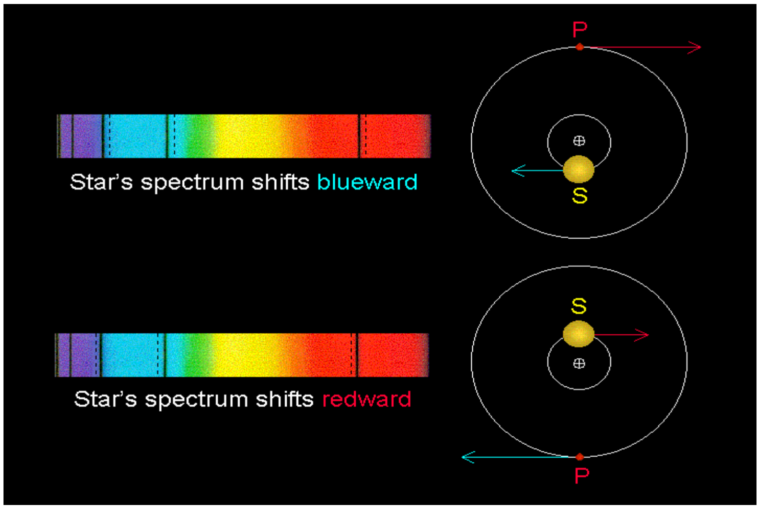
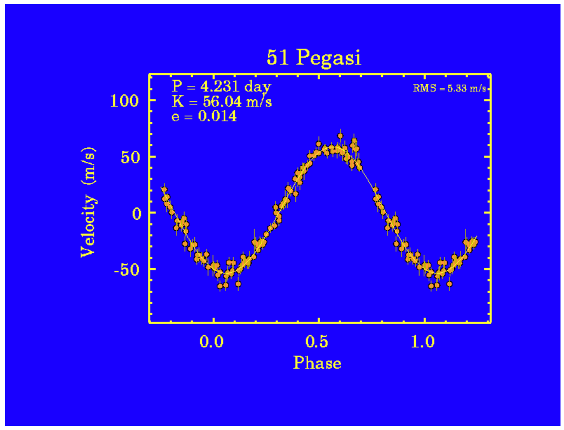
XII. Astronomy: Exoplanets and the Celestial Sphere

A. Astronomers who search for extrasolar planets, or explanets—planets in orbit around stars other than the Sun—have made tremendous progress in the past few years.
   1. In 1995, there were *zero* planets known around other normal stars.
   2. As of August 2013, the list has grown to over 930, and it, and it show no signs of slowing down.
   3. Although the discovered planets are massive gas/liquid giants similar to Jupiter, there is a great diversity in their orbital properties.
   4. Extrasolar planets generally can't be seen directly---the glare from the star that they orbit overwhelms their light.

B. The easiest way to find planets around normal stars is to use the Doppler effect: the shift in wavelengths of absorption lines due to radial motion of the star.
   1. This can be done with long-term monitoring of optical spectra of bright stars.
   2. One looks for a periodic Doppler wobble of the star (that is, a sinusoidal change in it's radial velocity) caused by motion of the planet around it.



      a. Knowing the period and amplitude (maximum change in radial velocity) of the wobble, the mass of the detected planet can be calculated by using Kepler's third law.
      b. Actually, one gets a minimum mass for the planet, because the inclination of the orbit is generally not know. The measured radial velocity of the star is only part of the total orbital velocity unless the orbital plane is perpendicular to the line of sight (that is, edge-on). Statistically, the correction is roughly a factor of 2.
      c. The spectra must have very high resolution and incredibly precise calibration of wavelengths.
      d. This technique works best for massive planets with small orbits, because the induced *reflex motion* of the star is then sufficiently large to measure.
      e. Even then, the expected shifts are tiny: Jupiter, for example, causes a reflex motion in the Sun of only about 10 m/s (For comparison, 2 m/s is rapid walking speed.)

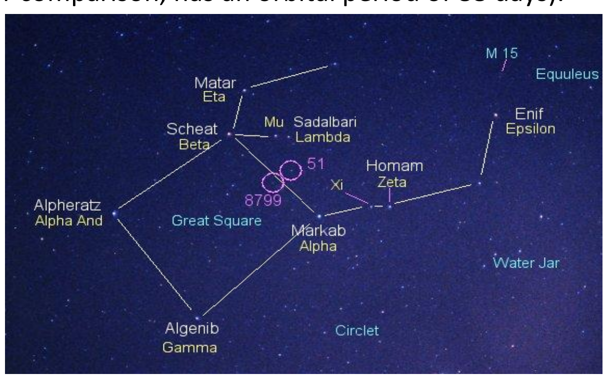


f. Present technology is sketchy to detect planets comparable to Earth in mass and orbital distance.

3. The reigning champion planet hunter is Geoff Marcy at the University of California, Berkeley. He and his team found a majority of the known extrasolar planets.
   a. Initially, they found planets with the 3 m reflecting telescope at Lick Observatory.
   b. Their work at Lick is continuing, but they are now finding planets more frequently with one of the Keck 10 m telescopes in Hawaii.

C. Most of the known extrasolar planets found thus far have startling properties.

1. Some, like that of 51 Pegasi (the first one found, by Swiss astronomers Didier Queloz and Michel Mayor), are very massive yet have tiny orbits with periods of only a few days. (The planet Mercury, for comparison, has an orbital period of 88 days).

