ASTR-1020: Astronomy II
Course Lecture Notes
Section V

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Edition 4.0

Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1020: Astronomy II at East Tennessee State University.

V. Stellar Evolution: Birth

A. Cloud contraction.

1. GMCs are usually in **hydrostatic equilibrium** unless some event occurs to cause a cloud to exceed its Jeans' mass (M_J) and/or Jeans' length, which is a gravitational stability criterion first derived by British physicist Sir James Jeans in the 1930s. 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 coalesce until $M > M_J$.

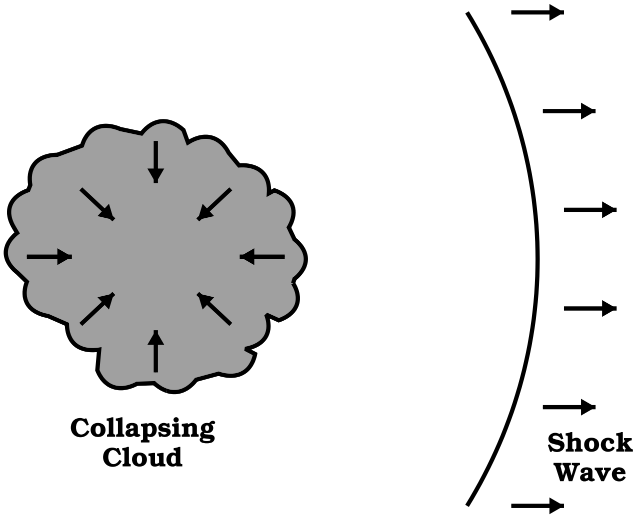
   b) **Shock Wave Compression**: A shock can be the trigger $\Longrightarrow$ it acts like a *snow plow* causing density to increase, and as a result, M_J drops.

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

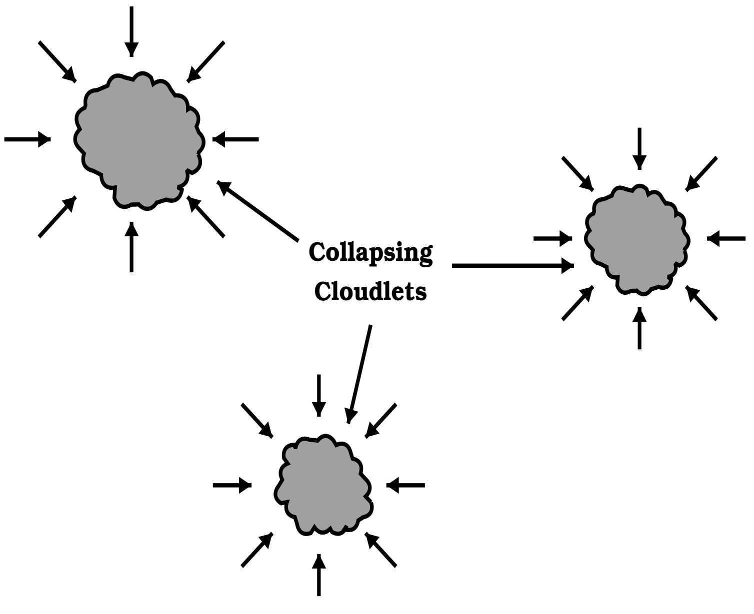
      ii) **Ionization Front**: O & B stars form very quickly once cloud collapse has started (see below). These produce H II regions from their strong ionizing UV flux, which initially expand outward away from the OB association. This ionization front heats the gas causing a shock to form. The shock can compress 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 as supernovae. The shock sent out by such a supernova can excite further star formation.

