Supernova remnants near molecular clouds

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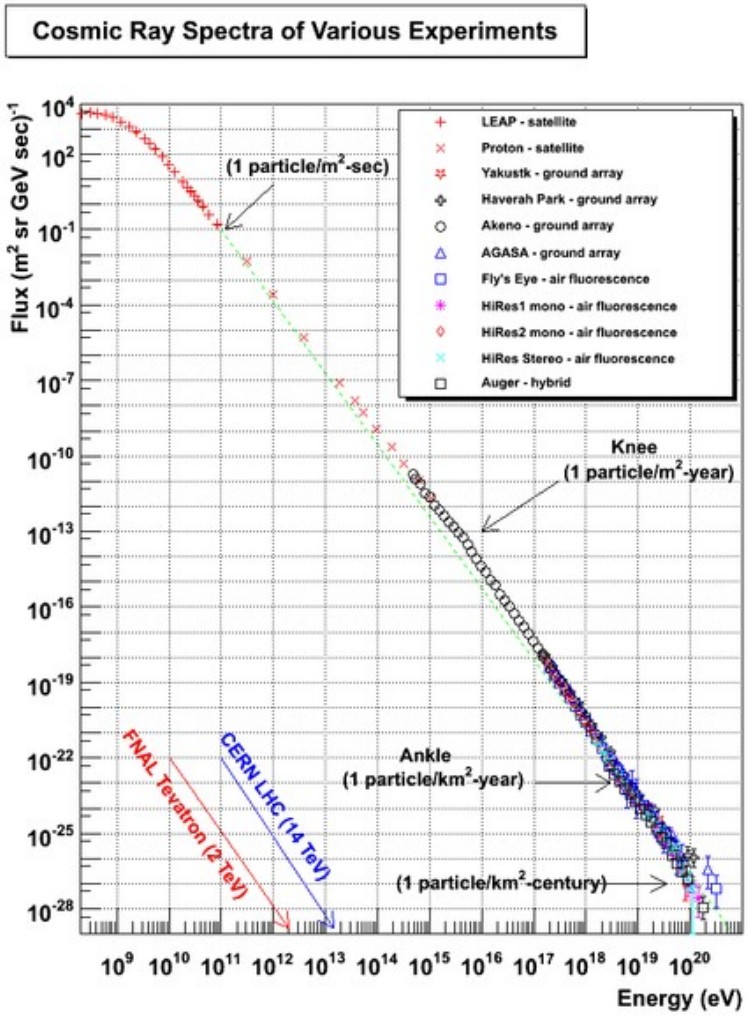
03.12.2021

Cosmic Rays



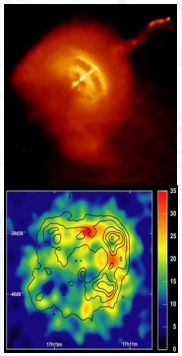
A cosmic ray is a high-speed particle

- Could be an electron
- Could be an atomic nucleus like hydrogen or helium stripped of its electrons
- These particles travel throughout the Milky Way galaxy
- Some come from the sun
- Some from outside the solar system
- Cosmic rays are the source of the highest energy particles known!

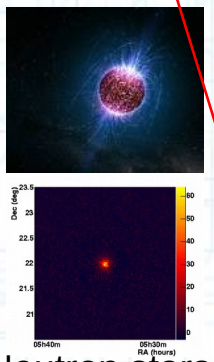
https://www.lpl.arizona.edu/~ffrasche/SNR.html

