Astronomy Bizarre | Wheeler
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Review for Test #1

SINGLE AND BINARY STAR STELLAR EVOLUTION

Four forces of nature

- Electromagnetic—long range force; force is between charges. Opposite charges attract each other; like charges repel each other. A reasonably strong force.
- Strong nuclear force—short range force; acts to hold nucleus together. The strongest of all the forces at short range.
- Weak nuclear force—also short range force; associated with converting neutrons to protons and protons to neutrons. Intermediate in strength. Now understood to be aspect of electroweak force.
- Gravity—long range force; force is between masses. Force is only attractive. The weakest of all the forces, by far.

Conservation laws. Physical interactions are often expressed in terms of "conserved quantities," properties of matter which can be neither created nor destroyed, but can be shifted from one form to another.

- Energy—Types of energy include energy of motion (when referring to the energy of motion of a bunch of atoms and molecules in a gas this energy is called thermal energy or heat), gravitational energy (or gravitational potential energy), quantum energy.
- Momentum—Momentum is defined as the mass of an object times the speed at which the object is traveling.
- Angular momentum—Defined as the mass of an object times the speed times the distance the object is from the center of its orbit.
- Charge—Matter can have a positive, negative, or neutral charge.
- Baryon number—Heavy particles interacting by the strong force. Protons and neutrons are examples of baryons.
- Lepton number—Light particles, electrons and neutrinos, are leptons.
- Antiparticles annihilate with particles to produce pure energy, all mass disappers. Positrons are the antiparticle of electrons. Antiparticles have negative lepton or baryon number, as appropriate.

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.

Quantum pressure. Electrons cannot occupy the same region of space if they have the same energy. As matter is squeezed down electrons develop more 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.

Stellar furnace—Nuclear fusion. On the Main Sequence stars fuse hydrogen into helium and thus supply energy by the net reaction:

4 protons $\rightarrow$ Helium + 2 positrons + 2 neutrinos. Subsequent to this reaction the positrons will annihilate with two electrons, adding a little to the energy. Note that every time a star manufactures a helium nucleus, it must make two neutrinos.

Solar neutrinos - recent experiments have proven that detected neutrinos come from the direction of the Sun but that there are too few in proportion to the luminosity of the Sun. The apparent explanation is that the electron-type neutrinos produced in the Sun are mostly converted to undetectable varieties of neutrinos as they pass through the Sun.

The life of a star. Starts out with cloud of cold, self-gravitating gas, a proto-star. *Energy is lost*, the proto-star contracts and *heats up*. Eventually center becomes hot enough to overcome charge repulsion between protons. Hydrogen fuses into helium. This new energy balances the energy radiated away in the form of light. The star has now entered its "main-sequence lifetime."

The burning is regulated. 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.

When hydrogen is burned out in the center, the helium in the center is too cool to overcome the charge repulsion of its two protons. The helium core leaks energy to the outer layers, contracts and heats up until the charge repulsion can be overcome and helium burning commences.

Excess heat flowing from the core causes the outer layers to *gain energy*. They then *expand and cool*. The outside becomes larger, cooler, and redder. The star becomes a red giant.

Stars pass through several burning stages, burning out a fuel, contracting to get hotter and able to overcome the charge repulsion of ever more protons per nucleus.

Primary heavy elements, C, O, Ne, Mg, Si, S, Ca, are multiples of He with equal numbers of protons and neutrons.

Loss of energy, 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, $\rightarrow$ explosion!

Most stars less than 8 $M_\odot$ eject their envelopes as planetary nebulae, core of C and O cools to become white dwarf, size of Earth, mass of Sun.

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

Above about 15 $M_\odot$, stars evolve iron cores. Iron has the highest binding energy, can only *absorb* energy. Stars that form iron cores quickly collapse as iron breaks down endothermically and some electrons are lost.

Collapse first yields a neutron star with the mass of the Sun, but only the size of Austin. As protons are converted to neutrons, a huge flood of neutrinos is produced.

If the collapse produces an explosion, the neutron star can be left behind. If the collapse is complete, a black hole results.

