Physics 2028: Great Ideas in Science II: The Changing Earth Module Notes

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Edition 2.0

Abstract

These class notes are designed for use of the instructor and students of the course Physics 2028: Great Ideas in Science II. This edition was last modified for the Spring 2009 semester.

I. Solar System Origin & Evolution

A. Solar System Formation.

1. The Sun and solar system form from the dust and gas that lie between the stars $\Longrightarrow$ the **interstellar medium**.

2. 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!

3. 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.

4. Stars and planets are formed from the material that lies between the stars $\Longrightarrow$ the **interstellar medium** (ISM). The regions in the ISM where stars form are called **stellar nurseries**. These stellar nurseries are found within **giant molecular clouds** (GMC) as shown in Figure I-1. The nearest GMC to the solar system is the Orion complex.

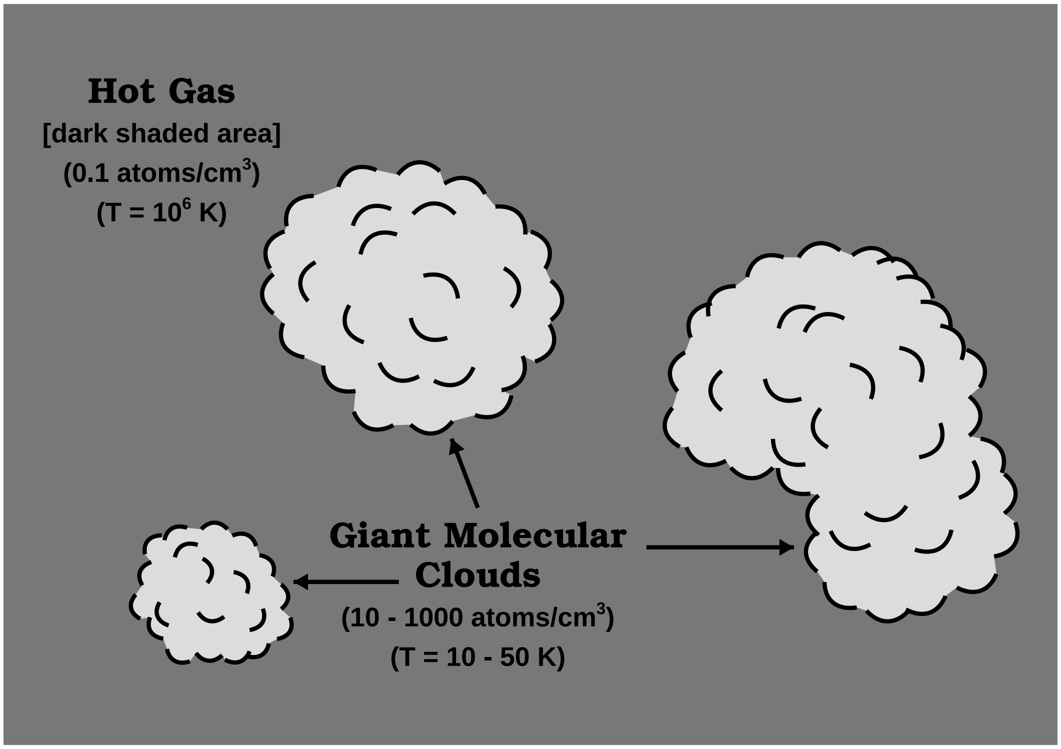


Figure I–1: Structure of the Interstellar Medium.

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.

5. GMCs are usually in **hydrostatic equilibrium** unless some event occurs to cause a cloud to exceed its Jeans' mass and/or Jeans' length as described last semester. What is the trigger? Any process that can cause a stable ($M < M_J$) cloudlet to become unstable ($M > M_J$).

a) **Agglomeration**: Component cloudlets of GMC's collide and sometime coallace until $M > M_J$.

b) **Shock Wave Compression**: A shock can be the trigger $\Longrightarrow$ it acts like a *snow plow* causing ρ to increase, and as a result, M_J drops (see Figure I-2).

