Distance:

A History of Parallax and Brief Introduction to Standard Candles

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“The chief characteristic of the universe is, I would say, emptiness. There is infinitely more nothing in the universe than anything else.” - John Updike in The Poorhouse Fair.

“Popular astronomy books are peppered with words like immense, far-flung, vast, gargantuan, enormous—and with prefixes like super-, mega-, and hyper-. Bigness is part of the mindset of the astronomer.” - Alan W. Hirshfeld in Parallax: The Race to Measure the Cosmos.

Abstract

This paper concentrates on the discussion of how astronomers were able to derive the distance to various celestial objects, with special emphasis on how parallax was used to get the distance to the stars as well as the distance of our own astronomical unit. The geometry (geocentric, heliocentric) of the solar system is also discussed.

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1. Introduction

The big question: “How far away is that ______ ?” Whether it’s the Moon, the Sun, a comet, a planet, etc. doesn’t matter. To answer the question, takes quite a bit of clever work over the years. It took over two-thousand years of waiting to get the first acceptable answer concerning the stellar parallax of the stars which in turn can give us distance.

2. Early measurement and shape of the Earth

Thales believed that the Earth was disk-shaped and floated in a cosmic ocean; however, Anaximander took the leap and imagined the disk-shaped [Hirshfled 4] (or cylinder-shaped [Hoskin 29]) Earth floated not in an ocean, but space [Hirshfeld 4]. Pythagoras imaged a globe-shaped Earth.

Aristotle also believed the Earth was circular in shape because he noticed that the shadow cast by the Earth on the moon during a lunar eclipse was always curved. He also believed the Earth to be rather small in size because he noticed stars are visible in Egypt that are never visible from the northern regions, as well as noting that some stars rise and set in Egypt that are always visible in the north. Aristotle reports that mathematicians had estimated the circumference of the Earth to be 400,000 stades (about 63,000 km), but history has no record of how this number was computed [Ferguson 9].

Eratosthenes was the first to get a measurement for the circumference of the Earth that was near the actual value. His experiment works as follows: A stick in Syene with one end on the ground and the other pointed to the sky will not cast a shadow at noon on the day of the summer solstice, but an identical stick in Alexandria, which he believed to be at the some longitude, would cast a shadow. He could do this experiment alone by measuring the angle of the stick's shadow in Alexandria when the shadow was at its shortest length. The shadow angle was 7 1/5 degrees which tells if lines were drawn from these two cities to the center of the Earth, by geometry, the lines would intersect with an angle also of 7 1/5 degrees.

By taking the distance between the two cities and multiplying them by this fraction of a whole circle (360/7 1/5), he computed (assuming 5000 stades distance) a circumference of 250,000 stades and later refined the number to 252,000 stades. Most historians agree that a stade works out to roughly 157.5 meters, which means his calculation resulted in a circumference of 39,690 km, which is very close to the modern values of 40,009 km for polar circumference and 40,079 km for equatorial circumference. Knowing the circumference, Eratosthenes then computed the diameter to be 12,631 km which is in good agreement with today's average value of 12,740 km (Furguson 18-21). One slight problem with his assumptions is that Syene and Alexandria do not lie along the same line of longitude. History has it that Eratosthenes sent someone to count the number of paces between the cities to arrive at the 5,000 stade distance.

3. Introduction to parallax

The word parallax comes from the Greek word "parallassein" meaning "to change". Parallax is the observed shift in position of an object when viewed from different positions. Human eyes are separated by about six centimeters, which is enough to make each eye see objects slightly differently. The human brain has is roughly able to compute the parallax of an object from the degree of eye-crossing [Hirshfeld 8]. We are not born with ability of depth perception—it is something the brain adapts to over time. Often one notices an infant in waving their hands about wildly believing they can reach the objects on an out-of-reach mobile suspended above their crib. These "lessons" will help the infant acquire depth perception over time. In a similar account, lifelong rainforest dwellers live in areas of such dense vegetation that their sight is only unobstructed, at most, for a few meters at a time. If taken to see an unobstructed vista, they will try to reach out and grab the mountains [Hirshfeld 51].

Humans can only accurately perceive distance if the object is within "tens of feet" of the observer [Hirshfeld 53]. This parallax is then interpreted as a distance. Objects close up have a large parallax, while those far away have a smaller parallax. The larger the baseline (distance between the two views), the smaller the measurable parallax [Hirshfeld 8]. Without using telescopes, the best measurements that can be expected from collaborating observers without using a telescope would be detection of parallax at a distance of 4 million Earth-diameters [Hirshfeld 15].

The larger the baseline used, the further away one can accurately measure distance using parallax. The baseline of 6 cm for the human eyes can be extended in several ways. One of the simplest ways to extend this baseline is by using a device called a binocular range finder (see Figure 1).

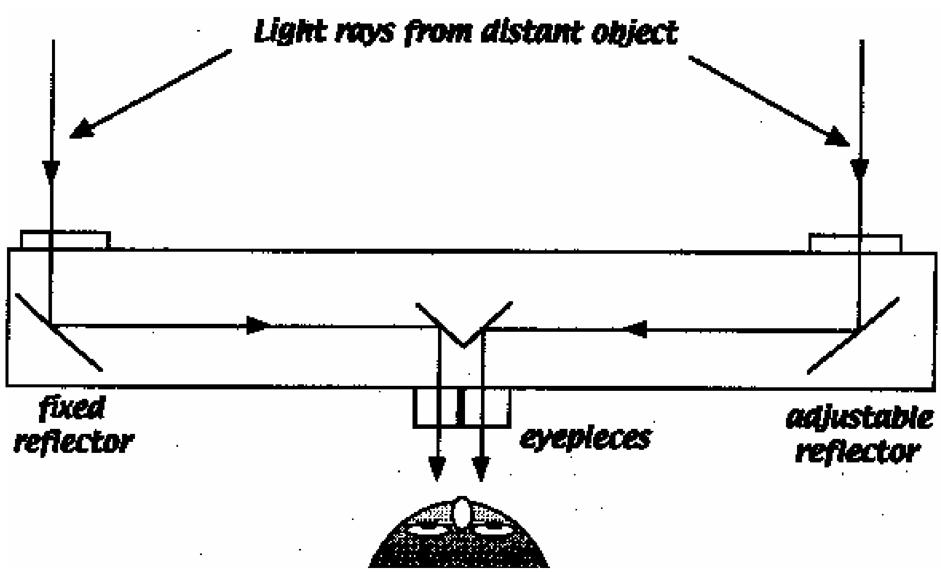

Figure 1. Binocular Range Finder (Hirshfeld 55).

The user of the range finder can adjust a dial that has calibrated markings for various distances. If the dial is not adjusted properly, the user will see two images. The user must turn the dial—which changes the angle of the internal, adjustable mirror—until the images precisely line up. The distance can then be read off the calibrated scale.

Devices such as this have proven valuable during wartime since it allows the troops to determine the approximate distance to the enemy targets. The U.S. Army has a portable ranger finder called the M7 that has a 99-cm baseline and an 14x magnification. It could determine the distance to targets nearly 5-km away to within 0.2-km [Hirshfeld 54-56].

Unfortunately, celestial objects are further than 5-km away, so we need another way to improve the parallax baseline. Surveyors use parallax (in their jargon they call it "triangulation") when they need to determine the distance to a remote object. A theodolite (spotting scope) can measure angles to within one arcsecond. Triangulation does not require simultaneous observations from each one of the baseline, so the surveyor is free to record one reading, move his theodolite to the other side of the baseline, and take a second recording. Simple trigonometry will yield the desired parallax and distance [Hirshfeld 56-57]. The only limits to this technique are that the surveyor must know the exact distance between the two end-points of the baseline, and the same object must be visible from both ends of the baseline. Triangulation can resolve distances of tens of kilometers. This technique can be adapted to work for items in the Earth's atmosphere such as meteors [Hirshfeld 58].

