, Nature 378, 255)

This talk => How does $E_{\text{max}}$ and hence particle acceleration vary with ambient B orientation?

Fabrizio Bocchino => Thermal X-rays from ejecta and shocked ISM
How does $E_{\text{max}}$ vary with ambient magnetic field orientation?

Spatially resolved spectroscopy of the synchrotron emission (+ radio flux)

=> Measurement of the averaged azimuthal variation of the synchrotron roll-off frequency along the shock

SN 1006: very strong variations of the synchrotron roll-off frequency

=> Maximum energy of accelerated particles must be higher at the bright limbs than elsewhere
XMM-Newton Large program on SN 1006

**Particle acceleration under scrutiny in SN 1006**

**Objectives:** particle acceleration, magnetic field amplification, heating of the electrons and ions at the shock, abundances and distribution of the chemical elements in the ejecta

**Co-Is:** G. Maurin, M. Miceli, F. Bocchino, G. Dubner, E. Giacani, J. Ballet, S. Orlando, J. Vink, E. Helder, D. Kosenko, Acero F., Cassam Chenai G.

**Method:** spatially resolved X-ray spectroscopy of the thermal and non-thermal components at a spatial scale close to the point spread function.

**Total LP observation time:** 650 ks

**Status:** all observations performed since september 2010

**Spatially resolved spectroscopy of the synchrotron emission**

⇒ Measurement of the azimuthal variation of \( \nu_{\text{cut-off}} \) along the SNR shock

**Data:** all XMM data available (LP + previous shallow observations)

~950 ks -> ~650 ks after flare rejection
Observing status after the SN 1006 XMM-Newton LP

2 north-western observations

2 south-eastern observations

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### Observations and effective observing time after flare rejection

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- **69%**
- **73%**
- **55%**
**Spectral modelling:**
- exponential cut-off power law model (SRCUT, Reynolds & Keohane 99)
- thermal plane-parallel non-equilibrium model (VPSHOCK, Borkowski et al. 01)
- interstellar absorption (WABS): $N_H \sim 7 \times 10^{20} \text{ cm}^{-2}$ (Dubner et al. 02)

**Images:**
- XMM-Newton
- Chandra
- Radio VLA

Spectral extraction in box of 16 arcsec width

Added to single dish data (Petruk et al. 09)
Along the two extended filaments, cut-off frequency shows:

- a rapid increase, followed by a plateau and a rapid decrease
- increase amplitude depends on filaments (from 4 to 10)
- the most outward filaments have larger cut-off frequency

(Vs ~ 5000 km/s, Katsuda et al. 09)
Along all filaments, same behaviour of the spectral index
• slight increase towards the pole and decrease outwards
• but exact dependence and values depend on radio maps

Using Dyer et al. 2009 map
Using Rothenflug et al. map
Using Petruk et al. 2008 map
Conclusion on particle acceleration at the north-east pole in SN 1006

At the north-east pole:

- Highest cut-off frequency
  => highest energy reached by particles
- Highest values for the outermost filaments
  => higher energy for higher shock velocity
- Plateau regime: saturation of the cut-off frequency near the pole: loss-limited?
  ⇒ highest acceleration efficiency/injection
  (Decourchelle et al., 2011, in prep)

Azimuthal dependence provides very strong constraints to the acceleration mechanism: dependence with obliquity angle between shock velocity and upstream magnetic field

=> detailed modeling required