Solar, stellar winds. Stars with $M > 50\ M_\odot$ lose so much mass they never become red giants, but evolve directly to cores of heavy elements. Stars with $30 \lesssim M/M_\odot \lesssim 50$ become red giants, but lose the extended envelope as a wind so that the core of heavy elements is exposed. Stars with $M < 30\ M_\odot$ have too small a wind to remove the envelope, but may lose the envelope to a binary companion star.

Wolf-Rayet star—evolving core of a massive star (supported by thermal pressure) from which hydrogen has been removed, presumably by a wind or transfer to a companion.

Orbits – Stars move in opposite directions around a center of mass (conservation of momentum). Smaller orbits have shorter period.

Kepler's Third Law – The total mass of the two stars can be determined by measuring the period of the orbit and the distance between the stars.

Roche Lobes -–Region of gravitational dominance of stars in a double system. More massive star reaches out further, has the largest lobe.

Inner Lagrangian Point – Connection point between Roche Lobes, point through which mass can be transferred between stars. Outer Lagrangian Points - Region beyond which matter orbits both stars or flows out of the system.

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.

Rapid Mass Transfer – When started, mass loss from more massive star causes the stars to spiral closer, the lobes shrink, causing more transfer.

Slow Mass Transfer -– After first star becomes the less massive the stars spiral apart as transfer continues, star must swell by evolving to keep up with expanding lobe.

Initially Small Separation – More massive star loses mass while still slowly burning hydrogen, its evolution slows down. The companion gains mass, evolves faster. Both stars try to fill their lobes simultaneously (contact binary). Mass can be lost into an excretion disk or more massive star may consume less massive one resulting in one star.

Initially Larger Separation – Mass transfer begins when 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. Core may cool (supported by quantum pressure) to become a white dwarf. Cores of more massive stars may continue to evolve and explode or collapse leaving a neutron star or a black hole.

With larger separation and with initial mass less than 8 $M_\odot$ the originally more massive stars will form carbon/oxygen white dwarfs when they lose their outer envelopes.

With initial mass in excess of 5 $M_\odot$ the originally more massive star will continue to evolve, supported and regulated by thermal pressure until an iron core forms and collapses. After the envelope is lost the exposed core, composed of helium and heavier elements, would resemble a Wolf-Rayet star.

Second Stage of Mass transfer—the star which initially had the smaller mass of the pair now burns out its hydrogen, tries to form a red giant and begins passing mass through the inner Lagrangian point of the Roche lobes to the remains of the first star—a white dwarf, neutron star, or black hole.

Gravitational Radiation – A systematic "wiggling" of the curvature of space sends out gravitational waves of space curvature. Carry energy, angular momentum from a binary star system.

SAMPLE QUESTIONS

9. The force that binds protons and neutrons to make helium is
   a) the electrical force
   b) gravity
   c) the nuclear force
   d) the weak force

10. The force that converts a proton into a neutron is
    a) the electrical force
    b) gravity
    c) the nuclear force
    d) the weak force

11. Charge repulsion is an application of
    a) the electrical force
    b) gravity
    c) the nuclear force
    d) the weak force

12. In the reaction $e^{-} + \rightarrow n + \nu$, the neutrino ($\nu$) can be thought to arise because of the law of conservation of
    a) energy
    b) charge
    c) baryon number
    d) lepton number

15. The final outcome of the evolution of a star is determined principally by
    a) the amount of heavy elements it is born with
    b) its mass
    c) the galaxy it is born in
    d) the age of the Universe when it is born

16. A star supported by quantum pressure
    a) heats when it loses thermal energy
    b) cools off when it loses thermal energy
    c) cools off when it gains thermal energy
    d) does not respond when it loses thermal energy

17. The effect of the quantum exclusion principle is that
    a) electrons can never get close together
    b) when compacted by gravity, electrons gain only thermal energy
    c) when compacted by gravity, electrons gain a quantum energy unrelated to their temperature
    d) the position of the electrons is uncertain

18. A star supported by thermal pressure
    a) heats when it loses thermal energy
    b) cools off when it loses thermal energy
    c) heats when it gains thermal energy
    d) does not respond when it gains thermal energy