DRAFT PAPER ON JACQUES CASSINI, JOHANNES KEPLER AND THE STARRY UNIVERSE

In 1717 Jacques Cassini published a paper in which he described a method for measuring the apparent diameter of the star Sirius. By this method, he said, that diameter could be determined to be five seconds of arc. In that 1717 paper, Cassini also published an observed parallax for Sirius. From his parallax and diameter measurements, and from certain assumptions about telescopic observations of the stars, Cassini determined a size and a distance for Sirius, and indeed a size for and a loose depiction of the observable starry universe. Other writers from the early to mid-eighteenth century cited and discussed his work. Edmund Halley rejected his measurements. When later writers, such as John Hill, who wrote on astronomy for broad audiences, engaged with Cassini's work regarding Sirius, they typically discussed only portions of his work, selected or abridged in such a way as to represent that work in a manner at odds with his depiction of the starry universe. The work of Cassini, Halley, and later writers tells a story about ideas regarding the starry universe in the eighteenth century, and the interplay between those ideas and data obtained from observations of the stars.

STAR DIAMETERS AND WORLD SYSTEMS

Pre-telescopic astronomers from Ptolemy in ancient times to Tycho Brahe in the late sixteenth century had attempted to measure the apparent diameters of the stars. Their results were that the apparent diameter of a first magnitude fixed star was roughly one fifteenth the apparent diameter of the moon. The wandering stars (planets) had similar apparent diameters.[1]

These apparent diameters spoke to the nature of the starry universe when interpreted with a world system in mind. Given an object of known apparent diameter, its true diameter will depend on its distance, with greater distance translating into greater true diameter (Figure 1). Consider a

[1] Albert Van Helden, *Measuring the Universe: Cosmic Dimensions from Aristarchus to Halley* (Chicago: University of Chicago Press, 1985), pp. 27, 30, 32, 50.

geocentric world system, such as that of Brahe (in which the sun, moon, and stars circled Earth while the planets circled the sun). In this system the fixed stars lay a little beyond Saturn. Thus a fixed star that appeared similar to Saturn in the sky would in fact be similar to Saturn in true size, as both had similar apparent sizes and similar distances. In the heliocentric world system of Copernicus, however, the fixed stars had to be farther away in order to explain the absence of any observable annual parallax in those stars. As seen in Figure 1, this increased distance translated into increased true size. Brahe, having searched for parallax but not detected it, stated that in a heliocentric universe fixed stars would have to be at least 700 times more distant than Saturn to explain the lack of detectable parallax.[2] This means they would also have to be 700 times greater in true diameter—far larger than even the sun. As Albert Van Helden has written, "Tycho's logic was impeccable; his measurements above reproach. A Copernican simply had to accept the results of this argument" and agree that the stars were giant.[3]

Johannes Kepler is one Copernican who did agree. By his estimations, all visible fixed stars were larger than Earth's orbit, and Sirius was larger than Saturn's orbit—and thus larger than an entire geocentric universe. Kepler also reasoned that the fixed stars were dim. This was because their combined power to illuminate the sky was insignificant compared to the sun, while the fraction of the sky that they together occupied was comparable to that occupied by the sun. Their distance could not excuse their dimness, Kepler said, because the farther away they were assumed to be, the larger they would have to be (again, Figure 1). Thus observations, measurements, and calculations seemed to show that the Copernican universe consisted of myriad vast, dim, distant stars enveloping a single, unique sun (itself both tiny and brilliant compared to them) and the sun's still tinier planets. Kepler used this to attack Giordano Bruno's notion that the stars were other suns, orbited by other Earths; what Bruno said was contrary to what any astronomer could easily determine for himself.[4]

[2] Ann Blair, "Tycho Brahe's Critique of Copernicus and the Copernican System," *Journal for the History of Ideas*, 51, 1990, p. 364; Kristian Peder Moesgaard, "Copernican Influence on Tycho Brahe," in *The Reception of Copernicus' Heliocentric Theory*, Jerzy Dobrzycki, ed. (Boston: D. Reidel, 1972), p. 51.
[3] Van Helden, *Measuring the Universe* (ref. 1), p. 51.
[4] Christopher M. Graney, "The Starry Universe of Johannes Kepler," *Journal for the History of Astronomy*, 50, 2019, pp. 162-66.

Thus Kepler embraced the giant stars that resulted from apparent diameter measurements applied to a heliocentric universe. Indeed, he argued in his 1606 *De Stella Nova* that the brilliant, tiny sun versus the dim, hulking stars testified to God's ability to create on a vast scale while still retaining full concern for the smallest things.[5] This was in contrast to Brahe, who saw the giant stars as a strong argument against heliocentrism. In Brahe's world system, all celestial bodies, including the stars, were commensurate in size, with the largest being the sun and the smallest being the moon.[6]

STAR DIAMETERS AND THE TELESCOPE

The advent of the telescope prompted a reassessment of the apparent diameters of stars. Galileo Galilei wrote in his 1610 *Starry Messenger* that the telescope showed stars to have no distinguishable form:

> [T]he fixed stars are never seen to be bounded by a circular periphery, but have rather the aspect of blazes whose rays vibrate about them and scintillate a great deal. Viewed with a telescope they appear of a shape similar to that which they present to the naked eye, but sufficiently enlarged so that a star of the fifth or sixth magnitude seems to equal the Dog Star, largest of all the fixed stars.[7]

However, what Galileo related in the *Starry Messenger* were the observations of a man who had been using a telescope for mere months. With a little more experience, he began to refer to stars as spheres. Thus as early as 1612-13, in his letters on sunspots, we find, "stars, whether fixed or wandering, are seen always to keep the same shape, which is spherical,"[8] and "the telescope shows us the shapes of all the stars, fixed as well as planets [wandering stars], to be quite round."[9] In subsequent work, Galileo consistently reported that the telescope reveals fixed stars

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[5] Christopher M. Graney, "As Big as a Universe: Johannes Kepler on the Immensities of Stars and of Divine Power," *Catholic Historical Review*, 105, 2019, pp. 75-90.

[6] Christopher M. Graney, *Setting Aside all Authority* (Notre Dame, Indiana: University of Notre Dame Press, 2015), pp. 34-37.

[7] Stillman Drake, *Discoveries and Opinions of Galileo* (Garden City, New York: Doubleday Anchor Books, 1957), p. 47.

[8] *Ibid.*, p. 100.

[9] *Ibid.*, p. 137.

to be round, with apparent diameters of some few seconds of arc. In his 1632 *Dialogue Concerning the Two Chief World Systems—Ptolemaic and Copernican*, he states that first-magnitude stars have an apparent diameter of five seconds of arc.[10]

Other astronomers also reported that the telescope revealed the stars to be round bodies. Simon Marius in his 1614 *The World of Jupiter* stated that “all the principal fixed stars are seen exquisitely round.”[11] Martin Hortensius and Johannes Hevelius both produced telescopically measured apparent diameters of fixed stars. The values they reported were a little larger than the five seconds stated by Galileo: Hortensius put the apparent diameter of Sirius at ten seconds, Hevelius at just over six.[12]

Obviously the telescope forced a re-assessment of the apparent diameters of the stars, and this held true for both fixed and wandering stars. The apparent diameters measured by pre-telescopic astronomers such as Ptolemy and Brahe were roughly 100 seconds of arc or more. The apparent diameters measured by means of the telescope were a fraction of that. Consider what the telescope showed in the case of the wandering star Venus. A keen eye sees Venus as a bright dot with an apparent diameter approximately one tenth that of the moon, as Ptolemy and Brahe said. But through the telescope, Venus’s disk appeared much smaller relative to the moon’s disk—the telescope seemingly enlarged the moon more than it enlarged Venus. Moreover, seen through the telescope, the disk of Venus significantly varied in apparent diameter over time, and showed the phases Galileo had discovered, ranging from nearly a full disk to a slim crescent (Figure 2). The explanation for all this was that the telescope stripped away the glare or “spurious rays” or “adventitious irradiation” from Venus, revealing the bare body of the wandering star, and thus its true form and its correct apparent size.[13]

