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Galactic Supernova Remnants: From radio frequencies to TeV

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Abstract. Supernova remnants are among the most valuable astrophysical laboratories to study numerous physical processes involved in their evolution and interaction with the surrounding interstellar medium. These objects are one of the most important sources of injection of mechanic energy and chemical enrichment of the interstellar medium, accelerate cosmic rays and generate strong shock waves in such conditions that cannot be reproduced in a terrestrial laboratory. The remnants can emit radiation from radio to gamma- rays. In this report I describe the relevant radiation processes in the different spectral regimes and the information obtained from multifrequency observations of supernova remnants, including some recent results.

Resumen. Los remanentes de supernovas constituyen un laboratorio astrofísico muy valioso para estudiar los numerosos procesos físicos que se desencadenan durante su evolución y en la interacción con el medio interestelar circundante. Ellos son una de las principales fuentes de inyección de energía mecánica y enriquecimiento químico del medio interestelar, aceleran rayos cósmicos y generan fuertes ondas de choque en condiciones que no se reproducen en un laboratorio terrestre. Los remanentes pueden emitir radiación desde el rango de radio hasta los rayos gamma. En este informe describo los procesos físicos generadores de la radiación en las distintas bandas del espectro electromagnético y la información brindada por las observaciones en cada una de esas bandas, incluyendo algunos resultados recientes.

1. Introduction

Supernova remnants (SNRs) are objects that are formed as the result of a violent explosion produced by a star when it loses its thermal or mechanical stability at the end of its life. The explosion of the star, called supernova (SN), is one of the most energetic events in the Universe.

According to the explosion mechanism, SNe can be broadly classified into two groups: **Type Ia**, which are probably caused by a thermonuclear disruption (detonation, deflagration, delayed detonation) of a carbon-oxygen white dwarf that has been acreeting matter from a companion star. These explosions lead to the complete destruction of the star. **Types Ib, Ic and II**, on the other hand, are the product of gravitational core-collapse of massive stars ($M \geq 8\ M_{\odot}$) that have exhausted all their nuclear fuel. Depending on the mass of the core of the star, it collapses leaving either a neutron star or a black hole.

Both types of explosions deposit about 10^{51} ergs of mechanic energy into the interstellar medium and eject several tens of solar masses of stellar material at speeds between 5000 and 10000 km/s. Then a supersonic shock wave is formed, which expands into the surrounding medium and sweeps up the interstellar gas. The result of the interaction of the stellar ejecta and the blast wave with the ambient gas plus the compact stellar core, constitute a SNR.

Supernova remnants modify irreversibly the interstellar medium (ISM). When their blast waves interact with the ISM, there is a change not only in the physical propertie, but also in the chemistry (dissociating molecules). In addition, the SN shocks accelerate, compress, heat, fragment and even destroy surrounding interstellar clouds; excite OH masers and probably initiate new cycles of stars.

At the same time, the observed morphology of the remnants in the different spectral regimes and their evolution are influenced by the mechanism of explosion, the properties of the progenitor star, the presence of a compact remnant, the density distribution of the circumstellar and of the ISM and the strengh and orientation of the ambient magnetic field. In what follows I will describe the origin of the radiation in each band of the electromagnetic spectrum together with the information obtained through the observations in each of them, illustrating with some recent results.

2. Radio Supernova Remnants

Radio observations were historically the earliest to provide systematic discovery and characterization of SNRs. In fact, most of them are radio objects.

Within this spectral regime, the emission is non-thermal, of synchrotron nature. The spectrum is characterized by a power law of the form $S_\nu \ \alpha \ \nu^\alpha$, where S_ν is the observed flux density at the frequency ν and α the radio spectral index.

