Physics 101 Final Exam, 2009 Spring

Order of Magnitude Physics

29 May, 2009 E. S. Phinney, D.J. Stevenson

Seniors, Grads: Due **4:00 pm** Thursday June 4
Fr-Jr undergrads: Due **4:00 pm** Thursday June 11, 2009

Hand your completed exam in to 150 South Mudd (please give the exam to one of the office occupants 8am-5pm; don't just stuff it under a door after hours.)

Do not download or open the exam until you are ready to take it.
Please write the exam in a **Blue Book** (available in the bookstore), and make sure your name and return mail-code is clearly written on the front of each blue book you use.

There are 6 short questions (S1-S5) and 5 long questions (L1-L5) offered, but:
YOU NEED ONLY ANSWER 4 SHORT and 3 LONG QUESTIONS! If you answer more, your score will be based on the best 4 short and/or best 3 long (maximum possible scores are $4 \times 10 = 40$ points in short questions and, $3 \times 20 = 60$ points in long questions for a total of 100 points).

The honor code is in effect. Please follow all of the following instructions regarding this exam. If you feel unclear about any of these instructions, you are required by the honor code to ask for clarification.

- You may not communicate with any other person (except Profs. Phinney or Stevenson) about the contents of this exam, until both you and the other person (if taking Ph 101) have submitted your exams.
- The exam must be completed in a single sitting of **4 hours**.
- A non-programmed calculator is permitted, and recommended. Computers and related programmable devices are **not permitted**.
- During this exam, you may not refer to anything other than these sheets of paper, your brain and the Purcell handout of numerical values. If you haven't already, you may print yourself a copy in advance of taking this exam from

  `http://www.its.caltech.edu/~oom/handouts/purcell.pdf`
- The exam score will account for 40% of your grade. Homework is 60%.

Your completed exam should be handed *in person* (do *not* stick the exam under doors) to 150 South Mudd by **4:00pm on Thursday June 4, 2009 if you are a senior or grad student** or by **4:00pm on Thursday June 11, 2009 if you are a freshman, sophomore or junior.**

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"Knowledge is an attitude, a passion, actually an illicit attitude. For the compulsion to know is like dipsomania, erotomania and homicidal mania in producing a character that is out of balance. It is not at all true that the scientist goes after truth. It goes after him. It is something he suffers from." —Robert Musil *Der Mann ohne Eigenschaften*, p 254

translation *The Man without Qualities* by Eithne Wilkins and Ernst Kaiser (NY, Capricorn Books, 1953).

The exam starts on the next page.

Answer ANY 4 **of questions S1-S6**: 10 points each for a total of 40 points.

S1. **Coal Mining.** States like Kentucky, Illinois, West Virginia and Pennsylvania lie on top of coal beds 1-2 meters thick. In many areas, old-fashioned underground mining has been replaced by "area mining" (where all the rock is removed from a giant pit, exposing the coal bed) and "mountain top removal" (where the top of a mountain is sliced off to expose the coal bed). In both cases, the government now requires that most of the removed material be put back in its original location.

To what depth of burial of the coal bed is this form of mining energetically efficient (i.e. the energy from combustion of the coal recovered exceeds the energy expended in mining it)? Consider both gravitational energy and the energy required to break the rock covering the coal into transportable pieces.

S2. **Failings of Maxwell.** Beyond what field strengths E and B do Maxwell's equations become nonlinear? This occurs because at high enough fields, the external field perturbs the quantum-mechanical vacuum which is made up of virtual particles.

a) Considering only classical properties of those particles (charge e, mass m along with the speed of light c), show that there is a unique combination with the right dimensions to make E (or B, which has the same units in Gaussian units). Also show that the minimum field is set by the lightest particle, and evaluate numerically for the electron.

b) Unfortunately the previous estimate is wrong because quantum mechanics matters. Add $\hbar$ to your list of properties, and show that there is no longer a unique combination with the units of E.

c) A proper estimate requires some physics. Consider a virtual particle of momentum $\sim mc$. Estimate the electric field required to accelerate it to a real positive energy $\sim mc^2$ in less than its quantum-mechanical wavelength. Again show that the critical field is determined by the lightest particle, and evaluate numerically for the electron.

d) Show that your answer to part (c) can be put in the form you predicted in your answer to part (b).