[10] Graney, *Setting Aside* (ref. 6), pp. 45-49.
[11] A. O. Prickard and Albert Van Helden, “The World of Jupiter, English Translation of *Mundus Iovialis*,” in H. Gaab and P. Leich, eds., *Simon Marius and His Research* (Springer, 2018), p. 8.
[12] M. Hortensius, *Dissertatio de Mercurio in Sole Viso* (Leiden, 1633), pp. 60-64; J. Hevelius, *Mercurius in Sole Visus* (Gedani, 1662), p. 94.
[13] See Galileo Galilei, *Dialogue Concerning the Two Chief World Systems: Ptolemaic and Copernican* (New York: Random House/Modern Library, 2001), pp. 418-19 for a discussion. Here Galileo refers to the telescope as “showing the disc of the star [either wandering, such as Venus, or fixed] bare and very many times enlarged.”

The telescope was thought to do the same thing for fixed stars. The telescopes of the seventeenth century indeed revealed fixed stars to be distinct disks. Refer to Figure 3, and consider the following observation recorded by John Flamsteed, the first English Astronomer Royal:

> 1672, October 22. When Mercury was about 10 deg. high, I observed him in the garden with my longer tube (of 14 foot); but could not with it see the fixa [fixed star] (near him), the daylight being too strong; only I noted his diameter 45 parts = 16″, or a little less; for, turning the tube to Sirius, I found his diameter 42 parts = 15″, which I judged equal to Mercury's. The aperture on the object-glass was ¾ of an inch: so that Sirius was well deprived of spurious rays, and shined not turbulently, but as sedate as Mercury; the limbs of both well defined, but Sirius best.[14]

Note Flamsteed's indication that the disk of Sirius was more clearly defined than that of Mercury. Note also Flamsteed's somewhat larger estimate for the apparent diameter of Sirius.

Giovanni Battista Riccioli also obtained a larger apparent diameter for Sirius. He conducted a thorough investigation of the apparent diameters of fixed stars, which he described in his 1651 *Almagestum Novum*.[15] Here Riccioli stated that determining the apparent diameter of fixed stars requires observing planets and comparing planetary and stellar diameters, using a telescope whose aperture had been restricted to help eliminate spurious rays. He described how he and his assistant Francesco Maria Grimaldi would observe Jupiter or Saturn and create an image on paper that matched the view of the planet through the eyepiece. When this was done, they would turn the telescope to a star, and determine its diameter by comparing it to the planetary image. Riccioli emphasized the importance of repeated and immediate comparisons between what was on paper and what they saw through the telescope—apparently they used a sort of "blink comparison," in which one eye observes the paper while the other observes the image in the telescope, or a similar method. He had other observers repeat this process, and all their observations were in close agreement; anyone with a good telescope and unbiased observers, he said, could use this method to reproduce the results of his observing team. The telescopically

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[14] Francis Bailey, *An Account of the Rev'd John Flamsteed, the First Astronomer-Royal, etc.* (London, 1835), p. 205.
[15] Works that have been translated into English I refer to by their English titles; works that have not I refer to by their original titles.

measured apparent stellar diameters he reported ranged from 18 seconds for Sirius down to just over 4 seconds for little Alcor in the handle of the Big Dipper.

But in 1659, Christiaan Huygens in his *Systema Saturnium* declared that telescopic observations of fixed stars filtered through a smoked glass showed that their apparent diameters were changed by greater filtering. This did not happen with the Moon or planets, he said. Then in 1662, Hevelius published observations by Jeremiah Horrocks reporting how when Horrocks and his friend William Crabtree had observed the Moon passing through the stars of the Pleiades, the stars had simply winked out as the Moon passed in front of them. Horrocks argued that this was evidence that stars have no true size, but are in fact mere points of light, "for the moment the Moon covered the true body of the fixed stars, the false rays vanished instantaneously. If they had been emitted from the true body, they would have vanished by degrees and not at all in a single moment."[16] In 1674, Robert Hooke noted in his *An Attempt to Prove the Motion of the Earth* that he had been able to observe through his telescope during the daylight a fixed star at the zenith, and that it appeared to be very, very small:

> [B]y this Observation of the Star in the day time when the Sun shined, with my 36 foot Glass I found the body of the Star so very small, that it was but some few thirds [i.e. *sixtieths* of an arc second] in Diameter, all the spurious rayes that do beard it in the night being cleerly shaved away, and the naked body thereof left a very small white point.[17]

Thus, various types of observations suggested that even telescopically measured stellar apparent diameters were spurious. However, not all astronomers accepted this. Flamsteed, for example, citing his own experience observing Sirius and Mercury, explicitly rejected Huygens's claims as "plain prejudice."[18]

[16] Graney, *Setting Aside* (ref. 6), p. 150-52.
[17] Robert Hooke, *An Attempt to Prove the Motion of the Earth from Observations* (London, 1674), p. 26.
[18] Graney, *Setting Aside* (ref. 6), p. 152.

Cassini on the Apparent Size and Parallax of Sirius

Thus when Cassini published "De la Grandeur des Etoiles Fixes, et de leur Distance a la Terre" in 1717, the subject he was addressing was certainly not new.[19] He opens the paper with some remarks on the history of estimates of stellar distances. He claims reluctance on the part of some in the past to embrace the large distances that astronomical observations indicated. He then gets to his own observations:

> We recognize no bounds to the immensity of the works of God, who has taught us through his prophet that the heavens and the firmament make known to us his glory and the excellence of his works. We will examine without prejudice what size of the fixed stars results from our observations.
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> We can hardly separate the consideration of the size of the fixed stars from that of their distances, because the reckonings of these two are united together so closely, that, one being determined, the other necessarily results. Indeed, geometry teaches us that having determined the apparent size of a far-away object and its distance, we know its true size; and in turn, knowing the apparent size of this object and its true size, we can determine its distance.
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> It is difficult to know the apparent size of the fixed stars exactly. This is because the rays that they throw out on all sides and the vivacity of the light [*la vivacité de la lumiere*] that surrounds them prevent us from distinguishing the edge of their circumference. From among the methods that can be used to determine it, we have selected that which results from the comparison of their size to the exactly-known size of one of the planets.[20]

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[19] J. Cassini, "De la Grandeur des Etoiles Fixes, et de leur Distance a la Terre," *Memoires de Mathematique et de Physique tires des Registres de l'Academie Royale des Sciences de l'Année MDCCVII* (13 Novembre 1717), pp. 256-68.