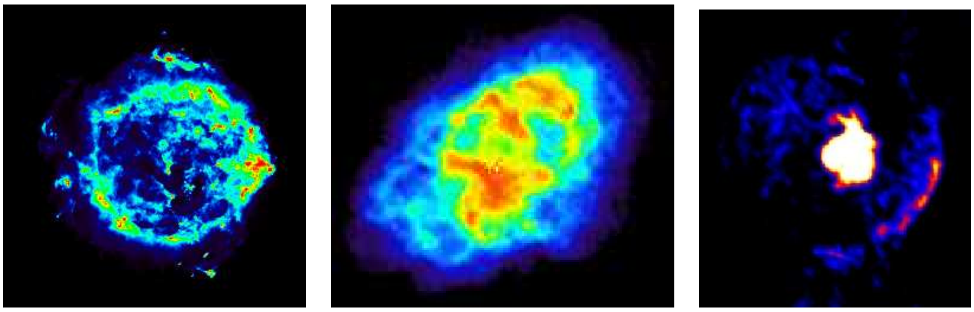
Based on their radio morphology, they have traditionally been divided into three different classes, namely:

a) shell-type: the appearance is like a hollow shell or ring with the radio brightness increasing from the center to the periphery. About 85 % of the catalogued Galactic SNRs belong to this group. In this case the particles responsible for the observed synchrotron radiation are accelerated at the shock front. For the Galactic shell remnants the distribution of α peaks around -0.55, ranging from -0.3 to -0.8, and the degree of linear polarization is between 3 and 5 %. Typical examples of this class are Cas A (Fig. 1a) and Tycho's SNR.

b) filled-center or plerionic: the radio brightness is centrally concentrated. Very few remnants belong to this group, less than 5 %. In this case the accelerated particles and magnetic fields responsible for the synchrotron emission are injected by a central pulsar generated in the supernova event. This pulsar transfers the bulk of its rotational energy in a wind of relativistic particles and Poynting flux. The wind interacts with the surrounding medium creating a synchrotron emitting nebula, also called "Pulsar Wind Nebula" (PWN). In the radio band they are characterized by a flat non-thermal spectrum ($-0.3 \leq \alpha \leq 0$) and high fractional linear polarization (20 to 30 %). PWNe can emite non-thermal radiation over the whole electromagnetic spectrum. For several decades the

Crab Nebula (Fig. 1b) was regarded as the prototype of this class, but in the last years new data with unprecedented spatial resolution have revealed that PWNe are highly structured objects which fall into a variety of morphological classes, depending on the properties and evolutionary state of the pulsar and its surroundings (Gaensler & Slane 2006 for a review). There are many SNRs with a plerionic component for which no pulsar has yet been found, however the detection of a PWN is a strong indication that the powering source must be a neutron star.

c) Composite: it includes both characteristics: the shell and the plerionic components. Figure 1c shows the SNR G0.9+0.1, a typical example of this class of objects.



(a) Shell-type SNR: Cas A. (Image courtesy of NRAO/AUI).

(b) Plerionic SNR: Crab Nebula. (Image courtesy of NRAO/AUI).

(c) Composite SNR: G0.9+0.1 (From Dubner et al. 2007).

Figure 1. Examples of different morphological classes of radio SNRs.

Radio continuum observations of SNRs at different frequencies provide information about the morphology, polarization and spectral index.

Observations with increasingly higher resolution and sensitivity allow us to identify and quantify structures in the shock front, as well as to locate contact discontinuities in the fluid (Dubner et al. 2000; Katz-Stone et al. 2000; Castelletti et al. 2006). This information is essential for improving the numerical simulations of the evolution of SNRs.

Polarization observations provide information on the intensity and degree of order and orientation of the magnetic field. Although in practice such observations can be compromised by effects, as for example the Faraday depolarization, some general results can be derived: young remnants have low polarized fractions and their ordered components are dominantly radial in orientation, while older remnants have more varied geometries with occasionally much higher polarized fractions amd tangential orientation (Reynolds 2004).

Finally, based on accurate radio spectral studies it is possible to constrain shock acceleration theories that predict subtle variations in both spatially resolved (Anderson & Rudnick 1993) and integrated spectra (Reynolds & Ellison 1992). In addition, high resolution ($\leq 1'$) low frequency (≤ 100 MHz) observations in direction towards SNRs are a powerful tool to differentiate physical processes taking place either in SNRs (e.g. shock acceleration) or in the ISM intervening along the line of sight towards them (e.g. thermal absorption) (Brogan et al. 2005).

