Hi AST 301 class—This email has two parts. The first is intended to urge you to try to be caught up before tomorrow's class.

The second part is a description ("tutorial") in everyday terms of what is supposed to give you a couple of useful ways to think about all this material, and I hope will help you not only remember it with no trouble at all, but remember it simply because you understand it.

We are trying to get through chapters 6 in the online ebook, and then jumping to 15, both available only in your online ebook. (If you have not tried to access this, do so! If you can't, tell me immediately—we have put two copies of the full text including those chapters on reserve in Physics-Math-Astronomy library in R. L. Moore Hall, but I need to know if there are more than a couple of students in this situation.

Last time (Monday), I basically talked through the material that is covered in sections 6.1 through 6.5 in the textbook. This is the same material that is covered in the first (of two) slide pdfs that accompany the lectures, except that we didn't get to the last few slides. Those have to do with how we can piece together a picture for how our solar system was formed (6.7). (It is described below.) That section leads naturally into the beginning of section 15.1, which deals in more detail with the formation of planets around stars in general—i.e. other planetary systems, which we call "exoplanets."

After you read what I wrote below, you should read 6.7 yourself and see if you understand the basics; we will try to jump to Chapter 15, 15.1-15.2 on Wednesday. I'd like to spend most of Friday on the most important topic, extrasolar planets, sections 15. 6 and 15.7. So I will get the rest of the "slides" online on Wednesday afternoon, and you should have them printed out and in class on Friday.

What to skip:

While we're at it: SKIP sec. 6.6 on space missions (of course read it over if you are interested, but "skip" means "not on exam"). The material in "More Precisely" 6-1 and 6-2 should be read, but you don't have to memorize any of it at all—it is just to help you understand the material. "Discovery 15-1" can be read for your own interest, but won't be on the exam. These are the same as statements on the big "Guide to Reading and Study: Chapters 1-3, 6, 15. One more thing—on the reading guide it says we are going to cover chapter 16 (the Sun) on exam 3. I don't think we are going to make a dent in it—if the first subsection or two will be on the exam, I'll let you know by Friday, but for now, save it.

CHAPTER 6.

In sections 6.1-6.5, the material is very straightforward—we went through an "inventory" of the solar system, emphasizing the planets (through 6.4), but also the "debris" or "interplanetary matter" covered in section 6.5—these are the asteroids, comets, and Kuiper belt objects. Your emphasis should be on a DESCRIPTIVE understanding of what these objects are, not specific numbers. For the planets, you should be able to name them in order of distance from the Sun, give the distance in a very rough way (how about the Earth to start? Then try Neptune—more like 3 AU, or 20 AU? Which is the biggest, smallest, which ones have a surface, which of those have an atmosphere, which have lots of moons, which have none, which planets have the smallest density (the most important property in some ways), and so on. The most basic distinction is between the terrestrial planets and the Jovian planets. You should already know the basics, ALL of which you can piece together if you understand two basic things about solid objects. I will write about those below.

Notice that this material is covered in more detail, and with an eye toward where it all came from, in sections 15.3 and 15.4, so you should look at those together with sec. 6.7. I will be covering all of that in class Wednesday.

A two- or three- page tutorial

HOW TO UNDERSTAND NEARLY EVERYTHING ABOUT OUR SOLAR SYSTEM AND WHERE IT CAME FROM (but which may lead you astray if you think that other planetary systems should look like ours).

REGULARITIES

It will help if you see that there it is easy, almost inescapable, to reach a certain conclusion about the origin of our solar system, if you just realize that :

all the planets orbit the Sun in nearly circular orbits,
all approximately in the same plane, and
all in the same direction (and most of them rotate in that same direction!).

This is so orderly—what does it suggest about how those planets formed, IF I tell you that they had to start with the leftover gas which didn't make it into the Sun? What shape does a rotating thing take? Why? This question will occur again and again, so it will help you a lot if you understand it now, in terms of something called "conservation of angular momentum" which I'll explain in class if you don't already understand it. Read about it first, if possible.

The answer is that the solar system looks just like the planets condensed, somehow, out of a rotating, flat, disk of gas that was spinning around the Sun when the solar system was just formed. As explained at the end of ch6 and in the slides, nearly every star that we see that we think is young (say less than 10 million years old, compared to 10 billion for the Sun), has evidence for a disk of gas and DUST grains around it, so this disk idea is almost too easy. The big question about how planets form is: How did balls of rock and ices and gas (for Jupiter and Saturn, the "gas giants") manage to form from a spinning disk of gas and dust? It is important that you accept, for now, that the original material was nearly all H and He gas, with less than a percent C, N, O, Si, Fe, everything else, but that a substantial fraction of that one percent was in the form of microscopic DUST GRAINS. In any theory of the formation of the terrestrial planets, planets come from the growth of dust grains—just how is still debated and we'll discuss a little.

