Cosmic Catastrophes
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Wheeler
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Review for Test #3
SUPERNOVAE (continued)

Kepler's Third Law — The total mass of two stars in orbit can be determined by measuring the period of the orbit and the distance between the stars. Subtracting the mass of the known star then gives the mass of the unknown star, often a white dwarf, neutron star, or black hole.

Roche Lobes — Region of gravitational dominance of each star in a double system. More massive star reaches out further, always has the largest lobe.

Inner Lagrangian Point — Connection point between Roche Lobes through which mass can be transferred between stars. Always closer to the lower mass star.

Algol Paradox — The evolved star is the less massive. Resolution: mass has been transferred between the stars.

Mass Transfer — Most massive star of close pair evolves first, fills its Roche lobe and some of its mass begins to leak through inner Lagrangian point to the companion star.

First stage of mass transfer — Mass transfer begins when the originally more massive star becomes a red giant with a tiny core. Transfer stops only when whole envelope has been stripped from the core and passed to the companion or lost from the system.

Second Stage of Mass transfer — the star which initially had the smaller mass of the pair passes mass through the inner Lagrangian point of the Roche lobes to a white dwarf. The result is a cataclysmic variable.

Cataclysmic variable — binary star system consisting of a white dwarf receiving mass from a companion via an accretion disk.

Accretion disk — matter streaming through inner Lagrangian point does not directly strike the tiny, orbiting, white dwarf (or neutron star or black hole), but circles around and forms a flat spiraling disk. The disk has its own "life" in the system.

Friction — matter at smaller distance from the center of the disk moves more quickly, rubbing against matter just beyond it moving more slowly and against matter interior to it moving more quickly. The result is friction and heat and light generated everywhere in the disk. The friction also drags material inward giving rise to the *accretion* onto the central compact star.

Disk radiation — the outer parts of disks typically have temperatures comparable to the Sun and shine with optical light. Middle parts are hotter and glow in ultraviolet light. This applies to white dwarfs. The innermost parts can be hot enough to emit X-rays. This applies to neutron stars and black holes.

Classical Novae — cataclysmic variables in which the layer of hydrogen that collects on the surface of the white dwarf explodes and blows some of the white dwarf away. Unlikely to make a Type Ia supernova.

Recurrent Novae — cataclysmic variables in which the layer of hydrogen that collects on the surface of the white dwarf explodes more gently, perhaps allowing matter to accumulate on the white dwarf, leading to a Type Ia supernova.

Final evolution of cataclysmic variables — one possibility is that the first white dwarf to form accretes matter from the companion, reaches the mass limit of 1.4 Msun, ignites carbon, and explodes.

Double white dwarfs — If the first white dwarf does not grow and explode, the second star can evolve to produce a white dwarf, resulting in two orbiting white dwarfs. These will spiral together by gravitational radiation, until the smaller mass, larger radius white dwarf fills its Roche lobe. Mass transfer causes the small white dwarf to be transferred essentially entirely to the larger one. If the larger mass, accreting white dwarf ends with less than 1.4 Msun, it will live as a single white dwarf. If it reaches the mass limit of 1.4 Msun, it will ignite carbon, and explode.

Gravitational Radiation — A systematic "wiggling" of the curvature of space sends out gravitational waves of space curvature. These carry energy and angular momentum from a binary star system and cause two stars to spiral together in the absence of any other physical effects.

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 and too few recurrent novae.

Light curves – brightness versus time of supernovae. Type Ia brightest, Type Ib, Type Ic, Type II dimmer.

Light curve mechanisms – shock energy plus radioactive decay. Ejecta must be large in radius, about 100 times the size of the Earth's orbit, before the matter is transparent enough for light to leak out. If the star is too small originally (Ia, Ib, Ic) all shock energy rapidly goes into energy of motion, and there is no heat left to make light. The light curve must be powered by 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 77days (half-life) to iron-56. Heat from gamma-rays produced in the radioactive decay provides delayed source of light in Type Ia, Ib, and Ic.

Type Ia brighter, need more nickel than Ib, Ic, hence different mechanism. A thermonuclear explosion of 1.4 Msun of carbon/oxygen produces ~1/2 Msun of nickel.

In core collapse supernovae, Type Ib, Ic, Type II, radioactive nickel is produced by the shock wave that induces rapid burning of the silicon layer surrounding the iron core. This produces ~ 0.1 Msun of nickel, so a dimmer light curve than Type Ia.

Type II arise in red giants that are already large prior to explosion so they do not lose much heat to expansion and cooling. They thus radiate energy from the original explosion in the "plateau" phase, with evidence for radioactive decay at a later time, after the original heat is dissipated.

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. Resolution: 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 since been detected. The dim compact object in Cas A might be related. A black hole is still a possibility, but a neutron star remains the most likely possibility.
- Light Curve of SN 1987A – Shock breakout in first day. Subsequent peak and tail of the curve are explained by energy of radioactive decay.
- 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. X-rays from the ring collision are lighting up the ejecta.
- Jets – The shape and motion of the matter ejected by SN1987A are more complex than predicted with the expanding “breadstick and bagel” configuration expected from the model of jet-induced supernovae

Superluminous supernovae – first discovered in Texas (big and bright!), rare, but 10 to 100 times brighter than normal Type II or Type Ia, b, or c.

Superluminous supernovae come from very massive stars than die near their birth sites, but they tend to occur in regions of active star formation in low mass, irregular galaxies.

There are three current hypotheses as to how the superluminous supernovae are so bright.

Shell shock model - The star casts off a massive shell of matter before actually exploding. The shell already sits at a distance of about 100 times the size of the Earth’s orbit when the star explodes. When the supernova hits this shell, the shell is already primed to radiate very efficiently. The collision turns nearly all the energy of explosion into radiation. This model definitely applies to the superluminous supernovae that are hydrogen rich. It may apply to those that are hydrogen deficient if the shell is composed of carbon or oxygen.

Pair-instability model – Very massive stars, nearly 100 Msun, are predicted to form matter and anti-matter (electrons and positrons) thus removing energy and pressure and causing the star to collapse during the oxygen core phase. The oxygen is fuel and burns violently, completely disrupting the star. In some circumstances, the explosion is predicted to produce 10’s of solar masses of radioactive nickel-56 and hence to produce a very bright explosion.

Neutron star power – One model that is especially applied to superluminous supernovae that show no hydrogen and no concrete evidence for either shell shock or radioactive decay calls for energy input from an especially powerful, rapidly-rotating, highly-magnetic neutron star.