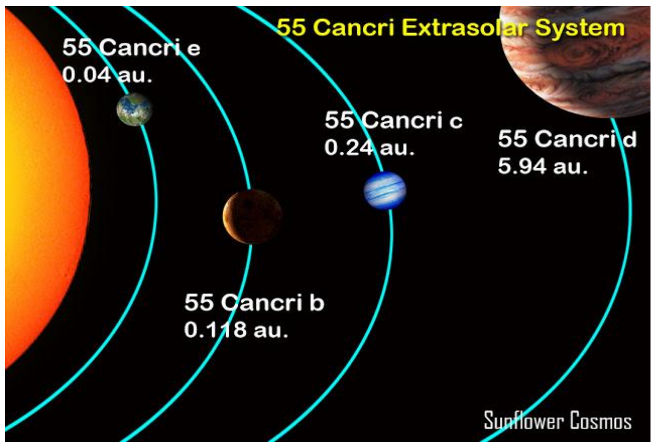


   a. It is not clear how they could have formed. If these planets are like Jupiter, the gases should never have been captured; if mostly rocky, there is a shortage of raw material. Almost certainly they formed farther out.
   b. They then spiraled inward because of friction with material remaining in the disk. The star may sometimes swallow planets migrating inward in this way.
   c. Gravitational interactions with other planets can also propel a planet into an orbit close to the star, and tidal effects subsequently make it circular.
   d. In some cases, the planets are so close to the star than they must be evaporating.

2. The orbits of other planets are reasonably large but highly eccentric, unlike those of all planets in our Solar System.

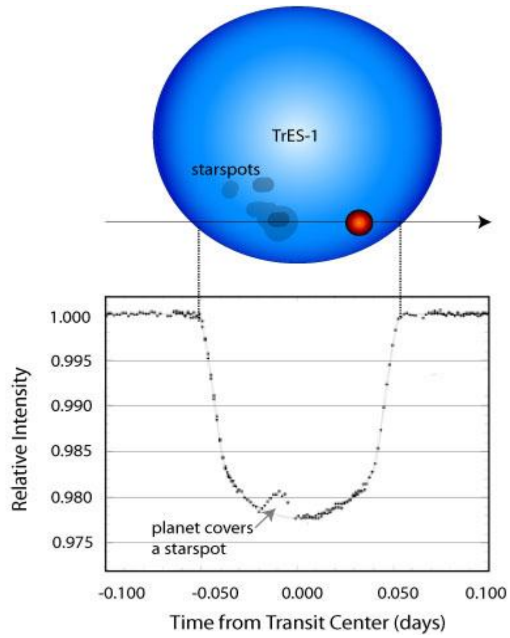
a. Probably their eccentricity is an indication of previous interactions with other bodies. The planets with which they interacted may have been ejected from the system.
b. Over long periods of time, planetary orbits that appear to be stable actually become chaotic, and eccentricities can arise.
c. Interactions with the protoplanetary disk during the formation process can also produce eccentric orbits.

3. Several systems containing more than one planet are now known.
   a. For example, the star Upsilon Andromedae has at least three planets.
   b. The star Gliese 876 has two known planets.
   c. The star 55 Cancri has at least four planets, two of which have about the orbital distances of Jupiter and Mercury. This system somewhat resembles our Solar System.



4. About 5% of Sun-like stars have a giant planet within 3 AU.
   a. It is estimated that more than 20% of Sun-like stars have giant planets at larger distances.
   b. An important recent discovery is that giant planets are much more common around stars that have a high abundance of heavy elements, rather than a low abundance. Apparently, a rocky, Earth-like core forms first, then attracts copious amounts of gas from it's surroundings.

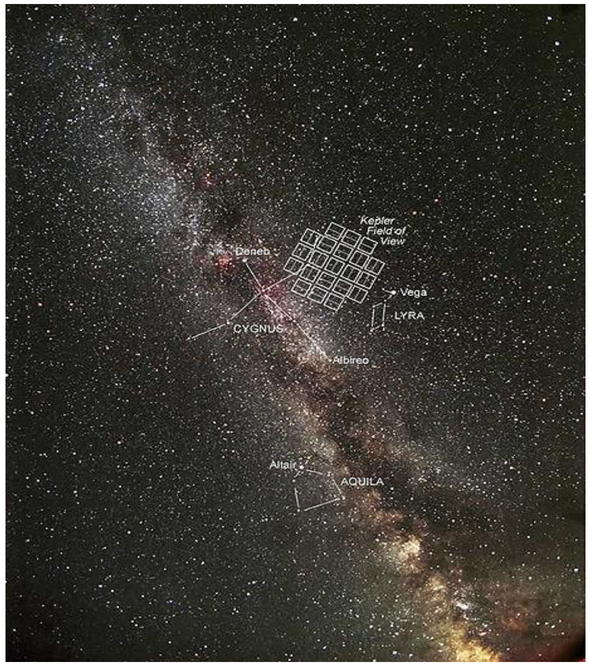
D. In several cases, an extrasolar planet has been detected as it passed between us and the star it orbits, slightly dimming the star's light.
   1. For a transit to happen, the planet's orbital plane must be aligned along our line of sight.
      a. Venus transits across the Sun occasionally. This last happened in 2004 and 2012.
      b. Mercury transited across the Sun in 1999 and in 2003.
   2. The most convincing extrasolar case is that of HD 209458. The measured light form the star diminished exactly when it was supposed to, according to the already known radial-velocity curve induced by the planet. (That is, we could predict when the light should fade).
      a. Incredibly good data were obtained with the Hubble Space Telescope: The light curve (plot of brightness vs. time) is so good that large moons and rings would have also been detected had they existed around the planet.



