

Week 3

April 14, 2018

Neutrinos Beyond the Solar System: Supernova Neutrinos



Supernovae are among the universe's most dramatic phenomena. In a tremendous explosion, a dying massive star can outshine a whole galaxy, which has fascinated astronomers for millennia. Today, we understand supernovae as a source of heavy elements essential to the formation of planets and life. Core-collapse supernovae produce a staggering number of neutrinos, the observation of which play a key role in understanding the dynamics of these important systems.

This week, we will discuss neutrinos from supernovae, how they are produced and detected, and prospects for future discoveries.

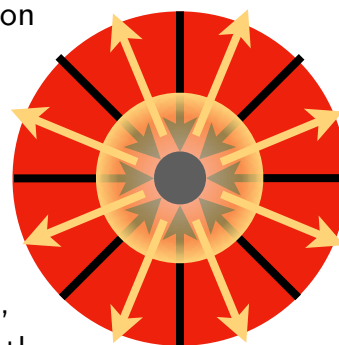
I. Supernovae

Supernovae occur in the final stages of life for certain types and sizes of stars. A tremendous amount of energy is released (about 10^{53} erg, or a billion billion billion times the energy of the most powerful nuclear bomb ever detonated). The small portion of energy released as electromagnetic radiation creates enough light that a supernova can be brighter than their entire host galaxy, and sometimes visible to the naked eye on Earth (the first such instance being recorded in 185 AD).

Taxonomy: Supernovae are typically classified according to their *light curves*, which is a measure of the amount of light observed over time. For the purposes of neutrino physics, we instead differentiate Type Ia (thermonuclear) from other types (Ib, Ic, II) in which the core of the star collapses, producing far more neutrinos than Type Ia. Indeed, about 99% of the energy released is via neutrino emission.

II. Core Collapse

Dynamics: The structure of a star is provided by a balance of inward gravitational pressure and outward thermal and electron degeneracy pressure (a result of quantum mechanics: electrons in the same state cannot occupy the same position). A large star will undergo nuclear fusion processes until a core of iron develops; this is the most tightly bound nucleus, and fusion is no longer energetically possible. Once this core reaches a certain mass (the Chandrasekhar limit), gravitational pressure overwhelms the internal pressure and the



core contracts. Electron capture ($e^- + p \rightarrow n + \nu_e$) converts electrons into neutrinos (which escape), reducing the electron pressure, and high-energy photons begin to disintegrate iron nuclei. Gravity collapses the core until it reaches the density of an atomic nucleus, causing a bounce that sends infalling matter backward as a very dense shock wave. Neutrinos are produced and trapped behind the shock wave, eventually emerging in a burst, and neutrino-antineutrino pairs are created in the new, very hot neutron star.

Detailed computer simulations of these processes provide predictions for the number of neutrinos produced, as well as their energies and time of production. Despite the huge number of neutrinos, astronomical distances mean that only about three core-collapse supernovae per century will be near enough to observe a neutrino burst.

SN1987A: In 1987, neutrinos from such a supernova in the Large Magellanic Cloud (170,000 light years away) were detected in three experiments. With approximately 20 neutrino interactions total, this event confirmed the basic model, but provides insufficient data for detailed studies. These were the first neutrinos ever observed from outside the solar system, and remain the only supernova neutrinos detected.

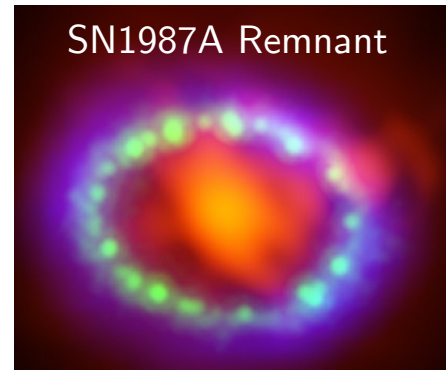


Image: ALMA (ESO/NAOJ/NRAO)/A. Angelich, ESA, NASA



Today: Now, many more (and much larger) experiments are online, such that a similar event would yield many thousands of neutrino interactions to study. A network of neutrino detectors known as SNEWS forms an "early warning system" for the astronomical community.

III. The Diffuse Supernova Neutrino Background

The DSNB is the diffuse bath of neutrinos emanating from past supernovae. These events may be too distant to see individually, but adding them all together can lead to an appreciable signal. A measurement of the DSNB would provide information about the average number and energy of supernova neutrinos, giving context for single-event observations like SN1987A.