[20] *Ibid.*, pp. 257-8: "Pour nous qui ne reconnoissons point de bornes à l'immensité des ouvrages de Dieu, qui nous a appris par son Prophete que les Cieux & le Firmament nous faisoient connoître sa gloire & l'excellence de ses ouvrages, nous examinerons sans aucun préjugé quelle est la grandeur des Etoiles fixes qui resulte de nos Observations. On ne peut guere séparer la consideration de la grandeur des Etoiles fixes de celle de leurs distances, puisque ces deux connoissances sont si étroitement unies ensemble, que l'une étant déterminée, l'autre en resulte necessairement. En effet, la Geometrie nous apprend qu'ayant déterminé la grandeur apparente d'un objet éloigné & sa distance, on sçait sa grandeur veritable, & que réciproquement connoissant la grandeur apparente de cet objet & sa grandeur veritable, on peut déterminer sa distance. A l'égard de la grandeur apparente des Etoiles fixes, il est difficile de la connoître exactement, à cause que les rayons qu'elles jettent de

Cassini states that he chose to measure the diameter of Sirius, for reason of its brilliance. He then continues,

> To decrease the vivacity of its light, we applied to the object glass of an excellent 34-foot telescope a piece of cardboard that covered the glass, except for a round opening of an inch and a half in diameter. The telescope being thus prepared, we directed it to Sirius. Its disk seemed to us to be well defined and despoiled of most of the sparkling rays which ordinarily surround it [see Figure 3].[21]

Next, he says, he directed the telescope toward Jupiter, which was also above the horizon at the time. Comparing Jupiter and Sirius (he seems to have used a modification of Riccioli's technique with the intermediate paper image omitted) he found the apparent diameter of Jupiter to be ten times that of Sirius. And, he says, as the apparent diameter of Jupiter was 50 seconds at that time, the apparent diameter of Sirius was about 5 seconds.[22] (Cassini also included this discussion of Sirius's apparent size in his 1740 *Elements d'Astronomie*.[23])

Cassini also reports on having measured the annual parallax of Sirius. To do this he had used a three-foot telescope fixed in position on a mural quadrant that had been solidly mounted on a wall for thirty years and thus was supposed to be very stable. The telescope had been outfitted with a crosshair, and Sirius had been observed over the course of a year, from April 1714 through June 1715. Cassini reports that, during this time, Sirius moved relative to the crosshair in

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toutes parts & la vivacité de la lumiere qui les environne, empêchent de distinguer le terme de leur circonference. Entre les méthodes qu'on peut employer pour la déterminer, nous avons preferé celle qui resulte de la comparaison de leur grandeur à celle des autres Planetes qui est connuë assés exactement."

[21] *Ibid.*, p. 258: "Pour diminuer la vivacité de sa lumiere, nous avons appliqué au Verre objectif d'une Lunette excellente de 34 pieds un Carton qui couvroit la plus grande partie de ce Verre, & ne laissoit qu'une ouverture ronde d'un pouce & demi de diametre. La Lunette étant ainsi préparée, nous l'avons dirigée à Sirius dont le disque nous a paru assés bien terminé & dépouillé de la pluspart des rayons étincellents qui l'environnent ordinairement." For a full technical discussion of this appearance of a star that Cassini describes, see Christopher M. Graney and Timothy P. Grayson, "On the Telescopic Disks of Stars: A Review and Analysis, etc.," *Annals of Science*, 68, 2011, 351-74.

[22] *Ibid.*, pp. 258-9: "Le diametre apparent de Jupiter étoit alors de 50 secondes, d'où il resulte que celui de Sirius étoit d'environ 5 secondes." This diameter value suggests that Cassini made these measurements in November 1715, when Jupiter was at opposition in Taurus, its apparent diameter was approximately 49 seconds of arc, and it was positioned north and west of Sirius.

[23] Jacques Cassini, *Elements d'Astronomie* (Paris, 1740). Some parts are repeated verbatim, including the sentence in the previous note (see p. 51).

a manner entirely consistent with annual parallax. Other possible causes for its motion had been explored and ruled out. The annual parallax of Sirius, according to Cassini, was 6 seconds of arc.

With the apparent diameter and parallax of Sirius in hand, Cassini proceeds to determine the true diameter of Sirius. Were Sirius assumed to be at about the distance of Saturn (as in Tycho Brahe's world system), that is, at a distance of 100,000 diameters of Earth, he writes, then its 5 second apparent diameter would translate into a true diameter of just over twice that of Earth. Were Sirius the size of the sun, as some suppose, then it would be 384 times more distant than the sun, he says, or 3,840,000 terrestrial semidiameters. This is because 5 seconds is 1/384th the apparent diameter of the sun. Cassini describes 3,840,000 terrestrial semidiameters as a "prodigious" distance, but states that the distance of Sirius required by the Copernican world system is far greater.[24] Using the observed annual parallax of six seconds of arc, he calculates the distance to Sirius to be 437,800,000 terrestrial semidiameters. At that distance, the apparent diameter of the star translates into a true diameter of 10,612 terrestrial diameters—more than the 10,000 terrestrial diameters that Cassini had used for the radius of Earth's orbit. Put another way, the distance to Sirius is 43,780 times the Earth-sun distance, and the true diameter of Sirius is roughly equal to the Earth-sun distance. Cassini notes that the true diameter of the sun is about 100 terrestrial diameters, so as the sun is to the Earth, so Sirius is to the sun. In terms of volume, the sun is a million times greater than Earth, and Sirius is a million times greater than the sun.

As for the other stars, they must be more distant than Sirius:

> if we judge that many of them are of uniform size, and that one only appears smaller than the other because of greater distance, then their distance from the Earth must be almost incomprehensible. For we perceive with simple eyesight stars that are very small compared to stars of the first magnitude. But those hardly need be mentioned, for with the help of our larger telescopes we distinguish in addition to them an infinity of others that appear [through the telescope] to be of the same size as the smallest we can see

[24] Cassini, "Grandeur [ref. 19]," p. 260: "...trois millions huit cent quarante mille diametres de la Terre. Quelque prodigieux que soit cet éloignement, il doit être encore sans comparaison plus grand, si l'on considere la distance des Etoiles fixes à la Terre qui resulte de l'hypothese de Copernic..."

> visually. The larger the telescope we use, the more stars we discover, so that they cannot be numbered.
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> Some of the telescopes we use increase the size of objects over 200 times. Thus, if we suppose that the apparent diameter of the smallest stars that can be discerned by simple sight is six times smaller than that of stars of the first magnitude,[25] then the apparent diameter of some of those we observe through our telescopes will be twelve hundred times smaller than that of the largest stars. And supposing uniform size, these stars will be twelve hundred times farther away from us than Sirius....[26]

Cassini concludes in the last paragraph of his paper that, if we presume that most fixed stars are like Sirius, the enormous sizes and prodigious distances that result are surprising, but "not incomprehensible to those who are accustomed to considering the immensity of the Works of God."[27]

Responding to Cassini with Rejection and Confusion

To Edmund Halley, Cassini's enormous sizes and prodigious distances were not something to be surprised about; they were something to dismiss as simply bogus. In a 1720 commentary on Cassini's paper, Halley walks through the key aspects of Cassini's work: the 34 foot telescope (36 English feet); the one and a half inch aperture; the 5 second apparent diameter; the 3 foot

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[25] Galileo stated in his *Dialogue* that sixth-magnitude stars have apparent diameters that are one-sixth of first magnitude stars. See Graney, *Setting Aside* (ref. 6), pp. 47-8.

[26] Cassini, "Grandeur [ref. 19]," pp. 259-60: "...si on juge que plusieurs d'entre elles ont une grandeur uniforme, & qu'elles ne paroissent plus petites les unes que les autres que parce qu'elles sont plus éloignées, leur distance à la Terre doit être presque incomprehensible. Car sans parler de celles que l'on apperçoit à la vûë simple, & qui sont trés petites par rapport aux Etoiles de la premiere grandeur, nous en distinguons encore une infinité d'autres par le secours de nos plus grandes Lunettes qui paroissent de la même grandeur que les plus petites que nous discernons à la vûë simple, & plus nous employons de grandes Lunettes, plus nous en découvrons, ensorte qu'il n'est pas possible d'en définir le nombre. Quelques-unes des Lunettes que nous employons augmentent plus de 200 fois la grandeur des objets, ainsi si l'on suppose que le diametre apparent des plus petites Etoiles que l'on peut discerner à la vûë simple est six fois plus petit que celui des Etoiles de la premiere grandeur, on aura le diametre apparent de quelques-unes de celles que nous observons par nos Lunettes douze cent fois plus petit que celui des plus grandes Etoiles, & supposant leur grandeur uniforme, ces Etoiles seront douze cent fois plus éloignées de nous que Sirius..."

