ASTR-1010: Astronomy I
Course Notes
Section VII

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Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1010: Astronomy I taught by Dr. Donald G. Luttermoser at East Tennessee State University.

VII. A Global View of the Solar System

A. Planetary Orbits

1. The order of the planets (on average) from closest to farthest from the Sun is Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto (see Table 7.1 in text).

2. In between the orbits of Mars and Jupiter lay a zone of planet fragments or asteroids $\Longrightarrow$ the **asteroid belt**.

i) Planets that lie within the asteroid belt (*i.e.*, closer to the Sun) are small and rocky $\Longrightarrow$ **terrestrial planets** or Earth-like planets.

ii) Planets that lie outside the asteroid belt are large and gaseous (except Pluto) $\Longrightarrow$ **Jovian planets** or Jupiter-like planets.

3. Average density = mass / volume (see Table 7.1 in text):

$$\rho = \frac{M}{4\pi\, R^3}, \tag{VII-1}$$

i) Water: $\rho = 1000$ kg/m^3.

ii) Typical Rock: $\rho = 3000$ kg/m^3.

iii) Earth: $\rho = 5520$ kg/m^3 (so it must have metal core).

iv) Saturn: $\rho = 690$ kg/m^3, composed primarily of hydrogen and helium (Saturn would *float* if you could find an ocean big enough).

B. Chemical Composition

1. Through visual, UV, and IR spectroscopy, we are able to ascertain the chemical composition of the planets and many of the moons in our solar system.

a) Planets *shine* because they reflect sunlight $\Longrightarrow$ they do not produce their own light.

b) Hence light that comes from the planets contains spectral lines from the planet, the Sun, and the Earth's atmosphere — the last two must be subtracted out.

c) Spacecraft flying past the planets have eliminated the Earth's atmospheric lines in planetary spectra.

d) The planets Venus, Mars, and Jupiter have had their composition analyzed chemically by spacecraft which have entered their atmospheres.

2. Light gases make up the bulk of the Jovian planets.

a) Molecular hydrogen (90%) and helium (9%) make up most of these gases (same as the Sun, except hydrogen is in atomic form in the Sun).

b) Methane (CH_4), ammonia (NH_3), water vapor (H_2O), and carbon dioxide (CO_2) make up most of the rest of the chemical composition.

3. The terrestrial planets are rocky with nickel-iron cores and possess thin or no atmospheres.

a) They contain virtually no free hydrogen or helium.

b) Mercury and the Moon contain no atmospheres.

c) Earth's thin atmosphere contains molecular nitrogen (N_2: 77%), molecular oxygen (O_2: 21%), with trace amounts of H_2O, CO_2, and argon (Ar).

d) Venus' atmosphere is relatively thick (100 Earth atmospheres) and contains mostly CO_2 (96%) and some N_2 (4%) with trace amounts of other gases (except O_2).

e) Mars' atmosphere is thinner than Earth's (1/100 Earth atmospheres) and contains mostly CO_2 (97%) and some N_2 (3%) with trace amounts of other gases (except O_2).

4. The chemical composition of the planets results from a variety of processes, the most important being the cosmic abundance of the elements (see Appendix 9 in text).

C. Formation of the Solar System

1. The planets, asteroids, and comets are the byproducts of the formation of the Sun — most of the mass in the solar system lies in the Sun!

2. The Sun and the solar system formed about 4.6 billion (4.6×10^9) years ago.

a) This age is deduced from the abundances of certain radioactive elements with respect to their stable decay elements in meteorites and Moon rocks.

Original Radioactive Isotope	**Half Life (10^9 yr)**	**Final Stable Isotope**
Potassium (^{40}K)	1.3	Argon (^{40}Ar)
Rubidium (^{87}Rb)	47.0	Strontium (^{87}Sr)
Uranium (^{235}U)	0.7	Lead (^{207}Pb)
Uranium (^{238}U)	4.5	Lead (^{206}Pb)

b) The current luminosity and temperature of the Sun fits stellar evolutionary models of a 4.6 billion year old, one solar-mass star.