Stellar parallax, specifically, will be discussed in much greater detail in later sections.

4. The solar system

Before we can start talking about the distances to the sun, moon, and planets, we first need to take a brief (de)tour through history and determine precisely the configuration of the solar system.

Pythagoras believed the Earth was surrounded by eight concentric, transparent "crystalline" [Ferguson 43] spheres, containing the Sun, Moon, five known planets

(Mercury, Venus, Mars, Jupiter, and Saturn), and fixed stars; however this simple model could not explain the observations of the planets (retrograde motion, varying brightness) and so Plato challenged his colleagues to come up with a better solution that shows the motions of the planets were are elegant as the motions of the Sun, Moon, and stars.

Eudoxus took on the challenge and developed a system using 27 spheres, with four spheres for each the five planets, three spheres each for the sun and moon, and one sphere for the fixed stars [Hoskin 36]. The spheres were tilted at various angles and interlocked in their rotation. Eudoxus has taken a simple model and transformed it into a clocklike machine in order to more accurately predict the planetary observations. In Aristotle's model, he used a total of 55 spheres. The Greeks did not necessarily believe is invisible concentric spheres, but used them only as geometrical models to describe the observations [Hirshfeld 4].

One major problem with all these nested spheres is that no solution would permit the other planets from varying their distance from Earth [Hoskin 36].

4.1. Geocentric system

Hipparchus felt that an Earth-centered universe could easily explain the detailed observations that he took over the course of several years. He developed a model for the motion of the Sun, in which the Earth was slightly off-center (eccentric) from a circle. The Sun continued to move at a constant speed, but had an apparent velocity change when viewed from the Earth. His model offset the Earth 1/24 of its radius from the center at an angle of 65.5 degrees [Hoskin 41], which also explained the inequality of the seasons measured by the solstices and equinoxes [Ferguson 30]. Hipparchus most likely was inspired by the works of Apollonius of Perga, whom introduced the concepts of eccentric circles, as well as epicycles and deferent. Epicycles are small circles carried around by deferent circles (not unlike an amusement park rides) that circle the Earth. Motion on an eccentric circle is equivalent to the combined motion of an epicycle and deferent.

Ptolemy used the ideas of Hipparchus and Apollonius of Perga (in fact, some historians submit that Ptolemy's work was nothing more than a "reediting" of Hipparchus' [Ferguson 32]) and combined it with the bulk of other astronomical knowledge at the time and created a thirteen volume Megale Syntaxis, or "Great Compilation" which was completed around 150 AD. During the ninth century, an Arabic translator renamed it Almagest, or "The Greatest". His model had almost universal acceptance for fourteen centuries [Hirshfeld 23] and ultimately became part of Christian doctrine after theologically driven modifications added by Thomas Aquinas [Hirshfeld 30].

The Almagest includes all the techniques required (numerous step-by-step examples) to compute the positions of the Sun, Moon, and the then-known five planets [Hirshfeld 24]. Ptolemy's contribution was the "equant", an imaginary point diametrically opposite of the offset Earth [Ferguson 42]. The epicycle *velocity* along its deferent *depends* upon the proximity of the equant—this summarily dismissed Aristotle's notion of uniform circular motion [Hirshfeld 28], and that resulted in much criticism from Islamic astronomers [Ferguson 46]. The planetary coordinates would routinely be several degrees off, but this was tolerated due to the inaccuracies in the astronomical instruments of the time [Hirshfeld 30-31].

Ptolemy ordered the celestial objects depending upon how fast they moved across the sky. The Moon was closest, followed by Mercury, Venus, the Sun, Mars, Jupiter, and then Saturn. "Each planet's epicycle and deferent circled within the hollow of its own thick, transparent, crystalline sphere and that these planetary spheres nestled around one another with no intervening gaps" [Hirshfeld 29].

The geocentric model seemed more intuitively obvious at the time. The ancient Greeks believed the Earth was the center of the universe because at any particular moment, exactly half of the fixed stars were visible no matter their locale. If the Earth were off-center, they hypothesized that one side of the Earth would see a smaller volume of the universe than those observing from the other side [Hirshfeld 6]. The model also seemed to agree with Aristotle's idea that dense materials converge toward the cosmic center—the Earth seemed incredibly dense when compared to ever-aloft evanescent material of the celestial bodies [Hirshfeld 5].

4.2. Heliocentric system

4.2.1. Aristarchus of Samos

The first person known to have suggested a universe without Earth at its center was Aristarchus of Samos, in the 3rd century B.C. His intuition led him to believe the Sun—the "lantern" that radiates its light amongst the celestial bodies—belongs at the center. It seemed logical that since the Earth was only a fraction of the size of the Sun (by his own calculations), the smaller body would circle the larger body [Hirshfeld 1]. Earlier Pythagorean philosophers had decided by the 5th century B.C. that the Earth was simply a planet and that the center of the universe, for symbolic and other religious reasons, would be an "invisible fire" [Ferguson 26].

Aristarchus believed that Earth completed a rotation every 24 hours, and this could explain the apparent motion of the celestial sphere. (Aristarchus, however, was not the first person to suggest a rotating Earth. Heraclides of Pontus, in the 4th century B.C. had suggested a rotating Earth, but in a geocentric universe.) The concept of a rotating Earth was met with great skepticism. Those that were aware of the size of the Earth dismissed the notation entirely because it would mean non-stop cataclysm: continents swirling around the axis at hundreds of kilometers per hour causing continuous, extreme wind which would hypothetically cause everything not bolted down to tumble off into the sky [Hirshfeld 7].

Unfortunately, Aristarchus was nearly alone in believing in a heliocentric universe. The only person from antiquity to be truly impressed with his theory was Seleucus of Seleucia, either a Chaldean or Babylonian astronomer [Ferguson 28].

The changes in brightness of the planets could easily be accounted for in a heliocentric model. The distances between planets continuously change during the course of a year. Sometimes a planet may approach closer to the Earth, and other times they may be receding. Another consequence of this is that so-called “fixed stars” are much further away than the planets since they do not vary in apparent brightness [Hirshfeld 8].

4.2.2. The Copernican Revolution

> “What appear to us as motions of the Sun arise not from its motion but from the motions of the Earth”—Nicolaus Copernicus [Hirshfeld 39].

It wasn’t until the 14th and 15th century that serious consideration was again given to the idea of a movable Earth. Both Nicole Oresme and Cardinal Nicholas of Cusa suggested there was no one had sufficiently proved that the Earth does not move

[Hirshfeld 49]. It would take Galileo's concept of inertia to convince people that a rotating earth was feasible [Hirshfeld 7].

Copernicus believed there were many serious faults in Ptolemy's model. The apparent size of the Moon should change by a factor of 2 during its phases if one were to strictly believe the wide epicycle selected by Ptolemy. Copernicus measured the diameter of the half-Moon on the night of March 9, 1497 during an eclipse of the star Aldebaran. Not even a subtle difference was detected between the full Moon and half-Moon's diameter [Hirshfeld 37].

Copernicus, seventeen centuries after Aristarchus had first suggested a heliocentric universe [Ferguson 26], finally reached the conclusion that the Earth was in motion around the Sun, and presented his initial findings in Commentariolus, or "Little Commentary" [Hirshfeld 39]. (There is a common misconception that the Church was opposed to the heliocentric notion from the very beginning, but this is not the case at all. The complete story is a long and complex one, and will not be presented here as the author considers it out of the scope of this paper.)