S3. **A pet star?**

a) How does the typical rate of energy output per unit mass of a mouse (or other small mammal) compare with the rate of energy output per unit mass of the Sun?

b) The mouse generates its heat from chemical reactions, while the star gets its heat from nuclear reactions. Use typical energies for such reactions, and your result of part (a) to estimate the lifetimes of the mouse and the star *if no refuelling occurs -i.e., you forget to feed the mouse, and the star does not accrete more gas.*

S4. **Rain power.** By how much does Earth's atmospheric temperature increase before and after a rainstorm

a) Because of the condensation of the rain drops?

b) Because of the gravitational energy release of the fallen raindrops?

S5. **Lava waves.** Construct a dimensionless number that involves only a lengthscale L, Earth's gravitational acceleration g and a kinematic viscosity ν. Hence estimate the shortest wavelength of a gravity wave on a sea of magma (molten tock) of viscosity $10^3 \text{cm}^2 \text{s}^{-1}$.

S6. **Latex paint.** Latex paint consists of small spherical particles (radius r) of rubber (elastic modulus $E \sim 10^7 \text{dyn cm}^{-2}$, density $\rho \sim 1 \text{g cm}^{-3}$) suspended in just enough water to keep them apart. As the water evaporates, the spheres initially form a close-packed lattice with water in the spaces between the touching spheres. As the water further evaporates, the water's surface tension $\gamma \sim 70 \text{dyn cm}^{-1}$ pulls the spheres ever more tightly together. Estimate the maximum radius r the latex particles can have if the surface tension is to be able to pull them together so tightly that the spheres distort into packed cubes, leaving a perfect film of paint with no pores.

Answer **ANY 3** **of questions L1-L5** 20 points each for a total of 60 points.

L1. **Ballerina Birds** (20 points, 10+10)

Certain birds (phalaropes) swim in tight circles and thereby create an updraft of water beneath them that carries small crustaceans (e.g., shrimps) to the surface, where they can then be eaten. The fluid motions are complex but have the property that vertical and horizontal motions are similar in magnitude and characteristic size scale to the motion and size of the bird. Assume a size of 20cm and characteristic velocity of 10cm/s for the large scale motions created.

a) What are the largest crustaceans (internal density 1.1g cm^{-3}) that can be carried up in this manner? (assume the crustaceans are not swimming).

b) What is the total mass fraction of edible matter in the upwelling (i.e., the ratio of crustacean mass to upwelling fluid mass in a given volume) for which this is an energetically worthwhile activity for the bird? For this you should assume a turbulent regime in which the characteristic timescale for decay of the fluid motions is of order the turnover time.

L2. **Exploding wires** (20 points, 6+6+8)

By use of a capacitor bank with negligible external resistance, a large voltage V is suddenly placed across a tungsten wire of length 1cm and radius 0.01cm. (Tungsten is a typical good metal. Assume that its conductivity doesn't vary much up until very high temperatures, if needed.)

a) How long does it take the wire to reach 10^4K (assuming V is large enough to do this)? The answer will be in terms of V.

b) For what choice of V is this timescale less than the sound speed travel time across the wire or the plasma it produces? Why is this significant?

c) For this choice of V, how does the magnetic field pressure compare with your estimate of the thermal pressure?

L3. **Drying your clothes** (20 points, 4+3+3+5+5)

It is presumed that you have used a washing machine and a clothes dryer. A typical load of clothes weighs 3kg when dry, more when wet. The spin cycles of horizontal-axis ("high efficiency") washing machines run at 850 rpm (rotations per minute)[1]

a) Estimate the centrifugal acceleration in units of gravity g experienced by the clothes during the spin cycle, and compute the pressure experienced by the clothes touching the drum. Compare to the pressure you could exert by squeezing with your hands.

b) Give common-sense estimates of

   i. The mass of water left in the load of clothes when it comes out of the spin cycle of the washing machine,

[1] The spin cycles of old american-style vertical axis machines run only up to about 500 rpm, and so extract less water.

ii. the time it takes to dry a load of clothes in the dryer, and
iii. the air temperature inside the dryer (in degrees C).

c) Estimate the energy the dryer has to supply to evaporate the water from the clothes. Convert your answer to kWh.

d) Estimate the airflow (cm^3s^{-1}) of heated moist (but not saturated) air that must be blown out from the dryer if your clothes are to dry in the time and temperature you estimated in part (b).

e) This moist air is exhausted through a vent pipe 10 cm in diameter. Dryer manufacturers require that this pipe, if smooth, straight, and horizontal, be no longer than $L = 20$ m. Explain why, with quantitative reasoning.