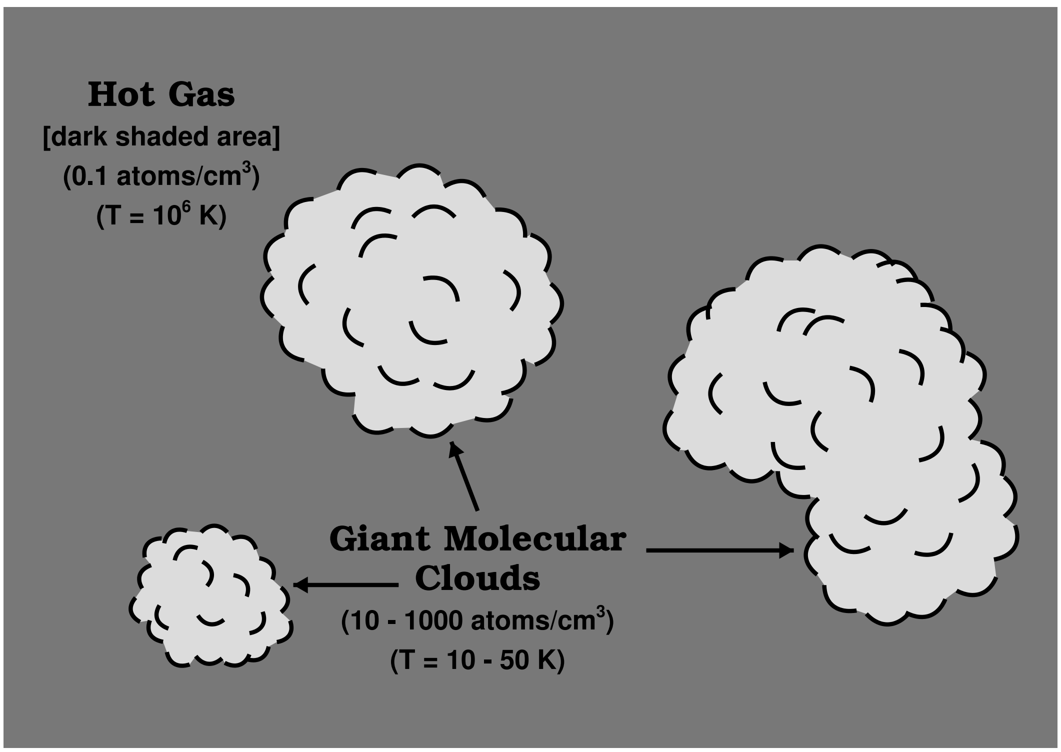
3. The Interstellar Medium (ISM).

a) Composition:

i) Gas: 75% H and 25% He by weight
90% H and 10% He by number
with trace amounts of C, N, O, Ca, Na, and heavier elements.

ii) Dust: C, Fe, and silicates, 1 to 2% by weight.

b) Structure:



c) Dust scatters blue light more effectively than red, stars appear redder when light travels through interstellar dust $\Longrightarrow$ **interstellar reddening**.

d) Besides seeing nebula, the existence of the ISM can be seen by:

i) Narrow absorption lines seen in stellar spectra —

lines formed in the atmosphere of stars are broader due to pressure broadening.

ii) Forbidden lines — these lines are not seen in stellar atmospheres since they can only be formed in low density gas.

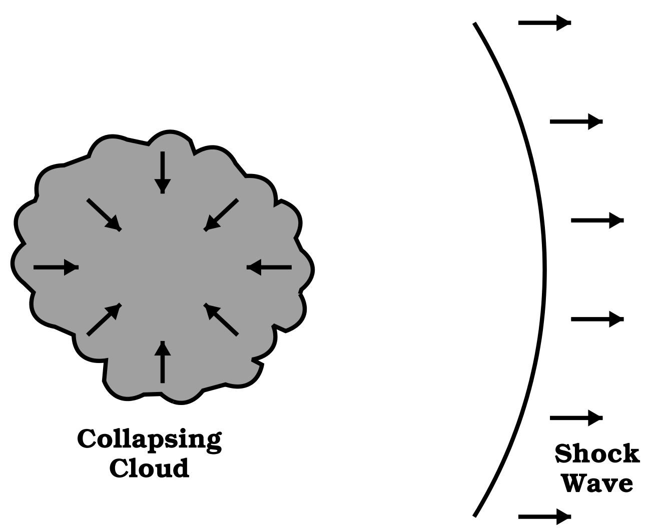
4. Cloud contraction.

a) Initial cloud collapse can be initiated by:

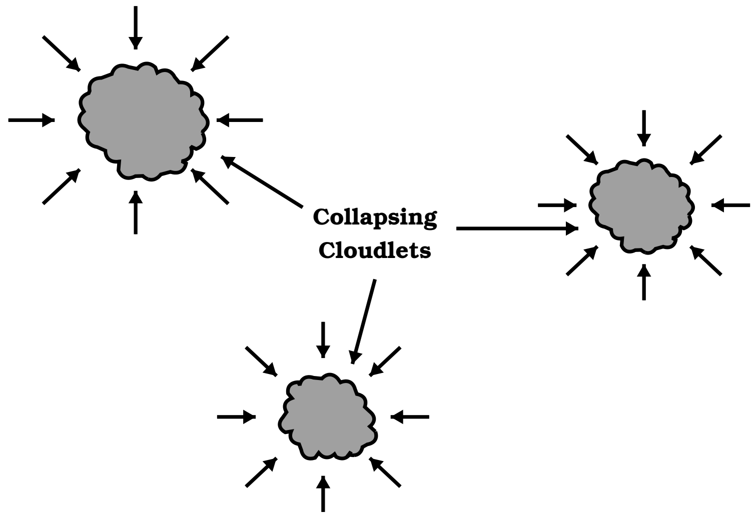
i) The cloud being so massive that its gravity overcomes the internal pressure.

ii) A shock wave (spiral arm of Galaxy or perhaps a nearby supernova) passes through the cloud and compresses the gas.

