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Gamma-ray probes of supernova engines

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Abstract. The convective-engine behind core-collapse supernovae has become the standard paradigm for normal core-collapse supernovae. Although a broad range of observations have helped to devise and confirm this paradigm, gamma-rays have played a special role in shaping the current picture of core-collapse supernovae. Here we review the role gamma-rays have played in understanding the engine of core-collapse supernovae.

Key words. Stars: Supernovae – Stars: abundances

1. Introduction

Core-collapse supernovae (CCSNe) are among the most powerful transients in the universe, injecting energy and heavy elements into their host galaxies as well as producing neutron stars and black holes. Although the basic power source for these supernovae (the potential energy released when the core of a massive star collapses down to a neutron star) had been proposed as soon as we began to understand the nature of the neutron (**?**). The energy released in such a collapse is 10^{53}erg, 100 times more powerful than the energy needed to explain CCSNe. But understanding how to convert that energy into an explosion has taken over half a century. Most of the energy diffuses out of the newly formed neutron star in the form of neutrinos that then stream out of the star, depositing energy in a small region just above the proto-neutron star.

The basic CCSN engine picture follows the following phases. Silicon shell burning adds mass to an iron core that is supported by thermal an electron degeneracy pressure. As the mass increases, the core contracts under its own weight, ultimately become sufficiently dense to cause electrons to capture onto protons (producing a neutron and an electron neutrino). This capture removes electron degeneracy pressure, causing the core to further contract, accelerating the electron capture and causing a runaway collapse. In addition, the iron atoms are dissociated into alpha particles, reducing the thermal pressure. The resultant implosion occurs nearly at free-fall with maximum velocities exceeding 1/10th the speed of light. This collapse continues until the core reaches nuclear densities where neutron degeneracy pressure and nuclear forces halts the collapse.

The original proposal for the engine behind CCSN argued that this bounce could drive the explosion **?**. However, the energy in this bounce shock is mostly stored in neutrinos and as soon as the neutrinos are no longer trapped in this shock (roughly at 50-100 km), this energy is lost. The shock does not have energy to eject the infalling star and it stalls. The theory evolved, invoking a revival of the shock due to heating from neutrinos leaking out of the proto-neutron star core **?**. In some stel-

