The Solar System (Ch. 6 in text)

We will skip from Ch. 6 to Ch. 15, only a survey of the solar system, the discovery of extrasolar planets (in more detail than the textbook), and the formation of planetary systems (also in somewhat more detail). No details on individual planets--but I suggest you flip through those chapters between 6 and 15. Remember: material is only online.

The solar system consists of the **Sun** (a typical star),

orbited by 9 (now 8) **planets** (be able to name them!),

about 40 **moons**,

asteroids,

and a large number of **comets**.

> Most of the objects have nearly circular (but still elliptical) orbits, but some (especially the comets) have extremely eccentric orbits. (Why?)

The sun is ~ 1000 times more massive than the rest of the solar system, and over 100,000 times more massive than the Earth, although it's radius is "only" about 100 times that of the Earth. (If these numbers were correct, can you tell whether the Sun is more or less dense than the Earth? Density = Mass/Volume.)

Because of its mass, the Sun's gravity controls the motions of the other members of the solar system. (Think: Newton's law of gravity)

Planets:

Name	Distance from Sun	Satellites	Year	Day
Mercury	0.4AU	0	0.2 yr	60 days
Venus		0	0.6 yr	243 days*
Earth		1	1 yr	1 day
Mars	1.5	2	2 yr	1 day

<u>Terrestrial planets</u> are similar in size, mass, density, and composition (*rock and iron*)

Asteroid Belt—probably "failed planet"

Jupiter (largest)	5	70?	12 yr	10 hr
Saturn (rings)	10	35?	30 yr	
Uranus	20	30?	80 yr	*
Neptune	30	15?	160 yr	

<u>Giant (or Jovian, or gas giant) planets</u> are larger, *much more massive*, much *lower density*
(showing they are composed of lighter elements, *especially large amounts of hydrogen*).

Belted weather systems (most famous feature: Jupiter's "Great Red Spot").

Pluto	40 AU	1	~250 yr	*

* means peculiar orbit or rotation.

--> 2006: Pluto demoted to non-planet status.

Notice that ***a few objects have peculiar orbits and rotation***; e.g. Venus, Neptune, Pluto,… This suggests collisions with other large "planetesimals" when solar system was forming.

They are crucial clues to the formation of our solar system.

The most important thing to remember is the differences in properties between the ***terrestrial planets*** and ***jovian planets***, as summarized in Table 6.2 (p. 152).

Those are also big clues about how the solar system formed, so you should remember them when you read Ch. 15.

To review: Describe in words the differences between the terrestrial and Jovian planets, including any details you recall, and any speculations about the differences.

Comets: Iceballs, most in highly eccentric orbits which extend far beyond Pluto.

Spend most of their time far from sun (in the "***Oort cloud***"; also the "***Kuiper belt***" comets outside of Neptune's orbit).

Comets and ***asteroids*** are "debris", but very important because they represent the solar system when it was first forming. Also, *they may have delivered the organic compounds used to produce biological molecules on the early Earth*. (Might be difficult to produce them on the Earth itself, although controversy about this.)

Age of solar system: From radioactive decay ages of meteorites and moon rocks: 4.6×10^9 yr (about ***4 or 5 billion years*** is good enough for memory).

Remember that sec. 6.6 (Spacecraft exploration of the solar system) is for your own interest, but will not be on the next exam.

Do **read Section 6.7: How did the solar system form? Important to realize how our ideas have changed now that we have discovered ~ 200 "extrasolar planets." Main things here: 1. Why rotating objects tend to form *disks*. 2. How could you get big blobs of gas or rock to condense out of the protosolar nebula?**

Formation of Planetary Systems (ch. 15)

This has become one of the most exciting fields in astronomy because since 1995 over 200 planets outside our solar system have been discovered (sec. 15.6), severely challenging theories of the origin of planetary systems, and opening the tantalizing possibility of discovering **earth-like worlds** in the future. We cover this in later notes, but it is not reflected in as much detail in your book.