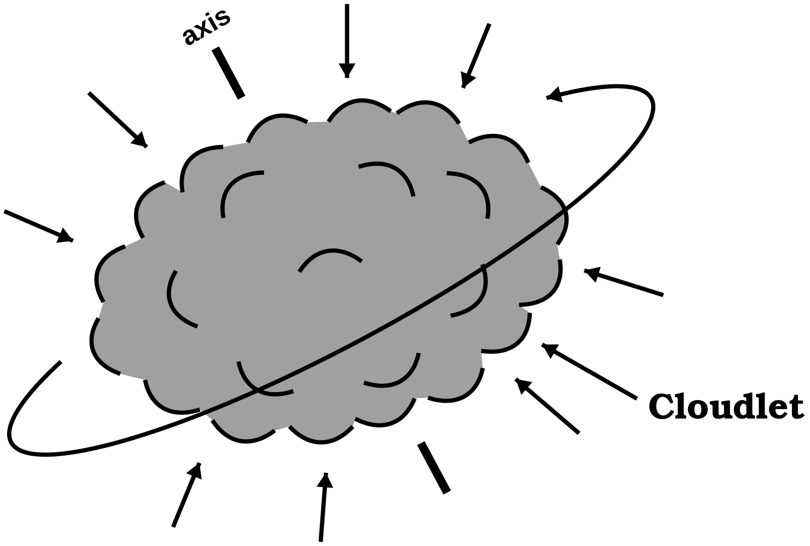
2. This compressed gas has a density enhancement over the surrounding ISM so that gravity becomes dominant over thermal pressures $\Longrightarrow$ the cloud collapses.



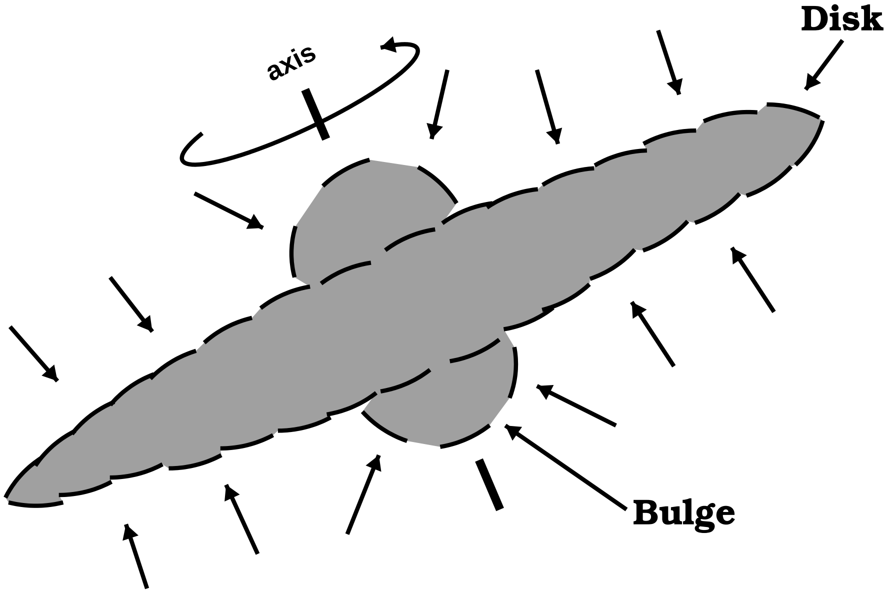
3. As a portion of a GMC begins to contract, cloud complexes with masses greater than $\sim 50\ M_\odot$ become unstable and fragment into smaller cloudlets (see next figure). Each little cloudlet continues to collapse as described above.



4. 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 below.