[27] *Ibid.*, p. 268: "...mais qui n'est pas incomprehensible à ceux qui sont accoutumés à considerer l'immensité des Ouvrages de Dieu."

telescope; the solid wall; the crosshairs; the 6 second parallax; Sirius being 100 times the true diameter of the sun; and so on. Then Halley proceeds to reject all Cassini's measurements.[28]

The supposed 6 second "parallax" is likely not parallax at all, he says. Rather, it is probably a refraction effect brought on by changing atmospheric pressure (Cassini did discuss refraction to some extent). And the supposed 5 second apparent diameter of Sirius is but an "optic fallacy," brought about by the reduction of the telescope's aperture via the cardboard cover on the object glass of Cassini's telescope:

> For we all know that the Diameters of *Aldebaran* and *Spica Virginis* are so small, that when they happen to immerge on the dark Limb of the *Moon*, they are so far from loosing their Light gradually, as they must do were they of any sensible magnitude, that they vanish at once with their utmost Lustre; and emerge likewise in a Moment, not small at first, but at once appear with their full Light, even tho' the Emersion happen very near the *Cusp;* where, if they were four Seconds in Diameter, they would be many Seconds of Time in getting entirely separated from the Limb. But the contrary appears to all those, that have observed the Occultations of those bright Stars. And tho' *Sirius* be bigger than either of them, yet he is by far less than two of them; and consequently his Diameter to theirs is less than the Square Root of 2 to 1, or than 14 to 10; whence, in Mr. *Cassini's* excellent 36 Foot Glass, those Stars ought to be about four Seconds in Diameter; and they would undoubtedly appear so, if view'd after the same manner; whereas we are *aliunde* [i.e. for other reasons] certain, that they are less than one single Second in Diameter. The great strength of their native Light, forming the resemblance of a Body, when it is nothing else but the spissitude [denseness] of their Rays.[29]

Not everyone rejected Cassini's work as Halley did, and what is striking are those who accepted selected portions of Cassini's work, supporting conclusions that were inconsistent with his findings. Before looking at examples of such selecting, it will be useful to consider a short commentary on Cassini's paper that was published together with it in 1719, titled "Sur la

[28] Edmund Halley, "Some Remarks on a Late Essay of Mr. Cassini, Wherein He Proposes to Find, by Observation, the Parallax and Magnitude of Sirius," *Philosophical Transactions*, 31, 1720-1721, pp. 1-4.
[29] *Ibid.*, p. 3.

distance des etoiles fixes à la Terre, & sur leur grandeur."[30] The author of this commentary provides an overview of Cassini's 1717 paper, relates Cassini's calculated distance to Sirius as being over 43,700 times ("*plus de 43700 fois*"[31]) the distance to the sun, and states Cassini's result that Sirius is to the sun as the sun is to the Earth. But then the author switches to speaking of Sirius as though it were equal to the sun in size. This remarkable sequence is as follows:

> The distance from Sirius found by Mr. Cassini being assumed…, it follows that the diameter of Sirius is 100 times larger than that of the sun, which is 100 times larger than that of the Earth.
>
> All the world knows that the fixed stars are divided into 6 classes in relation to their apparent size seen with the naked eye. If one supposes that they are more or less equal to each other, and that their apparent diameters decrease according to the proportion of the numbers from 6 to 1, those of the 6th magnitude, the smallest, will thus be 6 times farther than Sirius from Earth; and those that can only be seen with telescopes which magnify 200 times will be 1200 times farther away. But that all the fixeds are equal to each other is not an admissible supposition in good Physics; we can clearly see certain proportions in everything, but not equality.
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> If, on the contrary, we suppose all the fixed stars are equally distant from the Earth, those of the 6th magnitude will have a diameter 6 times smaller than that of Sirius, and consequently that will be the 6th part of that of the Sun, and more than 16 times larger than that of the Earth; and those that can only be seen with good telescopes will have a diameter 12 times smaller than that of the Earth.[32]

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[30] "Sur la distance des etoiles fixes a la Terre, & sur le grandeur," in *Histoire de L'Academie Royale des Sciences: Année MDCCXVII* (Paris, de l'Imprimerie Royale, 1719), 62-67.

[31] *Ibid.*, p. 65.

[32] *Ibid.*, pp. 65-6: "La distance de Sirius trouvée par M. Cassini étant suppose... il resulte que le diamètre de Sirius est 1oo fois plus grand que celui du Soleil, qui est 100 fois plus grand que celui de la Terre. Tout le monde sçait que les Etoiles fixes sont divisées en 6 Classes par rapport à leur grandeur apparente vue à l'œil nud. Si l'on suppose qu'elles soient à peu-prés égales entre elles, & que leurs diamètres apparents décroissent sélon la proportion des nombres depuis 6 jusqu'à 1, celles de la 6me. grandeur, qui est la moindre, seront donc 6 fois plus éloignées de la Terre que Sirius; & celles qu'on ne voit qu'avec des Lunettes qui grossissent 200 fois seront 1200 fois plus éloignées. Mais que toutes les Fixes soient égales entre elles, ce n'est point une supposition recevable en bonne Phisique, on voit bien par tout certaines proportions, mais non pas de l'égalité. Si au contraire on suppose toutes le Fixes également éloignées de la Terre, celles de la 6me. grandeur auront un diamètre 6 fois plus petit que celui de

In the next paragraph the author proceeds to argue that this shows that the equidistance assumption cannot be close to true, because, among other reasons, it is impossible that a body 1/12th the diameter of Earth could be seen at the distance of Sirius, even with a telescope. But in the last sentence of the paragraph the author equates being 12 times smaller than the diameter of Earth with being 120,000 times smaller than the true diameter of Sirius.[33]

Clearly an editorial or typographical error crept in here. The statement that a sixth-magnitude star has a true diameter 12 times smaller than the diameter of Earth proceeded from equating Sirius and the sun. That contradicts the previous statement that Sirius is 100 times the diameter of the sun, which in turn is 100 times that of Earth. Thus the number "120,000" comes from two contradictory ideas—that Sirius and the sun are equal, which makes a sixth-magnitude star 12 times smaller than Earth under the assumption of equidistance;[34] and that Sirius is 100 times the diameter of the sun, which makes it 10,000 times the diameter of Earth. The values of 12 and 10,000 were combined, again under the assumption of equidistance, to yield 120,000.

In his concluding paragraph, the author of "Sur la distance" fully returns to the idea that Sirius is far larger than the sun, stating that there is probably some variability in the true diameters of the fixed stars, as well as in their distances, and noting that some philosophers have suggested that "the sun is one of the smallest of the fixed stars, that is, one of the smallest of the suns."[35]

Thus in "Sur la distance" we see stated that Sirius and the sun are equal (and also, that Sirius and the sun are not equal). We also see stated the idea that the fixed stars are suns. "Sur la distance" was reprinted, uncorrected, in 1741.[36] We will see this equating of sun and Sirius appearing in the writings of later writers who discussed Cassini's work on Sirius. Cassini placed his discussion of the most distant stars being 1200 times farther away than Sirius just before introducing his parallax-based distance for Sirius, and just after calculating the distance Sirius

Sirius, & qui par consequent sera la 6me. partie de celui du Soleil, & plus de 16 fois plus grand que celui de la Terre; & celles qu'on ne voit qu'avec de bonnes Lunettes auront un diametre 12 fois moindre que celui de la Terre."

