EBERHARD KARLS UNIVERSITÄT TÜBINGEN
Mathematisch-Naturwissenschaftliche Fakultät
Institute for Astronomy and Astrophysics
Hign-Energy Astrophysics

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

Galactic and extragalactic supernova remnants as sites of particle acceleration

Manami Sasaki

Vulcano Workshop 2012, May 29, 2012

Outline

- Introduction
- Physics of SNR shocks and particle acceleration
- Galactic X-ray SNRs with indications of particle acceleration
- Extragalactic SNRs
- Summary

Introduction

Supernova remnants (SNR) were first identified in the optical as nebulae formed at the sites of historical supernovae (SNe).

Later, SNRs in our Galaxy were discovered as nonthermal, extended radio sources with a flux spectrum described by a power-law $S_\nu \propto \nu^\alpha$ with $\alpha \approx -0.5$. This emission was explained as synchrotron radiation emitted by a nonthermal, power-law populations of relativistic electrons.

An electron distribution of $N(E) = KE^{-s}$ electrons cm^{-3} erg^{-1} produces a power-law photon distribution with $\alpha = (1-s)/2$, thus $s = 2$ for $\alpha = -0.5$.

Electrons that emit radio synchrotron emission have energies in the GeV range.

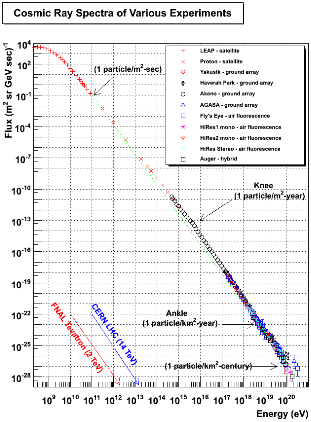
Particles of such energies and higher: cosmic rays!

Cosmic rays

The all-particle spectrum can be described by a power-law $\propto E^{-2.7}$ up to $\sim 3 \times 10^{15}$ eV (the *knee*) and then becomes steeper.

Origin of the cosmic rays:

- up to the *knee*: Galactic sources.
- at higher energies: extragalactic.



Hanlon, U. of Utah

SNRs as cosmic particle accelerator

Fermi (1949):

Particles can be accelerated in a diffusive process by collisions through magnetic mirroring between charged particles and interstellar clouds.

SNRs as cosmic particle accelerator

Fermi (1949):

Particles can be accelerated in a diffusive process by collisions through magnetic mirroring between charged particles and interstellar clouds.

Shell-type SNRs have kinetic energy of the order of 10^{51} erg.

About 3 SNe per century occur in our Galaxy, which can convert $\sim$10% of their kinetic energy into cosmic-ray energy.

SNRs are thus the primary sources of cosmic rays below 3×10^{15} eV(e.g., Ginzburg & Syrovatskii 1969).

What are SNRs?

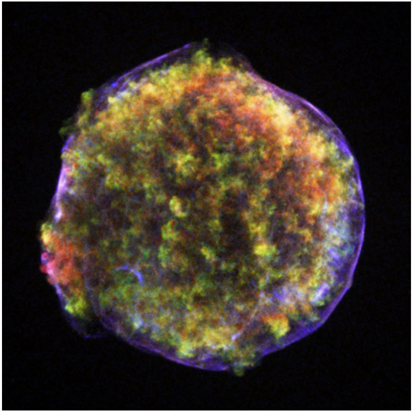
A supernova remnant is the remains of a supernova explosion.

They heat up the ISM, distribute heavy elements throughout the Galaxy, and accelerate cosmic rays.

