Extrasolar Planets:
The (more or less) Standard Theory for Planet Formation

[Textbook is weak on planet formation. But see pp. 14, 20-21 (especially study the beautiful illustration on p.21), and 264-265. Read this texbook material before studying these more detailed notes.

Also, these notes are meant to be read in conjunction with the lecture presentation. A pdf of the powerpoint presentation is available online, and a hardcopy version will be available at PMA.]

Theories for planet formation involve many thorny problems and hotly-contested ideas, but *they all star with a rotating disk*, and now we know observationally that this is a good assumption.

Minimum mass of the disk: probably ~ $0.01M_O$, similar to masses of observed disks (although these are very uncertain). Note that the sum of our solar system's planets' masses is about $0.001M_o$ (mostly Jupiter), but this is partly because most of the hydrogen and helium have been lost (escaped from planetary atmospheres because so light). Some models *do* assume more massive disks.

The main features to remember are that:

a. In all models, the temperature and density decrease with distance as you move out from the central star. (Observations suggest slower decrease of temperature than models predict, but both are uncertain.) This will make it fairly easy to understand *most* of the composition differences in terms of a "condensation sequence": different kinds of solids vaporize at different temperatures, so only "rocky" material can survive in the inner disk, while both rock *and* icy material can survive in the outer disk. (Illustrations in class in presentation on disks.)

b. These disks are mostly gaseous (~99% by mass), with a "cosmic composition" like the sun's and most other stars, but about 1% of the mass is in the form of microscopic dust grains, which play a fundamental role in the evolution of the model planetary systems. Presumably these grains are interstellar grains that happened to be dragged along with the gas into the protostellar disk.

The more-or-less standard "core-accretion" theory

Main stages in evolution of a disk toward a planetary system: (things in braces are references to technical papers that you can ignore)

1. Settling of the dust through the gas into a thin layer at the disk mid-plane. (Because gas is supported in vertical direction by pressure, dust isn't. Explained in class.).

Problem: How can the dust settle if the gas in the disk is turbulent? It would constantly be "stirred up."

2. *Collisional* “accretion” or “accumulation” of dust particles by other dust particles, leading to kilometer-size <u>planetesimals</u> in ~ 10^4 yr.

<u>Problem</u>: particle-particle collision velocities are large enough (~0.1 to 10 m/sec for sizes ~1mm to 1cm) that collisions should lead to *shattering*, not coalescence. So how can you get to 1 km planetesimals?

{Wurm et al. 2001 Icarus, 151, 318 offer a solution; many papers on this since then.}

3. *Gravitationally-aided* collisional accumulation of planetesimals through a process of “runaway growth” (explained in class), resulting in planetary embryos (Mercury- to Mars-size) in ~ 10^5 yr.

{“Dynamical friction” causes energy equilibration, so large bodies have enhanced rate of accumulation of other large bodies—this is a runaway process; new runaway due to size-dependent gravitational perturbations and gas drag: Kortenkamp et al. 2001, Science, 293, 1127.}

4. Giant impacts between embryos, resulting in full-size terrestrial planets in ~ 10^7 to 10^8 years (problem?—remember lifetimes of disks estimated above), but also causing large disturbances and destruction (e.g. formation of our Moon).

5. Farther out in disk, ices survived (because cooler), so more solids, and embryos may reach about 10 Earth masses in about 10^6 yr. After reaching this mass, the bodies can *gravitationally* accrete ~100 Earth masses of disk *gas* to produce giant planets like Jupiter and Saturn in about 10^7 yr. (Again, potential problem with timescales for disk disruption.)

Pictures of simulations of steps 4 and 5 are shown in lecture: result is formation of planets that look roughly like our solar system (except not enough time to make Uranus and Neptune—some people think they formed closer in and were “scattered” or “migrated” out to their present positions).

An alternative to this “<u>core-accretion</u>” mechanism (5) for forming giant planets: they form by the <u>gravitational collapse</u> of Jupiter-mass clumps of gas and dust in the disk. This might only require about 100 years. Pictures of simulations of this process are shown in the lecture presentation. The problem for this process is that it requires a fairly massive disk, and no one knows if the disk masses are sufficient (hard to measure from dust emission or CO emission lines).

If this model is correct, then giant planets formed *before* terrestrial-size planets. In that case the evolution of planetesimals was dominated *not* by their own (fairly feeble) interactions, but by much stronger *gravitational* perturbations from the massive planets. This might be a problem if you want to form terrestrial planets, because many giant planets undergo *migration* (see below).

Several illustrations of simulations of this process will be shown in class.

So the planetesimals are probably acted on by two competing forces:

1. Gravitational perturbations from the massive bodies “scatter” the planetesimals, increasing their orbital eccentricities and inclinations; in fact many of them must have been “kicked out” of our solar system (and probably others) by such a process, to account for the “Oort cloud” of comets (which are supposedly planetesimals scattered into very eccentric orbits). Also undoubtedly formed the “Kuiper belt” of comets (beyond Neptune). Some bodies must have been kicked into interstellar space (consider: “rogue planets” with no parent star). We’ll call this process “gravitational scattering.”

2. The planetesimals move around the central star faster than the gas (because the gas has pressure as a partial support, as well as rotation, while the planetesimals do not have a pressure). The resulting “gas drag” is strongest for smallest planetesimals. The drag force *reduces* orbital eccentricity and inclination, and also removes angular momentum, causing planetesimal orbits to slowly decay toward the star. This might cause some stars to “cannibalize” their own planets, or at least planetesimals.

Both processes cause **orbital migration**. (There are other processes that are involved in migration, but we will omit them here.) Fullly-formed planets feel the drag forces too, and are predicted to spiral into their parent star, *if* the gaseous disk is not blown away quickly. (No gas, no drag force on the planet.) You can see the crucial interplay between the timescales for the dispersal of the disk gas (and dust) by the protostellar wind, and the ability of giant planets and terrestrial-mass planets to form and survive.

This idea, that the planets did *not* start out at their present-day distances from the sun, is a major way in which current theoretical models differ from models that were popular before *extrasolar planets* were discovered. In fact we will see that, although this was theoretically predicted in the 1980s, it still seemed unbelievable until it was very abundantly verified by the first discoveries of extrasolar giant planets (“EGPs”)

Now we turn to details of techniques by which extrasolar planets have been and will be detected, and the perplexing results found so far.