ASTRONOMY 12 SECOND-HALF SYNOPSIS

O. Review the synopsis for the first half of the quarter handed out before the midterm.

I. The Interstellar Medium and Star Formation

About 5 - 10 % (baryonic) mass of our galaxy interior to the Sun's orbit.

Very tenuous gas. On the average about an atom every cm**3
dust is about 1% by mass of the ISM

Has complex history and ecology. Left over from galaxy formation (an ongoing process), then additions from stellar winds, planetary nebulae, and supernovae. Provides the necessary matter to make new stars.

Concentrated in the disk of the Milky Way Galaxy.

Clumpy and variable temperature - at least three components
See below

Local to the sun we have:

The local bubble - relatively low density region where the sun is located. ~100 pc, 0.01 particles/cm**3, 10**6 K, inflated by supernovae last few million years

Local "fluff" or local cloud - a small relatively high concentration within the local bubble, through which the sun is passing. ~10pc, 0.26 particles/cm**3, 6000 K

More generally, one has the

Cold neutral medium
H I Clouds 50 - 100 K, higher than average density 20 -50 per cm**3
Study with 21 cm
Molecular clouds (H_2) 10 - 20 K very high density 100 - 10**6 concentrated in a ring inside the sun's orbit around the center of the Milky Way. Contain about 40% of the baryonic mass of the ISM. Small fraction of the volume. Studied in radio and infrared. Most star formation goes on here

Warm neutral medium 5000 - 8000 K and warm ionized medium 6000 - 12000 K density 0.2 - 0.5/cm**3 study with 21 cm and H-alpha respectively

Hot Coronal gas (H II) 10**6 K very low density .0001 - 0.01 /cm**3. A large fraction of the volume of the ISM, but a small fraction of the mass. Heated by O and B stars in OB associations and by supernovae. Outflows and inflows into the Galaxy.

In addition there are

H II regions are regions of ionized hydrogen - generally pinkish in color due to H-alpha - surrounding small groups of young O and B stars. They are often found on the boundaries of molecular clouds And they light up the spiral arms of spiral galaxies like a string of pearls. They are also found in irregular galaxies like the Large Magellanic Cloud. An example is the Trapezium in the Orion Nebula.

Dust is found chiefly in the molecular clouds along with a host of molecules, many quite complex. Typical grains are about 0.1 to 1 microns in diameter - have a core of silicate or graphite and are covered with an icy mantle of methane, ammonia, and water. The icy mantles can only survive at low temperature.

The Jean's mass is that mass for which internal thermal kinetic energy and gravitational binding energy balance. Larger masses than the Jeans Mass with the given temperature and density will collapse. Lower masses will not. Only the molecular clouds seem unstable by this criterion

Cloud becomes unstable, contracts rapidly, fragments. The free fall time scale is shorter for higher density

End up with a core that is in hydrostatic equilibrium (pressure balances gravity) and shining by Kelvin-Helmholtz surrounded by shell of dust and gas still falling in.

Young stars often strong infrared emitters. May have jets. mass outflow and inflow.

T-Tauri stars are very young stars, still in their Kelvin Helmholtz stage. Found above HR diagram. Evidence for mass outflow. High lithium abundance. Rapid luminosity variations

Star formation and evolution may trigger the formation of other stars. Propagate like flame through a molecular cloud.

Overall efficiency for star formation from a cloud is low. Maybe ~1%. Most mass does not go into star but gets blown away.

Nuclear ignition is preceded by Kelvin Helmholtz stage.
tau_KH = Omega/2L. about 20 - 30 My in the sun.

Protostars lighter than 0.08 Msun, become degenerate before nuclear ignition. Make brown dwarfs.

II. Some stellar physics

Pressure - three kinds - which are sensitive to rho and which to T

Ideal and radiation pressure (nkT and aT**4)
Two kinds of degeneracy pressure and why (rho**(4/3 to 5/3)
electrons moving close to c or not))

Hydrostatic equilibrium - what it means   P_cent ~ GM rho/2 R

Tcentral about = GM/R for star supported by ideal gas pressure

Nuclear fusion reactions - requires high temperature but also made possible by barrier penetration - a quantum mechanical effect

The pp1 reaction sequence (know the reactions)

p+p --> ^2H +e^+ + nu + energy
(2*) ^2H + p --> ^3He + energy
^3He + ^3He --> ^4He +2p + energy

rate is proportional to T**4
slowest reaction is two stage p+p -> deuterium + e^+ + nu
overall effect is to turn 4 protons into one helium-4
and liberate about 7 x 10**18 erg/gm
can power the sun for 10**10 years if inner 15% burns

Central temperature on the main sequence increases with increasing mass. So does radius. Central density decreases with increasing mass.