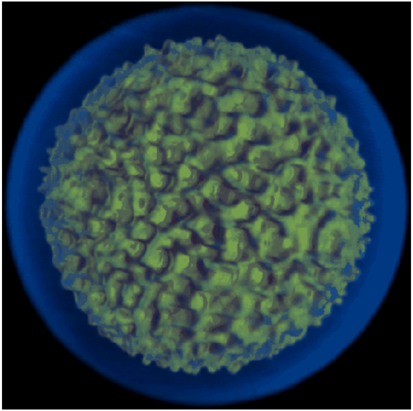
Evolution of SNRs:

1. Ejecta dominated phase: mass of the supernova ejecta, $M_{\rm ej}$, dominates over the mass of the swept up ISM.
2. Sedov-Taylor phase: $M_{\rm sw} > M_{\rm ej}$, but radiative losses are negligible. The SNR expands adiabatically.
3. Pressure-driven or "snow-plough" phase: radiative cooling has become energetically important. The evolution of the shock radius is best described by using momentum conservation.
4. Merging phase: the shock velocity and temperature behind the shock become comparable to the turbulent velocity and temperature of the ISM, respectively.

Young SNRs



Tycho's SNR. *Chandra X-ray Observatory*



SN 1006. Simulation by Miceli et al. 2009

Rankine-Hugoniot relation

A strong expansion due to stellar winds or supernovae form waves in the surrounding medium with high-amplitude disturbances resulting in a discontinuous flow: shock waves.
At the shock front, conservation laws of mass, energy, and momentum flow must be fulfilled.
For a monoatomic gas we have $\gamma = 5/3$ for the ratio of specific heats. For the Mach number $M^2 \gg 1$, we get

$$r = \rho_2/\rho_1 = u_1/u_2 = \frac{\gamma+1}{\gamma-1} = 4, \quad (1)$$

$$kT_2 = \frac{3}{16}\mu_2 m_p u_1^2, \quad (2)$$

But:

These relations are correct only if the energy loss due to radiation (or other causes) is negligible.

But:

These relations are correct only if the energy loss due to radiation (or other causes) is negligible.
If efficient acceleration of particles in shocks occurs, the energy loss by escaping particles can become significant.
In addition, a relativistic particle population will lower the mean adiabatic index from 5/3 to its fully relativistic value of 4/3.

> Radio emission from SNRs indicates the presence of ultrarelativistic electrons ($E \approx 10^4 m_e c^2$).

But:

These relations are correct only if the energy loss due to radiation (or other causes) is negligible.
If efficient acceleration of particles in shocks occurs, the energy loss by escaping particles can become significant.
In addition, a relativistic particle population will lower the mean adiabatic index from 5/3 to its fully relativistic value of 4/3.

Radio emission from SNRs indicates the presence of ultrarelativistic electrons ($E \approx 10^4 m_e c^2$).

Diffusive shock acceleration (DSA) is the primary mechanism discussed for producing energetic particles in SNR shocks (Drury 1983, Blandford & Eichler 1987, Jones & Ellison 1991, etc.).

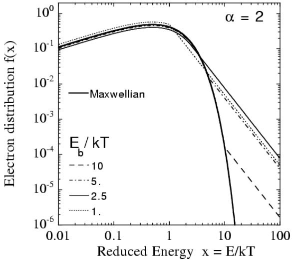
Particle scattering at the shock front

Scattering at magnetic fields:

In a collisionless shock wave, the velocities of particles are randomized by scattering from magnetic irregularities. A few of these particles may scatter back upstream and scatter at inhomogeneities in the magnetic fields in in the upstream medium.

Particles thus can cross the shock front many times and gain energy.

In addition to a Maxwellian distribution, the energy distribution of particles develops a nonthermal power-law tail.

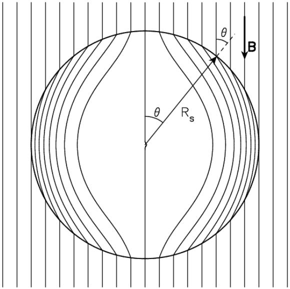


Porquet et al. 2001

Shock and magnetic field configuration

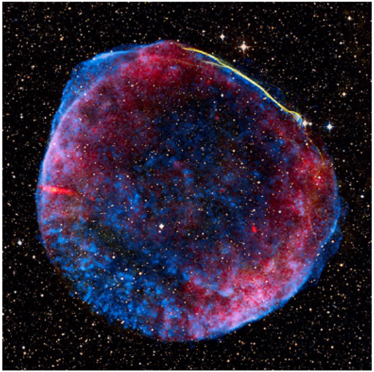
The angle between the shock normal and the upstream magnetic field is called the obliquity θ. Shocks with $\theta \approx 0$ are called parallel shocks, for $\theta \approx 90^\circ$ one has perpendicular shocks.