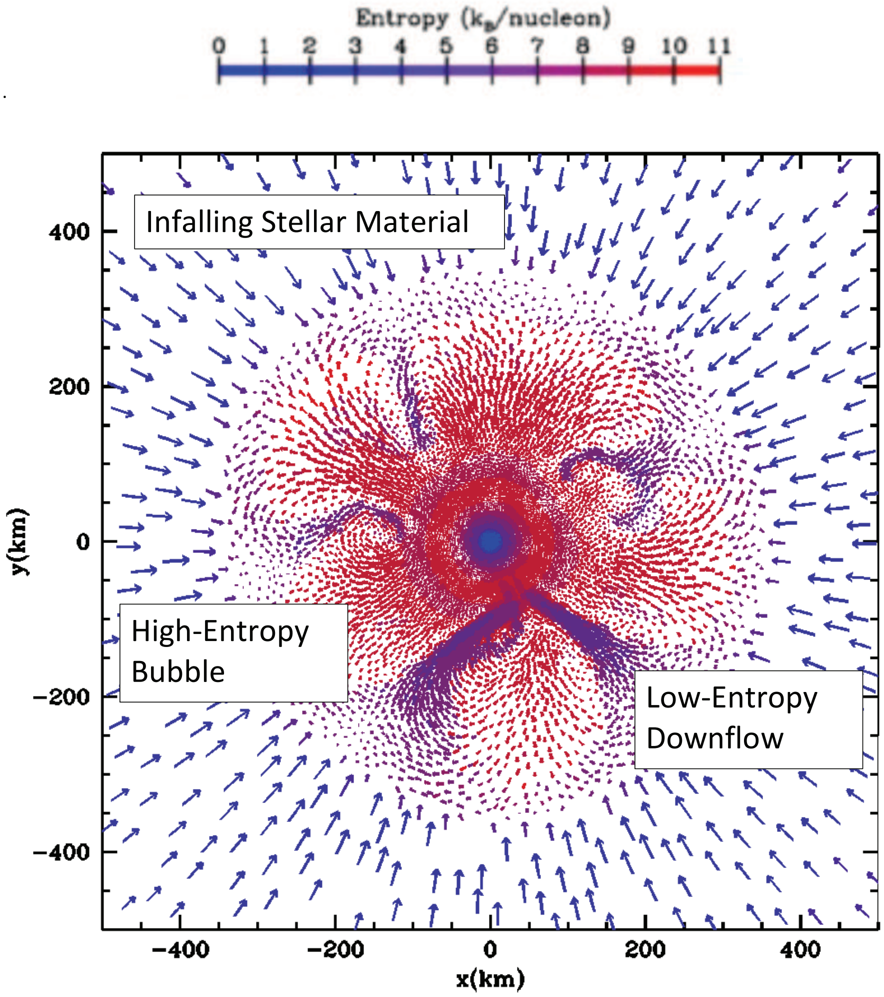

Fig. 1. Anatomy of the convective CCSN engine. The vectors denote the direction and magnitude of the velocity and the colors show entropy (red is high, blue is low). Low entropy downflows are heated by neutrinos and shocks and driven upwards. The downflows prevent material pile-up at the shock. The upflows allow hot material to use this thermal energy to escape the potential well and convert some energy into kinetic energy of the explosion.

lar collapses, the lowest mass cores, this simple picture may be enough. But for more massive stars, neutrino heating is unable to quickly revive the shock and, as mass piles onto the proto-neutron star, it becomes increasingly difficult to drive of matter. In addition, the infalling matter begins to emit neutrinos itself. The proto-neutron star accretes this matter until neutron degneracy pressure can no longer support the core and it collapses to a black hole. We know that some stars do fail to explode, forming black holes. But, in this simple 1-dimensional picture, too many stars failed to explode.

A number of ideas were proposed to enhance this engine, but none were succesful until **?** showed that the region above the proto-neutron star was susceptible to turbulent instabilities and this convection could enhance the neutrino heating by a) allowing energy deposited from neutrinos to convect outwards, converting this thermal energy to kinetic energy and b) preventing the pile-up of material by allowing material to flow down toward the proto-neutron star. This process can be seen in figure 1 with material decelerating at the stalled bounce shock and then convecting to the proto-neutron star in downflows. This material is neutrino-heated, causing some of it to rise and convert the neutrino-deposited thermal energy into an explosion. If it can revive the stalled shock, an explosion is launched.

This engine explains a number of features of supernovae including the fact that the energies of CCSNe are 10^{51} erg even though the collapse releases 10^{53} erg (**?**), high pulsar velocities (**?**), and the compact remnant mass distribution (**?**). But it was supernova asymmetries that led to the development of this engine and these gamma-ray observations have been a driving force and a final confirmation of the convective supernova engine.

2. The role of gamma-rays in the supernova engine

Let us review the role gamma-rays played in the quest to understand CCSN. The appearance of SN1987A in the Large Magellanic Cloud marked the dawn of a new era in supernova science. Before this time, although the CCSN engine seemed likely, there was no decisive evidence that this energy source was behind these cosmic explosions. With SN1987A, we not only observed the burst of neutrinos (**??**) from the collapsing core (a clear indication of either the formation or accretion onto a neutron star or black hole), but we observed, in images taken before the explosion, the progenitor star prior to collapse (**??**).

But not all of the observations supported the 1-dimensional picture of CCSN. The most glaring example was the observations of gamma-rays from SN1987A. Gamma-rays are produced by the decay of radioactive ^{56}Ni and its daughter product ^{56}Co. This ^{56}Ni is produced in the innermost supernova ejecta, material in the convective region and just above it, where the densities and temperatures are sufficiently high to fuse Silicon into α-rich isotopes such as ^{56}Ni and ^{44}Ti. Because these isotopes are produced deep in the stellar ejecta, the gamma-rays produced in the ^{56}Ni do not escape the star. 1-dimensional models argued that the gamma-rays would not be visible for nearly 250 d (**?**). The observed gamma-rays appeared within 150 d. By introducing artificial mixing of the ^{56}Ni through the star astronomers were able to reproduce the gamma-ray signal, but mixing just through Richtmyer-Meshkov instabilities as the supernova shock plowed through the star was insufficient to explain the observations (**?**).