Means of transporting energy - radiation, conduction, convection
core of sun transports energy by radiative diffusion
outer layers of sun transport energy by convection
white dwarfs transport energy by conduction

III. Life on the Main Sequence

Why the sun is stable - thermostat works for ideal gas
because pressure is sensitive to temperature.
Heating causes expansion which causes cooling.

Half of sun's luminosity generated in inner 12 - 15% of its mass

The central temperature of the sun is 15 million K. The central density is 150 g/cm**3

As raise temperature to above 18 million K a new series of reactions generates the energy. The CNO cycle. Also burn 4H to He-4, but C (or N or O) plays a catalytic role. Results in the conversion of C and O into 14N because 14N + p is the slowest rate in the cycle. Makes the energy in stars heavier than about 1.5 Msun.

Stars above about 150 Msun are pulsationally unstable on the main sequence because their internal energy is very nearly equal to their binding energy because radiation pressure is their dominant means of support. Such stars would lose mass rapidly until they finally became pulsationally stable.

IV The Sun

The sun transports energy by radiative diffusion in its inner 98% by mass (75% by radius). In the outer parts energy is transported by convection.

Sunspots are regions on the surface of the sun characterized by lower temperature (by about 1000 K) than their surroundings and have strong magnetic fields (1000 Gauss). They generally come in pairs with opposite magnetic polarity.

The sun experiences a 22 year cycle during which its magnetic field goes through one complete reordering of its magnetic field. The N pole becomes the S pole then N again. Related to this, sunspots and other solar activity has an 11 year cycle. During this time sunspots increase in number and intensity as their location progresses from high latitudes to the equator.

The rotates differentially with the equator completing a rotational period faster than the higher latitudes. In the Babcock Model, this differential rotation coupled to the convection of the solar surface creates magnetic field loops that erupt through the solar surface crating sunspots.

The magnetic field contains a great deal of energy that can occasionally be released explosively producing a solar flare or prominence. These eruptions also energize the solar corona, a low density (10(-16) g/cm**3) hot (> 10**6 K) region outside the solar photosphere. This corona expands off into space as the solar wind.

The solar wind impacting the earth affects aurorae, communications, and satellite health.

There are two other ways of completing the pp cycle (called the pp2 and pp3 chains). These are more important at high temperature and make a small (but important) fraction of the sun's luminosity. This series of reactions makes more energetic neutrinos than pp1.

These solar neutrinos have been detected by five experiments on Earth In all cases the signal in electron-flavored neutrinos is smaller than theory predicts. However, the Sudbury Neutrino Observatory measured the flux of all flavors of neutrinos (e, mu, and tau) and the total agrees with predictions. A process called "flavor mixing" is allowing electron neutrinos to turn into mu and tau neutrinos as they pass through the sun. The implies that the neutrino has a small, but finite rest mass. Neutrino flavor mixing has also been observed on the earth using neutrinos generated by nuclear reactors.

Lifetime on the main sequence goes approximately as
10**10 yr/(M/Msun)**2

The sun was less luminous in the past and will be more luminous in the future. Its radius is gradually increasing, but it is getting denser in its center.

V. Post Main Sequence Evolution of Stars Lighter than 8 Msun

Hydrogen fuel exhausted in inner 10 - 15% of mass. Helium core contracts and grows hotter.

Hydrogen continues to burn in an overlying shell that is super hot because of the contraction of the helium core to higher density

More energy is generated by the hydrogen shell than is required to stay on the main sequence. If star was convective (eg., M = 0.5) its luminosity increases immediately. Otherwise the radius increases at nearly constant luminosity until a temperature around 4000 K is reached at the surface and the envelope becomes convective. Then the luminosity shoots up. All the stars expand and become red giants. These red giants are powered nuclear energy from hydrogen shell burning.

For stars below 0.5 Msun, the hydrogen shell adds to the helium core until the hydrogen is gone. The core experiences the same problem a 0.08 Msun star did igniting H. It can't ignite He. Ends its life (sometime in the distant future) as a helium white dwarf. Never ignites helium burning.