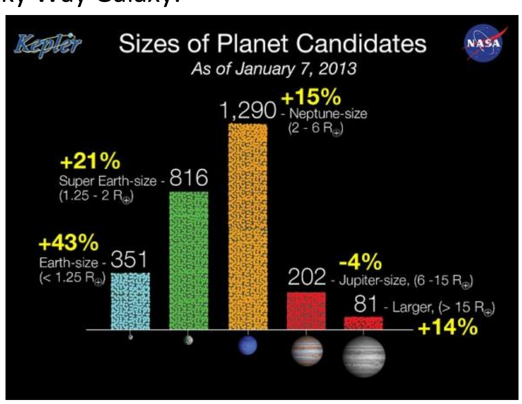
b. Some of the light form the star passed through the atmosphere of the planet, thereby opening the possibility that atoms and molecules might produce an absorption line in the star's spectrum.
   i) A weak line of neutron sodium was indeed detected.
   ii) This marks the first detection of the atmospheric gases of an extrasolar planet.
c. Such techniques might someday reveal evidence for life on extrasolar planets.
   i) The presence of absorption lines of oxygen and methane, for example, would imply life, because these molecules are highly reactive together and their supply must be continuously restored.
   ii) Biological processes are the only known continuous source of these specific gases.

3. Astronomers used the Hubble Space Telescope to search for transiting planets in the globular star cluster 47 Tucanae, with negative results or very few exoplanet were found.
   a. This is perhaps not surprising.
      i) Planets don't easily form if there are many interactions with other stars.
      ii) Planets don't easily form around stars with only a small amount of heavy elements (as in globular clusters.)
      iii) Gravitational interactions amount closely spaced stars tend to eject planets that may have formed.
4. Kepler, a spacecraft launched in 2006, searched for transiting planets by monitoring more than 100,000 stars simultaneously for four years. A major goal was to find terrestrial (Earth-like) planets, to see whether our Solar System is typical or a fluke.

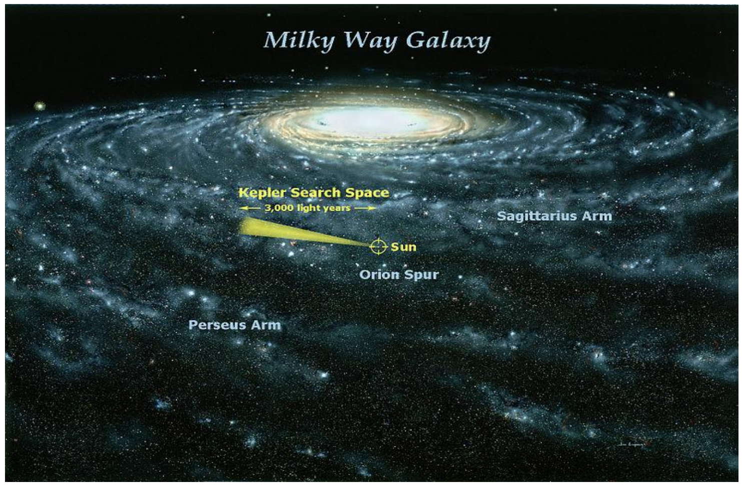
a. This was difficult to achieve, because the cross-sectional area of a terrestrial planet is small compared with the star that it orbits; thus, the amount of dimming is small.
b. Moreover, starspots (similar to sunspots) and other stellar activity could effectively obscure the dimming produced by a transiting planet. The astronomers wanted to see at least three transits before concluding that a given planet was present.
c. As of July 2013, Kepler found 134 confirmed exoplanets in 76 stellar systems, along with a further 3,277 unconfirmed planet candidates.



d. In January 2013, astronomers at the Harvard-Smithsonian Center for Astrophysics (CfA) used *Kepler's* data to estimate that "at least 17 billion" Earth-sized exoplanets reside in the Milky Way Galaxy.



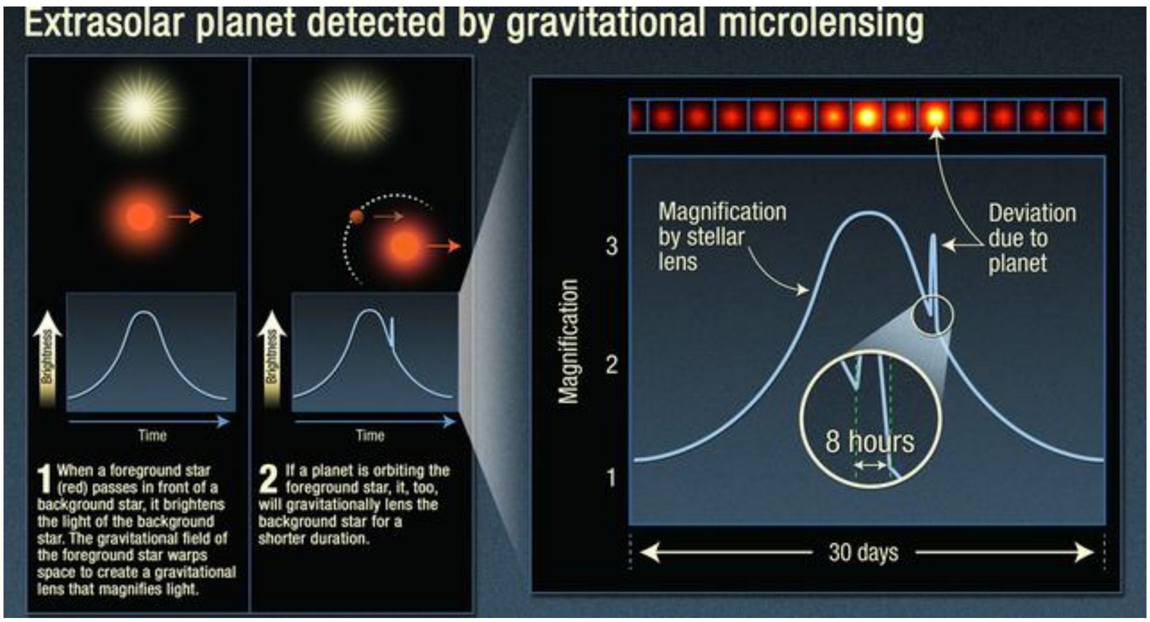
e. In April 2013, NASA announced the discovery of three new Earth-like exoplanets – Kepler-62e, Kepler-62f, and Kepler-69c – in the habitable zones of their respective host stars, Kepler-62 and Kepler-69. The new exoplanets, which are considered prime candidates for possessing liquid water and thus potentially life, were identified using the *Kepler* spacecraft. A more recent analysis has shown that Kepler 69c is likely more analogous to Venus, which is known to be one of the most inhospitable places in the Solar System, and thus unlikely to be habitable.