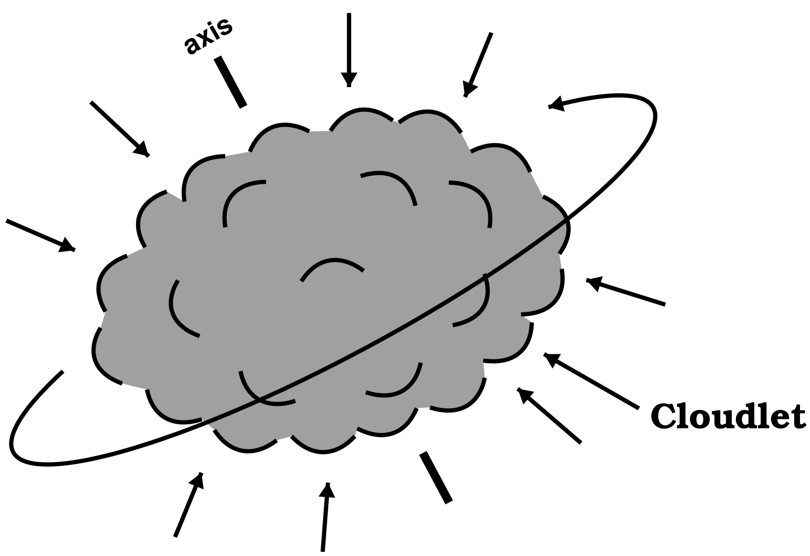
b) This compressed gas has a density enhancement over the surrounding ISM so that gravity becomes dominant over thermal pressures $\Longrightarrow$ the cloud collapses.



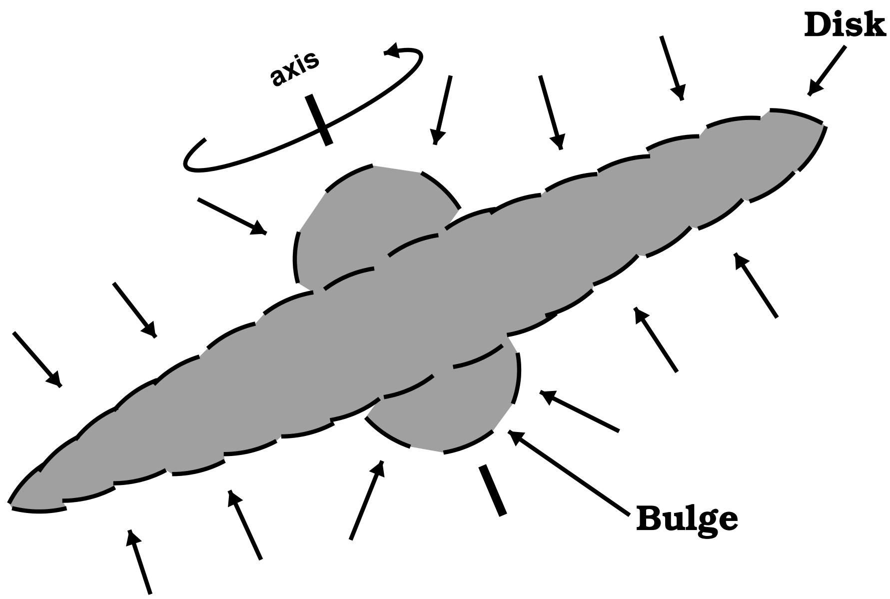
c) As large clouds contract, they become unstable and fragment into many dense cloudlets. Each little cloudlet continues to collapse.



d) As the large cloud was collapsing, there were many internal eddies and turbulent motions. Each little cloudlet has a rotation associated with it that was induced from one of these eddies.