The sources of cosmic rays

Galactic cosmic rays

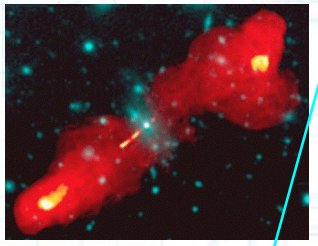


Supernova remnants

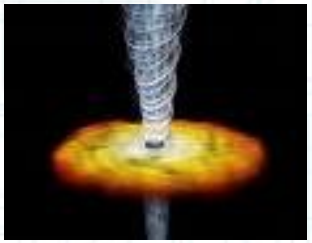


Neutron stars

Extragalactic cosmic rays

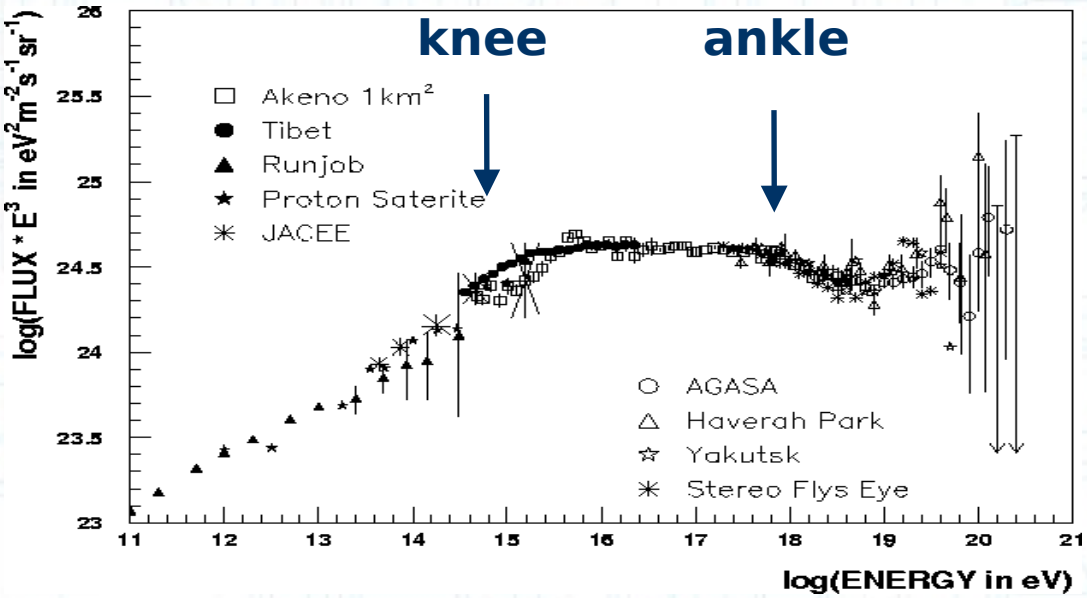


Active Galactic Nuclei



Quasars

Galaxy Mergers



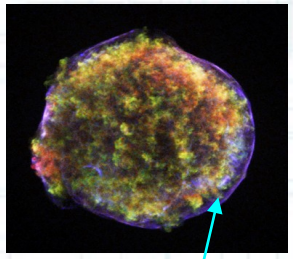
SNRs as a cosmic ray accelerators

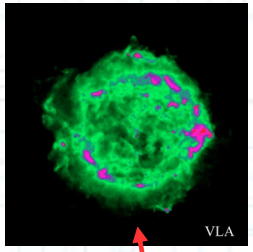
SNRs in our Galaxy: ***294*** ***(radio,*** ***Green catalog 2014)***