f. Kepler and similar missions are worthwhile and should eventually reveal a large number of planets ---hopefully, even some terrestrial ones.

E. The existence of *free-floating planets* is probable. (However, because they don't orbit a star, they are not really "planets" in the conventional sense of the word).
   1. Some planets are ejected from planetary system during gravitational interactions among the planets; they subsequently roam freely among the stars.
   2. Some free-floating planets may have formed from the gravitational contraction of gas in much the same way that stars form but with too little mass to undergo nuclear fusion.
   3. Recently, several teams of astronomers have claimed to detect free-floating plants, mostly form infrared surveys of star–forming nebulae.
      a. Many of these are probably brown dwarfs, not really planets.
      b. A few in the Orion nebula and elsewhere seem to have a mass less than 13 Jupiter masses, similar to normal planets.
      c. Additionally, researchers have discovered a free-floating planet, named CFBDSIR2149. The planet seems to be emerging from a nearby stream of young stars called the AB Doradus Moving Group.
         i) This is also the closest such free-floating planet candidate yet discovered, at only about 100 light-years away. Because it is somewhat close and there are no bright stars located near it, researchers have actually been able to study its atmosphere in very great detail.

4. Another technique for finding free-floating planets is to search for gravitational lensing of the light of a star by the planet that passes between the star and us.
    a. According to the general theory of relativity, the gravitational field of the planet warps the light from the background star, focusing it toward us and making the star briefly appear brighter.
    b. By monitoring a very large number of stars over a substantial amount of time, a few such events might be detected and studied in a statistical manner.
    c. The disadvantage is that a given planet should pass between a star and us only very rarely, making it difficult to gain confidence that a planet has been found.

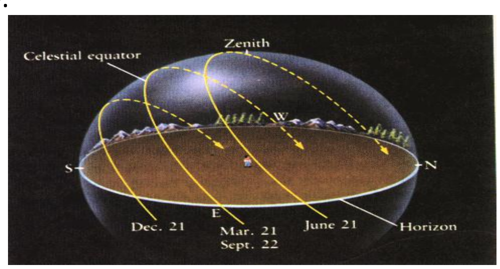


F. Although the light from a star generally drowns out the feeble reflected light from an orbiting planet, sophisticated new techniques might image planets during the next two decades.
    1. One goal of future optical *inteferometers,* for example, is to directly detect planets.
        a. The trick is to cleverly combine the light from two or more telescopes "out of phase" (that is, destructively), in such a way that the light from the star is largely cancelled.
        b. With the glare form the star severely diminished, dim planets should become visible.
    2. NASA's Space Interferometry Mission was being planned for launch around 2012, with the anticipation that it would directly detect planets. However, it was cancelled due to budget cuts.
    3. NASA's Terrestrial Planet Finder was also on the drawing board, specifically for the detection and study of Earth-like planets. They would like to have images of these planets that show some detail, such as continents or clouds. However, funding was also cancelled for this endeavor.
G. The discovery of more than 900 extrasolar planets has rekindled the question of whether we are alone in the cosmos.
    1. At times, it has been dangerous to voice the opinion that there are other planetary systems with life in them. Giordano Bruno was burned at the stake in Rome in 1600 for believing, "Innumerable suns exist; innumerable earths revolve around these suns in a