[33] *Ibid.*, p. 66: "Il n'est pas possible que des corps dont le diamètre seroit 12 fois plus petit que celui de la Terre, ou 120000 fois plus petit que celui de Sirius soient visibles, même aux Lunettes, à la même distance où est Sirius."

[34] If Sirius and the sun are equal, and the sun is 100 times the diameter of Earth, then a sixth-magnitude star at the same distance as Sirius is 100/6 times the diameter of Earth, and the smallest star visible through a 200-power telescope is (100/6)/200 = 1/12 the diameter of Earth.

[35] "Sur la Distance [ref. 30]," p. 67: "le Soleil étoit une des plus petites Etoiles fixes, ou des plus petits Soleils."

[36] *Histoire de L'Academie Royale des Sciences: Année MDCCXVII* (Paris, Rue S. Jaques, 1741), pp. 62-67.

would have were it equal to the sun. The source of the typographical or editing error thus may lie in a hasty reading of Cassini's paper.

Cassini Abridged

John Hill's 1754 book *Urania, or a Compleat View of the Heavens Containing the Antient and Modern Astronomy in Form of a Dictionary* borrows much from Cassini's work on Sirius. Consider *Urania*'s "dictionary" entry for "DISTANCE of the fixed Stars."[37] After a brief introduction, it proceeds to discuss how one fixed star differs from another. Fixed stars differ, the entry states, "in apparent magnitude, and in the degree of that brightness which is peculiar to them as fixed stars." *Urania* discusses how "magnitude" here means size; it is not the same as brightness:

> Those of the fixed stars which appear largest, appear also brightest, and the smallest faintest: this would refer the difference in apparent magnitude to distance only, but there are some exceptions. We know that distance diminishes light as well as bigness, but there are the Syrius, Aldebaran, and some others, which shine with a lustre greatly superior to the others, that are of equal apparent diameters; therefore there is some difference in the brightness of their fire.

However, it is the apparent size of stars that *Urania* is focused on here:

> [W]hen we consider the apparent bigness of the fixed stars, we naturally enquire also into their different distance from the earth. We see these two considerations too intimately united to be separated in our minds, for they depend in such a manner upon one another, that when the one is determined, the other naturally results from it... [I]n measuring the apparent diameter of an object, that is, in precise terms, the measuring the angle it makes with the eye, we may, on knowing its distance, determine what is its real magnitude, or

[37] John Hill, *Urania, or a Compleat View of the Heavens Containing the Antient and Modern Astronomy in Form of a Dictionary, Volume 1* (London, 1754). This book contains no page numbers. All the quotations following this note are from the few pages of the entry "DISTANCE of the fixed Stars."

> reciprocally, if we are assured of its real magnitude, we may discover this way its distance.

This of course is what we see in Figure 1. In the case of the sun, moon, and planets, *Urania* says, we can correctly determine the apparent diameters easily enough. However,

> it is otherwise with regard to the fixed stars; we find it extremely difficult to measure their apparent diameter, because of the vivacity of their light, and the rays they continually send forth; that twinkling which they have when seen by the naked eye, not being easily quite excluded in astronomical observations, and even when it is, their edges being by no means determinate. This is a consequence of their being in themselves bodies of fire, and not receiving their light, as the moon and planets do, from the sun, and sending it to us only by reflection.

Next *Urania* gives a detailed discussion of how to obtain a correct measurement of the apparent diameter of a fixed star. If the previous quotations sounded like Cassini, here it becomes apparent that Hill is indeed paraphrasing "De la grandeur":

> The most familiar manner of determining, with any degree of exactness, the different magnitude of these stars… is by comparing them with the diameter of some other heavenly body of known dimensions. Jupiter may be chosen for this purpose, as that is the planet of which we most certainly know the dimensions, the moon and sun excepted, whose apparent bigness is too much superior to render a comparison familiar or convenient. Now for a first consideration, with this view let us select the most conspicuous and the brightest of the fixed stars of our horizon, let us fix upon Sirius...

The rest of this discussion will be by now familiar: the thirty-four foot telescope; the hole of an inch and a half diameter; the disk of Sirius being "seen very clear, and all that twinkling or sparkling of rays, which confound the sight, being cut off, his Circumference will be determinate"; the comparison to Jupiter. A detail is added, suggesting that Hill has himself made this measurement:

> When [Jupiter] has been carefully viewed, the telescope is to be again directed to Sirius, for the difference is much more plainly seen in turning from a larger object to a smaller,

> than from a smaller to a larger. The alternate observation is to be several times repeated, and the result will be, that Jupiter appears ten times as large as Sirius...

Still, the numbers are Cassini's: apparent diameter of Jupiter, 50 seconds; of Sirius, 5. "This is not speaking with a perfect precision, but it is sufficient."

Urania now moves on to the distance and "the real bigness" of Sirius. A parallax would tell us these things, the entry says,

> but it must be confessed, that all the accuracy of astronomers has not certainly discovered that [the fixed stars] have any, or if any has been set down, it is so little, that it seems more probably owing to errors in the observations, than to any thing in nature.

The material that follows is clearly Cassini's work again, without mention of Cassini. *Urania* calculates the size Sirius would be were it at the distance of Saturn (stated as 100,000 diameters of Earth), namely 2 Earth diameters, which is "the least that it is possible to assign it, according to whatsoever system of the world we shall chuse." Next comes the calculation of the distance of Sirius were Sirius assumed to be another sun. This also follows Cassini, and the result is his: 3,840,000 terrestrial diameters.

Urania then launches into a discourse about how "if we agree with the generality of philosophers and astronomers, that the fixed stars are all of the same, or nearly of the same, [true] magnitude," then the other fixed stars are far more distant than Sirius, especially those visible only through a telescope, and all are suns, with planets in orbit around them:

> When we have viewed, in any part of the heavens, the number of those which are not to be seen by the naked eye, and appear to our telescopes, if we apply such telescopes as are of larger power, and direct them to the same parts of the heavens, we discover yet other stars which are too minute to be made visible by the first, and this without any end or stop: our instruments at length fail us, but the works of this part of the creation never. All these must be yet more and more remote in proportion to their minuteness as seen from the earth. What numbers then could convey the distances of the last, or of those yet unknown, which we fail to see in our most accurate researches, for want of yet more powerful instruments.

> The more we see of the works of the creation, the more we must admire and adore its Author. It does appear that the unbounded space is filled at proper distances with these stars: each of these is a sun; and if we continue the inquiry, reasoning by analogy, we shall determine that each of these suns has earthy planets rolling round it, for to what end else should they have been created? In this view, what, and how amazing is the structure of the universe!

Next comes more material clearly borrowed from Cassini:

> Some of the telescopes which are used to this purpose, magnify to so powerful a degree, that they make objects appear two hundred times greater than they do to the naked eye. Now as calling Sirius a star of the first magnitude, the diameter of the smallest of those which we see with the naked eye, is but about a sixth part as large as that of Sirius; consequently, some of those which we discover with our telescopes appear twelve hundred times smaller than Sirius, and the other large fixed stars.

