23.1.1 (after 22.4.2) 2/27/18

p.848 - Ch.23 - Formation of Planetary Systems

§23.1 Characteristics of Extrasolar Planetary Systems

Detections through the Reflex Radial Velocity technique

As the planet orbits, it pulls the star slightly back + forth, + this velocity is detected by Doppler effect. (Fig. 23.1)

Ex. 23.1.1 51 Peg same spectral class as sun $\Rightarrow M_{51} = 1 M_\odot$

Kepler's 3rd Law (eq. 2.37) w/ $m \ll M_{51}$ + $P = 4.230$ dys is

$$a = \left[\frac{GP^2(M_{51}+m)}{4\pi^2} \right]^{1/3} = \underset{64}{7.65} \times 10^9 \text{ m} = 0.051 \text{ AU}$$

Orbital speed of planet $v = 2\pi a/P = 131 \text{ km s}^{-1}$

Max. radial speed of star $v_{r,max} = v_{51} \sin i = 56.04 \text{ m s}^{-1}$ where i = inclination angle: the angle between the plane of the orbit + the plane of the sky.

Since both objects revolve around the center of mass, we have

(Eq. 7.5) $\dfrac{m_1}{m_2} = \dfrac{v_{2r}/\sin i}{v_{1r}/\sin i} = \dfrac{v_{2r}}{v_{1r}}$

So we have $m \sin i = \dfrac{M_{51} v_{51}}{v} \sin i = 0.45 M_J$ ← Jupiter

$\sin i \leq 1 \Rightarrow m > 0.45 M_J$

p849 Multi-Planet Systems

(Fig. 23.2) υ (upsilon) Andromedae has ≥ 3 planets.

Many more multi-planet systems have now been found.

p850 - The Mass Distribution of Extrasolar Planets

There is a selection effect in discovered exoplanets.

Heavier planets are easier to find since they move their star more.

Also, a planet must be observed over a significant fraction of its orbit, so planets in larger orbits take longer to find.

At the time (2007) of writing of this text there seemed to be a mass distribution $dN/dM \propto M^{-1}$. (Fig. 23.3)

From a 2015 paper by Malhotra (Fig. 1) - in Earth masses $M_\oplus$

The Distribution of Orbital Eccentricities - skip

p 852 The Trend Toward High Metallicity - skip

p 853 Measuring Radii + Densities Using Transits

When a planet transits across the disk of a star, its radius can be determined, + from that its average density.

It appears that Jupiter-mass exoplanets are similar to our gas giants, although the ones close to their parent star are puffed up due to extra heating.

23.1.1b

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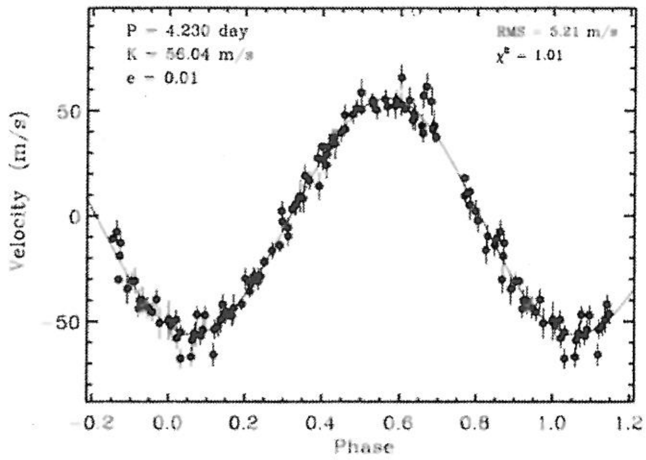

Fig. 23.1 Radial velocity of 51 Pegasi, revealing presence of planet orbiting 0.051 AU from star.

