Instructions: You may put your answers right on the exam sheets. If you need extra space feel free to attach additional pages, but indicate by the question that you've gone to extra pages. There is a stapler at the front of the room. The last page of the exam lists equations, constants, and conversions that you may need.
Remember: READ EACH QUESTION COMPLETELY!!!! SHOW YOUR WORK!!!! BE CAREFUL OF UNITS!!!!

True or False Section (circle T or F to indicate whether the statement is True or False, each is worth 2 points):

1. **T** or F The planets Uranus and Neptune are blue because the methane in their atmospheres absorbs red light, leaving the blue part of the light to get out.
2. T or **F** The clouds on Jupiter and Saturn are primarily made of methane ice.
3. T or **F** The Miller-Urey experiments showed that it is relatively easy to make amino acids (the building blocks of life) if you have an energy source, an oxidizing mix of gases, water, a surface, and a means of concentrating the chemicals.
4. **T** or F The seasons on Mars are caused by the planet's obliquity, but are "enhanced" (modified in length and intensity) by the planet's eccentric orbit.
5. **T** or F Titan's surface temperature is warmer than its effective temperature because of a greenhouse effect caused by nitrogen and methane.
6. **T** or F If we determine that the density of a small outer solar system body is around 2 g/cm^3 we surmise the body is made of half ice and half rock.
7. T or **F** Gas A has a larger cross section than gas B at a specific wavelength, so the optical depth of gas B at that wavelength will be larger than that of gas A for parcels of the same size and number density.
8. **T** or F The barometric equation tells us that if we assume an atmosphere is isothermal and gravity is constant, then the pressure will change by a factor of $1/e^2$ if you go up two scale heights in altitude.
9. **T** or F Because water can condense out adding heat to the air around it, a wet adiabatic lapse rate is less steep than a dry adiabatic lapse rate (meaning for the same change in altitude upwards, the temperature changes less if the air has more water in it).
10. T or **F** The light zones on Jupiter are indicative of downward moving air in which clouds have condensed, making them lighter in color.
11. T or **F** Escape speed for a molecule at the top of the atmosphere depends on the square root of the mass of the molecule escaping the planet.
12. T or **F** The sulfuric acid droplet clouds of Venus are the primary cause of the runaway greenhouse effect on that planet.
13. **T** or F Aurorae on planets occur when charged particles following magnetic field lines impact the upper atmosphere and excite the molecules and atoms causing them to give off light.

Multiple Choice Section (circle the letter corresponding to the best answer, each question is worth 3 points):

14. The most abundant element in the solar system is:
   a. Helium
   b. Hydrogen
   c. Oxygen
   d. Carbon
   e. Nitrogen

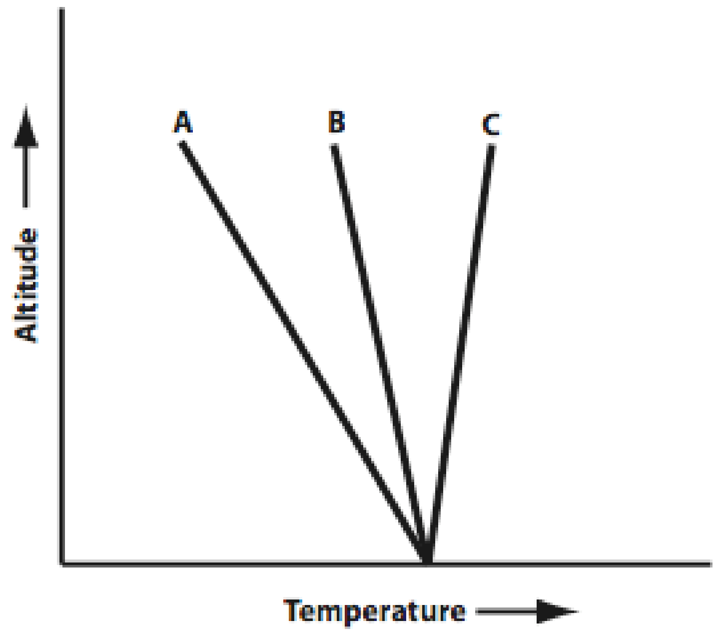
15. Planet A has an effective temperature of T_A. Planet B is identical to Planet A in size, albedo, mass, composition, rotation rate, and obliquity, **except** Planet B is twice as far from the Sun as Planet A. The effective temperature of Planet B is:
   a. $\left(\frac{1}{2}\right)^{1/4} \cdot T_A$
   b. $2^{1/4} \cdot T_A$
   c. $4^{1/4} \cdot T_A$
   d. $\left(\frac{1}{4}\right)^{1/4} \cdot T_A$