3. Infrared emission from Supernova Remnants

Infrared (IR) observations of SNRs primarily reveal the thermal continuum emission of shock-heated circumstellar/interstellar dust swept-up at the boundary of the SNR. The main mechanism to heat the dust is through collisions in the X-ray emitting material (Dwek et al. 1987). This fact is supported by the good spatial correlation observed in several SNRs among the infrared radiation and the emission in others spectral regimes (e.g. Tycho, Cas A, Cygnus Loop, IC443, Kepler). As an example, Figure 2 shows an image of Kepler's SNR in the IR, X-ray and optical bands. From this figure it can be noticed that the IR emission is well correlated with the outer blast wave as delineated by X-ray emission and by non-radiative (Balmer dominated) shocks seen in the optical (Blair et al. 2007).

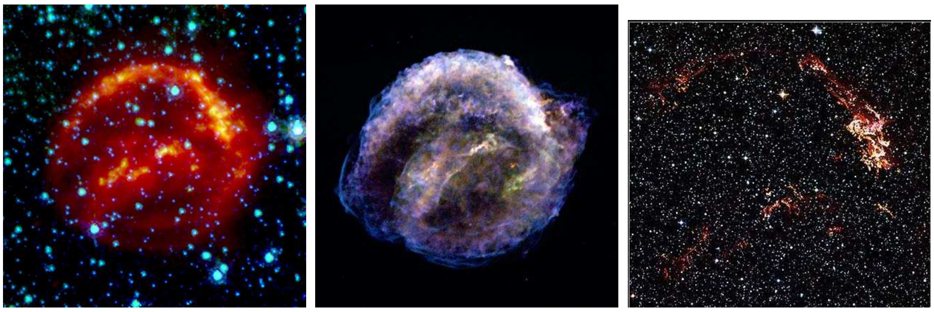


Figure 2. From left to right: *Spitzer* 24 μm, *Chandra* X-ray emission, *Hubble* H_α (From Blair et al. 2007).

Infrared observations towards the very youngest SNRs offer the possibility of detecting dust that has been formed from metal-enriched ejecta of the SN itself before it is dispersed and mixed into the general ISM. *Spitzer* IRAC images of Cas A have revealed the presence of shocked-heated dust from both ejecta and circumstellar medium (Ennis et al. 2006).

Furthermore, the expanding SN blast wave interacting with dusty material is also an important agent of grain destruction and processing in the ISM. Such a process has a profund effect not only on the optical and X-ray spectrum of the remnant, but also on the IR emission (for a detailed review see Dwek & Arendt 1992).

In addition to the thermal continuum emission for dust, shocked gas cools through atomic and molecular lines, many of which emit in the near and mid-infrared region of the spectrum. The dominant coolant for shocked molecular gas over a wide range of densities is H_2 line emission. Since this molecule is one of the main constituents of molecular clouds, its detection is a useful tool to trace regions of interaction between molecular clouds and SNRs.

Infrared atomic fine-structure lines, such as CII, NII, NIII, OI, OIV, FeII, arise from fast shocks cooling into moderately dense gas (e.g. 100 km/s shocks into gas with density $10^2 - 10^3$ cm^{-3}) (Reach & Rho 2000; Reach et al. 2006).

4. Optical emission from Supernova Remnants

The optical spectrum of most remnants exhibits forbidden emission lines produced by a wide variety of elements such us [OII], [OIII], [SII] and [NII] and fainter lines of HeI, HeII, [OI], [NI], [NIII], [FeII], [FeIII], [CaII] and [ArIII], as well as the hydrogen Balmer series. The wide range of ionization, the correlation of electron temperature with the ionization, and the abundances derived from the observed line strenghts, indicate that these lines arise from shocked interstellar material that is cooling radiatively (Smith et al. 1991).
A few remnants are characterized by a spectrum dominated by Balmer lines emission with little or no evidence of the forbidden lines. The nature of these Balmer-dominated shocks can be explained in terms of a high velocity non-radiative, collisionless shock moving into partially neutral interstellar material. These filaments define the current location of the blast wave and provide an important diagnostic of physical conditions in the forward shock (Chevalier & Raymond 1978; Chevalier, Kirshner & Raymond 1980). Figure 3 shows Balmer-dominated filaments delineating the shock front along the northwestern rim of the remnant of the SN 1006. The observations carried out in different epochs lead to measure the proper motions of the filaments (Winkler et al. 2003).