Copernicus took three-decades to finally complete his manuscript De Revolutionibus, "On the Revolutions". It took much convincing from Georg Joachim Rheticus (whose father, incidentally was beheaded for being a sorcerer [Ferguson 58]) to prod the elderly Copernicus to finish his work. Rheticus helped proofread the manuscript and also supervised production of 142 illustrations. The finished book, 404-pages, had a modern-equivalent price of over US$100. To alleviate ridicule, Andreas Osiander, stand-in for Rheticus while away on business, inserted an anonymous preface, seemingly from Copernicus himself, indicating the models offered in the book were purely hypothetical and where not meant to be taken literally. The title of the book was also changed to De Revolutionibus Orbium Coelestium, “On the Revolutions of the Heavenly Spheres”. Rheticus was infuriated and proceeded to cross out, in red ink, the preface and extended titling on every copy of the book he could get his hands on [Hirshfeld 42-43].

Copernicus was philosophically opposed to the equant-point concept and non-constant speed of the planets in Ptolemy’s model. He also believed Ptolemy had not adequately explained various irregularities in the duration of a year [Hirshfeld 39]. His strong belief in Neoplatonism encouraged him to look for simple mathematical and geometrical explanations in nature [Ferguson 51]. While he was able to expunge the equant, his model still possessed epicycles and eccentrics [Ferguson 59], and thus was just as complicated and erroneous as the Ptolemaic system [Hirshfeld 44]. Each planet circles the Sun at a constant speed in a small epicycle—this had been postulated two centuries earlier by Islamic astronomer Ibn as-Shatir [Hirshfeld 45]. Copernicus also concluded that the greater the planet-Sun distance, the more slowly the planet moves in its orbit [Hirshfeld 46].

Acceptance of Copernicus’ model was glacially slow, and historians count only ten people (seven Protestants, three Catholics) between the years 1543 and 1600 who agreed with his position [Ferguson 65]. The model was still mathematically complicated, and the results of the calculations of the planetary positions were not much better than the results obtained from Ptolemy’s model [Hirshfeld 46].

4.2.3. Kepler and Galileo

Johannes Kepler was believed in a Neoplatonic Christian faith and hypothesized that the universe must have a beautiful, yet hidden, harmony [Ferguson].

Kepler, while working with Tycho Brahe's detailed observations of the position of Mars, found that the orbit could be more accurately computed if he were to use elliptical orbits, rather than circular. This realization led to his first law that also postulated that the Sun had somehow exerted an influence on the planets [Hirshfeld 47], and was always at the one of the two foci of the ellipse. His second law stated that a planets speed through its orbit depends on an imaginary line, the radius vector, joining the center of the planet to the center of the Sun that "sweeps out" equal areas in equal time [Ferguson 78], and thus will always travel faster the closer its path brings it to the Sun [Ferguson 80]. Kepler's third law explores the relationship between the length of time it takes a planet to orbit the Sun its relative distance from the Sun [Ferguson 81].

One of Kepler's publications was <u>Mysterium Cosmographicum</u>, "Mystery of the Cosmos" with which Galileo read with great pleasure in August of 1597. The book discusses the harmony imposed by the Copernican system, but also has mystical ramblings complete with numerology [Hirshfeld 117] (perhaps somewhat inspired by his mother, whom experimented in the occult and was nearly burned as a witch) [Ferguson 70]. Galileo, whom Kepler once referred to as an "Italian whose last name was the same as his first", wrote to Kepler to say that he "adopted the teaching of Copernicus many years ago, but had not declared himself publicly for fear of professional ridicule". Kepler replied "Stand forth, O Galileo!" [Hirshfeld 117].

One of the problems with the heliocentric model was that there was no immediate way to prove it could be correct using only the naked eye. Galileo's observations of Venus (some historians claim it was his pupil, Benedetto Castelli [Ferguson 91]) showed that it cycles through phases just like the Moon. Venus would gradually cycle between a small, full disc and a larger crescent. The observation of a full disc phase for Venus proved the Ptolemaic system could not be correct, because this configuration would be a geometric impossibility (see Figure 2 below) as Venus allegedly lies between the central Earth and the radiant Sun [Hirshfeld 125]. The author encourages the inquisitive reader to visit the following web page:

http://www.astro.ubc.ca/~scharein/a310/SolSysEx/phases/Phases.html

The above page has an interactive Java-applet that runs from within the web browser. It allows the user to simulate how phases of Venus would appear in the two models.

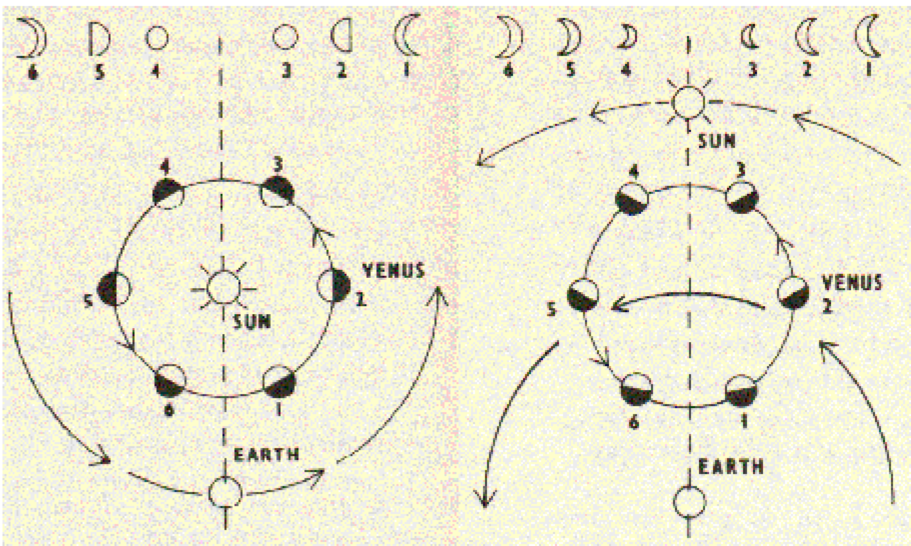

Figure 2. Left: Phases of Venus expected in a heliocentric model. Right: Phases of Venus in a geocentric model [Dunn 1996].

Unfortunately, even this astute observation could not prove the heliocentric theory as the phenomenon could be explained equally well with the Tychonic model—a hybrid of the geocentric and heliocentric model that continues to put the Earth at the center, with the Sun circling the Earth, but with all the other planets circling the Sun. Most astronomers believed it would require the undisputed measurement of stellar parallax—

using a baseline the size of the Earths orbit—to prove once and for all that the Earth orbits the Sun [Hirshfeld 125].

4.3 Distance to the Sun and Moon

Aristarchus of Samos (310-230 BC) was one the first person to make a reliable estimate of the distance to the Moon. Using a set of six assumptions (of which two were inaccurate), he computed that the relative distance to/diameter of the Sun was 19 times the distance to/diameter of the Moon. Using other geometrical assumptions, he concluded the Moon was a quarter of the size of Earth and its distance was roughly 60 times the Earth's radius. Plugging in the value Eratosthenes had previously computed for the radius of the Earth (6320-km), he arrived at a figured (in stades, but the answer is presented in kilometers) of approximately 379,000-km, very close to today's mean value of 384,400-km. His estimate of the distance to the Sun was grossly incorrect [Ferguson 26].

Hipparchus used observation accounts from the solar eclipse of March 14, 189 BC to determine the distance to the Moon. The eclipse was total in Hellespont, Turkey, but in Alexandria only four-fifths of the Sun's disc was covered at maximum. This was an opportunity to compute a parallax measurement for the Moon. By assuming the Sun is very far away compared to the Moon, and the fact that angle corresponding to one-fifth of the angular diameter of the Sun, about 0.1 degree, served as the parallax measurement. All that was then needed to compute the distance was the length of the baseline, i.e., the distance between Hellespont and Alexandria. He computed a distance between 35 and 41 Earth diameters, although the true value is closer to 30 [Hirshfeld 59].

Ptolemy asserted that the Moon's sphere was located in the region between 33 and 64 Earth radii away from the Earth, while the Sun's sphere occupied the region between 1079 and 1260 Earth radii away [Ferguson 45]. These numbers were roughly (with a large margin of error) in agreement with Aristarchus' results.