Astronomers began to study mixing in the engine itself and found that the conditions produced convective instabilities (**?**) and these models led to the first calculations following the collapse and explosion of a CCSN (**?**). These first simulations were followed by a host of calculations achieving varying success and different levels of asymmetry (e.g. **????**). Gamma-ray observations of SN1987A provided additional constraints on the extent of the asymmetries. One of the most amazing features of the gamma-ray lines is that they were redshifted, indicating that the ejecta was moving away, not toward us. This can be explained if the explosion was highly asymmetric, with a strong shock moving away from our line of site. Figure 2 shows the gamma-ray signal for

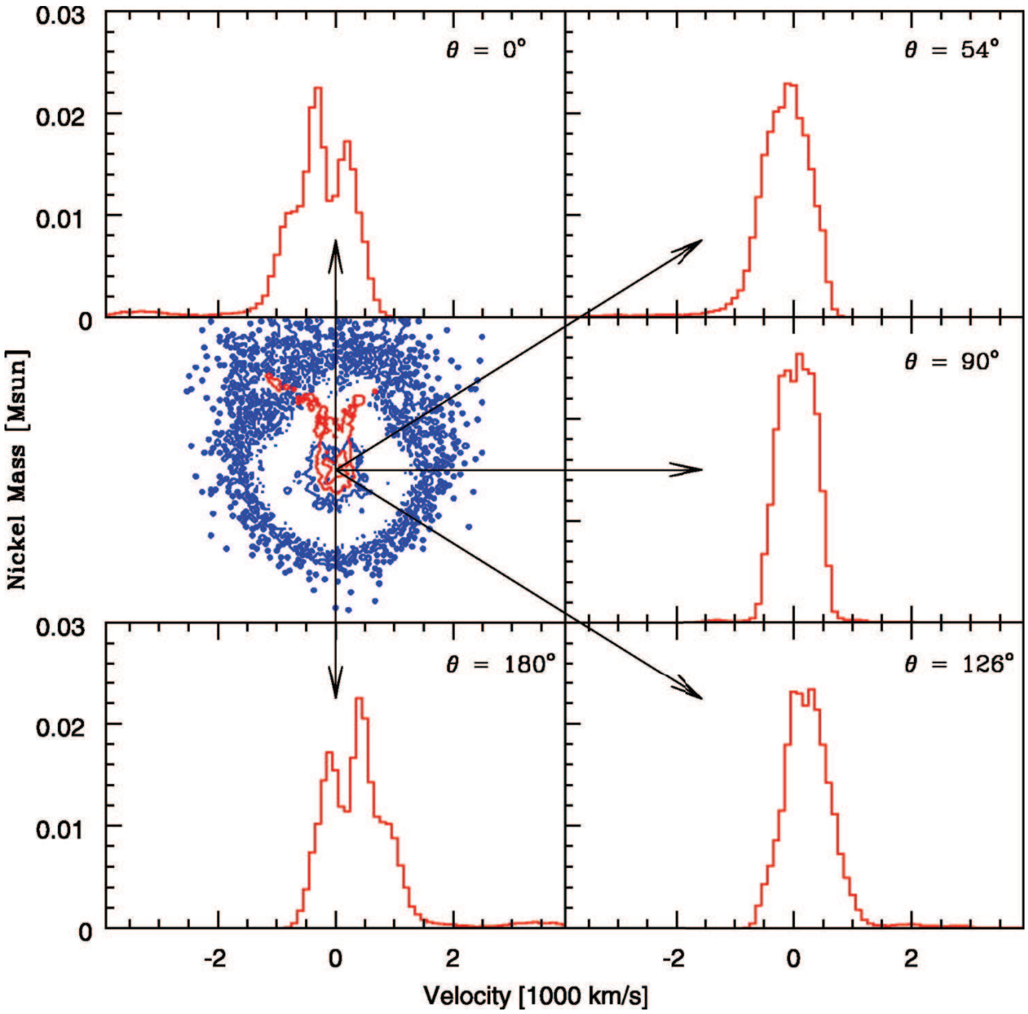

Fig. 2. ^{56}Ni distribution from a core-collapse supernova with a single large explosion. The corresponding gamma-ray line feature is shown for 5 different vieweng angles. For such a single lobe explosion, viewing angle can make a large difference in the whether the line is redshifted or blueshifted (**?**).

an explosion dominated by a single strong outflow. Depending on the direction we observe this supernova, we observe red or blue-shifted lines.