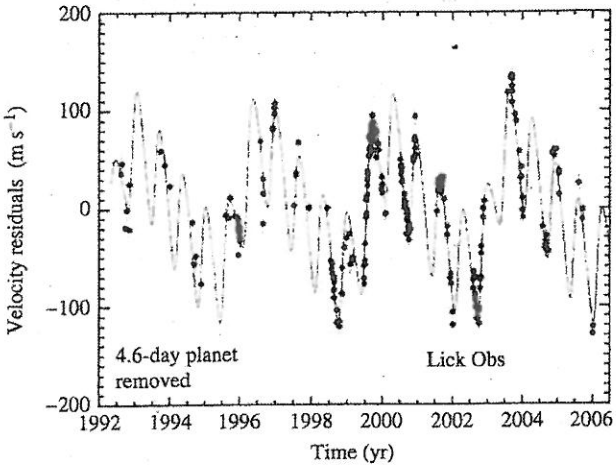

Fig. 23.2 Residuals in the radial velocity measurements of ύ (upsilon) Andromedae after gravitational permutations of the 4.6-day planet have been removed. ύ And contains at least 3 planets with periods 4.6 d, 241 d, & 1284 d, with m sin i's of 0.69, 1.89, & 3.75 M_J.

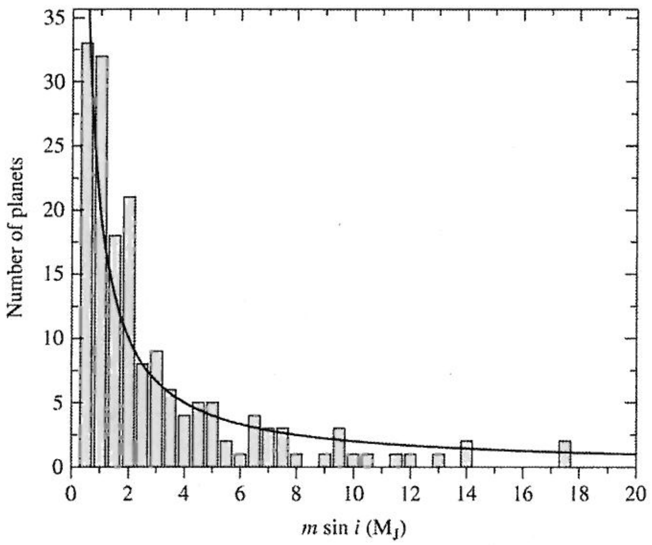

Fig. 23.3 The number of planets in mass bins of interval 0.5 M_J. The solid line is $dN/dM \propto M^{-1}$.

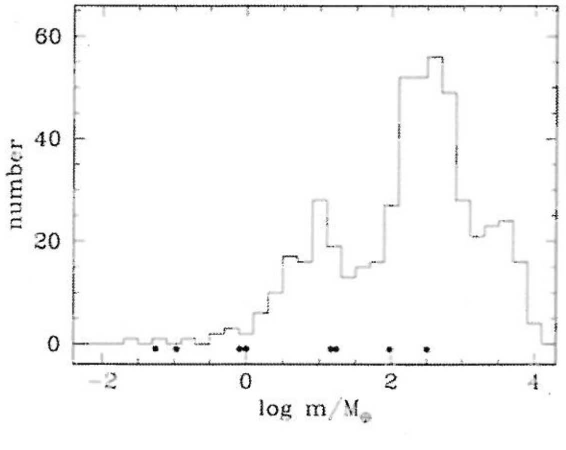

FIG. 1.— The distribution of log-mass of confirmed exoplanets with measured masses (data from (http://exoplanetarchive.ipac.caltech.edu/. retrieved on September 16, 2014). The black points indicate the masses of the solar system planets. Note that this is a semi-log plot.

From Malhotra Accepted to ApJ: June 2, 2015

23.1,2 2/27/18

p.854 The Detection of an Extrasolar Planet Atmosphere

Enhanced sodium absorption due to planetary atmosphere.

p.855 Distinguishing Extrasolar Planets from Brown Dwarfs - skip

An Image of an Extrasolar Planet (Fig. 23.7)

Future Space-Based Planet Searches skip

p.857 - §23.2 Planetary System Formation + Evolution

There have been many theories of formation of the solar system. We have now settled on simultaneus formation of sun + planets from same nebula.

