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Oh Glorious Geometry: Eclipses, Transits, and Occultations

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Abstract. Astronomical objects are like a grand clockwork in the sky; they follow steady patterns in time. However, these bright objects we see are not just points of light but have finite dimensions and thus can get in each other's way. As a result, some stars puzzle us by brightening or dimming, or the Sun can frighten us by going out unexpectedly when something else blocks its light. There is nothing unusual about these eclipses, occultations, or transits—they are demonstrations of simple physics—and we take some for granted, like the rotation of Earth moving us into darkness each night. The periodic dimming of a bright star worried mankind for millennia and helped give astronomy a shove. And unexpected events, like a solar or lunar eclipse, can inspire awe and change the course of history.

Now that we can observe through telescopes and travel by proxy throughout the solar system, we find the universe is rife with shadow and light shows. Those taking place within our solar system have been useful to astronomy (like the recent transits of Venus or the ever-present eclipses of the Jovian satellites), and were of considerable popular interest, allowing us to think beyond the confines of Earth. Now we detect distant exoplanets transiting their parent stars, announcing the presence of other solar systems in our corner of the Galaxy and changing the discussion about life elsewhere in the universe from mere speculation to plausible possibility. Distant galaxies can make visible ever-further galaxies by forming Einstein rings, allowing us to see behind them and make the structure of the universe more evident.

This paper will discuss these phenomena, from those visible easily on Earth to those that can now be seen for the first time from probes in space. We will also discuss how this has expanded popular knowledge of the universe we live in. This paper is illustrated by a number of examples ranging from eclipses and transits throughout the solar system and the nearby stars to the visibility of the gossamer-like strands of gravitational fields at the edge of the observable universe.

1. Prologue

The painting *Orion and the Sycamore* by Daniel Owen Stephens,[1] shown in Figure 1, illustrates the theme of this paper. A bare tree in the foreground almost obscures one of

[1]Daniel Owen Stephens (1893–1937) was an architect, artist, and amateur astronomer, whose paintings and sketches were largely on astronomical themes. He studied astronomy in college, but decided that was not a career choice for him and became a professional architect. He continued his interest in astronomy through his paintings. He joined several solar eclipse expeditions of the American Museum of Natural History as a staff artist and recorder, and made a number of paintings of the eclipses. In these paintings he did not strive for the scientific accuracy of Howard Russell Butler (Sinclair 2012), a contemporary painter of eclipses, but rather strived to record his impressions of these rare events.

the stars in the rising constellation Orion. On the frame is the line, "Oh Glorious Geometry! To hide a Sun behind a Twig." This records Stephens's feeling of amazement at the connection between the everyday world and the vastness of the universe.

Figure 1. Daniel Owen Stephens, *Orion and the Sycamore*, circa 1920, present whereabouts unknown. (Loring Starr)

His point, of course, is one of perspective: a small, nearby object can conceal, or eclipse, a larger, distant one. But to understand this painting, we have to know that a star which appears as a point of light in the sky is actually as large as our Sun. This requires that we know about the scale of the solar system and the visible universe, and a stars's size and its distance. Stephens assumed the viewers of his painting would know this. However, this is knowledge gained by modern astronomy only in the past few centuries, which shows how quickly the findings of science became part of our common knowledge and cultural heritage.

2. Size is in the Eye of the Beholder

Until the beginning of modern astronomy and the invention of the telescope, the stars and planets in the night sky were taken to be simple points, without dimension or structure. Most of these points—the stars—were fixed in place and moved as a whole, while a few—the planets—wandered through the sky in seemingly complex ways. A few stars, called novae, appeared suddenly and then faded away. One star was seen to vary periodically in brightness. Otherwise, the sky was a simple structure of constant, non-interacting elements. Only a few lights in the sky, such as the Sun and the Moon, the occasional comet and bolide, auroras, and a few unresolved smudges of light such as the Milky Way and the Magellanic Clouds, clearly had finite (i.e., nonzero) dimensions and details visible to the naked eye.

