

Review for Test #3
SUPERNOVAE

Historical Supernovae in the Milky Way - 7-8 seen with naked eye in last 1000 years. SN 1006 brightest, SN 1054, now the Crab Nebula, contains a rapidly rotating pulsar. Tycho 1572, Kepler 1604. Cas A not clearly seen about 1680 shows evidence for jets, and a dim compact object in the center. SN 1987A first obvious naked eye supernova since Kepler.

Our Galaxy contains about 200 known older supernova remnants, 10,000 to 100,000 years old. These are particularly notable by their radio emission. The average rate of explosion is about once per 100 years in the Galaxy.

Extragalactic Supernovae - many, but dimmer, more difficult to study.

Type I supernovae - no evidence for hydrogen in spectrum.

Type II supernovae - definite evidence for hydrogen in spectrum.

Type Ia Supernovae - brightest, no hydrogen, avoid spiral arms, occur in elliptical galaxies, origin in lower mass stars. Observe silicon early on, iron later. Unregulated burning, explosion in quantum pressure supported carbon/oxygen white dwarf of Chandrasekhar mass. Star is completely disrupted, no neutron star or black hole.

Type Ia - must generate explosion in old (1 to 10 billion years) stellar system. Most plausible mechanism mass transfer onto white dwarf.

Spectra of Type Ia reveal intermediate elements on outside (O, Mg, Si, S, Ca) and iron-like material on inside. Consistent with models of Chandrasekhar mass carbon-oxygen white dwarfs that begin with a subsonic *deflagration* and then ignite a supersonic *detonation*.

Identifying the binary evolution that makes a Type Ia has been difficult. Too much mass transfer will leave Hydrogen in the spectrum. Nova explosions will reduce the mass of the white dwarf, not grow it. There may be too few white dwarf pairs, too few recurrent novae, and too few supersoft x-ray sources.

Type II Supernovae - explode in spiral arms, never occur in elliptical galaxies, normal hydrogen, massive stars, recently born, short lived. Observe H early on, O, Mg, Ca later. Probably core collapse in O/Ne/Mg or iron core. Light curve often shows month's-long "plateau."

Type Ib Supernovae - no hydrogen, but spectrum different in detail than Type Ia. Observe helium early-on, O, Mg, Ca later. Occur in spiral arms. Probably core collapse.

Type Ic Supernovae - no hydrogen, little or no helium early on, O, Mg, Ca later. Occur in spiral arms. Probably core collapse.

Type II supernovae are expected in red giants and are expected to leave behind a neutron star. Explosions of massive stars in binary systems are expected to occur in a bare thermal pressure-supported core from which the outer layers of hydrogen have been transferred to the companion star. The core will continue to evolve to iron, even in the absence of the hydrogen envelope. This is probably the origin of Types Ib and Ic.

Hypernovae - a few recent supernovae seem to have ten times the energy of "normal" Type I and Type II.

Rate of explosion of Type II (about one per 100 years in a galaxy like ours) suggests they come from stars of about 8 to 20 solar masses. These stars probably leave neutron stars. Types Ib and Ic occur about as often as Type II, probably come from roughly the same mass range. Type Ic appear to lose their helium as well. Types Ib and Ic are also expected to leave neutron stars.

Supernovae produce some carbon, and all elements heavier than carbon, mostly from stars with mass greater than 15 solar masses. Above some mass, perhaps 30 solar masses, black holes may swallow all the heavy elements.

The collapse of the core, a gravitational collapse, causes essentially all the protons to be converted to neutrons, releasing a flood of neutrinos and forming a neutron star.

The core collapse explosion of the outer layers of the star may occur in one of three ways:

1. Prompt mechanism: The neutron star rebounds, driving a shock wave into the outer parts of the star.
2. Delayed mechanism: Neutrinos deposit heat behind shock and reinvigorate it.
3. Jet mechanism: the collapsing rotating neutron star squeezes the magnetic field and sends a jet up the rotation axis.