For perpendicular shocks, the gyromotion of particles carries them back and forth across the shock even in the absence of scattering (shock drift acceleration).

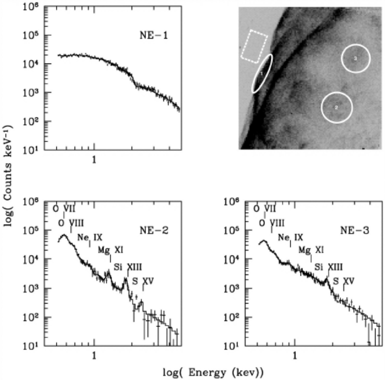


Völk et al. 2003

SN 1006: a cosmic particle accelerator

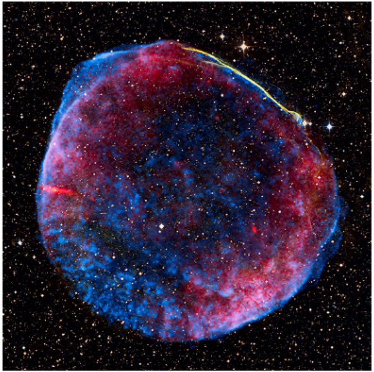


Red: radio (VLA/GBT). Yellow: optical (CTIO).
Blue: X-ray (Chandra).

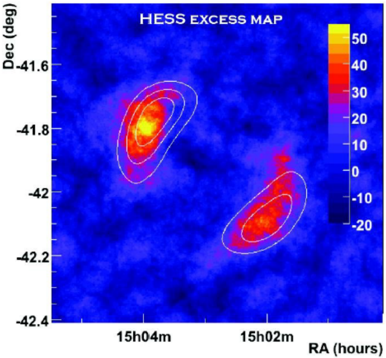


Long et al., 2003

SN 1006: a cosmic particle accelerator



Red: radio (VLA/GBT). Yellow: optical (CTIO). Blue: X-ray (Chandra).



Naumann-Godó, 2009

Nonlinear Effects

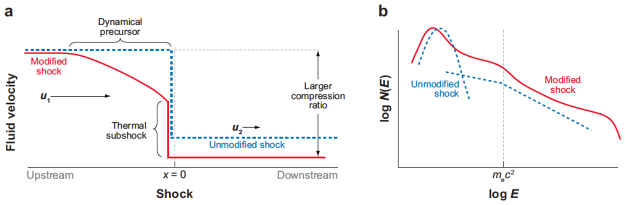


Figure 3

(*a*) Schematic shock profile. Dotted blue line, unmodified shock; solid red line, shock modified by accelerated particles.
(*b*) Corresponding schematic particle energy distributions from unmodified shock (*dotted blue lines*) and modified shock (*solid red line*).

Reynolds 2008

Nonlinear Effects

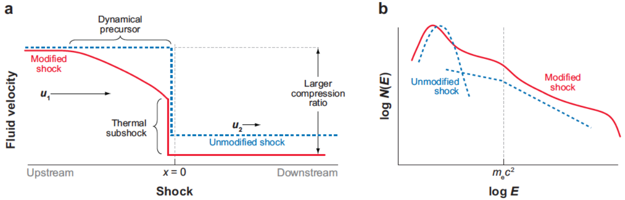


Figure 3

(*a*) Schematic shock profile. Dotted blue line, unmodified shock; solid red line, shock modified by accelerated particles.
(*b*) Corresponding schematic particle energy distributions from unmodified shock (*dotted blue lines*) and modified shock (*solid red line*).

