

But Still, It Moves: Tides, Stellar Parallax, and Galileo's Commitment to the Copernican Theory

Christopher M. Graney^a

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Galileo found the Copernican heliocentric theory of the universe so persuasive owing to its mathematical elegance that he embraced it even when his theory of the tides stood in opposition to it. Further support for Galileo's deep commitment to the Copernican heliocentric theory is found in his recently discovered unpublished observations of the double star Mizar in 1617, which exhibited no annual stellar parallax and hence indicated that the Earth does not move, in contradiction to the Copernican heliocentric theory. Further, Galileo did not mention this contradiction in his *Dialogue Concerning the Two Chief World Systems* of 1632. I conclude that he was so deeply committed to the Copernican heliocentric theory that he was unswayed even when observations undermined it, and I suggest that if he had published his observations on the double star Mizar, general acceptance of the Copernican heliocentric theory by astronomers would have been delayed even more than it was.

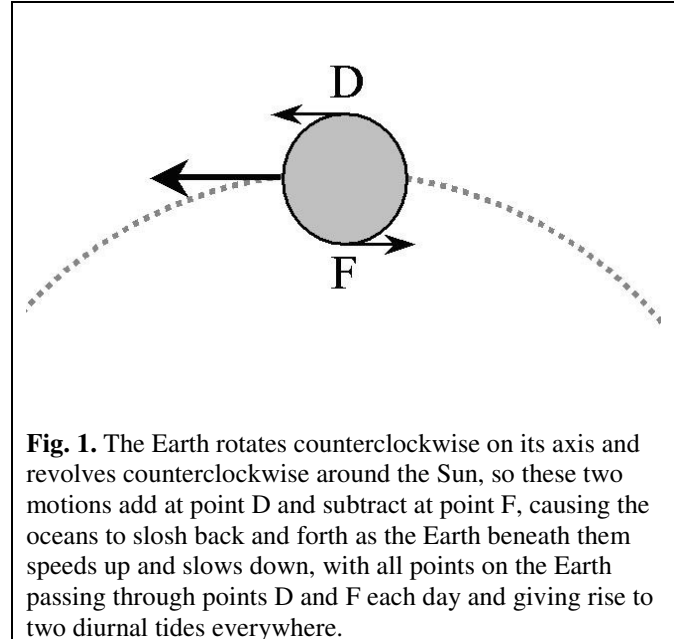
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^a Christopher M. Graney teaches physics and astronomy at Jefferson Community College in Louisville, Kentucky, and runs the college's observatory at Otter Creek Park in Louisville.

Jefferson Community College
1000 Community College Drive
Louisville, KY 40272 USA
e-mail: christopher.graney@kctcs.edu

Introduction: Galileo, Tides, and Mizar

Galileo Galilei (1564-1642) argued in his *Dialogue Concerning the Two Chief World Systems* of 1632 that tides are direct evidence for the Earth's motion, because the Earth is both rotating about its own axis and revolving about the Sun (figure 1). His theory, however, would lead his readers to expect to see one high tide and one low tide each day instead of the two that actually



occur, and that the time of day at which tides occur varies slowly over the course of a year as the Earth revolves around the Sun instead of over the course of a month as the Moon revolves around the Earth. Neither Johannes Kepler (1571-1630) nor René Descartes (1596-1650), two other prominent Copernicans, subscribed to Galileo's theory of the tides. Further, the commission that Pope Urban VIII (1568-1644) appointed to evaluate Galileo's *Dialogue* singled out his theory of the tides for refutation, pointing out that high and low tides are observed not once but twice each day. Moreover, Galileo's telescopic observations of the phases of Venus, sunspots, and the moons of Jupiter could be reconciled with a stationary Earth. Nevertheless, Galileo stood by the Copernican heliocentric theory, apparently convinced of its validity by its mathematical elegance, even if it entailed predictions that were not in agreement with observation.¹

