<u>Extrasolar Planets: Molecules and Disks</u>

The basic question: Is our solar system typical of what we should affect around other stars (inhabited or not), or is it an unusual freak?

One approach is to look at theories for how our solar system formed.

The most striking thing about our solar system is it's mixture of regularities and oddities.

<u>Regularities</u>:
Orbits *and* spins of *most* planets and satellite systems are in same direction (and same as sun's rotation direction) AND
The orbits are nearly circular AND
The orbits are in nearly the same plane.
The spacing increases with distance from the sun in a nearly regular (roughly logarithmic) manner (often called "Bode's law")
Planetary composition varies with distance:
Inner 4 "terrestrial" planets are rocky, small, thin atmospheres
Outer 4 "gas giants" are icy/gaseous, large, mostly atmosphere.

Can understand this for the most part on the basis of models in which planets form in disks rotating about their parent star: <u>protostellar disks</u>. Our solar system for the most part looks like a rotating disk in which, *somehow*, the gas and dust condensed into the much denser objects we call planets and satellites.

<u>Irregularities</u>:
Uranus' rotational tilt, Triton spins the "wrong" way, elemental composition anomalies (e.g. Mercury, Moon), Pluto's large orbital eccentricity and inclination, … We'll come back to this.

For now, let's concentrate on disks: why they are important, how common or uncommon they are (observationally), and how planets might form from them.

Part of the interest in disks is because of their potential for forming planets.

But another big reason is that the gas in those disks may have been the ultimate source of <u>prebiotic organic molecules</u> for the Earth (and other habitable planets if there are any). In nearly all pictures for the origin of life, the process begins with certain key organic molecules (those involving carbon and hydrogen) ranging from simple organics like formaldehyde (H_2CO), hydrogen cyanide (HCN) (which can undergo reactions to make, e.g. amino acids), to sugars, to more complex organics like polycyclic aromatic hydrocarbons (PAH's). So we need to first discuss the existence of complex molecules in the regions where stars form.

Complex Molecules in Space

Before discussing disks and how they might result in planet formation, let's review the evidence that complex organic molecules are common in the universe.

All the simple and complex organic molecules named above, and more, have been observed (through their spectral line signatures) in dense interstellar clouds that inhabit the space between the stars. These include molecules with up to 13 atoms, and carbon ring molecules (PAHs) and long linear molecules (e.g. polyynes). [Examples of molecular spectra and a list of interstellar molecules, will be shown in lecture.] Since stars are observed to form from such clouds, it is possible that the disks obtained their organics in the cloud from which they formed, and that they later got incorporated into icy or rocky bodies (like asteroids or comets) which delivered the molecules to Earth (or other planets on which they could survive).

In fact a large number of organics, even amino acids (!) have been found in meteorites (asteroid and comets that make it to the Earth's surface). The most recent "missing" prebiotic organic, a sugar, was found in a meteorite in Jan. 2002.

Most molecules do not survive the high-temperature ride through the earth's atmosphere, but they *can* be observed through their spectral line signatures in comets, where many interesting organic molecules have been seen. (e.g. Giotto spacecraft spectra of Halley's comet in 1986. Table shown in lecture.)

Many people think that much of the pre-biotic organics needed for life were delivered to the Earth, possibly along with the water that makes up our oceans (!), by comets or asteroids. Most comets *are* mostly water ice.

How do these molecules form in the seemingly hostile environment of interstellar space? Actually the ultraviolet and x-ray radiation and high-energy cosmic ray particles that propagate throughout our galaxy, and even within interstellar clouds, are thought to *induce* complex chemistry on the icy surfaces of interstellar dust grains, which then get incorporated into any protostellar disk that forms in the cloud. Making complex molecules requires a source of energy, and the seemingly hostile environment can actually supply this energy when the molecules reside on solid surfaces.

A big question is: Can these molecules survive their incorporation into the disks? (That is discussed in the outside reading assignment in Ch. 4 of Koerner and LeVay's book.) But the point is still clear that <u>"prebiotic" organic molecules are apparently easy to produce</u>. (Later we'll see that getting these molecules to combine to form very complex molecules as needed for life is *not* easy at all.)

Are Disks Common?

Now let's return to the question of disks. What fraction of stars are born with them? How long do they survive? (i.e. how long a period of time is there to convert the disks into planets?) We can get answers from observations in this case.

Several lines of evidence that disks are common around young stars:

<u>"Infrared excesses"</u> in the spectrum—known since the 1960s, but could be circumstellar shell, not disk. (Explained in class, with illustration)

<u>IRAS satellite</u> (1994) gave evidence that lots of young (<10 Myr) stars are surrounded by disks. But resolution not good enough to tell if really disks. If so, over half of young stars have them. (Think: why is the infrared best for this kind of work?)

<u>Hubble Space Telescope (HST)</u> – "<u>proplyds</u>" in Orion Trapezium region (~1 Myr old; pictures shown in class, and in text): visible wavelength disks seen in silhouette against the bright nebula. (Note need for high spatial resolution here.)

Carbon monoxide (CO) radio wavelength line mapping of nearby protostellar T Tauri stars (usually 1-10 Myr old): shows (by Doppler effect) that disks are rotating, and as a Keplerian disk (i.e. rotating according to Kepler's laws rather than, say a solid body rotation—will explain in class if not clear).

Infrared images with Keck telescope: HR 4796 (about 10 Myr old) could be a disk with empty *hole* in center! HST coronagraph image confirms this. Maybe that central dust has been converted to **planetesimals** (meter to kilometer sized solid bodies) or even planets.

Debris disks. Leftover material around older (ages ~ few hundred Myr) stars, detected in infrared, but then sharper images in visual. Beta Pictoris is the best-known and studied example (see text; more pictures shown in class). Evidence for central hole (where the mass has been converted into a planetary system??); inner disk tilt could be due to a Jupiter-mass planet within the hole. Also a recently discovered "blob." [Pictures shown in class]

So plenty of evidence that disks are extremely common around young stars (of all masses, even brown dwarfs!). But how long do they survive?

Can answer this by looking at how strong the infrared excess is as a function of the age of the parent star (known only approximately, within about 30% or so).

Result: Dust disks start to disappear after about 3 Myr and are almost completely gone by 6 Myr. (This assumes that we can get the age of the central pre-main sequence protostar at least roughly—get it from comparing position of star in H-R diagram with theoretical evolutionary tracks.)

This isn't much time to form planets, but may be enough to form the planetesimals (which would be too large to be seen in infrared easily because total emitting area reduced), which then become planets. Still a serious problem. (See below)

The satellite observatory SIRTF (Space Infrared Telescope Facility), just launched late in 2003, has as a primary goal to detect such planetesimal disks.