Five Leading Figures of 17th Century Science

Johannes Kepler (1571-1630) -- German, living in Austria

Galileo Galilei (1564-1642) -- Tuscany (and Venitian Republic)

René Descartes (1596-1650) -- French, living in Holland

Christiaan Huygens (1629-1695) -- Dutch, often living in Paris

Isaac Newton (1642-1727) -- English, Cambridge (later London)

Galileo's Publications

(Numerous manuscripts on motion and other subjects before 1607, not published until after Galileo died)

1607 ***Operations of the Geometric and Military Compass***

1610 ***Siderius Nuncius***

1612 ***Bodies that Stay Atop Water, and Move in It***

1613 ***Letters on Sunspots***

1619 ***Discourse on Comets*** **(against Tycho's claims)**

1623 ***The Assayer***

1624 ***Reply to Ingoli***

1631 ***Report on Flood Control on the Bisenzio River***

1632 ***Dialogue concerning the Two Chief World Systems***

1638 ***Discourses concerning Two New Sciences***

(All the works and manuscripts of Galileo, with links to other related works from the period and often translated into English, are available via the internet at The Institute and Museum of the History of Science in Florence, Italy, *www.imss.fi.it* – as are various simulations of what Galileo must have actually seen using his telescopes. Among the vast literature on Galileo, the most useful biography in English is *Galileo at Work* by Stillman Drake; and on the trial the most reliable references are *Galileo: For Copernicanism and for the Church* by Annibale Fantoli, *The Galileo Affair: A Documentary History*, by Maurice A. Finocchiaro and *Retrying Galileo: 1633-1992* by Finocchiaro. Two more recent books by highly qualified authors are *Galileo* by John L. Heilbron and *Galileo in Rome*: *The Rise and Fall of a Troublesome Genius* by William R. Shea and Mariano Artigas)

CHRONOLOGICAL
summary of Galileo's life

1564 Galileo born at Pisa, Italy, on February 15.

1575–7 Began formal schooling at the Monastery of Vallombrosa.

1578 Entered the Vallombrosan Order but left before completing the year of novitiate.

1581 Begins studies at the University of Pisa.

1586 Invents a hydrostatic balance.

1588 Writes a treatise on the center of gravity in solids which wins him some acclaim.

1589 With the help of Guidubaldo del Monte, Galileo obtains a professorship of mathematics at the University of Pisa.

1591 Galileo resigns from Pisa after conflicts with Aristotelians. G. del Monte helps him obtain the chair of Mathematics at the University of Padua.

1597 Writes to Kepler that he has been a Copernican "for several years."

1600 Daughter Virginia (later Sister Maria Celeste) born out of wedlock.

1601 Daughter Livia (later Sister Archangela) born.

1605 Returns to Florence during the summer to tutor Prince Cosimo.

1606 Birth of a son, Vincenzio.

1608 Invention of the telescope by Hans Lippershey.

1609 February ——Prince Cosimo becomes Grand Duke of Tuscany.
July–August —Constructs a telescope and begins observing the heavens.

1610 March ——publishes the *Sidereus Nuncius*.
June ——resigns from the University of Padua.
September, returns to Florence as Ducal Philosopher and Mathematician to Cosimo II.

1611 Makes triumphant journey to Rome. Jesuit astronomers confirm his discoveries. Wins election to the *Accademia dei Lincei*. Returns to Florence and gets involved in a dispute concerning the behavior of bodies in water.

1612 Publishes discourse on floating bodies and writes letters on the sunspots. Mistakenly accuses Father Lorini of attacking him from the pulpit.

1613 Letters on the sunspots published by the Lincean Academy. Hears from Father Castelli that his doctrine has been challenged on the basis of Holy Scripture at the court of the Grand Duke. Writes Letter to Castelli.

1614 Publicly attacked by Father Caccini.

1615 Letter to Castelli denounced to the Holy Office but judged in favor of Galileo. Father Foscarini publishes a book trying to reconcile the new astronomy with Sacred Scripture. Cardinal Bellarmine writes Letter to Foscarini warning him and Galileo to stay in the area of hypothesis until demonstrative proof is produced. Galileo goes to Rome to defend his position. Thomas Campanella writes his *Apologia pro Galileo* at the request of Cardinal Gaetani.

1616 February 19 —Theological Consultors of the Holy Office summoned to give their opinion on the Copernican doctrine.
February 23 —Consultors censure Copernican opinion as heretical.
February 25 —Pope Paul V assigns Cardinal Bellarmine to tell Galileo not to hold or defend his theory.
February 26 —Date of the famous injunction recorded in the Holy Office files which claims that Galileo was told by the Commissary General not to discuss his theory in any way.
March 3 ——Cardinal Bellarmine gives Galileo a certificate with which to combat the lies which were being spread about him.

SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

6.4. The title-page of Galileo's *Sidereus nuncius* (1610), with a summary of the discoveries announced in the work. Special prominence is given to the satellites of Jupiter, named for Galileo's patron, Cosimo de' Medici.

SIDEREAL MESSENGER

unfolding great and very wonderful sights
and displaying to the gaze of everyone,
but especially philosophers and astronomers,
the things that were observed by

GALILEO GALILEI,

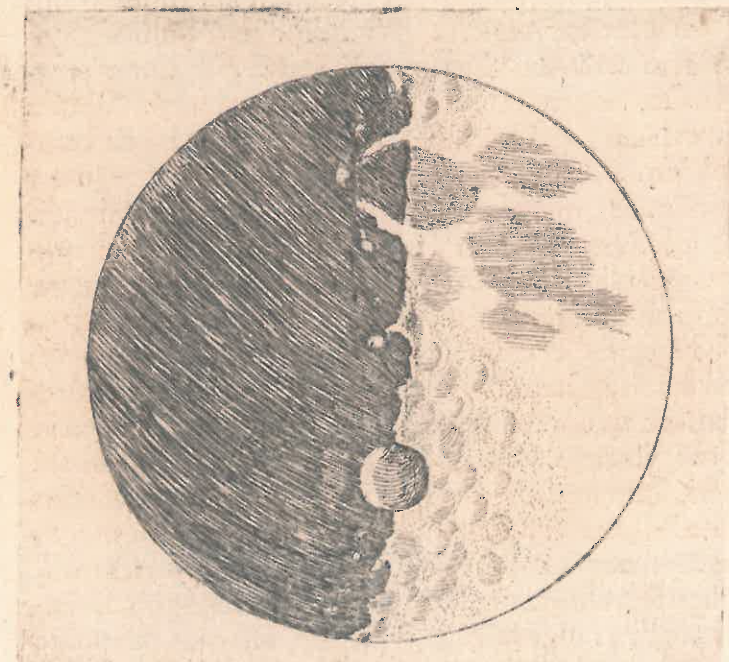
Florentine patrician
and public mathematician of the University of Padua,
with the help of a spyglass lately devised by him,
about the face of the Moon, countless fixed stars,
the Milky Way, nebulous stars,
but especially about
four planets
flying around the star of Jupiter at unequal intervals
and periods with wonderful swiftness;
which, unknown by anyone until this day,
the first author detected recently
and decided to name

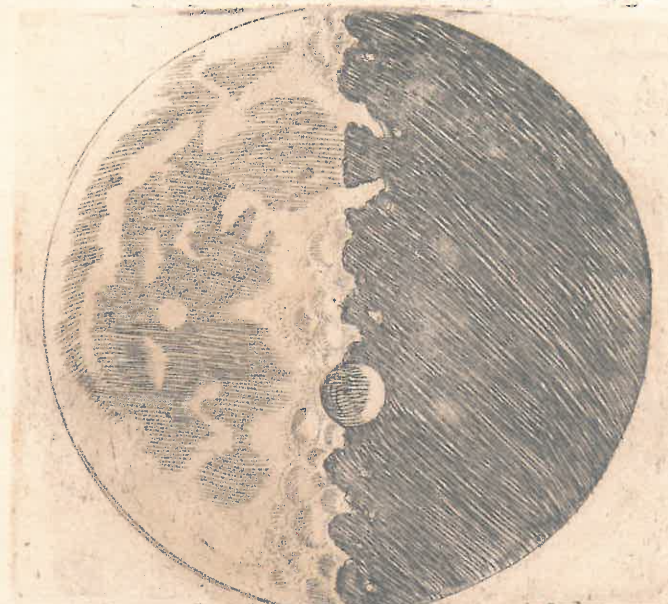
MEDICEAN STARS

Venice, Thomas Baglioni, 1610

with permission and highest privilege

ctum ducturam. Depressiores insuper in Luna cernuntur magnæ maculæ, quàm clariores plagæ; in illa enim tam crescente, quam decrescente semper in lucis tenebrarumque confinio, prominente hincindè circa ipsas magnas maculas contermini partis lucidioris; veluti in describendis figuris obseruauimus; neque depressiores tantummodo sunt dictarum macularum termini, sed æquabiliores, nec rugis, aut asperitatibus interrupti. Lucidior verò pars maximè propè maculas eminet; adeò vt, & ante quadraturam primam, & in ipsa fermè secunda circa maculam quandam, superiorem, borealem nempè Lunę plagam occupantem valdè attollantur tam supra illam, quàm infra ingentes quæda eminentiæ, veluti appositæ præseferunt delineationes.





Hæc eadem macula ante secundam quadraturam nigrioribus quibusdam terminis circumuallata conspicitur; qui tanquam altissima montium iuga ex parte Soli auersa obscuriores apparent, quà verò Solem respiciunt lucidiores extant; cuius oppositum in cauitatibus accidit, quarum pars Soli auersa splendens apparet, obscura verò, ac vmbrosa, quæ ex parte Solis sita est. Imminuta deinde luminosa superficie, cum primum tota fermè dicta macula tenebris est obducta, clariora mõtium dorsa eminenter tenebras scandunt. Hanc duplicem apparentiam sequentes figuræ commostrant.

dentalis proxima min. 2. ab hac vero elongabatur oc-

Ori. * O * * Occ.

cidentalior altera min: 10. erant præciſè in eadem recta, & magnitudinis æqualis.

Die quarta hora ſecunda circa Iouem quatuor ſtabant Stellæ, orientales duæ, ac duæ occidentales in

Ori. * * O * * Occ.

eadem ad vnguem recta linea diſpoſitæ, vt in proxima figura. Orientalior diſtabat à ſequenti min. 3. hęc verò à Ioue aberat min. 0. ſec. 40. Iuppiter à proxima occidentali min. 4. hæc ab occidentaliori min. 6. magnitudine erant ferè ęquales, proximior Ioui reliquis paulo minor apparebat. Hora autem ſeptima orientales Stellæ diſtabant tantum min. 0. ſec. 30. Iuppiter

Ori. ** O * * Occ.

ab orientali viciniori aberat min. 2. ab occidentali verò ſequente min. 4. hæc verò ab occidentaliori diſtabat min. 3. erantque æquales omnes, & in eadem recta ſecundum Eclypticam extenſa.

Die quinta Cœlum fuit nubiloſum.