Reynolds 2008

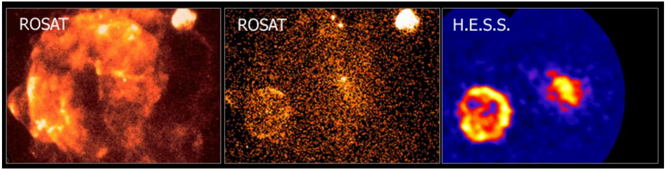
Bell's mechanism (1978):

Accelerated particles, which scatter ahead of the shock, might themselves excite MHD waves. These self-generated waves can scatter subsequent generations of particles. These upstream waves can also move energy from fast particles back to the thermal plasma.

X-ray synchrotron sources

Reynolds & Chevalier (1981) first proposed that DSA might cause X-ray synchrotron emission in SNR 1006.
In addition, two synchrotron-dominated shell-type X-ray SNRs were discovered in the 1990s:

- RX J1713.7-3946 (G347.3-0.5, Koyama et al. 1997, Slane et al. 1999).
- Vela Jr. (G266.2-1.2, Aschenbach et al. 1998, Slane et al. 2001).



Aharonian et al. 2006

Also in remnants of historical SNe RCW 86 (SN 185), Tycho (SN 1572), Kepler (SN 1604), or Cas A (SN ∼1667) synchrotron emitting thin filaments were found.

Deriving B from thin filaments

The very thin synchrotron filaments found in X-rays parallel to the remnant edge indicate fast drop of synchrotron emissivity behind the shock.

Deriving B from thin filaments

The very thin synchrotron filaments found in X-rays parallel to the remnant edge indicate fast drop of synchrotron emissivity behind the shock.

- Far too fast to be explained by adiabatic expansion of electrons and the magnetic field!
- Either X-ray emitting electrons disappear through radiative losses or the magnetic field disappears through some damping mechanisms.

- If electron losses are the cause, the filament width corresponds to the distance electrons convect in the postshock flow within synchrotron loss time.
- Typical filament thicknesses of ~ 0.01 pc imply immediate postshock magnetic field strengths between 50 and 200 μG for the historical SNRs.

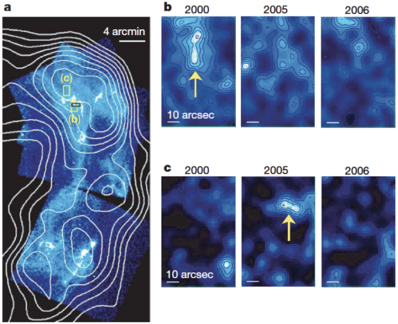
Magnetic field amplification

Non-thermal X-ray hot spots were found in SNR RX J1713.7–3946, which brightened and decayed on a one-year timescale (Uchiyama et al. 2007).

Ultrarelativistic electrons produce synchrotron X-rays.

The rapid variability shows that electron acceleration is associated with an amplification of the magnetic field by a factor of more than 100.

> Interstellar magnetic field can be amplified at the shock of young SNRs through MHD waves generated by accelerated particles.



SNR RX J1713.7–3946: Chandra with H.E.S.S. contours

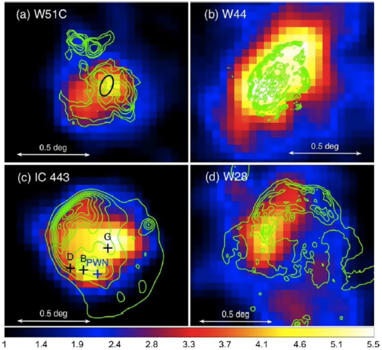
Uchiyama et al. 2007

SNRs interacting with molecular clouds

SNRs located in an inhomogenous ISM and interacting with molecular clouds are likely to produce gamma rays through the hadronic process: e.g., IC 443, W28, W51C.

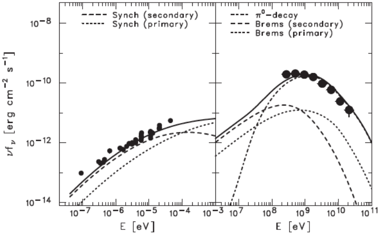
- Protons and ions accelerated in the SNR shocks can produce pions through inelastic scattering on thermal protons.
- π^0 will decay to gamma rays, producing a spectrum peaking at energy $m_\pi/2 = 68$ MeV and continuing to higher energies with the same shape as the primary ion spectrum.