Giovanni Domenico Cassini, after finding the parallax for Mars (see §4.4) in August 1673, was able to plug the distance into Kepler's formula and obtain a measurement for the astronomical unit—140 million kilometers—close to the present-day value of 149.5 million km. This value was significantly larger than those calculated by his predecessors. Copernicus believed the distance to be 3 million km, Tycho Brahe 8 million, and Kepler no more than 14 million km [Ferguson 121]. Unfortunately, Cassini's results were so questionable that it prompted historian Albert van Helden to claim the value was simply "a convenient estimate wrapped in the cloak of authority" [Hirshfeld 61].

James Bradley, in an attempt to measure stellar parallax, instead made the serendipitous discovery of a phenomenon known as aberration in 1728. This is the result of the effect of the Earth's velocity on stellar observations. This effect would only be observable if the Earth were truly in motion around the Sun. Bradley was able to calculate that light takes 8 minutes and 12 seconds to reach the Earth, results very close to the present-day estimate of the Sun's distance when measured in light-minutes. The discovery of aberration finally shattered the geocentric model [Hirshfeld 159-161].

Nicolas Louis de Lacaille arranged a party to use convention surveying triangulation techniques to measure the parallax of the Moon. Measurements made from the Cape of Good Hope and in Europe simultaneously—a baseline of 9300-km—measured a parallax of two degrees in 1751 [Hirshfeld 60].

In 1945 Lt. Col. John H. DeWitt initiated "Project Diana" at Signal Corps Engineering Laboratories in the United States. They embarked on an experiment to measure the distance to the Moon using radar signals that were bounced off the Moon and reflected back to Earth. By measuring the two-way-travel time, it seems a trivial matter to calculate the distance. In actuality, other factors must be taken into consideration such as the Doppler effect, i.e. the relative velocities of the Earth and the Moon vary as much as +1500 km/hr at moonrise to –1500 km/hr at moonset, which affects the frequency that must be tuned in when waiting to receive the reflected signal. The experiment proved to be a success—on January 10, 1946 they measured a two-way-travel time of 2.5 seconds [Mofenson 1946]. Another group made a similar measurement from Hungary that same year.

The modern way to measure the distance to the Moon is currently a technique called laser-ranging. For example, the McDonald Laser Ranging Station in the United States possesses the capability of measuring round-trip time to the lunar retro-reflectors left by the Apollo 11, 14, and 15 astronauts, and two French-built packages that were deployed by unmanned Soviet landers. Distance precision is 1-cm and timing precision is 35-picoseconds [UTWS 2000]. Laser-ranging has been performed for three-decades (since 1969) and measurements from several facilities around the world have shown that the Moon is receding from the Earth at a rate of 3.8-cm/year. Variations in the Moon's rotation have also been detected, and this implies the existence of a small core with a radius of less than 350-km. Knowledge of changes of the Earth's rotation rate and the precession of its spin axis has also been improved from these measurements [LPI 1997].

4.4 Distance to the planets

Ptolemy "calculated" the relative distances (from the Earth) to the planetary spheres with the following results: Mercury (shuffles back and forth in its sphere—a region between 64 and 166 Earth radii), Venus (166-1079), Mars (1260-8820), Jupiter (8820-14189), and Saturn (14189-19865) [Ferguson 45].

The heliocentric model uniquely specifies the relative distances (from the Sun) to the planets as follows: Mercury (0.38 Earth-Sun distance), Venus (0.72), Mars (1.5), Jupiter (5.2), and Saturn (9.5) [Hirshfeld 46]. The challenge then becomes determining the absolute distance to *any* one planet. If a parallax measurement could be accurately obtained for *any* single planet, *all* the other distances would be trivial to calculate by Kepler's laws, and the determination of the long-sought astronomical unit (AU), the distance from the Earth to the Sun would no longer be in dispute [Hirshfeld 60]. The problem is that even the closest planet, Venus, is more than 100 times the lunar distance—meaning the parallax angle of Venus will be less than 1% that of the Moon [Hirshfeld 60].

4.4.1 Parallax of Mars

Tycho realized that the best time to measure the parallax of a planet is during opposition, when the Earth passes directly between the planet and the Sun. The planet becomes closer to Earth at this time than most others, and will consequently have a larger parallax. Tycho attempted to measure the parallax of Mars during the opposition of 1582. His technique, "diurnal parallax" [Ferguson 121], was to measure Mars' position amongst the background of stars twice a day from the same location—once before dawn, and once after sunset. In the interim, the Earth would have completed roughly half a rotation providing a planet-wide baseline. Tycho claimed success, but it would have been impossible. The true parallax of Mars is only 0.012 degrees with an Earth-diameter baseline, which is far too small to have been measured by Tycho's naked-eye instruments [Hirshfeld 60-61].

Cassini and his assistant Jean Richer attempted to measure the parallax of Mars between August and September during the opposition of 1672. Cassini made observations from Paris and Richer from Cayenne in what is now French Guiana on the South American coast. They concluded that Mars was 4,000 Earth-diameters from the Sun at opposition. The results were inconclusive, though, because of the high uncertainties in their position measurements [Hirshfeld 61]. The longitude of Cayenne was not certain and the best clocks at the time were pendulums that could not stay synchronized during the sea voyage; however this problem was apparently solved by an ingenious way of determining the time by using the moons of Jupiter [Ferguson 119]. John Flamsteed used Tycho's diurnal parallax technique to obtain a value for Mars that seemed to be in agreement with Cassini's [Ferguson 121].

4.4.2 Transits of Venus

Edmond Halley rejected Cassini and Flamsteed's measurements for the parallax of Mars (and the derived value for the astronomical unit), and devised a better scheme for accurately determining the parallax of a planet. His proposed target was Venus—it swings closer to the Earth than Mars, but astronomers had been choosing Mars up to this point because inner planets have their opposition during the daytime. The parallax of

Mars can be measured against the starry background, but stars are not generally visible during the day.

Halley remembered watching the transit of Mercury across the face of the Sun on November 6, 1677 from the south Atlantic island of St. Helena. James Gregory had postulated in 1663 that the Sun's disc might provide a sharp reference mark against which to measure the parallax of Mercury. Each observer would need to record the exact times Mercury crossed the Sun's disc. The times would be different for each location, and once combining the results from every observer, a parallax could be ascertained. However, Halley was disappointed to discover only one other astronomer had watched the transit. The need for coordination and cooperation was great.

Halley believed the same technique would work better for Venus because of its larger angular size. Because Venus is closer, the observed crossing times could potentially differ by as much as five minutes, so timing errors of several seconds would not have much impact on the results. The only required instruments would be an accurate clock and a quadrant (portable position-measuring telescope). His prediction was that the results would have an error of at most one percent.

The problem: Transits of Venus are incredibly rare. They occur in pairs, about once per century: {…, June 1761, June 1769, December 1874, December 1882, June 2004, June 2012, …}. Halley published a paper in 1716 describing the techniques that future astronomers would need to heed, for he knew he would not live to see such a transit [Hirshfeld 61-64].

"Halley" became a household word in 1758 with the return of the comet with his namesake. This inspired scores of astronomers [Ferguson 133], nineteen years after his death, from eight countries to embark to every corner of the globe for the June 6, 1761 on June 3, 1769 transits. Astronomers were prepared to determine the parallax of Venus (and the value of the astronomical unit) with certainty. 150 observations of the transit were recorded, but there was a kink in the chain—it was discovered that Venus had a thick atmosphere which tended to blur the sharp Venusian disc as it was lit by the Sun. This made is nearly impossible to determine the exact times of contact. The 1% error Halley was hoping for was not obtainable, but from the parallax measurements, a figure of 146 million-km [Hirshfeld 64-65] (or 153 million-km [Ferguson 135]) was nevertheless derived for the astronomical unit.