The extent to which Galileo was committed to the Copernican heliocentric theory, despite the absence of direct evidence of the Earth's motion, has been greatly reinforced by the work of the Czech amateur astronomer Leos Ondra, who recently unearthed evidence that Galileo was among the first astronomers to observe a double star.² The Bolognese Jesuit astronomer Giambattista Riccioli (1598-1671) has been commonly credited with the first observation of a double star around 1650, but Ondra, suspicious that this was simply old lore that had been passed down from generation to generation, tracked down the original sources, finding notes by Galileo proving that he had observed the double star Mizar in the middle of the handle of the “Big Dipper” much earlier, in 1617; had resolved its two component stars; and had measured their separation and sizes. Thus, the first scientist who is known to have observed the heavens with a telescope in 1610 was also the first scientist to observe a double star. Ondra also noted that Galileo and Benedetto Castelli (1577-1643) had observed another close grouping of stars, the Trapezium in the constellation Orion, hoping that such groupings would provide direct evidence that the Earth moved. In fact, as early as 1611, Galileo had received a letter from one Lodovico Ramponi (baptized in 1577), who suggested that the observation of a double star could serve as a test of whether the Earth moved, and encouraged Galileo to attempt such a test.³

The Absence of a Crucial Test between the Geocentric and Heliocentric Theories

In rejecting the Ptolemaic geocentric theory of the universe, Galileo appealed to the simplicity and mathematical elegance of the Copernican heliocentric universe.⁴ As his character Salviati expressed it in the *Dialogue*:

See, then, how neatly the precipitous motion of each twenty-four hours is taken away from the universe, and how the fixed stars (which are so many suns) agree with our sun in enjoying perpetual rest.⁵

Still, if the Earth moved, the observed positions of stars should change during the course of a year, but such annual stellar parallax had not been observed. Moreover, the hybrid geocentric theory that Tycho Brahe (1546-1601) had proposed, in which the Sun, Moon, and stars circle the fixed Earth while the planets circle the Sun, was mathematically equivalent to the Copernican heliocentric theory and thus retained its advantages,⁶ while also retaining key advantages of the Ptolemaic geocentric theory, such as explaining the absence of stellar parallax.

Furthermore, Galileo's telescopic observations of the phases of Venus, which he announced in December 1610, were fully compatible both with Tycho's hybrid geocentric theory and with the Copernican heliocentric theory, because in both theories Venus revolved about the Sun. The phases of Venus thus did not provide direct evidence for the motion of the Earth. This lack of direct observational evidence made it difficult to persuade intelligent skeptics, such as Cardinal Robert Bellarmine (1542-1621), who wrote to Paolo Antonio Foscarini (1565-1616) on April 12, 1615, that:

if there were a true demonstration that the sun is at the center of the world and the earth in the third heaven, and that the sun does not circle the earth but the earth circles the sun, then one would have to proceed with great care in explaining the Scriptures that appear contrary, and say rather that we do not understand them than to say that what is demonstrated is false. But I do not believe that there is such a demonstration, until it is shown me.⁷

Bellarmino noted further that being able to explain the motions of the planets by supposing that the Earth circles the Sun is not direct evidence for the motion of the Earth. That offered an opening to Galileo: If he could find direct observational evidence that the Earth moved, then Bellarmine and other skeptics might change their minds.