Early proponents of nebular theories were Descartes (1596-1650), Kant (1724-1804) + Laplace (1749-1827).

Accretion Disks + Debris Disks

Accretion disks (see Ch.12) are thin disks of gas, while debris disks are collections of solid objects incl. dust.

p858 - Angular Momentum Distribution in the Solar System

$L_J \sim 20 L_\odot$, + Sun's spin axis tilted by 7° wrt $L_{planets}$.

The question of the distribution of L (ang. mom.) is unsolved.

p859 Composition Trends throughout the Solar System

Any formation theory must explain composition trends in solar system. Inner planets have much less volatile material than outer planets, + Jupiter + Saturn contain the vast majority of system's volatiles. There are also composition trends in moons of Jupiter, + of other planets.

The Temperature Gradient in the Solar Nebula

Composition trends can be largely explained by temperature gradients. (Fig. 23.9) At this time no ices could condense inside of 5 AU.

p860 Consequences of Heavy Bombardment

Collisions have had a big effect on planetary formation + evolution. For example, Uranus' rotation is retrograde.

p861 The Distribution of Mass within Planetary Systems

Also need to explain the small mass of Mars, the existence of the Oort Cloud + the Kuiper Belt + the existence of "hot Jupiter's" - gas giants near the parent star in other systems.

Formation Timescales

§12.2: After collapse begins need $\sim 10^5$ yr to form protosun + nebula-disk.
§12.3: violent outbursts (T-Tauri + FU Orionis activity) begin in $10^5 - 10^7$ yr sweeping away gas + dust ⇒ planet formation must be done by then.

There are various other age constraints, such as the fact that the

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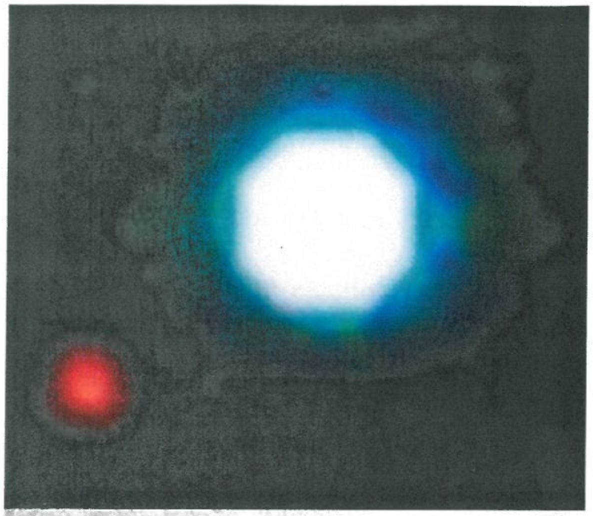
3/1/18



FIRST IMAGE OF AN EXOPLANET?

In July 2004 a group of astronomers led by Gael Chauvin took this image of a planetary-mass object in orbit around brown dwarf 2M1207.

(Like Fig. 23.7)

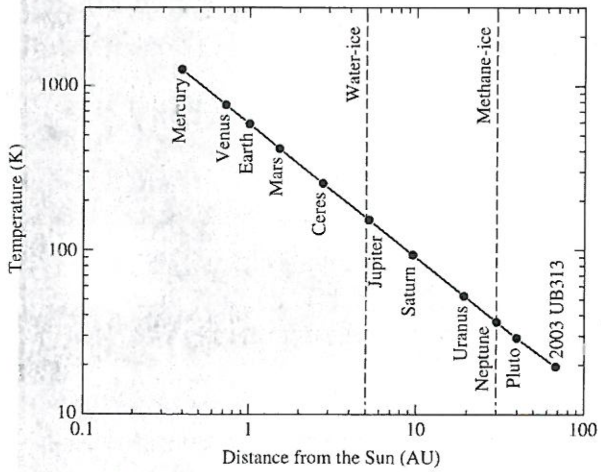


Fig. 23.9 An equilibrium model of the temperature structure of the early solar nebula. Notice the radii beyond which water-ice & methane-ice could condense. Positions of planets are their present-day positions.