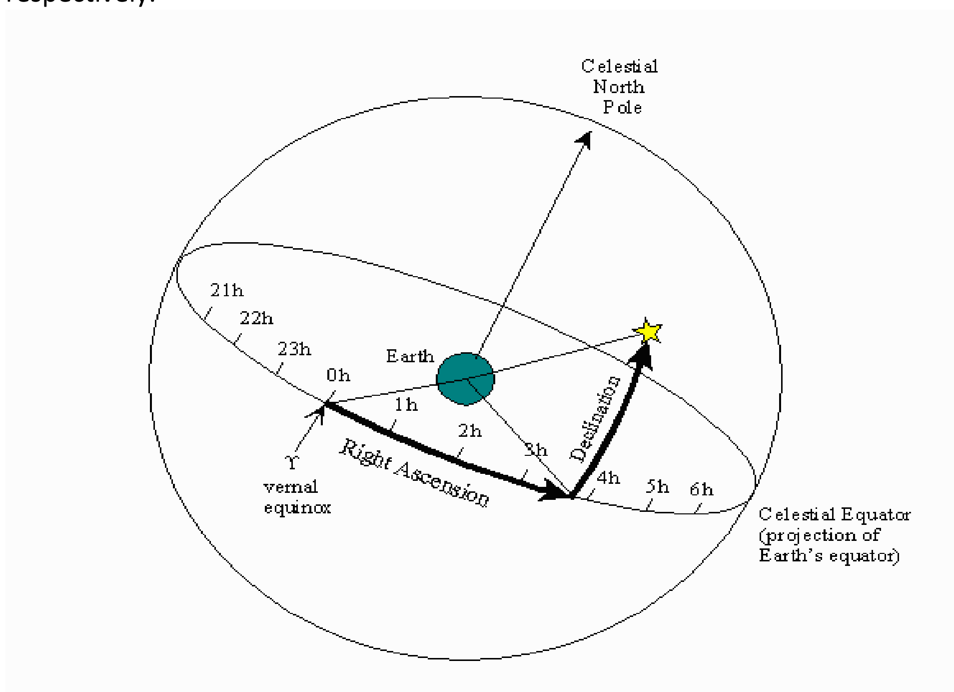
manner similar to the way the seven planets revolve around our Sun. Living beings inhabit these worlds."

2. Fortunately, we can now freely pursue this question, and we even have some clues regarding where specifically to search for signals from intelligent life.

H. Let us now consider the celestial sphere.
   1. Ancient astronomers in Egypt and elsewhere grouped the visible stars into constellations.
      a. These were given names, occasionally because they resembled something (e.g. Scorpius, the Scorpion), but mostly to honor the object.
      b. Easily recognized patterns of stars that do not constitute a constellation are called asterisms. The most familiar example is the Big Dipper, which is part of the constellation Ursa Major (the Great Bear).
      c. Most of the names and legends we now associate with constellations are from Greek mythology, but some of the ones visible only from the Earth's southern hemisphere have more modern origins (e.g., Telecopium")
      d. Astronomers now officially recognize 88 constellations, and each point in the sky is assigned to only one of them.
      e. The stars in most constellations and asterisms are at different distances from Earth, and are not physically associated with each other, but simply appear along nearly the same line of sight.
         i) The big Dipper is somewhat of an exception to this: five of its seven stars probably formed together, and are moving through space in roughly the same direction.
         ii) Nevertheless, even these stars now have different distances from us, and in any case the other two stars are not at all associated, and are more distant.
      f. The apparent shapes of constellations and asterisms change slowly with time, as the stars move relative to each other.
         i) The handle of the Big Dipper, for example, was slightly straighter 50,000 year ago, and will be significantly more bent 50,000 ear form now.
         ii) Note that these changes are produced by motion across the sky (i.e., perpendicular to the line of sight). The radial motions of stars (i.e. along our line of sight, and measurable with the Doppler effect) do not contribute.
   2. Stars appear to be fixed to a very large celestial sphere that rotates around us.
      a. This is a consequence of the enormous distances of stars.
         i) We have no depth perception, because the stars are so far away.
         ii) Regardless of one's place on Earth, a given star appears along the same absolute direction in space, since it's light rays are essentially parallel.
      b. When standing at a given location, the zenith is defined to be the point straight overhead, and the horizon is 90^0 away in all directions, along lines tangent to the smooth surface (ignore irregularities like mountains and valleys).
      c. The north and south celestial poles are the extensions of the Earth's axis of rotation to the celestial sphere.

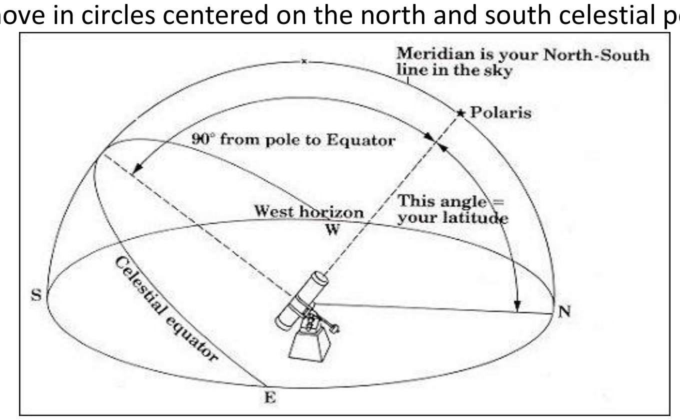


d. The celestial equator is the projection of Earth's equator onto the celestial sphere. It is a "great circle" – that is , a circle formed by the intersection of a sphere and a plane that passes through the center of the sphere.
e. The meridian is the great circle through the celestial poles and the zenith. When a star reaches it's highest position in the sky, it is crossing the meridian.
f. Each object in the celestial sphere can be assigned coordinates analogous to longitude and latitude on earth. These are called "right ascension" and "declination," respectively.



g. Form any point on Earth that has a clear horizon, one can see only half of the celestial sphere at any given time. This can be visualized by extending a plane tangent to the surface so that it intersects the very distant celestial sphere.

3. The rotation of the celestial sphere is a consequence of the Earth's rotation about it's own axis: as Earth rotates in one direction, the stars move across the sky in the opposite direction.
   a. Stars move in circles centered on the north and south celestial poles.