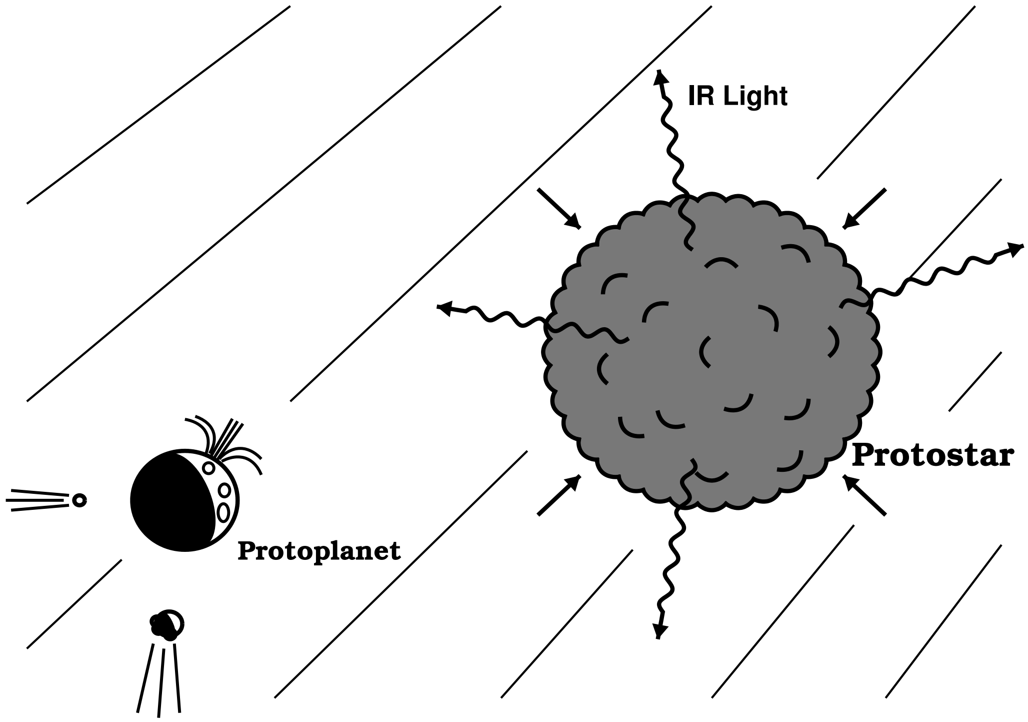


e) As the cloudlet contracts, it spins faster due to the conservation of angular momentum. This increased spin causes the equatorial region to bulge outward which flattens the cloudlet. This continues until a central bulge with an equatorial disk forms.

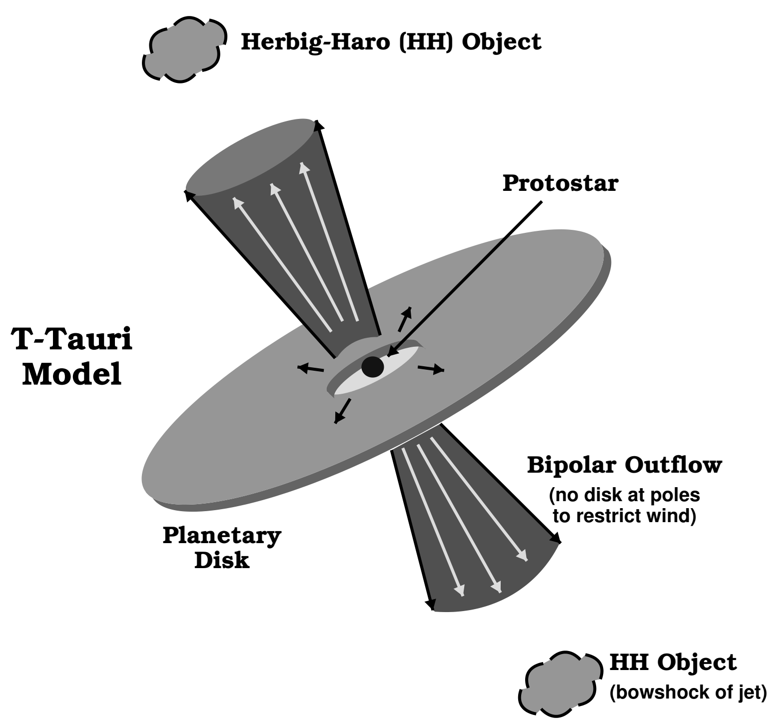


f) As this contraction continues, the temperature and the pressure at the center of the cloud rises. There comes a time when this center gets so hot, it starts emitting visible photons. The surrounding gas and dust in the cloudlet (*i.e.*, the cocoon) absorbs the visible light and re-emits it as infrared light. The contracting cloudlet now is called a **protostar**.

g) In the surrounding disk, dust grains begin to stick together from condensation and accretion, building in size to form planetesimals. These planetesimals conglomerate further into protoplanets.



h) The visible light now reaches the surface of the protostar (still being power by gravitational contraction) and the pressure from this light starts to push out the unused material in the planetary disk. This spring cleaning phase is called the **T-Tauri stage** of the star.