Thus *Urania* concludes that these stars must be 1200 times more distant than Sirius, etc. *Urania* goes on to provide further discussion of Earth's orbit and parallax, before concluding the "DISTANCE of the fixed Stars" entry with:

> When the best possible methods have been employed to discover the parallax of the fixed stars, whatsoever has appeared to favour the opinion of their having any, seems, as said already, to a judicious enquirer, rather the result of some little error in the observation, or of the very aberration of light, than in the thing itself; and the consequence of this is, that the distance of the fixed stars from the earth is so immensely great, that the whole diameter of the earth's orbit, the extent of which is about sixty millions of leagues, is as a point to it, or cannot be considered in any degree of comparison. According to this, the real distance of the fixed stars, even of the nearest of them, is great beyond all computation; and there is all the reason in the world to conclude, that those, which appear smaller and fainter to the eye, are, in reality, more and more distant in a degree proportioned to that first distance. There are some who allow the largest of the fixed stars no apparent diameters, but this seems carrying it too far.

Cassini's parallax measurement and his distance of 437,800,000 terrestrial diameters for Sirius are not mentioned in the "DISTANCE of the fixed Stars" entry. It is the 3,840,000 terrestrial diameters distance value that is most mentioned, the value Cassini had calculated from the assumption that Sirius is a sun—an assumption made only for illustration, just like the assumption that Sirius lay just beyond the orbit of Saturn that he used to calculate Sirius's true diameter to be twice that of Earth. That distance of 3,840,000 terrestrial diameters is entirely incompatible with the inability to detect annual parallax that Hill urges; the parallax of a star at that distance would be as many times greater than Cassini's 6 seconds of parallax as 437,800,000 is greater than 3,840,000.

Hill mentions Cassini's measurement of the apparent diameter of Sirius in several places within *Urania*, along with the idea that stars have no measurable apparent diameters. In the entry for "TWINKLING of the fixed Stars" we find this:

> [A cause of the twinkling of the fixed stars] is the smallness of their apparent diameters; for whatever we may imagine from the blaze which we see, occasioned by their rays, and which enlarges and extends their apparent surface, we may be assured, that, in reality, they do appear to us extremely small. We find, that the largest of them by the telescope, allowing all that is required for the most favourable observations, appear but of four or five seconds in diameter, and there are those, of the greatest eminence, who will not allow even that, who refer the extent of surface to defects in the observation, and assert, that the greatest of them have no diameters at all, as seen by the best glasses; but allowing the largest of them, even the full five seconds in measure, as seen by powerful telescopes, what are they when viewed by the naked eye? take away their rays, and they can be only lucid points, or specks.

In the entry for "STARS, fixed," we find this:

> The observation of Sirius's diameter being five seconds, had, for its author, one of the most accurate, and most judicious astronomers the world has ever known, Cassini, and, whenever it is repeated with the same apparatus, it succeeds in the same manner, and verified very punctually; and other stars have also apparent diameters of nearly the same extent. This is, however, a point that has been combated very strenuously since, and some

of the greatest of our own astronomers have not only taken away so great an apparent diameter from this star, but all diameter whatsoever. They assert, that all the fixed stars are mere lucid points, and advise the viewing them, not through an object-glass, the aperture of which is limited as in this observation, but through one that has been smoaked black, and they assert, that, thus, neither Sirius, nor any other of them, have any the least measurable diameter. In favour of this last system it is advanced, that, when any of these large fixed stars immerge behind the dark edge of the moon, they are seen to plunge in at once, and, in the same manner, burst out at once again in an instant in their full splendor. The admeasurement of Cassini sets these bodies at an immense distance; this observation would place them at a much larger. It was but equitable to state the two opinions, and, where so great authorities as that of Cassini on one part, and that of Halley on the other, are opposed, it may be well to advise repeated experiments and observations farther to determine which is right.

John Hill may have viewed Cassini as a great authority, and as one of the most accurate, and most judicious astronomers the world has ever known, but nevertheless he abridges Cassini's work in *Urania*. Cassini reported measuring an apparent diameter and an annual parallax for Sirius—data which indicated Sirius to have a true diameter 100 times that of the sun, and a volume a million times that of the sun. Cassini supposed that many stars were of more or less uniform size, and so in the starry universe as he saw it, bodies such as Sirius were common. In short, Cassini's 1717 work indicated a universe of stars much like the starry universe of Kepler—one in which, in the words of the author of the 1719 commentary on Cassini's paper, "the sun is one of the smallest of the fixed stars, that is, one of the smallest of the suns." Unlike Kepler, Cassini did not comment on the dimness or brightness of Sirius or other stars. However, had Kepler been in possession of Cassini's data, Kepler would have seen nothing to contradict his general picture of the starry universe, for following Kepler's method of reckoning, Cassini's Sirius would be very dim versus the sun.[38]

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[38] Cassini determined the apparent diameter of Sirius to be 1/384th that of the sun. The area of the sky occupied by the sun would thus be 384^2 = 147,456 times that occupied by Sirius. Kepler had argued that the stars must be dim because, even though combined they occupied a fraction of the sky comparable to that occupied by the sun, their combined light output was negligible compared to the output of the sun—with the distance of the stars being irrelevant since, following Figure 1, greater distance translated into greater true size: "If the little disks of 10,000

Thus Cassini's Sirius dwarfed the sun, as did Kepler's, and Cassini's Sirius was very dim compared to the sun, as was Kepler's. So what might Kepler have had to say about the fact that Hill uses Cassini's work to promote a Bruno-style universe, in which "each of [the stars] is a sun; and... each of these suns has earthy planets rolling round it"? Yes, Hill does equally consider Halley's view regarding apparent stellar sizes. However, the discussion about 200-power telescopes and the calculations regarding stars 1200 times the distance of Sirius is predicated on stars having measurable, magnifyable apparent diameters that reflect their distances and true diameters. Moreover, it is Cassini's determination of Sirius's apparent diameter that, according to Hill, "whenever it is repeated with the same apparatus, it succeeds in the same manner, and verified very punctually"—that is, it is Cassini's determination that yields reproduceable results. Meanwhile, the idea that stars have no measurable apparent diameter is something Hill rejects as "carrying it too far," while he also dismisses any claimed measurement of annual parallax. A measurable apparent diameter and no measurable parallax is something that cannot be reconciled with stars being the size of the sun. If the annual parallax of Sirius is less than Cassini claimed, then Sirius must be more distant than he determined, too, and thus even larger than he determined. As Christoph Scheiner pointed out in 1614, if stars have any measurable apparent diameter, but no measurable parallax, then—given stellar bodies detectable against the expanse of the starry universe of the heliocentric world system, but Earth's orbit not—the true sizes of

stars are fused into one, how much more will their visible size exceed the apparent disk of the sun? If this is true, and if they are suns having the same nature as our sun, why do not these suns collectively outdistance our sun in brilliance? Why do they all together transmit so dim a light...? When sunlight bursts into a sealed room through a hole made with a tiny pin point, it outshines the fixed stars at once. The difference is practically infinite.... Will my opponent tell me that the stars are very far away from us? This does not help his cause at all. For the greater their distance, the more does every single one of them outstrip the sun in diameter." So, using Kepler's reasoning and Cassini's measurements, were Sirius a sun, then roughly, 150,000 identical Siriuses in the night sky would equal the sun in light output. However, on the modern magnitude scale, Sirius is magnitude -1.5, while the sun is -26.7, a magnitude difference of 25. A difference of 5 on the modern scale is a difference of 100 in brightness: a magnitude 1 star is 100 times brighter (power per area at Earth) than a magnitude 6 star, so 100 magnitude 6 stars would equal a magnitude 1 star. The sun, exceeding Sirius by 25 modern magnitudes, is then 100^5 times brighter. To equal the sun would require 10^{10} Siriuses—recall Kepler's comment about a "practically infinite" difference between the sun and a star. Thus, according to Cassini's measurements, Sirius is far outclassed by the sun in terms of light output. Cassini's Sirius was exactly what Kepler said stars were: giant compared to the sun, and also dim compared to the sun. Kepler quotations here are from Johannes Kepler, *Kepler's Conversation with Galileo's Sidereal Messenger, trans. Edward Rosen* (New York: Johnson Reprint Corporation, 1965), pp. 34-35. See also Graney, "Starry Universe [ref. 4]," pp. 155-73.

stars must exceed Earth's orbit.[39] How could Hill have reconciled all this? Perhaps he latched on to the equating of Sirius and the sun found in the 1719 commentary on Cassini's paper.

