The 68th Compton Lecture Series

Stars: Their Life and Afterlife

Lecture 1: A Tale of Two Supernova Remnants

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http://kicp.uchicago.edu/~humensky/ComptonLectures.htm
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Part 1. What's this lecture series about?

I started my career in nuclear and particles physics. As I was finishing my Ph.D. and deciding where to go next, high-energy astrophysics caught my eye. I thought it was awe-inspiring that we could build machines capable of accelerating particles to high energies and then use those particles to study the nature of matter and the fundamental forces. How much more amazing is it, then, to see that nature already has its own particle accelerators that are capable of producing particles with energies far beyond anything we can consider at this point? In order to have the chance to study how these natural particle accelerators work – among other things – I decided to switch fields from particle physics to high-energy astrophysics.

This is what motivates this series of lectures: there are some amazing objects hanging in the sky, and I find them fascinating not only for what they are and what they do, but how they come to be that way and how they influence their surroundings (including us!).

This lecture series is going to be about stars: how they form (and why they differ), how they evolve, and – especially – how they die and what they leave behind. All along, I want to draw out the interplay between a star and its environment: how does a star's evolution depend on its environment, and what impact does a star – especially in its end stages – have on its environment and neighbors? So to put it another way, we're going to try to answer this series of questions:

- What determines how a star evolves? In particular, how does the environment in which a star evolves influence its fate?
- What final states can a star evolve into?
- How does a star influence its own environment and affect its neighbors?
- What kinds of nonthermal radiation can stars produce, and why are they interesting?

Some of this material may sound familiar to those of you who attended Elizabeth Hays' Compton Lectures on "The Quest for Gamma Rays" (65th Series, Spring 2007). That is because we were colleagues at the U of C for several years, working together on the gamma-ray observatory VERITAS. Dr. Hays is now at the Goddard Space Flight Center working on the Fermi Gamma-ray Space Telescope and is still involved in VERITAS. I promise not to overlap her lectures too much!

Part 2. A Tale of Two Supernova Remnants: SN 1006 and IC 443

As an illustration of how environment impacts the evolution of a star – or in this case its remains – we're going to talk about two supernova remnants (SNRs): SN 1006 and IC 443. We're jumping ahead of ourselves here; in the next few weeks, we'll back up and talk a bit about the interstellar medium, how stars form and evolve, and how they explode, before returning to supernova remnants and other forms of stellar afterlife in more detail. The rest of this lecture is meant to whet your appetite and give you a preview of the kinds of topics we'll cover later in the series – if there's a bit too much jargon, don't worry! We'll cover it in the next couple lectures, and in the meantime you should feel free to ask me questions as we go!

As we look at SN 1006 and IC 443, we'll see that they differ in a lot of ways:

1. They are developing in very different environs: a fairly uniform, low-density region for SN 1006 compared to a dense, clumpy, cloudy environment for IC 443.
2. Their progenitor stars were probably of very different types – but different in ways that make sense for their environments.
3. The supernova remnants are evolving quite differently in response to their environs.

SN 1006 is the remains of a historical supernova, according to records from China, Japan, Europe, and the Arab world. It is relatively nearby (~7000 light years) and unusually far from the galactic plane (~1600 light years). The progenitor star was a white dwarf in a binary system. Mass transferred from the companion to the white dwarf until the white dwarf hit a critical limit and exploded due to runaway thermonuclear fusion. Nothing is left behind in this kind of supernova (called a "Type Ia" supernova).

Figure 1 shows a composite image of SN 1006 as it looks now, combining data taken in radio, optical, and X-rays. It has a round, almost regular shape, with a fairly sharply defined edge and a diameter of 0.5° (~60 light years). The bright rim is a projection effect: the SNR is expanding as a sphere, in 3-d. We see the edges as much brighter than the interior because we are looking through a lot more of the shell at the edge – this is called "limb brightening."

When a star explodes, it sends out a shell of matter at very high speeds, initially 10,000-20,000 km/s. As this shell expands, it sweeps up ambient matter and slows down. How quickly matter is swept up and the shell decelerates depends on the density of the interstellar medium, with a denser medium slowing the shell more quickly. The typical interstellar density is ~1 cm^{-3}. Because SN 1006 is in a rarified medium with a density of ~0.05 cm^{-3}, it's still expanding very quickly – with a speed of ~4500-5000 km/s around most of the remnant. On the northwest (upper-right) side, where it is believed to have recently encountered a region of higher density (~0.2 cm^{-3}, still quite low), the expansion speed is measured to be ~2900 km/s.