- **i)** At the center, the temperature and pressure build so high that nuclear reactions start $\Longrightarrow$ **A STAR IS BORN**. The star (*i.e.*, the Sun) is now a main sequence star and only planets and asteroids remain in the inner solar system.

5. In the outer planetary disk, ice crystals condensed out of the gas along with some dust grains.

6. In the inner solar system, it was too hot for ice crystals to form, only dust condensed out.

7. The dust (and ice) began to conglomerate together in a process known as **advection** (similar to building a snowman), building bigger and bigger particles. This processed continued until boulder to mountain sized objects existed $\Longrightarrow$ the **planetesimals**.

8. Planetesimals would smash into each other from time to time, sometimes destroying each other, sometimes sticking together to form even bigger planetesimals $\Longrightarrow$ **accretion**.

- **a)** The outer planets formed first since the temperatures in that region of the protoplanetary disk were low enough for condensation to occur there first. Four giant planets formed with enough mass to gravitationally attract much of the H and He gas in the vicinity.

- **b)** These large planets had their own mini-solar systems that formed around them. Ices composed a large part of their composition.

c) Far from the Sun, the icy planetesimals never formed large planets. They still exist today as **comets**.

d) The inner planets than began to form after the formation of the Jovian planets. However they were too close to the Sun, hense too hot, and not massive enough to hang onto the H and He gas, which was later lost when the Sun went through its T-Tauri stage.

e) The terrestrial planets were not big enough to form their own *planetary disks* like the Jovian planets did.

f) Jupiter's strong gravitational field prevented a protoplanet from being formed between its orbit and Mars' — the unused planetesimals are still in existence today $\Longrightarrow$ the **asteroid belt**.

9. During the accretion process, the inner planets existed in a molten state due to the energy of all of the planetesimal impacts.

a) During this time the heavier elements (Fe & Ni) sank towards the center of the planets and the lighter elements (C, N, & O) floated towards the top $\Longrightarrow$ these planets became **differentiated**.

b) As the protoplanets cooled, a crust formed. The molten rock below caused numerous volcanos which outgassed copious amounts of N_2 and CO_2. The initial atmospheres of all the inner planets contained mostly CO_2 (about 95 to 97%) with a small amount of N_2 (about 3 to 5%).

10. A few final large planetesimal collisions took place, one Mars sized planetesimal struck the protoearth and knock mantle material into orbit which gave rise to the Moon and knocked the Earth sideways so that the spin axis was tilted about 23° with respect to its orbit normal line.

a) Venus too suffered one, possibly 2 large final collisions, which knocked its spin axis by nearly 180° (the planet rotates backwards as a result)! No large amounts of material were ejected here however.

b) Uranus suffered a similar collision knocking it on its side.

11. The terrestrial planet atmospheres took different evolutionary paths. Two things account for how well a planet can hold on to an atmosphere.

a) Temperature of the atmospheric gas, which dictates how fast the gas particles are traveling following the formula:

$$v = \sqrt{\frac{3kT}{m}}, \qquad \text{(VII-2)}$$

where v is the gas particle's velocity, T is the temperature, m is the mass of the particle, and k is Boltzmann's constant. The closer a planet is to the Sun, the higher T and the higher v. Also, the lighter the gas (*i.e.*, lower m), the higher v, so H and He would have a higher velocity than N_2 and CO_2.

b) The gravitational field of the planet, which dictates the escape velocity of the planet:

$$v_{\rm esc} = \sqrt{\frac{2GM}{R}}, \qquad \text{(VII-3)}$$

where M is the mass of the planet, R is the radius of the planet, and G is Newton's universal gravitational constant.

c) If $v > v_{\rm esc}$, then such a gas will escape the gravitational field of the planet, this is why the terrestrial planets do not have any H and He in their atmospheres.

12. Both Mercury and the Moon had too low a mass and too close to the Sun to retain any gases over more than just a few million years — they currently have no atmospheres.

13. Mars was just massive enough to hang on to a slight atmosphere for its distance from the Sun.

14. Venus' atmosphere experienced a runaway greenhouse effect which increased T to even higher values which baked out more CO_2 from the planet's interior and *evaporated out* all the water vapor from the atmosphere.

15. The Earth's distance from the Sun gave temperatures that allowed the water vapor in its atmosphere to condense out, forming liquid water oceans.

a) Liquid water reacts with gaseous CO_2 — the CO_2 solidifies in the water and sinks to the bottom producing a limestone sediment.