There were early speculations about the size and distance of astronomical objects, but these had little empirical verification and were lost in a thicket of a priori ideas. Solar and lunar eclipses were largely the subject of folklore and mythology, even though the causes were slowly becoming understood. This changed in 1610 when the telescope began to show that the points in the sky had size and structure—astronomy became a science. It was only in 1639 that the distance to the planets (and thus their sizes) was determined with any accuracy, and not until 1838 that the distance to a nearby star was first accurately measured. In 1915, the size and nature of galaxies was first shown, and finally in 1920 the first direct measurement of the diameter of a star (other than our Sun) was made (Rowan-Robinson 1984). This measurement was of the brightest star in Orion, Alpha Orionis (traditionally called Betelgeuse), and showed it was several hundred times larger than our Sun (Michelson & Pease 1921). Although Stephens probably chose Orion for his painting because it is an easily recognizable constellation, it is possible that Stephens had also heard of this unusual result, and had it in mind when he showed Betelgeuse about to be hidden by the sycamore tree's branches.

But more than thinking of the symbolism of hiding a star with a twig, or the Moon with a thumb, we now understand that because astronomical bodies are of finite sizes and are continually in motion, they can, from our point of view, occasioanlly get in each other's way, concealing one another briefly. We can predict these events with high accuracy and use them as new ways to study these bodies. Such events like eclipses, the transits of Venus, or the rare disappearance of a star when it is briefly covered by an asteroid, have become popular events, although most of them still go unnoticed outside scientific circles.

We distinguish between three ways that one astronomical body can interact visually with another. Consider this entry in Whitaker's Almanack (1910) concerning the visibility of the satellites of Jupiter as they move in and out of our sight: "Only Satellite IV will be visible at 2:30 a.m. February 24, Satellite II being in transit, Satellite III occulted, and Satellite I eclipsed." Here are three different phenomena—eclipses, transits, and occultations—occurring within the Jovian system at once. We will consider them one at a time.

3. Eclipses

> An interception or obscuration of the light of the sun, moon, or other luminous body, by the intervention of some other body.

We usually reserve the word *eclipse* for bodies of roughly the same apparent size, such as the Sun and the Moon. Eclipses of the Sun and the Moon have occurred for eons, long predating human observers. Now that humans are here to observe them, these eclipses are the most spectacular events caused by one body getting in the way of another. They were a mystery for most of that time—a solar eclipse would come unexpectedly; for a few minutes the sun would disappear and in its place was a black hole in the sky. Then the Sun would reappear, first as a sliver of light, then gradually it resumes its full shape. In the days before easy travel, few people ever saw solar eclipses, and only very rarely did people see more than one in their lifetime. They were things of wonder and dread, and people worried what they could presage.

We now have a simple mechanical explanation for these events. We know that eclipses need three bodies to occur in a line: usually one is luminous, the second (of order the same apparent size as the first) casts a shadow, and the third (with an observer on board) is in the shadow and, thus, loses the light of the first for a while. Thus when the Sun, the Moon, and Earth are so placed that the shadow cast by the Moon just touches Earth, those lucky enough to be in the small shadow zone see the Sun's light completely blocked by the Moon for a short time. Solar eclipses happen somewhere on Earth every year or so, but occur at any one location perhaps every three hundred years. Thus, for millennia, few people ever saw one. There have been presentations at earlier INSAP meetings which have explored the varied reaction of artists to solar eclipses (Sinclair 1995, 2012; Pasachoff & Olson 2015).

Similarly, when the Moon passes through Earth's shadow, sunlight is blocked from it for up to an hour, and the full moon becomes a ghostly, reddish color. Lunar eclipses (which also happen roughly annually) are visible over a good part of Earth, so they are seen by many more people, but still have been looked upon with fear (Figure 2).

Figure 2. Edward S. Curtis, photograph of the Kwakwaka'wakw People (also known as the Kwakiutl) dancing to restore the Moon-lunar eclipse, British Columbia, circa 1910. (Edward S. Curtis Collection, US Library of Congress)

Nowadays, with our understanding of celestial mechanics, eclipses are simply accurately predicted shadow-and-light shows. The wonder is still there, and even some of the earlier fears are still with us. These fears may be allayed by recalling that the Sun disappears every night behind Earth's limb as we rotate from sunlight into shadow.

Solar eclipses are not limited to our planet and its moon, of course. All the planets and moons cast their own shadows. Rather than wait for a solar eclipse to come to us, we can pack up and go to a convenient shadow and use it to block out the sunlight that otherwise fills the solar system. For example, we can now place cameras (and thus our eyes) on an automatic space station behind Saturn and see something never before seen: we can watch Saturn eclipse the Sun for us while its ring system continues to shine brightly in the sunlight (Figure 3).