What is seen in Hill's work can be seen in the works of other writers as well. These tend to be brief compared to Hill. The *Universal-Lexicon* cites Cassini's parallax-based distance to Sirius in a discussion of the enormity of the universe and the smallness of the Earth. Charles Hutton's 1795 *Mathematical and Philosophical Dictionary* mentions Cassini's five second apparent diameter for Sirius. *Maandelyke Uittreksels* of 1760 relays Cassini's idea that the breadth of Sirius is such that it would reach from Earth to the Sun, and states Cassini's distance to Sirius of 43,700 solar distances. Jean Sylvain Bailly's 1785 *Histoire de l'Astronomie Moderne* provides a longer discussion (although still brief compared to Hill), relaying Cassini's parallax and diameter measurements and also his idea of a telescope revealing stars 1200 times more distant than Sirius, etc.[40]

These sources are like Hill in that they cite Cassini's work on Sirius, but they do not reflect Cassini's ideas about the starry universe. Hutton uses Cassini's five second apparent diameter measurement, the supposition that "the real magnitude of Sirius is equal to that of the sun," Cassini's statement that the apparent diameter of the sun is 384 times that of Sirius, and an Earth-sun distance of 12,000 terrestrial diameters to calculate a distance to Sirius that is 4,608,000[41] terrestrial diameters. *Maandelyke* cites Cassini as part of a discussion about stars being other suns that are in turn centers of their own planetary systems. Bailly, noting Halley, rejects Cassini's measurements.

[39] Graney, "Starry Universe [ref. 4]," p. 157; Christopher M. Graney, *Mathematical Disquisitions: The Booklet of Theses Immortalized by Galileo* (Notre Dame, IN: University of Notre Dame Press, 2017), p. 30.
[40] "Erde," *Grosses vollständiges Universal-Lexicon aller Wissenschafften und Künste, Acht Band* (Leipzig, 1734), p. 1539; "III. Hoofsduck: Godvruchtige en proef Kundigebeschouwingenvan, etc.," *Maandelyke Uittreksels, of de Boekzael der geleerde Werrelt*, April 1760, pp. 410-13; Charles Hutton, *Mathematical and Philosophical Dictionary, volume 2* (London, 1795), p. 492; Jean Sylvain Bailly, *Histoire de l'Astronomie Moderne, nouvelle éditione, tome second* (Paris, 1785), pp. 656-60.
[41] 4,608,000 = 12,000 × 384.

CONCLUSION

Jacques Cassini published an apparent diameter and an annual parallax for Sirius in 1717. From these measurements he determined that Sirius was as much larger than the sun as the sun was larger than the Earth. By assuming that other stars were more or less like Sirius, and by making some assumptions about what a 200-power telescope revealed, he estimated distances to even those stars barely visible in a telescope. Thus he described a universe of very large stars, a universe somewhat like that promoted by Kepler. Cassini was not an unknown and not a crackpot. His annual parallax measurement would be approximately reproduced by other astronomers.[42] His method for measuring apparent stellar diameters telescopically was similar to that established by Riccioli decades previously, and yielded reproduceable results. We might expect that his ideas about stellar sizes and the starry universe would have been influential.

But they seem not to have been. Of course, Halley dismissed Cassini's work. However, we must be careful here. In considering Halley and others who argued that even telescopically measured stellar diameters were spuriously large, we should keep in mind that, at the time, Halley's "optic fallacy" idea might not have seemed so obviously correct as it does today. Consider Flamsteed's dismissal of the idea that the apparent diameter of Sirius seen through a telescope was spurious. Also, consider the observations of Horrocks that Hevelius published, about the moon passing through the Pleiades and the stars winking out as the moon approached them. Horrock's comments are intriguing, and a clear record of an astronomer discovering that the telescope was producing spurious information as regards the stars. His report is an accurate reflection of how stars are seen to behave when the Moon passes in front of them. However, he gives this report while seeking to justify the small size of Venus that he recorded during its transit across the Sun. He goes on to discuss planetary sizes as though the planets increase in size in proportion to their distance from the Sun, so that, were they observed from the Sun, they would all have the same apparent size. This seems clearly counter to the most basic of telescopic observations—the apparent sizes of planets seen through a telescope refute this idea almost at a glance. Thus the

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[42] Nevil Maskelyne obtained a parallax of four seconds from measurements made in 1751-52, and Giuseppe Piazzi also obtained four seconds, based on observations made from 1792-1804. See Nevil Maskelyne, "A Proposal for Discovering the Annual Parallax of Sirius, etc.," *Philosophical Transactions*, 51, 1759-60, pp. 889-95; Thomas Henderson, "On the Parallax of Sirius," *Monthly Notices of the Royal Astronomical Society*, 5, December 14, 1839, p. 5; Agnes M. Clerke, A. Fowler, Ellard Gore, *Astronomy* (New York, 1898), p. 421.

remarks of Horrocks about the sizes of stars and planets may contain excellent observations, but they also contain nonsense obvious to any careful observer.[43] Finally, consider that there was no full explanation for the "optic fallacy" idea—that would come with the wave theory of light and George Biddell Airy in the early nineteenth century.[44] We might suppose that, were telescopic stellar apparent diameters so obviously spurious, Cassini would not have in 1740 again published his apparent diameter measurement for Sirius and the method he used to make it.

Meanwhile, writers who rejected Cassini's work still reported on that work. Indeed, Hill relied on it extensively. Moreover, they fixed upon his example of the distance Sirius would have were it the equal of the sun—despite the enormous parallax that would result were Sirius at that distance, and even when they insisted that no parallax of Sirius could be detected. They repeated Cassini's idea about the faintest stars visible in a 200-power telescope being 1200 times farther away than Sirius—an idea predicated on Sirius's telescopic apparent diameter not being fallacious. Even though Cassini argued from his measurements that Sirius was a sun-dwarfing body at a vast distance from Earth, and that it was the nearest such body in a universe thoroughly populated by such bodies, extending out to at least 1200 times the distance of Sirius, those who

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[43] Graney, *Setting Aside* (ref. 6), p. 150-51.

