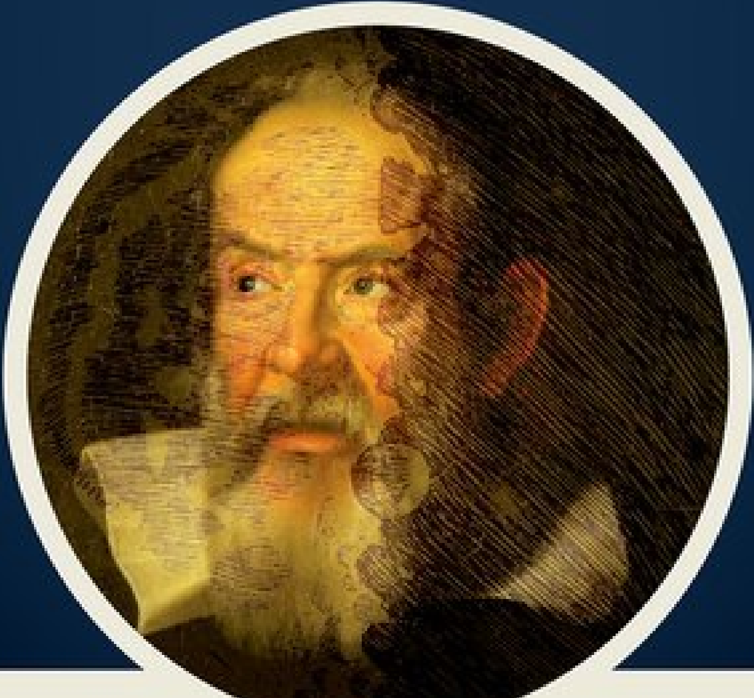
MARCO PICCOLINO AND NICHOLAS J. WADE

GALILEO'S VISIONS

PIERCING THE SPHERES OF THE HEAVENS BY EYE AND MIND



OXFORD

Galileo's Visions
Piercing the spheres of the heavens by eye and mind

Marco Piccolino and Nicholas J. Wade

OXFORD
UNIVERSITY PRESS

intercommunicating rods and because of the extensive convergence at the subsequent stages, and thus fail to be transmitted towards the ganglion cells. On the other hand, in the presence on the retina of a light pattern of great extension there is a chance that the electrical events generated in the rods of the pool are correlated and thus sum together and produce a visual response.

The negative consequence of the extensive convergence existing at various levels of the rod pathways is the degradation of the spatial performance of our vision when passing from the high luminance behaviour dominated by cones, to the dim light condition dominated by rods functioning (illustrated by the lowermost graphs of Figure 8.5). As one could expect, rod vision plays an important role in the naked eye observation of the stars. This accounts for the fact that the dimmest stars are not perceived when looking directly at them (when their image would be focused in the rod-free fovea), but are better seen with lateral view (about 20° out of axis, which brings the image on the region of the retina richer in rods).

To conclude, this long digression allows us to understand the complexity of the phenomena involved in the vision of stars and other celestial objects and situate better the discussions on this matter in Galileo's age. In the case of the observation of the nocturnal sky, vision shifts from a condition indicated as mesopic, in which both cones and rods work together (as, for instance, when observing the most luminous stars) to a decidedly scotopic condition (when looking to very faint stars), to a more photopic condition when observing the moon. In general, the pupil is dilated in night vision, which results in an extension of the image of stars due to increased spherical aberration. As the condition of light adaptation moves towards the mesopic phase, the ensuing reduction of light sensitivity contributes to make the image sharper. In the case of the observation of very dim stars the system is extremely sensitive, but because of the faint light reaching the eye, only a part of the image of the star is above the threshold for detection (and the star appears small). In the case of bright stars, the modest decrease of light sensitivity due to the relatively intense light reaching the retina is compensated by the strong effect of contrast which is particularly effective in mesopic condition.