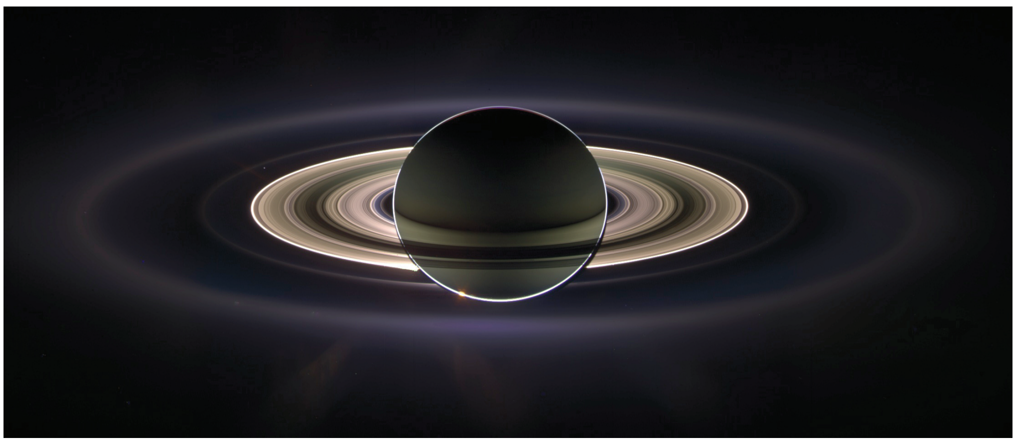

Figure 3. Saturn eclipsing the Sun, leaving the ring structure illuminated (color contrast exaggerated). From a series of photographs taken by the Cassini-Huygens Robotic Spacecraft wide-angle camera September 15, 2006, at a distance of 2.2 million kilometers (1.3 million miles) from Saturn. The Cassini-Huygens mission is a cooperative project of NASA and the Jet Propulsion Laboratory, the European Space Agency, and the Italian Space Agency. (NASA/JPL/Space Science Institute)

One star can eclipse another if they form a close binary pair. Then they can alternately pass in front of each other to become an *eclipsing binary*. For example, in the constellation Perseus there is a moderately bright star called Algol (Beta Persei). It is remarkable in that approximately every three days its light dims rather suddenly for several hours before returning to its former brightness. This change in brightness is sufficiently large to be apparent to the naked eye. This unusual behavior of Algol was apparently known in antiquity, hence the traditional names Winking Demon Star or the Raging One (Wilk 1996; Jetsu et al. 2013); however, the reason for this change in brightness was not understood. It is now known to be a pair of stars in close orbit, one significantly brighter than the other, dimming briefly when the darker star eclipses the brighter one (Figure 4).[2]

[2]There is also a small dip in brightness, not visible to the eye, when the brighter star passes in front of the dimmer one. The data in Figure 4 are based on the observations appearing in Stebbins (1921), later confirmed and turned into an idealized diagram by L. McNish (private communication).

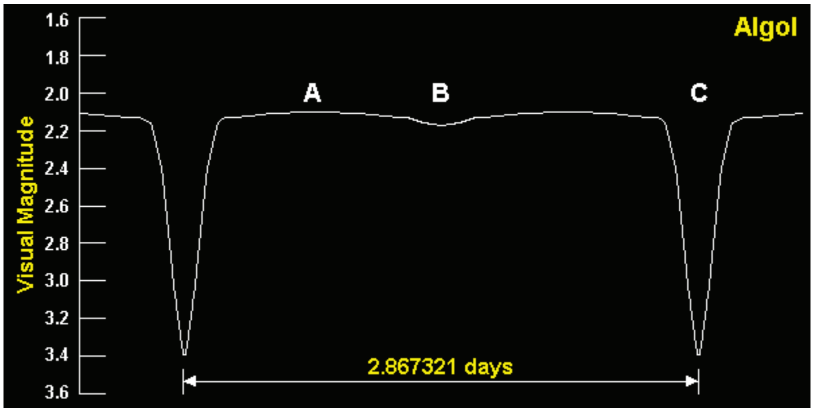

Figure 4. Light curve for Algol (Beta Persei). *A* marks the steady light from both stars of the pair, *B* marks the eclipse of the dimmer star by the brighter one, and *C* marks the eclipse of the brighter by the dimmer. Illustration from L. McNish (private communication) based on the data of J. Stebbins (1921). (Larry McNish, Calgary Centre of the Royal Astronomical Society of Canada)

In this discussion of eclipses, we have assumed that astronomical bodies cast sharp geometrical shadows. This is largely true for small bodies like planets and satellites. But for heavier bodies we enter a strange, new world in which eclipses are not that simple and don't happen in the typical sense—here the proper description requires the general theory of relativity. The more massive a body is, the more it distorts the space around it, so light passing nearby a massive body follows a curved path.