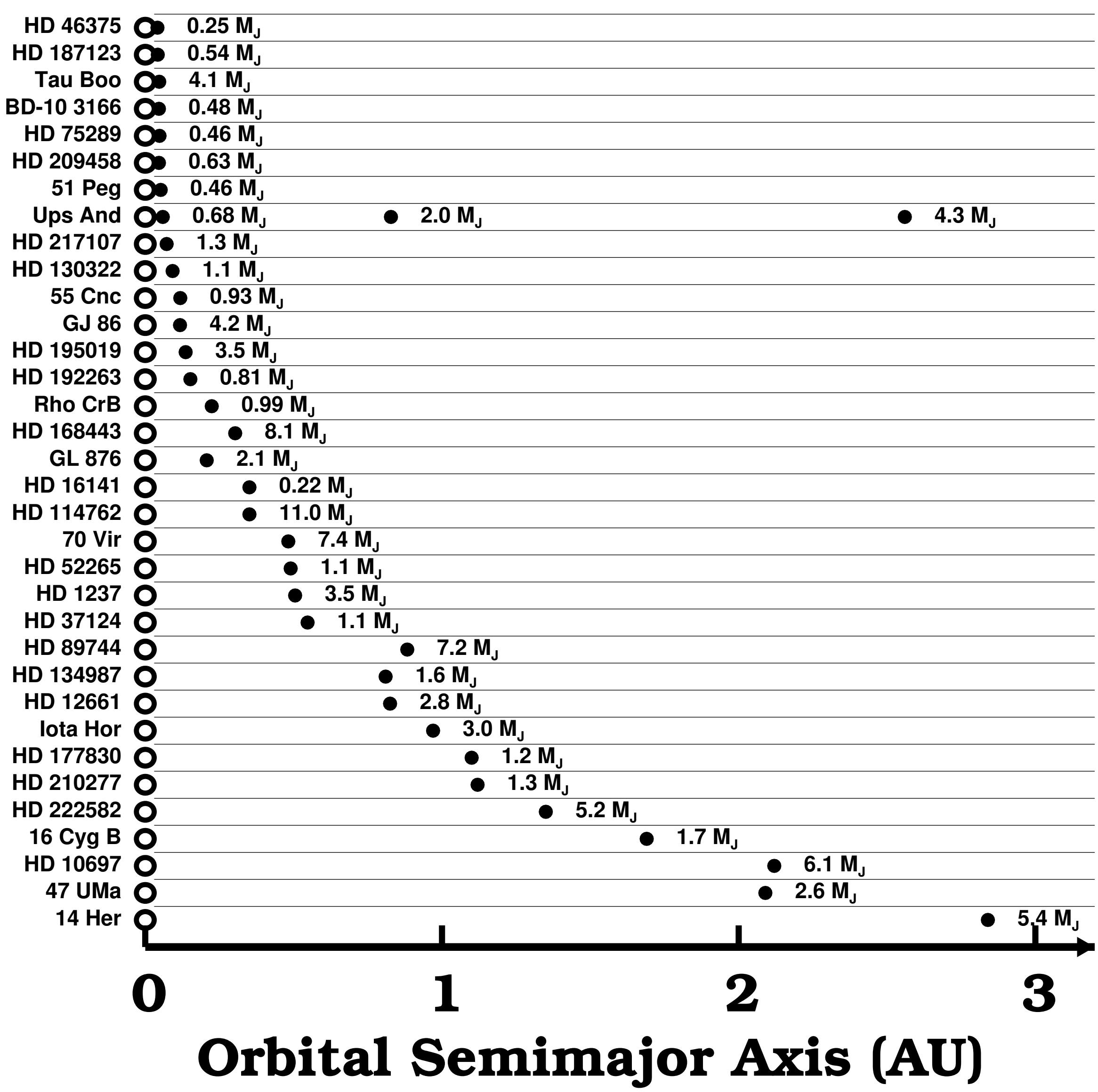
b) During the first half-billion years, the Earth's oceans eliminated most of the CO_2 from the atmosphere leaving an N_2 atmosphere with traces of CO_2 and H_2O vapor.

c) Life formed a few 100 million years after that in the form pre-algae type organisms. These organisms, the first plant life, consumed CO_2 and excremented O_2 as a waste product.

d) Over the 4.6 billion year life span of the Earth, life grew into more complex organisms, and the O_2 content continued to increase to its present day value: N_2 at 77% and O_2 at 21%.