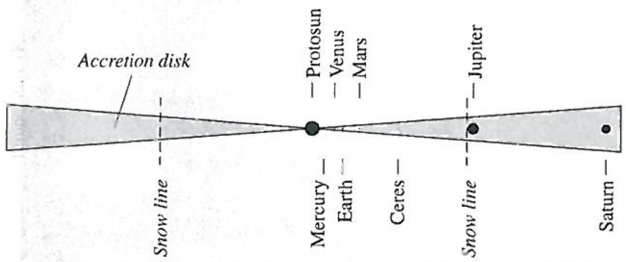


Fig. 23.10 Schematic drawing of solar nebular disk, showing water-ice "snow line" 5 AU from protosun.

23.2.1 3/1/18

oldest meteorites are 4.566 Gyr old, while the Sun is 4.57 Gyr.

p.862 the Gravitational Instability Formation Mechanism

2 competing mechanisms: gravitational instability + accretion.

In grav. inst. model, higher-density regions in solar accretion disk collapse, increasing their gravitational influence + causing more accretion!

But this mechanism doesn't appear fast enough to create Uranus + Neptune.

Because of this + other theoretical problems, the favored model is now...

p.863 the Accretion Formation Mechanism

... small grains collide + stick together.

The Formation of the Solar System: An Example

Within a giant gas + dust cloud, parts cooled enough to begin to collapse.

The biggest parts collapsed the fastest, forming very massive stars which went through their life cycle + supernova'd in several Myr.

Smaller parts like our presolar nebula collapse much slower.

When the SN remnant struck our presolar nebula, it enriched it with heavier elements + may have actually caused it to start collapsing.

The nebula collapsed + formed an accretion disk.

p.864 The Hill Radius

Dust grains w/ icy mantles collide + stick together, eventually getting big enough to start accumulating matter gravitationally!

The Hill radius R_H is the distance from the planetesimal such that a test particle orbiting at that radius has the same orbital period as an orbit about the Sun at radius a.

The period of an orbit of radius R about mass M is $P = 2\pi\sqrt{R^3/GM}$, so $\sqrt{\frac{a^3}{M_\odot}} = \sqrt{\frac{R_H^3}{M}} \Rightarrow R_H = (M/M_\odot)^{\frac{1}{3}} a$. Writing the masses in terms of the densities + radii gives: $R_H = R/\alpha$, $\alpha \equiv (\rho_\odot/\rho)^{1/3} R_\odot/a$

p.865 the Formation of the Gas + Ice Giants (Fig. 23.10)

Jupiter grew the fastest of all planets because it is beyond the "snow line", but relatively close to the protosun so the nebula was denser.

When its core became 10-15 $M_\oplus$ in size, it was able to start accreting gas (H + He). The process took ~ 10^6 years.

p866 the Formation of the Terrestrial Planets + the Asteroids

In the inner solar system, iron + rock planetesimals formed + grew by collision.

When they got large enough, radioactive decay + collisions heated them enough that they could melt + undergo gravitational differentiation.

When Jupiter got big enough, its gravitational influence caused planetesimals' orbits to become eccentric, so they got incorporated into Sun or Jupiter or ejected from solar system.

This depleted material so that Mars couldn't get very big.

23.2.2 3/1/18

& not much material was left in the asteroid belt.

p867 The Process of Migration

Planets can migrate inwards or outwards via interactions with the disk & with planetesimals.

It appears that Saturn, Uranus, & Neptune formed closer to Sun where nebula was denser, but were caused to migrate outwards due to Jupiter, which moved inwards by 0.5 AU.

p868 Resonance Effects in the Early Solar System

As they migrated, at some point J & S were in 2:1 orbital resonance, at which point their combined effect would perturb the orbits of asteroids & Kuiper belt objects, causing the "episode of late heavy bombardment" which seems to have accurred ~700 Myr after formation of terrestrial planets.

The Formation of CAI's & Chondrules - Skip

CH