Review for Test #2
SUPERNOVAE (continued)

Stellar balancing act — dynamic equilibrium. A star spends most of its lifetime at a relatively constant size, temperature, luminosity, etc. while it fuses some fraction of its hydrogen into helium. During this time there is a balance between the forces inward and the forces outward.

Forces inward — due to gravity, without the forces acting outwards the star would collapse.
Forces outward — pressure

Thermal pressure — For most of the lifetime of the star this is the dominant source of outward pressure. With this pressure a star can regulate its temperature.

Regulated temperature – the nuclear burning is regulated when thermal pressure dominates, for instance, on the main sequence. If too much energy is temporarily lost, the star contracts and heats, increasing nuclear input. If too much energy is temporarily gained, the star expands and cools, and nuclear input declines.

Quantum Theory – Exclusion principle, uncertainty principle.

Quantum pressure — Electrons cannot occupy the same region of space if they have the same energy. As matter is squeezed down, electrons develop more “uncertainty” energy depending only on the density and independent of the temperature. The electrons’ resistance to being squeezed any closer together provides pressure independent of temperature. With this pressure, a star cannot regulate its temperature.

Unregulated temperature — the process of energy loss, contraction, and heating is stopped when the core becomes so compact and dense that electrons are squeezed together and the quantum pressure dominates. Broken thermostat. If such a star (or core) loses energy, it cools since pressure does not depend on the temperature, so there is no loss of pressure and the star does not contract and heat. If the star gains energy, it heats up, more nuclear reactions, more heat, explosion!

Red Giant — when hydrogen burns out in the center, excess heat flowing from the contracting core causes the outer layers to *gain energy.* They then *expand and cool.* The outside becomes larger, cooler, redder, and more luminous.

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.

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, supported by the thermal pressure, will continue to evolve to iron, even in the absence of the hydrogen envelope. This is probably the origin of Types Ib and Ic.

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 highly 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.

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 standing 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.

Standing shock – a strong pressure wave that forms due to neutron-star bounce, but which stalls a certain distance from the neutron star as outer material rains down on it.

All core-collapse supernovae measured to date, Type Ib, Ic, and II, are not spherical. They may be “football” shaped or “pancake” 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 rather has jets in one direction and a torus expanding at right angles to the jet.

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, He, are ejected in the equatorial torus. This may provide an observational test of the model.

Betelgeuse – red giant 427 light years away, 15 to 20 $M_\odot$, is expected to explode within 10,000 years, maybe tonight, as core collapse Type II supernova. Keep an eye on it.

Failed explosion - if there is no core collapse explosion, outer layers fall in, crush neutron star (maximum mass about 2 solar masses) to form a black hole.

White Dwarfs. Size of Earth, mass of Sun. Supported by the quantum pressure. Most are single stars, mass about 0.6 $M_\odot$, cooling time longer than the age of the Universe.

Maximum mass of white dwarf, Chandrasekhar Mass ~ 1.4 $M_\odot$, that can be supported by quantum pressure of electrons.

Type Ia - must generate explosion in old (1 to 10 billion years) stellar system. Most plausible mechanism, explosion of a white dwarf.

Intermediate mass elements are produced in massive stars before they explode, in white dwarfs during explosion.

White dwarfs nearing 1.4 solar masses made of C/O will explode completely after igniting carbon under conditions of quantum pressure support.

Spectra of Type Ia reveal intermediate elements (O, Mg, Si, S, Ca) on the outside and iron-like material on the inside. Consistent with models of Chandrasekhar mass carbon-oxygen white dwarfs that begin with a subsonic *deflagration* ("flame" or "burning") and then ignite a supersonic *detonation* ("bomb" or "explosion").
Deflagration – a flame, propagates slower than the speed of sound

Detonation – burning drives a self-propagating *supersonic* shock wave.

Shockwave – a supersonic wave that involves a sudden, steep increase in pressure at the wave front. The force, related to the rate of charge of pressure, is especially destructive.

A deflagration flame will make a transition to a detonation if there is sufficiently strong turbulence to fold and pack the flame.

Pressure waves and exploding stars expand at about the speed of sound, faster than a deflagration, slower than a detonation.

Thermonuclear burning of carbon and oxygen at white dwarf densities will produce iron. Burning at lower densities in an expanding, exploding white dwarf will produce intermediate mass elements.

Deflagration burning can never catch up with the outer expanding matter. Detonation burning will overtake the outer expanding matter.

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