i) **Spiral Density Wave**: As Milky Way Galaxy rotates, its two spiral arms can compress a GMC, which then leads to star formation.

ii) **Ionization Front**: O & B stars form very quickly once cloud collapse has started (see below). These produce H II regions from their strong ionizing UV flux, which initially expand outward away from the OB association. This ionization front heats the gas causing a shock to form. The shock can compress the gas such that $M > M_J$, which once again, leads to star formation.

iii) **Supernova Shocks**: O & B stars evolve very quickly on the main sequence and die explosively

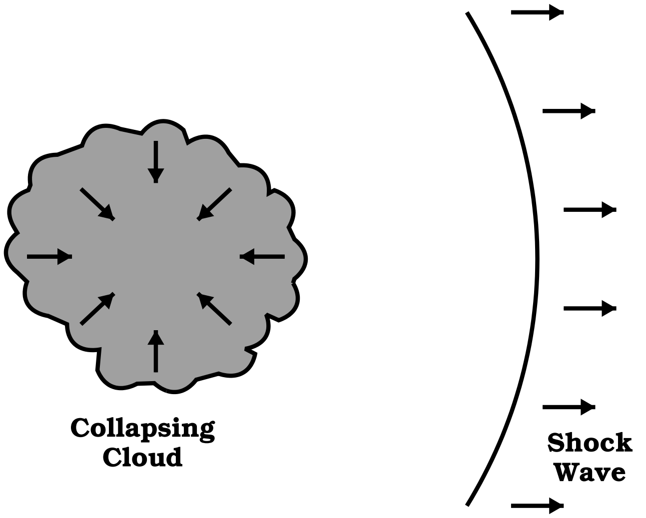


Figure I–2: Shock wave induced collapse.

as supernovae. The shock sent out by such a supernova can excite further star formation.

B. The Free-Fall Stage of the Solar System's Birth.

1. As a portion of a GMC begins to contract, cloud complexes with masses greater than $\sim 50\ M_\odot$ become unstable and fragment into smaller cloudlets (see Figure I-3). Each little cloudlet continues to collapse as described above.

2. As a large portion of the GMC collapses, many internal eddies and turbulent motions can exist within the cloud. As a result, when fragmentation to stellar-mass sizes occur, each little cloudlet has a rotation associated with it that was induced from one of these eddies as shown in Figure I-4.

3. As the cloudlet contracts, it spins faster due to the conservation of angular momentum $L = M\,R^2\,\omega$, where ω is the angular velocity of the protostellar *cloudlet* $\Longrightarrow$ since M is constant, as R gets smaller, ω gets larger. This increased spin causes the equatorial region to bulge outward which flattens the cloudlet. This

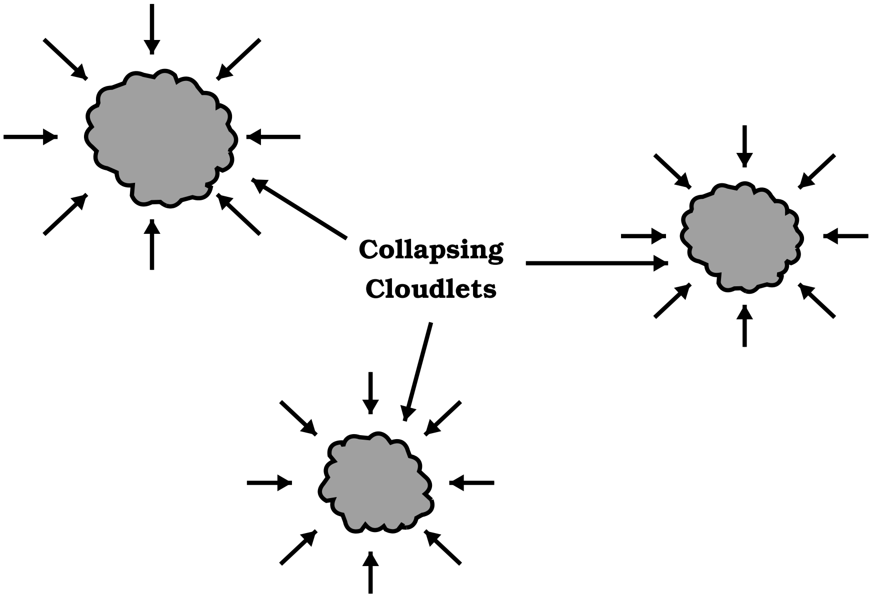


Figure I–3: Collapsing cloud fragmentation to smaller collapsing "cloudlets."

