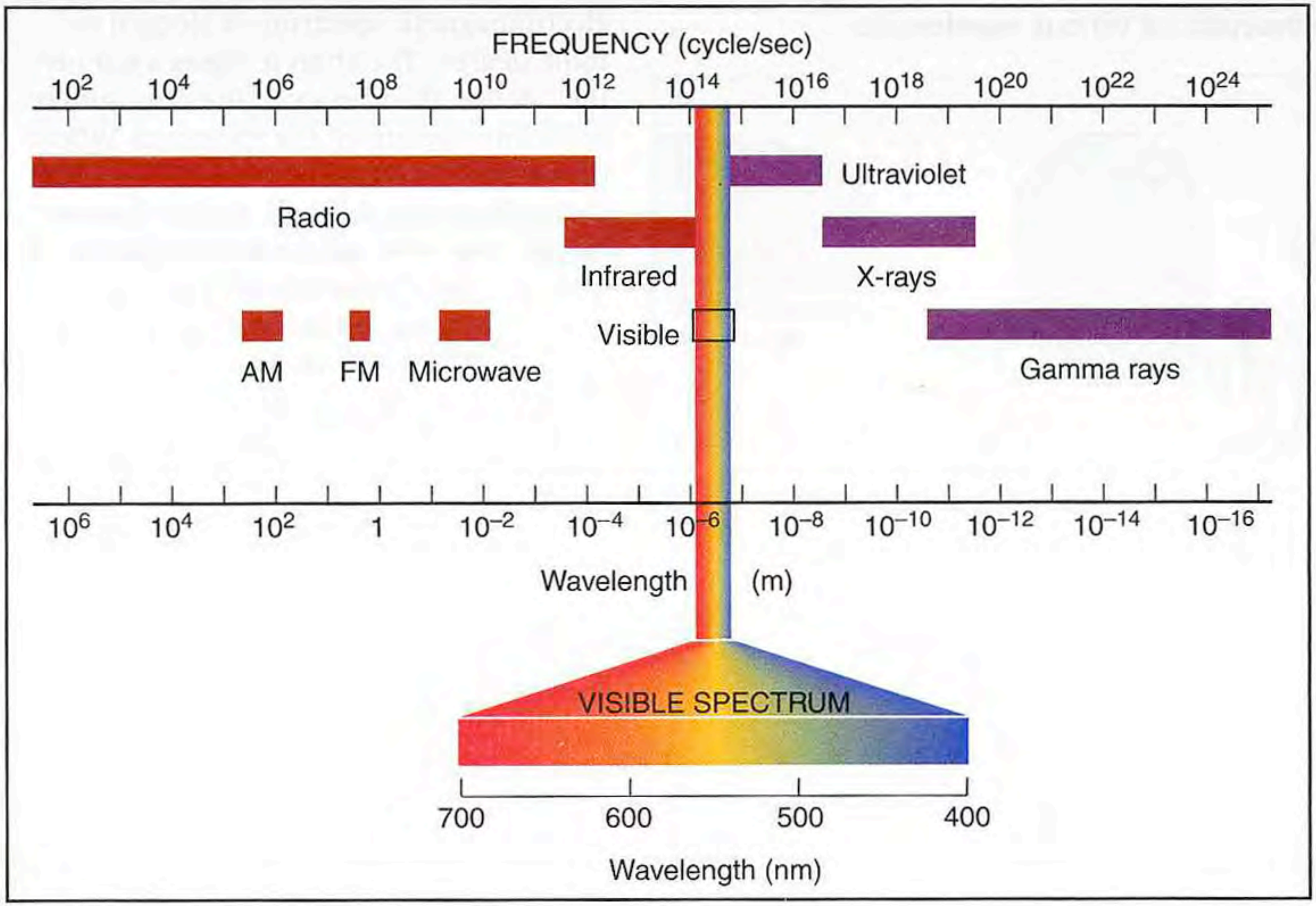
Main topics of next few lectures

- Review of the electromagnetic spectrum: how the continuous spectrum of an object tells you its temperature
- Ubiquity of complex organic molecules: interstellar star-forming regions
- Planet formation
    1. Inferences from our own solar system
    2. Observational evidence for disks
    3. Theory of planet formation

Wavelength Regions in the Electromagnetic Spectrum



All objects emit at all wavelengths, but usually have a dominant wavelength region, where most of their energy is emitted or reflected. But in the cases shown below, the color you perceive is *not* related to the temperature; if you could see all wavelengths, you would see both cases as having a peak in the infrared (we will see why).

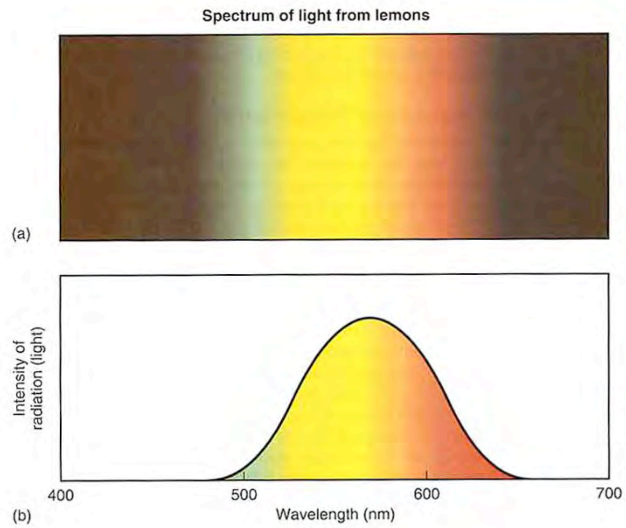


Figure 4-7
(a) If light reflected from the lemons were sent through a prism to reveal its spectrum, we would see that the lemons reflect mostly yellow light.
(b) This graph indicates the relative intensity of the various wavelengths of light from the lemons.

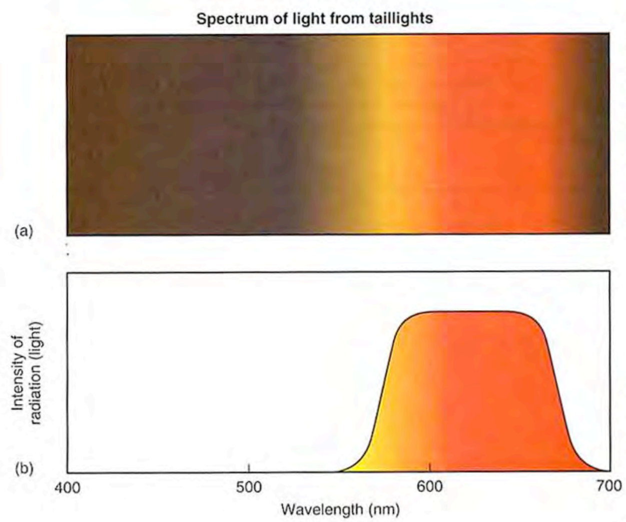
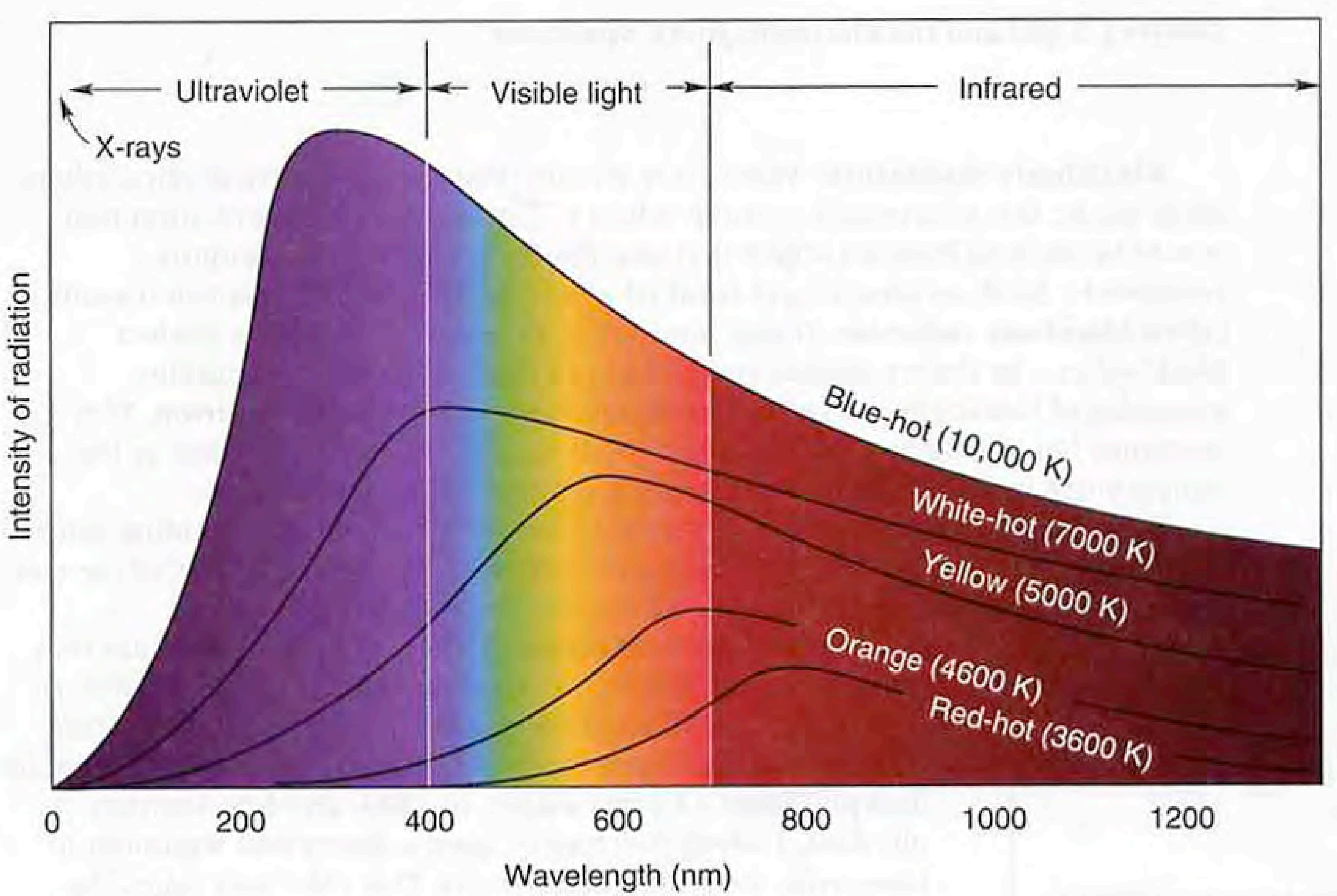