Die ſexta duæ ſolummodo apparuerunt Stellæ me-

Ori. * O * Occ.

dium

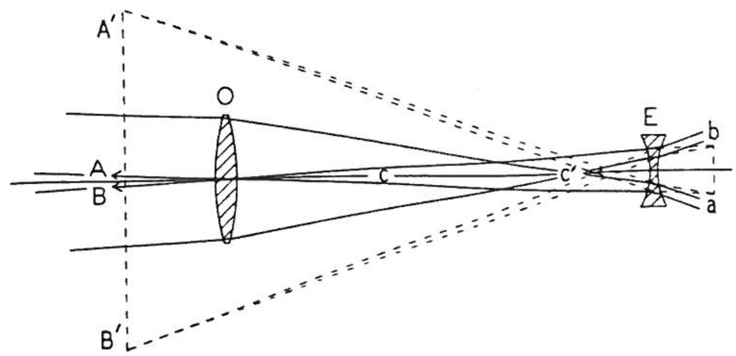


Fig. 2. Image formation in the Galilean (erecting) telescope.

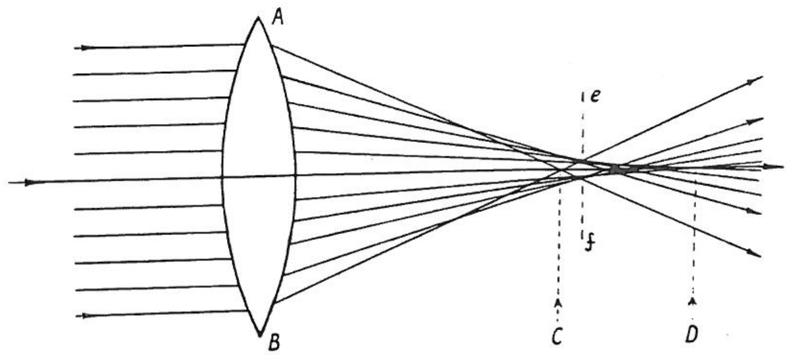


Fig. 18—Spherical aberration

AB	Biconvex lens
C	Focus for rays incident on marginal zone of lens
D	Focus for rays incident on axial zone of lens
CD	This distance is the longitudinal spherical aberration
ef	The position of the circle of least confusion

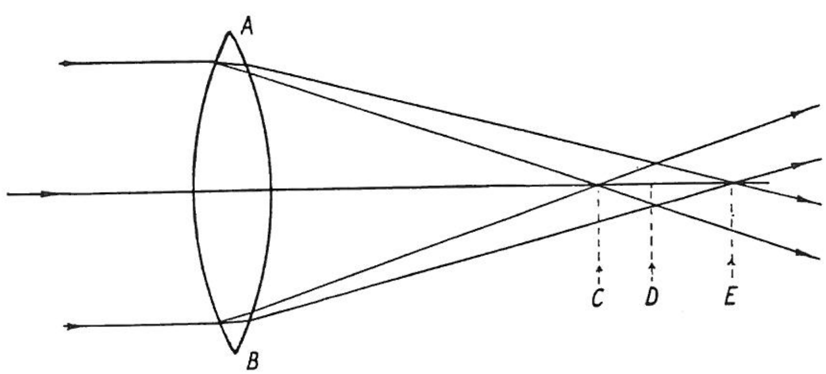


Fig. 19—Chromatic aberration

AB	Biconvex lens receiving parallel rays of white light
C	Focus for blue rays
D	Focus for yellow rays
E	Focus for red rays

Optical tests of Galileo's lenses

Vincenzo Greco, Giuseppe Molesini and Franco Quercioli

The science museum in Florence has two telescopes and a single lens attributed to Galileo. Tests conducted with modern interferometric equipment show that Galileo was able to obtain nearly perfect optical quality.

ACCORDING to biographies, Galileo is supposed to have made several telescopes, purchasing some lenses and polishing others himself, yet only the optical apparatus now in Florence, collected and handed down by the Medici family[1], appears to have survived. The authenticity of the telescope tubes seems certain, but some doubts remain about the lenses, apart from the single lens, which was used in the discovery of the Medici stars.

The Medici collection was examined in 1923[2,3], but we have now taken the telescopes apart and tested them with state-of-the-art optical equipment. Analysis of the optical quality of Galileo's lenses is of interest for understanding both the development of optical technology and the observational capabilities of early astronomers. Before Galileo's time, observations were made with the naked eye, for which the resolution is about 1 arc minute. Lenses were used only as eyeglasses or as magnifying lenses, for which applications the poor glass purity and optical figure then feasible were nevertheless adequate.

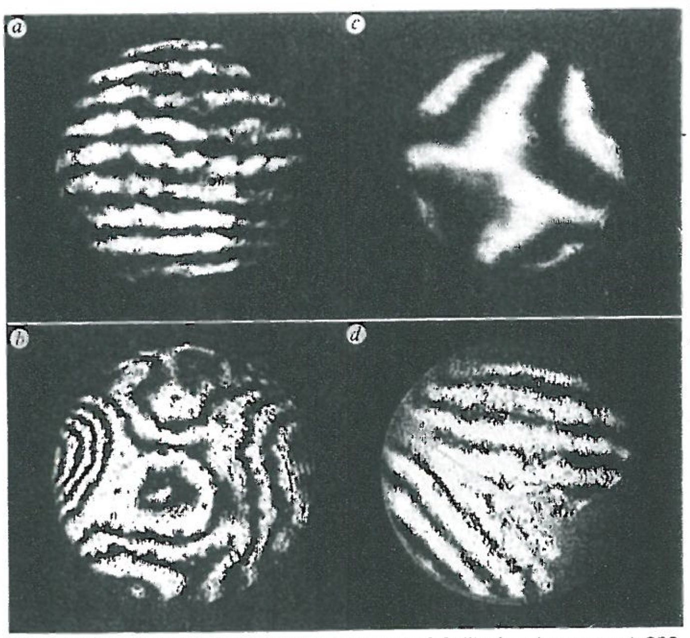
We have examined Galileo's optics with modern methods. We call the telescopes I (paper coated, longer tube) and II (leather coated, shorter tube). Their optical configuration is based on a positive objective and a negative eyepiece with a common focus. The table summarizes the measurements of the geometry and the first-order optical parameters. The focal lengths are measured in the centre of the visible spectrum (550 nm). From the lens geometries and focal lengths, we calculate that the refractive index of the glasses is 1.51 – 1.55. The relative apertures of the objectives are *f*/51 for telescope I, *f*/61 for telescope II and *f*/45 for the single lens. The magnification of the telescopes is 14 for I and 21 for II.

OPTICAL DATA OF GALILEO'S LENSES

	Front radius	Back radius	Central thickness	Full diameter	Aperture diameter	Focal length
Objective I	2,700	950	2.5	51	26	1,330
Eyepiece I	plane	48.5(*)	3.0	26	11	−94.0
Objective II	535(*)	Plane	2.0	37	16	980
Eyepiece II	51.5(*)	51.5(*)	1.8	22	16	−47.5
Single lens	940	12,000	4.0	58	38	1.710

Asterisks, data from ref. 3. Dimensions are in mm.

We used a 633-nm digital phase-shift Fizeau interferometer to study the regularity of the optical surfaces and the wavefront distortion in transmission. Typical fringe patterns are shown in the figure. As far as regularity is concerned, the quality of the objective lenses is far better than the quality of the eyepieces. But because the used diameter per field angle at the eyepiece is much smaller than the clear aperture of the objective, the effect of the lower quality of the eyepieces is negligible. It is surprising that the plane surfaces of eyepiece I and objective II (*c* in the figure) are really plane to a fraction of a wave, although flatness of these surfaces is not required in terms of image quality. (Polishing a surface to such flatness is not trivial even for today's crown glasses.)



Fizeau fringe patterns of the optical elements of Galileo's telescopes at 633 nm. The fringe maps show the deviation of the wavefront from a sphere or a plane. For reference, a diffraction-limited wavefront produces no fringes, or straight and equally spaced fringes if some tilt is added. *a*, Double-pass interferogram of objective I, folded with a reference mirror. Deviations from straight fringes are of the order of half a pitch, meaning a departure from the ideal wavefront of the order of a quarter of a wavelength. *b*. Reflection interferogram of the concave surface of eyepiece I. Fringes are highly irregular. *c*, Reflection interferogram of the plane surface of objective II. The quadrant fringes show astigmatism. *d*, Double-pass interferogram of the single lens.

A further observation comes from the appearance of the concave surface of eyepiece I (*b*). In addition to the interference fringes, a pattern of ring shadows appears, as if the surface had traces of a turning process. The wavefront distortion of objective I is very small (*a*). The best quality belongs to the single lens, which can be considered as nearly diffraction-limited (*d*). According to the Rayleigh criterion, its resolution at 633 nm is of the order of 3 arcseconds. Of course, the optical performance of the telescopes is degraded for several reasons, mainly chromatic aberration. Computer simulations taking dispersion into account lead to estimates of only 10–20 arcseconds resolution over the visible spectrum.

Altogether, our tests of the lenses (made 350 years after Galileo's death) show that they are polished to a good spherical shape, and the presence of proper apertures on the objectives also shows Galileo's awareness of the need to tune the optical performance. As a result, although affected by intrinsic chromatic aberration, at single wavelength the telescopes are nearly diffraction-limited, that is, optically perfect. □

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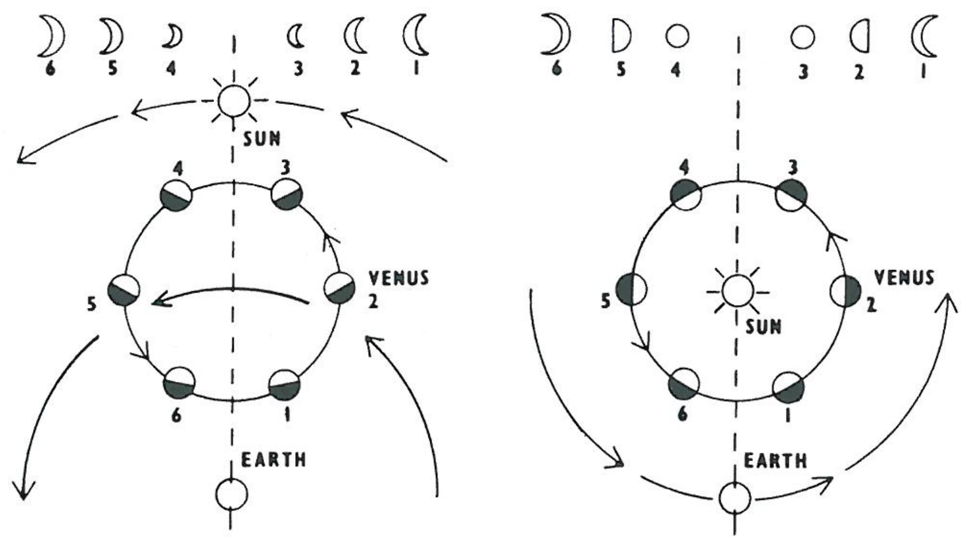
ACKNOWLEDGEMENTS. We thank P. Galluzzi and M. Miniati for discussions, and the *Istituto e Museo di Storia della Scienza* for permission to publish the material in this paper.

1. Bonelli, M. L. in *Proc. 1964 Symp. Galileo* 125–127 (Marzocco, Florence, 1967).
2. Abetti, G. *L'Universo*, **4**, 685–692 (1923).
3. Ronchi, V. *L'Universo*, **4**, 791–804 (1923).