IRREGULARITIES

The other thing to know is that this orderly motion of our solar system's planets is completely deceptive, giving the impression that planets quietly grew like little seeds in a rotating disk. This is what led astronomers to expect other planetary systems to look like ours. Instead, there are IRREGULARITIES that tell you just as much as those nice circular orbits. They are listed in the book—you should be able to name a few. They suggest that the early solar system was instead a chaotic environment with gigantic rocks of all sizes whirling around, colliding with each other, sometimes smashing up, sometimes fusing with each other, sometimes falling into the Sun, sometimes "bouncing" at such high speeds they are ejected out of the solar system, or at least become comets.

There, you have actually covered not only 6.7, but also 15.1 and 15.2 on more details about the origin of the solar system and planets in general. You need one more thing···

WHAT HAPPENS TO HOT ROCKS?

You need two facts about rocks that should explain whatever else you need to piece together why our solar system looks the way it does (at least for the terrestrial and Jovian planets).

FIRST, something you should already know: Objects, whatever they are made of, will reach a temperature that is larger if they are closer to the Sun, no different from you getting closer to a light bulb (ok, a little different). So although the planets are much cooler than stars, there is a big variation in surface temperature, from Mercury (take a guess), to Earth (about 300K), to Uranus (say 100 K, that is 100 degrees above absolute zero, that is 173 degrees below the freezing point of water), to a comet at its farthest distance from the Sun (just a few degrees above absolute zero). So always think of the earliest solar system, or any disk around any star, as hot on the inside, cold far from the star. So answer in your own words: Why are comets the coldest objects in the solar system?

SECOND, if you make some material (like ice, or iron) too hot, it will vaporize, go from the solid phase to the gas phase (no liquid phase because of low pressures compared to here; technically, the correct word is "sublimation" when you go from solid to gas, but we don't care about terminology here). You know this for ice, which vaporizes at the Earth's temperature, and I'm hoping it makes sense for other materials. If you heat up a piece of plastic, it decomposes, into a gooey liquid here, but into a gas in space, because the heat is equivalent to the atoms or molecules in the substance moving around faster, and at some critical temperature, they are moving fast enough to break the chemical bonds that holds them together.

EACH MATERIAL HAS A SOMEWHAT DIFFERENT VAPORIZATION TEMPERATURE:

Water ice vaporizes around 350 deg K (that's roughly the 80 degrees Centigrade, which should seem more familiar to you), while some ices, like methane ices, can't even make it to 200deg K.

ICES ARE FRAGILE and vaporize at fairly low temperatures. This kind of substance is usually called a "volatile" (you don't have to know the word). They have loose bonds—in a sense, that is why they usually have very low densities. The density of water ice is an easy-to-remember 1 gram per cubic centimeter—just remember what it feels like to hold an ice cube in your hand.

But other materials ("refractories"—again just FYI), for example (and obviously) rocks on the Earth's surface, which are mostly silicon mixed with oxygen and maybe magnesium, don't vaporize until much higher temperatures, so that they are solid even at 1000 K for **silicate rocks**; **carbon** materials can make it to about the same temperature, depending on the kind of carbon (obviously not organic carbon in organisms, but certainly diamonds or even coal); these materials are denser than ices, with densities right around 3 grams per cubic centimeter; if you want a sure fire way to remember it, find a rock about the size of an ice cube and bring it home and hold it in one hand, with an ice cube in another. Then wash up, please.

As a final example, **iron**, which is the most abundant of the heavier elements, doesn't vaporize until nearly 2000K. Iron is also the DENSEST of the materials we've mentioned, coming in around 7 grams per cubic centimeter (you might strain to hold an "iron cube" in your palm because it would be so heavy).

OK, now think of rocks growing, somehow, out of the microscopic grains in the early solar system—they might have some combination of ices (volatiles) and rocks (refractories—silicates, iron, and other substances). But the inner planets are so hot that the ices can't be ices—they vaporize. Those ices contained most of the oxygen, carbon, and nitrogen in the early solar nebula, which is most of the mass of the solids—because (just believe it) silicon and iron have much smaller abundances than these. So at the temperatures of the terrestrial planets, what could have condensed into a growing gigantic piece of rock that would become a planet? ONLY the material that can survive at those temperatures—but that leaves out most of the solid material! So that is why the inner (terrestrial) planets have rocky compositions, high densities, and virtually no ices.

Now explain why Uranus and Neptune are pretty massive compared to the Earth, but may be made almost completely of ices. If this is obvious, then you not only understand this, but you understand what we expect for planets forming around any star.

Left unexplained (I actually explained in class on Monday): Why are Jupiter and Saturn made mostly of hydrogen and helium? Why doesn't the Earth or the other terrestrial planets have much hydrogen or helium? After all, hydrogen and helium were certainly the most abundant elements in the solar nebula, as they are everywhere, and they don't make solids. If you know the answer, you are probably well into chapter 15.

This is the next level in understanding the difference between the two theories for the origin of gas giant planets: What your book calls the "**nebular theory**," involving the collapse of a blob in the disk under its own gravity to make a planet, or the "**condensation theory**," which is the growth of the cores of the giant planets, like Earths buried in the center, by collisional sticking of larger and larger particles, until that core could capture hydrogen and helium from the surrounding gas. Most astronomers refer to the former idea as the theory of "**gravitational collapse**" and the second as the "**coalescence**" or "**agglomeration**" theory, which is controlled by a "snowball effect," and gravity has very little to do with it.