Chap. 15 of the text gives an excellent discussion of the theory, so only brief outline here.

Clues:

Regularities--orbital shapes and planes; spin directions of planets and moons; "differentiation" (difference in chemical composition) between terrestrial and Jovian planets.

Irregularities—Unusual planet and satellite rotations (Venus, Uranus, Pluto).

Also: cratering history of planets and especially the moon (preserved because no erosion). (When you see this later, you should know why this is an important clue!)

Theory almost universally accepted: Stars form by gravitational contraction of gas clouds (Fig. 15.1).

A contracting *rotating* object will spin faster as it contracts (conservation of "angular momentum") and *flatten* into a ***disk*** ⇒ "protosun" surrounded by rotating **disk** or "protosolar nebula" ("protostar" and "protostellar" for other stars).

See Fig. 15.1 for general cartoon, Fig. 15.2 for an image of a dense interstellar cloud that might someday form stars and planets, 15.3 and below to see a few disks around young stars --notice how they can be detected by excess radiation of a certain wavelength. [*Why that wavelength region?]*

For stars younger than a few million years, almost all the stars like our sun, or less massive than the sun, appear to have disks of dust and gas around them.

So by now can make a strong case that young stars have rotating disks—the question is just about whether and how that disk turns into planets. But these detections of disks give strong support to the standard theory that planets form out of the debris leftover from the formation of stars, and that debris begins its life in the form of a disk. But how?

The standard picture to get the process started: Microscopic dust grains (about 1% by mass) grow by collisions with other grains. Snowball effect called "accretion" (meaning accelerated collisional growth here) leads to growth of larger bodies called "*planetesimals*" (ranging from large rocks to small moons in size).

There is some debate over whether collisions dominate or whether they lead to growth at all. (It isn't so easy to get two pieces of rock to stick as the result of a collision if they are moving too rapidly.)

More collisions:

Slow-speed collisions: Merging, "coagulation", and "accumulation" of planetesimals into planets (note that this is sometimes called "accretion" in your text). Either get terrestrial-like planets (if close to the star, where it's too warm for "volatiles" to be solid or liquid) or Jovian-type planets (further from star, where cooler, so "accretion" of H-rich gas can occur on top of core—this is accretion of gas, not particle collisions).

Important to understand the dependence of composition of the inner vs. outer planets in terms of the temperatures at which icy ("volatiles") and rocky or iron solids could condense or be vaporized.

Intense study of Fig. 15.8 is recommended, until you understand the phases and terms used in it.

Jovian planets could have also formed by direct gravitational instability of the disk, with no accretion at all. In this case they would have only taken about 1000 years to form (see Fig. 15.7). In this case no collisional growth of a core, followed by accretion of gas, is needed. But some evidence Jupiter has a core, and the question of whether a protoplanetary disk can become unstable this way is unsettled.

High-speed collisions: fragmentation of planetesimals; these "leftovers" either bombarded the planets and their moons (see our Moon) or underwent gravitational encounters with young planets (not direct collisions) and became asteroids or comets. (See sec. 15.4 for a good list of unusual objects in our solar system that can be explained by catastrophic high-speed collisions. We will briefly discuss in class.)

Be sure to read sec. 15.4 on the Asteroid Belt, and on Comets and the Kuiper Belt.

This process of ejection of planetesimals (and maybe even some planets) to form the Kuiper Belt and Oort cloud (or even escape completely) is extremely important (see Fig. 15.9).

The remaining debris of gas and dust that *wasn't* incorporated into a planet or other body was probably swept out of the forming planetary system by the intense stellar winds that are observed around all young stars. (See Fig. 15.4) But some solid particles were "left over," since we now know of many "debris disks" around older stars.

The whole process probably took 10 to100 million years, although this is wildly uncertain. The main thing that is certain is that the formation time was very short compared to the age of our solar system (about 4.5 Gyr = 4.5 billion years = 4500 million years).