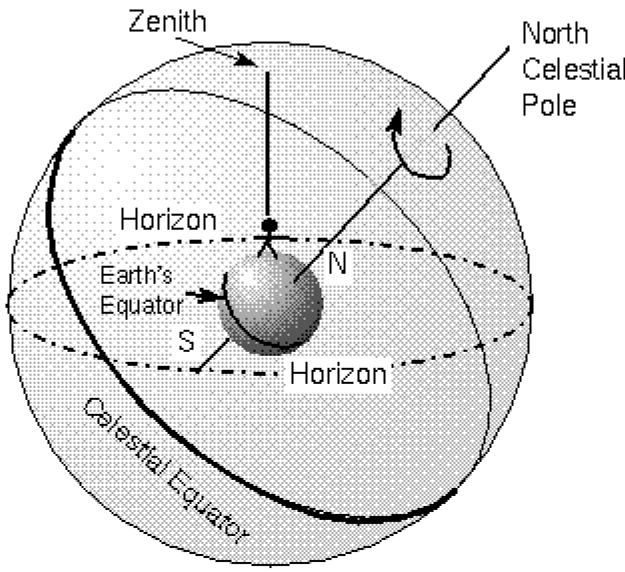


   b. If one is standing at the Earth's north or south poles, stars move in circles parallel to the horizon; the altitude of a star never changes.
      i) All the visible stars are "circumpolar" –they are always above the horizon.

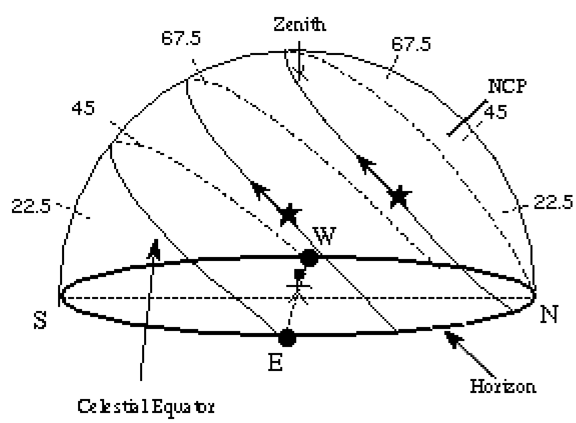
ii) Only half of the entire celestial sphere (either the northern or southern hemisphere) is observable over the course of a 24-hour day (or even a year).

c. If one is standing at the Earth's equator, stars rise straight up, cross the sky, and set straight down; the altitude of a given star changes with time.

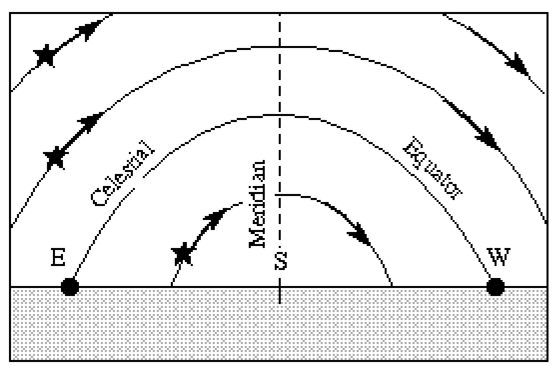
i) Stars sufficiently close to the celestial pole are circumpolar.



The celestial sphere for an observer in Seattle.
The angle between the zenith and the NCP = the angle between the celestial equator and the horizon.
That angle = 90° – observer's latitude.



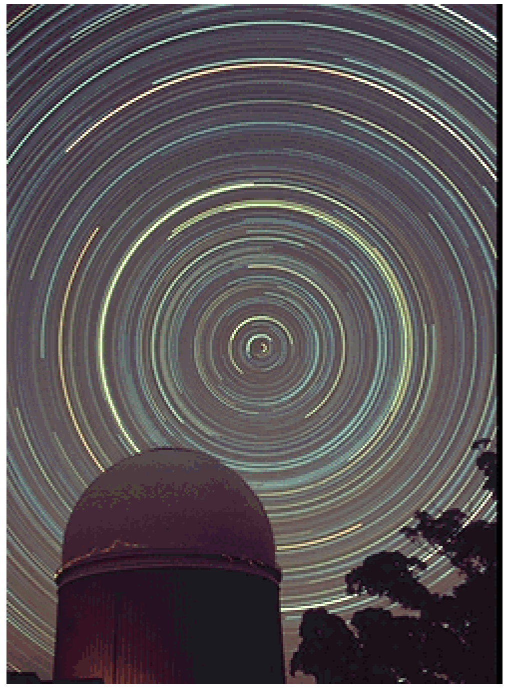
Stars motion at Seattle. Stars rotate parallel to the Celestial Equator, so they move at an angle with respect to the horizon here. Altitudes of 1/4, 1/2, and 3/4 the way up to the zenith are marked.



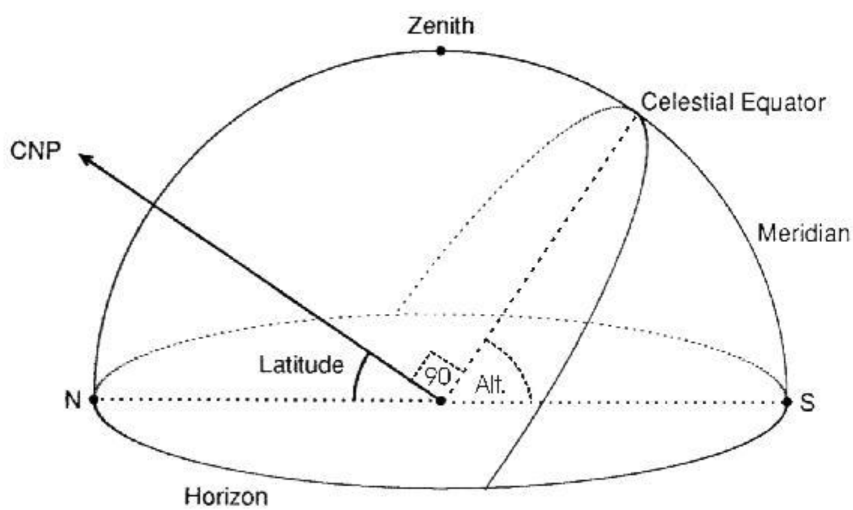
Your view from Seattle. Stars rise in the East half of the sky, reach maximum altitude when crossing the meridian (due South) and set in the West half of the sky. The Celestial Equator goes through due East and due West.

