The 65^{th} Compton Lecture Series

The Quest for Gamma Rays:
Exploring the Most Violent Places in the Universe

Lecture 2: When Stars Explode

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Slides and additional information can be found at *http://kicp.uchicago.edu/∼ehays*

1 What are supernova remnants?

Supernova Facts

- Bright explosion signaling the death of a star
- The supernova dims gradually over the following weeks and months
- Supernovae have been seen in our Galaxy every 50-100 yrs, but the last one was observed over 400 years ago by Johannes Kepler
- SN 1987a occurred nearby in the Large Magellanic Cloud and gives a spectacular opportunity to study the earliest development of the remnant. As the blast moves outward, it starts to run into material cast off by the progenitor star some time before the explosion.
- The supernova remnant consists of the expanding shockwave shell caused by the explosion and in some cases a remaining core.
- The shockwave expands at a very high speed, more than 10,000 mi/hr, over a few hundred years sweeping up the material surrounding the original star. After a thousand years the energy has mostly dissipated into the surrounding medium and the remnant will fade away.

Types of Supernovae

- **Gravititional Collapse** - After a star stops burning, the star can no longer hold up its own weight. The outer layers of the star compress its core. When the core can not be compressed any more, it rebounds causing a powerful shockwave. Stars with mass more than 8 times the mass of our Sun can produce supernovae. The core compresses to a dense neutron star[1] and may rotate rapidly forming a pulsar.

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[1] Walter Baade and Fritz Zwicky published this important result on the formation of neutron stars in 1934.

The most massive stars compress the core to the point of forming a black hole. The shock wave that occurs when the core is compressed to the point that it rebounds generates emission at several wavelentghs for hundreds of years following the initial blast.

- **Thermonuclear Explosion** - Stars close to or less than the mass of our Sun do not produce a supernova when the burn out. Instead they shed their outer material and condense into a white dwarf star. White dwarf stars cannot exceed 1.4 × the mass of our Sun[2] or they set off a nuclear chain reaction as electrons and protons combine to form neutrons. It is this type of supernova, known as Ia, that can be used to probe the expansion of the universe.

Are cosmic rays accelerated in supernova remnants?

Cosmic rays permeate space, but we don't know exactly where they originate and how they are accelerated. They are made up of protons and the nuclei of atoms. Their paths are bent by the magnetic fields in our Galaxy causing their direction to change over time. When they arrive at the Earth, they appear to come from all directions in the sky. Those with energies up to about 100 TeV are accelerated somewhere within our Galaxy.

The leading candidates for accelerating the cosmic rays are supernova remnants. There are two good reasons for this.

- **Energy budget** - Supernova remnants release the right amount of energy $10^{51}\ ergs$ to explain the amount of energy contained in cosmic rays in our Galaxy based on what we see at the Earth.
- **Shock Theory** - The best model we have for acceleration of nuclei to TeV energies is diffusive shock acceleration. The shock waves produced by supernova explosions in combination with magnetic field variations can increase the energies of cosmic rays over time. Some cosmic rays can undergo extreme acceleration if the magnetic field conditions are right. The predictions made for the energies and numbers of cosmic rays arriving at the Earth match what is measured. Other predictions must be tested by measuring the properties of the cosmic rays at the site of acceleration.

Gamma Rays to the Rescue

We can measure cosmic rays near the Earth, but that doesn't tell us about where the cosmic rays are accelerated or what cosmic rays are like at their acceleration sites. To complete the picture of cosmic ray acceleration we have to find a way to measure cosmic rays in distant parts of our galaxy. Luckily for us, the places that accelerate cosmic rays are sources of gamma rays. The question is can we see them? Cosmic rays consist of a variety of nuclei, but protons dominate. When protons collide with matter they interact to make pions. It is the decay of the pions that makes the gamma rays we hope to detect.

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[2] This limit was discovered in 1931 by Subrahmanyan Chandrasekhar, later a University of Chicago faculty member. He received the Nobel prize for this and related work in 1983.

pion decay - Highly energetic protons interact with matter to produce particles called pions. Shortly after being created the pion decays to two gamma rays.