8.3 **The Copernican system, a world of absurdities**

Galileo's concerns about vision had an important cosmological dimension, and this was also in the case of the vision of stars. This particular aspect has to do with one of the most significant objections addressed to the Copernican system. In the *Dialogue* the discussion on this topic is centred mainly on the criticism raised by Simplicio on the basis of the work of Galileo's adversary, Christoph Scheiner. In 1614 Scheiner had published a series of theses defended publicly by a student, Johann Georg Locher, in order to obtain the degree of *Magister artium et philosophiae* from the University of Ingolstadt.[3] Some of the theses were aimed at demonstrating the incongruities and absurdities of the Copernican system based on both theological issues in addition to mathematical and astronomical arguments. The objection expounded in Proposition XIII under the title *Argumentum ex motu et orbe annuo* ('Argument derived from annual motion and orb') was stated in this way:

> According to the opinion of Copernicus and all the Copernicans it is in no way perceptible the proportion that exists between the radius of the Great orb, i.e. the distance of Sun from earth, and the radius of firmament, i.e. the distance from earth of any fixed star whichever; but this is absurd and generates other absurdities as it will appear from what follows. (Scheiner & Locher, 1614, p. 29)

[3] We have mentioned this work in Chapter 4.

Why did Scheiner/Locher say that the proportion between some of the fundamental measures of the cosmos (the radius of the Great orb and the radius of firmament) was in 'no way perceptible'? The traditional model of the cosmos was based on the idea that all stars (with the exception of the sun) are located in a specific crystalline orb or sphere, the eight orbs, also called the sphere of fixed stars. Moreover, on the basis of approximate measurement of the distance from the earth of the various planets, the apparent movement of the various spheres was considered as harmonic, and a measure had been proposed for the diameters of the various orbs, including those of the fixed stars.

For this sphere no direct measurements were possible, other than those depending on logical inferences and philosophical and theoretical mathematical assumptions. This is because the appearance of an orb of fixed stars is based on a perceptual illusion due to the tendency of our visual system to locate all objects at the same distance (see Chapter 2). In the ancient cosmology there was, however, an important limit that constrained the lower figure for the diameter of the eight spheres. This was the absence of any parallax, that is, the absence of any change of the relative position of nearby stars with changes in the relative position of the observer on the earth's surface (see Figure 8.6).

Because of this awareness, old scholars (Archimedes among others) had agreed that the distance of the fixed star should be very large relative to the dimensions of the earth. During the Renaissance a commonly accepted value for the radius of the eighth sphere (or radius of the

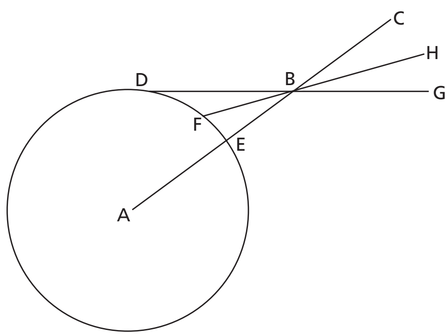


Figure 8.6 Galileo's illustration of parallax, from a dissertation written in 1624 in the form of a letter addressed to Francesco Ingoli. Ingoli was an important catholic prelate and author of a pamphlet entitled *De situ et quiete Terrae contra Copernici systema, Disputatio*. It was written following the condemnation of Copernican theory by the Catholic Church and attempted to demonstrate its untenability on the basis on a variety of arguments, largely derived from the Bible and the ideas of Tycho Brahe. An object in the sky (B) will appear visually at C when viewed from E, but will change its apparent position to H and G when the observer moves to F and D. The more distant the celestial object the smaller is the parallactic change for a given displacement of the observer. Notice that, because of the relative daily rotation of earth's surface relative to the vault of heaven, a parallactic change would occur during the day, even with no real motion of the observer (diurnal parallax). Galileo's example concerns the parallax of a planet, i.e. a celestial globe situated nearer to earth than the fixed star. However, a change would occur also in the relative visual position of nearby fixed stars if they were situated at a relatively short distance from the earth. It is easy to understand this by reference to the figure, by supposing that C, H, and G are three fixed stars of the eighth sphere and noticing that the visual angle separating them would change with the change of the observer's position.

firmament) was that provided by the Persian astronomer al-Ferghani (Alfraganus in Galileo's spelling of the name), i.e. about 20,110 terrestrial radii (amounting to a little more than 128 million km). This distance rendered all possible parallatic changes due to displacements of the observer on the surface of the earth undetectable to the ordinary astronomical tools of the period.