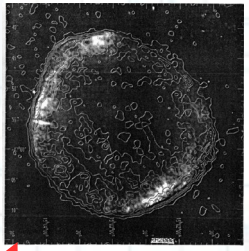
with *nonthermal X-ray emission* *~ 10*

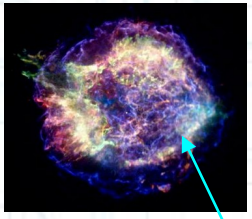
with *TeV γ-ray emission* *~ 10*

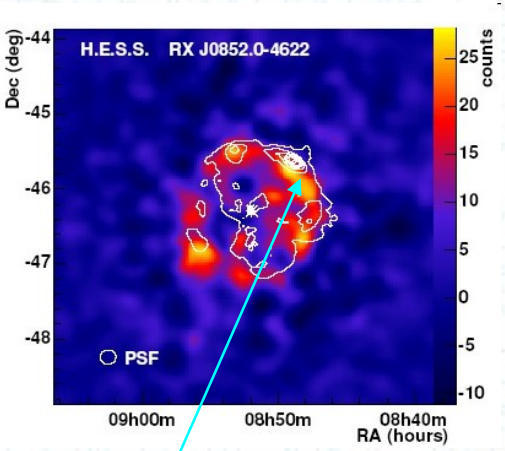
Best candidates …

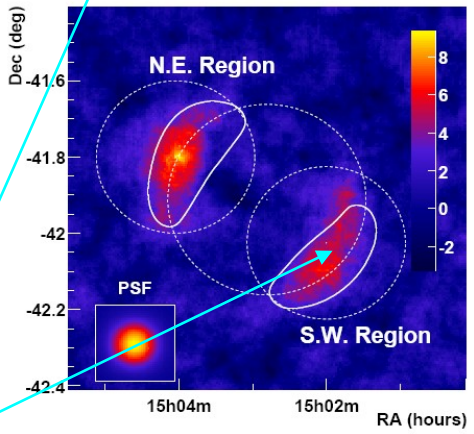






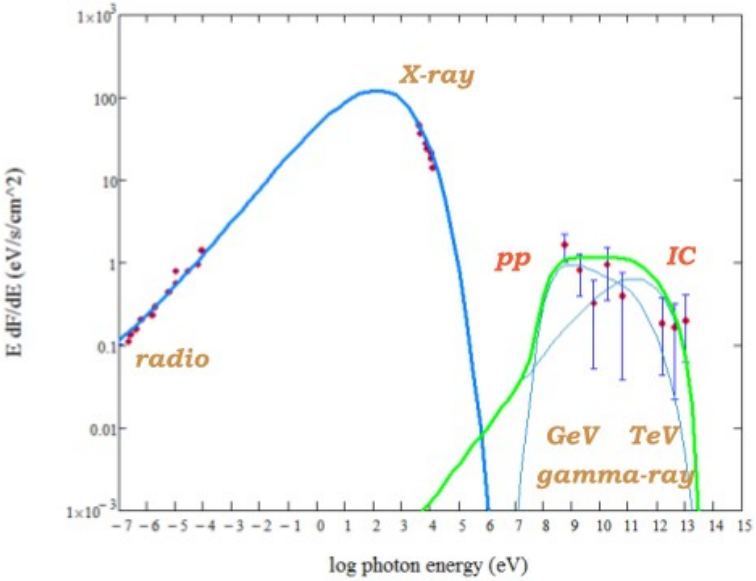


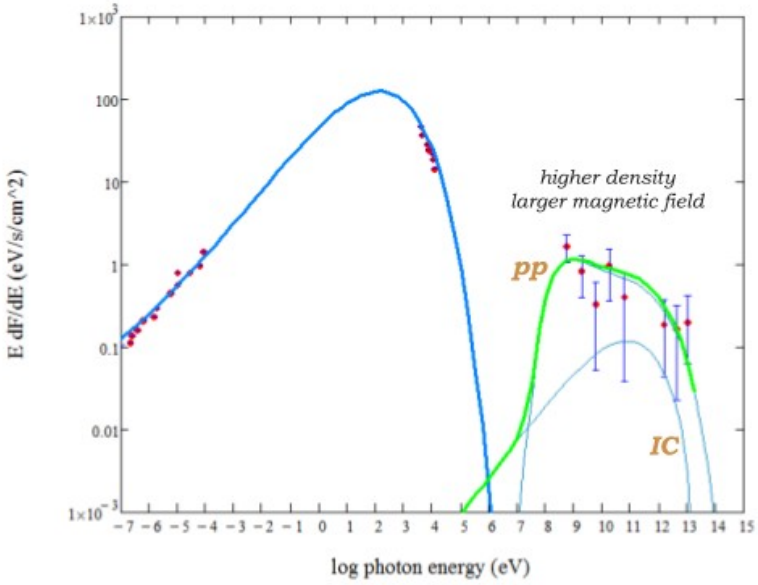




Radiation from radio to high energy γ-ray

Spectrum of SNRs



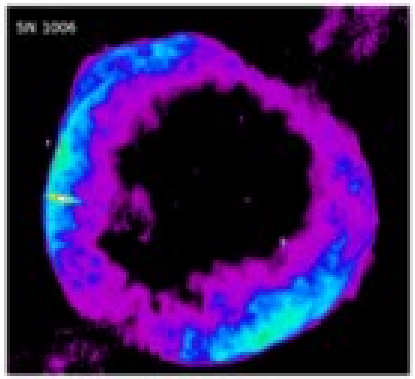


- The only way “to see“ protons in the accelerator is the pion-decay γ-rays.
- Dominant hadronic γ-rays are expected where.
    1. the target proton density is high;
    2. leptonic emission is low due to the high magnetic field.
- Such conditions could naturally be present in SNR-MC associations

Images of SNRs

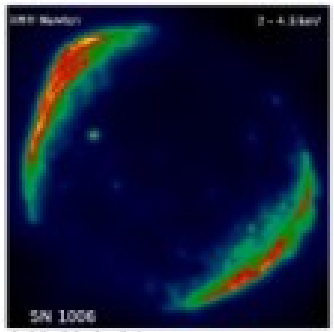
Since 2004, there are more than 15 SNRs with known pattern of surface brightness distribution in TeV gamma-rays.

Radio

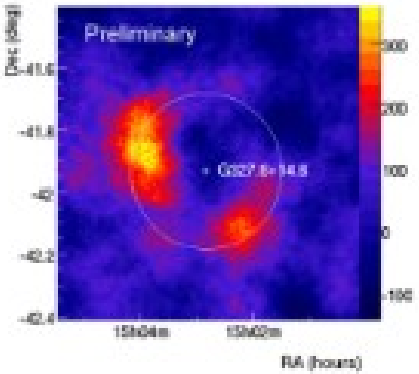


Rothenflug et al. 2004

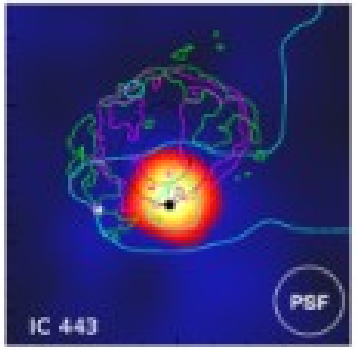
X-ray



XMM Newton



Acero et al. 2010



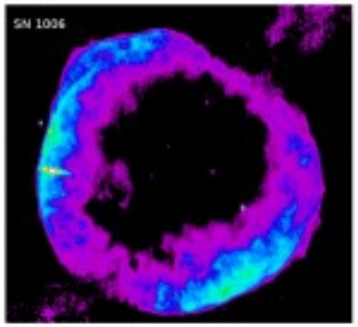
Aharonian et al. 2008

Gamma rays

Morphology of SNRs

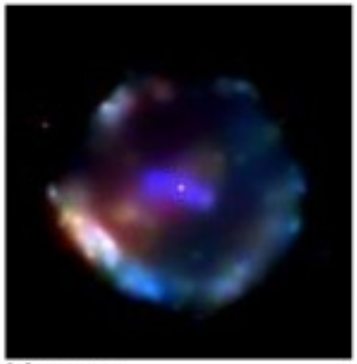
There are four morphological classes of SNRs:

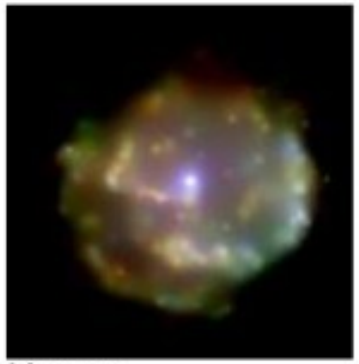
- shell-like;
- Crab-like (plerionic);
- composite;
- thermal X-ray composites (TXCs; or mixed-morphology).



sn 1006

Crab Nebula


Kes 75


Kes 79

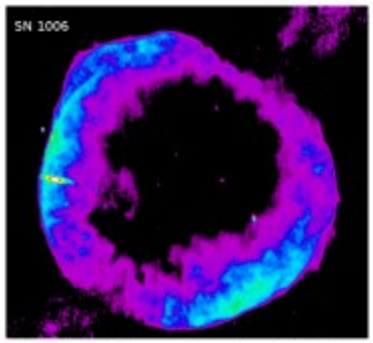
Shell-like

Shell-like supernova remnants

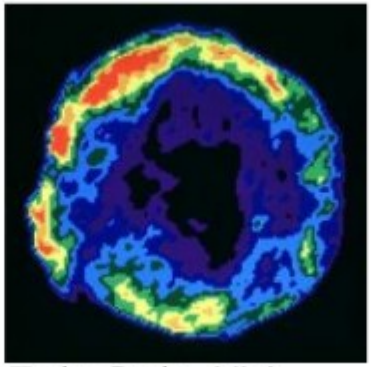
• SRNs with shell-like structure in radio, x-ray and γ-ray;

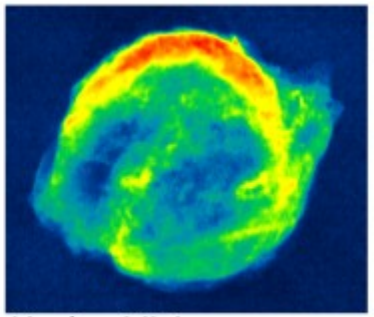
• Type Ia supernovae (thermonuclear explosion in binary system);

• there are ~200 SNRs are observed as a shell-like (Green catalogue 2014).