The Sun is massive enough to deflect the beam of light from a star by a small, but measurable, amount; hence, the apparent position of the star during a solar eclipse is slightly inaccurate. A galaxy (with the mass of billions of stars) can deflect and amplify light from a more distant (and otherwise unseen) galaxy positioned behind it into a brighter Einstein ring (if they are lined up) or into brighter arcs (if they are not). We can thus "see around" the eclipser. Space is rich with a kaleidoscope of these rings and arcs, each making visible the gossamer-like strands of the gravitational fields throughout the observable universe. We can now study distant galaxies beyond those galaxies we normally see in our telescopes, and, therefore, learn much more about the nominally eclipsed objects as well as the eclipsers (Wambsganss 2001).

4. Transits

> The passage of an inferior planet (Mercury or Venus) across the sun's disk, or of a satellite or its shadow across the disk of a planet.

A transit occurs when a small, dark body crosses in front of a much larger, luminous one, so that only a little of the larger body is hidden. Disregarding such transits as a flock of geese flying across the disk of the Moon, and considering only those in the astronomical sense, the first and most famous transits are those of Mercury and Venus across the Sun.

During a transit, Mercury or Venus is seen as a tiny black dot crossing the Sun's surface. But this can be seen only with a special projecting telescope, since the Sun is too bright to look at directly. For this reason, observing such a transit had to wait for the invention of this equipment. Although these transits have occurred as long as the planets have circled the Sun, they remained unseen until Jeremiah Horrocks (1618–1641), who observed a transit on November 24, 1639 (Julian calendar), at about 3:15 p.m. He was the first person to predict and then observe a transit of Venus.

Transits of Venus are rare, occurring twice in eight years, then another pair of transit events happen a little more than a century later. Careful measurement of these transits allows a determination of the size of the solar system, and was thus of great interest to astronomers who traveled afar to places where each transit was best observed. (Transits of Mercury occur more often, usually a dozen or more per century, but are not useful for this purpose.) For example, the Venus transit of June 6, 1761, was observed at Cape Town by the British astronomer Charles Mason (1728–1786) and the British surveyor Jeremiah Dixon (1733–1779), whose efforts appeared in a novel by Thomas Pynchon (1997).[3]

Following that, the first voyage to the South Pacific by Lieutenant (later Captain) James Cook, RN (1728–1779) was nominally to observe the transit of June 3, 1769, on Tahiti and other nearby islands.

Despite their rarity and difficulty to observe, transits were taken up by the popular imagination. A century after Cook's voyage, the next pair of transits was widely known publicly and John Philip Sousa contributed his *Transit of Venus March*[4] for the transit of December 6, 1882.[5]

The recent transits of 2004 and 2012 were well watched and inspired their share of art, as described at INSAP V (Bueter 2012). For those who did not see the two transits of Venus this century, I am afraid you will never see one—the next ones will occur in 2117 and 2125. But cheer up, there are other transits in the solar system.

We have observed transits of Mars's moons across the Sun from the Martian surface using the cameras on our "roving geologists," the Jet Propulsion Laboratory's Mars Rovers, as astronomical instruments. And from Mars we could observe transits of Earth, although during the last one in 1984, we did not have an "observer" on Mars. The next one will not be until 2084. The late Sir Arthur C. Clarke (1917–2008) wrote a story in 1971 looking ahead to the 1984 transit, in which he imagined a doomed mission to Mars whose last survivor had his final glimpse of Earth as it transited the Sun (Clarke 1971).

Of course transits occur everywhere there are stars and planets. New planets around other stars, called exoplanets, are being discovered daily by patiently monitoring the brightness of nearby stars and watching for the telltale tiny drops in luminosity that are the signals of planets transiting the stars' disk. Some two thousand such planets, often in complex planetary systems, have been confirmed to date by this method, with twice that number of candidate systems remaining to be studied further (Heng & Winn 2015).

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[3]Interestingly, they also separately observed the next transit of that pair in 1769, with Mason in Ireland and Dixon in the north of Norway, after having completed the Mason-Dixon Line survey in the United States.