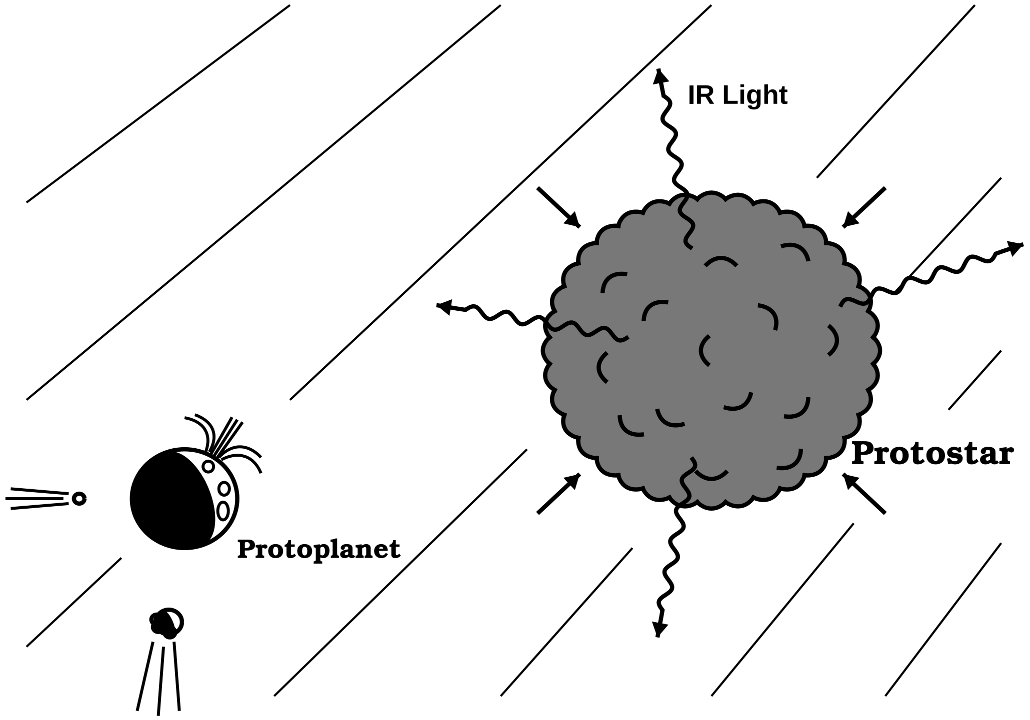
5. As the cloudlet contracts, it spins faster due to the conservation of angular momentum $L = M\,R^2\,\omega$, where ω is the angular velocity of the protostellar *cloudlet* $\Longrightarrow$ since M is constant, as R gets smaller, ω gets larger. This increased spin causes the equatorial region to bulge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



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**.