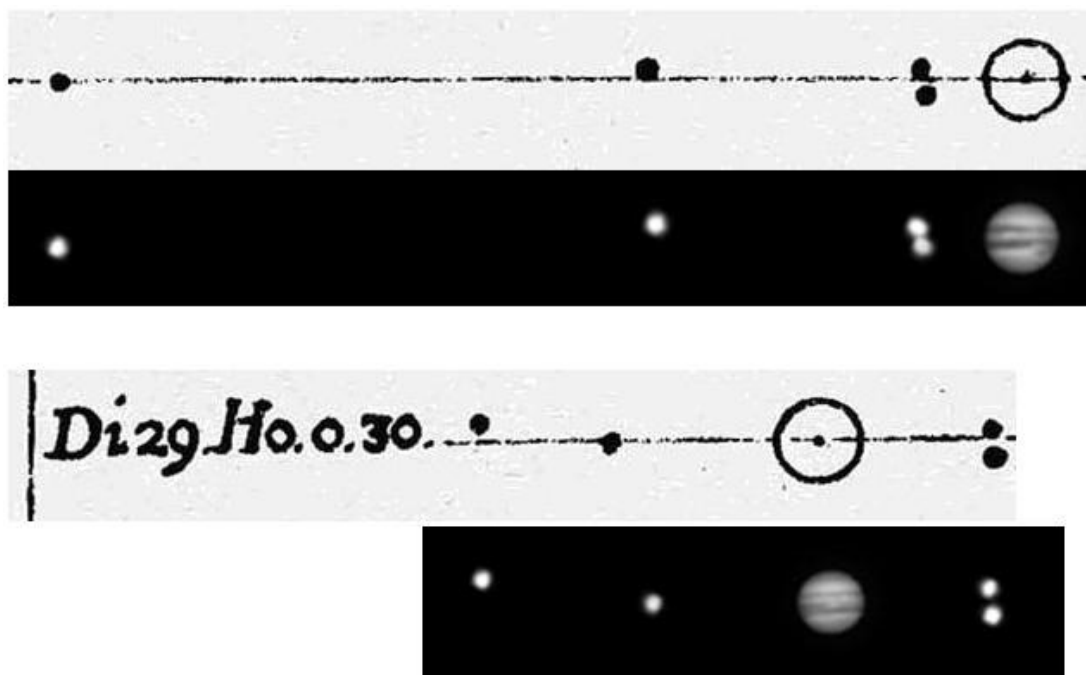


Fig. 2. Galileo's sketches of the Jovian system on March 25, 1613 (*top*), and on March 29, 1613 (*bottom*), as compared to the outputs from the Stellarium open-source planetarium software (available at the website <http://www.stellarium.org>). Differences do exist between Galileo's sketches and the Stellarium outputs owing possibly to a combination of Galileo's errors, Stellarium's errors, and my errors in estimating the moments in time the sketches represent, but the similarity between the two at each date is remarkable nonetheless. The sketches can be found in Antonio Favaro, ed., *Le Opere di Galileo: Edizione Nazionale Sotto gli Auspicii di Sua Maestà il re d'Italia* (1890), Vol. 5, p. 241 and p. 243. An on-line version of the Opere which allows users to browse the 20-volume work by selecting volume and page number is available at the website <http://moro.imss.fi.it/lettura/LetturaWEB.DLL?AZIONE=CATALOGO>.

Galileo's Conclusive Mizar Observations

Galileo realized that observations of a close grouping of stars, such as Mizar in the middle of the handle of the “Big Dipper” or the Trapezium in the constellation Orion, should provide direct evidence for the motion of the Earth. As Ramponi had suggested, stars at different distances from the Earth but closely spaced in the sky would exhibit annual stellar parallax. Galileo's notes on Mizar and the Trapezium can be dated to early 1617--two years after Bellarmine had written to Foscarini.⁸

Galileo's notes indicate that he determined the apparent sizes of Mizar's two component stars A and B as being six and four arc-seconds, respectively, with a gap between them of ten arc-seconds, which corresponded to a center-to-center separation of fifteen arc-seconds. Galileo's observations agree well with modern measurements for the separation of Mizar A and Mizar B. His excellence as an observer highlights his skill and sophistication as an instrument maker, telescopic observer, and data recorder (figures 2 and 3).

Galileo determined the distances to Mizar A and Mizar B by assuming that both are the same size as the Sun, and since the size of Mizar A at six arc-seconds was 1/300 of the apparent size of the Sun at 1800 arc-seconds ($\frac{1}{2}$ degree), Mizar A had to be 300 times farther from the Earth than the Sun or, in modern parlance, at a distance of 300 astronomical units (A.U.).⁹ The corresponding distance to the smaller Mizar B at four arc-seconds then had to be 450 A.U.

