

The 68th Compton Lecture Series

Stars: Their Life and Afterlife

Lecture 6: A Galactic Bubble Bath, and Other Considerations

Brian Humensky, lecturer

<http://kicp.uchicago.edu/~humensky/ComptonLectures.htm>

November 15, 2008

Introduction

Today we are going to look at how supernova remnants impact the galaxy at large. We will see that massive stars also play a significant role and cannot be ignored. What kinds of effects do supernova remnants (SNRs) and massive stars cause in the galaxy?

- They create and disperse the heavy elements
- They trigger new rounds of star formation
- They form large-scale structures in the galaxy, called “superbubbles”

Part 2. Winds from massive stars

When we talked about stellar evolution, we saw that during a star’s giant phases its stellar wind could carry off a substantial amount of mass. This is because the star’s large radius means that gravity is a lot weaker in the outer layers than for a smaller star. In addition, the outer layers are cooler – cool enough that heavy elements (“metals”) are not completely ionized, but have some of their inner electrons. These ions are able to absorb starlight (particularly in the UV) in reactions that cause their electrons to remain bound but transition to higher energy levels. Since the starlight is trying to flow out from the star, the absorbed starlight gives the ions momentum that propels them away from the star’s surface.

The fraction of heavy ions in the plasma of the stellar atmosphere is low compared to the amount of hydrogen and helium ions, but collisions in the plasma quickly distribute the outward momentum between all particles, generating a radiation-driven wind. These winds carry a substantial amount of mass from the star:

- Our Sun’s solar wind has a mass-loss rate of $10^{-14} M_{\odot}/\text{yr}$, so it will lose only a tiny fraction of its mass over its 10^{10} year main-sequence lifetime.
- Winds associated with the central stars in planetary nebulae lose mass at a rate of $10^{-7} - 10^{-9} M_{\odot}/\text{yr}$.
- Massive main-sequence and supergiant stars can have mass-loss rates up to $10^{-5} - 10^{-6} M_{\odot}/\text{yr}$.

- Wolf-Rayet (old, very massive stars that have already completely blown away their outer layers) stars have mass-loss rates of $10^{-4} - 10^{-5} M_{\odot}/\text{yr}$, while Luminous Blue Variables (LBVs), known for their instability and mass ejections, can reach $10^{-3} M_{\odot}/\text{yr}$.

In massive O and B stars, the winds are driven with high speeds, up to 2000 km/s (in contrast to the 10-30 km/s for red giants). This high speed, combined with the high mass in the winds, means that the winds carry a lot of energy. Over their lifetime, these massive stars will release $\sim 10^{51}$ ergs in their winds – an amount of kinetic energy comparable to what they will release in supernovae!