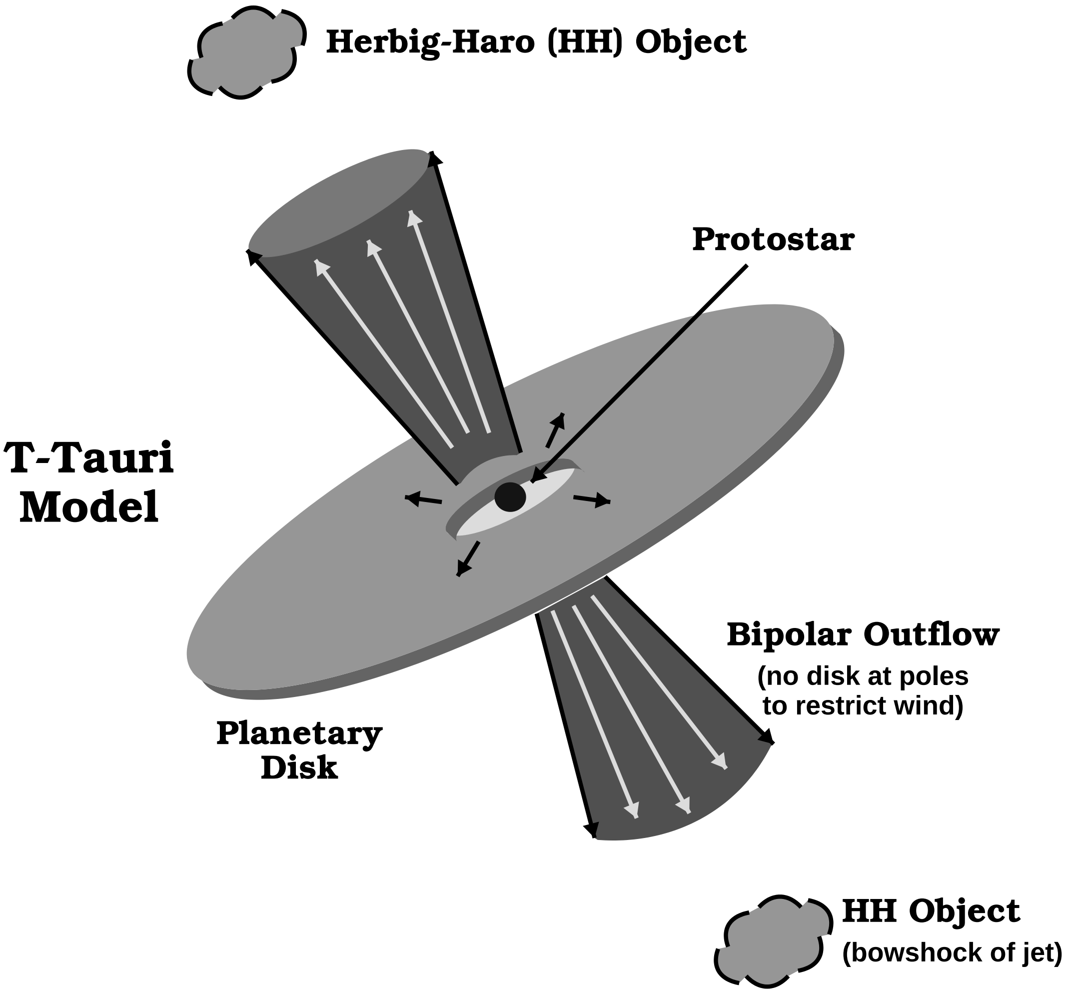
b) Numerous such disks have been seen in stellar nurseries with the *Hubble Space Telescope*. They are especially easy to see at IR wavelengths.

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.



6. 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**.

7. 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.



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

9. Stars form in groups or clusters. The oldest star clusters in the Galaxy are the **globular star clusters** and the youngest are **open star clusters**.

10. Massive stars form first in a cluster, evolve rapidly and supernova, causing further star formation in nearby regions.

  a) These massive stars have an enormous luminosity and emit most of their light at UV wavelengths.

  b) This UV light ionizes the surrounding ISM gas producing an **H II region**. These look red in photographs due to electrons cascading back down from the ionized state through the 3rd level of H down to the 2nd state and finally to the ground "1st" state. The H 3-2 transition is called the **H**α line which is a red line.

  c) H II regions always signify a stellar nursery $\Longrightarrow$ off in the direction of the constellation of Orion is the closest giant molecular cloud, H II region (*i.e.*, the Great Nebula), and stellar nursery to the solar system.

B. Extrasolar Planetary Systems.

1. The details on the formation of planets in the planetary disk of the T-Tauri stage is covered in Astronomy I. From what we understand of chemistry and physics, small *rocky* planets should form close to star, and large *gaseous* planets, with smaller *icy* planets and moons, should form far away from the central star (as is the case with the solar system we live in).

  a) In the case of our Solar System, Mercury, Venus, Earth, and Mars are the inner, small, rocky planets — the so-called **terrestrial** (Earth-like) **planets**.