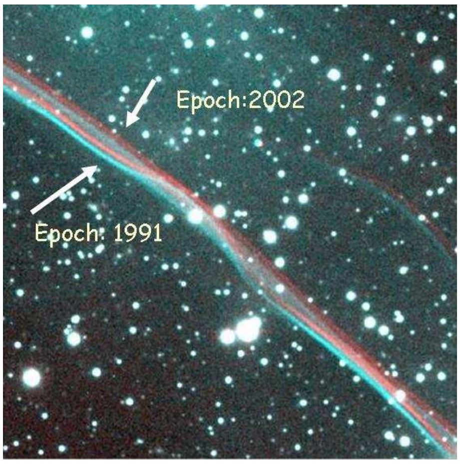


Figure 3. CCD images of the Balmer filaments of the NW rim of SN 1006. The images were taken in 1991 and 2002. The offset of the filaments shows how much they have moved over 11 years. (Courtesy: Middlebury College/NOAA/AURA/NSF).

Interestingly, there are some SNRs, the so called "O-rich", which have a higher oxigen yield. The most prominent members of this group are Cas A, Puppis A and G292.0+1.8. The X-ray spectroscopy confirms that these remnants are also O-rich in this band. Taking into account the abundance of the oxygen it was suggested that these remnants are the product of the most massive stars, possibly remnants of Type Ib/c SNe. In addition, the optical filaments that characterize the O-rich remnants are fragments of nearly pure ejecta that were launched from the core of the progenitor star during its explosion and that remain virtually incontaminated through interaction with interstellar and circumstellar material. Therefore, they are good candidates to obtain a more complete understanding of nucleosynthesis yields.

5. X-ray emission from Supernova Remnants

In the X-ray regime, SNRs are classified by their morphology and the nature of the emission. They can have either a shell or a filled-center morphology, and at the same time the emission in each of them can be thermal or non-thermal in origin.

For most of the shell-like SNRs, the X-ray emission is thermal and it is generated as the result of the blast wave propagating through the ISM. The spectrum is a combination of a thermal bremsstrahlung continuum and emission lines from highly ionized species such us C, N, O, Fe and α elements Ne, Mg, Si, S, S and Ca.

The quantitative analysis of thermal X-ray spectrum provides immense detail regarding the temperature, composition, distribution, and ionization state of material synthesized and ejected in SN explosions, as well as that for swept-up material from the circumstellar and interstellar medium. For very young SNRs the X-ray spectrum is typically dominated by emission from the ejecta. As the blast wave sweeps up ambient material, a reverse shock associated with the deceleration of the ejecta propagates inward, resulting in the formation of two distinct X-ray emitting zones: the forward shock-heated circumstellar/ISM component associated with the explosion blast wave, and a hot ejecta associated with the reverse shock.

With the new generation of X-ray satellites *XMM-Newton* and *Chandra*, it became possible to spatially separate these two shocks and to investigate the structure of the interaction region. In Tycho's SNR, for example, an accurate measurement of the relative distance between the forward and the reverse shocks has provided constraints on the efficiency of particle acceleration at the shocks (Decourchelle et al. 2000). On the other hand, the X-ray high resolution spectrum of Cas A (see Fig. 4), has uncovered remarkable complexity in the structure and kinematics as seen in different elements, providing strong evidence for extensive mixing between different compositional layers during the explosion (Hughes et al. 2000; Hwang et al. 2000).

