The 68th Compton Lecture Series

Stars: Their Life and Afterlife

Lecture 5: Supernova Remnants and Cosmic Rays

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Introduction

As supernovae expand, they begin to sweep up matter from the interstellar medium. The expansion slows, and the nature of the light we see from the supernova remnant changes. After a few years, it is no longer powered primarily by radioactive decay of elements, but instead by gas heated by the passing of the supernova's shockwave or by various kinds of nonthermal radiation produced by particles accelerated by the shockwave. Today we will talk about how supernova remnants (SNRs) evolve and what kinds of radiation they can produce. We will also look at how SNRs accelerate particles, creating cosmic rays.

A quick matter of definition: "supernova remnant" refers to the extended structures formed following the supernova: matter ejected in the supernova explosion plus any matter it sweeps up, and/or a pulsar-powered nebula (pulsar wind nebula, PWN) if one exists. SNRs do not include any compact object (neutron star or black hole) that might be left behind. We will talk about those compact objects and PWNe later in the series; for now, we will focus on shell-type supernova remnants like SN 1006 and Tycho.

Supernova remnants go through several evolutionary stages, each of which is heavily influenced by the environment around the star, before fading into obscurity:

1. A free-expansion phase immediately after the explosion, during which the SNR expands with the speed imparted by the explosion.
2. The Taylor-Sedov phase, during which the expanding shell becomes dominated by swept-up matter. The expansion slows, and the ejecta are heated.
3. The Snowplough phase, in which new mechanisms for cooling the gas in the SNR begin to operate.
4. The dispersal phase, in which the SNR loses its identity and mixes completely with the interstellar medium.

Within a few hundred thousand years, a SNR is completely dissipated, its matter – including any metals and heavy elements synthesized in the explosion – mixed with and enriching the interstellar medium. Compare this to the time scales of stellar evolution: even the most massive stars spend several million years on the main sequence, the Sun will live more than 12 billion years, and very light stars are expected to live hundreds of billions of years. Compared to a star's lifetime, its SNR afterlife is a blink of the eye!

Supernova remnants share a lot in common with planetary nebulae, which last some tens of thousands of years. Supernova remnants are able to survive longer – perhaps ten times as long – because of the higher mass and higher speeds involved.

Supernova remnants are fairly large structures: even young remnants, expanding at a few percent of the speed of light, reach sizes of light years pretty quickly – for example, SN 1006 has a diameter of ~ 60 light years after 1000 years of expansion! Older SNRs can reach sizes of hundreds of light years. Since the typical spacing of stars in a cluster is on the order of light years, it's clear that SNRs can impact their stellar neighbors – next week we will take a look at some of the ways they can do that.

Part 1. What kinds of radiation do SNRs produce?

Supernova remnants produce many kinds of radiation. Each one tells us something about conditions in the SNR, and some of them provide key information in decoding what kind of supernova led to the SNR. Let's take a look at those radiations, how they're produced, and what they tell us:

- **Thermal radiation**: Produced both in the shell of the supernova remnant and its interior, in X-rays for young (free expansion and Taylor-Sedov) SNRs, moving to optical and radio for older SNRs.

- **Radioactive decay and ion emission lines**: X-ray and gamma-ray emission lines from the decay of long-lived radioactive elements and from highly ionized heavy elements tell us about the composition of the supernova remnant, and about the types of nucleosynthesis processes that occurred during the late stages of the progenitor's life and during the supernova explosion. The composition of the remnant's interior is often a strong clue as to the type of supernova - thermonuclear or core collapse.

- **Maser emission**: One special kind of emission occurs when a SNR's shock wave hits a molecular cloud: under the right conditions, maser emission from hydroxyl molecules (OH) can be seen in the radio at 1720 MHz. Creating this maser emission requires the presence of a population of OH molecules in an excited state, and this can happen when a SNR shock propagates into a molecular cloud, creating a large number of high-speed collisions between molecules. The observation of maser emission provides a smoking gun for interactions between a SNR and a cloud, and can be used in studying cosmic-ray generation in SNRs.