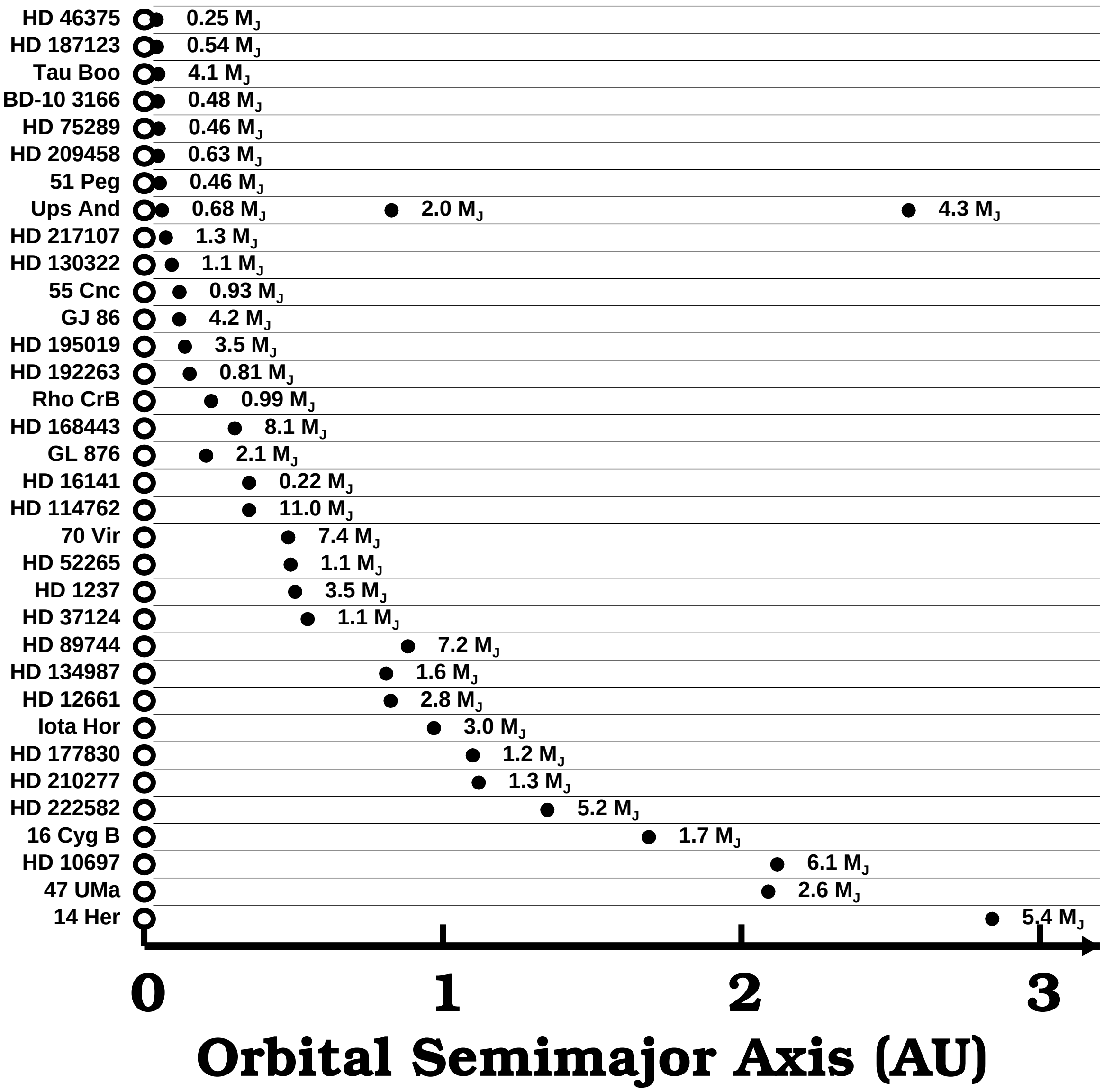
b) Jupiter, Saturn, Uranus, and Neptune are the outer, large, gaseous planets — the so-called **Jovian** (Jupiter-like) **planets**.

c) Pluto and the other Kuiper belt objects, and most of the moons of the outer planets are icy in composition.

d) Jupiter is the *king* of the planets, it is the largest and most massive by far.

2. Over the past few years, a variety of planets have been discovered around nearby stars. However, these planetary systems are quite unlike our solar system — large Jupiter-sized planets have been found close to the star of the system.