D. ExtraSolar Planetary Systems.

1. Over the past decade, a variety of planets have been discovered around nearby stars.



2. There are a variety of techniques used in determining whether or not a star has a planetary system around.

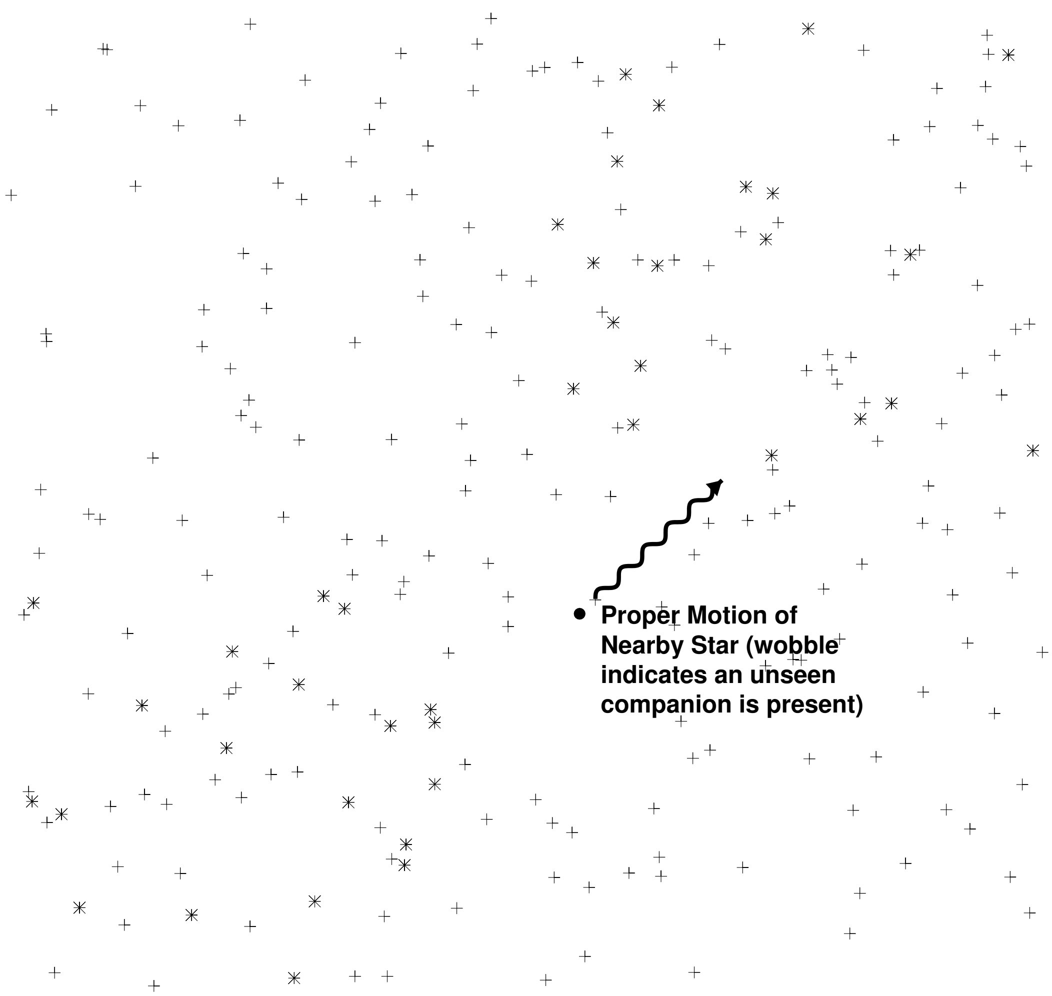
a) **Direct imaging**: Getting pictures of the actual planets. This would be difficult to do due to the large distances of the star and the relative small size of planetary systems. A planet like Jupiter, 5 AU from the brightest star in the sky Sirius, would only be 2.0 arcsecs from the star and the brightness of the star would hide such a planet in its glare.

b) **Detection of a "wobble" in the proper motion of a star**: As stars orbit the center of the Milky Way Galaxy, stars change their relative positions to each other (*i.e.*, star have both a radial (*line-of-sight*) velocity component and a velocity in the plane of the sky perpendicular to the radial velocity called the star's **proper motion**).