16. Ganymede and Titan are nearly identical in size and bulk composition, but Titan has a substantial atmosphere and Ganymede hardly has any atmosphere. This is because:
   a. Titan is closer to the Sun and therefore is warmer and has outgassed more volatiles to make up its atmosphere.
   b. Titan is farther from the Sun and therefore is colder and its atmosphere hasn't escaped as rapidly as Ganymede's has.
   c. Ganymede had an atmosphere, but it was stripped away in collisions with magnetized particles in the rings of Saturn.
   d. Dr. Eparvier is pulling my leg, neither satellite has an atmosphere.

17. One of Kirchoff's laws states that a low pressure gas at high temperatures will:
   a. Emit light at discrete wavelengths (emission line spectrum).
   b. Emit light in a continuum of wavelengths (continuum emission spectrum)
   c. Absorb light in a continuum of wavelengths (continuum absorption spectrum)
   d. Start to undergo fusion and emit neutrinos (nuclear resonance spectrum)

18. Volatiles are:
   a. Metallic substances with densities greater than 5 g/cm^3.
   b. Rocky substances with densities around 2.5-3.5 g/cm^3.
   c. Icy substances with densities around 1 g/cm^3.
   d. Substances which would naturally be found as liquid or gas on Earth.
   e. Both a. and d.
   f. Both c. and d.

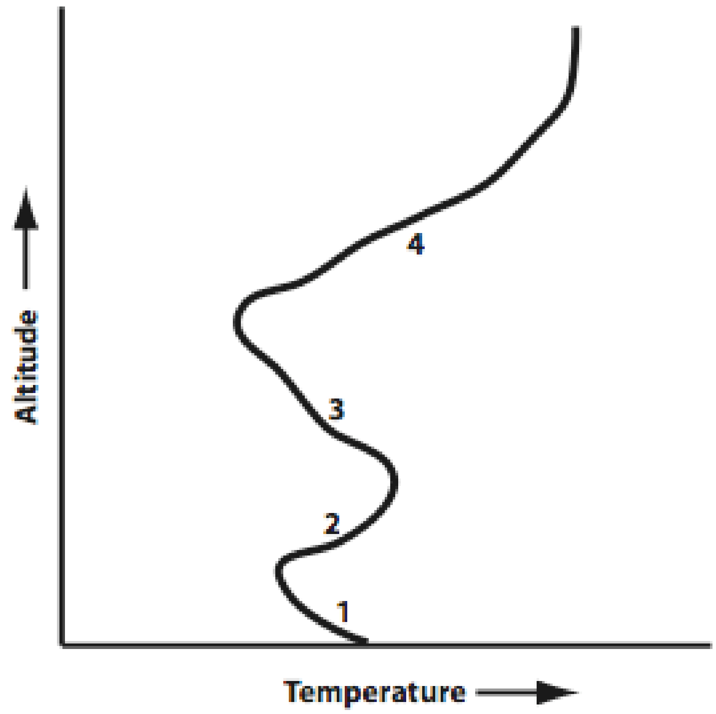
Questions 19 and 20 refer to the figure below which depicts three tropospheric temperature profiles.



19. Assume that all three temperature profiles in the graph above occur on planets of the same radius, are at the same distance from the Sun, and have atmospheres of the exact same composition. The only thing that is different is that gravity is different for the planets. Which is the temperature profile of the atmosphere on the planet with the strongest gravity?
    a. **Profile A**
    b. Profile B
    c. Profile C
    d. It is impossible to determine from the information given

20. Forget the assumptions made in qestion 12. This time assume that all three profiles in the graph occur on the same planet and that profile B represents the adiabatic lapse rate for the troposphere of the planet. For which of the other two profiles will convection occur driving the temperature profile towards the adiabatic one?
    a. **Profile A will have convection**
    b. Profiles A and C will both have convection
    c. Profile C will have convection
    d. Neither Profile A nor Profile C will have convection

Questions 21, 22, and 23 refer to the figure below depicting the temperature profile of the Earth's atmosphere.



21. The temperature increase with altitude that occurs in the region labelled 2 in the above plot of the Earth's atmosphere is caused by:
    a. Radiative cooling-to-space via infrared emissions.
    b. Radiative heating of ozone by ultraviolet sunlight.
    c. Radiative heating by extreme ultraviolet sunlight dissociating and ionizing the atmospheric species.
    d. Convective heating driving the lapse rate towards adiabatic.