There is a growing number of shell remnants that present a non-thermal X-ray component of synchrotron origin in their spectrum. As pointed out by Slane (2007), in several cases the synchrotron component completely dominates the thermal one, and the X-ray spectra from the shells are featureless, e.g. SN1006 (Koyama et al. 1995), G347.3-0.5 (Koyama et al. 1997) and G266.2-1.5 (Slane et al. 2001). For other SNRs like Cas A (Gothhelf et al. 2001),Tycho (Hwang et al. 2002) and Kepler (Bamba et al. 2005) thin rims of nonthermal emission surround the remnant directly along their forward shock. The detection of non-thermal X-ray from the shells of SNRs provides evidences that SNRs shocks are capable of accelerating electrons to very high energies.

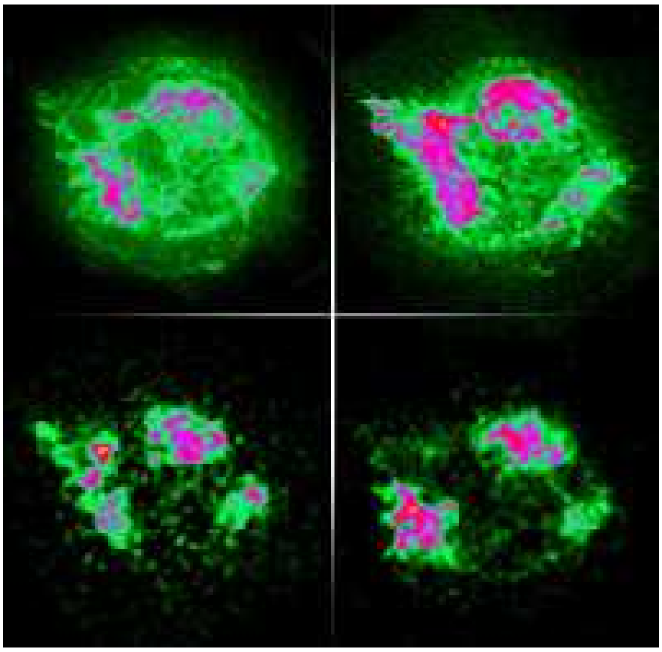


Figure 4. Distribution of some elements ejected in the explosion that produced Cas A. From left to right, top to bottom: Broadband X-ray, silicon, calcium and iron. (From Hwang et al. 2000).

For filled-center SNRs in which the X-ray emission is non-thermal, its origin is synchrotron powered by a central pulsar. In the cases that the emission is thermal its origin has not yet been established. Several scenarios have been proposed to explain it, such as thermal conduction in the remnant interior (Cox et al. 1999), evaporation of clouds that are left relatively intact after the passage of the SNR blast wave (White & Long 1991) or projection effects (Petruk 2001).

6. Gamma-ray emission from Supernova Remnants

6.1. Very high γ-ray emission

Shell-type SNRs have long been considered to be the primary candidates for accelerating particles up to energy close to the "knee" ($\sim 10^{15}$ eV) in the energy spectrum of cosmic rays. This statement is supported by theoretical considerations as well as by experimental facts. From a theoretical point of view, well established models exist explaining how particles can be accelerated in supernova shocks to energies close to the knee (see for example Malkov & O'C Drury 2001; Hillas 2005). Experimental evidence is supported mainly by X-ray synchrotron observations of several SNRs as was mentioned in section 5, indicating an electron population extending up to $\sim$ 100 TeV. Recently, a more direct proof has been provided by the detection of TeV γ-ray emission from a number of galactic SNRs, both shell-type and plerionic in nature with the H.E.S.S. (High Energy Stereoscopic System) instrument. The H.E.S.S. telescope system is currently the most sensitive instrument for γ-ray astronomy in the energy regime above

100 GeV. Figure 5 displays TeV γ-ray excess maps for RX J1713.7-3934 and RX J0852.0-4622. Both γ-ray emitting objects show a shell-like structure with unprecedented detail and with a surprising resemblance of their respective X-ray morphology.