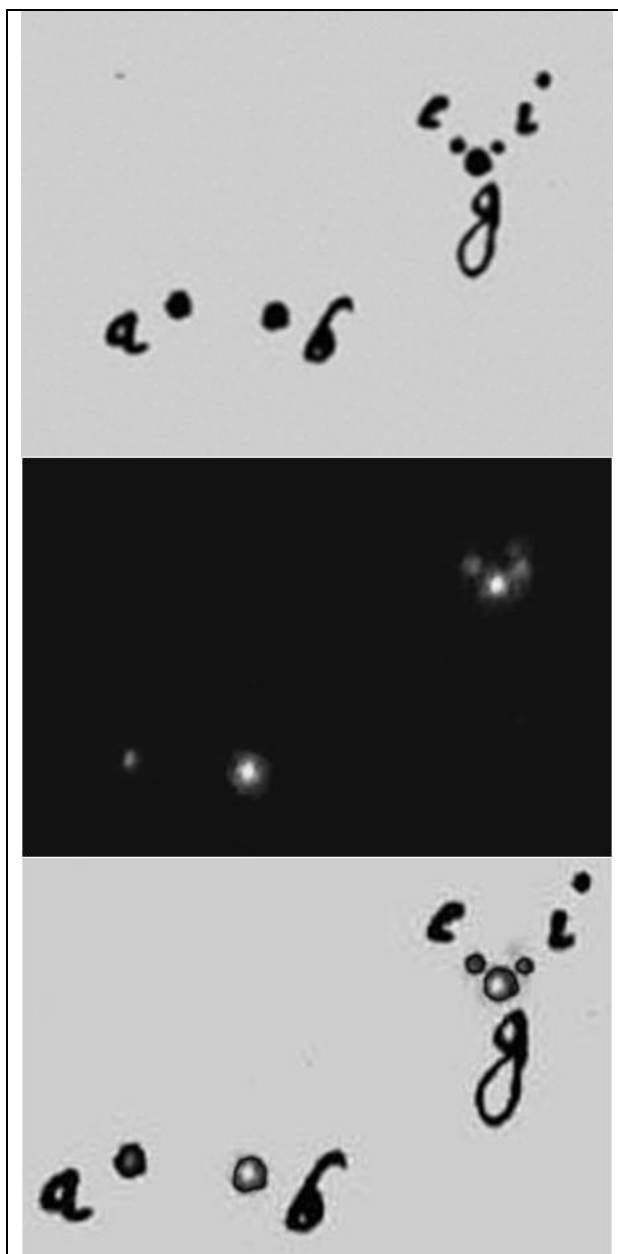


Fig. 3. The upper picture is Galileo's sketch of the Trapezium and nearby stars; the closely grouped Trapezium stars at *g* are separated from each other by less than 15 arc-seconds. The middle image is of the same region as obtained by Tom Pope and Jim Mosher, "CCD Images from a Galilean Telescope," at the website <www.pacificer.com/~tpope>, using a Galilean telescope and digital camera. The lower picture is Pope and Mosher's superposition of Galileo's sketch over their image, which illustrates the accuracy with which Galileo recorded his observations. *Credit:* Images used by permission of Jim Mosher.