[4]Available in the Library of Congress, `http://lcweb2.loc.gov/diglib/ihas/html/venus/venus-home.html`

[5]For information on these and other observations of all these transits see (Sheehan & Westfall 2004).

5. Occultations

> The concealment of a celestial object by another interposed between it and the observer. Commonly used in cases where the occulting body is of much greater apparent size than that occulted. In the case of a planet's satellites, such as those of Jupiter, an eclipse takes place when a satellite passes into the planet's shadow, an occultation when it passes behind the planet's disc.

Occultations occur often, but they do not seem to attract as much popular attention as transits, and certainly not as much as eclipses. The Moon in its monthly passage across the constellations occults the stars in its path for an hour or two each. But no one seems to worry about this, perhaps since the brightness of the Moon tends to wash out the other stars. However, as the dark edge of the waxing Moon occults a star, careful observations of the light at that moment have shown that many of the stars so occulted are actually binary pairs, too close to have been discovered by other means. Figure 5 shows the light curve of the star Sigma Scorpii as the Moon occulted it. The step in the light curve, lasting only one-half second, shows that this star actually consists of a close pair. Many of these occultations are studied by amateur astronomers with appropriate equipment.

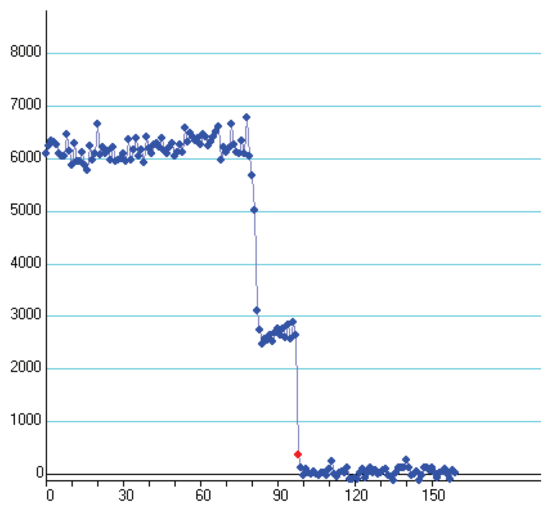

Figure 5. Light curve of lunar occultation of Sigma Scorpii, observed August 14, 2005, 10:25:16.62 UT at Brian Loader's home observatory in Darfield, New Zealand. The left part of the curve shows the star preoccultation. The right part of the curve shows the complete obscuration of the star by the Moon. The middle part along the drop in light signals the existence of a binary, which is shown singly for a half second while the Moon has covered its companion. (Brian Loader and Steve Kerr, Director of the Royal Astronomical Society of New Zealand Occultation Section)

The observations of the occultations (and eclipses) of the Jovian satellites by Jupiter did lead to the first determination, in 1676, of the speed of light by the Danish astronomer Ole Rømer (1644–1710). These occultations and eclipses also furnished, for a time, a certain utility for surveyors and mariners because the timing of these events could be calculated accurately at, for example, Greenwich. Thus they acted as a clock in the sky that read Greenwich Time, available anywhere in the world. Comparing that time with the local time of the observer yielded the observer's longitude. This somewhat clumsy technique was made obsolete by the invention of reliable chronometers on ships, which enabled Greenwich Time to be known everywhere (Sobel 1995).

One recent occultation did receive considerable advance publicity. Regulus (Alpha Leonis), the brightest star in the constellation Leo and one of the brightest stars in the night sky, was occulted by the asteroid 163 Erigone (a mere forty-five miles in diameter), which caused the star to disappear for 14 seconds around 2:00 a.m. on March 20, 2014. This rare event (Preston 2014) could have been seen along a path cutting across New York State and New York City had it not turned out to be uniformly cloudy along the path. No one has reported seeing it (Beattie 2014).

6. Conclusion

In conclusion, the bodies that make up the universe continue an endless square dance with gravity as the caller. To an observer, sometimes they seem to get in each other's way. This proves to be a particularly useful tool to understand the nature of these bodies. It also leads to surprises that—depending on how we interpret them—can give us moments of unexpected beauty or fear.

Acknowledgments. The idea for this paper came from the painting *Orion and the Sycamore*. Loring Starr (Montpelier VT), a granddaughter of the artist, kindly furnished me with a color photo of the painting and gave me permission to use it here. Ed Krupp (Griffith Observatory) was particularly helpful in sharing his knowledge of the transits of Venus and Mercury.

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