Rothenflug et al. 2004


Tycho Brahe, VLA

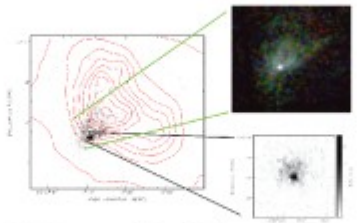

Kepler, VLA

Crab-like (plerionic)

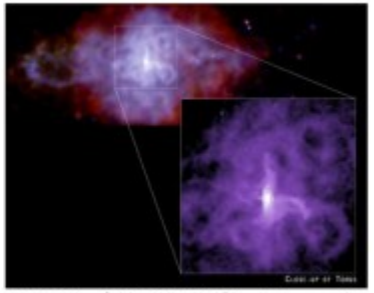
Crab-like supernova remnants

- SNR with fast rotation central compact object;
- Type II supernovae (star collapse);
- there are ~10 SNRs that have a plerionic structure (Green catalogue 2014).

Crab Nebula (3C144, SN1054)



CTB 87, Safi-Harb 2012

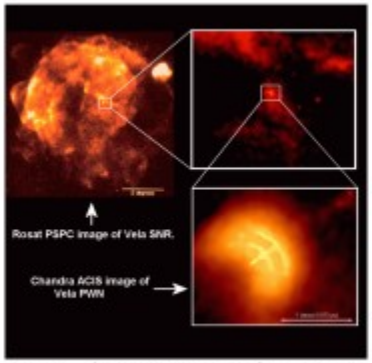


3C58 (SN1181), Chandra

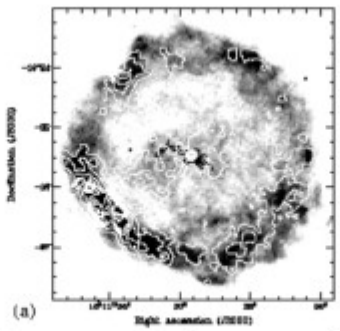
Composite

Composite

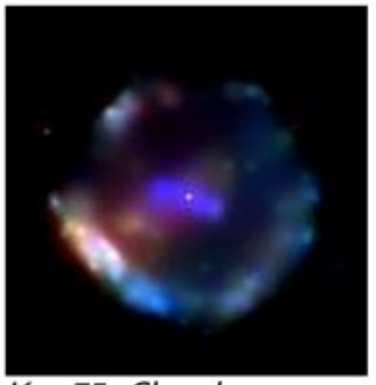
- SNRs with central object and shell in radio;
- Type II Sepernovae (star collapse);
- There are ~5 SNRs with composite structure.



Vela (G263.9-3.3), Chandra



G11.2-0.3, Roberts et al. 2002

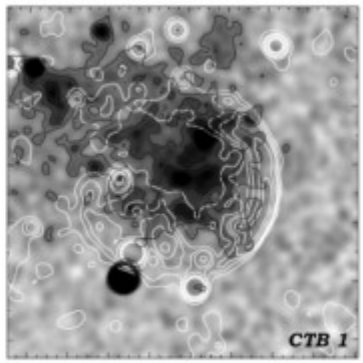

Kes 75, Chandra

Thermal X-ray composites (or mixed-morphology)

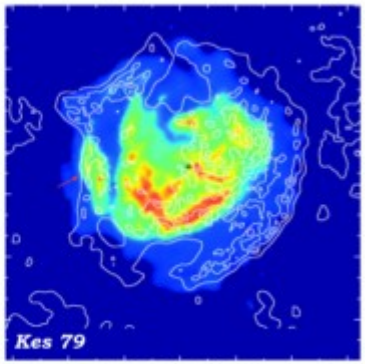
Thermal X-ray composites (TXCs)

- SNRs with shell in radio and centrally peaked in thermal X-rays;
- Type II supernovae;
- ~17 SNRs - TXCs.

Name of the class: mixed-morphology SNRs (Rho & Petre 1998) thermal X-ray composites (Jones et al. 1998)



Lazendic & Slane 2006

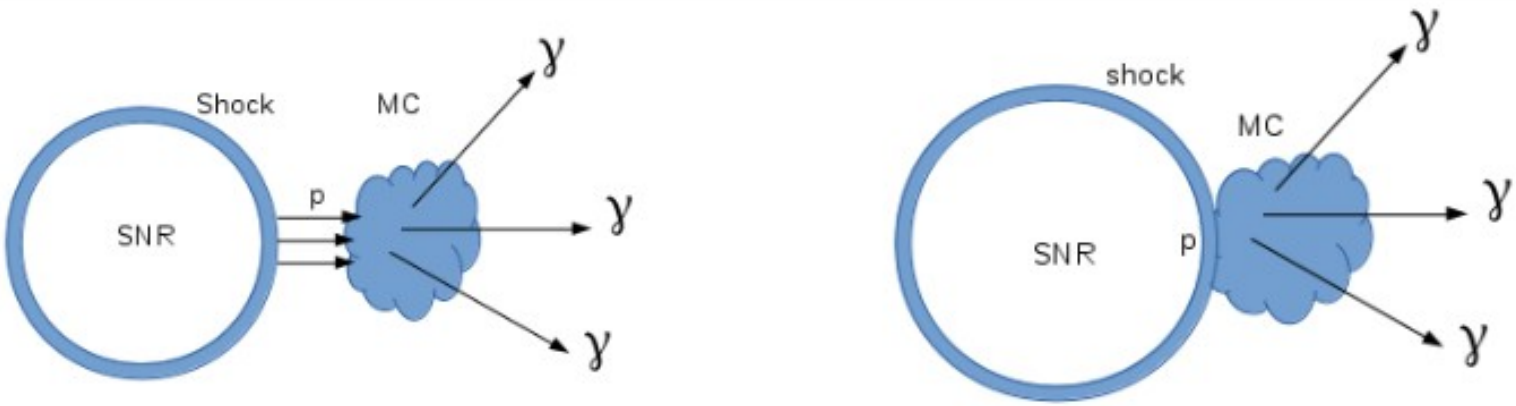


Sun et al. 2004

SNRs near molecular clouds

Two scenarios for γ-rays from SNR + MC

- SNR and MC are separated: protons diffuse toward MC
- SNR and MC are interacting: protons illuminate MC directly