L4. **Are sports records really records?** (20 points, 7+8+5)

The Olympic men's hammer is a 12 cm diameter steel ball weighing 7.26 kg. The difference between the world record men's hammer throw (Yuriy Syedikh 1986, 86.74m) and the second place record (Ivan Tikhon 2005, 86.73m) is only 1 cm. The distances are measured with a steel measuring tape, but there is no requirement that the temperature, atmospheric pressure, or direction of throw be recorded.

a) Estimate the difference in distance covered between eastward and westward throws with the same initial velocity, due to the Coriolis force. If Tikhon wishes to overcome Syedikh's record next time, should he throw east or west?

b) Estimate the amount by which air drag reduces the hammer throw distance (compared to a throw in vaccuum).

i. Given reasonable variations in atmospheric temperature and pressure with weather and altitude, what variation would you expect in the distance of throws of the same hammer with the same initial velocity?

ii. Though the weight of the hammer is fixed at 7.26 kg, the Olympic rules permit its diameter to be anywhere between 11.0 and 13.0 cm. How much would this variation in diameter affect the range of hammer throws with the same initial velocity?

c) How much error in the distance measurement could thermal expansion of the steel tape measure plausibly make?

L5. **New or Old Physics?** (20 points, 6+7+6)

The Pioneer 10 and 11 spacecraft, launched in 1972 and 1973, were the first spacecraft to fly by Jupiter and Saturn. These flybys put them onto hyperbolic orbits escaping the solar system, and the last communication from their fading radio signals was received in 2003, when Pioneer 10 was 1.2×10^{10}km from the sun (80 astronomical units = 80 times the earth-sun distance, twice the semi-major axis of Pluto's orbit).

During the two decades that they were cruising out from Saturn, the sun and other solar system bodies exerted a gravitational force on the spacecraft, decelerating them. Tracking of both spacecraft showed that they were decelerating a bit too much to be consistent with Newtonian gravitational attraction from the known solar system bodies (plus best-effort modeling of other effects discussed below). The "anomalous deceleration" was $a_a \sim 10^{-9}$m s^{-2}.

Some people have excitedly noticed that $a_a \sim cH_0$ (H_0 is the Hubble constant, roughly the reciprocal of the age of the universe), and proposed modifications to gravity and fundamental physics. Others have noted that if a_a also applied to Neptune, its predicted orbit would deviate from the measured orbit by more than 100 times the measurement error, and have looked for less exotic explanations of the Pioneer anomaly.

Each spacecraft has a mass of $\sim$ 250kg, an edge-to-edge size of about 2 m (quite complicated shape with various antenna dishes, booms, electronics boxes, buses and thrusters sticking out), and thermoelectric generators with total thermal power of 2.5 kW (from decay of plutonium-238, half life 88 years; about 5% of this power is converted to electricity to run the spacecraft).

a) Estimate the uncertainty (due e.g. to fading or flaking paint) in the acceleration of the spacecraft due to solar radiation pressure when it was at 40 astronomical units.

b) Estimate the acceleration of the spacecraft which could be caused by a reasonable asymmetry (again, say due to asymmetric fading or flaking paint) in the radiative cooling of the thermoelectric generators.

c) The spacecraft has several gas thrusters spaced around its edges. All their valves were supposed to be closed tight during the periods when the anomalous deceleration was measured, but valves sometimes leak, and the reaction force of the escaping gas might accelerate the spacecraft. However, the spin rate of the spacecraft was monitored over the years, and changed at a mean rate of only 0.02 rotations per minute per year. Estimate an upper limit to the acceleration due to leaky thrusters consistent with this rate of change of spacecraft spin.