3. The plot on the next page represents extrasolar planets found by the Berkeley group through the summer of 2000. The name of the star (represented by an open circle), which the planet circles, is listed on the lefthand side, and the distance (*i.e.*, the semimajor axis of its orbit) that the planet is from the central star is indicated in astronomical units (AU) on the plot. The measured mass of the planet (in Jupiter masses, M_J) is indicated to the right of the planet (represented by a large dot).



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

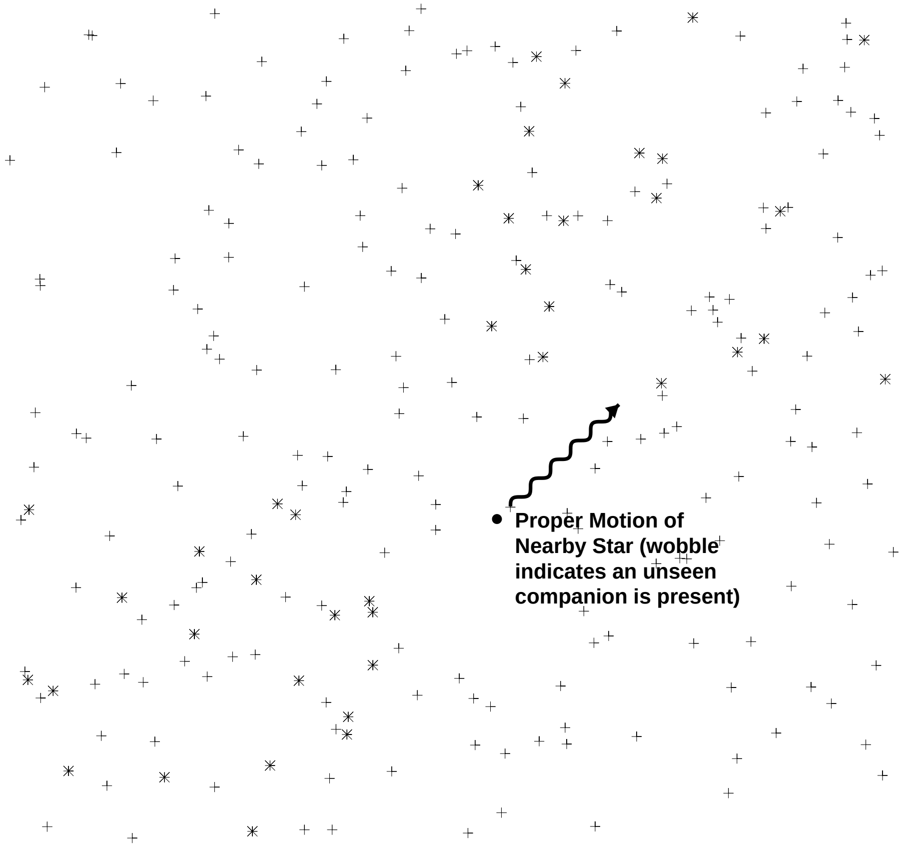
   a) **Direct imaging**: Getting pictures of the actual planets. This is virtually impossible to accomplish due to the large distances of the stars and the relative small size of planetary systems with respect to these distances. A planet like Jupiter, 5 AU from the brightest star in the sky, Sirius, only would 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 $\Longrightarrow$ stars have both a radial (*line-of-sight*) velocity component and a velocity component in the plane of the sky perpendicular to the radial velocity called the star's **proper motion** (see §III.A).

  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 *wavy* line) corresponds to one orbit of the unseen companion about the visible star. If the picture below corresponds to a change of position of the visible 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.