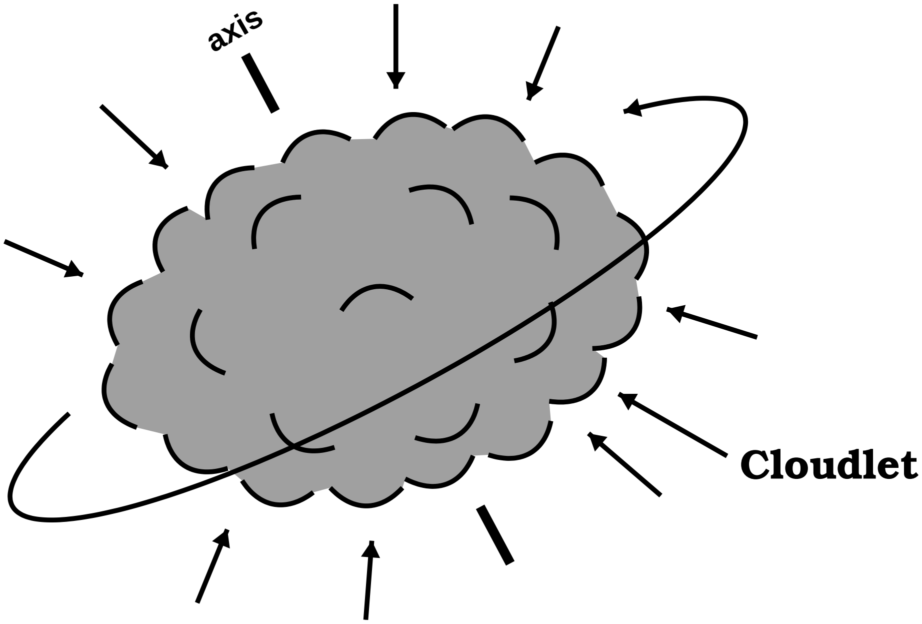


Figure I–4: Cloudlet contraction and spin as a result of internal eddies.

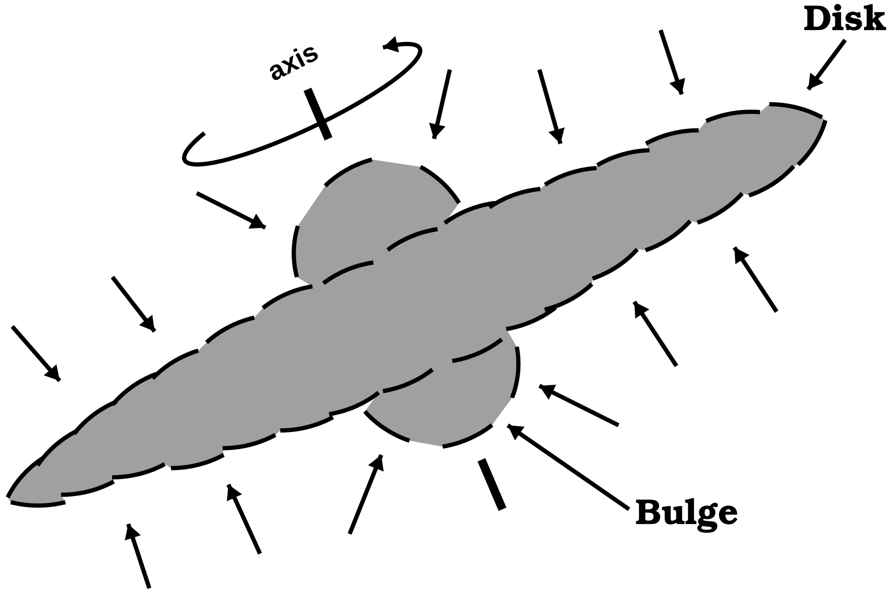


Figure I–5: Formation of protostar and protoplanetary disk.