Polarized light from supernovae - the light from a supernova will not be polarized if the explosion is spherically symmetric. All core-collapse supernovae measured to date, Type Ib, Ic, and II, show appreciable polarization and hence are not spherical. They may be "bread stick" shaped or "bagel" shaped or some combination of elongation and flattening.

Jet-induced explosions - Supercomputer computations show that sufficiently powerful jets can blow up a star. The jets plow up and down along one axis creating a "bread stick" shape and driving bow shocks. The bow shocks propagate away from the jets toward the equator where they collide. The result of this collision is to blow much of the star out along the equator in a torus or "bagel" shape. The final configuration is far from spherical, but has jets in one direction and a torus expanding at right angles to the jet. This configuration is consistent with the polarization observations and perhaps with the rings, images and spectra of SN 1987A.

Jet mechanism - computer calculations show that rotation wraps up magnetic field "lines of force" causing the magnetic field and trapped matter to be expelled up (and down) the rotation axis. The generic phrase for this jet mechanism is the "tube of toothpaste effect." It is an open question whether or not sufficiently strong jets to explode a star can be produced in this way when a neutron star forms, but the Crab pulsar and other young pulsars show evidence of jet-like features.

Failed explosion - if there is no core collapse explosion, outer layers fall in, crush neutron star (maximum mass $2-3M_{\odot}$) to form a black hole.

In some cases, maybe Cas A, SN1987A, there might be an explosion and still leave behind a black hole.

Light curves - brightness versus time of supernova. Type Ia brightest, Type Ib, Type Ic, Type II dimmer.

Light curves - shock energy plus radioactive decay. Ejecta must be large before transparent enough for light to leak out. If too small originally (Ia, Ib, Ic) all shock energy goes into energy of motion, light curve must be from radioactive decay. Type Ia brighter, needs more nickel than Ib, Ic, hence different mechanism, a thermonuclear explosion of carbon/oxygen, not core collapse.

Type II show shock energy in plateau, with evidence for radioactive decay at later time.

Explosion of carbon and oxygen or silicon - equal numbers of protons and neutrons, so first make nickel-56. Weak force causes radioactive decay in 6 days (half-life) to cobalt-56 and then in 77 days (half-life) to iron-56. Heat from decay provides delayed source of light.

In core collapse supernova, Type Ib, Ic, Type II, radioactive nickel is produced by shock wave that induces rapid burning of silicon layer surrounding iron core. This produces $\sim 0.1 M_{\odot}$ of nickel.

Betelgeuse - 427 light years away, 15 to $20M_{\odot}$, expected to explode within 10,000 years as core collapse Type II supernova.

Supernova 1987A

- The first supernova observable by the naked eye in about 400 years. It is directly observable only in the southern hemisphere.
- Large Magellanic Cloud—small irregular satellite galaxy about 150,000 light years from the Milky Way, the site of the explosion of Supernova 1987A.
- 30 Doradus or the Tarantula Nebula—the glowing region of new star formation near the site of the explosion of SN 1987A.
- SN 1987A was detected in radio, infrared, optical, ultraviolet, X-ray, and gamma ray bands of the electromagnetic spectrum.
- The star that exploded was Sanduleak -69 202, a blue super giant. There was initial confusion over the identity of the star that exploded. Two stars are visible in photographs taken before the supernova, and two stars were still detected by satellite in the ultraviolet after the explosion. There originally were three stars in the same vicinity.
- Neutrinos were detected, proving that SN 1987A underwent iron core collapse to form a neutron star. No neutron star has been detected.
- Light Curve of SN 1987A
Peak and tail of the curve are explained by energy of radioactive gamma rays from Nickel-56 and Cobalt-56 as they decay to form iron. Gamma rays, high-energy photons, were also directly observed by satellite.
- Rings
The rings around SN 1987A were created by the star before it exploded, perhaps when it consumed a companion star. The ejecta of the supernova have begun to collide with the ring.
- Jets
The shape and motion of the matter ejected by SN1987A are roughly consistent with the expanding "bread stick and bagel" configuration expected from the model of jet-induced supernovae. The "bread stick" is nearly perpendicular to the rings and the "bagel" is expanding in the plane of the inner ring.