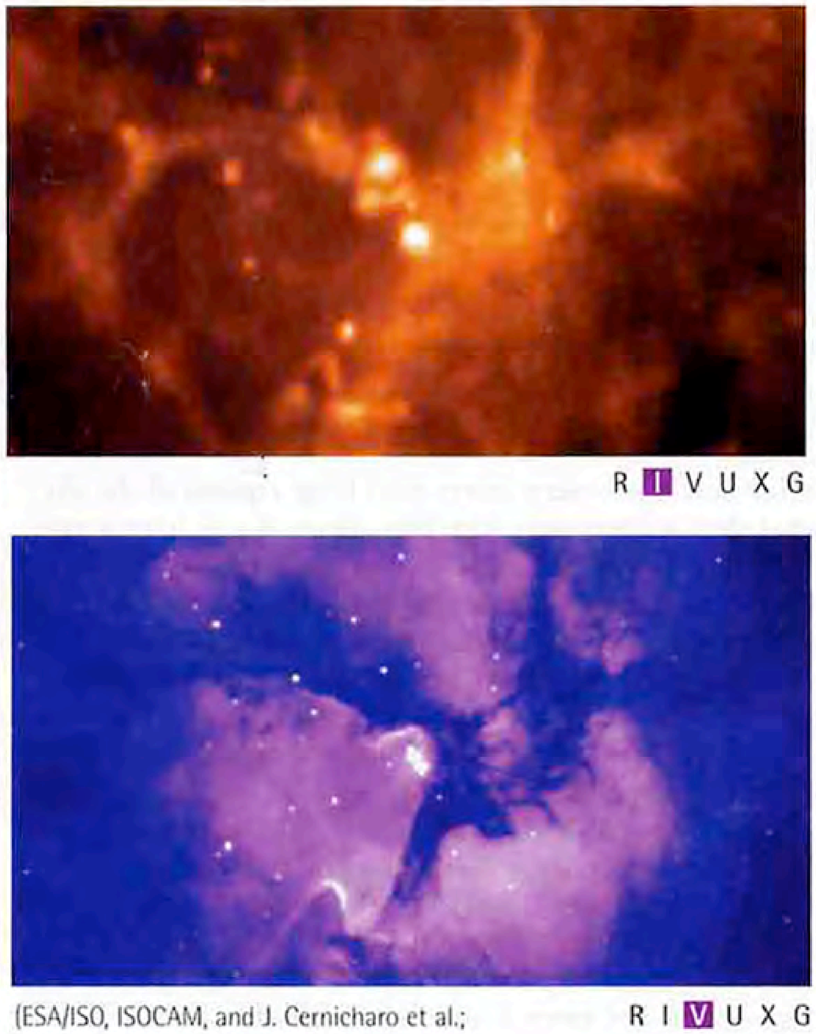
Figure 4-8
The spectrum of light from the taillight of this particular car. The light bulb emits white light, but the plastic cover over the bulb absorbs much of the light, letting pass some wavelengths in the red, orange, and yellow regions of the spectrum.

Many objects in the universe emit light in a continuous spectrum that is well-approximated by the "blackbody" formula. This shows that where most of the energy is emitted (the peak in the continuous spectrum) depends on the *temperature* of the object. But solid around stars (dust grains in protoplanetary disks, planets themselves) are at temperatures around 100 to 500 K, so they will emit mostly in the infrared, just as objects around you do.



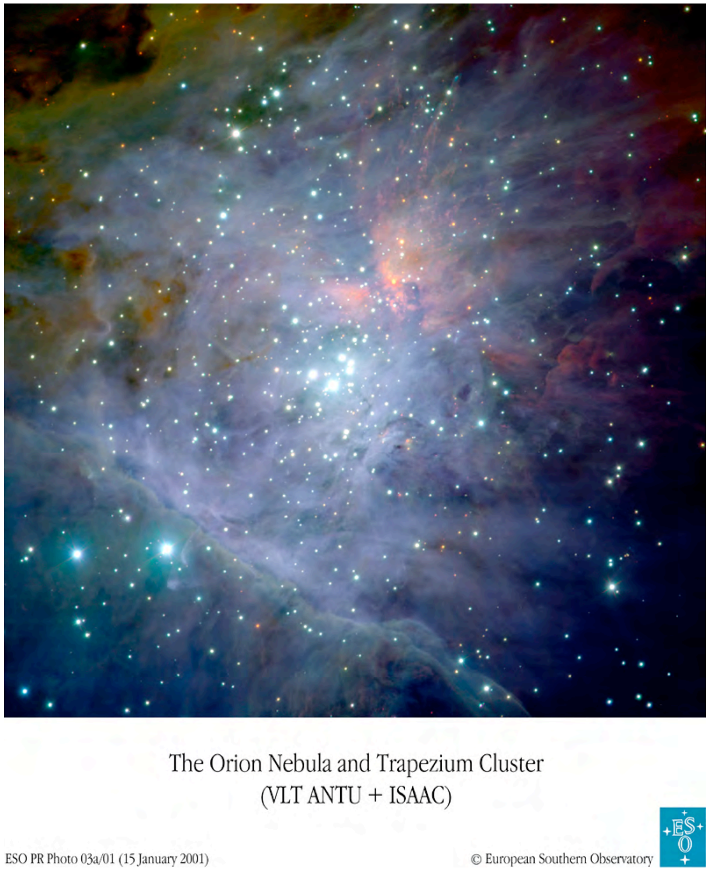
Star formation regions (and the entire interstellar medium) contain about 1% dust grains, which are believed to play an essential role in the formation of planets. The dust glows in the infrared (top; why IR?) and appears dark in the visual part of the spectrum (bottom)

Triffid Nebula: star formation in the infrared and visual



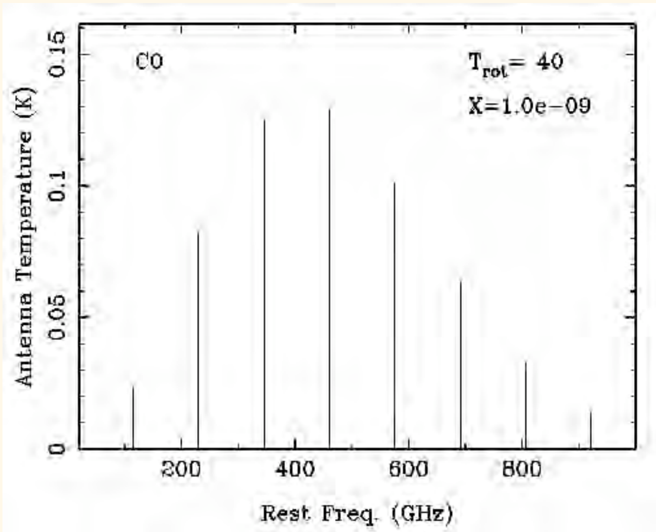
(ESA/ISO, ISOCAM, and J. Cernicharo et al.; IAC, Observatorio del Teide, Tenerife)