And it is now known that the gas and dust grains started to disappear within about 5-10 million years, so giant planets had to form faster than this (think: why?)

Notice that there are two types of planetary "migration" briefly discussed:

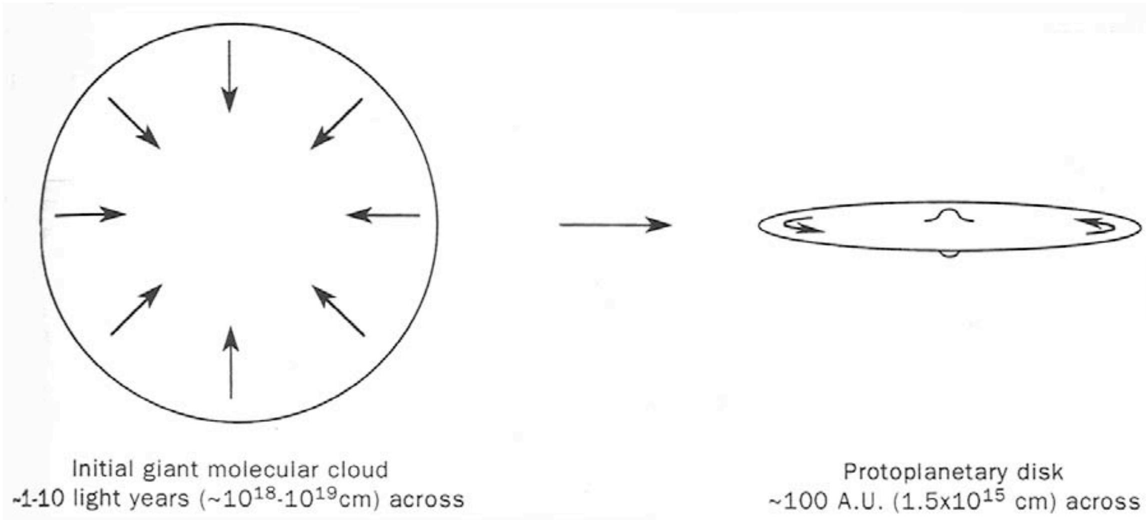
1. Early migration of giant planets due to interactions with other forming giant planets and the disk itself (p. 397; we will see there is evidence for this in extrasolar planets), and

2. Later migration due to the interactions that eject planetesimals (p. 399).

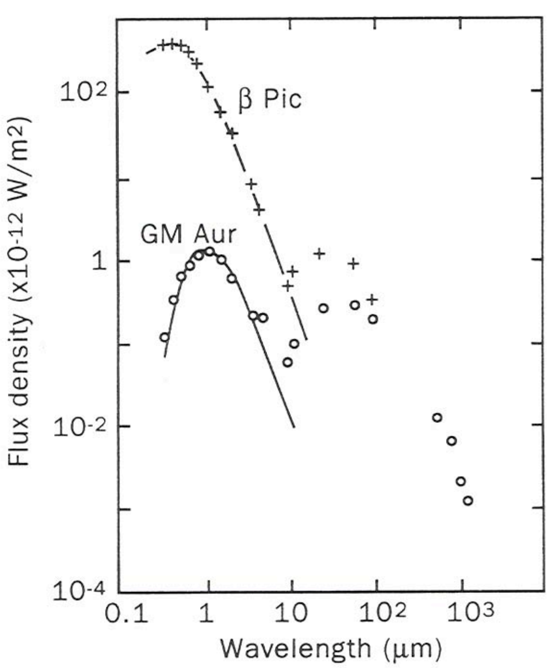
Consider danger to inner rocky planets if a Jupiter-mass planet is migrating inward while the inner planet is forming. What might happen?

Common feature of all models for formation of planets:

Collapsing, *rotating*, gas cloud becomes a disk with star at center.