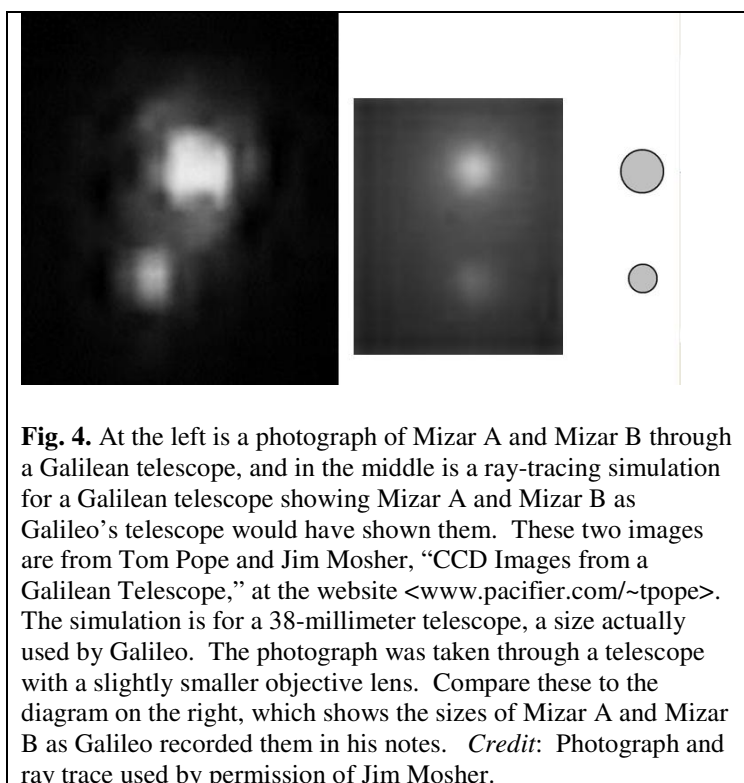
This geometric method works perfectly fine for the determination of distances to church steeples, people, ships, and the like, and Galileo used it implicitly in arguing that the sizes of Venus (as well as its phases) and of Mars show that these planets circle the Sun.¹⁰ But Galileo could not have known that this geometric method cannot be used to determine the distance of a star from the Earth, since he did not

know that light emitted from a point source is diffracted when passing through a circular aperture like the objective lens of his telescope. We know, however, that the size of “Airy’s disk” owing to the diffraction of light from a point source when passing through Galileo’s telescope is a couple of arc-seconds, regardless of the actual size of the star (figure 4).

Galileo himself necessarily took his

measurements of the sizes of stars to be valid, as well as his calculations of their distances from the Earth under the assumption that they were like our Sun.

Galileo thus must have expected that the double star Mizar would provide proof that the Earth was in motion. Based upon his calculations of the distance to Mizar A, he would have expected it to have a parallax angle of ± 11.5 arc-minutes, and Mizar B to have one of



± 7.6 arc-minutes,^b so that their relative motion over a period of months, the difference of the two, would be several arc-minutes, or more than an order of magnitude greater than their separation of fifteen arc-seconds (figure 5). Mizar A and Mizar B should have swung around each other dramatically as Galileo observed them over time.

Instead, Mizar A and Mizar B did not budge. Galileo did not know that diffraction (Airy's disk) masked their actual sizes; he did not know that they were impossibly far away from the Earth; he thus did not know that their annual stellar parallax was impossibly small (so small, in fact, that it would not be detected for any star for another two hundred years). Galileo's measurements and calculations predicted, however, that Mizar A and Mizar B would swing around each other dramatically over the course of a few months, in clear contradiction to his observations. Logically, therefore, Galileo had to conclude that either the Earth was not moving, or that his calculation of the distances of Mizar A and Mizar B from the Earth was in error by an order of magnitude or more.^c

^b To wit, $\tan^{-1}(1/300) = 0.191^\circ = 11.5'$; $\tan^{-1}(1/450) = 0.127^\circ = 7.6'$.

^c There are three possible assumptions about the stars that would have been compatible with Galileo's Mizar observations, as follows: (i) The stars are all at the same distance from the Sun; they lie on a solar-centric sphere. Galileo measured Mizar's two components to be separated by $\Delta = 15$ arc-seconds. Assuming conservatively that Galileo could detect variations of this value, calculations like those in the previous footnote show that Galileo could detect relative changes in their separation owing to parallax if Mizar B were 2.2% farther from the Earth than Mizar A. If, however, Galileo could detect relative changes comparable to the radii of the stars that he measured, so that $\Delta = 3$ arc-seconds, then Mizar B could be no more than 0.4% farther from the Earth than Mizar A. This also would require that the stars are not all like the Sun, so that the differences in the sizes of Mizar A and Mizar B reflect differences in their actual sizes and not differences in their distances from the Earth. (ii) The stars are more than an order of magnitude larger in size than the Sun and thus lie more than an order of magnitude farther away from the Earth than Galileo calculated. If Mizar A and Mizar B were then at distances of 3000 A.U. and 4500 A.U., respectively, then a separation of $\Delta = 23$ arc-seconds, calculated as above, would still have been detectable by Galileo even under conservative assumptions about his observational skill. (iii) Close star groupings were not chance line-of-sight alignments; stars are of different sizes and grouped, so that Mizar A and Mizar B are at the same distance from the Sun, but other stars are at different distances; stars do not lie on a solar-centric sphere. This was an idea that lay well in the future. In all three cases the universe does not look like Salviati's fixed stars as being so many suns. One possibility that will not do is that the absence of annual stellar parallax occurs because stars emit different amounts of light. Since Galileo knew nothing about diffraction (Airy's disk), he would have assumed that he was seeing the full disk of a star, much as he saw the full disk of Mars or Jupiter. Galileo would expect that two stars of the Sun's size at the same distance from the Earth, but emitting different amounts of light, would have different surface brightnesses.