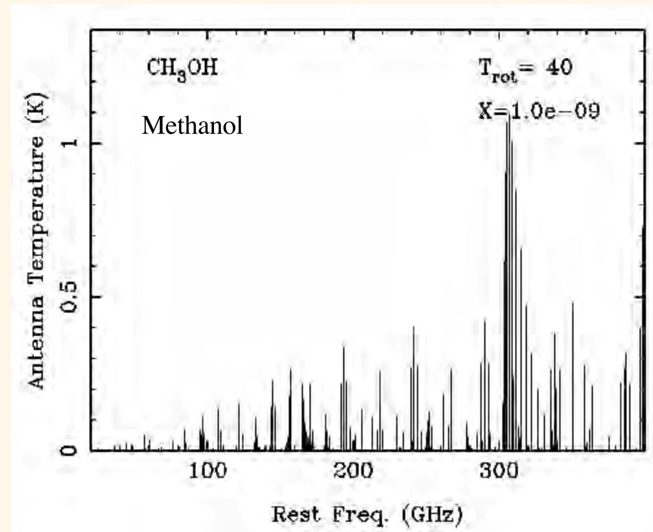
Planets must form as part of the star formation process

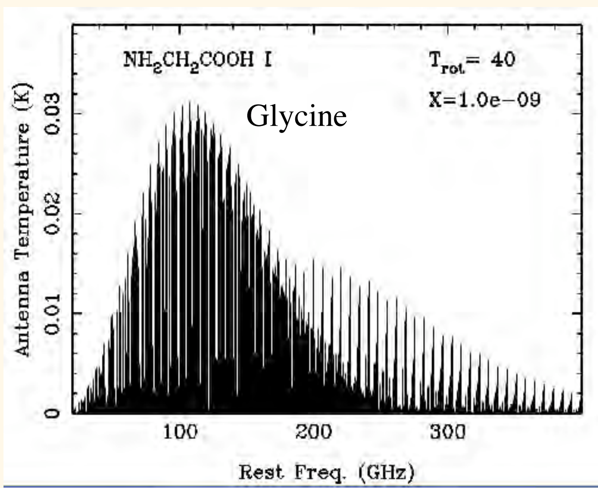


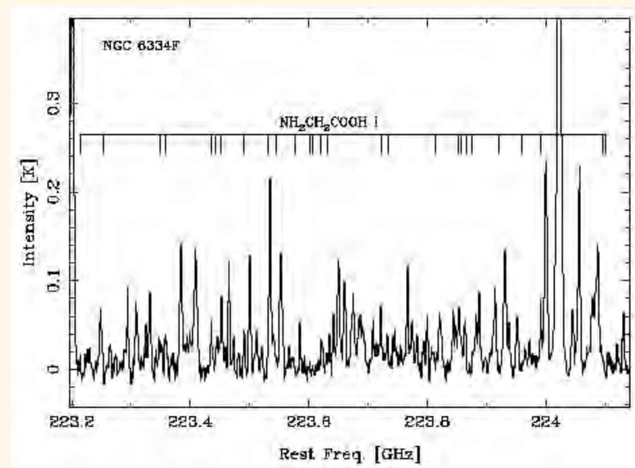
These images are the Orion and Omega Nebulae: star-forming regions as observed in the visual part of the spectrum. These regions are typical, containing hundreds to thousands of newly-formed (and forming) stars from ~ 0.1 to 100 solar masses. The gas is glowing because of the radiation from the massive young stars. The "dark lanes" are dense regions in front of the glowing gas; they are dark because of the dust they contain. Planets will have to form amidst this energetic activity due to the massive stars (winds, jets, explosions), so it is not obvious whether the formation of planets is likely.

One promising result is that many molecules, some complex, are observed, mostly through their spectral lines due to rotational transitions in the radio part of the spectrum.
Some examples of molecular rotational spectra, from simple to more complex, are shown below.