Evidence for disks: Infrared excesses in spectra of very young stars



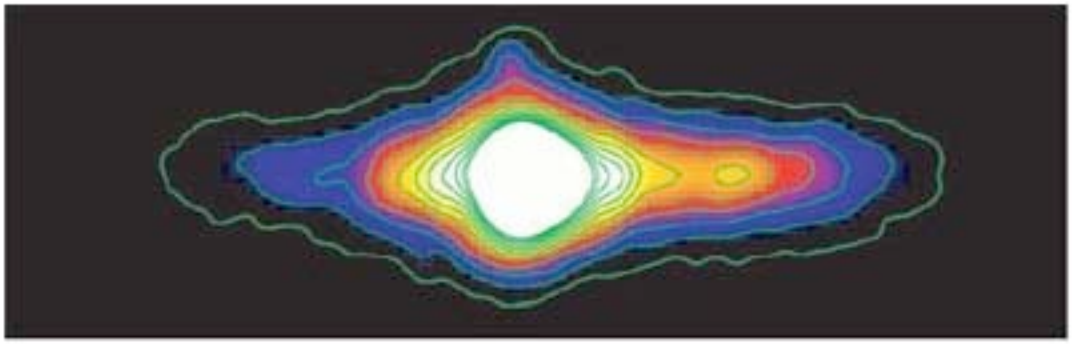
