Review for Test #2
SUPERNOVAE

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.

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 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 H early on, O, Mg, Ca 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, O, Mg, Ca later. Occur in spiral arms, never in elliptical galaxies. Probably core collapse.

Type Ic Supernovae - no hydrogen, little or no helium early on, O, Mg, Ca 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 1c 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.

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 and 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 and finally a core of iron.

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.

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 100x more energy than needed to create an explosion, but most of that energy is carried off by neutrinos.

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. 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, O, Mg, Ca, 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 ~2$M_\odot$) 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 (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*.

Identifying the binary evolution that makes Type Ia at the rate of 1 per 300 yrs in a galaxy like ours 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 curve mechanisms - shock energy plus radioactive decay. Ejecta must be large 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, produce ~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 ~ 0.1 $M_\odot$ of nickel.

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

SN 2006X discovered February 7, showed O, Si, Ca. It is a Type Ia.

SN 2006aj discovered February 18. Showed no H or He. It is a Type Ic and is associated with gamma-ray burst GRB060218.