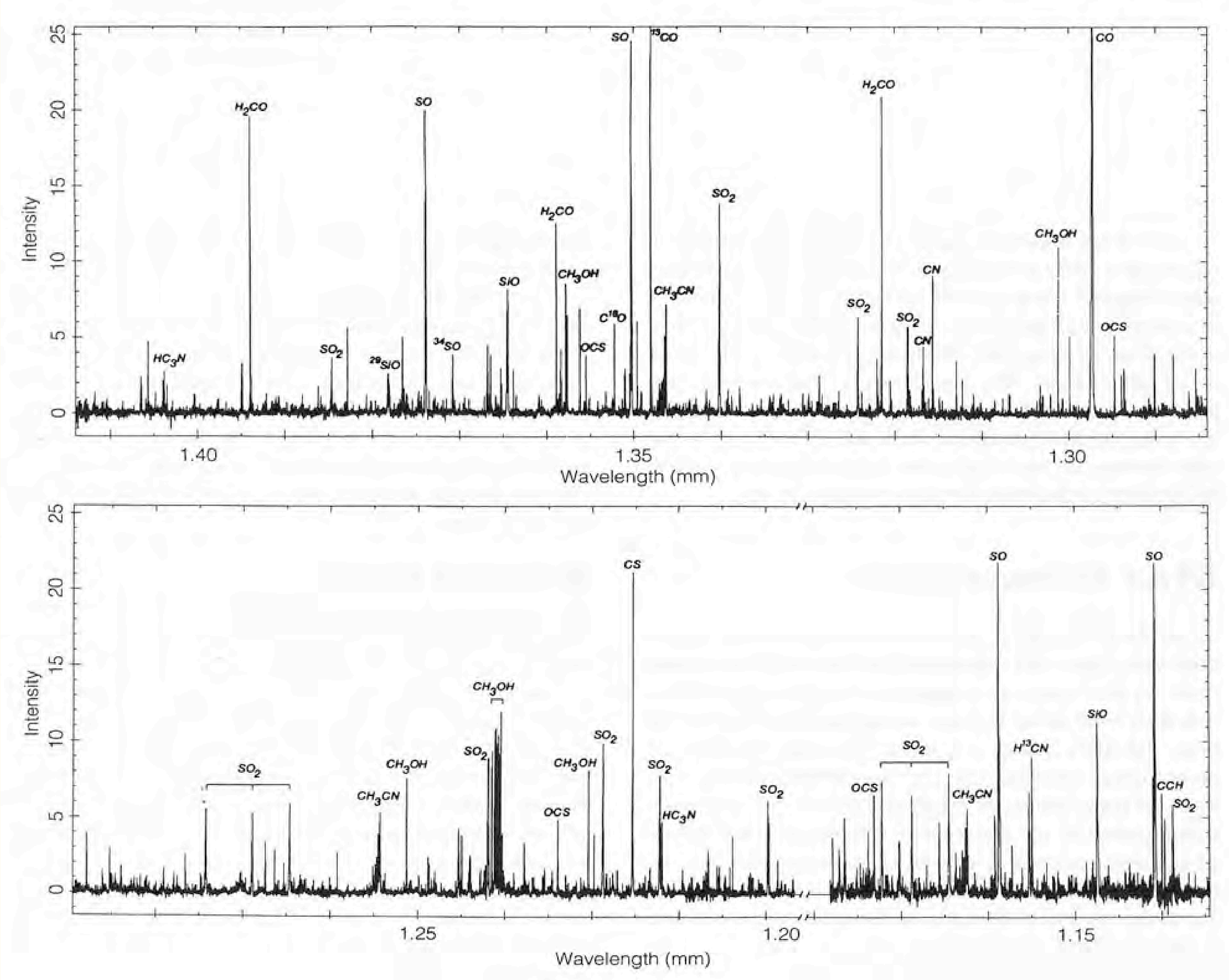








Radio molecular emission lines observed in the Orion Nebula

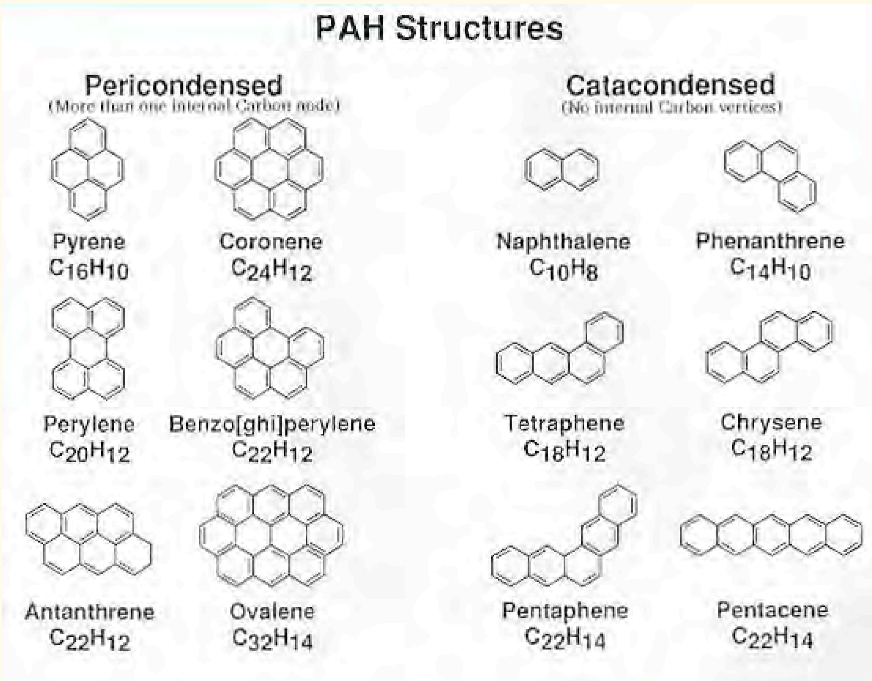


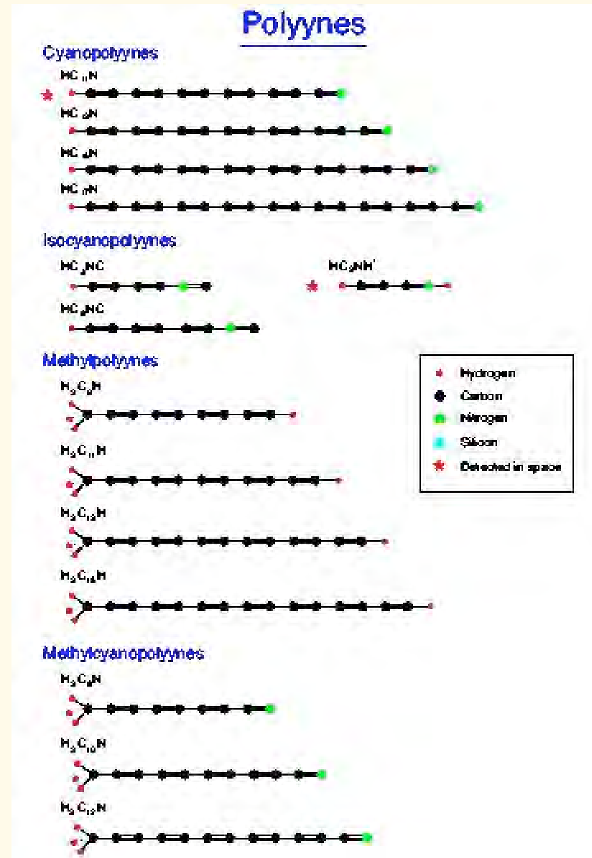
Molecules identified in dense interstellar clouds (where stars and planets form!)

Identified Interstellar Molecules Classified by Number of Atoms per Molecule

2 Atoms	*3 Atoms*	*4 Atoms*	*5 Atoms*	*6 Atoms*	*7 Atoms*	*8 Atoms*	*9 Atoms*	*10 Atoms*	*11 Atoms*	*13 Atoms*
H_2	H_2O	NH_3	SiH_4	CH_3OH	CH_3CHO	$HCOOCH_3$	CH_3CH_2OH	CH_3C_5N?	$H(C\equiv C)_4CN$	$H(C\equiv C)_5CN$
OH	H_2S	H_3O^+	CH_4	CH_3CN	CH_3NH_2	C_7H	$(CH_3)_2O$	$(CH_3)_2CO$		
SO	SO_2	H_2CO	HCOOH	CH_3NC	CH_3CCH	H_2C_6	CH_3CH_2CN			
SO^+	N_2H^+	H_2CS	$H(C\equiv C)CN$	CH_3SH	CH_2CHCN	CH_3C_3N	$H(C\equiv C)_3CN$			
SiO	HNO	HNCO	CH_2NH	C_5H	$H(C\equiv C)_2CN$	CH_3COOH	$H(C\equiv C)_2CH_3$			
SiS	C_2O	HNCS	NH_2CN	HC_2CHO	C_6H	CH_2OHCHO	C_8H			
NO	HCN	C_3N	H_2CCO	C_2H_4	$HCOCH_3$					
NS	HNC	HCO_2^+	C_4H	H_2CCCC						
HCl	HCO	SiC_3	C_3H_2	HC_3NH^+						
NaCl	HCO^+	c-CCCH	CH_2CN	l-H_2C_4						
KCl	N_2O	$HCNH^+$	C_5	$HCONH_2$						
AlCl	OCS	C_2H_2	SiC_4	C_5O						
AlF	NaCN	HCCN	H_2CCC	C_5N						
PN	HCS^+	H_2CN	HC_2NC							
CH	C_2H	C_3O	HNC_3							
CH^+	C_2S	C_3S	H_2COH^+							
CN	C_3	C_3H								
CO	c-SiC_2									
CO^+	NH_2									
CS	CH_2									
C_2	H_3^+									
HF	MgCN									
SiN	CO_2									
CP	HOC^+									
LiH	MgNC									
CSi										
NH										
SH										

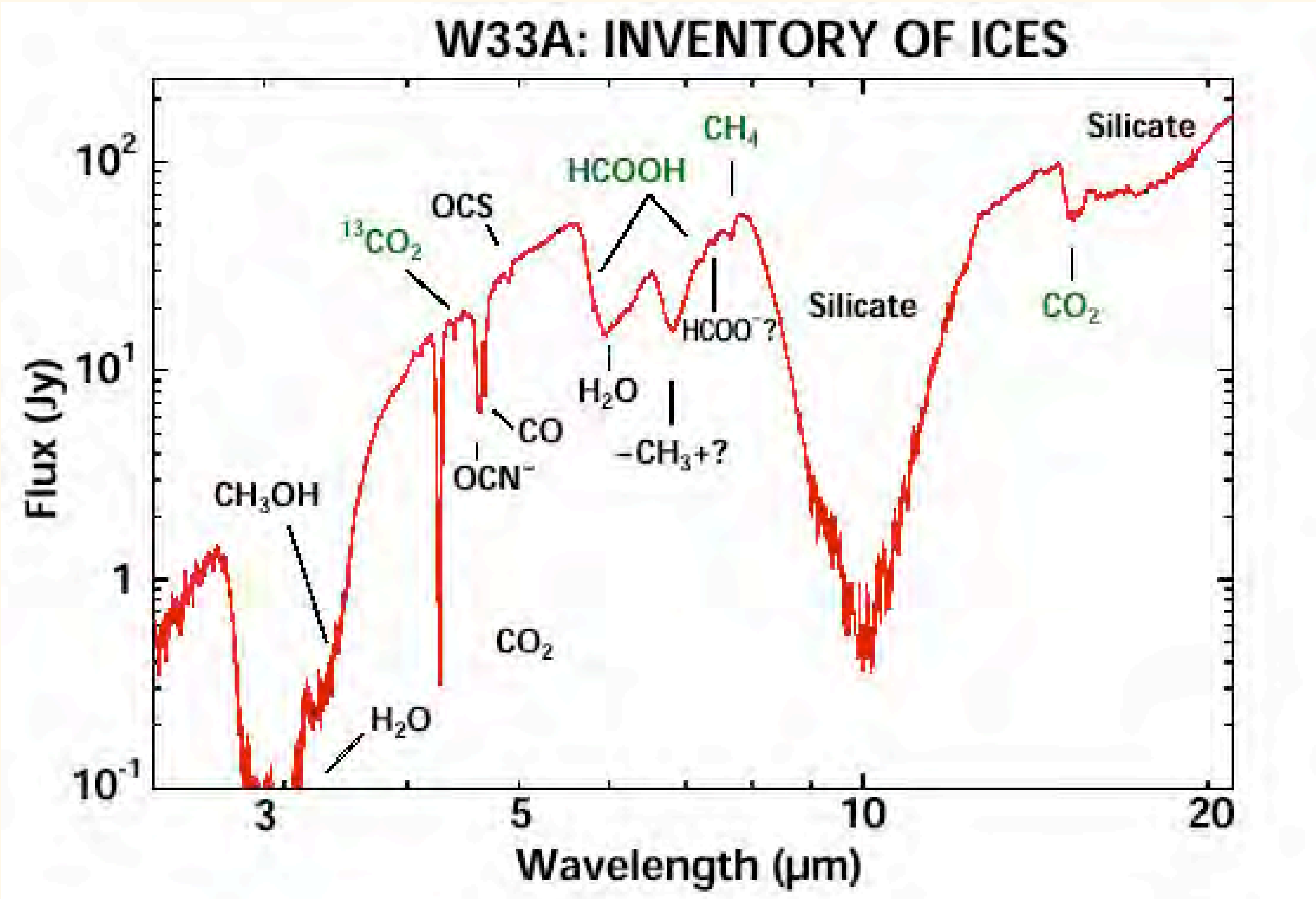
Complex organic molecules can form in dense interstellar clouds, where they are protected from UV radiation. Some of the most interesting are PAH's (polycyclic aromatic hydrocarbons) and long linear polyynes. Not shown are the cage-like "Buckeyball" molecular structures that have been identified.





All of this evidence suggests that forming complex organic molecules is probably not very difficult. Getting to the much more complex *bio*molecules is a much more difficult problem, but interstellar(and comet) molecules show that the basic building blocks should be available.

Many types of molecules in the *solid* form have been identified in the spectra of interstellar dust grains in the near-infrared part of the spectrum. This spectrum of the very young star-forming region W33A shows many mineral (silicate), ice (water, carbon dioxide,…), and gas phase features. Notice that these are some of the most important solids for terrestrial-like planets.