4.4.3 Jupiter and the speed of light

Ole Roemer, in 1676, while making detailed observations of eclipses of Jupiter's moons noticed that the elapsed time between the disappearances behind Jupiter depended on the Jupiter-Earth distance. Roemer believed the speed of light was causing the apparent shifts in the time-tables: Eclipses were ahead of schedule in Jupiter was nearer to Earth and behind schedule when further away [Hoskin 213]. He calculated the speed of light to be 225,000-km/sec [Ferguson 122].

4.4.4 Radar

Present-day astronomers are able to accurately measure the distance to many solid bodies in the solar system by bounding radar signals off of the surface of the planet and timing the amount of time it takes for the signal to echo back to the Earth. In 1961, NASA's Jet Propulsion Laboratory successfully bounced a radar signal off of Venus. The two-way-travel-time was five minutes.

The Arecibo dish has been used to bounce signals off of Mercury, Venus, and Mars. In 1991, radar signals were bounced off of Saturn's moon Titan [JPL 1991]. Irwin I. Shapiro measured the time-delay of radar reflections from the surface of Mercury. The interesting result is that the Sun's gravitational field of is so strong, that a relativistic correction must be made to the raw two-way-travel-time [Sweetser 1997].

4.5 Distance to comets, asteroids, meteors

Aristotle believed that comets were nothing more than combustible gases in or slightly above the Earth's atmosphere. Tycho knew that if this were the case, comets would have a large parallax. Tycho made detailed observations of the comet of 1577 and compared his results with those of other astronomers. He was able to conclude that the comets showed no measurable parallax (with his naked-eye instruments), and hence must be greatly beyond the distance of the Moon [Hirshfeld 89].

Triangulation has been applied to meteors as they hurl through the atmosphere—by examining photographs taken at different locations, the background stars can be compared, and a parallax can be computed to determine the meteor's height [Hirshfeld 58].

Some asteroids, such as Eros, routinely come close enough to the Earth so that they are within a range that allows distance to be computed by triangulation. In 1931, Eros was photographed by astronomers from fifteen countries during a close approach. Three thousand photographs were analyzed over ten years in order to measure its parallax. The distance determined during the approach was 26 million-km, and from this, the present-day value of the astronomical unit, 150 million-km was finally obtained [Hirshfeld 65-66].

Radar ranging of asteroids is routinely performed to determine their distance.

5. Distance to the stars

Ptolemy calculated an absolute distance to the fixed stars of 569,463,333 stades, or roughly 80 million kilometers [Ferguson 45]. Islamic astronomer Al Fargani revised this figure to approximately 120 kilometers [Ferguson 48].

Archimedes, in The Sand-Reckoner, attempted the task of measuring the volume of the universe. He assumed the stars of the celestial sphere were 100 million Earth-diameters away, and further assumed that the diameter of the Earth was 1 million stadia, and postulated to the universe was approximately 100 trillion stadia in radius, thus requiring 10^{63} grains of sand to fill the volume of the universe. This was more an exercise in mathematics than anything else—he chose the heliocentric model for the computation because it purported to have a larger universe rather than the geocentric model that he favored, and also admittedly “fudged” many of the numbers used in his assumptions [Hirshfeld 15].

The above early measurements of distance to the stars were horrendous. It would take men and women centuries to finally come up with the first reasonable estimate for the distance of a star.

Christiaan Huygens developed a photometric technique that he believed would help compute the distance to Sirius. He would look at the Sun through a small hole in a disk. He continued to make the hole smaller until the perceived intensity of the Sun through the hole appeared as bright as his recollection of Sirius brightness. This technique assumes Sirius is an exact duplicate of the Sun. By comparing the relative brightness of the Sun and Sirius with the size of the hole, he computed a distance of 27,664 astronomical units in 1698 [Hirshfeld 167].

Newton had a technique that allowed him to measure distances without needing to measure a parallax shift; however, it relied on one the same hefty assumption that Huygens had used—he assumed that *all* stars have the same absolute magnitude! Modern-day astronomer Own Gingerich calls it the “faintness means farness” method [Hirshfeld 166]. To compare the intensity of the Sun with the intensity of a star required a clever trick that had been suggested by James Gregory. The trick involved two additional assumptions: 1) Saturn would reflect 25% of the light radiated to it by the Sun; and 2) One-billionth of the light radiated from the Sun hits Saturn. One can then deduce that the intensity of light we perceive from Saturn is actually equal to one-forth of a billionth of the intensity of the light from the Sun.

In Newton’s photometric method, if a given star had the same apparent magnitude as Saturn, it would be 100,000 times farther away from the Earth than the Sun is. Needless to say, any results that may have been close to today’s values were simply a coincidence [Ferguson 129]. Newton’s method assumes the stars are all at different distances from the Earth (otherwise every star would have the same apparent magnitude). He compared the relative brightness between Saturn and Sirius in 1686 and published his result in 1728 concluding that Sirius is one million astronomical units from the Earth.

Other astronomers had also attempted to measure the distance to Sirius using photometric techniques that were just as faulty. In 1744, Philippe Loys de Chesaux determined the distance to be 240,000 AU; in 1760 J.H. Lambert calculated 500,000 AU; and in 1767 John Michell computed 440,000 AU. These numbers were all bogus, based on mostly groundless assumptions. The actual distance is 600,000 AU [Hirshfeld 167]. What astronomers really needed was a measurement of stellar parallax.

> "It is a difficult matter, and one that requires a subtle mind, to try to determine the distances of the stars from us, because they are so incredibly far removed from the Earth." - Tycho Brahe in De Nova Stella.

5.1 Changes in the "fixed" stars

Hipparchus was the first astronomer to notice a change in the so-called "fixed" stars. In 134 B.C. a never-before-seen star appeared in the heavens. At the time, this was an event unprecedented in astronomy—the fixed stars may no longer possess their omnipresent status. Modern historians believe this star was either a nova (a temporary, non-destructive eruption on the surface of a very hot star) or a tailless comet [Hirshfeld 21,82].

Hipparchus also noticed something peculiar when examining records of observations from astronomers 160 years in his past—a subtle, but systematic shift in the relative positions of the equinoxes and stars [Ferguson 32] by about one-degree every century. The celestial sphere was slowly tipping! Hipparchus had discovered the phenomenon of precession. (It took another eighteen centuries—until Isaac Newton came along—to explain why precession takes place. Newton explained that the gravitation tug of the Moon makes the Earth's axis gyrate similar to a spinning top. The period of precession was 26,000 years.) Halley confirmed Hipparchus' findings [Hirshfeld 22-23].

Tycho became awestruck when on the night of November 11, 1572, he noticed a new star in Cassiopeia as bright as Venus—he could not believe his own eyes, and began to ask others if they could see it too! Historians believe Tycho saw a supernova (the titanic explosion of a dying star). Tycho had earlier dismissed the ancient tale of Hipparchus' new star as a tailless comet, so he still believed the heavens to be unchanging. The supernova remained visible for eighteen months and could initially be seen in the daylight—through clouds!—and its color changed gradually over time. Tycho had to determine whether this new star was actually on the celestial sphere, or whether it was simply some new phenomenon in the atmosphere. He attempted to measure the parallax, but detected none, so he had to assume it was not any kind of comet or meteor, but an object much further away than the moon. He then became a firm believer in a changing celestial sphere [Hirshfeld 81-83].

Another supernova erupted in October 1604. This was observed by Tycho's successor, Johannes Kepler. The next naked-eye supernova did not occur until 1987 [Hirshfeld 83,118].

Edmond Halley, when comparing his observations with those of Hipparchus, he noted that several stars (Sirius, Aldebaran, and Arcturus) had shifted slightly since antiquity. This was not the same systematic shift caused by precession, but instead a long-term stellar movement known as the proper motion [Hirshfeld 204].