SNRs interacting with molecular clouds



Fermi LAT 2 – 10 GeV count maps with VLA radio contours.
Ellipse: shocked CO clumps, crosses: OH masers.

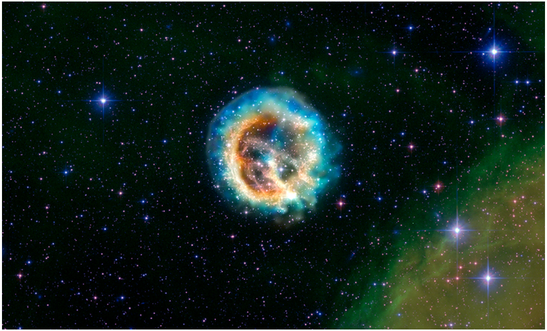
Uchiyama et al. 2010



Radio and γ-ray spectra of SNR W44 with models.

Thompson et al. 2011

SNR 1E 0102.2–7219



X-ray (NASA/CXC/MIT/D.Dewey et al. & NASA/CXC/SAO/J.DePasquale); Optical (NASA/STScI)

Brightest X-ray SNR in the Small Magellanic Cloud (SMC) with strong line emission of highly ionized O, Ne, and Mg (Hayashi et al. 1994, Gaetz et al. 2000, Rasmussen et al. 2001, Sasaki et al. 2001).

SNR 1E 0102.2–7219

Optical filaments with radial velocities of –2500 to +4000 km s^{-1} w.r.t. the SMC (Tuohy & Dopita 1983).

Chandra grating spectrum indicates velocities of $\pm$1000 km s^{-1} (Flanagan et al. 2004).

SNR 1E 0102.2–7219

Optical filaments with radial velocities of –2500 to +4000 km s^{-1} w.r.t. the SMC (Tuohy & Dopita 1983).

Chandra grating spectrum indicates velocities of $\pm$1000 km s^{-1} (Flanagan et al. 2004).

Hughes et al. 2000: optical filaments and extent measurements from Chandra images indicate a higher expansion velocity than what corresponds to the post-shock electron temperature derived from the X-ray spectra.

SNR 1E 0102.2–7219

Optical filaments with radial velocities of –2500 to +4000 km s^{-1} w.r.t. the SMC (Tuohy & Dopita 1983).

Chandra grating spectrum indicates velocities of ±1000 km s^{-1} (Flanagan et al. 2004).

Hughes et al. 2000: optical filaments and extent measurements from Chandra images indicate a higher expansion velocity than what corresponds to the post-shock electron temperature derived from the X-ray spectra.

Non-equilibrium ionization effects are not sufficient to yield such an inconsistency. Therefore, cosmic rays must have carried a significant faction of the SNR shock energy away.

SNR 1E 0102.2–7219

Optical filaments with radial velocities of –2500 to +4000 km s^{-1} w.r.t. the SMC (Tuohy & Dopita 1983).

Chandra grating spectrum indicates velocities of ±1000 km s^{-1} (Flanagan et al. 2004).

Hughes et al. 2000: optical filaments and extent measurements from Chandra images indicate a higher expansion velocity than what corresponds to the post-shock electron temperature derived from the X-ray spectra.

Non-equilibrium ionization effects are not sufficient to yield such an inconsistency. Therefore, cosmic rays must have carried a significant faction of the SNR shock energy away.

Nonlinear effects in particle acceleration mechanisms can yield a mean postshock temperature of ~ 1 keV for SNR 1E 0102.2–7219 (Decourcelle et al. 2000, Ellison 2000), consistent with the observed temperature (e.g., Hughes et al. 2000, Sasaki et al. 2006).