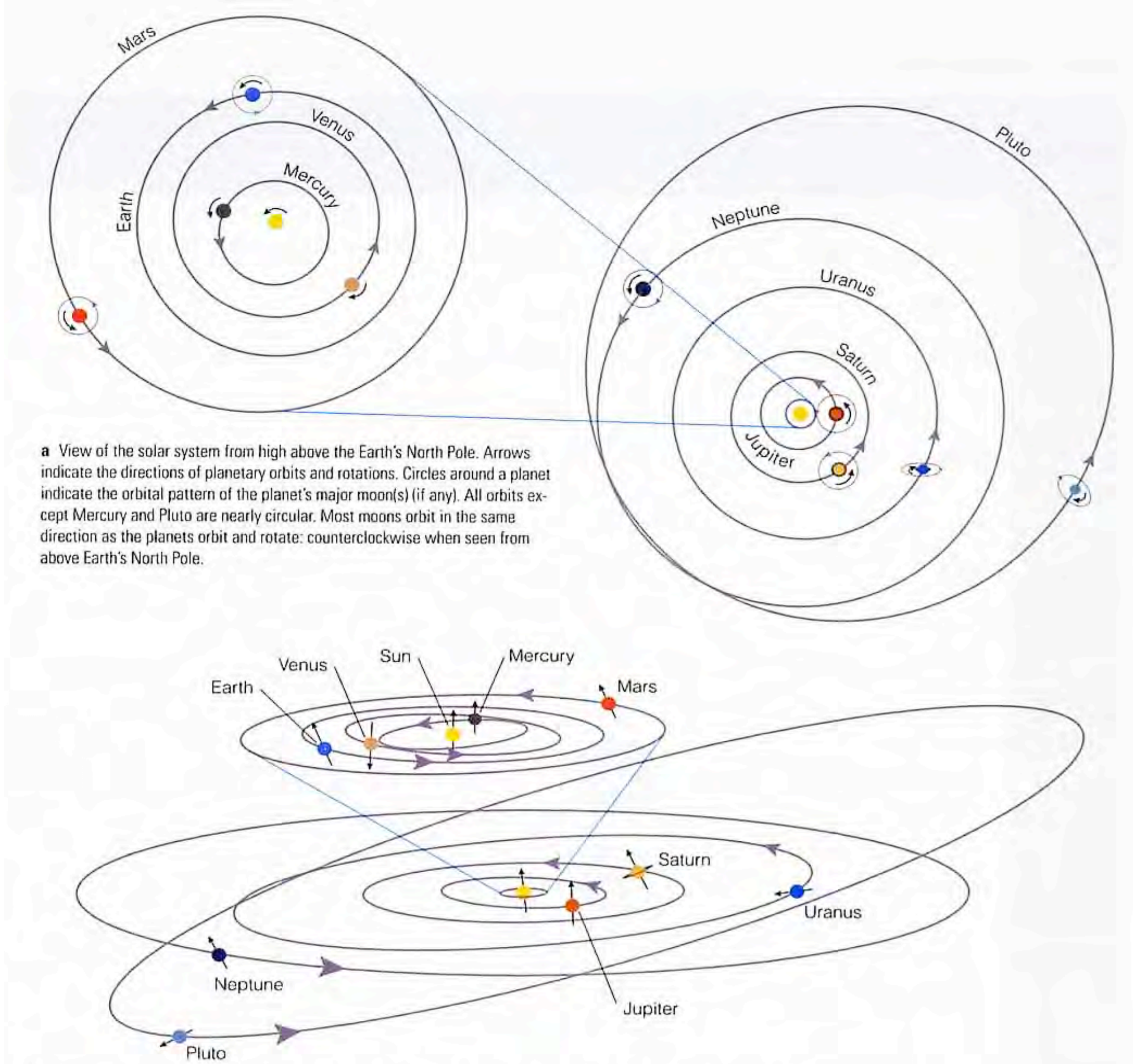


Molecules Detected in Comet Hale-Bopp

Molecule	Abundance as a Percentage of the Amount of Water (Ice) in the Comet
H_2O	100
CO	20
CO_2	6
CH_3OH	2
H_2S	1.6
H_2CO	1
CH_4	1
NH_3	0.6
SO	0.6
OCS	0.5
C_2H_2	0.5
C_2H_6	0.5
HCN	0.2
CS_2	0.2
SO_2	0.15
HNCO	0.1
HCOOH	0.05
$HCOOCH_3$	0.05
HNC	0.03
H_2CS	0.02
CH_3CN	0.02
HC_3N	0.02
NH_2CHO	0.01
S_2	0.005

Molecules identified in a comet

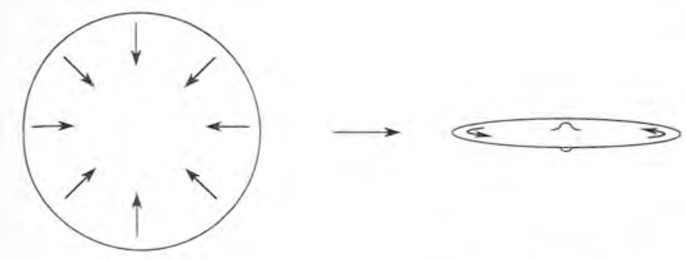
Formation of planets: Clues from Solar System orbits--notice regularities and exceptions



a View of the solar system from high above the Earth's North Pole. Arrows indicate the directions of planetary orbits and rotations. Circles around a planet indicate the orbital pattern of the planet's major moon(s) (if any). All orbits except Mercury and Pluto are nearly circular. Most moons orbit in the same direction as the planets orbit and rotate: counterclockwise when seen from above Earth's North Pole.

b Side view of the solar system. Arrows indicate the orientation of the rotation axes of the planets and their orbital motion. (Planetary tilts in this diagram are aligned in the same plane for easier comparison. Planets not to scale.)

Theoretically, we expect a collapsing, rotating gas cloud to form a rotating disk, because of conservation of angular momentum. Because of this, and the regularities in our solar system, this is one of the oldest, and basically the only, theory for the origin of planets. But do disks actually occur as part of the star formation process? Must look at protostars in star-forming clouds.



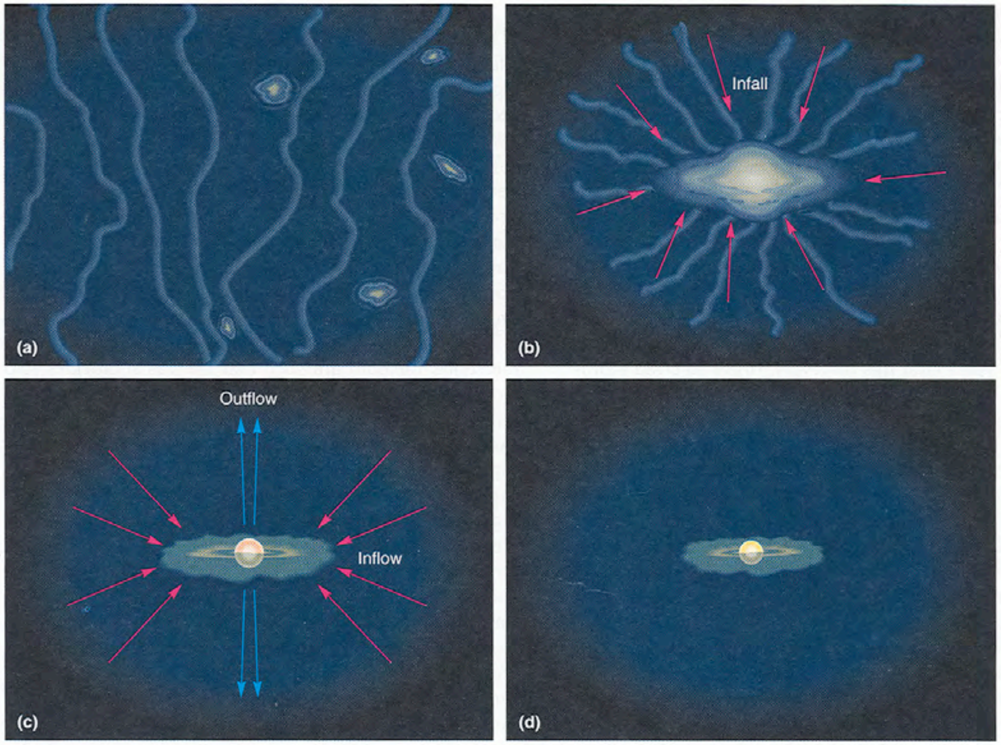
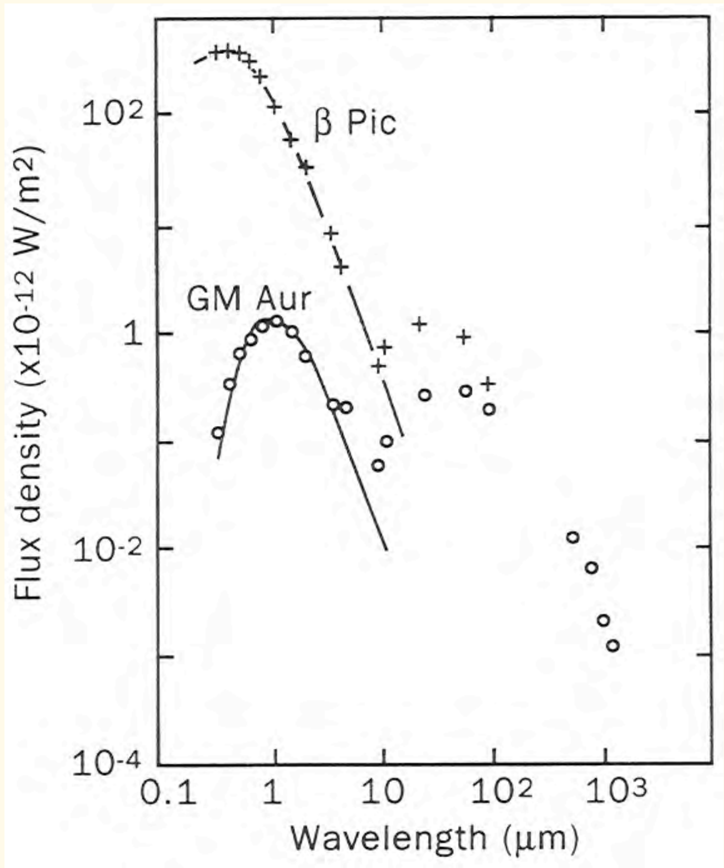


