STAR AND PLANET FORMATION
Lecture 3-Ed Churchwell

I.WHERE ARE STARS FORMED?

All stars in the process of forming are found in molecular clouds (dark clouds).

Why?

Molecular cloud properties favor star formation.

Properties:

They are cold: $8 \leq T \leq 20$ K ; typically ~10 K
They are mostly neutral: $n_e/n \leq 10^{-6}$
They are dense: $n_H \geq 10^3$ cm^{-3}
They are massive: ~10^4 to 10^6 M_o
They are large: diameter ~ 100 ly
They are clumpy

II. WHAT IS REQUIRED FOR A STAR TO FORM IN A MOLECULAR CLOUD?

Self gravity has to be larger than internal pressure

⇨ require small internal pressure
⇨ or large external pressure
⇨ and/or large self gravity

Gas pressure: $P \propto nT$
⇨ decrease internal pressure if T, or n, or both decrease

Gravity $\propto M/R^2$
=> increase gravitational force if the mass M is large and matter is close to the center (R is small)

How can the external pressure be increased?

Partially focused shocks: **3 slides- M17**
Ionization of gas around a molecular clump:

3 slides –M16 http://oposite.stsci.edu/pubinfo/pr/95/44.html

2 slides –M20 (can't duplicate these)

Molecular clouds have the "right stuff " for star formation:
Molecules provide efficient coolants => low temps
High density => self gravity large
High mass => lots of material available for star formation

III.Process of Star Formation

A. Systematics of the Solar System

Any successgul theory of the formation of the Sun (and other stars) and its planets must be able to explain the following systematic features of the Solar System.

1) The 4 inner most planets are small, rocky , and metal rich.
2) There is less matter closer to the Sun than in the outer regions (Jupiter's orbit and greater)of the solar system.
3) Volatile elements (such as H, D, He, and Li) are very underabundant relative to that in the outer giant planets (Jupiter, Saturn, Uranus, and Neptune).
4) With the exceptions of Venus and Uranus, all planets and all true moons rotate about their axes and revolve about the Sun in the same direction (i.e. the rotate and revolve in the prograde direction).
5) Planetary orbits are co-planar.
6) The massive outer planets are composed mostly of H and He like the Sun. In fact, their compositons are very similar to that of the Sun.
7) Most angular momentum in the solar system resides in the 4 outer giant planets.
8) Most of the mass in the solar system resides in the Sun

B. Initial Collapse

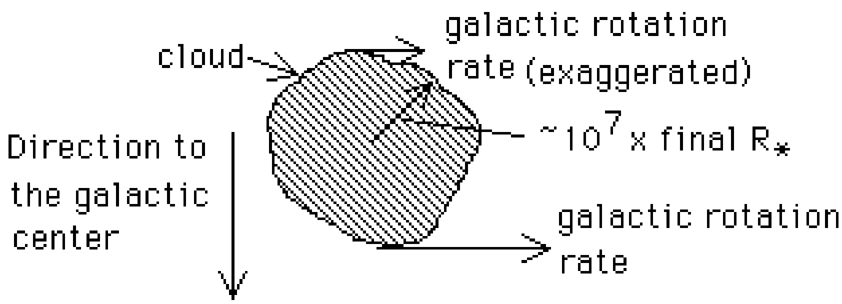
The mechanism that initially causes a cloud to become unstable to its own gravity is not fully understood, but it probably has something to do with accretion of mass to the point where gravity becomes greater than its internal pressure. As mass increases, cooling rates increase in proportion to density squared so the internal pressure may decrease eventhough the average density increases because temperature decreases even faster as mass increases which makes the cloud tend toward instability. Later in the evolution toward a star, the cooling is not so effective because the cloud becomes opaque to cooling radiation and the cloud cannot cool as effectively. The requirements for a cloud of a given temperature, density, and composition to become gravitationally unstable were solved by James Jeans in the early part of this century. These are often referred to as the Jeans criteria for collapse and they give the cloud mass and size at which a cloud is just balanced between gravity and internal pressure.

Collapse to a Star

Once a cloud becomes gravitationally unstable and begins to collapse onto its center of mass, the cloud still has a difficult time making a star. The main problem is overcoming angular momentum.