22. Which region of the Earth's atmosphere in the plot above is called the mesosphere?
    a. Region 1
    b. Region 2
    c. Region 3
    d. Region 4

23. Which region of the atmosphere is most affected by the variability of solar brightness in the EUV throughout the solar cycle?
    a. Region 1
    b. Region 2
    c. Region 3
    d. Region 4

24. At present we have discovered about 107 extrasolar planets (planets orbiting other stars). Most of those detections have been made using which method?
    a. Direct imaging (we've taken pictures of the planets).
    b. Detection of gravity waves and neutrinos from the planets.
    c. Enhancements on the star's blackbody radiation curve.
    d. Doppler spectroscopy showing wobbles in the stars' motions due to the gravity of planets.
    e. No planets around other stars have ever been detected.

25. The Earth has a significant amount of O_2 in its atmosphere but the other terrestrial planets don't. This is because:
    a. Earth had/has liquid water oceans which give off O_2 when subjected to tidal heating.
    b. The other terrestrial planets had O_2, but lost it in the runaway greenhouse effect.
    c. The Earth was the right distance from the Sun for O_2 to condense out of the early solar nebula 4.5 billion years ago.
    d. Earth had/has photosynthesizing life forms which produced the O_2 over a long period of time.
    e. Radioactive decay destroyed it on the other terrestrial planets.

26. What is it about the extrasolar planets discovered so far that has challenged our story of the formation of our own solar system?
    a. Extrasolar planets are seen around pulsars
    b. Many extrasolar planets are very massive and orbit very close to their stars
    c. Many extrasolar planets have orbits with very large eccentricities
    d. All of the above
    e. None of the above

27. Spectroscopy can be used as a diagnostic for:
    a. Composition
    b. Concentration
    c. Temperature
    d. Relative motion
    e. All of the above
    f. A and C only

28. The Hubble Space Telescope observes a new storm appear in the northern hemisphere of Saturn. From the fact that the storm rotates clockwise we determine that the storm is a:
    a. Low pressure system
    b. High pressure system
    c. Result of a comet impact
    d. None of the above

29. If an atmosphere has multiple constituents that each absorb light of a particular wavelength, the total optical depth of the atmosphere at that wavelength is:
    a. **The sum of the individual optical depths of the constituents**
    b. The product of the individual optical depths of the constituents
    c. The sum of the reciprocals of the individual optical depths of the constituents
    d. The square root of the sum of the squares of the individual optical depths of the constituents

30. Assume that planet A and planet B are the same size and have the same albedo. If planet A is hotter than planet B then the thermal emission spectrum (blackbody curve) of planet A will:
    a. Peak at a longer wavelength than the spectrum of planet B
    b. Be lower in overall intensity than the spectrum of planet B
    c. Peak at a shorter wavelength than the spectrum of planet B
    d. Be higher in overall intensity than the spectrum of planet B
    e. Both A and B
    f. **Both C and D**
    g. Both A and D
    h. Both B and C

31. In general the motion of air is such that it tries to:
    a. Move from low pressure to high pressure
    b. Move from high pressure to low pressure
    c. Rise where it is cold and sink where it is warm
    d. Sink where it is cold and rise where it is warm
    e. Both A and D
    f. **Both B and D**

Calculations (Perform the requested calculations. Show your work as partial credit will be given even if you screw up the math. Remember to watch your units! Each question is worth 5 points.):

32. Imagine that our solar system has another Jupiter-like planet at 6.5 AU from the Sun, with an albedo of 0.5. Observations show that the planet is radiating in the infrared at 8.25 Watts/m^2. Calculate the internal energy source (in Watts/m^2) for this planet.

The internal energy source is given by the difference between the observed energy output and the energy input from the Sun:

$$F_{internal} = F_{measured} - F_{solar},$$

where the solar energy input is given by rearranging the effective energy equation:

$$F_{solar} = \sigma \cdot T_{eff}^4 = \sigma \cdot \left[\left(\frac{S_o}{D^2} \cdot \frac{(1-A)}{4 \cdot \sigma} \right)^{\frac{1}{4}} \right]^4 = \frac{S_o}{D^2} \cdot \frac{(1-A)}{4} = \frac{1368 \frac{W}{m^2}}{(6.5)^2} \cdot \frac{(1-0.5)}{4} = 4.05 \frac{W}{m^2}$$

So that gives an internal energy source of: $F_{internal} = 8.25 \frac{W}{m^2} - 4.05 \frac{W}{m^2} = 4.2 \frac{W}{m^2}$