continues until a central bulge with an equatorial disk forms as shown in Figure I-5.

a) The equatorial disk flattens rather quickly (hundreds of years) during this stage. At this point, the disk is now referred to as a **proplyd** or **protoplanetary disk**. In the case of the solar system, we call this stage the **solar nebula**.

b) Numerous such disks have been seen in stellar nurseries with the *Hubble Space Telescope.* They are especially easy to see at IR wavelengths.

c) In this protoplanetary disk, dust grains begin to stick together from condensation and accretion, building in size to form planetesimals. These planetesimals conglomerate further into protoplanets (see Figure I-6).

- **i)** In the outer protoplanetary disk, ice crystals condense out of the gas along with some dust grains.

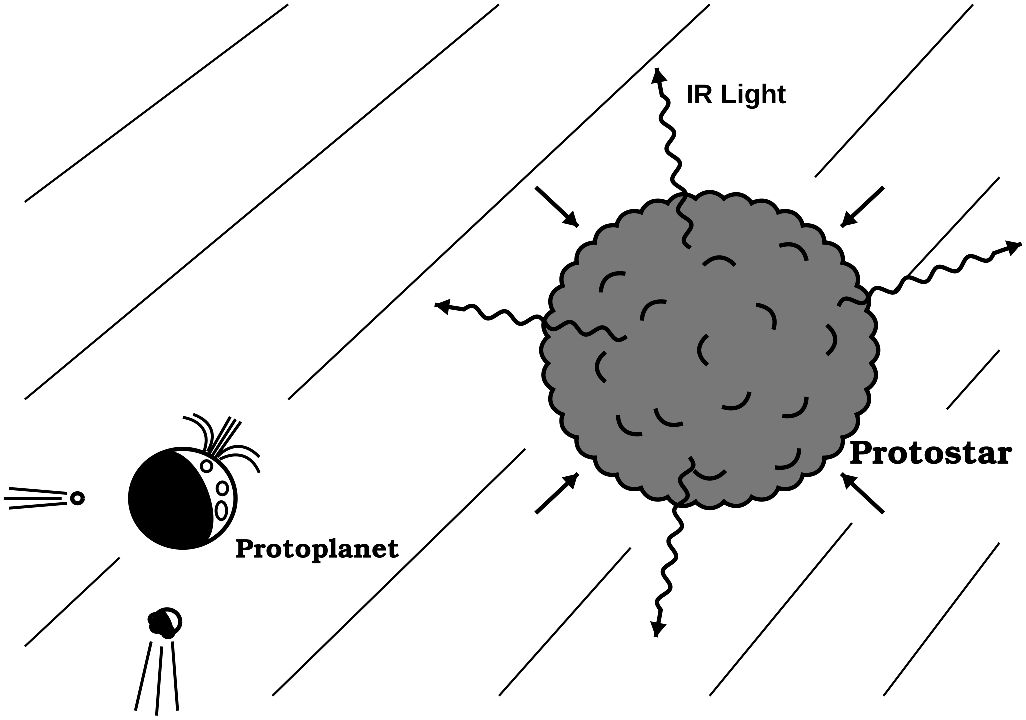


Figure I–6: Inside the protoplanetary disk of the collapsing cloudlet.

ii) In the inner protoplanetary disk, it is too hot for ice crystals to form, only dust condenses out.

iii) The dust (and ice) begin 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**.

iv) Planetesimal is the name given to big rocks in orbit about a "protostar." Due to their small size ($D < 1000$ km), they are not spherical in shape.

- The "rocky" planetesimals are now called **asteroids**.
- The "icy" planetesimals are now called **comets**.

v) Planetesimals occasionally smash into each other, sometimes destroying each other, sometimes sticking together to form even bigger planetesimals $\Longrightarrow$ this is a process known as **accretion**.

- 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.