- **Bremsstrahlung**: German for "braking radiation," it refers to the radiation emitted when charged particles are accelerated as they pass through the electric field of an ion or nucleus. In SNRs, Bremsstrahlung radiation is mostly observed in X-rays and is mostly produced by electrons that have been heated to tens of millions of degrees by the passing of the SNR's shock wave. In this context, it is often referred to as "thermal Bremsstrahlung" since its production is tied to the presence of a *hot* (thermal) population of electrons.

- **Synchrotron radiation**: The radiation produced by charged particles when they are accelerated by a magnetic field. In SNRs, synchrotron radiation is emitted in the radio and X-rays and is often responsible for a large fraction of the radio emission seen from the shell. Some young SNRs show sharply defined X-ray filaments in their shells that are produced by synchrotron radiation. The energetic electrons that create these filaments must be accelerated right at the filaments because they lose energy too quickly to synchrotron radiation to propagate very far; this is why the filaments are so sharply defined! The width of these filaments can be measured and used to estimate the strength of the magnetic field in the shell.

- **Cosmic rays**: Charged particles that have been accelerated to high energies by various mechanisms; most cosmic rays are thought to be created in SNRs. We discuss below how they are thought to be generated. It is the cosmic rays that produce the synchrotron and inverse Compton radiation in SNRs.

- **Inverse Compton scattering**: The transfer of energy from a cosmic ray (usually an electron) to an ambient photon, producing a gamma ray.

- **Neutrinos and gamma rays**: When cosmic rays collide with interstellar matter in and near a SNR, the resulting nuclear reactions can produce neutrinos and gamma rays. These gamma rays have been detected by satellites like EGRET and the Fermi gamma-ray space telescope and by ground-based gamma-ray telescopes like VERITAS and HESS, but the neutrino signal has so far been elusive. Both the neutrino and the gamma ray fluxes should be much higher when an SNR is interacting with a molecular cloud, since a cloud's high density greatly increases the frequency of collisions. Maser emission is therefore a useful tool in identifying regions where very-high-energy neutrinos and gamma rays might be present in detectable fluxes.

Part 2. How do SNRs evolve?

Supernova remnants go through several evolutionary stages, each of which is influenced by the environment around the star, before fading into obscurity:

Beginning with the supernova explosion, the nascent remnant goes through a **free-expansion** phase. In this phase, the supernova ejecta are sweeping up interstellar matter as they expand, but there is too little interstellar matter swept up to significantly impede the SNR. The expansion begins with a speed of 10-20 thousand km/s, a few percent of the speed of light. The expansion proceeds adiabatically[*]: work is done on what little matter is swept up, transferring kinetic energy to it in order to carry it along with the expanding blast wave – and cooling the supernova ejecta. However, right at the shock, gas is strongly compressed and heated to high temperatures – hot enough to shine in X-rays. This phase lasts as long as the swept-up interstellar matter is much less in mass than the matter ejected from the star – typically several hundred years, possibly longer. The youngest known SNR in the galaxy, G1.9+0.3, is still in this phase (see Figure 1). It is only ~100-150 years old, but is located near the galactic center, far enough from earth that its explosion would have been obscured by dust.

As the amount of matter swept up by the SNR approaches and passes the mass of the ejecta, the SNR transitions to the **Taylor-Sedov** phase, named for the physicists who did a lot of the early, foundational work in this area in the 1950's (mainly motivated by the study of atomic bomb explosions). In this phase, the SNR has swept up enough matter that the mass of the shell is dominated by interstellar matter rather than stellar ejecta, and the SNR's expansion is slowing.

The outermost layers of the shell decelerate first, and are rammed by the layers interior to them. This sets up a new, reverse shock that propagates backwards into the remnant, heating the gas as it goes – and converting a lot of the SNR's kinetic energy of expansion into heat. This is a key difference from the first phase: In the free-expansion phase, the kinetic energy of expansion was being transmitted into the swept-up interstellar gas (both heating it and causing it to expand outward), but in this second phase the kinetic energy is being redirected back into heating the SNR ejecta. As in the first stage, this causes the SNR to radiate in X-rays. Cas A (~300 years old) is probably transitioning now from stage 1 to stage 2; Tycho (~400 years old) is an example of an SNR already in stage 2.

