

Review for Test #2
SUPERNOVAE

Historical Supernovae in the Milky Way - several seen with naked eye in last 1000 years. 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.

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. 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 H early on, O, Mg, Ca later. Probably core collapse in 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.

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

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, 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, but they may just explode faster in some directions than others.

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. Types Ib and Ic are also expected to leave neutron stars.

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.

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.

Iron (with 26p and 30n) is endothermic, absorbing energy. This will reduce the pressure 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.

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. This is known to occur, but to be insufficient to cause an explosion.
2. Delayed mechanism: Neutrinos stirred out by the boiling neutron star deposit heat behind 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 "bun" shaped or "bagel" shaped or some combination of elongation and flattening.

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, other young pulsars, and Cas A 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 "bun" 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.

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.

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.

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 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.

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

Type II supernova.