Jiang et al. (2010):

64 SNRs total: 31 shells (48%), 17 TXC+5 composites (34%), 3 plerions

19 of these SNRs are observed in γ-rays: 8 shells, 8 TXC+2 composites

The models of thermal X-ray composites

White, R. L., & Long, K. S. (1991). The Astrophysical Journal, 373, 543.)

That the central thermal emission is caused by dense “cloudlets” that have survived the passage of the forward shock, but are slowly evaporating inside the hot interior medium due to saturated thermal conduction

Cox et al. (1999). The Astrophysical Journal, 524, 179.

The supernova remnant evolve inside a relatively high density of 6 cm −3 . The forward shock has decelerated to velocities below ∼ 200 km s −1 , resulting in a strongly cooling shell; too cool to emit X-ray emission. Because the shocks are radiative, the shock compression factors are large, giving rise to strongly compressed magnetic fields, and compressed cosmic-ray electron densities. As a result the radio synchrotron emission from the shells is strongly enhanced

TXCs as a projection of SNR

A&A 371, 267–273 (2001)
DOI: 10.1051/0004-6361:20010312
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Astronomy & Astrophysics

Thermal X-ray composites as an effect of projection

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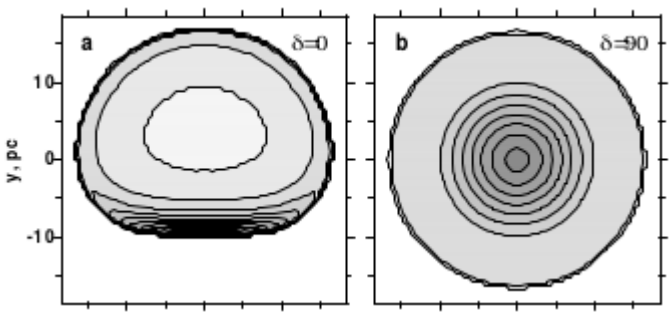
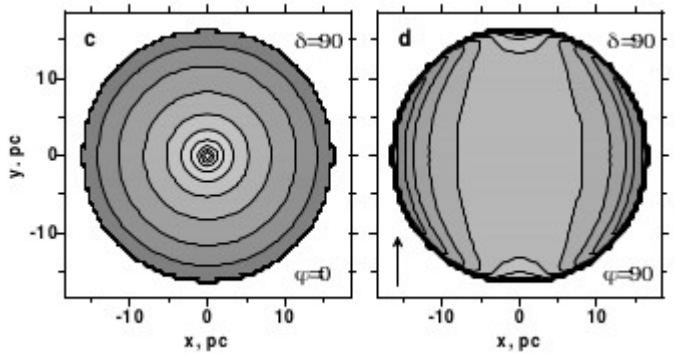
Abstract. A new possibility is proposed to explain the nature of thermal X-ray composites (TXCs), i.e. a class of supernova remnants (SNRs) with a thermal X-ray centrally-filled morphology within a radio shell, as a projection effect of the 2- or 3-dimensional shell-like SNR evolved in a nonuniform medium with scale-height $\leq$10 pc. Both X-ray and radio morphologies, as well as the basic theoretical features of this kind of SNR and the surrounding medium, are considered. Theoretical properties of a shell-like SNR evolved at the edge of a molecular cloud correspond to the observed properties of TXCs if the gradient of the ambient density does not lie in the projection plane and the magnetic field is nearly aligned with the line of sight. So, at least a part of objects from the class may be interpreted within the framework of the considered start. The proposed model suggests that SNRs with barrel-like radio, and centrally-brightened thermal X-ray morphologies should exist. The model allows us to consider TXCs as prospective sources of proton-origin γ-rays.

Key words. ISM: supernova remnants – X-rays: general – radio continuum: general – gamma rays: theory





MHD simulations (Pluto code)

Supported Physics Modules

- Classical hydrodynamics (Euler equations)
- **Magnetohydrodynamics (MHD)**
- Special Relativistic hydrodynamics (RHD)
- Special Relativistic MHD

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &+ \nabla \cdot (\rho \mathbf{v}) &&= 0 \\
\frac{\partial (\rho \mathbf{v})}{\partial t} &+ \nabla \cdot \left(\rho \mathbf{v}\mathbf{v} + p_\mathrm{t} - \frac{1}{4\pi}\mathbf{H}\mathbf{H} \right) &&= 0 \\
\frac{\partial E}{\partial t} &+ \nabla \cdot \left(\mathbf{v}\left[E + p_\mathrm{t}\right] - \mathbf{H}(\mathbf{v}\cdot\mathbf{H}) \right) &&= L \\
\frac{\partial \mathbf{H}}{\partial t} &+ \nabla \cdot (\mathbf{v}\mathbf{H} - \mathbf{H}\mathbf{v}) &&= 0
\end{aligned}
$$

Available Numerical Methods

- Time stepping: RK2, RK3, **Characteristic Tracing**, or MUSCL-Hancock;
- Interpolation: Slope-limited TVD, PPM, WENO and MP5;
- Riemann Solvers: Two-Shocks, Roe, HLLD, HLLC, **HLL** and Lax-Friedrichs.