FIGURE 13–3

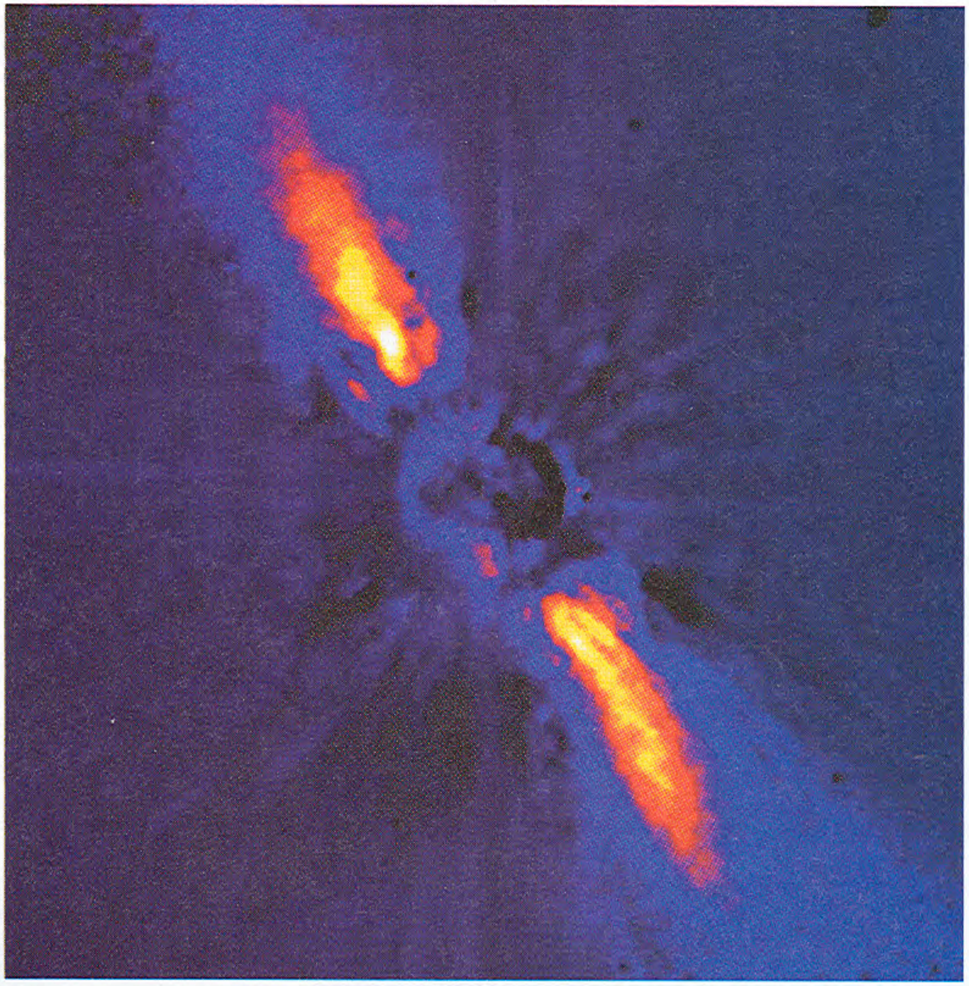
The main stages of star formation. **(a)** The dense cores of molecular clouds can collapse as the magnetic field slowly diffuses away and the cloud loses magnetic support. **(b)** The material around the protostar collapses from the inside outward. **(c)** A stellar wind blows along the poles of the rotating system, leading to bipolar outflows or jets. **(d)** The infall finally terminates, revealing the newly formed star. (SOURCE: Adapted from a diagram by F. Shu.)

One way to search for disks, or at least circmumstellar dust: an “infrared excess.” The dust in the disk is at a much lower temperature than the star, and so radiates at much longer wavelengths (in the infrared--recall our earlier discussion of blackbody spectra). Two examples are shown below.

Studies of the infrared spectra of a large number of young stars of different ages have shown that dust disks are very common around the youngest stars, but start to disappear at ages of around 3-5 million years. Did the dust (and gas) get transformed into planets? Or was it just blown out of the system? In either case this gives a very serious time constraint for the formation of planets.

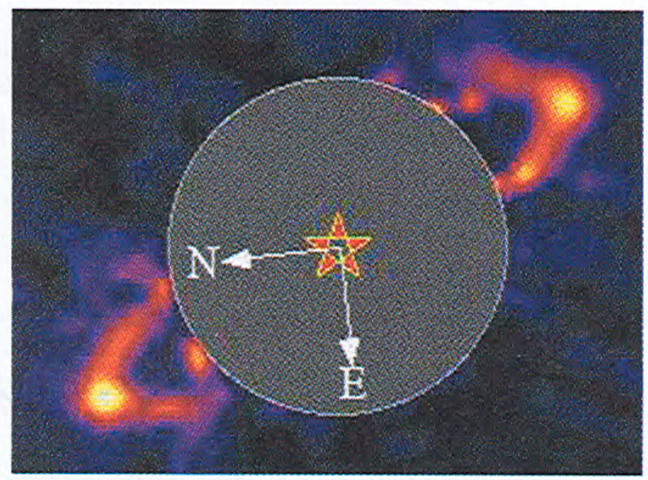


Infrared images of two young (but not very young) stars, showing the presence of disks, even with evidence for internal structure. The ß Pictoris disk (left) is the most famous and well-studied disk, but note that it is a “debris disk, containing leftovers from a time perhaps 100 million years earlier.