Next Apelles suggests that sunspot observations afford a method by which he can determine whether Venus and Mercury revolve about the sun or between the earth and the sun. I am astonished that nothing has reached his ears—or if anything has, that he has not capitalized upon it—of a very elegant, palpable, and convenient method of determining this, discovered by me about two years ago and communicated to so many people that by now it has become notorious. This is the fact that Venus changes shape precisely as does the moon; and if Apelles will now look through his telescope he will see Venus to be perfectly circular in shape and very small (though indeed it was smaller yet when it [recently] emerged as evening star). He may then go on observing it, and he will see that as it reaches its maximum departure from the sun it will be semicircular. Thence it will pass into a horned shape, gradually becoming thinner as it once more approaches the sun. Around conjunction it will appear as does the moon when two or three days old, but the size of its visible circle will have much increased. Indeed, when Venus emerges [from behind the sun] to appear as evening star, its apparent diameter is only one-sixth as great as at its evening disappearance [in front of the sun] or its emergence as morning star [several days thereafter], and hence its disk appears forty times as large on the latter occasions.

These things leave no room for doubt about the orbit of Venus. With absolute necessity we shall conclude, in agreement with the theories of the Pythagoreans and of Copernicus, that Venus revolves about the sun just as do all the other planets. Hence it is not necessary to wait for transits and occultations[1] of Venus to make certain of so obvious a conclusion. No longer need we employ arguments that allow any answer, however feeble, from persons whose philosophy is badly upset by this new arrangement of the universe. For these opponents, unless constrained by some stronger argument, would say that Venus either shines with its own light or is of a substance that may be penetrated by the sun's rays, so that it may be lighted not only on its surface but also throughout its depth. They take heart to shield themselves with this argument because there have not been wanting philosophers and mathematicians who have actually believed this—meaning no offense to Apelles, who says otherwise. Indeed, Copernicus himself was forced to admit the possibility and even the necessity of one of these two ideas, as otherwise he could give no reason for Venus failing to appear horned when beneath the sun.[2] As a matter of fact nothing else could be said before the telescope came along to show us that Venus is naturally and actually dark like the moon, and like the moon has phases.



The appearance of Venus predicted by the
Ptolemaic and Copernican systems

Galileo's Telescopic Discoveries

Announced in *Siderius Nuncius*

- Surface of the Moon irregular, including mountains 4 miles high
- "Earth shine": reflected light from the Earth lights the Moon
- Fixed stars do not appear as disks when viewed in telescopes
- Planets do appear as disks when viewed in telescopes
- Fixed stars are "so numerous as almost to surpass belief"
- Milky way consists of congeries of innumerable stars grouped in clusters
- So too for the celestial objects theretofore called nebuli
- Four "planets" are in orbit around Jupiter, lending support to Copernicanism

Announced in "Letters on Sunspots"

- Venus exhibits phases, akin to those exhibited by the Moon
- The Sun's surface displays spots, persisting in relation to one another
- As inferred from the spots, the Sun rotates on its axis (roughly 25 days)
- Saturn exhibits two "small stars" tied to it on opposite sides

1616 March 5 ——Decree of the Congregation of the Index prohibits Copernicus's *De revolutionibus* until corrected and made more hypothetical.

1618 Appearance of the great comets stirs up discussion.

1619 Galileo enters the controversy by writing the "Discourse on Comets" and publishing it under the name of his disciple, Mario Guiducci.

1620 The Congregation of the Index publishes a list of corrections making it possible for anyone to read Copernicus's work.

1621 The deaths of Pope Paul V, Cardinal Bellarmine, and Grand Duke Cosimo II alter the scene considerably. Galileo begins work on *The Assayer* in answer to Father Grassi's *Astronomical Balance.*

1623 Maffeo Cardinal Barberini is elected Pope and takes the name Urban VIII. Galileo dedicates *The Assayer* to him.

1624 Galileo goes to Rome to try to get the Copernican censure revoked. He has six long talks with Pope Urban and is encouraged to write but told to stay within the limits of a hypothetical treatment.

1625 Begins work on the *Dialogue on the Two Great World Systems* which he intends to be "a most ample confirmation" of the Copernican opinion.

1626–1629 Illness and necessary interruptions prevent him from completing the *Dialogue.*

1630 January ——Completes the *Dialogue.*

May ——Galileo goes to Rome and works a publishing arrangement with Father Riccardi.

August ——Prince Cesi, Founder of the Lincean Academy and close friend of Galileo, dies.

1631 Galileo sends request to Rome that the printing be done in Florence. Niccolini is able to convince Riccardi to grant the necessary permission.

1632 February ——The *Dialogue* is published.

August ——Sales and publication are halted by order of the Holy Office.

October ——Galileo is summoned to Rome.

1633 February ——Galileo arrives in Rome and is allowed to stay at the Tuscan Embassy.

April ——Questioned twice by Father Firenzuola. Firenzuola and Cardinal Barberini, the Pope's nephew, desire to deal leniently with Galileo.

May ——Galileo gives his defense to the Holy Office. A misleading report on the proceedings is sent to the Pope.

June 16 ——Pope Urban decrees that Galileo is to publicly abjure his opinion and his book is to be prohibited.

June 22 ——Galileo abjures. His sentence was commuted and he was released in the custody of the Archbishop of Siena.

December ——Galileo returns to his Villa at Arcetri, near Florence.

1637 Galileo loses sight in both eyes and has to move into the city of Florence. He continues to work on his new book, the *Two New Sciences.*

1638 The *Discourses on Two New Sciences* is published at Leyden.

1642 January 8 ——Galileo dies.

THE ASSAYER

In which
With a delicate and precise scale
will be weighed the things contained in
The Astronomical and Philosophical Balance
of Lothario Sarsi of Siguenza

Written in the form of a Letter
to the Illustrious and Reverend Monsignore

DON VIRGINIO CESARINI

Lincean Academician
Lord Chamberlain to His Holiness

BY

SIGNOR

GALILEO GALILEI

Lincean Academician
Gentleman of Florence
Chief Philosopher and Mathematician
to the
Serene Grand Duke of Tuscany

ROME

MDCXXIII

DIALOGO

DI

GALILEO GALILEI LINCEO

MATEMATICO SOPRAORDINARIO

DELLO STVDIO DI PISA.

E Filoſofo, e Matematico primario del

SERENISSIMO

GR.DVCA DI TOSCANA.

Doue ne i congreſſi di quattro giornate ſi diſcorre ſopra i due

MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;

Proponendo indeterminatamente le ragioni Filoſofiche, e Naturali tanto per l'vna, quanto per l'altra parte.

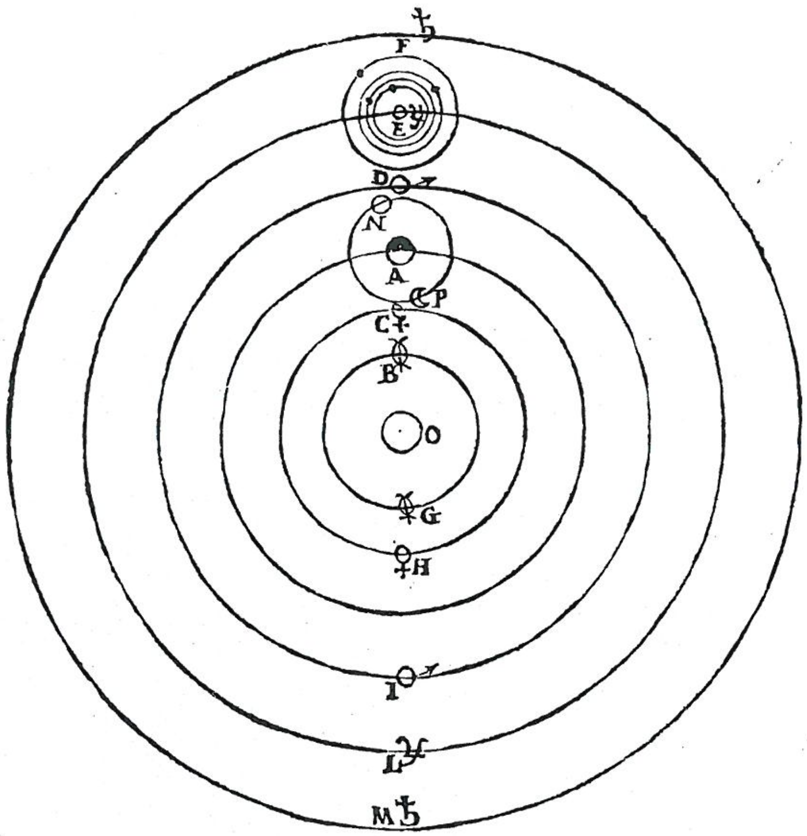
CON PRI

VILEGI.

IN FIORENZA, Per Gio:Batiſta Landini MDCXXXII.

CON LICENZA DE' SVPERIORI.

6.13. The title-page of Galileo's *Dialogue Concerning Two Chief World Systems* (1632). The two systems are the Ptolemaic (against which Galileo had powerful arguments) and the Copernican: he makes little mention of the Tychonic and semi-Tychonic systems which by then had superseded the Ptolemaic.



6.14. The Copernican system as depicted in Galileo's *Dialogue Concerning Two Chief World Systems.* On the Copernican view the Earth had been anomalous in having a satellite, but Galileo's telescope had shown that at least one other planet also had satellites.

Salviati. But we cannot yet determine surely the law [*governi,* not *legge*!] of revolution and the structure of the orbit of each planet (the study ordinarily called planetary theory); witness to this fact is Mars, which has caused modern astronomers so much distress. Numerous theories have also been applied to the moon itself since the time when Copernicus first greatly altered Ptolemy's theory.

Galileo, *Dialogue*, Day Four, p. 528

Salviati. … To Mercury and Venus you [Simplicio] have attributed a circular motion around the sun without embracing the earth. Around the same sun you have caused the three outer planets, Mars, Jupiter, and Saturn, to move, embracing the earth within their circles. Next, the moon cannot move in any way except around the earth and without embracing the sun…. It now remains to apportion three things among the sun, earth, and stellar sphere: the state of rest, which appears to belong to the earth; the annual motion through the zodiac, which appears to belong to the sun; and the diurnal movement, which appears to belong to the stellar sphere, with all the rest of the universe sharing in it except the earth. And since it is true that all planetary orbs (I mean Mercury, Venus, Mars, Jupiter, and Saturn) move around the sun as a center, *it seems most reasonable* for the state of rest to belong to the sun rather than the earth – just as it does for the center of any movable sphere to remain fixed, rather than some other point remote from the center.

Next as to the earth, which is placed in the midst of moving objects – I mean between Venus and Mars, one of which makes its revolution in nine months and the other in two years – a motion requiring one year may be attributed to it much more elegantly than a state of rest, leaving the latter to the sun. And such being the case, it necessarily follows that the diurnal motion, too, belongs to the earth. For if the sun stood still, and the earth did not revolve upon itself but merely had the annual movement, our year would consist of no more than one day and one night; that is, six months of day and six months of night.