The momentum problem

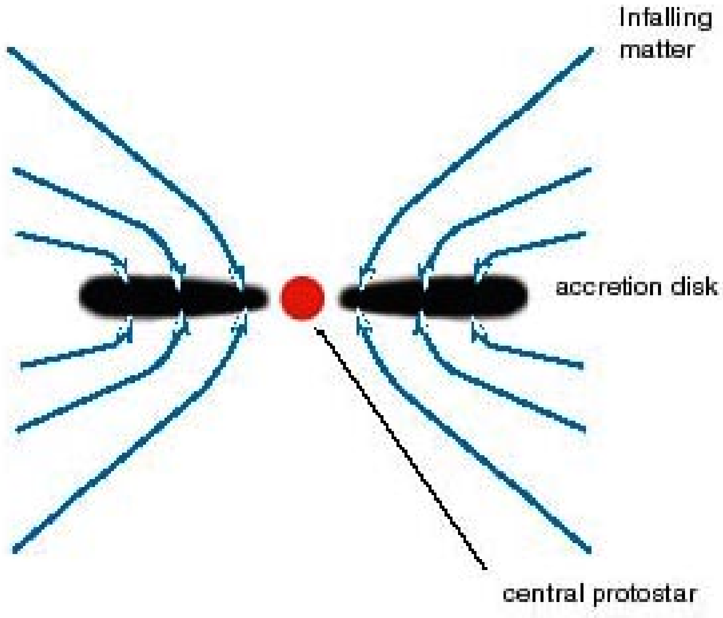
Initially a cloud will have a small net angular momentum (i.e. a small amount of spin), if for no other reason, because of the differential rotaion of the Galaxy (i.e. the part closest to the center of the galaxy revolves faster than the most distant part of the cloud). This is illustrated in the schematic below.



One can show that the size of a cloud that just becomes gravitationally unstable is initially about 10^7 times bigger than the size of the final star that it produces. A cloud that has to shrink this much will amplify the spin rate by the same factor as matter falls toward the center because of the conservation of angular momentum. This presents a serious problem because a clump of matter in the cloud at an initial radius r, will achieve a centrifugal acceleration equal to the acceleration of gravity by the time it has shrunk to a radius of only about r/2. This is referred to as the centrifugal barrier. At this point the matter cannot fall any further toward the center because centrifugal forces balance gravity. How do stars solve this problem?

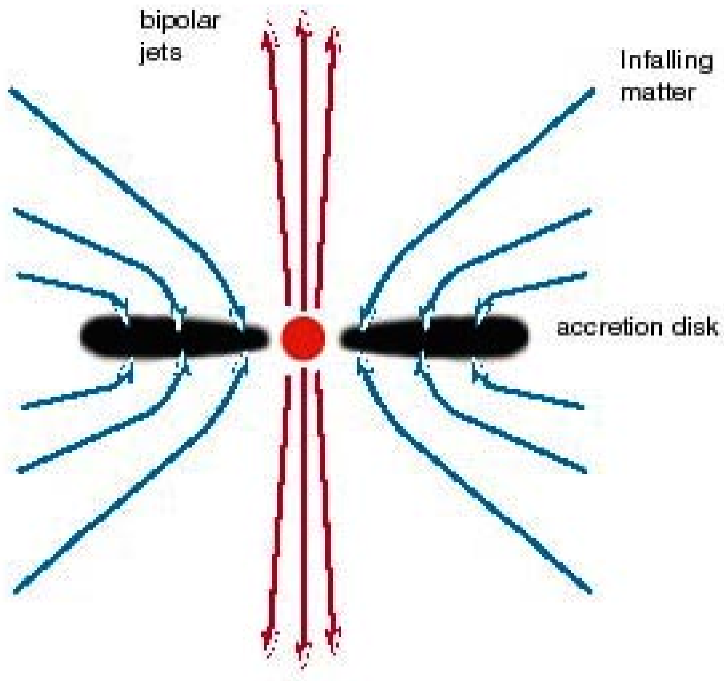
1) They form equatorial accretion disks

As a clump of matter spirals toward the center, its radial and orbital motion accelerates. As it approaches its centrifugal barrier its path deviates ever more sharply from the radial direction toward the equatorial plane and it finally crashes into the equatorial plane at the radius of its centrifugal barrier. This is illustrated in the schematic below.



One cannot keep dropping high angular momentum material onto a forming star indefinitely. It would soon be rotating so fast that it would break itself a part.

2) **They form high-speed bipolar jets**
A protostar's solution to this angular momentum dilemma is to form a high-speed gas jet along the spin axis of the protostar (perpendicular to the accretion disk) which carries off angular momentum from the system. This allows matter from the accretion disk to fall onto the protostar in proportion to the rate of angular momentum carried off by the jets. It is not understood how matter is diverted from the disk to the high speed jets. At any rate this provides a modified picture of a star in in the process of forming which is illustrated in the following figure.



Both the equatorial accretion disks and bipolar jets are observed in several prtotostellar systems in the following slides.

3 slides- disks around Orion stars (can't duplicate these)
slides – HH jets http://oposite.stsci.edu/pubinfo/pr/95/24.html

Summary: OH-Schematic of initial stages of star formation
OH- later stages of star formation

IV. Planet Formation

Planets are believed to form from the accretion disk left over after the central star stops accreting matter. This is an integral part of the process of star formation.

The disk material slowly accretes into small "planetesmals" which over a few times10^5 years continue to grow, ultimately concentrating most of the residual mass of the accretion disk into a few planets.

slide- planet formation (sorry I can't duplicate this)

V. Summary

The accretion disk – bipolar jets account for:

1) Small, rocky, metal rich, inner planets
2) The absence of volatile elements (H, He) in the inner solar system.
3) Prograde rotation and revolution of planets and true moons.
4) Co-planar planetary orbits
5) Massive outer planets composed mostly of H and He (similar to the composition of the Sun).
6) Most angular momentum in the solar system is carried by the outer planets (mostly Jupiter and Saturn) and most of the mass is in the Sun.