2 Detecting Gamma Rays from Supernova Remnants

Ground-based gamma ray telescopes using the atmospheric Čerenkov imaging technique have produced the most interesting results for gamma rays from supernova because of their good angular resolution. This makes it easier to identify the remnant and to correlate the gamma rays with observations at other wavelengths.

Ground-based gamma-ray telescopes can not look at gamma rays directly. The Earth's atmosphere absorbs gamma rays efficiently. Instead they look at large particle showers caused by the gamma ray interaction high above the ground.

Particle Air Showers in the Atmosphere

Ground-based gamma-ray telescopes take advantage of the large air shower of particles and light caused by a gamma ray after entering the Earth's atmosphere. A gamma ray initially produces an electron-positron pair about 12 miles above the ground. The electron and positron are highly relativistic and shortly interact to create more photons through electron brehmsstrahlung. The photons then create more electron and positron pairs and so on. This cascade continues until the individual particle energies drop too low, typically around 5 miles above the ground.

Čerenkov light - Čerenkov light is caused by relativistic particles that exceed the local speed of light in materials like air or water. The local speed of light can be smaller than the speed of light in vacuum and is determined by the index of refraction of the material. The particle interacts electrically with the surrounding molecules causing them to radiate.

The electrons in an air shower travel faster than the speed of light in air. This is analogous to sonic booms that occur when a plane exceeds the speed of sound. The Čerenkov photons are beamed in a cone along the path of the electron. The opening angle of the cone depends on the density of air and increases deeper in the atmosphere. The light arrives within a few nanosecods on the ground in an area of about 200 meters in diameter. The image of the shower can be viewed from anywhere on the ground within this region provided you have the proper sort of camera.

The image of the Čerenkov light contains information about the initial gamma ray.

- The shape of the image indicates the track of the air shower, and therefore the direction of the initial gamma ray. This means that taking images of the shower allow you to map where the gamma rays come from int he sky.
- The amount of Čerenkov light in the image gives the energy of the initial gamma ray. This means that a spectrum for the gamma rays can be made that shows how bright an object is at different gamma ray energies.

Telescopes like VERITAS record images of the sky, a few hundred every second, to look for the images that correspond to gamma rays. The spectrum of the gamma ray sources is a critical test for determining what produced the gamma rays.

Gamma Rays from Supernova Remnants

Ground-based telescopes have detected several supernova remnant shells in our Galaxy.

- **RX J1713.7-3946** - The shell from this remnant is large, about 1° in diameter. The remnant is only a few kiloparsecs (some 10,000 light years) away. Recent higher resolution images from H.E.S.S. show that gamma rays are produced over the whole shell and that the structure is very similar to the X-ray emission. H.E.S.S. has measured gamma rays with energies above 30 TeV. This is the first indication that particles producing the gamma rays must be at eneries close to 100 TeV.
- **Cassiopeia A** - This remnant is further away from the Earth, and so it is fainter than the other detected remnants and appears smaller. The original detection took more than 200 hours, but newee telescopes will be able to see it in a fraction of that time. The size is too small for gamma ray telescopes to detect any structure.
- **Vela Junior** - This is a nearby remnant with similar structure and spectrum to RX J1713.7-3946.
- **SN 1006** - This is one of the remnants which has a known age, which helps in interpreting the data. However, earlier detections have not been confirmed by the newer telescopes.

Although other supernova remnants are detected by gamma-ray telescopes, the emission from these comes from the core region and not the shell. In some cases, there may be gamma rays produced in molecular cloud regions near a supernova remnant instead of in the shell. This kind of object could be an even better test for cosmic ray nuclei because the separated accelerator and target regions make it clearer to distinguish the gamma rays produced by nuclei as opposed to electrons.

The shell remnants that have been detected are used to look for connections to cosmic ray acceleration. The results favor protons as the accelearated particles, but do not yet show that only proton models can explain the gamma rays. The spectrum for RX J1713 shows that although a proton model fits the data well, a model based on electrons can still make an adequate fit. These two models have different expectations for high energy as opposed to very high-energy gamma rays. Further observations of more remnants and also complimentary measurements of high-energy gamma rays using an upcoming space telescope, GLAST, will help to clear up the mystery.