As the SNR continues to expand, the accumulated mass gradually cools. When the temperature drops below one million degrees, new ways for the gas to cool begin to operate, and the cooling accelerates. To compensate, the gas right behind the shock front compresses, and the remnant enters its "**snow plough**" phase. IC 443, with an age of a few thousand years and developing in a fairly dense medium (where its shock speeds have dropped to a few hundred km/s or less) is probably in this phase. IC 443's shell still radiates in the optical and radio, but has cooled too much to radiate in X-rays (IC 443's interior, however, is still filled with an X-ray-emitting hot gas formed from the evaporation of the molecular cloud as the shock wave passed by thousands of years ago).

Up till now, the SNR has been expanding supersonically – the ejecta moving faster than the speed of sound in the interstellar medium (~ 20 km/s – 1/1000th the SNR's initial speed!). Eventually the SNR's expansion slows to subsonic speeds, and the SNR moves into the **dispersal** phase, in which it loses its identity and mixes completely with the interstellar medium, enriching it with the heavy elements synthesized during the star's life and death. The Cygnus Loop (~ 50 kyr) is an example.

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[*] Adiabatic expansion – expansion in which a gas exerts pressure on an external medium; in performing work on the external medium, internal energy is lost from the gas, causing it to cool.

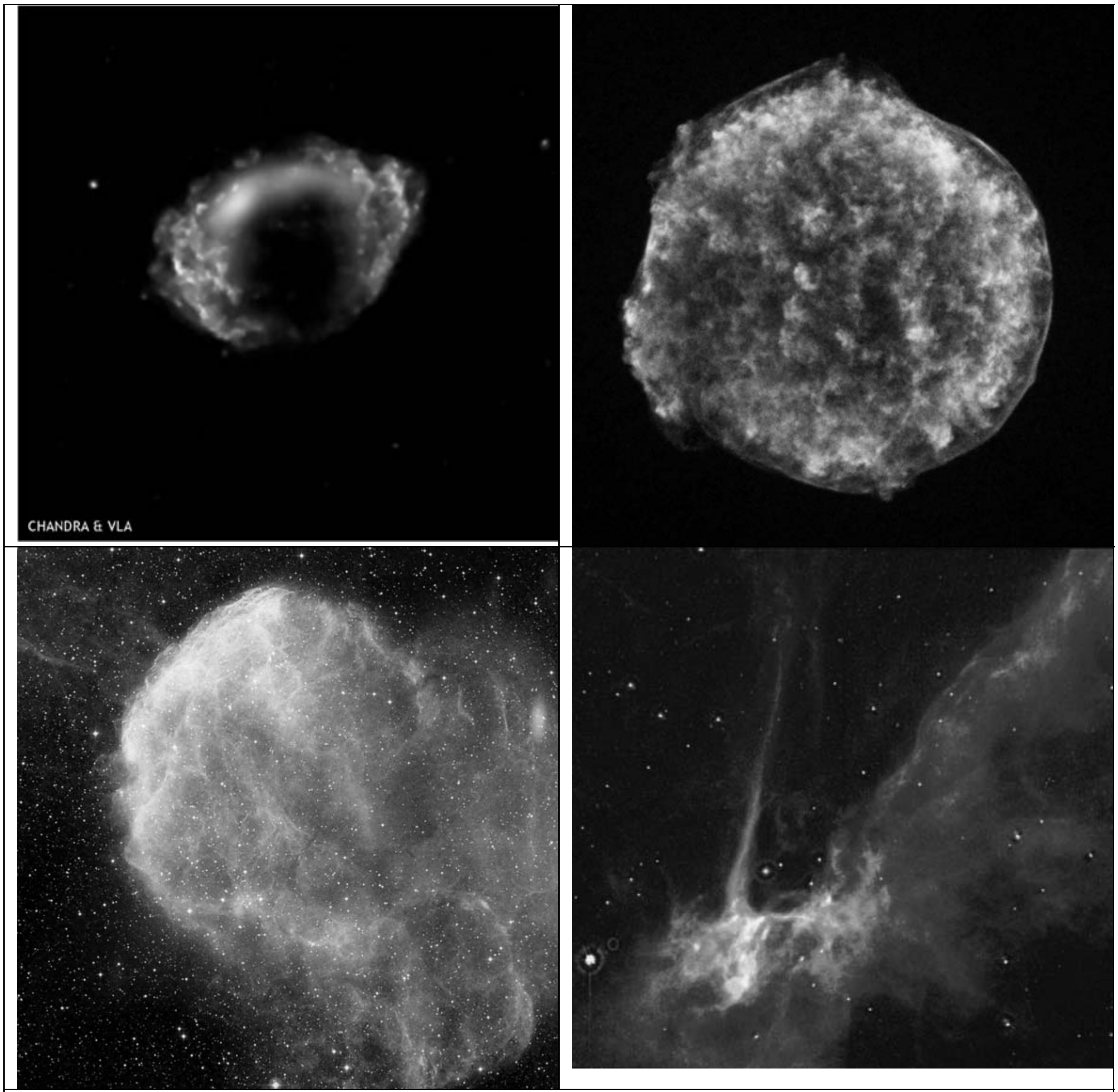

Figure 1. Supernova remnants at different stages of evolution. (upper left) SNR G1.9+0.3, the youngest known galactic SNR at ~100-150 years. It is still in the free-expansion phase. (upper right) Tycho's SNR, ~430 years old and in the Taylor-Sedov phase. (lower left) IC 443, at least a few thousand years old, and in the snow plough phase. (lower right) A section of the Cygnus Loop, ~50 thousand years old, it is gradually dispersing and mixing into the interstellar medium.

Part 3. What are cosmic rays?