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

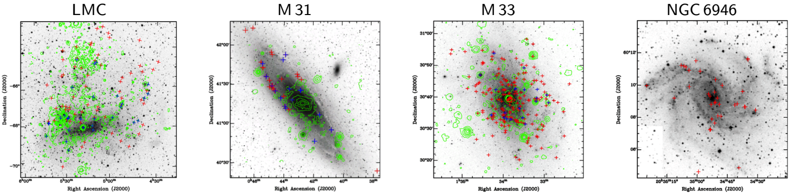
MATHEMATISCH-
NATURWISSENSCHAFTLICHE
FAKULTÄT
Institute for Astronomy and Astrophysics
Hign-Energy Astrophysics

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

SNRs in nearby galaxies

As SNRs are believed to the be primary sources of Galactic cosmic rays, the number distribution of SNRs in our Galaxy is a crucial basis for the modeling and understanging of the cosmic ray distribution in our Galaxy.

However, our vantage point is not ideal to study the source distribution in our Galaxy. To understand the distribution of SNRs in a spiral galaxy, it is thus necessary to study other nearby spiral galaxies.



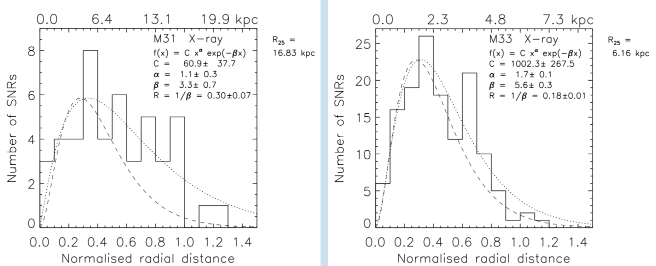
Red: radio SNRs, blue: X-ray SNRs, green contours: X-ray emission (ROSAT).

Sasaki et al. 2004

Radial distributions of SNRs in M 31 and M 33

New complete sample of X-ray SNRs in M 31 based on XMM-Newton Large Programme survey data (Sasaki et al. 2012).

Radial surface density of SNRs and candidates in M 31 and M 33 (dotted: fit model function [Stecker & Jones 1977], dashed: for the Milky Way, normalized).



Sasaki et al. 2012

Radial distributions of SNRs in M 31 and M 33

Distribution of SNRs, as primary sources of cosmic rays, is essential for the understanding of injection and diffusion of Galactic cosmic rays.

SNR distributions in M 31 and M 33 are similar but slightly flatter than in the Milky Way:

- The distribution of SNRs in M 31 is correlated with that of gas in M 31, wich shows with ring-like structures with the most prominent ring at a radius of $\sim$ 10 kpc (Sofue & Kato 1981, Braun 1991).
- The flatter SNR distribution in M 33 is consistent with M 33 being a typical flocculent spiral galaxy with discontinuous spiral arms and prominent on-going star formation regions in these arms.

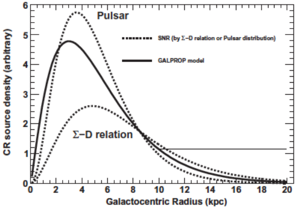


Fig. 5. CR source distribution from one GALPROP model (solid line), compared with the SNR distribution obtained by the Σ–D relation [31] (see [32] for a critique of this method, however) and that traced by the pulsar distribution [33] shown by dotted lines. The thin solid line represents an example of the modified distributions introduced to reproduce the emissivity gradient observed by the LAT [28].

Thompson et al. 2011

Summary

- In shocks of SNRs particles can be accelerated through diffusive shock acceleration.
- The primary agent of this process are the magnetic fields, which can be also modified and amplified by the relativistic particles.
- GeV to TeV observations of SNRs confirm the existence of ultrarelativistic particles in SNRs.
- Relativistic particles carry away energy from the SNRs.
- X-ray synchrotron emission gives information about the magnetic fields.
- SNRs interacting with dense molecular clouds are also likely to produce γ-rays via π^0 production and decay.
- Distribution of SNRs in a galaxy can shed light on the propagation of cosmic rays in the galaxy.