Parameters for numerical simulations

Uniform ambient MF

Model:

- MHD simulation
- $n(x) = n_o + n_c \exp(-x/h)$

Parameters:

- $n_o = 0.1\ cm^{-3}$; $n_c = 100\ cm^{-3}$
- $E_o = 10^{51}\ erg$

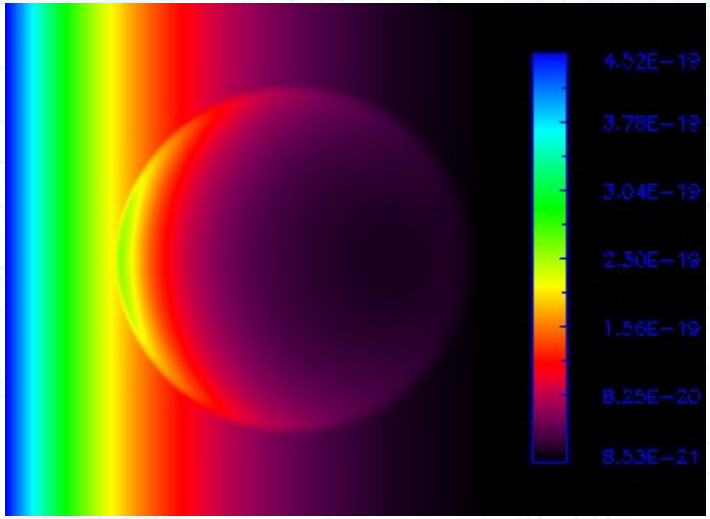
Model:

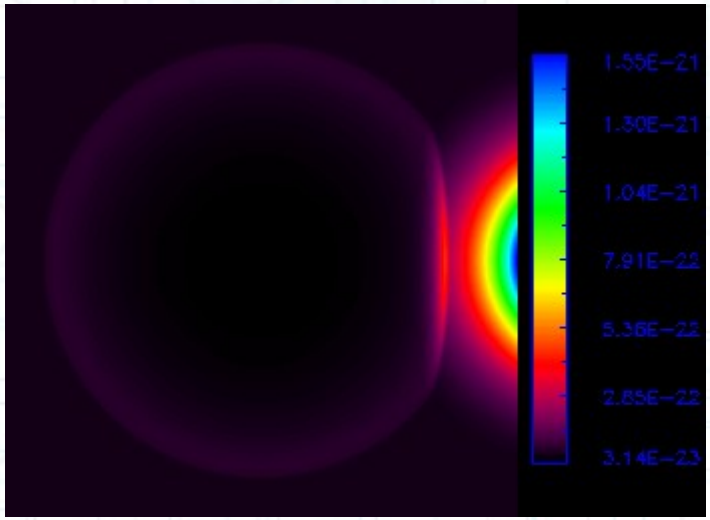
- MHD simulation
- R(MC)= 17.6 pc
- R(SNR)=R(MC)

Parameters:

- $n_o = 0.1\ cm^{-3}$; $n_c = 100\ cm^{-3}$
- $E_o = 10^{51}\ erg$
- $t = 6.8\ kyrs$; $h = 2.5\ pc$