5.2 Early attempts to measure stellar parallax

> "[To measure the distance to a star] has been the object of every astronomer's highest aspirations ever since sidereal astronomy acquired any degree of precision. But hitherto it has been an object which, like the fleeting fires that dazzle and mislead the benighted wanderer, has seemed to suffer the semblance on an approach only to elude his seizure when apparently just within his grasp, continually hovering just beyond the limits of his distinct apprehension, and so leading him on in the hopeless, endless, and exhausting pursuit."—John Hershel, to the Royal Astronomical Society, February 12, 1841.

5.2.1 Tycho

Tycho was obsessed with accuracy. His observations were meticulous. He had no telescopic equipment, yet was able to determine the positions of stars to within one arcminute of their actual positions. This was a tenfold increase in the level of accuracy to that of previous star catalogues. He had hoped to make a measurement of stellar parallax in order to determine the distance to the fixed stars, but his tries where in vain—no one at the time knew stellar parallax measurements were far, far smaller than the one arcminute accuracy he was capable of detecting with his equipment. He calculated that the stars must be at least 700 times further than Saturn, otherwise he would have detected a parallax shift.

This was too large a universe for Tycho to conceive, so he concluded that the Earth must be fixed at the center of the universe—in an Earth-centered universe the maximum baseline for a parallax measurement is the diameter of the Earth, while a Sun-centered universe has a maximum baseline of the diameter of the Earth's orbit around the Sun. An Earth-centered universe would mean the stars would be much, much closer than the 700 times Saturn distance he computed. Note that modern measurements put the *nearest* star at 30,000 times the distance of Saturn [Hirshfeld 90-91].

5.2.2 Galileo

Galileo gave out some advice for would-be parallax hunters. He developed two schemes that he felt would delivery a reasonable chance of detecting stellar parallax. In his first scheme, a telescope must be attached to a frame or post such that it points straight up. Stars will swept through the eyepiece of such a fixed telescope due to the rotation of the Earth. If a star on one night passes in a line exactly through the center of eyepiece, one must observe it again, six months later, and see if the star has been offset by the center. A shift would mean a definitive measure of parallax (assuming the telescope had not been moved in the intervening six-month period) [Hirshfeld 130].

Galileo's second scheme relies on the assumption that the stars are not on a fixed sphere, i.e., that all the stars are at different distances. For each nearby star, there might be countless others seemingly infinitely far away. To measure the miniscule parallax of a nearby star, the star would need to be alongside the background stars in the same field of view. Double stars seemed to be obvious candidates for this scheme. He attempted to inspire people to hunt for double stars of a specific type—those with both bright and dim companions. He would then assume the dim star is the distant star. The main problem with this technique is that most double stars are actually true binary systems in which both stars are roughly the same distance from Earth. For parallax techniques to work, at least one real background star must exist [Hirshfeld 131-132].

5.2.3 Robert Hooke

Robert Hooke became inspired by Galileo's first method. He cut a whole through the roof of his dwelling and mounted a fixed, vertical telescope. He wanted to be the first person to measure the parallax of a star. Hooke, living in London, realized that the star Gamma Draconis would pass through his new telescope every night. The reason for zenith-pointing telescope was two-fold: 1) A plumb bob could be attached to the telescope to ensure it was pointing exactly vertical, and 2) There is no atmospheric refraction occurring at the zenith. Any other angle could require making corrections in the raw data because of the shifts caused by refraction. Hooke boldly named his telescope the "Archimedean Engine", a reference to the notion that if one were to build a long-enough lever and a place to stand, the Earth-itself could be moved—and proving the

Earth moved would be exactly what Hooke would be doing if he were to observe a stellar parallax shift.

Hooke made only four observations with his “Engine”, not enough to confirm his results. His firs three measurements showed Gamma Draconis passing north of the zenith by just over two arcminutes. His final result had the star passing less than two arcminutes north of the zenith. Due to failing health and uncooperative weather, Hooke gave up after the final, fourth observation. There were too many possible sources of error (e.g., the telescope’s tube swayed depending upon the wind and weather, etc.) in his data to prove anything conclusively. Hooke estimated the parllax to be approximately 30 arcseconds, although the true parallax is closer to 0.03 arcseconds [Hirshfeld 144-148].

5.2.4 James Bradley

Reverend James Bradley was no slouch when it came to astronomy. He and his Uncle James Pouch had together measured the diameter of Venus and the parallax of Mars. Bradley alone calculated the orbits of two comets. Bradley and Molyneux, a wealthy amateur astronomy, teamed up and obtained much better equipment than Hooke every had access to, in an attempt to duplicate Hooke’s attempt to determine the parallax of Gamma Draconis. The telescope, however, was designed to tilt slightly north or south by turning a micrometer screw. When Gamma Draconis would pass overhead, they would tilt the scope such that the star would cross through the center of the eyepiece. The tilt reading could then be recorded and later analyzed.

Bradley already knew that the signature for stellar parallax should look like: the star should wobble cyclically each year along a north-south line: southernmost in December, northernmost in June; and in March and September, the star should be deadcenter. The first observation was made December 3, 1725. The telescope was determined to have an accuracy approaching one-arcsecond—beating Tycho's instruments by a factor of sixty. The duo made eighty measurements over two years, but they reached a startling conclusion: Gamma Draconis was wobbling by 40 arcseconds a year—on a 365-day cycle. This meant it was linked to the orbital motion of the Earth around the Sun, but was perplexingly not what they expected to see. The maximum southward deviation occurred in March, not December, and likewise, the maximum northward deviation occurred in September, not June.

After laboriously checking the telescope for any potential defects and finding none, Bradley acquired a new, even more accurate telescope to attempt to see if they observe anything fishy with other stars. He determined that same wobble existed in every star he studied. What he had discovered was aberration (previously mentioned in §4.3). Knowing the accuracies of his telescope, he was able to make a minimum distance estimate for Gamma Draconis. It could be no closer than 6 light-years, otherwise the parallax would have been detected.

Bradley later discovered yet another pesky phenomenon—nutation—the cyclic wobbling of the Earth's axis caused by the Moon's gravitational tug on the non-spherical Earth. This effect could introduce errors of up to nine arcseconds. Bradley still had not found any parallax, but he was surely finding new ways to complicate the measurement. The prospective parallax hunter has to be able to make corrections in their data for: 1) nutation, 2) precession, 3) aberration, 4) refraction by atmosphere, and 5) any wobbles introduced by the telescope itself. Even after taking all these effects into account, Bradley would be unwilling to use the data unless it passed rigorous statistical analyses that he had developed.

With the ever-increasing accuracy of the instruments he was able to acquire after succeeding Halley as England's Astronomer Royal in 1742, and utilizing all corrective techniques he now possessed, Bradley was still unable to determine any stellar parallax [Hirshfeld 153-165]. He laid out advice for future seekers of stellar parllax: Rather than choosing a star for convenience (like Gamma Draconis), the brightest stars should be chosen (believing that they may in fact be closer). He also reiterated Galileo's second suggestion: Look for double stars with a bright and dim partner [Hirshfeld 168-169].

5.2.5 William Herschel

William Herschel became famous in 1781—not by measuring a stellar parallax, but by becoming the first person to discover a planet—Uranus—in a large, but homemade telescope! He was confident that he would be able to determine dozens of stellar parallaxes by using Galileo's second method. The first goal would be to sweep the heavens and find all the double-star pairs. He believed he was the man who could do this—he often boasted his telescopes could magnify several thousands times while the next best in the world could only magnify several hundred times [Hirshfeld 173].

Herschel's prime targets were tight doubles having no more than five arcseconds of separation. The stars appeared so close that distorting factors such as atmospheric refraction, aberration, etc. could be neglected. To measure the separation, he used a device called an eyepiece micrometer: a pair of movable, parallel wires within the field of view [Hirshfeld 187]. Unfortunately, the entire basis of Herschel's work would soon be called into question—tight doubles may not have been a good choice.