RECENTLY DISCOVERED

PLANETARY SYSTEMS

Lecture 3-Ed Churchwell

I. Introduction

First: HD114762 (Brown Dwarf or a planet?) 1989

Second: 3 planets reported around a pulsar 1992

Third: 51 Pegasus 1995

Now: About a dozen systems have been detected via orbital reflex motion

II. Techniques for finding Planets: Indirect Methods

1) Angular Motion relative to Distant Stars

This is probably the most difficult method of detecting planets around a star because it requires extremely accurate position measurements over long periods of time. Consider the motion of a star and a planet around their center of mass (bary center) in the rest frame of the center of mass as illustrated below.

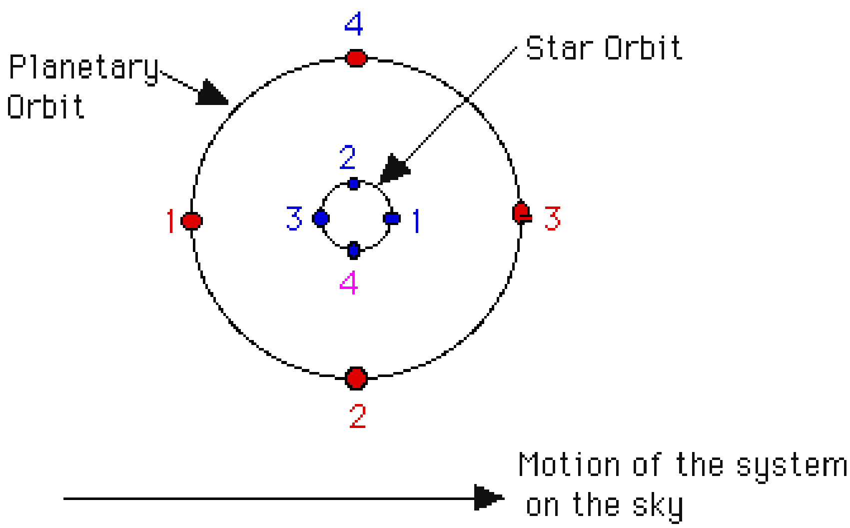


Figure 1—Schematic of the motions of a planet and its central star around their common center of gravity.

This motion as seen from the earth projected onto the sky will appear as shown below

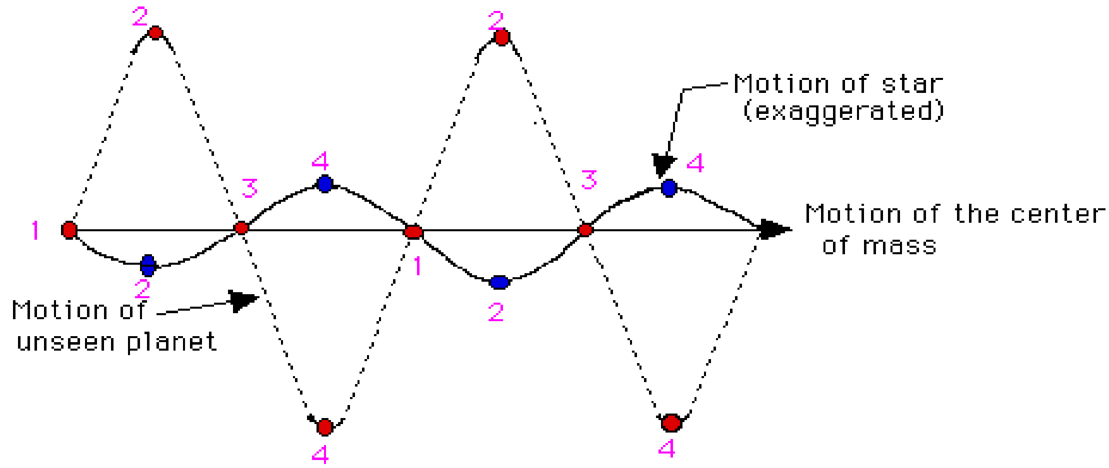


Figure 2—Schematic of the "wobbly" motion of the central star caused by the reflex motion of the orbiting planet .