ii) More than half of the celestial sphere is observable over a 24-hour day.

d. Stunning photographs of the motions of stars can be easily made by putting a single-lens reflex camera on a tripod, aiming at one part of the sky, and opening the shutter for an extended period of time (say, a few minutes to a few hours). Be sure to turn of the flash!

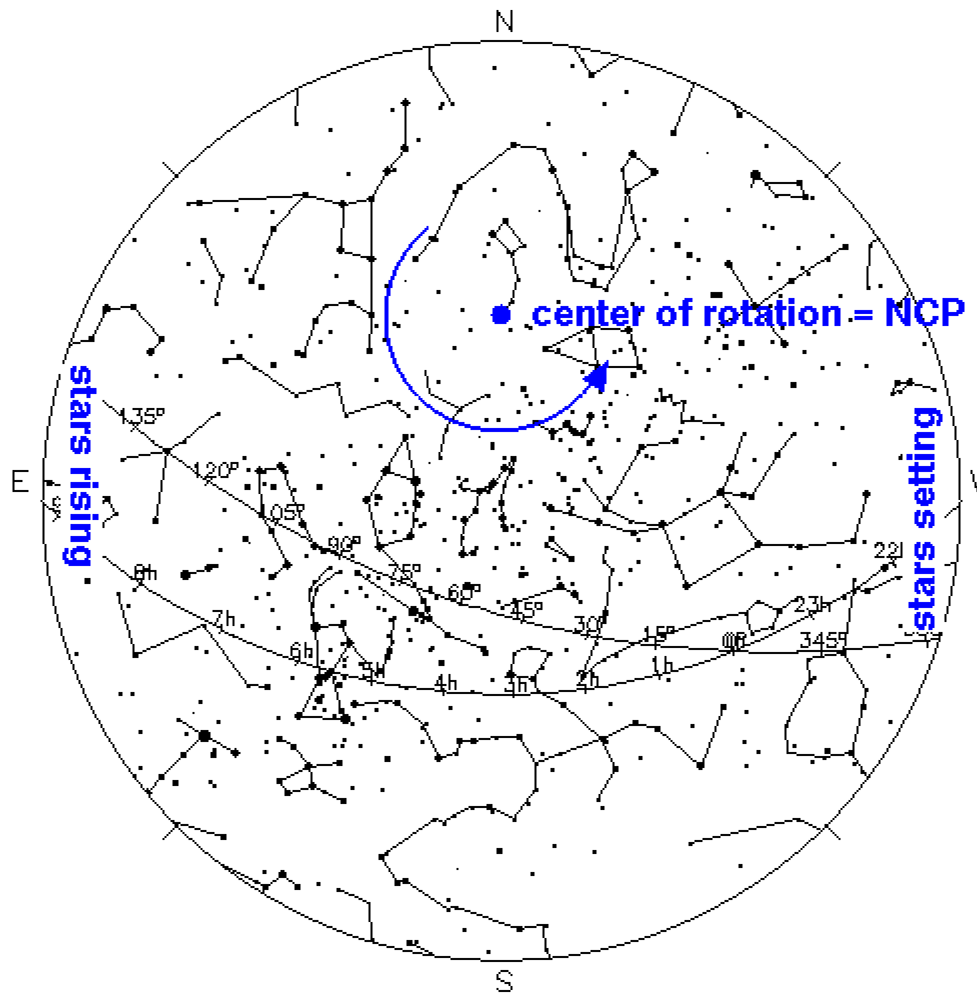


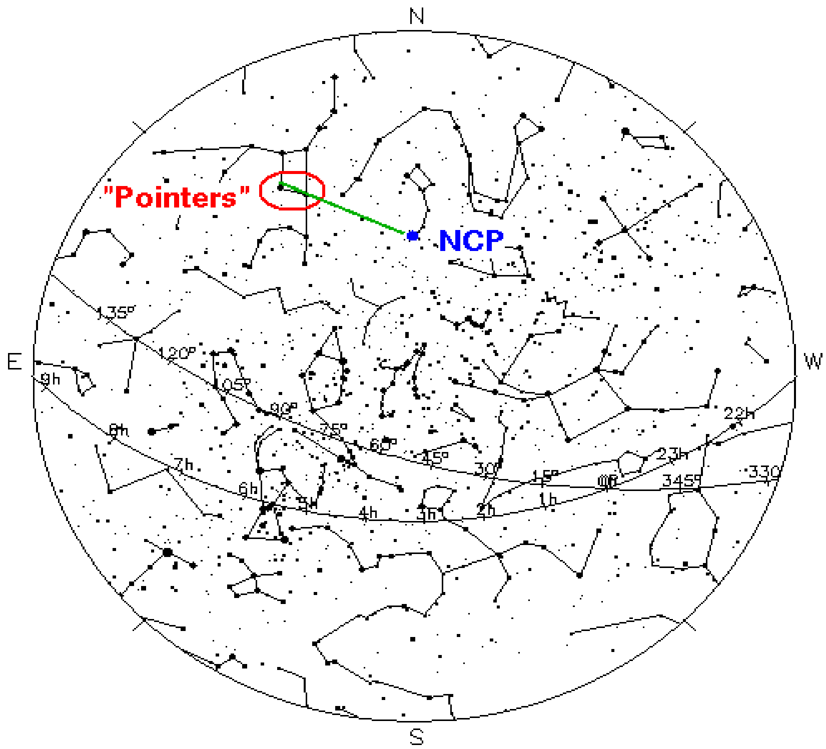
4. Polaris, the "North Star", is nearly at the location of the north celestial pole.