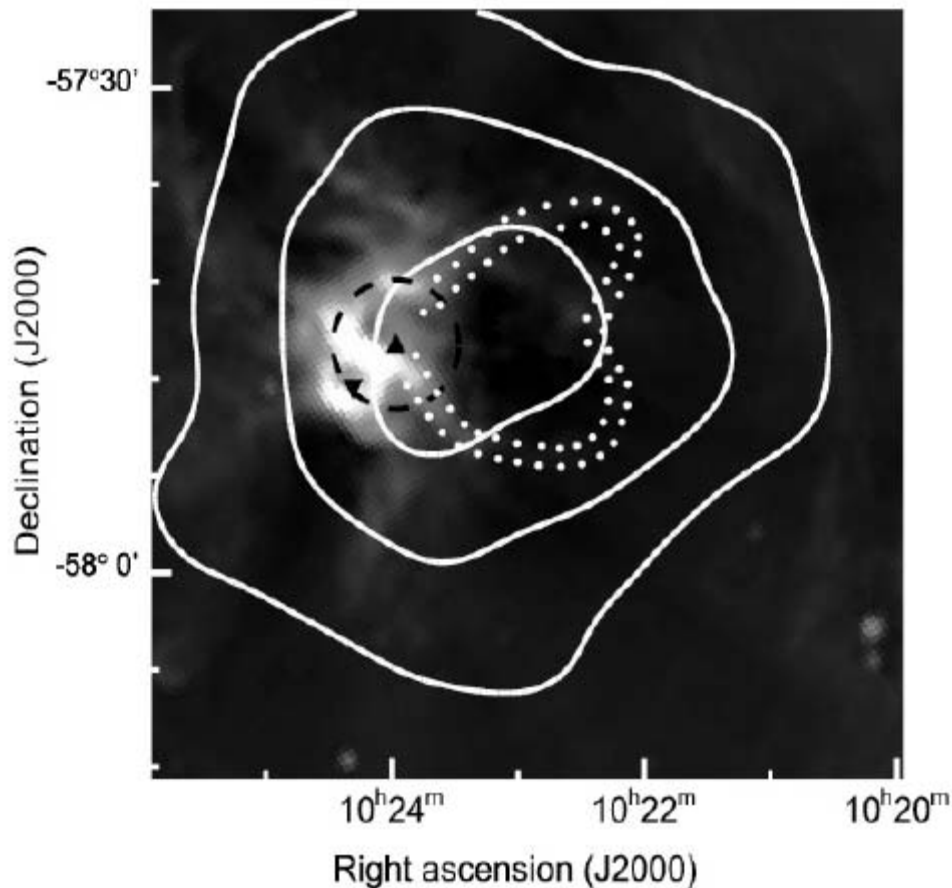


Figure 1. Radio image of the region around the Westerlund 2 star cluster taken at 843 MHz with the Molonglo Observatory Synthesis Telescope (gray scale), with the TeV gamma-ray emission contours overlaid (solid white lines). The black dashed circle indicates the Westerlund 2 cluster; the upright filled triangle is the star WR 20a and the reversed filled triangle is WR 20b. The white dotted lines indicate a low-density “blister” next to the stellar cluster. One scenario suggests that cosmic rays are accelerated in the edges of the blister and propagate through the entire region, producing TeV gamma rays when they interact with ambient gas.

What are the effects of these massive, high-speed winds?

- They carve out a large (several light-year or more radius), low-density cavity around the star, surrounded by a shell of swept-up matter.
- In clusters and OB associations, these cavities can overlap and merge, playing a role in superbubble formation.
- It's been suggested that there may be cosmic rays accelerated at the shock waves where these winds collide with the interstellar medium or with winds from other stars. The HESS observation of TeV gamma-rays from the massive star cluster Westerlund 2 supports this idea (see Figure 1).
- Metals synthesized in the massive star and transported to the surface can be blown off to mix with and enrich the interstellar medium.

Part 3. Superbubbles

Superbubbles are large cavities of hot, low-density plasma that are created by the collective effects of a large number of massive stars. We saw earlier in the lecture series that stars tend to form in clusters as a giant molecular cloud contracts. This means that they not only tend to form close together in space, but also in time – and so, for massive stars, they will also die relatively close together in space and time.

Superbubbles form from OB associations. OB associations are clusters of massive stars of spectral types – you guessed it – O and B.

- O stars are blue-violet in color with surface temperatures of 30,000 – 50,000 K.
- B stars are blue-white in color with surface temperatures of 11,000 – 30,000 K.

The stars are not gravitationally bound to one another, and are “associated” by virtue of having been born in the same giant molecular cloud. Each star is born with a small velocity in a random direction; in an association, these velocities are typically $\lesssim 3$ km/s – a fairly small velocity dispersion. OB associations have a lifetime of ~ 20 million years, the amount of time it takes for their velocity dispersion to, well, disperse the stars. They have typical sizes of $\sim 50 - 150$ light years.

The massive stars in OB associations have fairly short lifetimes: an $8-M_{\odot}$ star lives ~ 40 million years, while a $36-M_{\odot}$ star lives ~ 6 million years, and the most massive stars ($\gtrsim 100 M_{\odot}$) have lifetimes of ~ 3 million years.