2) Radial Velocity Shifts (Doppler Effect)

Here one measures the small shifts in the spectral lines of the star caused by the reflex motion of the star around the star-planet center of mass. This is illustrated below:

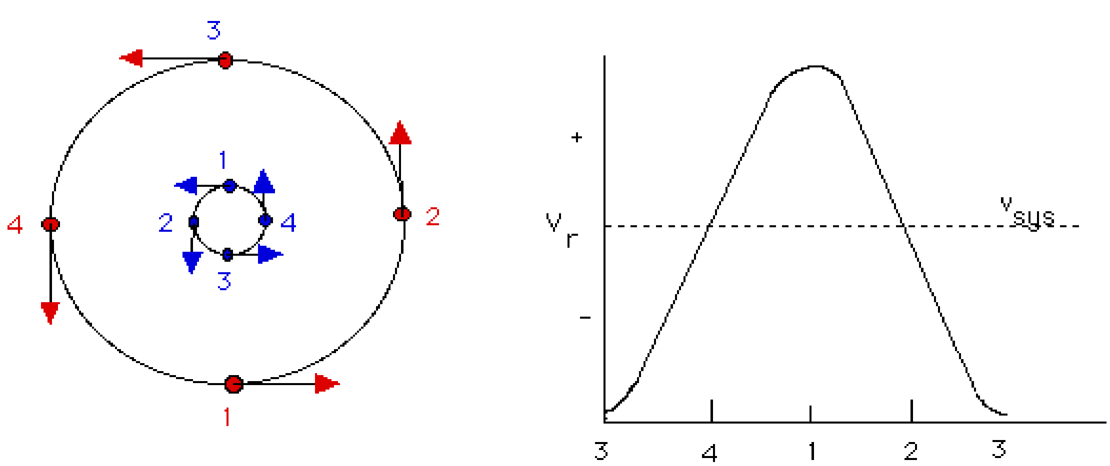


Figure 3—Schematic of radial motions as seen from the left.

3) Pulsar reflex motion:

It is also possible to detect planets orbiting a pulsar by detecting small changes in the pulse period with position in the orbit.

III. Techniques for Detecting Planets: Direct Methods

It is difficult to see a planet in the glare of a star which is typically a factor of 10^6 times brighter than the planet, which only
shines by reflected star light.

Direct Methods:

1) Direct observations of planets by blocking out the light of the central star. This is very difficult and has not yet been successful, but new space telescopes currently being planned may be successful in the future.
2) Observations with the Hubble Space Telescope (HST) at visible or ultraviolet wavelengths might possibly detect planets directly because of its diffraction limited seeing (very high resolution). It has succeeded in detecting a brown dwarf orbiting around Gliese 229A.

Figure 4- Gliese 229A&B
Sept. 1996, Phys. Today-link to
http://oposite.stsci.edu/pubinfo/pr/95/48.html

3) Infrared Imaging

The Earth and Jupiter are about 1000 times brighter at 10μm than in visible light. At the same time, the Sun is fainter in infrared light. Thus the contrast between the brightness of the Sun and a planet decreases in the infrared and we have a much better chance of seeing a planet against the glare of the central star in the infrared than we do at visible and ultraviolet wavelengths.

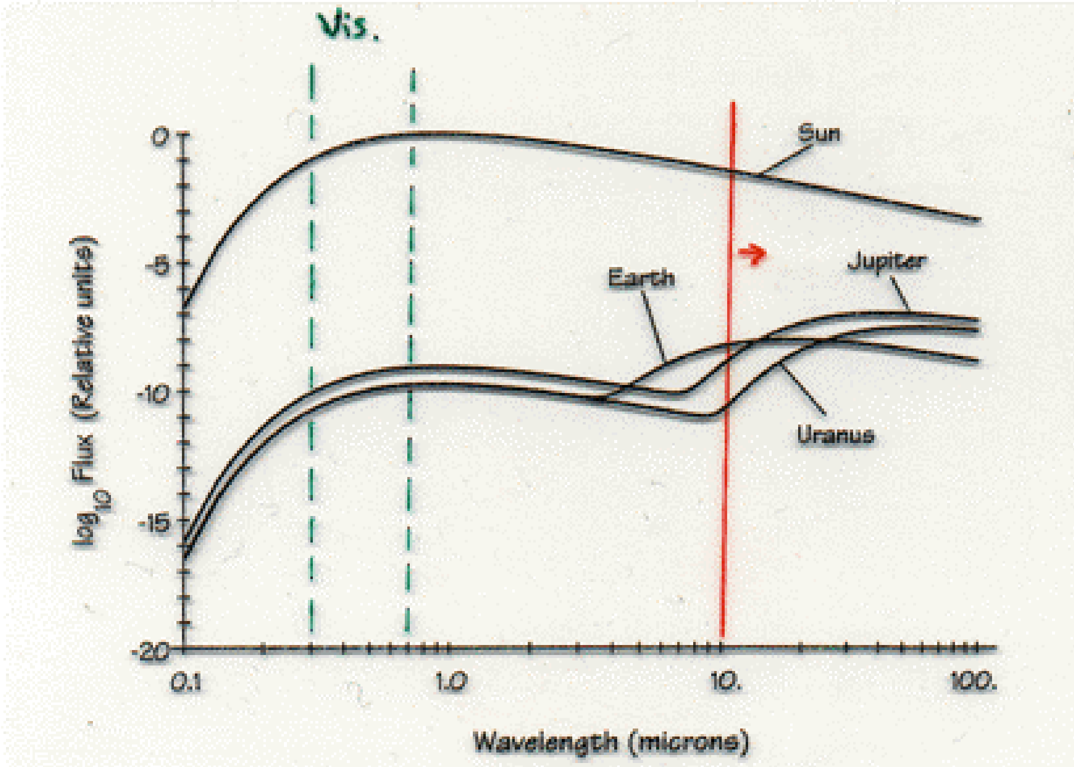


Figure 4-1. The spectral energy distributions of the Sun, Jupiter, Earth, and Uranus as they would appear at 5 pc, averaged over a 10% spectral bandpass. Note the decreased ratio of solar to planetary flux in the thermal infrared, compared to visible wavelengths.