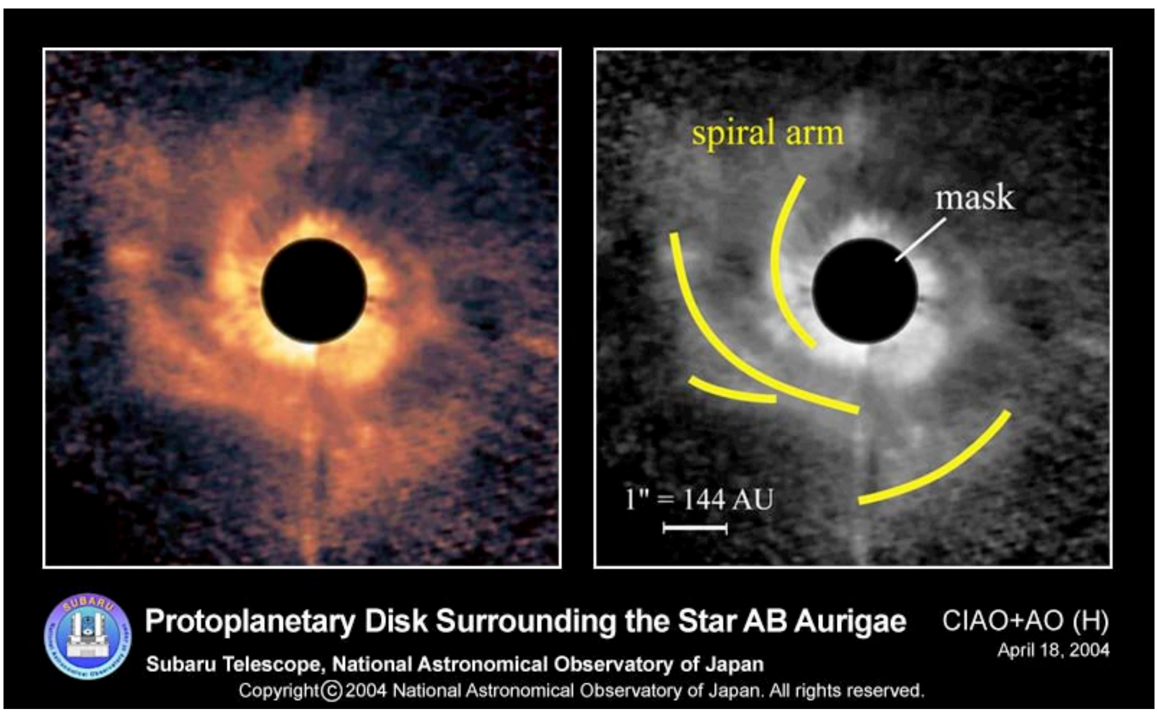
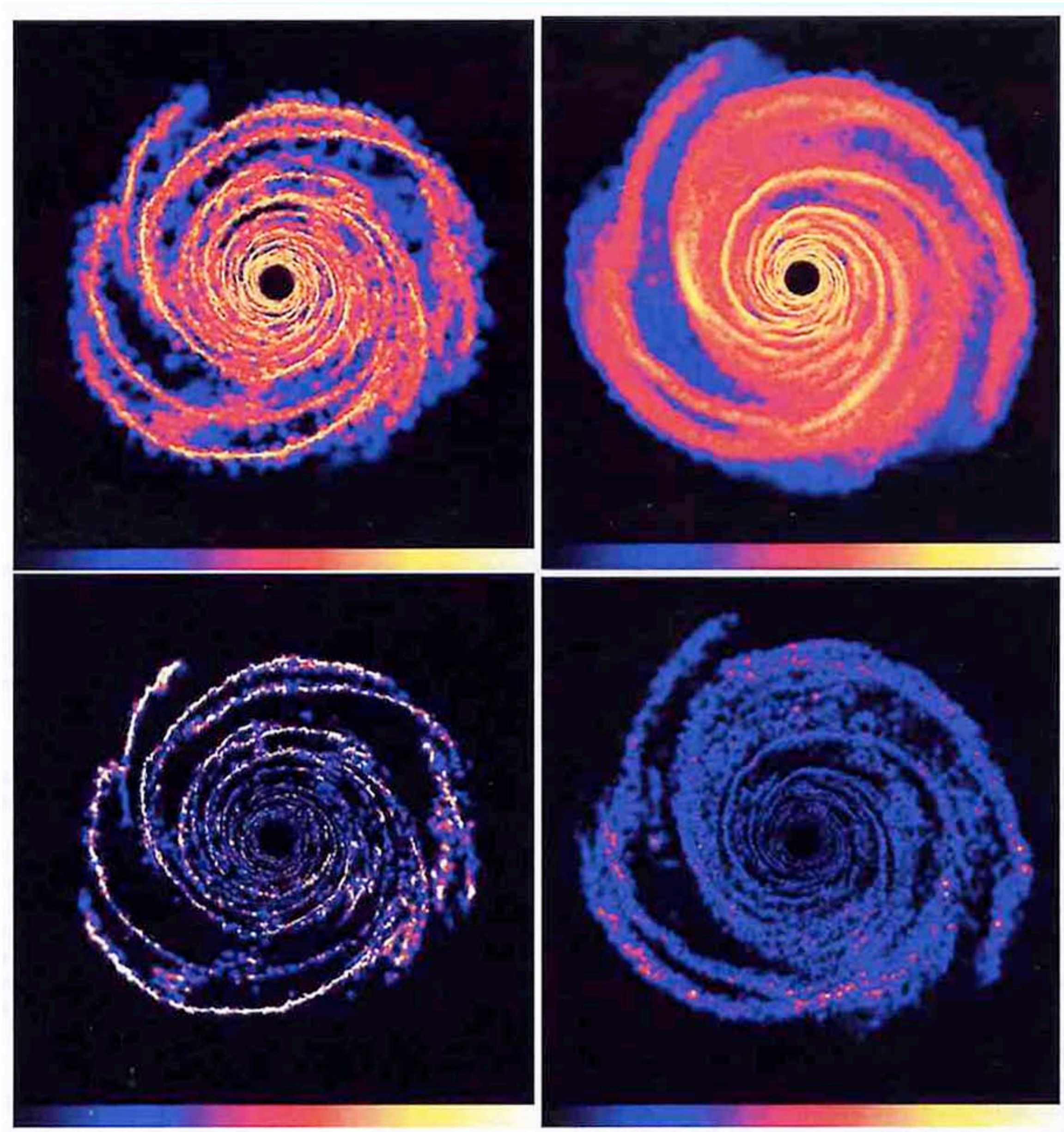