For stars from 0.5 to 2 Msun the star evolves to the upper right hand part of the HR diagram where it finally ignites helium. In the sun. This happens at 150 million K, 10**5 g/cm**3, conditions that are decidedly degenerate. Helium burning ignites in a flash below about 2 Msun. The flash blows out the hydrogen burning shell as well as helium core burning. The star moves back down the HR diagram quickly (2 M years for the sun) to the horizontal branch where it ignites helium burning again, this time non-degenerately. Above 2 Msun, helium ignites stably the first time and there is no flash.

Stars on the horizontal branch have much smaller radii than red giants and are typically bright blue. A color photo of a globular cluster shows many red giants and horizon-al branch stars. The remaining main sequence stars and white dwarfs are fainter.

Helium burning is the fusion of 3 helium-4 nuclei to 12C. It also involves the capture of an additional helium on the carbon to make oxygen. This is how oxygen and carbon get made in nature. It releases about 10% as much energy per gram as hydrogen burning. Nitrogen is turned into rare isotopes of oxygen (O-18) and neon (Ne-22).

Stars lighter than about two solar masses burn helium on the horizontal branch - lower mass stars farther to the left (higher surface temperature) until helium is gone form the central regions. This takes about 100 My years in a solar mass star.

Stars then burn helium in a thin shell and ascend the giant branch for a second time (hence "asymptotic giant branch" star or AGB star). This thin helium burning shell is pulsationally unstable. This thin shell helium burning phase lasts about 500,000 years in the sun. As the pulsations grow more violent, sound and shock waves sent out into the envelope drive a superwind. During the last roughly 10,000 years, the envelope is ejected as a planetary nebula. A white dwarf composed of carbon and oxygen is left behind. This white dwarf is initially very hot (about 20,000 to 100,000 K surface T)

During this stage of thin helium shell burning side reactions in an AGB star release free neutrons that capture on heavy elements (iron and heavier, $Z > 26$) to make most of the elements up to lead ($Z = 82$). This slow neutron capture is called the "s-process".

VI. White Dwarfs

Carbon-oxygen white dwarfs are made by stars in the 0.5 to 8 Msun range. Above 8 Msun, carbon burning ignites

White dwarfs are supported by electron degeneracy pressure.

They obtain their luminosity from the stored heat in the carbon and oxygen nuclei left hot after helium burning.

They have low luminosities and can shine for very long times on this internal heat store. Because of their small radii they are hot, most are currently strong ultraviolet emitters. Billions of years in the future they will grow cool and invisible, but they are permanently stable.

They evolve in the HR diagram along a line of nearly constant radius below the main sequence, sliding slowly from left (hi T) to right (low T, low L)

More massive white dwarfs have smaller radii. A typical radius is 5,000 km.

More massive white dwarfs also have higher central densities.

At about 10**7 g/cm**3 the electrons become relativistic and P-degenerate switches form from rho**5/3 to rho**4/3.

Above 1.4 Msun = Chandrasekhar mass there can be no stable white dwarf

VII. The Late Evolution of Massive Stars (M > 8 Msun)

Move to right in HR diagram after leaving the main sequence.

Become red supergiants (usually) and stay that way until their death as supernovae. Do not make planetary nebulae. Do not make white dwarfs, do not have thin unstable helium shells. Do however, lose a lot of mass to winds. Stars over 35 Msun may lose their entire envelope this way, ending up as bare helium cores (then they are no longer giants). Lower mass stars may also lose their envelopes if they are in interacting binaries close enough for mass exchange during the red giant phase.

Ignite carbon burning non-degenerately. Also have stages of oxygen, and silicon burning. Develop a layered structure. These burning stages make most of the abundant elements from neon (Z = 10) through calcium (Z = 20). Each stage operates on the ashes of the previous one at a higher temperature and density. Carbon burns at 800 million K silicon at 3.5 billion K.

These advanced burning stages occur at an accelerated rate because of neutrino losses from electron-positron pairs made in copious quantities inside the star after carbon ignition. Carbon burning typically takes a thousand years, silicon burning a few days. Neutrino losses increase as a high power of the temperature.

The iron nucleus is the most tightly bound configuration of neutrons and protons that can exist. Once a star has made a core of iron, that core can no longer release positive energy from further nuclear fusion.

The iron core, typically 1.5 Msun, becomes unstable and collapses. 3 instabilities - photodisintegration, electron capture on protons in the nucleus, and neutrino losses

This collapse becomes very fast (v approaching c/4), the outer layers of the star including its many burning shells hang there unable to respond rapidly to the core collapse.