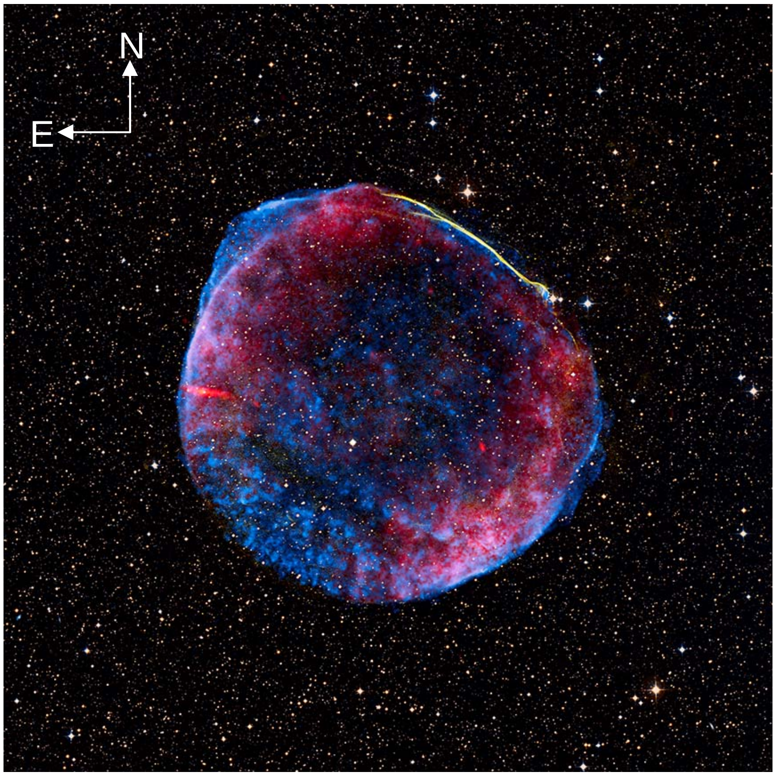

Figure 1. This is a composite image of the SN 1006 supernova remnant, which is located about 7000 light years from Earth. Shown here are X-ray data from NASA's Chandra X-ray Observatory (blue), optical data from the 0.9 meter Curtis Schmidt telescope at CTIO (yellow) and the DSS (orange), plus radio data from the NRAO's VLA and GBT (red).

Note how the northeast and southwest rims have bright, narrow filaments of X-rays (blue). This is related to the magnetic field in the SNR, which runs parallel to those bright rims, with poles at the dim regions (where the field runs perpendicular to the shell). Electrons are being accelerated at the shock front, and they decelerate by emitting synchrotron radiation. The electrons tend to follow the magnetic field lines, and since the field lines are running parallel to the shock front in the northeast and southwest, the electrons can spend a longer time near the shock than they would in the northwest or southeast and can therefore be accelerated to higher energies, high enough that they emit synchrotron radiation in the X-ray band. Synchrotron radiation is a very efficient cooling mechanism for electrons. This means that an electron that wanders too far from the shock front – far enough to no longer be accelerated – will quickly lose too much energy to continue radiating X-rays. This is why the X-ray filaments that trace the shock front along the northeast and southwest are so narrow and sharply defined. We'll talk in more detail in a few weeks about supernova remnants and cosmic ray acceleration.

Now on to IC 443: this is a very different remnant. Figure 2 shows IC 443 in the radio, optical, and X-rays. IC 443 is believed to be a little closer than SN 1006, ~5000 light years away, and it has a similar angular diameter, about 0.75º, for a physical size of ~65 light years. Unlike SN 1006, we don't know very accurately how old IC 443 is. Recent detailed measurements using the X-ray satellite XMM-Newton suggest an age of a few thousand years, at least several times older than SN 1006 and perhaps more. Given that age difference and a diameter that is similar to SN 1006's, it follows that the shell of the remnant must be expanding a lot slower than SN 1006. Now why would that be? Let's take a closer look at IC 443 and the environment into which it is expanding.