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

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

- The inner planets than began to form after the formation of the Jovian planets. However they were too close to the Sun, hence 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 (see Figure I-7).

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

- Jupiter's strong gravitational field prevented a protoplanet from being formed between its orbit

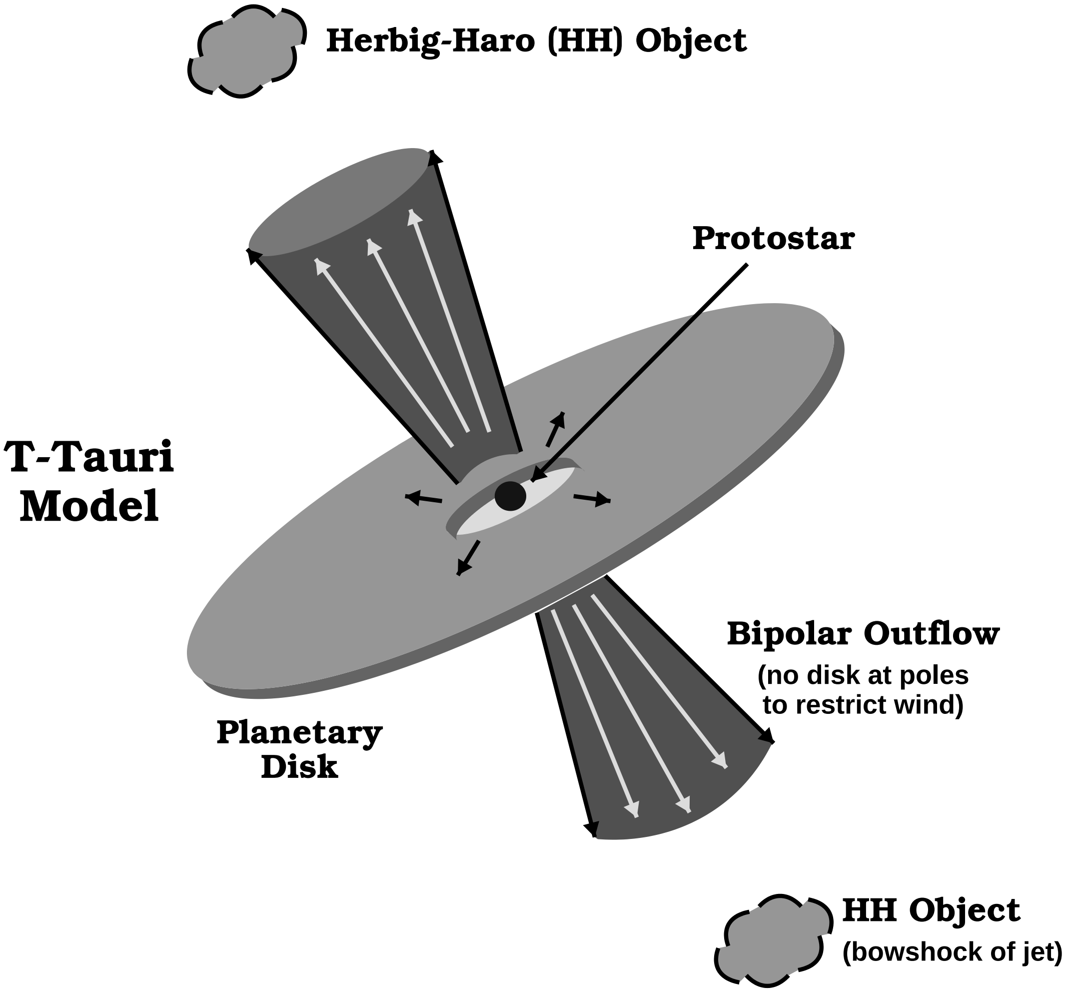


Figure I–7: Model of the T Tauri (spring cleaning) phase.

and Mars' — the unused planetesimals are still in existence today ⟹ the **asteroid belt**.

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

  i) 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 ⟹ these planets became **differentiated**.

    - **ii)** 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%).

  - **e)** 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.
    - **i)** 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.

    - **ii)** Uranus suffered a similar collision knocking it on its side.