   a. However, this will not always be the case. Owing to the gravitational influence of the Moon and Sun, the Earth's axis of rotation slowly changes orientation, tracing a full circle in the sky (of radius 23.5^0) over the course of 26,000 years.
   b. Currently there is no bright star near the south celestial pole.
5. Our view of the night sky changes over the course of a year.
   a. In December, the constellation Orion crosses the meridian at midnight.

b. 3 months later, in March, when the Earth has moved through ¼ of it's orbit around the Sun, the constellation Virgo crosses the meridian at midnight, when Orion is setting. Orion crosses the meridian at sunset (i.e. 6 hours earlier than in December).
c. Thus, each successive night, Orion crosses the meridian about 4 minutes earlier: 3 months is about 90 days, and (4 minutes/day)(90 days) = 360 minutes = 6 hours.
d. 3 months later, in June, Orion crosses the meridian another 6 hours earlier –i.e., at noon. Hence, it isn't visible at night. Instead, the constellation Ophiuchus crosses the meridian at midnight.
e. Thus, a given star rises (and crosses the meridian) 4 minutes earlier each day, and our overall view of the celestial sphere gradually changes during the year.
f. Microscopically, what happens is that the Earth travels roughly 1^0 along it's orbit each day. The changing perspective causes the "solar day" (the time interval been two consecutive meridian crossings of a given star). The actual difference is 3 minutes and 56 seconds.
g. As seen from Earth, the yearly path that the Sun follows among the stars (due to Earth's orbital motion) is called the ecliptic. It is the great circle formed by the intersection of Earth's orbital plane and the celestial sphere.

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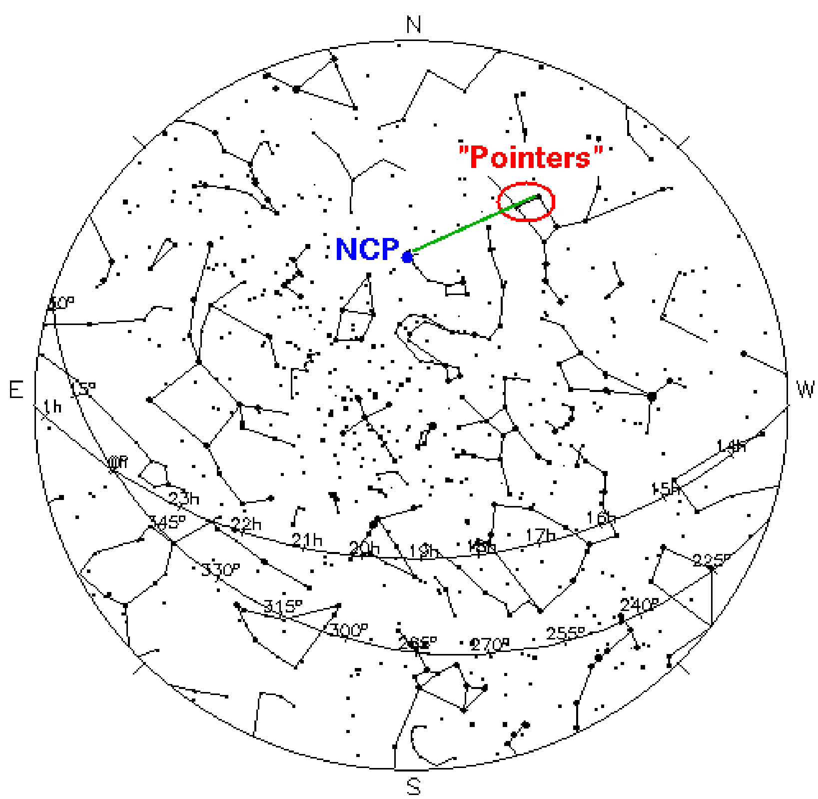
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I. Questions:

1. What are the pros and cons of the different techniques use (or potentially used) to detect and study extrasolar planets?

2. Why can we generally measure only the minimum mass of an extrasolar planet using the Doppler wobble techniques?

3. What is a free floating planet and what are it's characteristics?

4. Too date, how many exoplanets have been confirmed.
5. Explain the Kepler project? What was the objective? What technique of explanet confirmation did it use? Explain.

6. Explain gravitational lensing and how it could apply in finding exoplanets?

7. Define various terms associated with the celestial sphere, such as the celestial poles, celestial equator, horizon, zenith, and meridian.

8. Summarize what an observer viewing the celestial sphere would see from different locations on Earth and at different times of the night.

9. Explain why the constellations visible in the evening sky gradually change over the course of a year.

10. At the Earth's poles, why does the sun (or part of the Sun) actually appear above the horizon for somewhat more than 6 continuous months, rather than exactly 6 contiuous months?