[44] For a full, technical discussion, see Graney and Grayson, "On the Telescopic Disks [ref. 21]." While a full theory of the apparent sizes of stars came with Airy, even prior to Airy discussions of why stars appeared spuriously large could be creative and persuasive. Consider this, from John Keill, *An Introduction to the True Astronomy, etc. Second Edition* (London, 1730), p. 39: "Since the fixed Stars… subtend at the Eye such unperceivable Angles, some will wonder how they come to be at all seen, since there are Bodies which would shew themselves under larger Angles, that are yet so small as not to be looked at without a Microscope: But all flaming and fiery Bodies can be seen at great Distances, even at such from whence other Bodies, which have as large apparent Diameters, do quite disappear, and become invisible. Thus the Flame of a Candle in the Night-time is easily perceived at the Distance of two Miles, whereas in the Day-time an opake Object, tho' strongly illustrated by the Sun, and six times bigger than the Flame of a Candle, is not to be observed with the naked Eye at that Distance. For the native Light that these fiery and flaming Bodies send forth, is stronger and more piercing, and acts upon the nervous Fibres of the Retina with a greater Force, than the Light reflected from opake Objects; for all Light is much weakened by Reflection. And it is upon the account of this brisk and strong Light which flows from fiery Bodies, and which makes so sensible Impressions on the Retina, that such Bodies are judged to be so big in comparison of others which affect us with a weaker Light." Kiell argues against the idea that stars are giant (p. 37), and for the idea that they are suns, surrounded by planets because "It is no ways probable that GOD Almighty who always acts with infinite Wisdom, and does nothing in vain, should create so many Suns, and place them alone in indefinite Space, at such great Distances from each other, and not have made other Bodies, which he has placed near them, to be nourished, animated and refreshed with the Heat and Light of these Suns [p. 40]." Kiell also includes a discussion of the magnification of Sirius by the ever-present 200-power telescope in which he states that he "cannot but wonder" how Riccioli measured its apparent diameter to be 18 seconds of arc, and in which he confuses telescopic and naked-eye estimates of the apparent diameters of Sirius and Mars (p. 38). Thus Kiell provides another example of the strange things written in regards to observations of stars.

cited his work tended to use it while promoting a universe of sun-like stars, themselves surrounded by Earth-like planets.

With modern knowledge in hand we see that Cassini was incorrect in that the apparent diameter that he determined for Sirius was indeed spurious, and stars are not all, or even in large part, sun-dwarfing bodies. But those who dismissed his ideas or abridged them so as to leave out his depiction of the starry universe were likewise incorrect in that the stars are not all the equal of the sun. They are all sun-like in that they are all gravitationally-bound balls of mostly hydrogen, heated to incandescence by nuclear fusion occurring in their cores. However, they are diverse. While stars of the size Cassini determined for Sirius, and indeed of even larger size, do exist, far more are roughly comparable to the sun. Moreover, we now understand the vast majority of stars to be "red dwarfs" that are far outclassed by the sun; most of the 100 stars that are nearest neighbors to the sun emit but a tiny fraction of the sun's light. Studies of planets and exoplanets have found similar diversity among planets and planetary systems. Thus it seems that this idea of Cassini (and of Kepler) of a universe which is "Copernican" (in that the sun is the center of its planetary system), but not "Bruno-esque" (in that the stars are not all equals to the sun), seems today relevant and deserving of study.

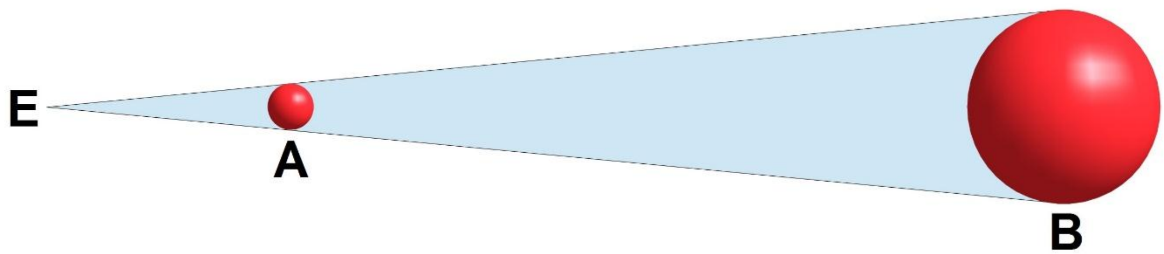

Figure 1. The more distant an observed object is from Earth (E), the greater its true size must be to retain the same apparent diameter (indicated by the shaded region). A and B will each have the same apparent diameter as seen from E, but B is over four times more distant from E than is A, so B has over 4 times the actual diameter of A, and over 64 times (4 cubed) the volume of A.

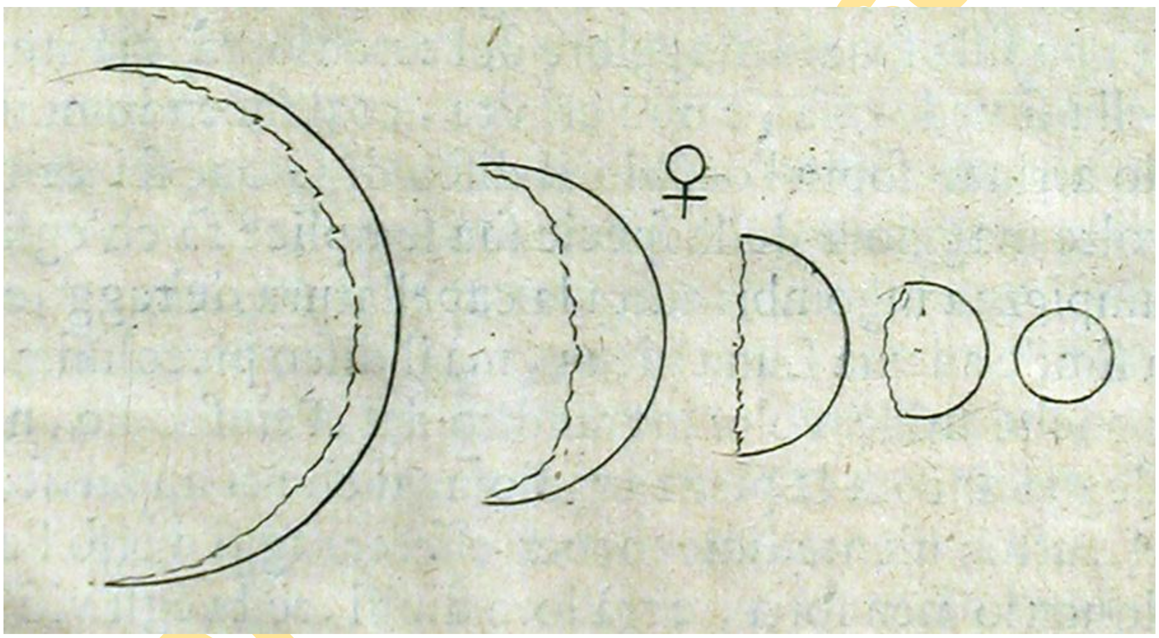

Figure 2. Galileo's illustration of the changing phases and apparent diameter of Venus.

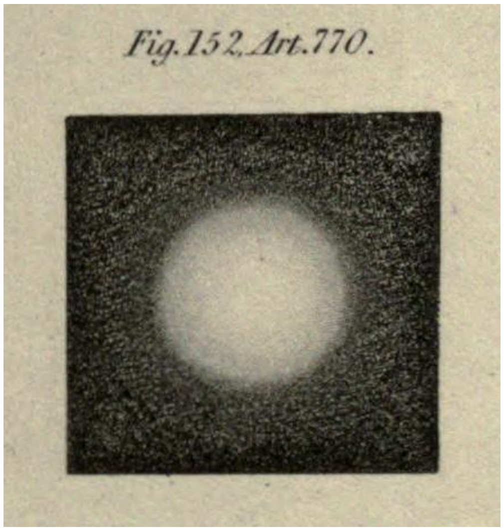

Figure 3. Illustration by John F. W. Herschel of a star as seen through a telescope of aperture similar to what was used for stellar observations in the seventeenth century.[45] The diffraction of light waves through the telescope's aperture creates the spurious globe-like appearance seen here, greatly inflating the star's apparent size.

[45] J. F. W. Herschel, *Treatises on Physical Astronomy, Light and Sound Contributed to the Encyclopædia Metropolitana* (London and Glasgow, 1828), p. 491 and plate 9.