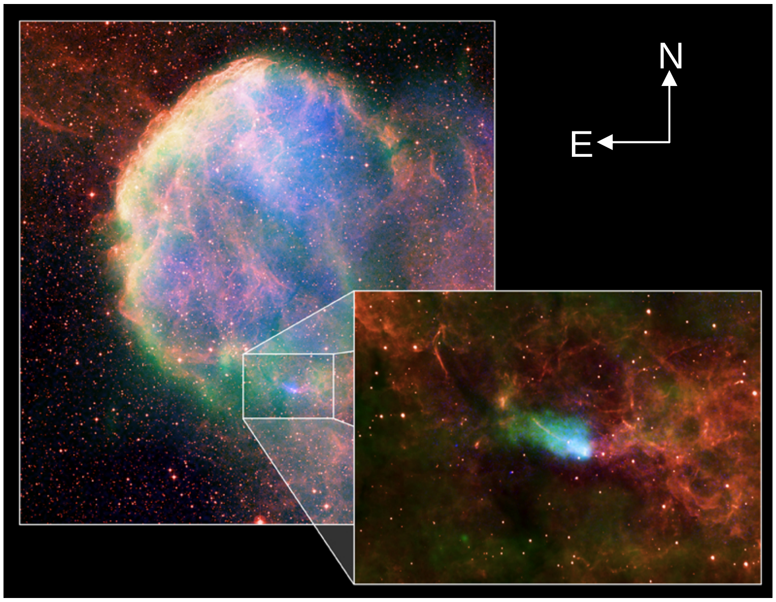

Figure 2. This wide-field composite image was made with X-ray (blue/ROSAT & Chandra), radio (green/Very Large Array), and optical (red/Digitized Sky Survey) observations of the supernova remnant, IC 443. The pullout, also a composite with a Chandra X-ray close-up, shows a neutron star that is spewing out a comet-like wake of high-energy particles as it races through space.

IC 443 is in a very complex region. Figure 3 shows IC 443 more schematically, in a way that helps draw attention to some key features in the composite image of Figure 2. In contrast to SN 1006's fairly uniform shell, IC 443 actually has two subshells. The smaller one is expanding to the northeast into a fairly dense region, while the larger is expanding to the southwest into a lower-density region. Where the subshells meet, a ring-shaped giant molecular cloud encircles the remnant – the dark band across the remnant (towards the right side of the main image in Figure 2; unfortunately the pull-out blocks the lower part of it) is due to attenuation of optical and X-ray light by the part of this cloud that lies in the foreground.

The northeast rim of IC 443 (bright red in Figure 2) has encountered a cloud of atomic hydrogen gas; it is the shock of the expanding SNR hitting the cloud that produces the bright optical filaments. This is similar (if different in scale) to the northwest rim of SN

1006, where bright filaments of X-ray and optical emission indicate an encounter with a denser medium.

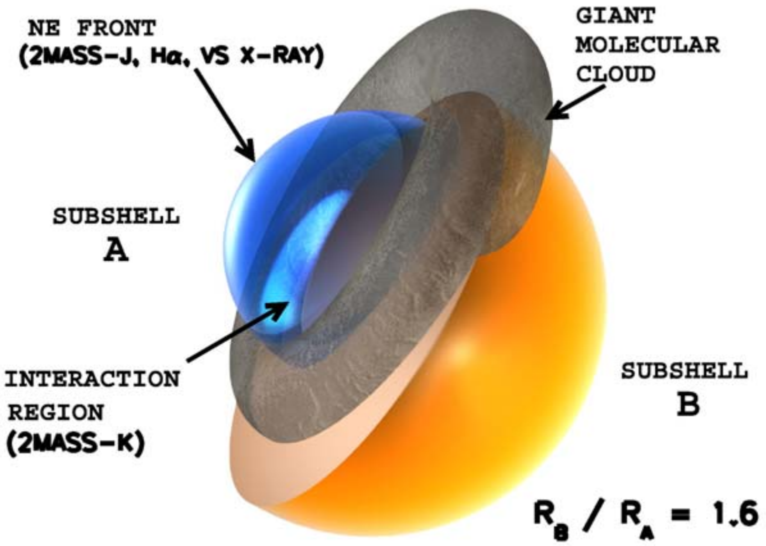

Figure 3. Reproduction of Figure 9 from Troja et al. (2006), showing a simplified view of IC 443 and its environs.