A paper published in 1767 (Herschel read it in 1782) by John Michell indicating that double stars might actually be pairs of stars orbiting each other rather than chance alignments viewed from Earth. It was highly improbable that a random distribution of stars in space would have led to so many double stars. If this were true, the pair would roughly be at the same distance from Earth, and a stellar parllax measurement would always produce a nil result because neither star would act as the far, background object. Herschel decided to take another look at stars observed twenty-five years earlier, and found that most of them had moved with respect to the other—they were orbiting each other. At this point, he ended his quest for parallax [Hirshfeld 187-189].

5.3 Successes of Bessel, Henderson, and Struve

Besides the men previously mentioned, several other astronomers (Piazzi, Calandrelli, Arago, Mathieu, Baron von Lindenau, and Johann Schroter) had announced and published parallax measurements, but in every case, the results were met with extreme skepticism. Reverend John Brinkley published results for the parallax of Vega, Altair, Arcturus, and Deneb and the results were personally disputed by England's then-Astronomer Royal, John Pond prompting him to say "The history of annual parallax appears to me to be this: in proportion as instruments have been imperfect in their construction, they have misled observers into the belief of the existence of sensible parallax" [Hirshfeld 218-219]. After centuries of struggle, three men independently measured the first reliable stellar parallaxes over roughly the same period.

5.3.1 Friedrich Wilhelm Bessel and 61 Cygni

Bessel, very good at computing orbits of comets and other solar system bodies decided to measure the position of stars with unprecedented precision. He felt that these astrometry observations would assist in the location of any undiscovered planets if any subtle shifts in the known planets would ever be detected. By building better telescopes, he felt accuracies of up to one-millionth of a degree could be determined [Hirshfeld 214-215]. He even spent seven years of his life “reducing” stellar data obtained earlier by James Bradley, performing sequences of mathematical calculations to correct the raw data in the positions of more than three-thousand stars [Hirshfeld 217].

Later, as Bessel became more interesting in finding proof of stellar parallax, he concluded that the best targets would be stars that have had large observed proper motions—surely these stars must be close to the Earth. 61 Cygni (in Cygnus, the Swan) was one of the fastest (apparent) moving stars visible in the northern hemisphere—its proper motion 5.2 arcseconds/year. He found this “Flying Star” in the list of more than 7,600 stars that Father Giuseppe Piazzi had compiled into a catalogue [Hirshfeld 221].

61 Cygni is an *apparent* double star. To measure the separation between two stars, Bessel had a device called a heliometer. The objective lens of the telescope had been sliced into two precisely even halves by a diamond cutter. Turning a thumbscrew would slid the two sides laterally across each other. When the lens was offset, double images of all the stars would appear. Bessel intended to use the device to make the background star near 61 Cygni line up on top of 61 Cygni itself in order to get a very precise angular separation. The design was such that it canceled out the effects of atmospheric turbulence [Hirshfeld 258-259]. Bessel spent five years testing and calibrating the instrument to make sure it provides the highest quality results. He even took into consideration the effect that temperature has on the thumbscrew [Hirshfeld 260,262].

Unfortunately, the companion star to 61 Cygni was too faint to be seen at all times, and this caused Bessel to temporary abort his attempt to measure the parallax in 1834. Three years later, he picked *two* brighter nearby stars to measure the separations from 61 Cygni, and became nearly possessed in an attempt to measure the parallax with as great of precision as possible. He would take sometimes sixteen measurements per night and average them together for greater accuracy. This mad-paced fury was ignited by Wilhelm Struve's preliminary, and admittedly uncertain, parallax results for Vega.

Bessel had recorded hundreds of position measurements (derived from thousands of individual observations) for 61 Cygni by October 1838. He felt he had enough observations to present his case to the world. The star appeared to have the tale-tale signs of stellar parallax, just as had been predicted many years earlier—the star weaved at its maximum amount in June and December. He published his results in Astronomische Nachrichten with the title "Determination of the distance of the 61st star of the Swan" in December 1838. Astronomers had been waiting two millennia for this news.

The parallax angle of 61 Cygni was 0.3136 arcseconds [Ferguson 142], with an uncertainty of less than five percent. The stars distance was 660,000 astronomical units—96 *trillion*-km. The 5.2 arcseconds/year proper motion could now be converted into an absolute speed, and it could be said that 61 Cygni was moving through space at 270,000-km/hour. Bessel later refined his results to a parallax angle of 0.348 arcseconds on a second attempt at data collection. The modern-day value is 0.287 arcseconds (within 10% of Bessel's original estimate), putting the star 11 light-years from Earth [Hirshfeld 261-263].

5.3.2 Thomas Henderson and Alpha Centauri

Thomas Henderson reluctantly accepted a position in the Southern hemisphere, at the Cape of Good Hope. He couldn't stand the place once he arrived in April 1832 (and still hated it when he left only a year later), and routinely called it a "dismal swamp" with uncountable "insidious, venomous snakes" [Hirshfeld 201-202]. He was one of the first British astronomers to check the accuracy of his observations according to the mathematical theory of statistics [Hirshfeld 203].

Henderson had made nineteen precise measurements of the position of Alpha Centauri, the third brightest star, but also one invisible from European observatories. One of his colleagues sent him a report that indicated astronomers at St. Helena had determined that Alpha Centauri was moving quickly; i.e., it had a large proper motion—3.6 arcseconds/year. Henderson suspected that stars with large proper motions would be relatively close to the Earth, so Alpha Centauri made for an excellent target for stellar parallax measurement.

He believed he could see the expected pattern of stellar parallax, but he knew that nineteen measurements were insufficient to prove without doubt that Alpha Centauri's parallax had truly been measured. His measurements were also taken from instruments (mural circles) that had a reputation for being inaccurate. Rather than risk professional scorn and be labeled as yet another fool who tried to measure parallax and failed, he decided to wait for additional supporting data from his assistant before publishing the results [Hirshfeld 203-205].

Henderson published his results two months after Bessel's announcement. The parallax of Alpha Centauri was just over one arcsecond, putting it at a distance of 200,000 astronomical units, or one-third as far as 61 Cygni [Hirshfeld 263]. This figure was later refined to 0.76 arcseconds, or 1.3 parsecs, 4.3 light-years ago. This is actually a triple system, and the star Proxima Centauri is currently the closest to our Sun [Ferguson 142].

5.3.3 Friedrich von Struve and Vega

Bessel and Struve had met in the summer of 1814. They were friends, and it is possible that Bessel's interest in measuring stellar parallax also sparked Struve's interest in the same. Struve had in fact published a measurable parallax for a star in the Little Dipper, but his results were found to be questionable.

Struve obtained an incredible accurate telescope, the "Great Refractor" from Fraunhofer, and recorded the positions of over three-thousand double and multiple star systems—two-thirds of which new discoveries. He took a particular interest to Vega, the fifth brightest star. Vega had a companion 43 arcseconds away, but these two stars had different proper motions—most likely meaning they were not in the same system.

Struve realized that Bessel's 61 Cygni was a much better target, but Struve was unable to fit 61 Cygni and its reference star in the same field of view in his "Great Refractor". He made seventeen observations of Vega between November 1835 and December 1836, and computed a rough parallax of one-eight of an arcsecond. He published the preliminary, uncertain results, and spent the next year refining the data.

During the coarse of that year, Struve added ninety-six new measurements and by late 1839 was able to claim Vega had a parallax of 0.2613 arcsecond with 10% uncertainty, putting the star at roughly 800,000 astronomical units, or 8.3 parsecs, 26 light-years [Ferguson 142]. This parallax angle was twice as his preliminary result, and this made his entire process seem dubious. Vega's distance is greater than both Alpha

Centauri and 61 Cygni, so Struve's results were the hardest to compute (i.e., having the smallest parallax) [Hirshfeld 260-264].