Galileo, *Dialogue*, Day Three, p. 379
(italics added)

Salviati. This we have already examined at length by showing that all terrestrial events from which it is ordinarily held that the earth stands still and the sun and fixed stars are moving would necessarily appear the same to us if the earth moved and the others stood still. Among all sublunary things it is only in the element of water (as something which is very vast and is not joined and linked with the terrestrial globe as are all its solid parts, but is rather, because of its fluidity, free and separate and a law unto itself) that we may recognize some trace of indication of the earth's behavior in regard to motion and rest. After having many times examined for myself the effects and events, partly seen and partly heard from other people, which are observed in the movements of the water; after, moreover, having read and listened to the great follies which many people have put forth as causes of these events, I have arrived at two conclusions which were not lightly to be drawn and granted. Certain necessary assumptions having been made, these are that if the terrestrial globe were immovable, the ebb and flow of the oceans could not occur naturally; and that when we confer upon the globe the movements just assigned to it [earlier in the *Dialogue*], the seas are necessarily subjected to an ebb and flow agreeing in all respects with what is to be observed in them.

Sagredo. The proposition is crucial, both in itself and in what follows as a consequence; therefore I shall be so much the more attentive in listening to its explanation and verification.

Salviati. In questions of natural science like this one at hand, a knowledge of effects is what leads to an investigation and discovery of the causes. Without this, ours would be a blind journey, or one even more uncertain than that; for we should not know where we wanted to come out, whereas the blind at least know where they wish to arrive. Hence before all else it is necessary to have a knowledge of the effects whose causes we are seeking.

Galileo, *Dialogue*, Day Four, p. 484

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Re-examining Galileo's Theory of Tides

PAOLO PALMIERI

Communicated by C. WILSON

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according to the hypotheses of the Newtonian equilibrium theory, where there is no need for a dynamic response of water, given that the whole phenomenon, which is controlled exclusively by tide-generating force, is quasi-static, i.e. in essence, extremely slow). On the contrary, water passes beyond the 'equilibrium point' and only by 'repeated oscillations of travel' does it reduce itself to 'a state of rest'. What Galileo has in mind here is the image of a swinging pendulum. In fact the passage quoted above goes on to explain that

> In exactly this way we see that a weight suspended by a cord, once removed from the state of rest (that is, the perpendicular), returns to this and comes to rest by itself, but only after having gone to and fro many times, passing beyond this perpendicular position in its coming and going.[15]

And this image becomes the *trait d' union* with the statement of the laws of motion of water within basins that immediately follows

> [...] the reciprocations of movement just mentioned are made and repeated with greater or less frequency (that is, in shorter or longer times) according to the various lengths of the vessels containing the water. *In the shorter space, the reciprocations are more frequent, and they are rarer in the longer*, just as in the above example of the plumb bobs the reciprocations of those which are hung on long cords are seen to be less frequent than those hanging from shorter threads. [...] it is not only a greater or lesser length of vessel which causes the water to perform its reciprocations in different times, but a greater or lesser depth does the same thing. It happens that *for water contained in vessels of equal length but of unequal depth, the deeper water will make its vibrations in briefer times, and the oscillations will be less frequent in the shallower.*[16]

Thus, Galileo knew exactly that: a) thanks to gravity – be it an internal tendency or an external accidental cause – water contained in vessels continues to oscillate freely after having been excited; b) the frequency of free oscillation depends on the width and depth of the vessel, i.e. on its geometry; c) the frequency increases in relation to the depth of the vessel and decreases in relation to its width. What he almost certainly did not know, or, at least, what he was not able to work out satisfactorily enough to support his claims, was the quantitative relations by means of which the two laws of basins might be expressed in an appropriate mathematical language. This lack of 'quantitative' refinement

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where the author discusses the question in relation to Galileo's concept of inertia and projectile motion; P. Galluzzi, *Momento. Studi Galileiani*, Roma, Edizioni dell' Ateneo & Bizzarri, 1979, particularly pp. 309–329, where Galileo's different theories of 'acceleration' and its cause are discussed). However that may be, Galileo's analysis of the oscillatory behaviour within basins appears to be totally independent of the question as to the physical cause that determines its behaviour. And whether 'gravity', or 'heaviness', acts as an internal principle 'naturally' common to all heavy bodies, or as an external 'accidental' cause, so that weight is simply proportional to this cause, Galileo's description of oscillating phenomena emerges unscathed.

[15] G. Galilei, *Dialogue on the Two Chief World Systems, op. cit.*, p. 428.

[16] *Ibid.*, pp. 428–429. Italics are mine.

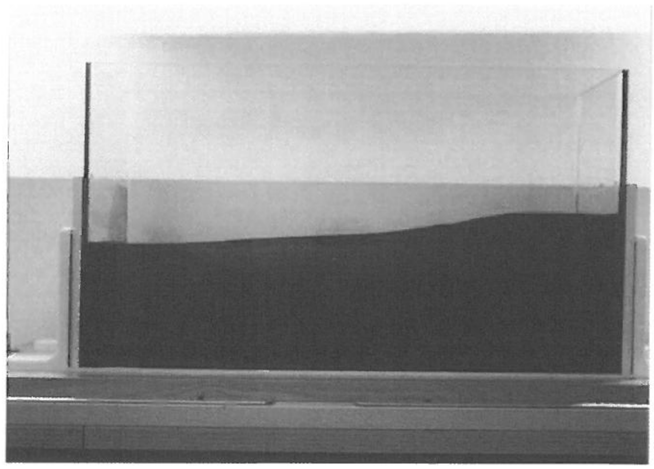


Figure A4.6

Whether Galileo even suspected such 'regularity' and performed these simple calculations, or simply accepted the more qualitative evidence stemming from such experiments without any further investigation, we do not know. But one thing is clear: the law of depth and the law of width (which may be verified by a practically identical procedure so that we can spare the reader the boredom of analogous data and computations) were well within the 'compass' of experiments the same or similar to these. Yet, it must have been the astonishing complexity of the many combinations of motions that waves display that in the end prevented Galileo from making public his results and furnishing the necessary evidence that such important discoveries would have deserved.

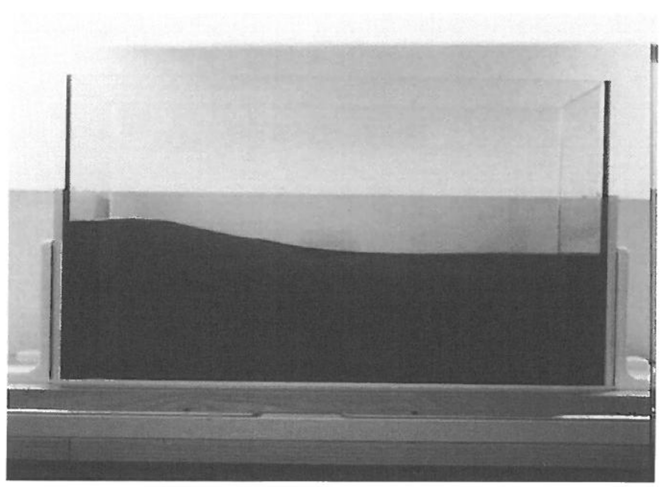


Figure A4.7

Francesco Barberini, with the title of San Lorenzo in Damaso; and Marzio Ginetti, with the title of Santa Maria Nuova, of the order of deacons;

By the grace of God, Cardinals of the Holy Roman Church, and especially commissioned by the Holy Apostolic See as Inquisitors-General against heretical depravity in all of Christendom.

Whereas you, Galileo, son of the late Vincenzio Galilei, Florentine, aged seventy years, were denounced to this Holy Office in 1615 for holding as true the false doctrine taught by some that the sun is the center of the world and motionless and the earth moves even with diurnal motion; for having disciples to whom you taught the same doctrine; for being in correspondence with some German mathematicians about it; for having published some letters entitled *On Sunspots*, in which you explained the same doctrine as true; for interpreting Holy Scripture according to your own meaning in response to objections based on Scripture which were sometimes made to you; and whereas later we received a copy of an essay in the form of a letter, which was said to have been written by you to a former disciple of yours and which in accordance with Copernicus's position contains various propositions against the authority and true meaning of Holy Scripture;

And whereas this Holy Tribunal wanted to remedy the disorder and the harm which derived from it and which was growing to the detriment of the Holy Faith, by order of His Holiness and the Most Eminent and Most Reverend Lord Cardinals of this Supreme and Universal Inquisition, the Assessor Theologians assessed the two propositions of the sun's stability and the earth's motion as follows:

That the sun is the center of the world and motionless is a proposition which is philosophically absurd and false, and formally heretical, for being explicitly contrary to Holy Scripture;

That the earth is neither the center of the world nor motionless but moves even with diurnal motion is philosophically equally absurd and false, and theologically at least erroneous in the Faith.

Whereas however we wanted to treat you with benignity at that time, it was decided at the Holy Congregation held in the presence of His Holiness on 25 February 1616 that the Most Eminent Lord Cardinal Bellarmine would order you to abandon this false opinion completely; that if you refused to do this, the Commissary of the Holy Office would give you an injunction to abandon this doctrine, not to teach it to others, not to defend it, and not to treat of it; and that if you did not acquiesce in this injunction, you should be imprisoned. To execute this decision, the following day at the palace of and in the presence of the above-mentioned Most Eminent Lord Cardinal Bellarmine, after being informed and warned in a friendly way by the same Lord Cardinal, you were given an injunction by the then Father Commissary of the Holy Office ⟨404⟩ in the presence of a notary and witnesses to the effect that you must completely abandon the said false opinion, and that in the future you could neither hold, nor defend, nor teach it in any way whatever, either orally or in writing; having promised to obey, you were dismissed.

Furthermore, in order to completely eliminate such a pernicious doctrine, and not let it creep any further to the great detriment of Catholic truth, the Holy Congregation of the Index issued a decree which prohibited books treating of such a doctrine and declared it false and wholly contrary to the divine and Holy Scripture.

And whereas a book has appeared here lately, printed in Florence last year, whose inscription showed that you were the author, the title being *Dialogue by Galileo Galilei on the two Chief World Systems, Ptolemaic and Copernican*; and whereas the Holy Congregation was informed that with the printing of this book the false opinion of the earth's motion and sun's stability was being disseminated and taking hold more and more every day, the said book was diligently examined and found to violate explicitly the above-mentioned injunction given to you; for in the same book you have defended the said opinion already condemned and so declared to your face, although in the said book you try by means of various subterfuges to give the impression of leaving it undecided and labeled as probable; this is still a very serious error since there is no way an opinion declared and defined contrary to divine Scripture may be probable.

Therefore, by our order you were summoned to this Holy Office, where, examined under oath, you acknowledged the book as written and published by you. You confessed that about ten or twelve years ago, after having been given the injunction mentioned above, you began writing the said book, and that then you asked for permission to print it without explaining to those who gave you such permission that you were under the injunction of not holding, defending, or teaching such a doctrine in any way whatever.

Likewise, you confessed that in several places the exposition of the said book is expressed in such a way that a reader could get the idea that the arguments given for the false side were effective enough to be capable of convincing, rather than being easy to refute. Your excuses for having committed an error, as you said so foreign from your intention, were that you had written in dialogue form, and everyone feels a natural satisfaction for one's own subtleties and showing oneself sharper than the average man by finding ingenious and apparently probable arguments even in favor of false propositions.