4) Solar Gravitational Lens

A gravitating object such as a star can cause light from a distant object to be focused according to the theroy of relativity. This is illustrated below.

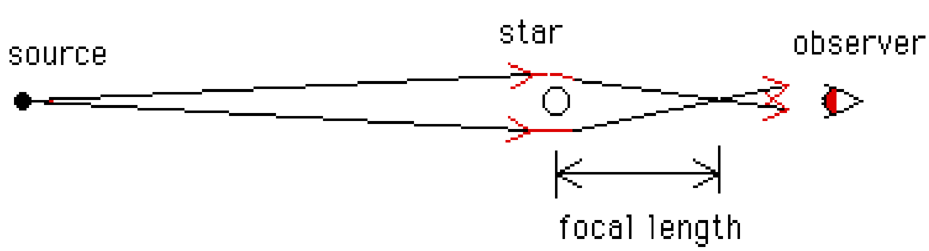


Figure 6- Schematic of a gravitational lens

For the Sun the focal length is 542 AU ~ 3.17 light days (Maccone 1995, Asp. Conf Ser, 74, 407). Thus, if we could put a satellite with a sensitive infrared detector in orbit around the Sun at this radius, it might be possible to detect stars (only in the ecliptic plane) which have planets in orbit around them. For an instant the light from such a planet could be amplified by many orders of magnitude . Such flashes would definitely be systems that we would study using other methods. This is illustrated below.

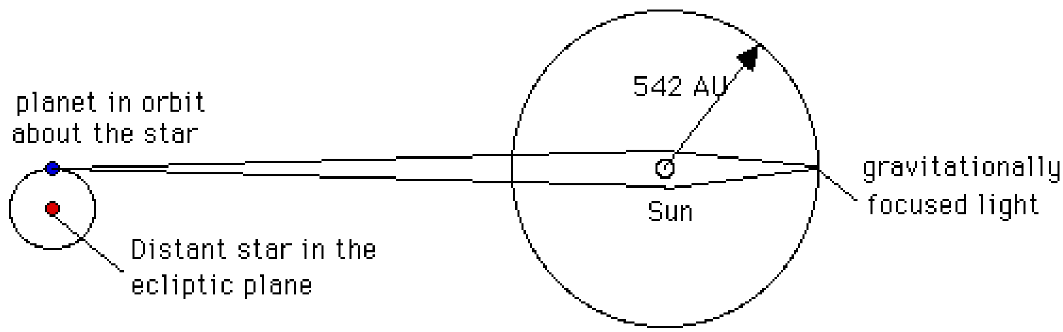


Figure 7—Schematic of the Sun as a gravitational lens

5) Observe spectra to detect molecules in planetary atmospheres that do not occur in stars such as CO_2, NH_3, O_3, H_2O, etc. Examples of the spectra of the atmospheric gases around planets in our solar system are shown below.