Figure 1 The β Pic disk, imaged in the mid-infrared at 11.7 μm

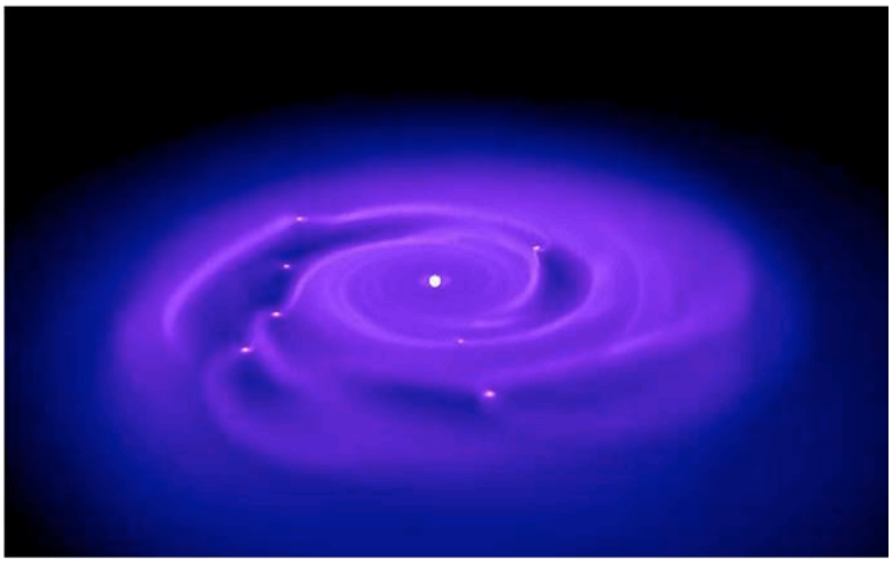


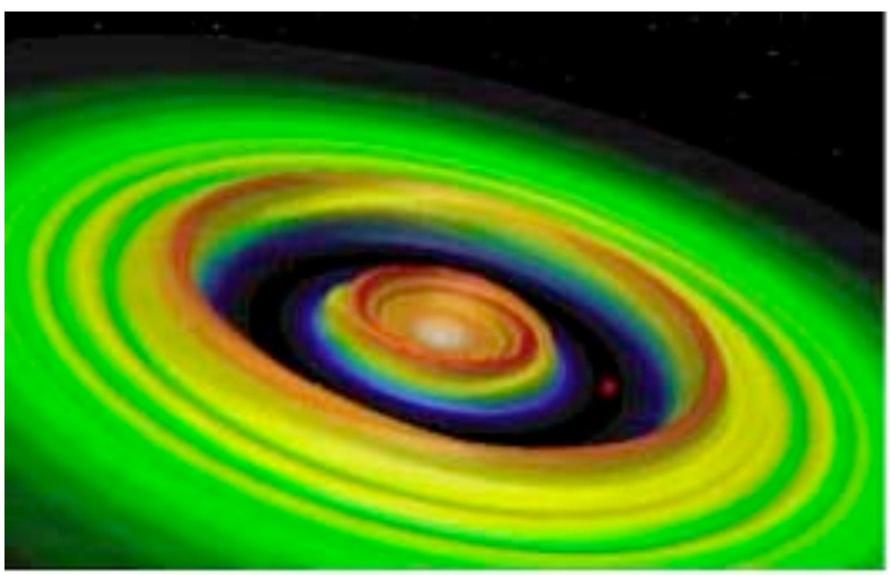


Computer simulation of gas and dust grains in a protostellar disk, for different size grains. Note how grains can be accumulated in the spiral waves (lower left).

Presence of planets can open up "gaps" and inner holes in disks—indirect way to detect (giant) planets!

Illustrations below are *numerical simulations* of evolving disks, not images of real protoplanetary disks.





Bryden et al. 1999