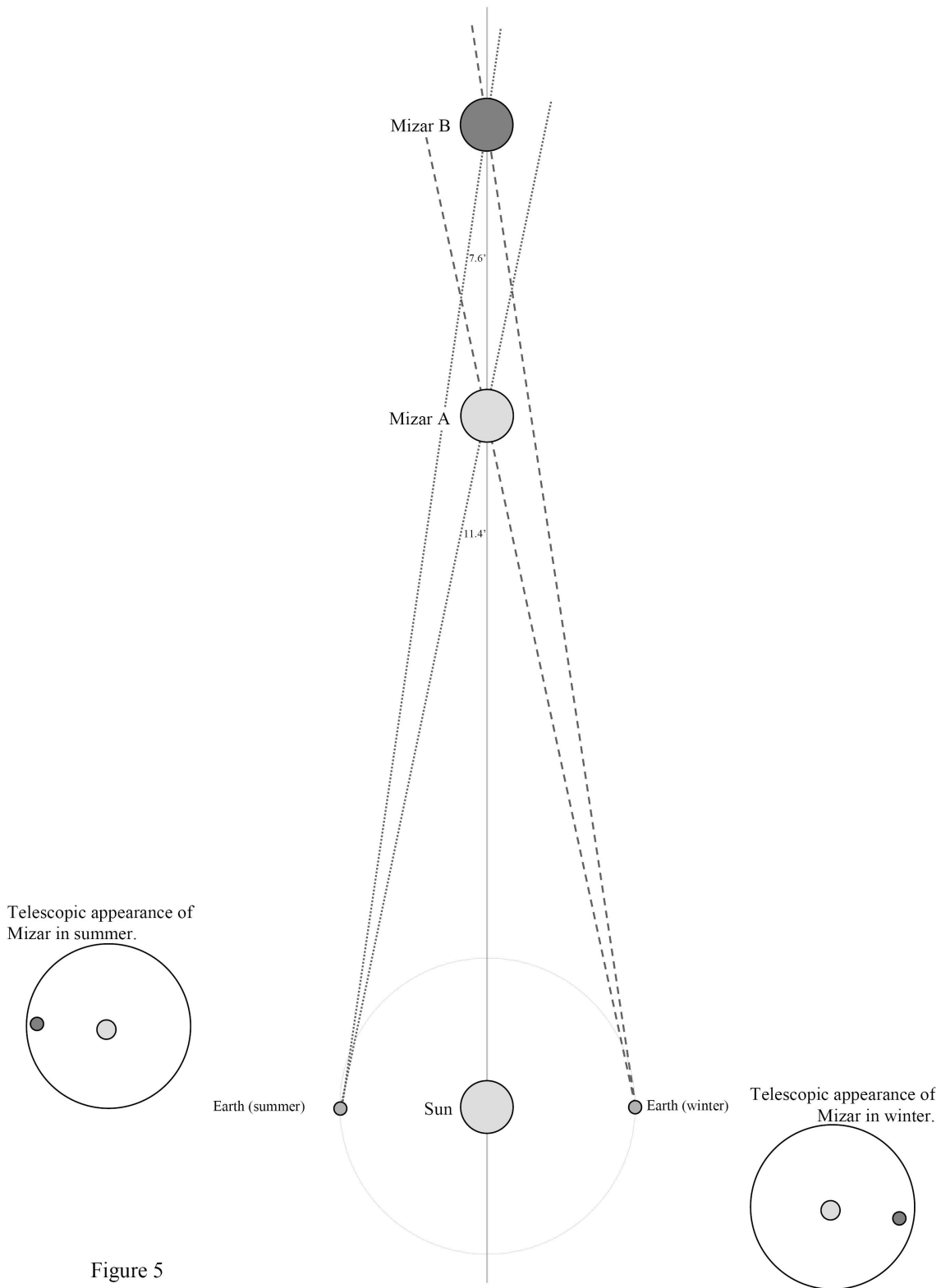


Figure 5

Fig. 5. Author's sketch of the Earth, the Sun, and Mizar A and Mizar B according to Galileo's measurements and his assumption that both are the same size as the Sun. The Sun-Mizar A distance is 300 times the Earth-Sun distance, while the Sun-Mizar B distance is 450 times the Earth-Sun distance. The difference in the parallax angles of the two stars is such that their relative positions should change dramatically as the Earth moves from one side of its orbit to the other. Since the change is much greater than the angular separation of the two components, it should have been easily observable by Galileo, which would have been direct evidence that the Earth is in motion. Galileo did not know that the size of the image of a star in his telescope is determined by diffraction (Airy's disk), so that his estimates of the distances to Mizar A and Mizar B were much too small.

Double Stars and Galileo's *Dialogue*

Nonetheless, Galileo asserted in his *Dialogue* of 1632, a decade and a half after observing Mizar A and Mizar B and the Trapezium, that the Earth is moving and that the stars are suns at different distances from the Earth. In its Third Day, after his character Salviati stated that the fixed stars are so many suns, he argued that first-magnitude stars have an apparent size of 5 arc-seconds (that is, 300 “thirds,” where one third is one-sixtieth of an arc-second), and that sixth-magnitude stars have an apparent size of $5/6$ arc-second (50 “thirds”)—both of which were in line with his Mizar observations. Then, assuming that the stars are suns, he argued further that, since $5/6$ arc-second is $1/2160$ of the size of the Sun, sixth-magnitude stars are at a distance of 2160 A.U. from the Earth. This was in line with his Mizar calculations.¹¹

Galileo's character Salviati then compared the retrograde motions of the outer planets to the annual parallax of the stars caused by the Earth's motion. Thus, the retrograde motions of the outer planets are similar to, but larger than the expected annual parallaxes of the stars. The retrograde motions of the planets can be observed against the background of the fixed stars, but the annual parallaxes of the stars will be difficult to observe, because there is no more distant background of anything at all against which they can be observed.¹² Salviati (Galileo) then continued:

it is not entirely impossible for something some time to become observable among the fixed stars by which it might be discovered what the annual motion does reside in. Then they, too, no less than the planets and the sun itself, would appear in court to give witness to such motion in favor of the earth. For I do not believe that the stars are spread over a spherical surface at equal distances from one center; *I suppose their distances from us vary so much that some are two or three times as remote as others. Thus if some tiny star were found by the telescope quite close to some of the larger ones, and if that one were therefore very remote, it might happen that some*

sensible alterations would take place among them corresponding to those of the outer planets
[my italics].¹³

This reads as though Galileo had never observed the double star Mizar. Mizar A and Mizar B had already appeared “in court” in 1617, a decade and a half earlier, in the manner he had just proposed.^d To the best of his knowledge, Mizar A and Mizar B had already given witness--and their testimony had contradicted the views of his character Salviati.^e

Tides and Stellar Parallax: Mathematical Elegance *versus* Observation

Galileo’s assertions in his *Dialogue* thus were in direct conflict with his observations of the double star Mizar. He therefore clearly found the Copernican heliocentric universe so compelling that he stood by it even in the face of contradictory observations—both with respect to numerous observations of the tides and with respect to his own observations of the double star Mizar. In the case of the tides, however, the contradictory observations struck only at Galileo’s theory of the tides: The Copernican heliocentric theory still could be valid even if Galileo’s theory of the tides were not, as Kepler and Descartes had maintained. As historian David B. Wilson has argued,