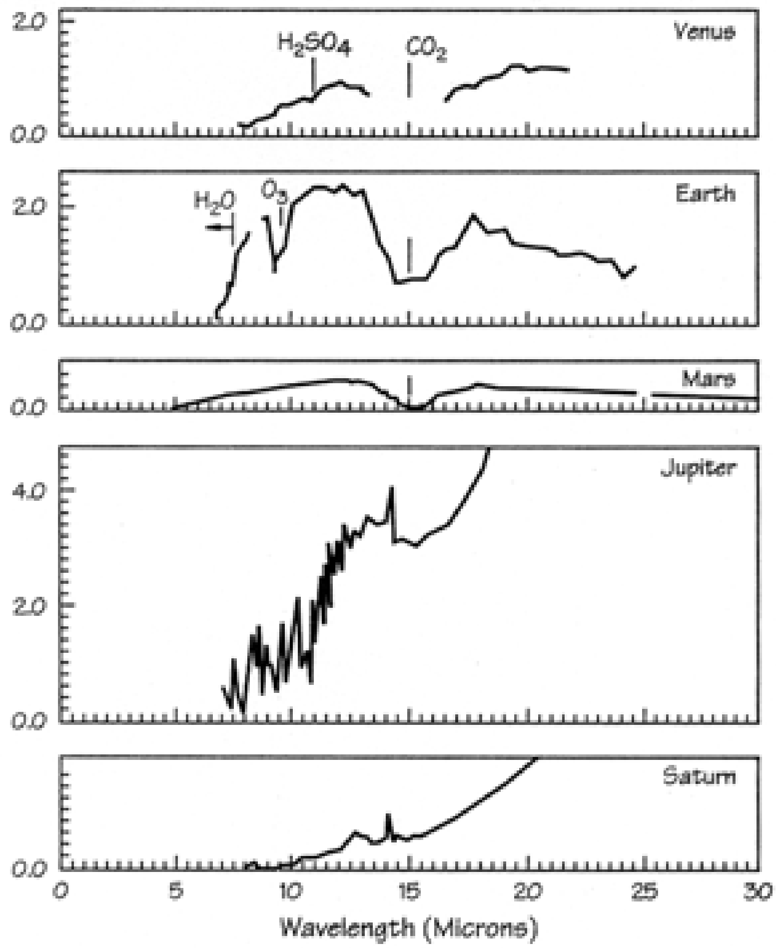


Figure 4-3. Spectra of three terrestrial planets (Venus, Earth, and Mars) and two gas giants (Jupiter and Saturn) showing prominent absorption and emission features due to atmospheric constituents.

IV. Detected Planetary Systems

A. Pulsar Timing Measurements

The first unambiguous detection of a planetary system was obtained from observations of tiny changes in the period of the millisecond pulsar PSR1257+12 (Wolszcan & Frail 1992, Nature, 355, 145). Pulse period changes were of the order of ~15 picosecs = 1.5×10^{-11} secs.

PSR 1257+12: Period ~ 6.2 msec

Age ~ 10^9 years

Distance ~ 500 pc ~ 1630 ly

Precise timing measurements indicate that at least 2 planets are orbiting this spinning neutron star. Their properties are:

Mass $M_{\oplus}$	Orbital Radius AU	Orbital Eccentricity	Orbital Period days
______	_______	_______	______
2.8/sin i	0.47	~0	98.2
3.3/sin I	0.36	~0	66.6
~0.015/sin I	----	----	----?

The last entry is uncertain. Residuals in the timing measurements indicate that another planet may be present, but this still has to be confirmed.

B. Radial Velocity Shifts

At present about 21 stars have been discovered to have LOW-MASS, NON-LUMINOUS companions orbiting about their common centers of mass (bary centers).

About 11 of these are believed to be planets. **Planets have mass less than about 1.4% of the Sun's mass or less than about 15 Jupiter masses and are formed by accretion of planetesimals in a cold accretion disk.**

About 10 are almost certainly "brown dwarfs". **Brown dwarfs have mass greater than about 15 Jupiter masses or about1.4% of the Sun's mass and are formed by fragmentation of the natal cloud which formed the primary star.**

None of the "planetary " systems discovered so far are similar to the Solar system. THIS IS NOT SURPRISING! The observational techniques used to detect them (periodic radial velocity changes) select "massive" planets with small orbital radii. The reflex orbital radial velocity of a star (V_r^*) due to a planet of mass M_p orbiting at an average radius $\bar{r}$ around it is given by:

$$V_r^* \propto M_p / \sqrt{\bar{r}}$$

In the following figure, the orbital eccentricities are plotted against the masses (in Jupiter masses) of all the stars found to have planets or brown dwarfs orbiting them as of early 1998. The dashed vertical line is drawn at ~15 Jupiter masses which should have the planetary systems to the left and the brown dwarfs to the right side.