Having been given suitable terms to present your defense, you produced a certificate in the handwriting of the Most Eminent Lord Cardinal Bellarmine, which you said you obtained to defend yourself from the calumnies of your enemies, who were claiming that you had abjured and had been punished by the Holy Office. This ⟨405⟩ certificate says that you had neither abjured nor been punished, but only that you had been notified of the declaration made by His Holiness and published by the Holy Congregation of the Index, whose content is that the doctrine of the earth's motion and sun's stability is contrary to Holy Scripture and so can be neither defended nor held. Because this certificate does not contain the two phrases of the injunction, namely "to teach" and "in any way whatever," one is supposed to believe that in the course of fourteen or sixteen years you had lost any recollection of them, and that for this same reason you had been silent about the injunction when you applied for the license to publish the book. Furthermore, one is supposed to believe that you point out all of this not to excuse the error, but in order to have it attributed to conceited ambition rather than to malice. However, the said certificate you produced in your defense aggravates your case further since, while it says that the said opinion is contrary to Holy Scripture, yet you dared to treat of it, defend it, and show it as probable; nor are you helped by the license you artfully and cunningly extorted since you did not mention the injunction you were under.

Because we did not think you had said the whole truth about your intention, we deemed it necessary to proceed against you by a rigorous examination. Here you answered in a Catholic manner, though without prejudice to the above-mentioned matters confessed by you and deduced against you about your intention.

Therefore, having seen and seriously considered the merits of your case, together with the above-mentioned confessions and excuses and with any other reasonable matter worth seeing and considering, we have come to the final sentence against you given below.

Therefore, invoking the Most Holy name of Our Lord Jesus Christ and his most glorious Mother, ever Virgin Mary; and sitting as a tribunal, with the advice and counsel of the Reverend Masters of Sacred Theology and the Doctors of both laws, our consultants; in this written opinion we pronounce final judgment on the case pending before us between the Magnificent Carlo Sinceri, Doctor of both laws, and Prosecuting Attorney of this Holy Office, on one side, and you the above-mentioned Galileo Galilei, the culprit here present, examined, tried, and confessed as above, on the other side:

We say, pronounce, sentence, and declare that you, the above-mentioned Galileo, because of the things deduced in the trial and confessed by you as above, have rendered yourself according to this Holy Office vehemently suspected of heresy,[86] namely of having held and believed a doctrine which is false and contrary to the divine and Holy Scripture: that the sun is the center of the world and does not move from east to west, and the earth moves and is not the center of the world, and that one may hold and defend as probable an opinion after it has been declared and defined contrary to Holy Scripture. Consequently you have incurred all the censures and penalties imposed and promulgated by the sacred canons and all particular and general laws against such delinquents. We are willing to absolve you from them provided that first, with a sincere heart and unfeigned faith, in front of us you abjure, curse, and detest the above-mentioned errors and ⟨406⟩ heresies, and every other error and heresy contrary to the Catholic and Apostolic Church, in the manner and form we will prescribe to you.

Furthermore, so that this serious and pernicious error and transgression of yours does not remain completely unpunished, and so that you will be more cautious in the future and an example for others to abstain from similar crimes, we order that the book *Dialogue* by Galileo Galilei be prohibited by public edict.

We condemn you to formal imprisonment in this Holy Office at our pleasure. As a salutary penance we impose on you to recite the seven penitential Psalms once a week for the next three years. And we reserve the authority to moderate, change, or condone wholly or in part the above-mentioned penalties and penances.

This we say, pronounce, sentence, declare, order, and reserve by this or any other better manner or form that we reasonably can or shall think of.

So we the undersigned[87] Cardinals pronounce:

Felice Cardinal d'Ascoli.
Guido Cardinal Bentivoglio.
Fra Desiderio Cardinal di Cremona.
Fra Antonio Cardinal di Sant'Onofrio.
Berlinghiero Cardinal Gessi.
Fabrizio Cardinal Verospi.
Marzio Cardinal Ginetti.

Galileo's Abjuration (22 June 1633)

I, Galileo, son of the late Vincenzio Galilei of Florence, seventy years of age, arraigned personally for judgment, kneeling before you Most Eminent and Most Reverend Cardinals Inquisitors-General against heretical depravity in all of Christendom, having before my eyes and touching with my hands the Holy Gospels, swear that I have always believed, I believe now, and with God's help I will believe in the future all that the Holy Catholic and Apostolic Church holds, preaches, and teaches. However, whereas, after having been judicially instructed with injunction by the Holy Office to abandon completely the false opinion that the sun is the center of the world and does not move and the earth is not the center of the world and moves, and not to hold, defend, or teach this false doctrine in any way whatever, orally or in writing; and after having been notified that this doctrine is contrary to Holy Scripture; I wrote and published a book in which I treat of this already condemned doctrine and adduce very effective reasons in its favor, without refuting them in any way; therefore, I have been judged vehemently suspected of heresy, namely of having held and believed that the sun is the center of the world and motionless and the earth is not the center and moves.

Therefore, desiring to remove from the minds of Your Eminences and every faithful ⟨407⟩ Christian this vehement suspicion, rightly conceived against me, with a sincere heart and unfeigned faith I abjure, curse, and detest the above-mentioned errors and heresies, and in general each and every other error, heresy, and sect contrary to the Holy Church; and I swear that in the future I will never again say or assert, orally or in writing, anything which might cause a similar suspicion about me; on the contrary, if I should come to know any heretic or anyone suspected of heresy, I will denounce him to this Holy Office, or to the Inquisitor or Ordinary of the place where I happen to be.

Furthermore, I swear and promise to comply with and observe completely all the penances which have been or will be imposed upon me by this Holy Office; and should I fail to keep any of these promises and oaths, which God forbid, I submit myself to all the penalties and punishments imposed and promulgated by the sacred canons and other particular and general laws against similar delinquents. So help me God and these Holy Gospels of His, which I touch with my hands.

I, the above-mentioned Galileo Galilei, have abjured, sworn, promised, and obliged myself as above; and in witness of the truth I have signed with my own hand the present document of abjuration and have recited it word for word in Rome, at the convent of the Minerva, this twenty-second day of June 1633.

I, Galileo Galilei, have abjured as above, by my own hand.

Some Figures in the Assimilation of the Two Revolutions in Astronomy

Christoph Clavius, S.J. (1537-1612)

Thomas Harriot (ca. 1560-1621)

David Fabricius (1564-1617);

Johann Fabricius (1587-1615)

Nicholas Claude Fabri de Peiresc (1580-1637)

Christoph Scheiner, S.J. (1573-1650)

Simon Mayr (1573-1624)

Philip van Lansberge (1561-1632)

Christian Sorensen Longomantanus (1562-1647)

Pierre Gassendi (1592-1655)

Johann Baptiste Cysat, S.J. (1586-1659)

Johannes Remus Quietanus (worked ca. 1610-1640)

Martinus Hortensius (1605-1639)

Francesco Fontana (1580-1656)

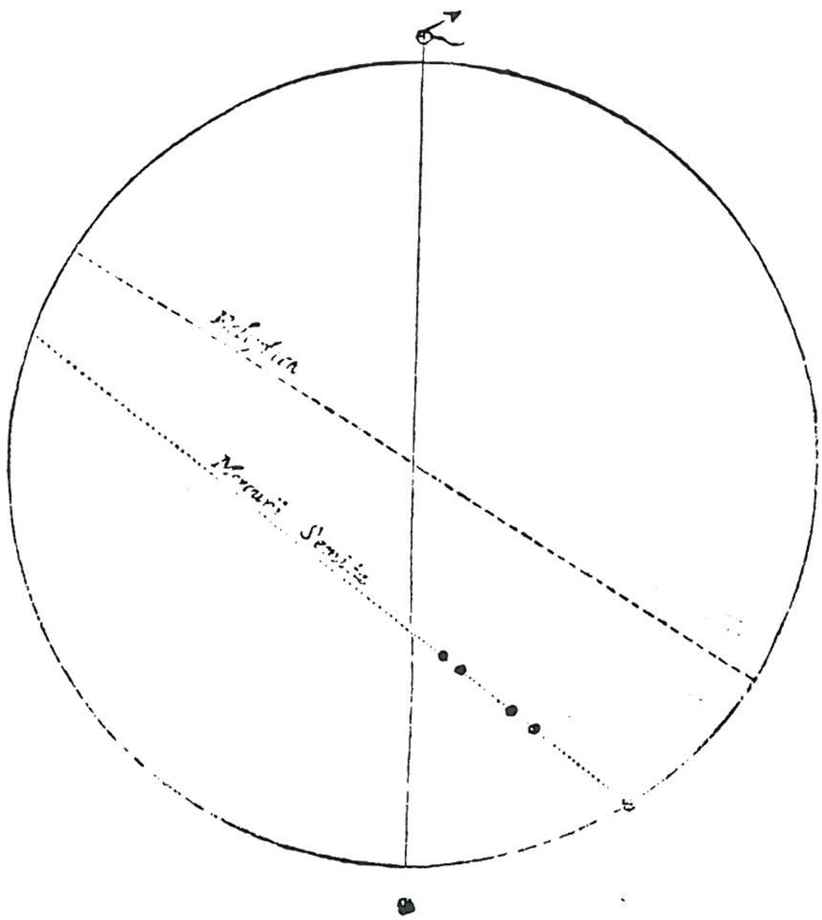
William Gascoigne (ca. 1612-1644)

William Crabtree (1610-1644)

Jeremiah Horrocks (ca. 1618-1641)

Michael Florent Van Langren (ca. 1600-1675)

Discus Solis cum trajiciente Mercurio, prout intra obscuram Scenam se inversus in Circulo citra Telescopium objecto exhibuit.

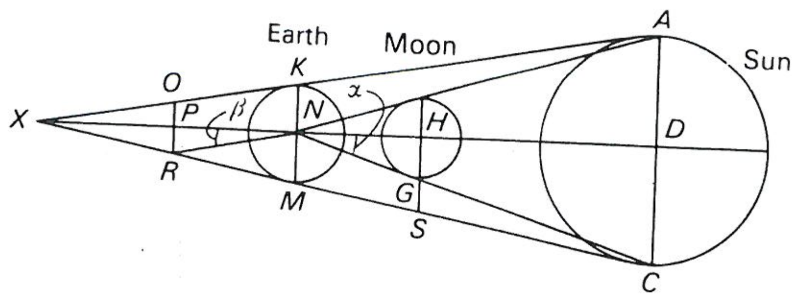


7.2. The 1631 transit of Mercury, from Gassendi's *Institutio astronomica* (1656).

TABLE 13 Hortensius's Planetary Sizes

Planet	Apparent Diameter at Apogee	Apparent Diameter at Perigee	[Actual Diameter] [Earth = 1][a]	Volume (Earth = 1)
Mercury	10"	28"	1/18.7	1/6510
Venus	15⅓"	1'40"	1/10.35	1/1109
Mars	9"	1'4"	1/11.53	1/1534
Jupiter	38½"	1'1⅓"	1/1.08	1/1.25
Saturn	31"	42⅓"	1.30	2⅓

[a]Not given by Hortensius.