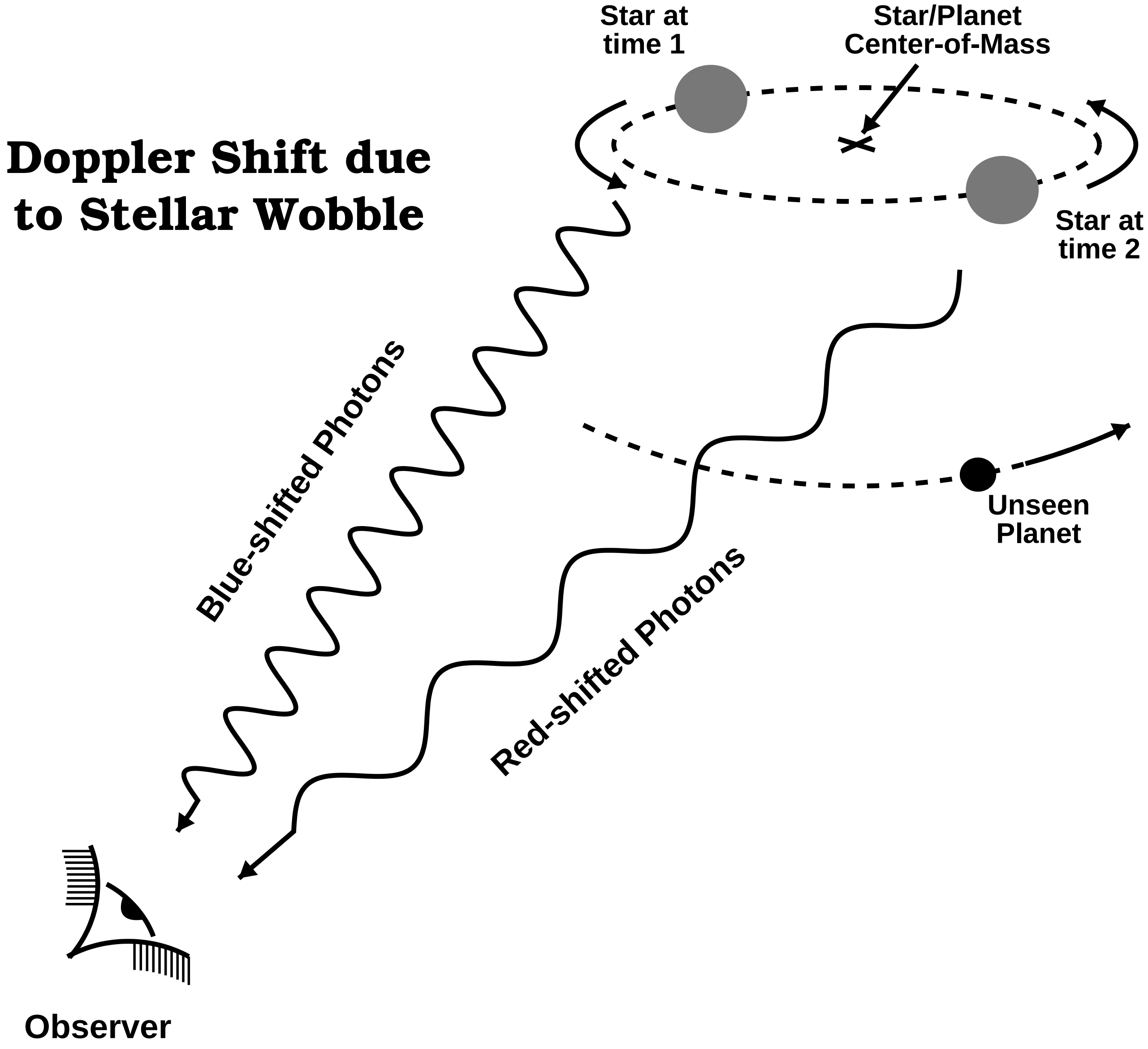


c) **Doppler shifts in spectral lines as the star orbits the center-of-mass**: The figure below shows the physics of the situation. As the star and planet orbit a common center-of-mass, the spectral lines of the star will shift back and forth due to the changing orbital velocity.

- **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 detected extrasolar planets.

iii) This technique however will only find those planetary systems with large Jupiter-like planets close in to the star. It would be impossible to find a system like our solar system with small inner planets and large outer planets using this technique.



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.

5. 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.