density



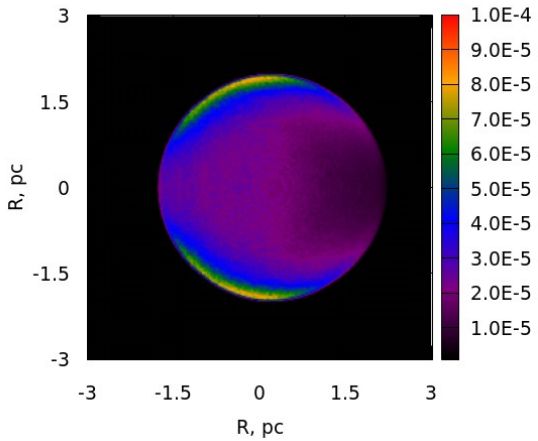


Images for different orientations density gradient

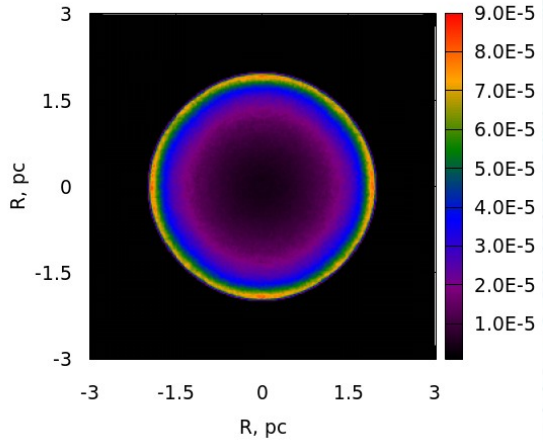
I~KB$^{3/2}$

Radio

$\phi_o = 0$



$\phi_o = 90$



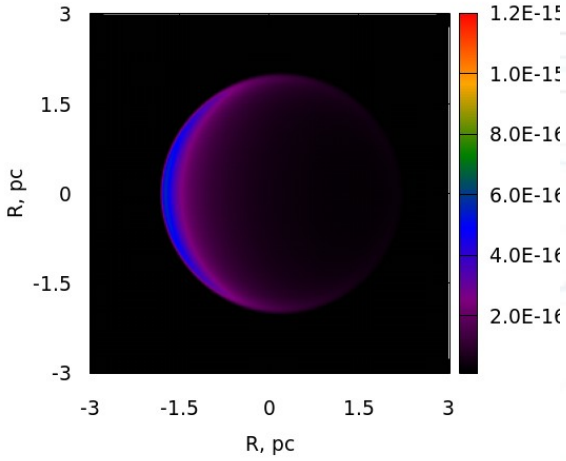
h = 2.5

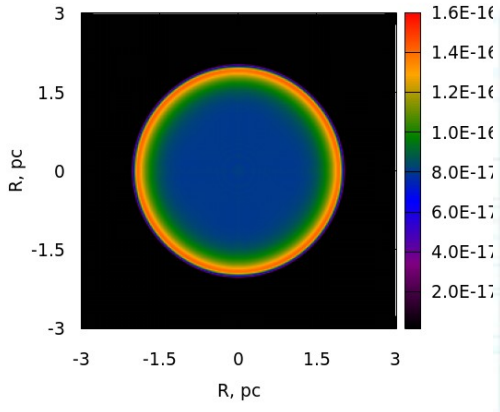
$$n(x) = n_o + n_c \exp(-x/h)$$

h = 2.5

Thermal X-rays

I~ $\rho^2 \Lambda$(T)





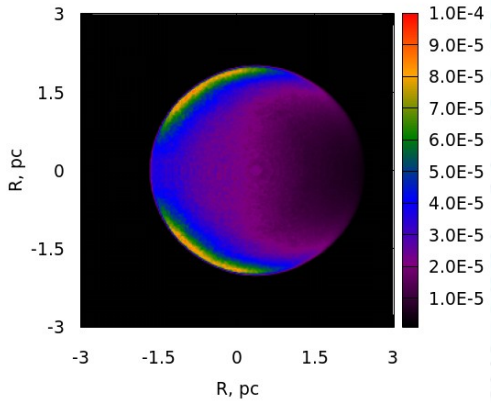
Images for different orientations density gradient