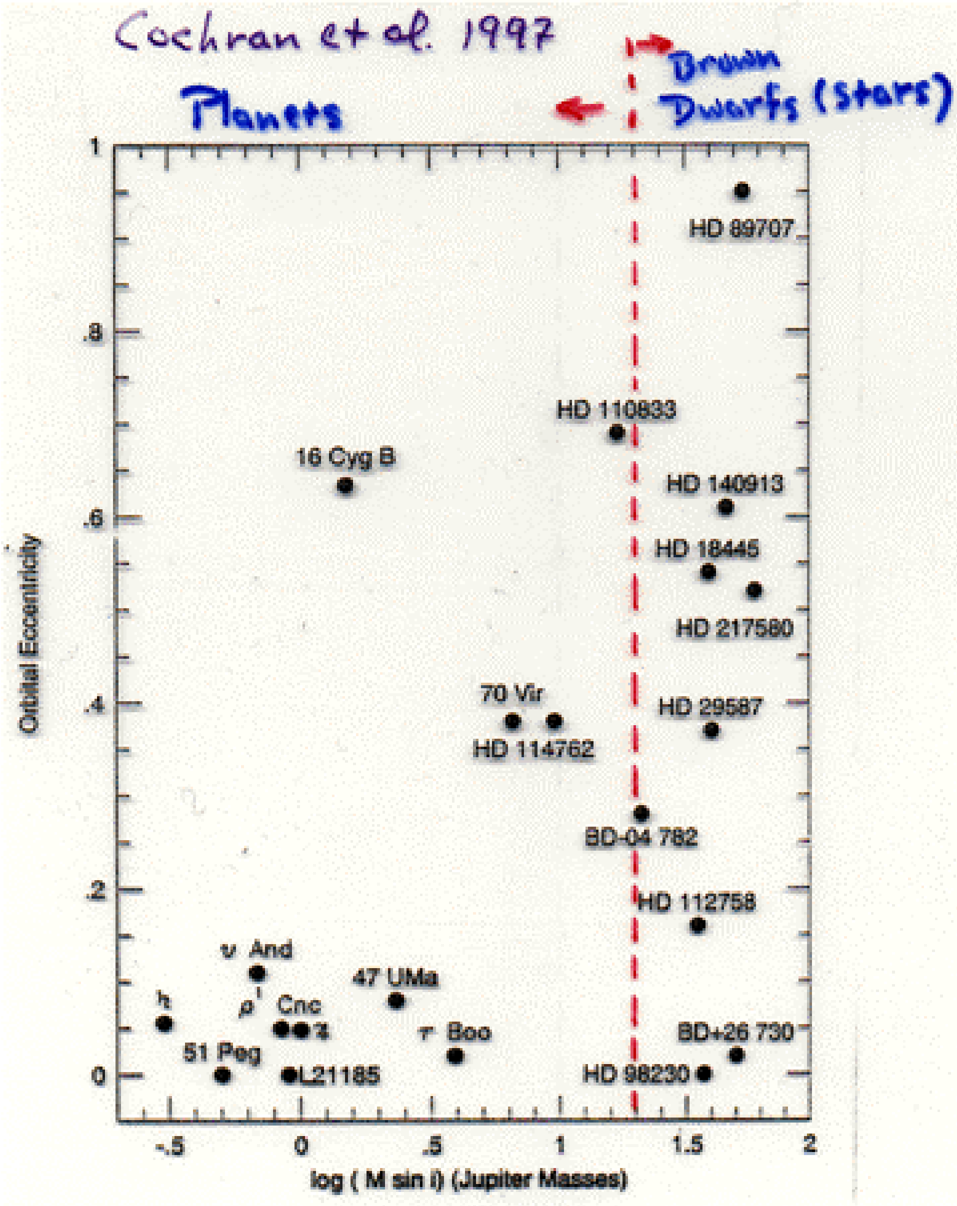


FIG. 3.—Relationship between eccentricity and minimum mass for the substellar companions (both planets and brown dwarfs) found so far.

A table of the properties of the extrasolar planets and brown dwarfs detected as of early 1998 is given below.

Extrasolar planet and brown dwarf properties

Object	Mass	a (AU)	e	Reference	
PSR B1257+12				3	1994
B	$>0.015\ M_⊕$	0.19	≈ 0.0		
C	$>3.4\ M_⊕$	0.36	0.018		
D	$>2.8\ M_⊕$	0.47	0.026		
PSR B0329+54 B	$>2\ M_⊕$	7.3	0.23	13	1995
HD 114762 B	$>10\ M_J$	0.4	≈ 0.33	14	1989
51 Pegasi B	$>0.47\ M_J$	0.051	≈ 0	2	1995
47 Ursae Majoris B	$>2.4\ M_J$	2.1	≈ 0	15	1996
70 Virginis B	$>6.6\ M_J$	0.45	0.4	16	1996
55 ρ^1 Cancri				5	1996
B	$>0.78\ M_J$	0.11	≈ 0		
C	$>5\ M_J$	≈ 5	Unknown		
Lalande 21185				4	1996
B	$\approx 1.5\ M_J$	≈ 10	≈ 0		
C	$\approx 1\ M_J$	≈ 2.5	Unknown		
τ Bootis B	$>3.7\ M_J$	0.047	0	5	1996
BD – Gliese 229 B	20 to 50 M_J	≈ 44	Unknown	1	1995
Upsilon Andromedae B	$>0.6\ M_J$	0.054	≈ 0	5	1996

$M_⊕$ = mass of Earth = 5.974×10^{24} kg.
M_J = mass of Jupiter = 318 $M_⊕$.
a = semimajor axis of planet's orbit.
e = eccentricity of planet's orbit.
AU = astronomical unit (Earth–Sun distance) = 1.496×10^{11} m.
B = secondary companion (for example, 51 Pegasi B) to a star (51 Pegasi A).

V. Planetary Types

As of 1998 five categories of extrasolar planetary types had been recognized.

1) 51 Peg Type
   Members: 51 Peg, τ Boo, 55 Cuc, v And
   Planetary masses: greater than one Jupiter mass
   Orbital periods: several days => very small orbits!

These planets are believed to have formed in much larger orbits and subsequently were perturbed into much smaller obits.