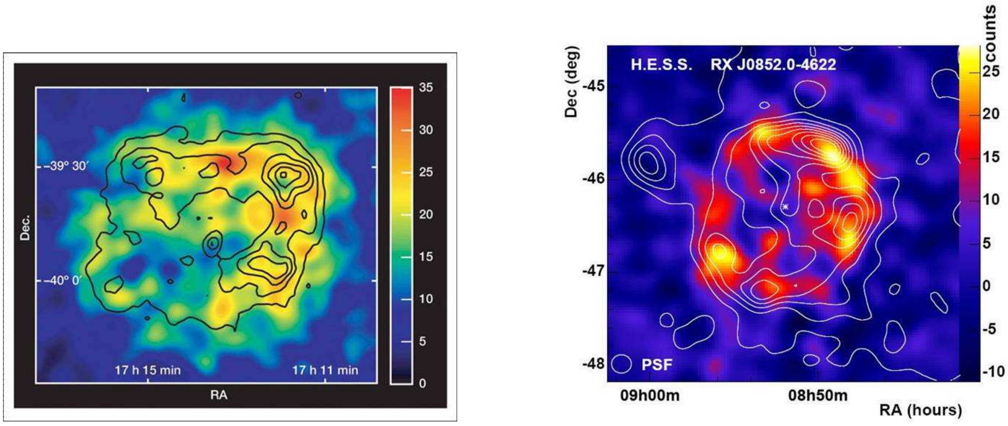


Figure 5. *Left:* TeV γ-ray image of the SNR RX J1713.7-3946 obtained with the H.E.S.S. telescope overlaid with the ASCA X-ray contours in the 1-3 keV range. (From Aharonian et al. 2004).
Right: TeV γ-ray image of the SNR RXJ0852.0-4622 obtained with the H.E.S.S. telescope overlaid with contours of the X-ray data from ROSAT All Sky Survey. (From Aharonian et al. 2005).

Several mechanisms have been invoked to explain the origin of the very high energy γ-ray emission from SNRs: a) non-thermal bremsstrahlung of electrons colliding with ambient gas; b) inverse Compton scattering of ambient photons, such as the cosmic microwave background and c) the decay of neutral pions created by the collision of energetic protons. The latter, if definitively proven, would be the first experimental evidence of proton acceleration in SNRs. All these processes have been extensively modeled for SNRs by several authors (Lazendic et al. 2004; Baring et al. 2005; Malkov et al. 2005; Porter et al. 2006). In spite of the very good morphological and spectral detail provided by the H.E.S.S instrument, without additional constraints, it is difficult to differentiate between these mechanisms and at the moment no strong conclusions on the particle population responsible for the γ-ray emission can be derived. The upcoming GLAST satellite, measuring in the energy range between 30 MeV and 300 GeV might be able to distinguish between the hadronic and leptonic origin for the γ-ray production.

6.2. Explosive nucleosynthesis

Supernovae and their remnants are the main galactic nucleosynthesis sites of production of radioisotopes which are potentially observable through their γ-ray line emission from several tens of keV to MeV energies. Among them, ^{44}Ti is a radiactive nucleus thought to be exclusively produced in supernovae during the first stages of the explosion, although with a large variation of yields depending on the mechanism of explosion, the progenitor mass and the mass cut, which defines the mass of the stellar remnant (Woosley & Weaver 1994, 1995) This make ^{44}Ti an ideal tool to study the inner regions of the supernova explosions. Since the decay time of ^{44}Ti is about 86 years, it is expected this line emission from young (few centuries old) SNRs, as exemplified by the detection of ^{44}Ti in the youngest known galactic SNR Cas A (Iyudin et al. 1994) by the *INTEGRAL* observatory. In this way, the detection of this line becomes a potential method to discover young, missing, probably hidden SNRs.

7. Summary

This report summarizes the valuable information that can be obtained from high quality observations of SNRs throughout the whole electromagnetic spectrum. Many topics, like the parent SN (and hence on the latest stage in the stellar evolution), the properties of neutron stars, the action of strong shocks on the surrounding matter, the mechanisms of particles acceleration, the origin of cosmic rays, and the origin of the gamma radiation, are now better understood on the basis of extended observations and modeling.

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