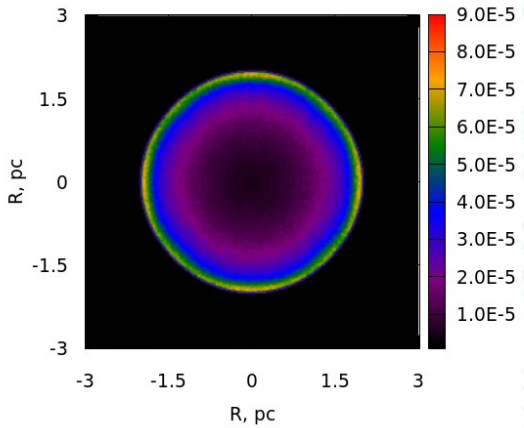
$\phi_o = 0$

Radio

I~KB$^{3/2}$

$\phi_o = 90$





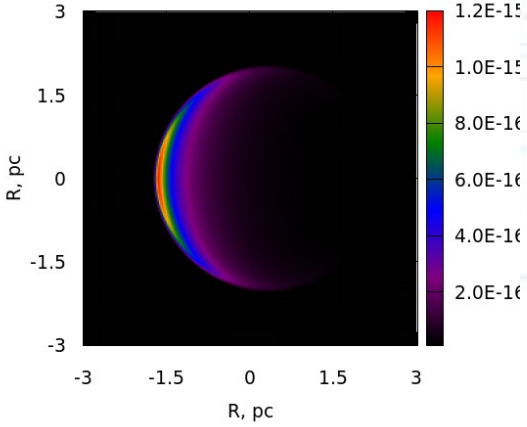
h = 1.5

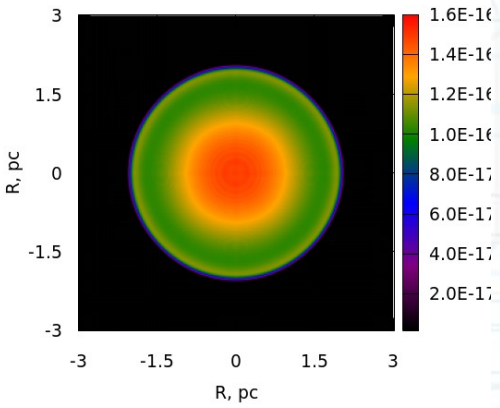
$$n(x) = n_o + n_c \exp(-x/h)$$

h = 1.5

Thermal X-rays

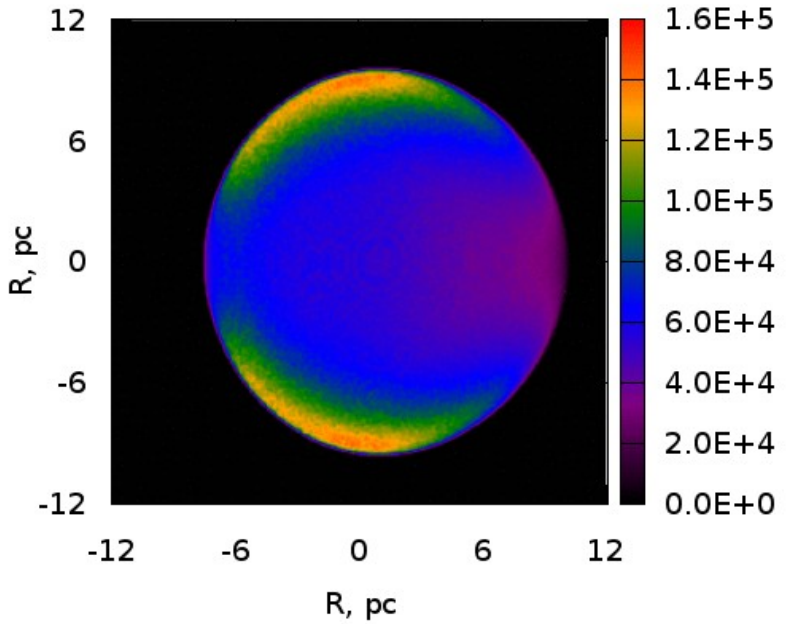
I~ $\rho^2 \Lambda(T)$



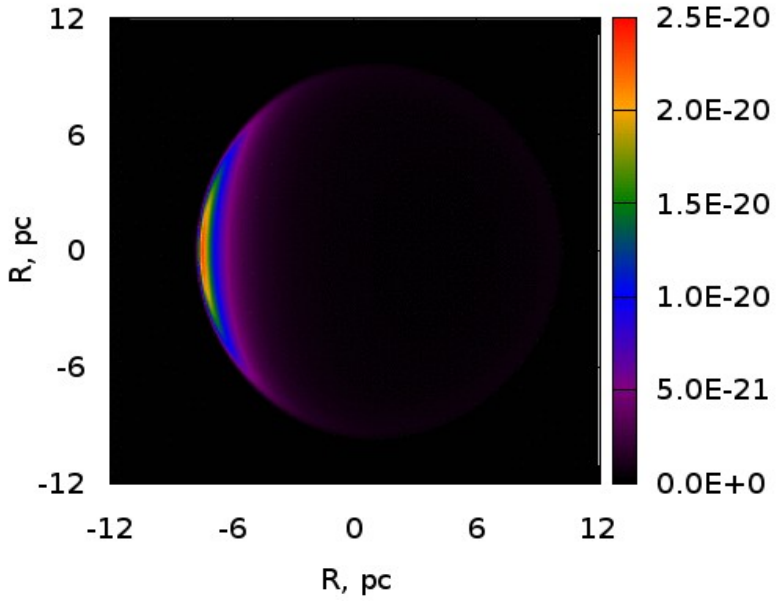


Animatons for different orientations

Radio



Thermal X-rays



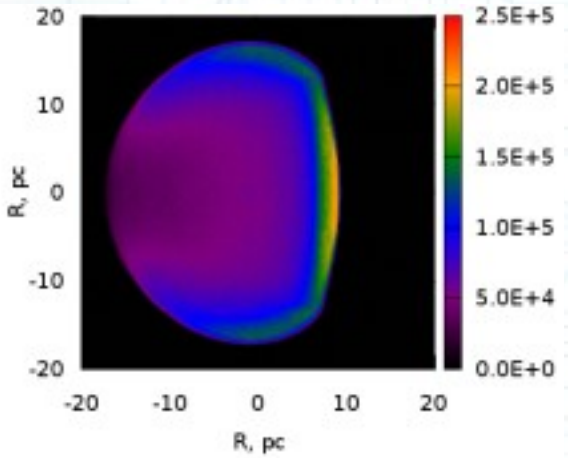
ϕ_o=0-90

Images for different orientations MC

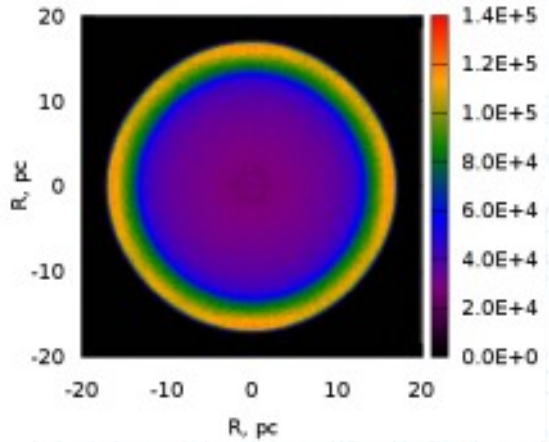
Radio

$I \sim KB^{3/2}$

$\phi_o = 0$

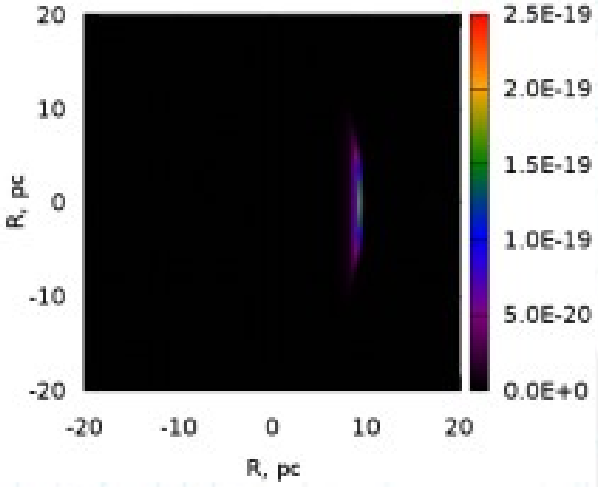


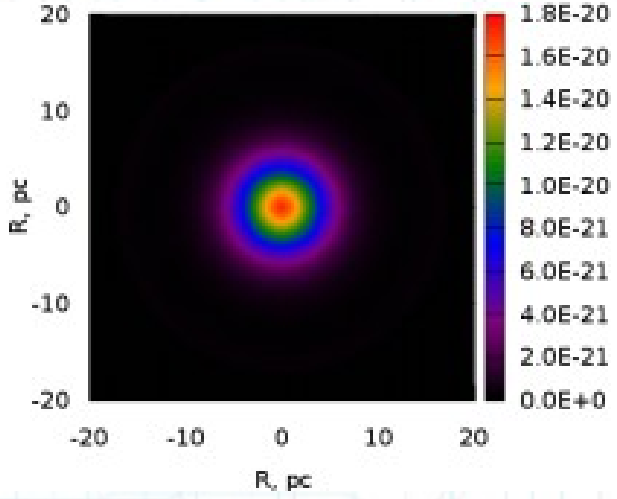
$\phi_o = 90$



Thermal X-rays

$I \sim \rho^2 \Lambda(T)$





Conclusions

- MHD simulations of SNR for different parameters are conducted
- SNR images are built for radio, thermal X-rays, nonthermal X-rays
- Effect of projection of SNR interacting with cloud on LoS is demonstrated