

Review for Test #2  
SUPERNOVAE

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Historical Supernovae in the Milky Way - several seen and recorded with naked eye in last 2000 years. SN 386 earliest on record, SN 1006 brightest, SN 1054, now the Crab Nebula, contains a rapidly rotating pulsar and suggestions of a jet. Tycho 1572, Kepler 1604. Cas A, not clearly seen about 1680, shows evidence for jets, and a dim compact object in the center. The events that show compact objects also seem to show evidence of "elongated" explosions or "jets." SN1006 and SN 1572 were probably Type 1a.

SN 1987A in a very nearby galaxy shows elongated ejecta, produced neutrinos so we know it was powered by core collapse.

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

Common elements produced in supernovae, carbon, oxygen, magnesium, silicon, sulfur, calcium, are built up by adding "building blocks" of helium nuclei consisting of four particles, 2 protons and 2 neutrons.

Type I supernovae - no evidence for hydrogen in spectrum.

Type II supernovae - definite evidence for hydrogen in spectrum.

Type Ia supernovae - brightest, no hydrogen or helium, 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. Expected to occur in a binary system so white dwarf can grow. Star is completely disrupted, no neutron star or black hole. Light curve shows peak lasting about a week.

Type II Supernovae - explode in spiral arms, never occur in elliptical galaxies, normal hydrogen, massive stars, recently born, short lived. Observe hydrogen early on, oxygen, magnesium, and calcium later. Probably core collapse in iron core of massive star. Light curve often shows month's-long "plateau." Characteristic of explosion in a red giant.

Type Ib Supernovae - no hydrogen, but observe helium early on, oxygen, magnesium, and calcium later. Occur in spiral arms, never in elliptical galaxies. Probably core collapse.

Type Ic Supernovae - no hydrogen, little or no helium early on, oxygen, magnesium, and calcium later. Occur in spiral arms, never in elliptical galaxies. Probably core collapse.

Light curves of Type Ib and Ic are similar to Type Ia, but dimmer at maximum brightness.

Massive star binaries - Explosions of massive stars in close 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, in the absence of the hydrogen envelope. This is probably the origin of Types Ib and Ic.

Hypernovae - a few recent Type Ic supernovae seem to have ten times the expanding motion energy of "normal" Type I and Type II, but they may just explode faster in some directions than others.

To burn a thermonuclear fuel, the star must get hotter to overcome the charge repulsion. This happens automatically in massive stars supported by the thermal pressure that regulates their burning. These stars produce shells of ever-heavier elements and finally a core of iron.

Iron (with 26p and 30n) is endothermic, absorbing energy. This will reduce the pressure in the core and cause the collapse of the iron core to form a neutron star.

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.

Repulsive nuclear force between compressed neutrons and neutron quantum pressure halt the collapse and allow the neutron star to form.

Neutron star – mass of Sun, but size of a small city. Huge density, surface gravity. Maximum mass of about 2 solar masses.

Forming a neutron star by core collapse produces about 100 times more energy than needed to create an explosion, but most of that energy is carried off by neutrinos.

Ideas to power a core collapse explosion of the outer layers of the star:

1. Prompt mechanism: The neutron star rebounds, driving a shock wave into the outer parts of the star. The bounce shock occurs, but is insufficient to cause an explosion.
2. Delayed mechanism: Neutrinos stirred out by the boiling neutron star deposit heat behind the shock and reinvigorate it. Not clear this is sufficient.
3. Jet mechanism: the collapsing rotating neutron star squeezes the magnetic field and sends a jet up the rotation axis. Naturally makes asymmetric explosion, but not yet clear sufficiently strong jets are produced.

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 “breadstick” shaped or “bagel” shaped or some combination of elongation and flattening.

Jet mechanism - rotation will produce a dynamo amplifying magnetic fields. 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, other young pulsars, Cas A and SN 1987A show evidence of jet-like features.

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 “breadstick” 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.

Jet-induced asymmetry – in addition to producing the jet/torus shape, the jet model predicts that iron is blown along the jet and other elements in the outer layers, oxygen, magnesium, and calcium are ejected in the equatorial torus. This may provide an observational test of the model.

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

Pair-formation explosion – very massive stars, more than  $100 M_{\odot}$ , are supported by thermal pressure and get hot enough to create matter and anti-matter, electrons and positrons when the core of oxygen develops. The conversion of energy to electrons/positrons removes thermal pressure. The oxygen core contracts and then explodes completely; producing a huge amount of radioactive nickel and a very bright luminosity, but no compact remnant. Such an event might have been recently discovered.

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 (O, Mg, Si, S, Ca) on outside 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*.

Detonation alone would turn whole white dwarf to iron. Deflagration alone leaves too much unburned carbon. A combination of deflagration converting to detonation seems to account for the observations.

Identifying the binary evolution that makes Type Ia has been difficult. 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.

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

Light curve mechanisms - shock energy plus radioactive decay. Ejecta must be large in radius before the matter is transparent enough for light to leak out. If the star is too small originally (Ia, Ib, Ic) all shock energy goes into energy of motion; light curve must be from radioactive decay.

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.

Type Ia brighter, need more nickel than Ib, Ic, hence different mechanism, a thermonuclear explosion of carbon/oxygen, not core collapse, produces  $\sim 1/2 M_{\odot}$  of nickel.

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

In core collapse supernovae, 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.

Pair-formation supernovae are predicted to produce 10-20  $M_{\odot}$  of nickel.

Betelgeuse - 427 light years away, 15 to  $20M_{\odot}$ , is 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 170,000 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 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. Dim compact object in Cas A might be related. A black hole is still a possibility.
- Light Curve of SN 1987A - Shock breakout in first day. Subsequent 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 produced specifically by Cobalt-56, were also directly observed by satellite. SN 1987A ejected  $0.07 M_{\odot}$  of radioactive nickel.
- 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 “breadstick and bagel” configuration expected from the model of jet-induced supernovae. The “breadstick” is nearly perpendicular to the rings and the “bagel” is expanding in the plane of the inner ring.