For questions 33, 34, and 35 assume that the atmosphere of Triton is composed of N_2 only, the surface pressure is $1.5\text{x}10^{-5}$ bar, the temperature is 37 K, the atmosphere is isothermal, the albedo is 0.72, the mass of Triton is $2.15\text{x}10^{22}$ kg, the radius of the satellite is 1353 km, the distance to the Sun is 30.0 AU, the mass of a N_2 molecule is $4.65\text{x}10^{-26}$ kg, the absorption cross section of N_2 at a wavelength of 121 nm is $2\text{x}10^{-27}$ m^2, and the flux of 121 nm sunlight at 1 AU is $1\text{x}10^{15}\,\frac{photons}{m^2\cdot \text{sec}}$.

33. Given the above information, calculate the scale height of Triton's atmosphere.

The equation for scale height is $H = \dfrac{k\cdot T}{m\cdot g}$*. You are given T (37K) and m (mass of N2 molecule, but you aren't given g, the acceleration due to gravity. To calculate this use Newton's Law of Gravitation:* $F = m\cdot a = \dfrac{G\cdot M\cdot m}{r^2}$*, the small m is the mass of any object and it cancels out, and the a is the acceleration due to gravity, which we can also call g. So plug and chug the other given numbers to get:*

$$g = a = \frac{G\cdot M}{r^2} = \frac{\left(6.67\times 10^{-11}\,\frac{Newton\cdot m^2}{kg^2}\right)\cdot\left(2.15\times 10^{22}\,kg\right)}{\left(1353km\cdot\frac{1000m}{km}\right)^2} = 0.78\,\frac{m}{sec^2}$$

Next plug this back into the equation for the scale height:

$$H = \frac{k\cdot T}{m\cdot g} = \frac{\left(1.38\times 10^{-23}\,\frac{Joules}{K}\right)\cdot(37K)}{\left(4.65\times 10^{-26}\,kg\right)\cdot\left(0.78\,\frac{m}{sec^2}\right)} = 1.40\times 10^{4}\,m = 14.0km$$

34. Next, calculate the vertical optical depth of the atmosphere of Triton at a wavelength of 121 nm.

Vertical optical depth is given by $\tau_{vert} = \int \sigma\cdot n\cdot dz$*, but this simplifies because the cross section and temperature are assumed constant:* $\tau_{vert} = \sigma\cdot\int n\cdot dz = \sigma\cdot N = \sigma\cdot n_0\cdot H$*, so before you can figure out the optical depth you have to figure out the surface number density. You can do that by rearranging the ideal gas law to get:*

$$n_0 = \frac{p_0}{k\cdot T} = \frac{\left(1.5\times 10^{-5}\,bar\right)\cdot\left(10^{5}\,\frac{Pascal}{bar}\right)}{\left(1.38\times 10^{-23}\,\frac{Joules}{K}\right)\cdot(37K)} = 2.94\times 10^{21}\,m^{-3}$$

Which then gives you

$$\tau_{vert} = \sigma\cdot n_0\cdot H = \left(2\times 10^{-27}\,m^2\right)\cdot\left(2.94\times 10^{21}\,m^{-3}\right)\cdot\left(1.4\times 10^{4}\,m\right) = 0.082$$

35. Finally, calculate the flux of 121 nm sunlight at a point on the surface of Triton where the Sun is 30˚ down from overhead.

Use the Beer-Lambert law to determine the flux of sunlight after it has gone through a gas: $I = I_0 \cdot e^{-\tau}$*, but you'll have to determine what the flux is at the top of the atmosphere given the flux at 1AU. This is siimply* $I_0 = \frac{I_{1AU}}{D^2} = \frac{1 \times 10^{15} \frac{photons}{m^2 \cdot sec}}{6.5^2} = 2.37 \times 10^{13} \frac{photons}{m^2 \cdot sec}$*. You also can't just use the vertical optical depth, you'll have to adjust it for a solar zenith angle of 30°, giving you* $\tau_{30^\circ} = \frac{\tau_{vert}}{\cos 30^\circ} = \frac{0.082}{\cos 30^\circ} = 0.095$*. So plugging these two numbers back into the Bee-Lambert Law gives you*

$I = I_0 \cdot e^{-\tau} = \left(2.37 \times 10^{13} \frac{photons}{m^2 \cdot sec}\right) \cdot e^{-0.095} = 2.16 \times 10^{13} \frac{photons}{m^2 \cdot sec}$*, so most of the 121 nm light from the Sun that is at the top of the atmosphere makes it to the surface of Triton.*