4. 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:

$$v = \sqrt{\frac{3kT}{m}}, \qquad \text{(I-1)}$$

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:

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

   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.

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

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

7. 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.

8. 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.

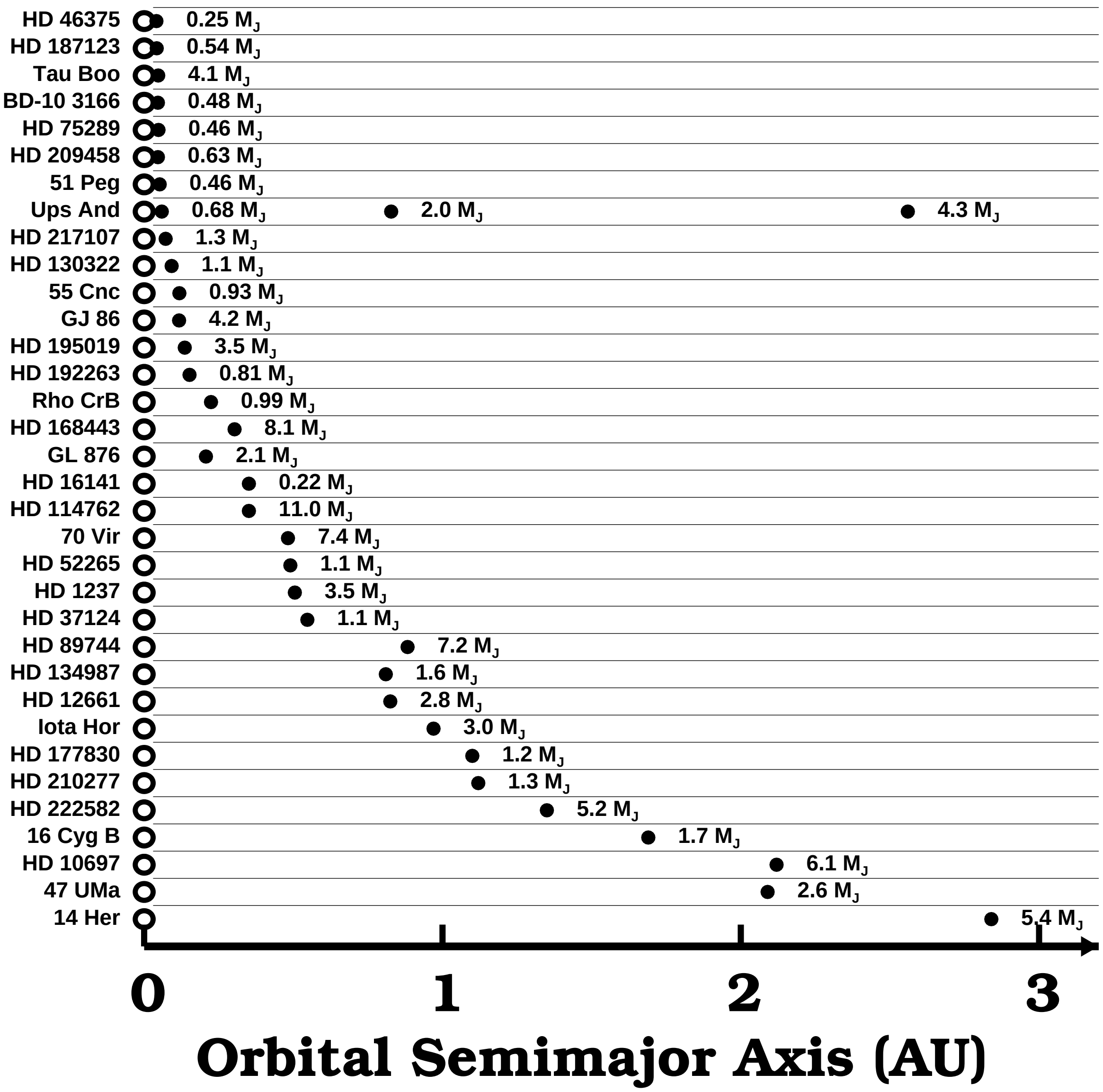
b) During the first half-billion years, the Earth's oceans eliminated most of the CO_2 from the atmosphere leaving an N_2 atmosphere with traces of CO_2 and H_2O vapor.