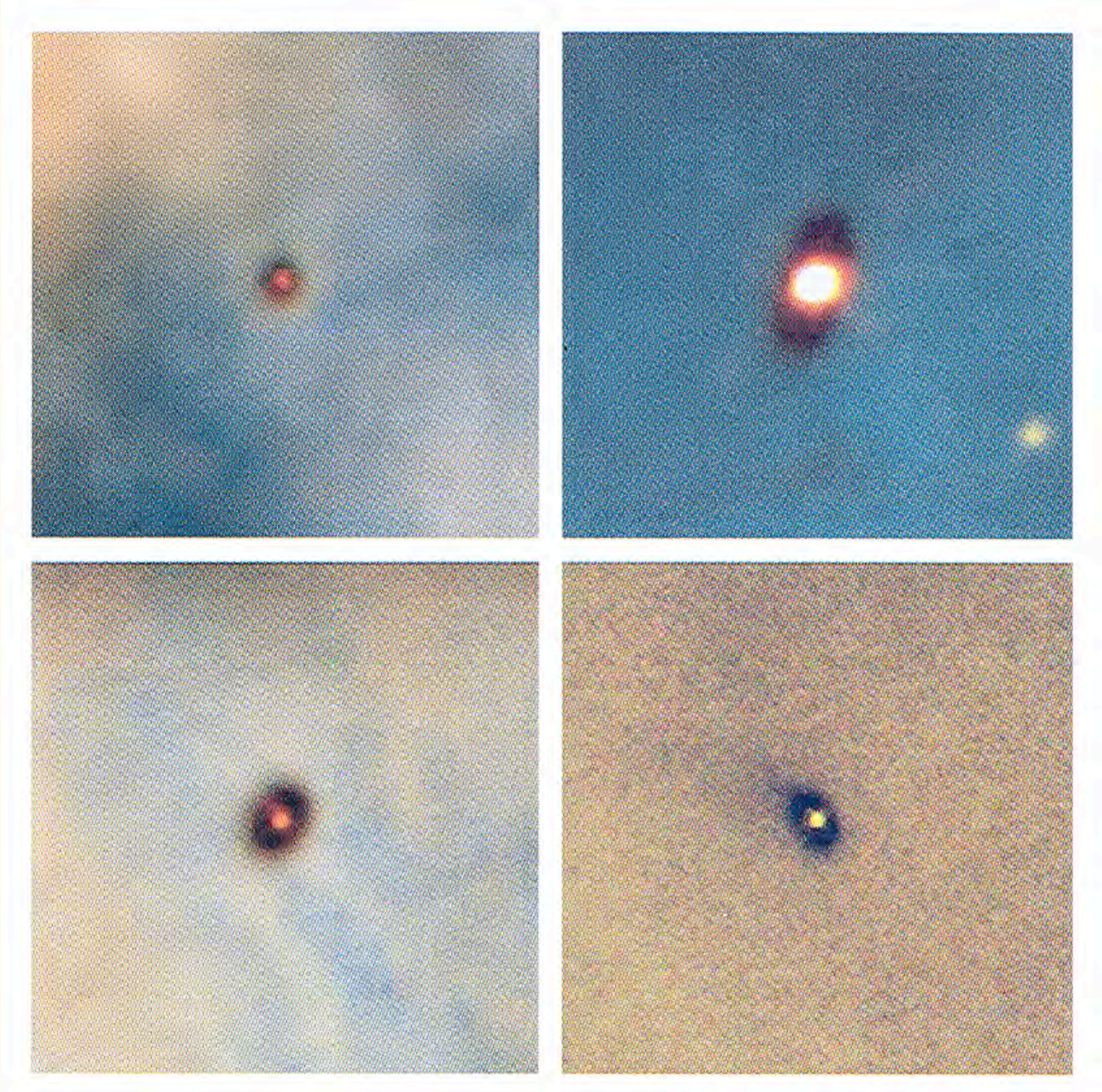
(a)

(a) This is an infrared photo of β Pictoris, obtained with the ESO ADONIS adaptive optics system (Grenoble Observatory). The star itself has been blocked out, and the disk of particles around it is visible. (b) This infrared image was taken by the Hubble's NICMOS camera and shows a disk around the star HR 4796A.

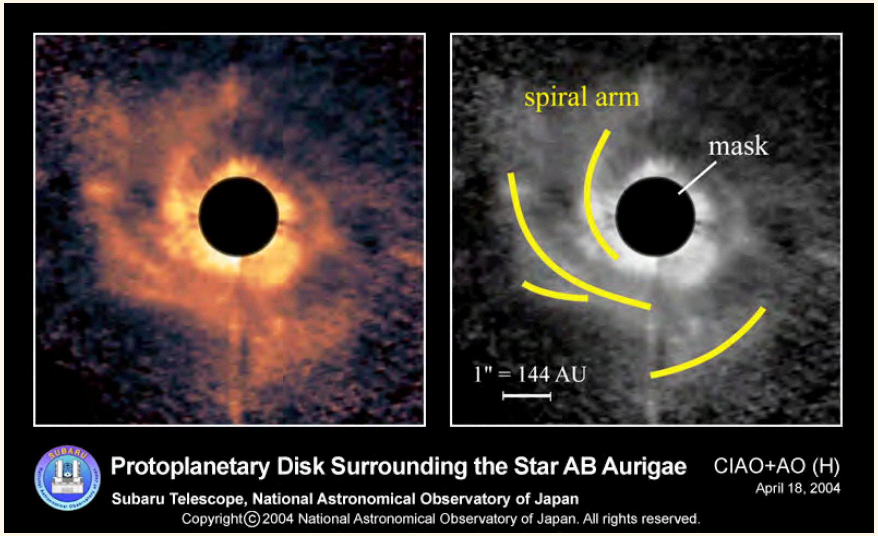


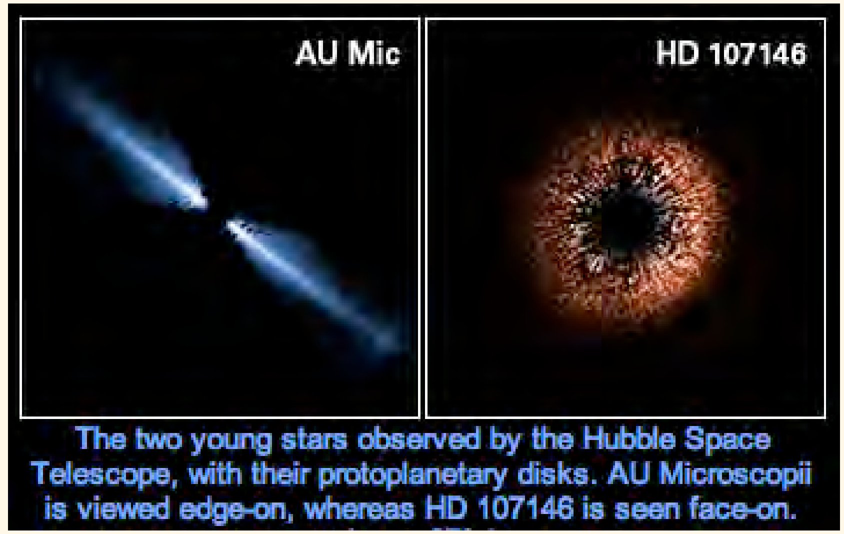
(b)

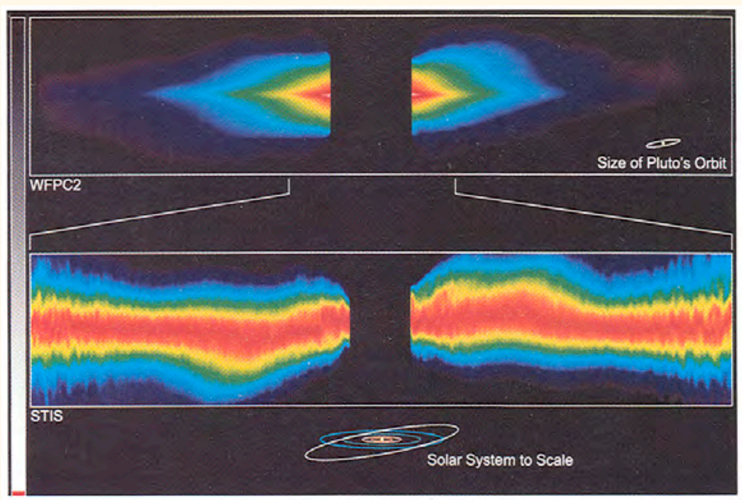
Four examples of “proplyds” (protoplanetary disks) observed in silhouette in front of glowing gas in the Orion Nebula using the Hubble Space Telescope



More views of resolved disks around young stars. The lower two images are ß Pictoris again. Notice the “warp” in the left-hand image, and the “bulge” in the right-hand image (recently obtained). These could be signatures of planets (or late planetesimal collisions).







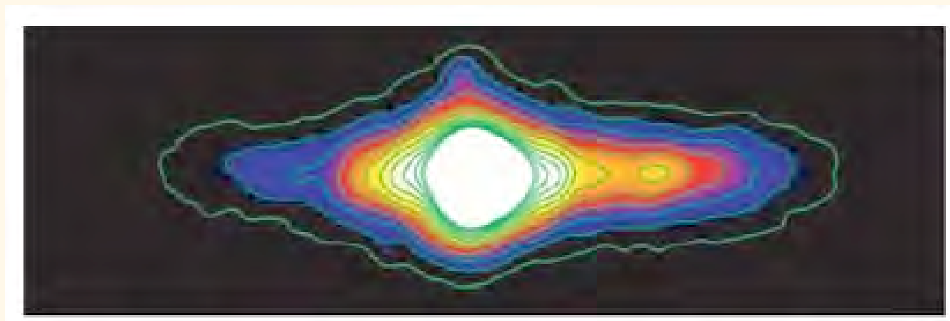
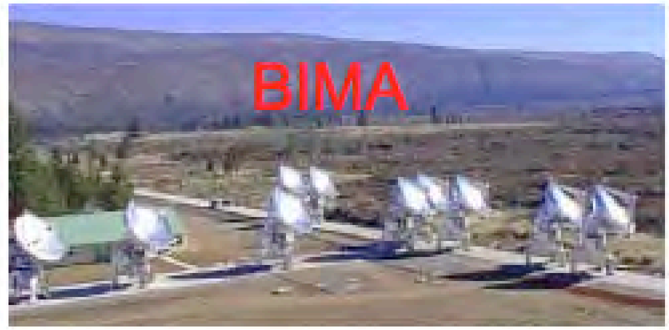