^d The Trapezium gave witness as well. Galileo recorded that the stars in the Trapezium varied in size by about four or five times, as compared to Mizar A’s and Mizar B’s one and one-half times. Thus, Galileo also should have observed annual stellar parallax in the Trapezium, even if its stars were very distant from the Earth. Siebert found that Galileo and Castelli communicated with each other about four different close star groupings, at least, during the course of a decade. Besides Mizar and the Trapezium (which they observed in early 1617), these included a grouping between Orion and Canis Major that Castelli observed in early 1617, and one in Scorpius that Castelli observed in 1627; see Siebert, “Early Search” (ref. 3), pp. 260-262.

^e One might argue that it never occurred to Galileo to look for annual stellar parallax in close groupings of stars, since to my knowledge nowhere in his notes does he state explicitly, for example, that “I have been observing Mizar and the Trapezium for months now and there is no sign of parallax.” However, since we know that Ramponi had outlined this idea to Galileo in 1611, if one argues that Galileo never looked for annual stellar parallax in the close groupings of the stars he observed, then one must explain why he did not when his measurements and calculations would have led him to believe that annual stellar parallax would be easy to observe.

because of his [Galileo's] commitment to mathematically elegant theories of nature, he held his theory of the tides in spite of its conflict with experience and in preference to various alternative theories.¹⁴

Wilson has compared Galileo to Copernicus, who maintained that Venus orbited the Sun even though it did not show the expected phases; Galileo, perhaps in analogy to Copernicus, expected that empirical support for his theory of the tides would be forthcoming in the future.

In the case of annual stellar parallax, however, Galileo's observations of the double star Mizar and of other close star groupings struck directly at the Copernican heliocentric theory of the universe. Nonetheless, Galileo was not swayed in his commitment to it, which again underlines his strong commitment to mathematically elegant theories. Indeed, if Galileo had been swayed by his Mizar observations and had concluded that the Earth is not moving, he might have advocated Tycho Brahe's hybrid geocentric theory, which Robert Hooke (1635-1703) even later considered as a viable possibility in a lecture of 1670 (which was published in 1674),¹⁵ because annual stellar parallax still had not been observed by then. Further, had Galileo published his Mizar observations, it seems likely that some contemporary astronomers who were sympathetic to the Copernican heliocentric theory might have questioned it instead. In the end, James Bradley (1673-1762) was the first to observe stellar aberration in 1727, and to interpret it as proving the motion of the Earth.¹⁶

Finally, one might speculate that if Galileo's adversaries had known when he published his *Dialogue* in 1632 that he was sitting on observations of the double star Mizar that contradicted the Copernican heliocentric theory, they would have sharpened their knives even more. They in fact may have done so, since Galileo shared his work with many in the Roman Catholic Church, such as Castelli, who thus may have known about Galileo's unpublished Mizar observations. In any case, as Wilson has noted,

in depositions to the Holy Office in 1633 he [Galileo] denied holding the Copernican system and swore that far from defending Copernicanism, the *Dialogue* was intended to refute it!¹⁷

We now see that if Galileo truly had wanted to refute the Copernican heliocentric theory, he could have done so by publishing his observations on Mizar and other star groupings.

Conclusion

Galileo's theory of the tides shows that Galileo found the Copernican heliocentric theory so persuasive that he supported it even when observations did not agree with its predictions. Leos Ondra recently has shown that Galileo was among the first to observe a double star, and I have argued that Galileo's commitment to the Copernican heliocentric theory was so deep that he stood firm even after his own telescopic observations on the double star Mizar provided no evidence of annual stellar parallax, which struck directly at the Copernican heliocentric theory. I suggest that if Galileo had published his Mizar observations, then widespread acceptance of the Copernican heliocentric theory would have been significantly delayed, regardless of whether or not Galileo himself had been swayed in his commitment to it.

Acknowledgment

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