Cosmic rays are (primarily) charged particles with very high energies that bombard the earth nearly uniformly from all directions. They were discovered in 1912 by Victor Hess, who measured the rate of ionizing radiation as a function of altitude in a series of balloon flights. It had been known for some years that natural radioactivity, present in the earth and even in the materials used to build scientific apparatus, could ionize gas. The thought was that if one got away from the earth by going to higher and higher altitudes, the rate of ionizing radiation should drop with altitude, as more and more air provided a buffer or shield from earth-bound radioactive elements. By an altitude of several hundred meters, the rate of ionizing radiation should be almost zero. However, what Hess found was that at high enough altitudes (above ~ 1.5 km) the rate of ionizing radiation stopped declining and began to rise again. Table 1 shows data from a similar balloon flight that confirms this result. This meant the radiation had to originate beyond the atmosphere – a clear sign of "cosmic" rays!

Table 1. The variation of the ionization rate as a function of altitude, as measured in a balloon flight by Kolhorster in 1913, confirming Victor Hess's measurements.

Altitude (km)	Change in Ionization Rate from Sea Level (* 10^6 ions/m^{-3})
0	0
1	-1.5
2	1.2
3	4.2
4	8.8
5	16.9
6	28.7
7	44.2
8	61.3
9	80.4

Cosmic rays are primarily protons and helium nuclei, but there are also electrons, positrons, and nuclei of heavier atoms. In a general sense, the term "cosmic ray" can also be taken to include gamma rays and neutrinos as well – but it usually refers to charged particles.

Ever since cosmic rays were discovered, physicists and astrophysicists have been working to understand questions like

- Where do cosmic rays come from?
- How are normal particles accelerated to such enormous energies?
- How doe cosmic rays propagate through the galaxy?
- Is the flux of cosmic rays the same everywhere?

One of the key difficulties in studying cosmic rays is that they are *charged* particles, and therefore their paths bend in magnetic fields. Since they do not travel in straight lines, we cannot observe their directions to identify their sources, as we do with radio waves, X-rays, visible light, and gamma rays[†].