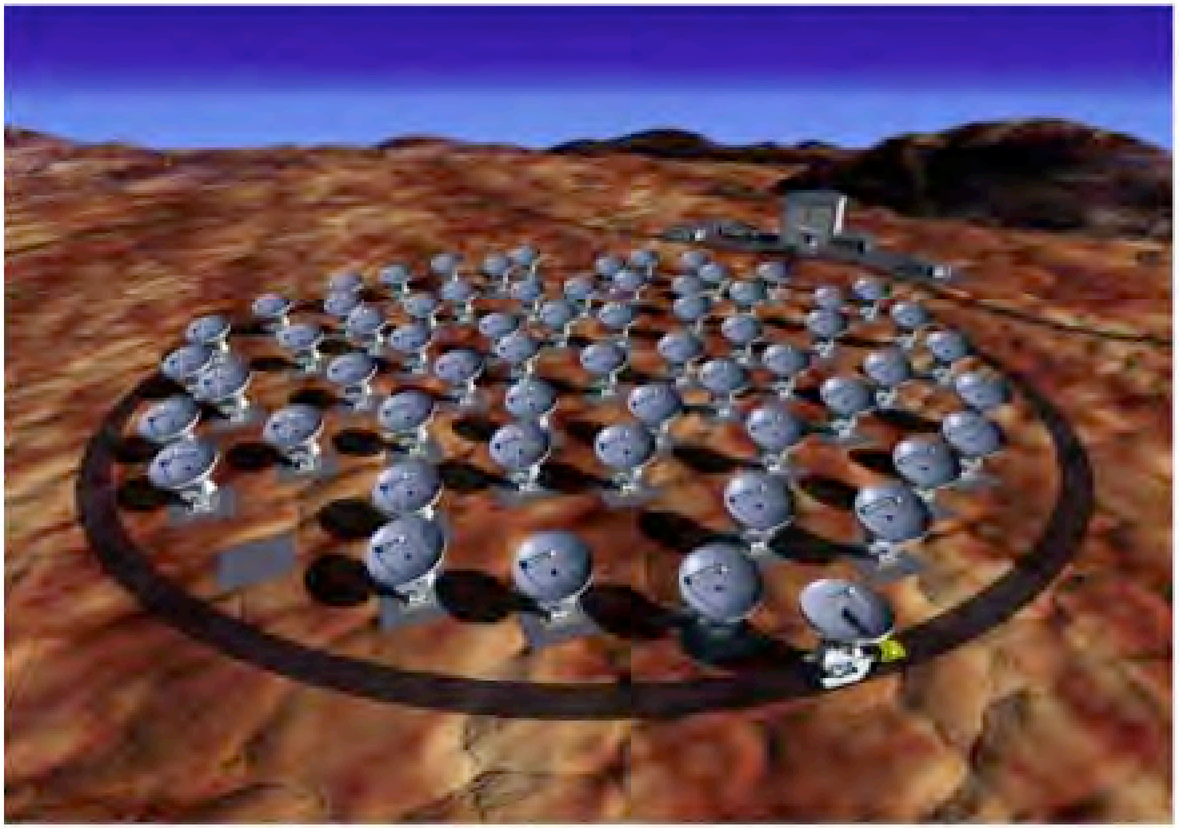
Figure 1 The β Pic disk, imaged in the mid-infrared at 11.7 μm

Millimeter Interferometry: Facilities



Atacama Large Millimeter Array

- large! 64 x 12m (+12 x 7m) telescopes; 18 km → < 0.01 arcsec at 870 μm



ALMA at Chajnantor

ESO PR Photo 06b/05 (25 February 2005)

©European Southern Observatory

early science: 2008
full operation: 2012

VertexRSI prototype antenna, Socorro, NM

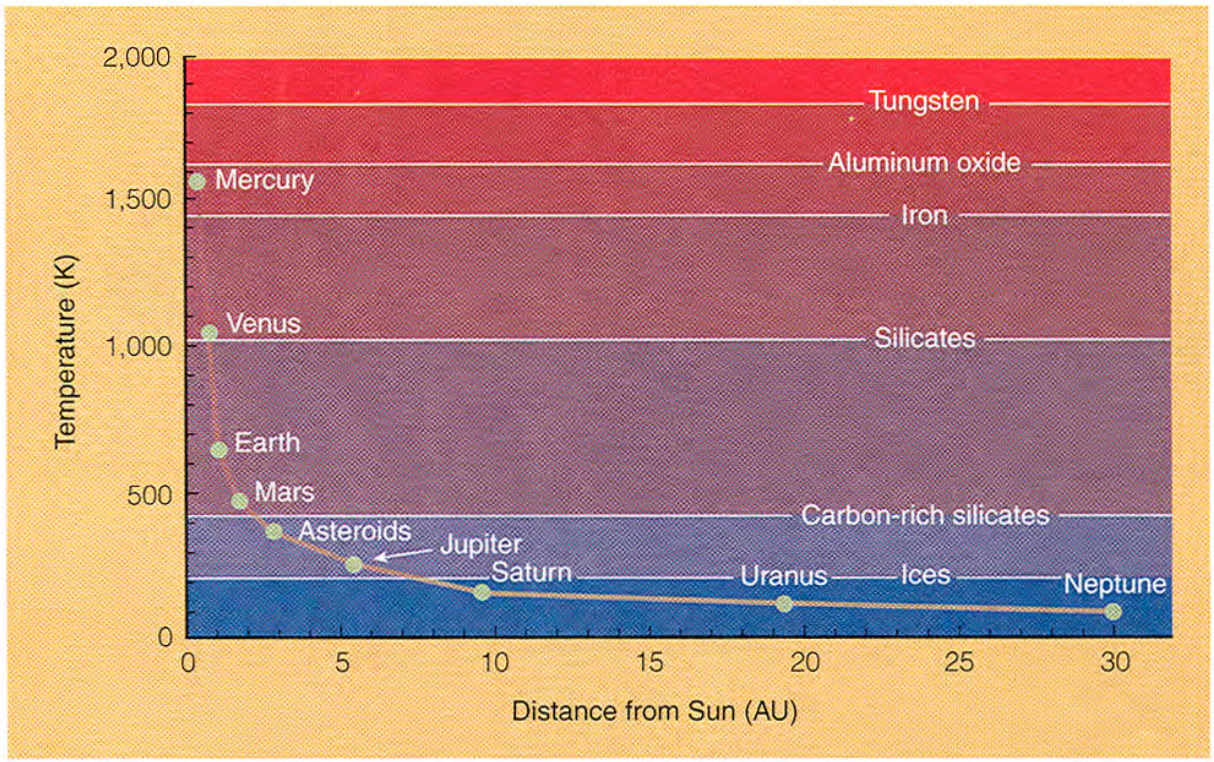
We can understand the basic features of the composition differences between the inner and outer planets just by considering that different elements condense at different temperatures, and some (hydrogen and helium for example) do not condense at all.

Materials in the Solar Nebula

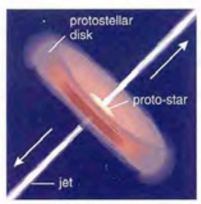
	Metals	Rocks	Hydrogen Compounds	Light Gases
				
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	(0.2%)	(0.4%)	(1.4%)	(98%)

Solids in the protosolar nebula were at various distances from the sun (and hence different temperatures), explaining the basic features of the composition of the planets in terms of the "condensation sequence" for different solids as shown below.
So we think that planets form in disks, which are common, and we can understand the compositions of solar system planets in terms of condensation, but how did the planets themselves condense out of the gas and dust grains that were present in the protostellar nebula, and in other protoplanetary nebulae? That is the difficult theoretical problem.s

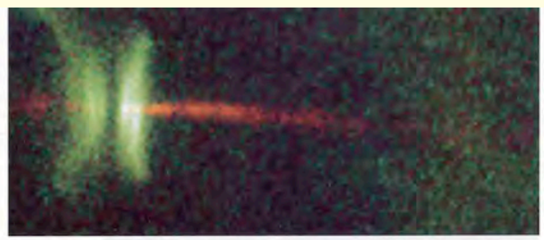
The condensation of different chemicals depends on the distance from the Sun. This plot shows the temperature at various distances from the Sun at the time that condensation stopped. At Earth's distance, only metals, oxides, and silicates condensed. At Saturn's distance and beyond, all materials including ices condensed. As a consequence, moons in the outer solar system have a significant ice content.



General conclusion: expectation from observations and theory is: cloud ⊥disk ⊥(?) planet(s)
It is the last stage that is the difficult one (next lectures). But one thing we have be aware of: protostars have very strong jet-like winds. Eventually the wind is going to blow away the remains of the disk that has not already formed planets.



a Schematic illustration of protostellar disk–jet structure.



b Photograph of a protostellar disk and jet. We are seeing the disk edge-on, as in (**a**). The disk's top and bottom surfaces, illuminated by the protostar, are shown in green, and the jets emerging along the disk's axis are shown in red. The dark central layers of the disk block our view of the protostar itself.

c A wider-angle photograph of a jet emanating from a protostar (left) and ramming into surrounding interstellar gas (right).

FIGURE 16.4 Some protostars can be seen shooting jets of matter into interstellar space.