VIII. The Explosion Mechanism

The collapsing core, which now has become very neutronized, exceeds nuclear density (2.4 x 10**14 g /cm**3). It overshoots and bounces on the repulsive hard core of the strong force. The inner half rebounds running into the outer half.
A shock wave is born. All positive velocities disappear from this shock however by the time it reaches the edge of the iron core.

The proto-neutron star experiences its Kelvin-Helmholtz evolution, contracting from about 30 km to 10 km in about 10 seconds and releasing about 3 x 10**53 erg of neutrinos. This neutrino burst was detected from supernova 1987A.

About 0.5% of these neutrinos deposit their energy in a region just outside of the neutron star. This heats the region causing it to expand, blowing a big bubble inside the massive star. The outer boundary of this bubble, a reborn shock wave, pushes almost all the matter external to the neutron star making the supernova.

The kinetic energy imparted to these ejecta is about 10**51 erg. They are made of unburned stellar envelope (usually most of the mass) but also the ashes of many different stages of nuclear burning that were going on outside the core.

IX. Neutron stars

Gigantic nuclei, mostly neutrons, supported by a combination of neutron degeneracy pressure and nuclear force.

Typical mass 1.4 Msun (neutrinos carry away significant mass energy in the explosion). Typical radius 10 km. Central density over 10**15 g/cm**3.

Like white dwarfs have a maximum mass, but the value is uncertain. Probably near 2 Msun. If the supernova leaves behind a remnant larger than this it will be a black hole.

Many neutron stars (but not all) are seen to be pulsars. A pulsar is a rotating, magnetic, neutron star with its magnetic and rotational axes not aligned.

Pulsars are observed to have periods between 1 ms and about 10 s. They gradually slow down with time and become fainter Their magnetic fields may decay. In any case, after about 10**7 years they quit being bright pulsars.

X. Supernova Nucleosynthesis and Light Curve

As shock wave moves out through silicon shell, it raises it to high temperature. About 0.1 Msun of radioactive 56Ni is produced. This 56Ni decays to 56Co in about a week and to 56Fe (abundant form of iron) in about 3 months. These decays release gamma-rays that are important to the supernova light output.

The light curve of a Type II supernova (the kind with hydrogen) has 3 stages - shock break out, envelope recombination (main optical display, about 5500K, R = 10**15 cm approximate blackbody lasting 3 months), and radioactive tail powered by 56Co decay

XI. Type Ia Supernovae

Thermonuclear instability in a white dwarf accreting mass from a companion star. Accretion rate must be high (about 10**(-7) Msun/yr) to avoid the nova instability and for the white dwarf to grow.

Leave no neutron star or black hole behind. Still remnant may glow as the shock wave runs into interstellar medium.

In a typical model, the white dwarf grows to nearly M_chandra, ignites carbon burning at 2 x 10**9 g/cm**3 and experiences a severe thermonuclear runaway. About 2/3 of the white dwarf is burned to 56Ni. The decay of this 56Ni produces a very brilliant light curve. Lmax about 10**43 erg/s. Total light output about 10**49 erg. Total kinetic energy 10**51 erg.

XII. Supernovae in General

Two types - with hydrogen Type II, without - Type I.

Massive stars that keep their envelopes make Type II (the most common variety).

About 2 every 100 years in our galaxy.

The brightest supernova in 400 years was SN 1987A, the explosion of a 20 Msun star in the LMC. This is the only supernova to have the star identified before it exploded.

Type I is subdivided into Ia and Ib - Ia is exploding white dwarfs, Ib are massive stars that have lost their hydrogen envelopes. Except for their spectra and light curves, Ib is thus very similar to Type II - leave neutron star or black hole, make neutrino burst, occur in massive stars, etc.

Typical velocities in Type I and II range from 1000 to 30000 km /s

Type II and Ib leave neutron stars and black holes, Type Ia leaves nothing, therefore no pulsars or x-ray sources

Type Ia has a shorter (1 mo) brighter (2 x 10**43 erg/s at peak) display. The light from Type Ia is entirely powered by the decay of radioactive 56Ni and 56Co. Type II's have a peak L of about 4 x 10**42 erg/s for 3 months and then a radioactive tail from 56Co decay.

The nucleosynthesis from Type Ia is chiefly iron. 3/4 of the iron in nature comes from SN Ia. Type Ib and II also make some iron, but lots of other things including all of the elements from oxygen through calcium, the r-process, and part of the s-process. The most abundant product of Type Ib and II supernovae is oxygen, which is made during helium burning.