A single strong outflow is possible with the convective engine. But it is likely that the outflows have a more complex structure, following the convective flows in the engine, e.g. figure 1. Like ^{56}Ni, ^{44}Ti is produced in the innermost ejecta. Unlike ^{56}Ni, ^{44}Ti production is extremely sensitive to the outflow (**?**), making it a powerful probe of the details of the supernova engine. The longer decay half-life of ^{44}Ti ($\tau_{1/2} \approx 60$ y) means that it can be observed in hundred-year old remnants. Both its proximity and age make the Cassiopeia A remnant an ideal candidate to be studied in the gamma-rays. The NuSTAR telescope was able to map out this remnant, displaying multiple strong outflows in the 67.87 and 78.32 keV

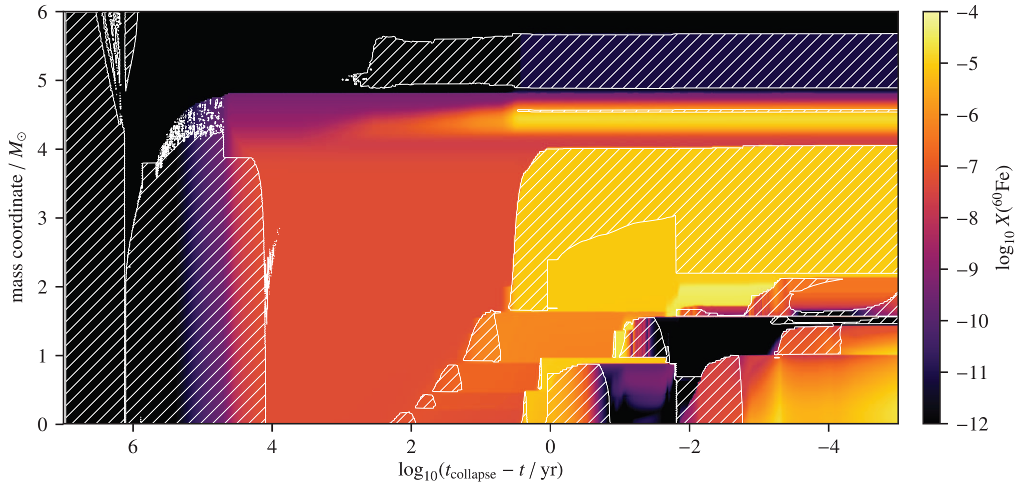

Fig. 3. ^{60}Fe distribution in the stellar interior as a function of time before collapse (**?**). ^{60}Fe is produced in specific burning shells. ^{26}Al probes different regions of the star, allowing astronomers to probe different aspects of stellar evolution.

lines of ^{44}Ti (**??**). The structures, matching expectations of the convective engine and in contrast to the expectations of competing magnetar models have sealed the convective engine as the standard explanation of normal CCSNe. Gamma-rays, which put theorists on the path to the convective engine in trying to match observations of SN1987A, were also able to confirm this engine with observations of the Cassiopeia A supernova remnant.

3. Gamma-rays in the future

Observations of Cassiopeia A have just scratched the surface of what we can learn from gamma-rays in the CCSN engine. Because of the sensitivity of ^{44}Ti production, continued study of the relative iron and titanium production will probe the exact details of the explosion. Currently ^{44}Ti has only been detected in two supernova remnants: Casioppeia A and SN1987A. Next generation telescopes could increase this sample 5-fold(**?**).

But this is not the only potential probe gamma-rays provide of the supernova engine. Gamma-rays probe the distributions of both ^{26}Al and ^{60}Fe, both produced in stellar interiors and transformed/ejected in supernova explosions. Figure 3 shows the production of ^{60}Fe within the layers of a star. This neutron-rich isotope depends sensitively on cross-sections that are, as yet. uncertain. Measuring these abundances could well probe nuclear physics. The decay half-lives of ^{26}Al and ^{60}Fe are long (roughly 1 million years) and current detections observe the diffuse emission in the Milky Way. Using this data to constrain cross-sections, stellar evolution or supernovae requires extracting the information from population models. However, astronomers are beginning to probe these isotopes in specific star-forming regions (**???**) and there is the potential that next generation detectors will observe old remnants (**?**).

Finally, if supernova rate estimates are at all accurate, we are overdue for a Galactic supernova. In such a scenario, broad multi-messenger diagnostics will probe all aspects of the explosion. But gamma-rays will continue to be an important aspect of this analysis. A host of radioactive isotopes probing both the stellar model and the supernova engine will all be observable (**?**). Gamma-rays continue to build on their strong role in directing astronomers only the right path behind the CCSN engine.

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