2) Massive Eccentric Orbits
Members: 70 Vir, HD114762
Planetary masses: ~6-10 Jupiter masses
Orbital radii: ~0.4 to 0.5 AU
Orbital eccentricity: 0.3 to 0.4

3) Pseudo-Jovian Planets
Members: 47 Uma, Lalande 21185
Orb. eccentricity: almost circular (~0)
Planetary masses: up to a few Jupiters
Orbital radii: greater than 2 AU

4)16 Cyg B
Members: 16 Cyg B
Orbital Period: $\geq$ 2 years
Orbital eccentricity: $\geq$ 0.6
Planetary mass: $\geq$ 1 Jupiter

6) Planets around pulsars
Members: PSR 1257+12, PSR 0329+54B

Below is an example of the data which shows that 51 Peg has at least one planet orbiting around it. Velocity curves are shown for two stars which have no planets orbiting them, and beside these is shown the velocity curve of 51 Peg. The sinusoidal curve shows that the star has clear reflex motion due to an orbiting planet. The properties of the star 51 Peg and the planet orbiting around it are shown in the two tables below the velocity curves. Most of the systems have been equally well observed. Note that the sinusoidal shape of the velocity curve for 51 Peg demonstrates that the planet has a circular orbit. Some stars have very different shapes, indicating that the palnetary orbit is not circular.

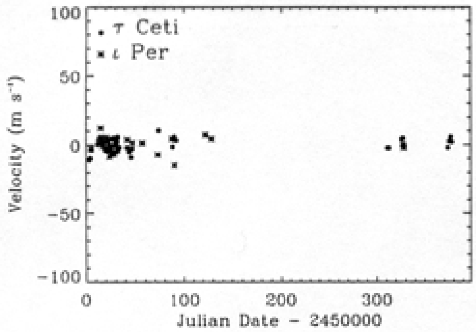


FIG. 1.—Doppler velocities of two stable reference stars. The rms scatter in the velocities of both τ Cet and ι Per is 5 m s^{-1}. These observations were made over the same time span as those for 51 Peg, and illustrate the typical long-term errors of the Doppler measurements.

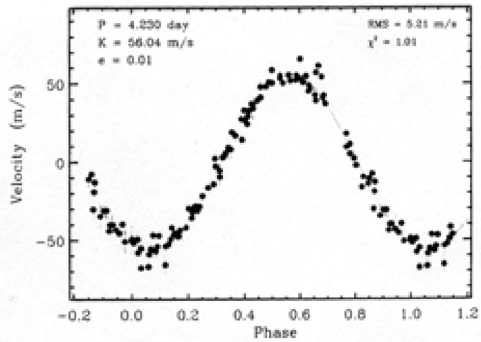


FIG. 3.—51 Peg velocities phased with the Keplerian fit. The variation is sinusoidal with a period of 4.231 ± 0.001 days. Phase stability is precisely maintained during 10 months.

TABLE 3

51 PEG PROPERTIES

Parameter	Value	Source
$T_{\rm eff}$ (K)	5724–5755	Valenti et al. 1995; Edvardsson et al. 1993
M_V	4.56	Perryman et al. 1996 (*Hipparcos*)
$L/L_\odot$	1.24	From $M_V - M_V(\odot)$
Log gravity (cgs)	4.18–4.3	Edvardsson et al. 1993; Valenti et al. 1995
$R/R_\odot$	1.13–1.27	L, $T_{\rm eff}$; log g
Spectral type	G2–3 V	Houk 1995
$R'_{\rm HK}$	−5.037	Noyes et al. 1984
$P_{\rm ROT}$ (days)	29–37	Baliunas et al 1997; Henry et al. 1996
V sin i (km s^{-1})	1.7–3	Hatzes et al. 1996
[Fe/H]	+0.06 to +0.192	Edvardsson et al. 1993; Valenti et al. 1995
Age (Gyr)	8.5	Edvardsson et al. 1993
Parallax (mas)	65.1 ± 0.8	Perryman et al. 1996

TABLE 2

ORBITAL PARAMETERS OF 51 PEG

Parameter	Mayor & Queloz	This Paper	Uncertainty
P (days)	4.2293	4.2311	0.0005
T_0[a] (JD)	2,449,797.773	2,450,203.947	0.03
e	…	0.012	0.01
ω (deg)	Undefined	Undefined	…
K_1 (m s^{-1})	59	55.9	0.8
a_1 sin i (m)	3.4×10^6	3.25×10^6	0.05×10^6
f_1 (m) ($M_\odot$)	9.1×10^{-11}	7.64×10^{-11}	…
N	35	110	…
rms $O-C$ (m s^{-1})	13[b]	5.2	…

[a] Time of peak velocity.
[b] After removal of long-term variations.

VI. What is the Significance of all this to Us?

1) It confirms that extrasolar planets indeed exist.
2) It gives strong support to the idea that planets are a natural consequence of star formation , as implied in the theory of star formation via accretion disks and bipolar outflows.
3) It give us an estimate of the factor f_p = the fraction of stars that have planetary systems , which appears in the Drake equation.

We now know that other stars have planets , so f_p is not zero.
If we combine this with the theory of star formation, it seems like a good approximation to assume that all single stars are likely to form planets from their accretion disks. Since ~ 1 /3 to ~1/2 of all stars are single, this would imply that about an equal fraction of all stars have planetary systems.

Thus we conclude that: $f_p \geq 1/3$