7.1. Ptolemy's use of an eclipse diagram to determine the solar distance.

Table 7.1 *Cosmic dimensions according to Al-Farghānī (c. AD 850)*

Body	Absolute distance in e.r.			Apparent Diameter at mean distance (Sun = 1)	Actual Diameter (Earth = 1)	Volume (Earth = 1)
	Least	Greatest	Mean			
Moon	$33\frac{1}{2}+\frac{1}{20}$	$64\frac{1}{6}$	$48\frac{5}{6}$	$[1\frac{1}{3}]$	$\frac{1}{3\frac{2}{5}}$	$\frac{1}{39}$
Mercury	$64\frac{1}{6}$	167	$115\frac{1}{2}$	$\frac{1}{15}$	$\frac{1}{28}$	$\frac{1}{22000}$
Venus	167	1 120	$643\frac{1}{2}$	$\frac{1}{10}$	$\frac{1}{3\frac{1}{3}}$	$\frac{1}{37}$
Sun	1 120	1 220	1 170	1	$5\frac{1}{2}$	166
Mars	1 220	8 876	5 048	$\frac{1}{20}$	$1\frac{1}{6}$	$1\frac{1}{2}+\frac{1}{8}$
Jupiter	8 876	14 405	11 640	$\frac{1}{12}$	$4\frac{1}{2}+\frac{1}{16}$	95
Saturn	14 405	20 110	17 258	$\frac{1}{18}$	$4\frac{1}{2}$	91
Fixed stars						
1st mag	—	—	20 110	$\frac{1}{20}$	$4\frac{1}{2}+\frac{1}{4}$	107
2nd mag	—	—	20 110	not given	not given	90
3rd mag	—	—	20 110	not given	not given	72
4th mag	—	—	20 110	not given	not given	54
5th mag	—	—	20 110	not given	not given	36
6th mag	—	—	20 110	not given	not given	18

1e.r. = 3 250 miles.

Table I. (Kepler)

	Mean Solar Distance from *Rudolphine Tables*	Mean Sidereal Motion in 365 days	Mean Solar Distance from Third Law	Difference in Predicted Longitude
Mercury Elongation from Sun	0.38806 22°50′2″	1493.7066°	0.38710 22°46′27″	3′35″
Venus Elongation from Sun	0.72413 46°23′47″	584.7792°	0.72333 46°19′48″	3′59″
Earth	1.00000	359.7469°	1.00000	
Mars Annual Parallax	1.52350 41°1′29″	191.2714°	1.52369 41°1′6″	0′23″
Jupiter Annual Parallax	5.20000 11°5′15″	30.3281°	5.20117 11°5′6″	0′9″
Saturn Annual Parallax	9.51000 6°2′9″	12.2125°	9.53809 6°1′5″	1′4″

Table VI. Some Observations of Horrocks compared with the tables of Kepler and Tuckerman

	Horrocks (H)	Kepler (K)	Tuckerman (T)	(H − K)	(H − T)
1. Venus 15 Dec. 1637 5 : 50 p.m.	314°51′	314°56 1/2′	314°50′	−5 1/2′	1′
2. Mars 13. Jan. 1638 7 : 05 a.m.	225° 4′	225° 4′	225° 2′	0′	2′
3. Jupiter 26 Jan. 1638 5 : 35 a.m.	214°53 1/2′	214°45 1/2′	214°54′	8′	−1/2′
4. Mars 30 Jan. 1638 6 : 30 a.m.	234°12	234°10′	234°10 1/2′	2′	1 1/2′
5. Jupiter 30 Jan. 1638 6 : 30 a.m.	215° 1 1/2′	214°53 1/2′	215° 2	8′	−1/2′
6. Mars 12 Feb. 1638 5 : 40 a.m.	240°46′	240°48′	240°48′	−2′	−2′
7. Jupiter 12 Feb. 1638 5 : 40 a.m.	215°10′	215° 1′	215°11′	9′	−1′

Table I), and Horrocks did not find it necessary to change these constants significantly. (He did at length come up against the fact of Saturn's inconstant "mean" motion; he called it "a Gordian knot, which has to be cut because insoluble"[52]; it once more raised disturbingly for him the question of the perfectibility of astronomy[53].) It was to Mercury or Venus that Horrocks had to turn if he was to produce essentially new evidence for the third law, and of Mercury he had difficulty in obtaining sufficient observations[54]. Venus it had to be, then, that led Horrocks, not only to his more famous triumph, the first observation of Venus *sub sole*, but also to his affirmation of the strict exactitude of the third law.

Something of Horrocks' course of thought as well as his observations of Venus can be followed in his correspondence with Crabtree. The reform of the Keplerian parameters for Venus was closely tied up with the correction of Kepler's value for the eccentricity of the sun or earth. In his letter of 3 June 1637, Horrocks points out that the *Rudolphine Tables* have the spring equinox occurring too soon, and he is proposing to remedy the mistake by changing the solar eccentricity from Kepler's 0.01800

[52] *Opera posthuma*, p. 322.
[53] *Ibid.*, p. 325.
[54] See *ibid.*, p. 17.

to 0.01770[55]. On 23 November 1637 he is admonishing Crabtree to make frequent determinations of the azimuthal differences between Venus and the sun, in order that, having found the place of Venus with respect to the fixed stars, it will be possible to compute the longitude of the sun and thus investigate its inequality[56]. By 19 January 1638 Horrocks has concluded that the earth's eccentricity should be reduced to 0.01730, so that the maximum equation of center becomes 1°59′ rather than Kepler's 2°4′[57].

Among the reasons he puts forward for this change are observations of Venus: for a maximum evening elongation of the planet at about the time of the spring equinox Horrocks finds its place according to the *Rudolphine Tables* to be too far ahead by 10′; and exactly the opposite happens when Venus is near maximum morning elongation at about the time of the autumnal equinox[58]. Both circumstances can be at least partly accounted for if the eccentricity of the earth's orbit is diminished to 0.01730, reducing the earth's heliocentric longitude in the spring and increasing it in the fall. Further correction could be effected by reducing the size of the orbit of Venus, but apparently Horrocks had not yet considered this possibility. A final 3′ of correction would been obtained by reducing the earth's eccentricity all the way to 0.01686, the value we find by using Newcomb's 1900 value and rate of change to extrapolate back to 1640. But Horrocks had his reason for choosing 0.01730. He knew that the Keplerian value rested on Tycho's empirical determinations of altitudes of the sun, and that Tycho in correcting the observed altitudes for parallax has assumed the sun's horizontal parallax to be 3′[59]. (This was the ancient value, but for Tycho it had the additional support of Johannes F. Offusius' number mysticism, in that it put the sun just 576 earth-diameters from the earth, 576 being a sacred number[60].) Kepler, after Tycho's death, found the horizontal parallax of Mars when at or near opposition to the sun, and thus only half as distant as the sun, to be negligible, and therefore took the step of reducing the horizontal solar parallax to 1′ in the *Rudolphine Tables*; he did not, however, undertake to alter the eccentricity in Tycho's solar theory in the way this correction would have required. Horrocks' value of 0.01730 for the eccentricity appears by his own account to be derived directly from Tycho's solar theory together with the new, Keplerian correction in solar parallax[61]. What Horrocks did not know was that Tycho's correction for refraction was also mistaken, being too small for the equinoctial sun by 40″; the correction of this mistake would have reduced the eccentricity still further. Horrocks' failure to correct for this last mistake causes him to obtain an exaggerated eccentricity for Venus.

[55] *Ibid.*, p. 288.
[56] *Ibid.*, p. 296.
[57] *Ibid.*, p. 301.
[58] *Ibid.*, p. 17.
[59] *Ibid.*, pp. 172, 301.
[60] See Tycho Brahe, *Astronomiae instauratae progymnasmata* (Prague, 1602), p. 472.
[61] See Horrocks, *Opera posthuma*, p. 301.

Horrocks' search for a satisfactory emendation of the Rudolphine parameters for Venus extends through the first eight months of 1638. On January 19 Horrocks is sure that the mean heliocentric longitude of Venus should be reduced by 15′[62]. By March 10 he is retracting this suggestion, and considering the possibility of adding 15° to the aphelion (too much) and subtracting 10′ from the mean heliocentric longitude; he allows, however, that this proposal does not satisfy all of Tycho's

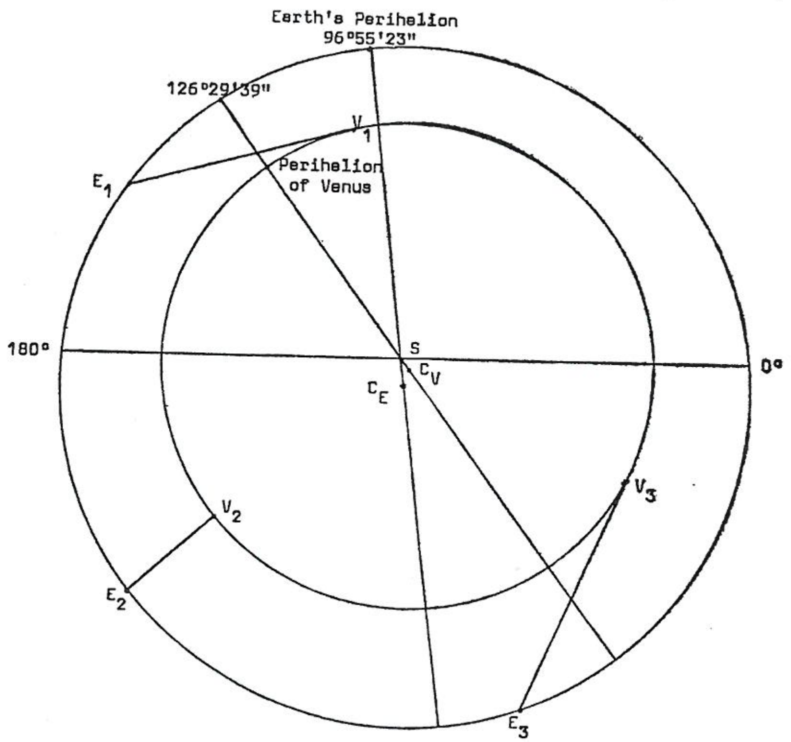


Figure I. Orbits of Venus and Earth in 1640
(C_V = center of Venus' orbit; C_E = center of Earth's orbit; eccentricities exaggerated)

and his own observations. One thing seems certain, he says: if a solar eccentricity of 0.01730 be retained, then the orbit of Venus has a smaller ratio to the orbit of the earth than Kepler gives, causing an observational difference of at least 5′ when Venus is in maximum elongation[63]. Venus, we note, had just gone through a maximum evening elongation on or about February 7, when it was near its perigee, and

[62] *Ibid.*, p. 302.
[63] *Ibid.*, p. 306.

it was probably from his observation of this that Horrocks was drawing his conclusion; the geometrical relations are shown in Figure I. On April 10, having been observing Venus as it came on toward its inferior conjunction (to occur on April 21), Horrocks writes that the geocentric longitude of Venus is 8′ or 9′ less than Kepler makes it, and that the discrepancy can be eliminated by reducing the solar eccentricity and the size of Venus' orbit as suggested in his previous letter, while also retracting the mean heliocentric longitude by 4′ or 5′; but he is not sure whether it is the mean heliocentric longitude or the eccentricity of Venus that should be changed[64].