[†] There is one exception: how much a cosmic ray bends depends on its energy, charge and mass – higher energy and lower charge and mass means less bending. At the highest energies, above 10^{19} eV, protons are expected to bend by only a few degrees even over intergalactic distances, and so "charged-particle astronomy" begins to become feasible. The Pierre Auger Observatory, in which the University of Chicago is playing a leading role, is the first cosmic-ray observatory large enough to acquire sufficient statistics at

Cosmic rays fill the galaxy with an average energy density of ~ 1 eV/cm^3, comparable to starlight, the Cosmic Microwave Background, and the galactic magnetic field. Wherever the cosmic rays are produced, they then diffuse in a random walk throughout the galaxy, and a few of them end up in our detectors on earth. Eventually, a cosmic ray's diffusion may take it out of the galaxy, and then it is lost – this happens on a timescale of ~ 10 million years. Replacing the energy in cosmic rays that is lost to diffusion requires a prodigious source of cosmic rays. From the point of view of the energy requirements, supernova remnants appear to be among the only class of objects with sufficient energy: if there is a way for SNRs to convert ~ 10 % of their kinetic energy into cosmic rays, then they can serve as the source of the galactic cosmic rays.

Enrico Fermi was the first to propose a viable mechanism for accelerating cosmic rays, and refinements of his ideas have led to a theory called diffusive shock acceleration that may explain how galactic cosmic rays are produced. In this theory, charged particles near an SNR's shock diffuse back and forth across the shock front many times, and each time they cross the shock front, they acquire a small energy boost (perhaps a few %).

Why do they gain energy each time they cross the shock? Because from the perspective of a nascent cosmic ray, each time it crosses the shock it makes a head-on collision with material flowing towards it.

Why do the cosmic rays continue to cross the shock rather than simply escape? When they cross from outside the shock to inside, there is a chance they will keep on going and be lost from the shock region – a fraction of the particles are lost each time they cross. However, the region immediately behind the shock front is very turbulent, full of complex magnetic fields. Most of the time, a particle will scatter off of these magnetic fields and its direction will be randomized. Eventually the particle is turned around to cross the shock again.

Charged particles streaming outbound across the shock into the interstellar medium manage to create their own fluctuations in the magnetic field, and they eventually scatter off of these fluctuations and return to the shock. So, by scattering off of magnetic fields, cosmic rays can be confined to the region near the shock for a long time, giving them the opportunity to cross the shock front many times and accelerate to very high energies, even exceeding the highest energies we can produce in terrestrial particle accelerators.

The energy gain in this process is proportional to the shock speed, with faster-moving shocks accelerating cosmic rays more efficiently. It is thought that cosmic rays are mainly accelerated during the free-expansion and Taylor-Sedov phases, and it is during these phases that the highest energies will be reached. Acceleration continues during the snow plough phase, but as the shock speed drops, so does the maximum energy that the particles can attain.

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such high energies that they can begin to see anisotropies in the particles' arrival direction – and hopefully, someday, will be able to identify the sources of the highest-energy cosmic rays!

If the cosmic rays were permanently confined to the SNR shock front, we would never see them. However, two factors eventually liberate the cosmic rays: First, the highest-energy cosmic rays are eventually able to overcome the magnetic fields and escape the SNR. In this way, the strength of the magnetic field limits the maximum energy to which a SNR can accelerate cosmic rays. Second, as the SNR evolves, the shock front slows down, decreasing the strength of the magnetic fields in the area, lowering the minimum energy at which cosmic rays can escape. Eventually all cosmic rays escape the SNR. Since the typical lifetime of an SNR (a few hundred thousand years) is much less than the typical lifetime of cosmic rays in the galaxy (~ 10 million years), from our perspective on earth it does not matter that the higher-energy CRs were released first from a particular SNR. We see a blend of all the CRs from an SNR, and more than that we see a blend of CRs from many SNRs!

Coming Up Next Week: Supernova Remnants Continued

Next week we'll look at how supernova remnants influence their environment, and how cosmic rays impact the galaxy at large.

References

Bell, A. R. MNRAS 182, 147 (1978)

Chandra X-ray Observatory website, http://chandra.harvard.edu/index.html

Freedman, R. A. and Kaufmann III, W. J. Universe, 8th ed. (2008)

Hubble Space Telescope website, http://hubblesite.org/

Longair, M. High Energy Astrophysics, 2nd ed. (1994)

Millar, T. J. and Raga, A. C., eds. Shocks in Astrophysics (1995) – especially article by L. O'C. Drury

Credits for Figures

Figure 1: Images of SNRs provided by the Chandra and Hubble websites.