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%.

C. ExtraSolar Planetary Systems.

1. Over the past two decades, 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.

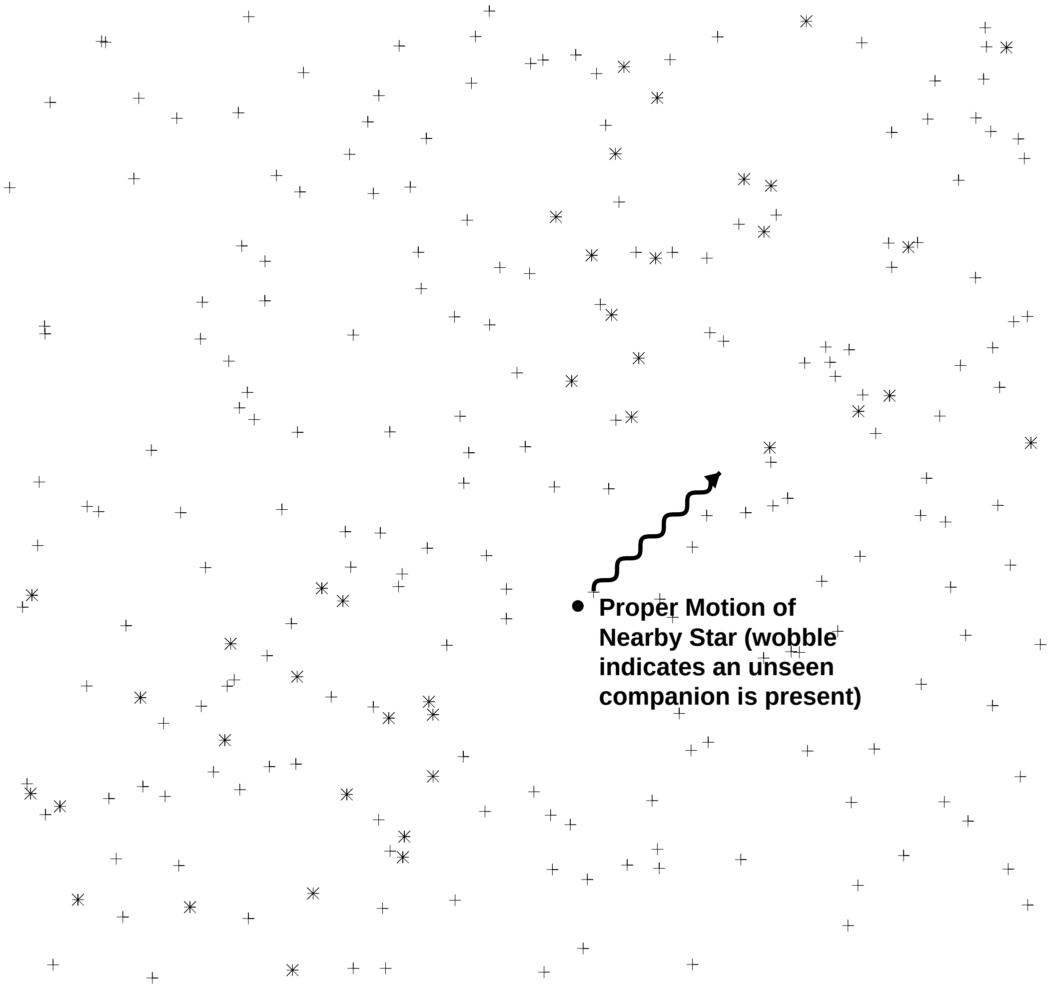
   a) **Direct imaging**: Getting pictures of the actual planets. This would be difficult to do due to the large distances of the star and the relative small size of planetary systems. A planet like Jupiter, 5 AU from the brightest star in the sky Sirius, would only be 2.0 arcsecs from the star and the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