Whereas SN 1006 had a distinct shell in radio, optical, and X-rays, IC 443 lacks an X-ray shell. Instead, most of the X-ray emission is in the interior of the remnant (blue haze in Figure 2). This is another indicator that IC 443 has always been developing in a denser, clumpier region than SN 1006, probably including many small molecular clouds. Unable to just push the clouds away, the shock wave's passage has evaporated the clouds and heated their gas up to X-ray-emitting temperatures.

The pull-out image in Figure 2 focuses on the southern edge of IC 443. The blue region (X-rays) is a Pulsar Wind Nebula (PWN), and the blue/white bright spot towards the right edge of that region is the neutron star that powers the nebula (we'll talk more about neutron stars, pulsars, and PWNe in a few weeks). It's quite possible (though not certain!) that the neutron star is the remains of IC 443's progenitor star, and that the supernova explosion gave the neutron star a "kick" that has it traveling south and away from the remnant. This is yet another difference from SN 1006: IC 443 is thought to be a Type Ib supernova, which leave behind a neutron star or black hole (in this case a neutron star). Type Ib supernovae are the explosions of massive stars, and it is quite natural to find massive stars along the galactic plane and near molecular clouds, as we will see next week.

To summarize, SN 1006 and IC 443 are similar in that both show expanding shells in radio and optical, representing radiation from material swept up, compressed, and heated by the SNR's shock wave. However, they differ in many ways: SN 1006 also has a sharply defined X-ray shell produced by synchrotron radiation, a sign that electrons are being accelerated to very high energies by the shock wave; IC 443 lacks this clear shell. Instead, the interior of IC 443 is filled with a hot, X-ray-emitting gas – the remnants of evaporated molecular clouds and material that its shock wave has already swept through. The ongoing encounters with this dense material has slowed IC 443's expansion to roughly one-tenth the rate of SN 1006's and is causing it to develop very differently in the northeast than in the southwest. Lastly, IC 443 appears to have an associated neutron star, consistent with having a massive star as a progenitor – not surprising given that the remnant falls along the galactic in a region of molecular clouds. On the other hand, no stellar remnant or compact object has been detected in SN 1006, as expected in the case of an exploding white dwarf.

Why did I pick these two SNRs? Together they demonstrate the wide range of features supernova remnants can have – and this kind of variety is common in many of the objects we'll be looking at. Both also emit very-high-energy gamma rays, making them particularly interesting to me. We'll talk more about their gamma-ray emission and its possible implications later in the series, when we talk about supernova remnants and cosmic rays in more detail.

Coming Up Next Week: Where Stars Come From

In which we discuss the interstellar medium, the birthplaces of stars, and stellar formation and evolution in order to set the stage for how they die and what comes after.

References

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Troja, E., Bocchino, F., and Reale, F., Ap. J. 649, 258 (2006)

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

Credits for figures:

Figure 1: X-ray: NASA/CXC/Rutgers/G.Cassam-Chenaï, J.Hughes et al.; Radio: NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS

Figure 2: Chandra X-ray: NASA/CXC/B.Gaensler et al; ROSAT X-ray: NASA/ROSAT/Asaoka & Aschenbach; Radio Wide: NRC/DRAO/D.Leahy; Radio Detail: NRAO/VLA; Optical: DSS

Figure 3: Troja, E., Bocchino, F., and Reale, F., Ap. J. 649, 258 (2006)

Questionnaire

Please either answer these questions before you go and leave them on the table in the back of the room, or bring them back with you next week. They are not a quiz or a test of what you learned today, just a chance for me to get a sense of what you hope to learn in these lectures and what you may already know.

1. What do you hope to get out of these lectures?

2. Have you ever taken a class on Astronomy or Astrophysics? If so, what was it on?

3. Astronomers think that on average a supernova occurs every ~30-50 years in our galaxy. However, we haven't seen one from earth in (most likely) about 400 years, since Kepler's SN of 1604. Why do you think that might be?