He finds an answer to this last question in the summer. On July 25 he writes that he has calculated all the Tychonic observations of Venus very accurately, and that they show the sun's eccentricity to be 0.01730. The eccentricity of Venus, he says, is a little larger than Kepler makes it. He has not yet fixed the exact magnitude of the corrections to be made in the orbital elements of Venus because he lacks observations of Venus near aphelion; but he proceeds in the very next line to report the raw data of two such observations, made on July 4 and 6, "as accurately as I could make them, by repeated checking"[65]. (Venus was in maximum morning elongation on July 1, fairly near its aphelion.) On September 3 he informs Crabtree that he has so corrected the motion of Venus, that he could hardly hope to do better[66]. On September 29 he reports his specific corrections, including an eccentricity of 0.00750 as compared with Kepler's 0.00692, and a mean orbital radius of 0.72333. Of the latter he adds:

> This I deduce from Kepler's harmonies and the proportions of equal motions; but observati ons precisely confirm it. Kepler has 0.72414, hence his *prostaphaeresis orbis* is always too large[67].

No doubt Horrocks was finding exactly what he was looking for, but there are indications that he was obtaining an exceedingly good empirical determination of the mean solar distance of Venus. He had made observations of Venus at maximum elongation near perihelion in February, 1638, and at maximum elongation near aphelion in early July, 1638 (the sightings $E_1 V_1$ and $E_3 V_3$ in Figure I). Now if one imagines determining the eccentricity of Venus' orbit from two such sightings, using Horrocks' solar theory with its exaggerated eccentricity as the basis of calculation, then it can be shown that, to obtain the value that Horrocks obtains, the observations will have to be accurate to within 20″ of arc. In other words, the error in the eccentricity of Horrocks' theory of Venus is a very accurate reflection of the error in the eccentricity he adopts for the sun. Presumably he used more than two observations and did some judicious averaging. But since the determination of the eccentricity of Venus is independent of the determination of the mean solar distance

[64] *Ibid.*, p. 307.
[65] *Ibid.*, p. 311.
[66] *Ibid.*, pp. 314—315.
[67] *Ibid.*, p. 320.

— though the same observations are used to determine both, an error in one does not imply an error in the other — it is plausible to suppose that Horrocks is determining the one with about as much precision as he is determining the other, namely to within less than a minute of arc. This would mean that Horrocks' empirically determined value for the mean solar distance fell within the range 0.7233 ± 0.0002[68].

Horrocks, of course, puts down the number as 0.72333, using all five places computed from the periodic times. In brief, he places his trust in Kepler's harmonic law. Horrocks' view of the cosmos, in fact, is very close to Kepler's. He accepts the main tenets of Kepler's celestial physics, while modifying the details. The rotating sun still moves each planet along its orbit by the extended arm of its "magnetic" virtue. But Horrocks objects to the manner in which Kepler accounts for the planet's libratory approach to and recession from the sun. Kepler had hypothesized certain magnetic fibers in the interior of each planet, supposing them to maintain their orientation with respect to the stars independently of the axial rotation of the planet's surface, and thus to bring about alternate attractions to and repulsions from the sun. To avoid such a complicated, ad hoc hypothesis, Horrocks brings in the analogy of the pendulum, and proposes a simple attraction to the sun combined with an inertial tendency on the part of the planet. For as he tells Crabtree,

> Nature is one, and all things have between them a consensus and harmony. And thus since the motions of the planets agree with the motion of the pendulum both in the figure of the orbits and in the translation of the aphelia, why should not the causes of the two be similar?[69]

That this same proposal might be used to eliminate the role of a solar virtue in effecting the circumgyration of the planets about the sun, does not appear to have occurred to Horrocks; his analogy tells him rather that the hand holding the pendulum suspension must move circularly if the pendulum bob is to move not rectilinearly but in an oval. The new mechanism no more accounts for the sesquialterate proportion between periods and distances than had Kepler's. For Horrocks, as for Kepler, the world is a cosmos beautifully and meaningfully arranged, and so Horrocks like Kepler sees the third law as a pattern directly imposed by a geometrizing creator.

In agreement with this view, Horrocks like Kepler expects that the sizes of the planets will also be found to fit a neat pattern: "Since the sun by its magnetic virtue regulates the motion of the six primary planets. I cannot conceive how it could

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[68] A similar result was obtained a few years earlier by Gottefried Wendelin (Vendelinus). For Venus he found an aphelion distance of 0.72783, a perihelion distance of 0.71903, and hence a mean distance of 0.72343; for Mercury, an aphelion distance of 0.47071, a perihelion distance of 0.30358, and hence a mean distance of 0.38711. Given Wendelin's predilection for "harmonies", there is a likelihood that he was guided to these results by Kepler's third law; the precision of the confirmation is otherwise astonishing. The eccentricities for both Venus and Mercury are much too small; the error can mean that he was using too small a value for the eccentricity of the Earth. See Wendelin's letter to Gassendi of 1 May 1635, in *Petri Gassendi Epistolae* (Lyon, 1658), Vol. VI, p. 428.

[69] Horrocks: *Opera posthuma*, p. 312 (from the letter of 25 July 1638).

proportion its force to the distance so perfectly, unless the globes themselves be similarly proportioned"[70]. But Kepler's proposal that it is the volumes of the planets that bear the same ratio as the solar distances is no longer tenable, for Gassendi in his observation of the Mercury transit of 28 October 1631 has found Mercury's diameter to be less than 20″, while Kepler's formula required than it be greater than 2′[71]. The idea comes to Horrocks that the direct proportion may hold rather between planetary *diameters* and solar distances; and as he indicates in a letter to Crabtree of 26 October 1639, it is the possibility of verifying this idea that especially excites him in the prospect of the approaching Venus transit of November 24[72].

In the event, Horrocks sees his hypothesis as vindicated; he finds Venus' diameter as it would be observed from the sun to be 28″, and is able to argue that the same will be true of the other planets[73]. One of these planets, of course, is the earth, and Horrocks is thus arguing from the assumed constancy of the ratio that the sun's horizontal parallax (or angle subtended by the earth's radius at the distance of the sun) is just 14″[74]. As we have seen, the effect of reduction in solar parallax on planetary parameters and especially on solar theory had been one of Horrocks' main concerns from the time he obtained the *Rudolphine Tables*; and the new analogy supports his earlier assumption that solar parallax is practically negligible in relation to the attainable observational precision. Just as important, the observational success of the new analogy signifies to Horrocks a triumph for the notion that the solar system is harmonically or architectonically arranged. Thus it joins with observation in supporting the hypothesis of the exactitude of Kepler's third law.

Such, we believe, was the Horrocksian basis for Streete's assertion that, "with the corrected Parallax of the Sun and Aequation of the Earth, the sesquialterate proportion proves most consentaneous unto observation and altogether indubitable".

As already noted, Streete's claims met with opposition. *The Holy Guide* of the astrologer John Heydon (fl. 1661), published in 1662 and claiming to teach "the knowledge of all things, Past, Present and to come; ... and to Cure, Change and Remedy all Diseases in Young and Old, with Rosie Crucian Medicines", included as an appendix an "Advertisement to Thomas Street", in which Streete's solar theory and character are alike attacked;[75] the objection to the solar theory reduces to a rejection of Streete's or Horrocks' value for the eccentricity, though the author of the appendix (who turns out to be John Gadbury[76]) does not appear to understand this fact.

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[70] Horrocks, *Venus in sole visa* (*ed. cit.*), p. 141.

[71] *Ibid.*, p. 142.

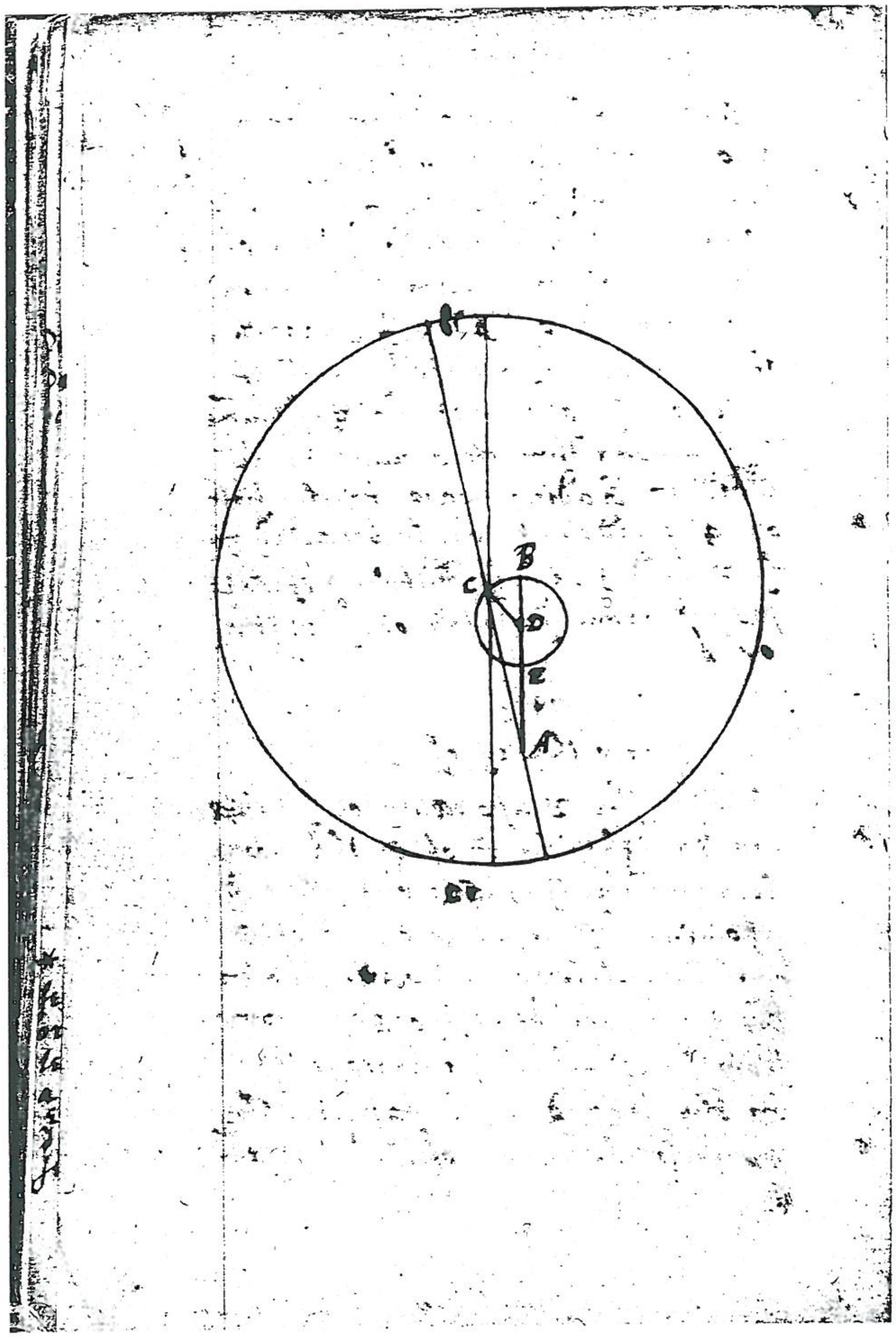
[72] Horrocks, *Opera posthuma*, p. 331.

[73] Horrocks, *Venus in sole visa*, pp. 137–143; *Opera posthuma*, pp. 160–174.