Superbubbles are formed from the combined effects of the winds from massive stars and from multiple nearby supernovae. Each supernova and stellar wind injects about 10^{51} ergs of energy into the local medium. Supernova activity begins in an OB association after $\sim 3-6$ million years, the lifetime of the most massive members. Initially, each SNR expands and evolves independently, but as they collide and merge with each other and with wind-blown cavities around other massive stars, the collective expansion begins to behave more like a single expanding wind than a collection of discrete SNRs. This behavior begins after ~ 5 supernovae have exploded in the cluster. In large clusters, it is possible that over some tens of millions of year, as many as 100 to 1000 supernovae may go off, supplying the superbubble with an energy of 10^{53} ergs or more.

The interior of the bubble is a hot, thin plasma glowing in X-rays. The boundary of the bubble is a thin shell of swept-up interstellar gas, visible in the optical and radio. Figure 2 shows the N44 superbubble in the optical, in which the outer shell is clearly visible but the interior appears empty.

As the superbubble expands, it engulfs the remaining stars in its cluster. Any ongoing star formation is cut off in the interior of the bubble, and stars in the interior are now evolving in this hot, low-density ($\approx 0.01 \text{ cm}^{-3}$) medium.

Most supernovae, about 85%, result from the core collapse of massive stars, and most massive stars form in clusters and OB associations – so it is possible that $\sim 75\%$ of all supernovae happen in superbubbles. SNRs produced inside of a superbubble evolve a bit differently from those we typically find in isolation. Most of the SNRs that we see in the galaxy are discovered in radio, while in their Sedov or radiative phases – after they have swept up a large amount of interstellar matter. Inside a superbubble, the density is so low that SNRs must expand to much larger sizes before sweeping up enough mass to radiate appreciably in the radio – and by then, they are so large that their surface brightness (radio light emitted per unit area) is very low. This may be one reason why we see fewer SNRs in radio than expected from the rate of supernovae.



Figure 2. The N44 superbubble in the Large Magellanic Cloud. This image was taken in the optical by the Gemini Observatory.

Locating such a large fraction of SNRs in superbubbles also has implications for cosmic-ray acceleration. First, cosmic-ray acceleration should be a lot more efficient inside superbubbles for a couple reasons:

- The density is very low, so the SNR shock wave expands at a high velocity for a longer time.
- The plasma is very hot, ~ 1 million K, so that it is completely ionized. This reduces the ways in which the shock wave can lose energy.

Second, the SNRs are accelerating matter whose composition has been enriched in metals by previous supernovae in the superbubble – taking this enrichment into account helps to resolve several anomalies in the composition of cosmic rays compared with the composition of our solar system.

Third, it may be possible to accelerate cosmic rays to higher energies inside of superbubbles than in SNRs evolving in the interstellar medium. The maximum energy depends on the strength of the magnetic fields inside the superbubble. So far there are no measurements of the strength of the magnetic fields inside of superbubbles, but given the high energy density inside a bubble, there is reason to believe they may be substantially stronger than in the ISM.

Fourth, the efficiency of cosmic-ray acceleration may also be higher inside of superbubbles because the medium is much hotter and more turbulent than the ISM. This means two things:

- The plasma is hot enough that most particles are sensitive to the shock wave, and gain energy upon crossing it. In isolated SNRs in the ISM, only 0.01-0.1% of particles (the high-energy tail of the thermal distribution) have enough energy to begin to be accelerated.
- Turbulent magnetic fields scatter particles more frequently, allowing them to cross the shock front more often and reducing the number that escape the acceleration process.

Coming Up Next Week: Life on, in, and near a Neutron Star

Next week we'll start to look at the compact remnants of core-collapse supernovae, starting with neutron stars, pulsars, and pulsar wind nebulae. Then, the following week, we'll cover black holes and X-ray binary systems.

References

- Aharonian, F. et al. *Astronomy & Astrophysics* 467, 1075 (2007)
- Boss, A. P. et al. *Astrophys. J. Letters* 686, L119 (2008)
- Cameron, A. G. W. and Truran, J. W. *Icarus* 30, 447 (1977)
- Freedman, R. A. and Kaufmann III, W. J. Universe, 8th ed. (2008)
- Gemini Observatory website, <http://www.gemini.edu>
- Higdon, J. C. and Ligenfelter, R. E. *Astrophys. J.* 628, 738 (2005)