5.4 Modern stellar parallax

There was a disconcerting feeling at the end of the nineteenth century—fewer than one-hundred stars had parallax results, and independent findings from different observatories often disagreed for the same star. It was usually systematic errors in the equipment that led to a particular observatories results being always either too big or too small [Hirshfeld 271].

The solution that would start run-away growth in the quantity of good parallax data was the camera. Each photograph, recording many stars on the same plate, was far more convenient to work with for the astronomer. The angular separations could be calculated in the daytime rather than at the eyepiece [Hirshfeld 272]. Charles Pritchard, in 1886, took 330 exposures of 61 Cygni over a two-year period. From the photographs, he was able to calculate a parallax of 0.45 arcsecond—the number is 50% off when compared to Bessel's, but it demonstrates the proof of concept of photography [Hirshfeld 274]. The CCD camera has improved photographic determinations of parallax roughly tenfold [Hirshfeld 275].

The Hipparcos—High Precision Parallax Collecting Satellite—launched in August 1989. The spacecraft was funded by the European Space Agency. A launch mishap left the spacecraft in a non-ideal orbit, but engineers were able to coax every scientific objective out of the satellite—to the delight of the astronomers. During its four year operational lifetime, it determined the parallax (and other properties) of 118,218 stars. Each star was observed about one-hundred times. The average precision of the parallax is 0.001 arcsecond. Hipparcos can find the distances to stars of up to 300 light-years away. 22,000 stars distances are now known to within 10%. Stars within 30 light-years have their distances known to within 1%. (Alpha Centauri is 4.395 light-years distant, Vega 25.3 light-years, and 61 Cygni 11.4 light-years.) The spacecraft has also directly measured the distance to the Hyades cluster (151 light-years) and the Pleiades (385 light-years) [Hirshfeld 276-277].

New spacecraft are in the works that will measure stellar parallax to even greater precision and greater distance. NASA's Full-sky Astrometric Mapping Explorer (FAME) may launch in 2004 and use parallax to measure stars up to eight-thousand light years away. The European Space Agency may launch Global Astrometric Interferometer for Astrophysics (GAIA) in 2009 that will have an accuracy in parallax measurement of 5-millioniths of an arcsecond [Hirshfeld 278]!

Why is there the need to know the distances to the stars so precisely? "Almost everything in astronomy depends in some way on knowing star distances"—Michael Perryman, former project scientist for the Hipparchus mission. It will help astronomers calibrate the light output of so-called "standard candles". These standard candles allow astronomers to measure the distance to far, away stars and galaxies that are no longer within the range of parallax. Mass of stars in a binary system can be determined more easily if we know how far away they are. Distance can be use to determine the true light output of the star in order to better derive the age and composition of star clusters, to determine if stars are really part of a cluster or just a "chance alignment", to explore how interstellar dust impedes starlight, and to deduce the overall patterns of movement of stars in our region of the galaxy.

6. Standard candles

6.1 RR Lyrae

RR Lyrae variables are stars that have the same periodic pulsations as Cepheids (see §6.2 below), but never change in luminosity, i.e., they always appear on the horizontal branch. RR Lyrae stars are very common in globular clusters. None of these types of stars are close enough for regular stellar parallax, but using statistical parallax, distances can be obtained to calibrate the system.

(Statistical parallax is based on the assumption that stars have random motions with respect to the Sun—extrapolating this infers that the mean motion along the Sun's line of light is the same mean motion perpendicular to the line of site.)

RR Lyraes have a fixed magnitude of 0.6 in the visible range. They are quite frequently found in globular clusters. By calculating the distance to the RR Lyraes in the globular clusters surrounding the Milky Way, one can actually compute when the size of the Milky Way [Smith 361-363].

6.2 Cepheids

Henrietta Swan Leavitt worked with Edward Pickering at Harvard College Observatory as a volunteer, but later was promoted to a paid position in 1902, and finally became head of the department. In 1908, while studying photographs of the Magellanic Clouds, she was looking for stars that vary in brightness. In the grand scheme of things, we can think of all the stars in the Magellanic clouds being more-or-less the same distance from Earth. This means it was safe to deduce any resolvable bright stars were truly brighter than any resolvable dim star. She was able to identity 2,400 variable stars in the Small Magellanic Cloud alone.

She soon discovered many of the variables had a repeatable pattern to their variation in light intensity. The light curves would always have a steep increase to maximum brightness followed by a gradual falloff. Some of the stars took longer to complete the pattern than others, and the ranges of brightness variations varied. The brighter a star, the longer it took to complete the pattern (one-to-three months) while the faintest took usually a day or two.

What Leavitt had found was a relationship between the star's period and brightness—the Period-Luminosity relationship. Looking closer to our own galaxy, she discovered the star Delta Cephei was also one of these types of variable stars. The relationship provided a far better way of pinpointing interstellar distance both in the galaxy and to other galaxies.

The relationship between magnitudes of two Cepheid's could be determined if one knew the relationship between their absolute magnitudes, i.e., if one Cepheid had a 3-day period, and another had a 30-day period, the second would be 6 times brighter than the first. These were relative distances though, not absolute distances. She needed at least one close by Cepheid to act as a calibration rod for her distance yardstick. However, the closest one, Polaris, was still not close enough to have its distance measured by parallax. Ejnar Hertzsprung used a modified form of statistical parallax to estimate the distance to two close by Cepheids [Ferguson 170-177].

There are two types of Cepheids (Population I and II) depending upon which stellar population the star belongs to. Population I Cepheids are four times brighter (1.5 magnitudes change) than Population II at a given period. Population II Cepheids appear in globular clusters, while Population I Cepheids never appear in Globulars [Smith 363].

Cepheids are luminous F-K giant stars, but they still fade into invisibility beyond 4-5 Megaparsecs [Smith 368].

6.3 Supernovae

Allan Sandage and others have discovered that supernovae in remote galaxies can also serve as yardsticks. They are extremely bright and can be seen from quite a distance away. In just a single minute, a supernova radiates more energy in the visible spectrum to outshine the entire galaxy in which it occurs. If these supernovae would reach the same brightness, they would serve as remarkable standard candles; but, there are more than one type of supernovae.

Most Type Ia supernova have the same brightness (although in the 1990's, it was discovered that brightness variations due occur). Type I supernova are exploding white dwarf stars. A white dwarf that acquires more than 1.4 Solar-masses will erupt into a supernova. Type I's are rare—and they are the brightest. In the Milky Way galaxy there have been only three in recorded history (1006, 1572, 1604). Astronomers must observe them in other galaxies with which the distance is already known in order to calibration the distance yardstick. Type II supernovae are exploding giant stars. While more powerful, less energy gets emitted at visible wavelengths. They are currently unreliable as distance metrics [Ferguson 233-236]. Type I supernovae have an absolute brightness of about –20 in the visual. It can be used to measure distance as far as 100 Megaparsecs [Smith 368-369].

7. Acknowledgements

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and Kitty Ferguson's Measuring the Universe: Our Historic Quest to Chart the Horizons of Space and Time.

8. Summary

This paper takes the reader through two-thousand years of history. It tries to answer one of the most basic questions: "How far away is that?" This seemingly simple question actually requires an answer that is gargantuan. It took two-thousand years, some very clever ideas, painstaking observations, and expensive custom-built equipment to get just the first measure of stellar distance. This paper only scratches the surface of the entire distance story. There was no mention of some of the more modern ways of computing distance (i.e., red shift using Hubble constant, main sequence fitting, Tully-Fisher and the 21 cm line, etc.) Many of the astronomers identified in this paper had to construct their own equipment, grinding and polishing mirrors, etc. Entire papers could be written on that alone. The main idea the reader should get is that determining distances to the stars is not an easy thing to do.

9. References

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