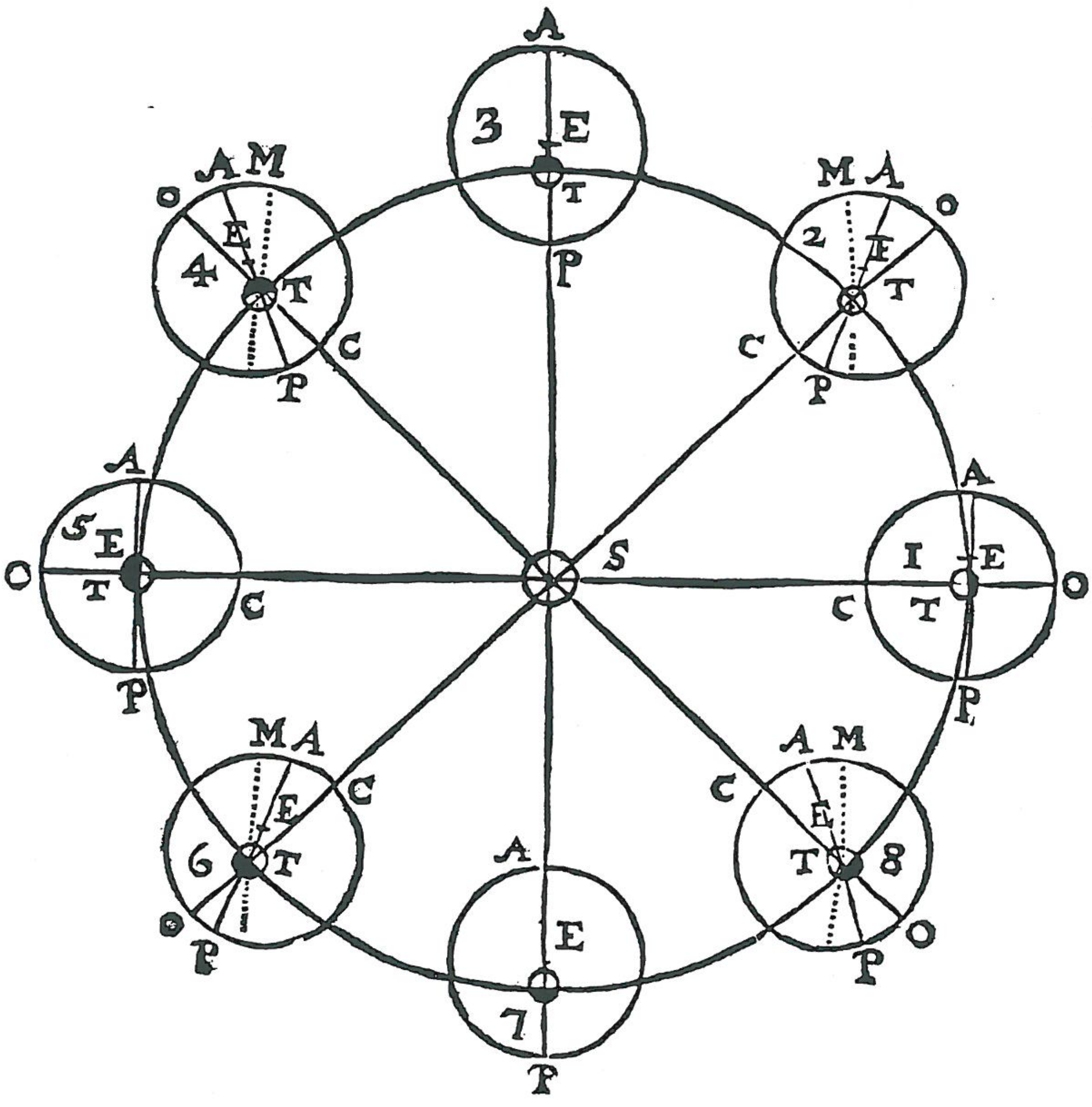
[74] Wendelin had reached exactly the same conclusion on the basis of his observations of planetary diameters and through exactly the same appeal to analogy; see the letter cited in note 68.

[75] John Heydon, *The Holy Guide* (London, 1662), Appendix, pp. 43–55.

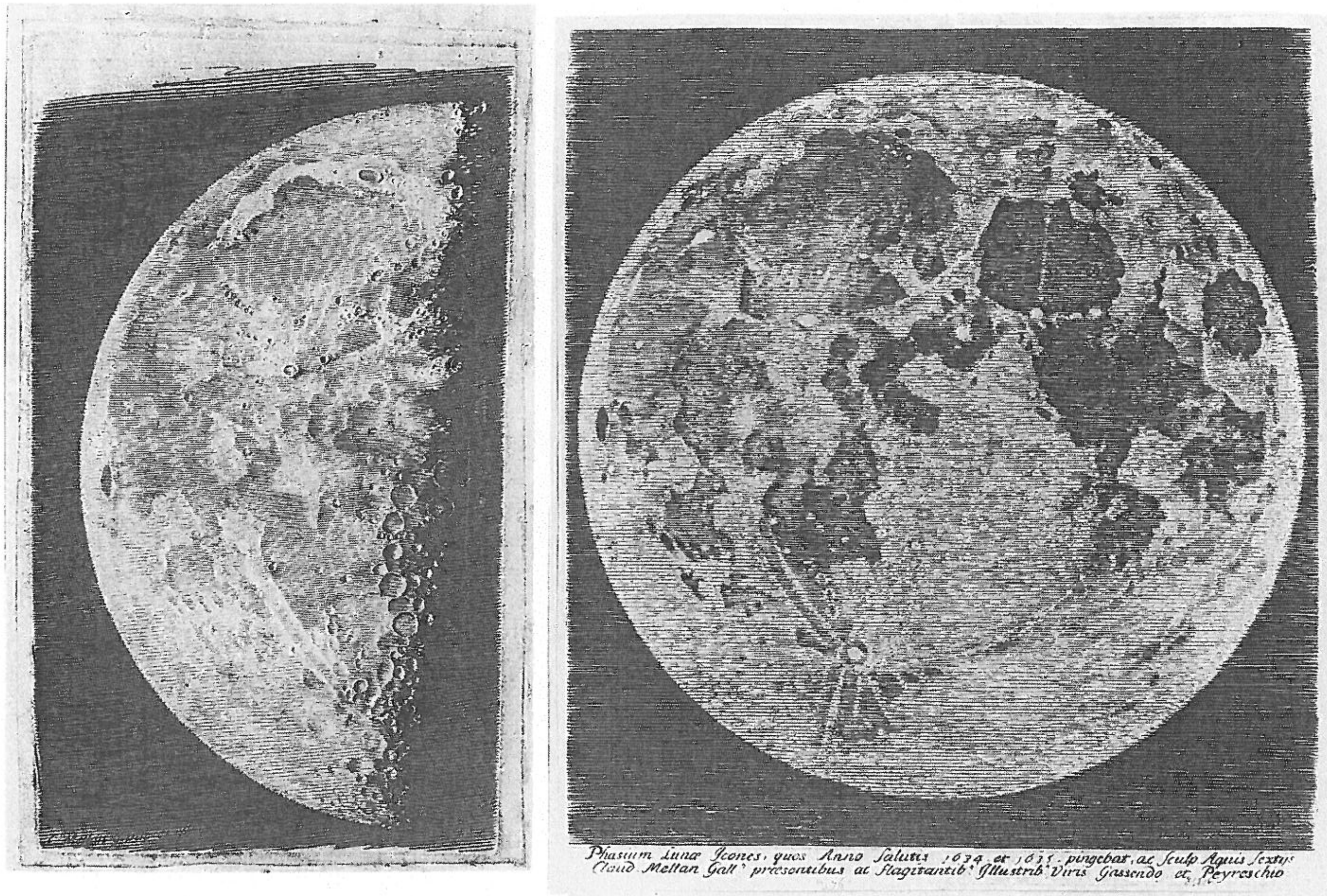
[76] See Thomas Streete, *An Apendix to Astronomia Carolina* (London, 1664), p. 26.



10.18. Horrocks's diagram for computing the semi-annual variations in the lunar eccentricity and apse.



10.19. Diagram to illustrate the Horrocksian theory of the evection (from Crabtree's letter to Gascoigne of June or July 1642).



8.7(*a*). Images of last quarter and full Moon, by Mellan for the Gassendi–Peiresc project, 1636.

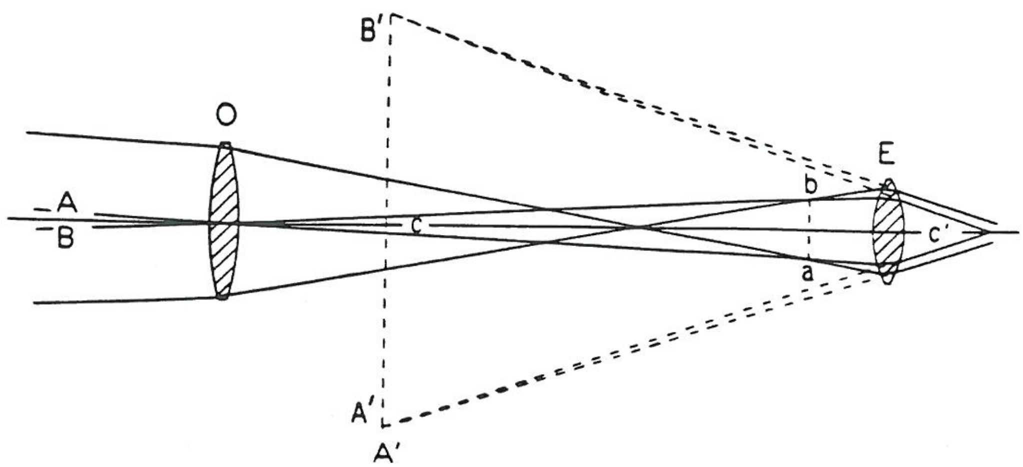


Fig. 3. Image formation in the Keplerian (inverting) telescope.

OPEN QUESTIONS IN ASTRONOMY, 1542

1. What is required in the way of updating and revision to the Alfonsine Tables to eliminate the large discrepancies in longitude and latitude that they currently exhibit?

2. Can an account of celestial motions of the sort that Rheticus has indicated Copernicus to be proposing, in which the Earth is in motion, save the salient orbital phenomena as well as the Ptolemaic account does?

OPEN QUESTIONS IN ASTRONOMY, 1642

1. Insofar as Copernican and Tychonic systems are both fully consistent with all accessible astronomical observations and several leading astronomers adhere to the latter, can any decisive evidence be adduced to settle the question whether the Earth is in orbit about the Sun or vice versa?

2. Granted that Kepler's claims about planetary orbital motion hold at least to high approximation, should they be taken to hold (1) for bodies beyond those now known to be orbiting the Sun and (2) for the bodies now known, indefinitely far into the past and future; and should they be taken to hold exactly, or only essentially exactly, or merely approximately; and if they do not hold exactly, should they be regarded as idealizations of some sort, and do they at least hold in the mean?

3. Granted that questions about relative distances of the planets, Sun, and Earth from one another have largely been resolved in units of the mean distance of the Earth from the Sun, what do these distances amount to in earthly units – e.g. in units of the radius of the Earth?

4. Is orbital astronomy ***perfectible*** at all – i.e. can the motions be mathematically characterized in a way that assures that conclusions drawn about the remote past and the remote future will hold at least to the same level of precision as conclusions about the present era?

5. Can the apparent motion of the Moon be mathematically characterized to the same level of precision as has been achieved for the planets?

6. What are comets, what trajectories do they describe in their observed motions, and are they governed by the same physical processes, whatever those may be, that govern the motions of the planets?