Commn Type Ia, Ib, Ic, and IIp supernovae have total kinetic energies of about 10**51 erg.

There are other forms of exotic ultra-luminous supernovae that have been discovered lately. They may be powered by superenergetic pulsars called "magnetars" or may be due to pair instability supernovae or a supernova colliding with a shell of matter that it previously ejected.

XIII. Other Phenomena in Accreting Binaries

Classical nova accreting white dwarf accumulates a critical mass of hydrogen and helium on its surface. A thermonuclear runaway occurs. The accreted matter gets ejected and a lot of light. These novae do recur (unlike SN) though the recurrence interval is very long (tens of thousands of years). Peak L is about 10**38 erg/s for a few months (100,000 times fainter than a Type I supernova). Classical novae can recur though over time scales of 10,000 to 100,000 years. The accretion rate is low - about 10**(-8) - 10**(-9) Msun/yr. About 40/yr in our Galaxy.

X-ray binaries - either a neutron star (without a strong magnetic field) or a black hole accreting matter from a companion. In this case the energy comes from gravity. L is about 10**37 to 10**38 erg/s. As a blackbody with radius 10 km, this implies a temperature in the x-ray band. (in the case of the black hole, the emission comes from the accretion disk).

If the x-ray emitting source in a binary can be shown to have a mass much in excess of 2 solar masses, it must be a black hole. Only neutron stars and black holes are compact enough to be powerful x-ray sources and there are no neutron stars over 2 solar masses.

XIV Black Holes and Gamma-Ray Bursts

Black holes are a state of matter that has collapsed as far as possible. They consist of a singularity surrounded by an event horizon. Once matter is inside the event horizon, no light - or anything else - can escape.

Tidal forces would rip apart anything trying to cross the event horizon of a stellar mass black hole, however, supermassive black holes of millions, even billions of solar masses are thought to exist at the centers of quasars. The tidal forces are weaker for such big holes.

Black holes warp space time. Clocks in a strong gravitational field run slower than for distant observers.

Gamma-ray bursts are enigmatic busts of high energy radiation visible only above the earths atmosphere. They occur in random directions, last a few seconds, and never repeat. Recently observations have shown that most gamma-ray bursts are in distant galaxies in star forming regions. They may be powered by an accreting rotating black hole formed in the middle of a massive star (collapsar) or by a very rapidly rotating, highly magnetic neutron star (millisecond magnetar). They are frequently accompanied by a supernova of an unusually energetic type.

There is also a version of gamma-ray bursts called "short hard" bursts that may be a result of merging neutron stars.

Material from the following summaries may be on the test:

Nucleosynthesis summary:

Element	**Made in**	**By**
H, He	Big Bang	as it cools and expands during the first 3 minutes
C	M < 8 ejected in wind and PN	helium burning
N	"	CNO cycle
O	massive stars pushed off in expl	helium burning
Ne,Mg Na, P	"	carbon burning
Si, S Ar, Ca	"	oxygen burning
iron group (Ti, V, Cr, Mn, Fe, Co, Ni)	massive stars, and SN Ia explosively	explosive silicon burning
s-process	M < 8 mostly some light s-process is made in M > 8	slow neutron addition during helium burning (AGB stars for M < 8)

r-process	Type II supernovae and merging neutron stars	rapid neutron addition

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Critical mass summary - in solar masses

0.08	Below this do not make a star. Make brown dwarfs. Above this ignite hydrogen burning
0.50	a) Critical mass for helium ignition. Below don't ignite helium. b) Below this stars completely convective on main sequence
1.4	The Chandrasekhar mass - maximum mass white dwarf
1.5	Between 0.5 and 1.5 stars have radiative cores and convective envelopes of decreasing mass. Above this the surfaces of stars are stable against convection Above 1.5 stars with solar composition burn by the CNO cycle
2.0	a) Above this the cores of stars are convective b) Below this (down to 0.5) have helium core flash; above it helium burning ignites gently c) Maximum mass neutron star. Above this, the compact remnant of a supernova is a black hole.
8.0	Critical mass for carbon ignition. Above this end point is a supernova plus neutron star or black hole. Below this the end point is a planetary nebula and a white dwarf
about 150	Maximum mass star. Above this stars are pulsationally unstable on the main sequence

Also know the evolutionary phases of the sun and what is going on in each phase
Main sequence, ascending red giant branch, He core flash, horizontal branch star, asymptotic giant branch (AGB) star, planetary nebula, white dwarf.