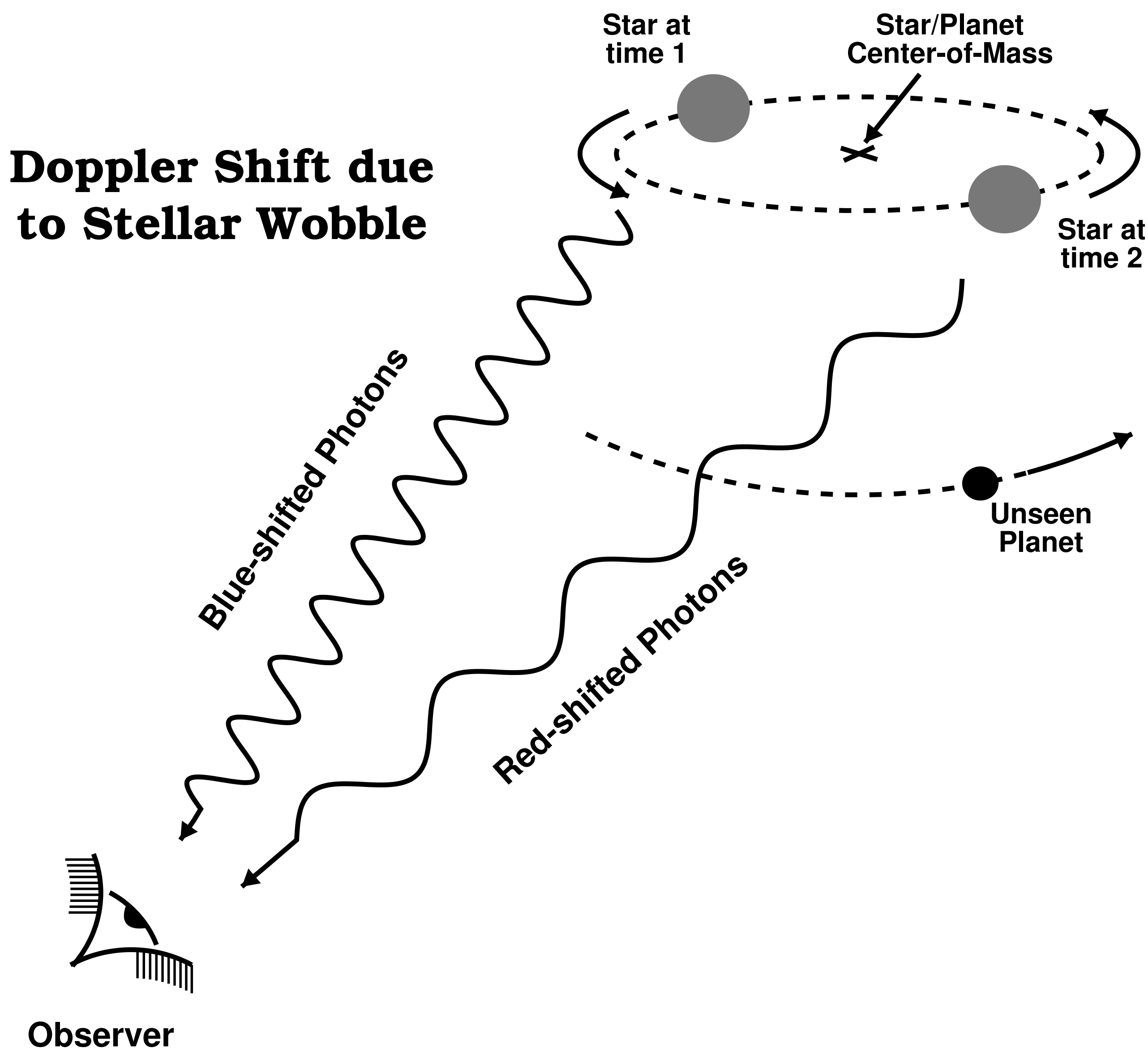
i) Large planets in orbit about a star would cause the star to wobble along its proper motion path across the sky as the star and the large planet both orbit about the common center-of-mass.

ii) Such a wobble would be a small scale effect and no planetary systems have yet to be discovered using this technique. For instance, the center-of-mass of the Sun and Jupiter is just outside the surface of the Sun some 4.6×10^7 m ($0.066\ R_\odot$) above the Sun's photosphere. From the distance of the nearest star α Cen, this corresponds to a total wobble deviation of 0.0038 arcseconds! This would be extremely hard to detect.

iii) Faint (unseen) stars (typically M dwarfs) have been detected in this manner. In the diagram below, each cycle of the wobble (*i.e.*, the time that passes between each "maximum" of the *wavey* line) corresponds to one orbit of the unseen companion about the visible star. If the picture below corresponds to a change of position (called a star's *proper motion*) of a visible, nearby star over 100 years, the orbital period of the unseen companion would be 16.7 years since there are a total of 6 cycles over this time period.



c) **Doppler shifts in spectral lines as the star orbits the center-of-mass**: The figure below shows the physics of the situation. As the star and planet orbit a common center-of-mass, the spectral lines of the star will shift back and forth due to the changing orbital velocity.



i) The velocity shifts of a planet star interaction would be very small — on the order of a few meters/second for a large Jupiter-like planet orbiting close to the star.

ii) This is the type of technique that has been used to detect these recently found extrasolar planets.

iii) This technique however will only find those planetary systems with large Jupiter-like planets close in to the star.

d) **Planet occulations of their parent star**: A few planets have been detected by variations in a star's light output. This will only be measurable if the planet is large and close in to the star with its orbital plane in the radial direction of the Earth. As the planet passes in front of the star, the star's brightness drops a tiny amount.

3. Due to these discoveries, we now know what stellar formation models were predicting all along — planetary system formation is a direct result of star formation. As such, planetary systems should be common in the Universe.