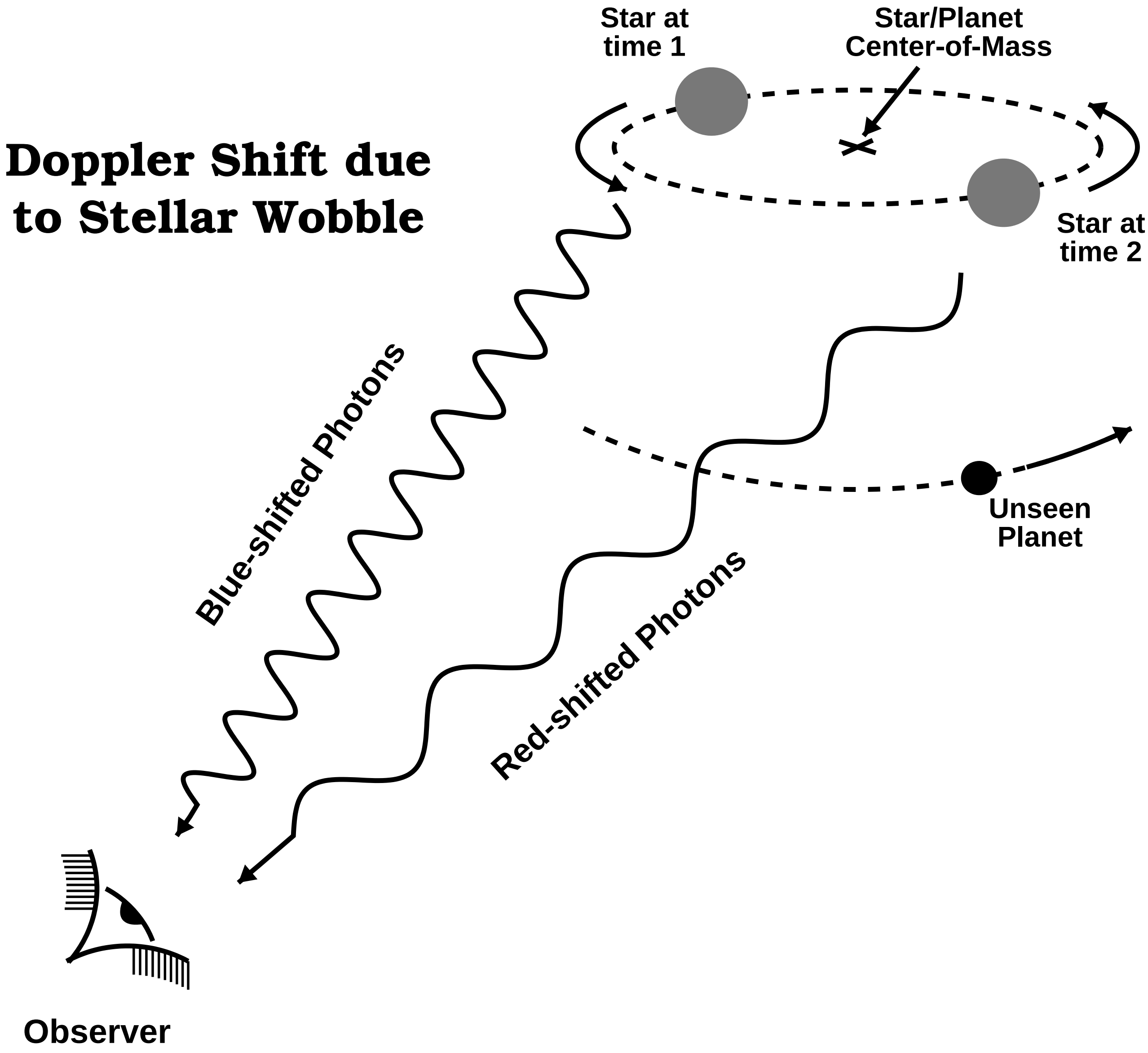
   i) Large planets in orbit about a star would cause the star to wobble along its proper motion path across the sky as the star and the large planet both orbit about the common center-of-mass.

   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 occultations 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.