However, the Copernican theory had introduced a much greater motion of the observer relative to the fixed stars, i.e. the movement along the so-called Great orb (*Orbis magnus*), which (as we now know) has a maximum diameter of about 300 million km. To account for the absence of an annual parallax of the fixed stars during such huge revolutions of the earth, Copernicus extended the width of the eighth sphere to values much greater than those previously assumed. The actual values for the distance of fixed stars given by the Polish astronomer cannot be easily rendered in modern terms because they were based on rather inaccurate estimations of some fundamental astronomical parameters (particularly the distance between the earth and sun which was largely underestimated). In modern terms suffice it to say that, assuming an annual revolution of the earth, in order that the parallaxes of the stars might be undetectable with astronomical instruments capable of resolving the angular distance of a minute of arc, the distance of stars needed to be greater than 40 billion km. Taking into account the much shorter distance of the planets, Copernicus's assumption of the immense distance of the fixed stars would have resulted in an almost empty cosmos, with the earth and planets being but extremely small specks within an immense cosmic space. This was one the absurdities addressed by Scheiner and Locher in their *Disputationes* (and also remarked on by other anti-Copernicans). To their eyes (as well as to those of many astronomers of the age) the cosmos of Copernicus appeared therefore to be full of absurdities, mathematically incongruent, and disharmonious.

Some of the absurdities pointed to by Scheiner and Locher were decidedly trivial. One concerned the astrological impossibility of the zodiacal constellations having an influence on earth due to the immense distance of stars. Others were more cogent. The main one had to do with the apparent dimensions of stars, i.e. with the size of the stars calculated on the basis of the immense distances of the fixed stars assumed by Copernicus and the angular size of the stars apparent to an observer. If one accepted the then current measures of these sizes this would imply that the largest stars would have dimensions corresponding to the greatest planetary orbs (Saturn), and the small stars a value corresponding to the dimension of the Great orb. Examples of contemporary measures (those of Tycho Brahe) were 2–3′ for the most luminous and remarkable stars of the sky, like Sirius, Vega, Arcturus, and of 20″ for the barely visible stars of magnitude 6. This was a real absurdity, and one that was not restricted to stubborn anti-Copernicans of Galileo's time, because it implied that the fixed stars were much bigger than our most familiar star, the sun.

8.4 **Great astronomers incapable of seeing**

But let us consider the matter in the way Galileo puts it in the *Dialogue*. It is Simplicio who illustrates the problem with reference to the book of Scheiner and Locher (evidently attributed only to the first author). He does it after having referred to the religious and theological objections raised by the two German scholars:

SIMPLICIO. Let us, then, listen to his other objections, which are more strongly supported. Now here, as you see, he deduces with very precise calculations that if the orbit in which Copernicus makes the earth travel around the sun in a year were scarcely perceptible with respect to the immensity of the stellar sphere, as Copernicus says must be assumed, then one would have to declare and maintain that the fixed stars were at an inconceivable distance from us, and that the smallest of them would be much larger than this whole orbit, while others would be larger than the orbit of Saturn. Yet such bulks are truly too vast, and are incomprehensible and unbelievable. (DIALOGO, p. 350; transl. p. 358)

To which Galileo's alter ego answers:

SALVIATI: I have indeed seen something similar argued against Copernicus by Tycho, so this is not the first time that I have revealed the fallacy—or better, the fallacies—of this argument, built as it is upon completely false hypotheses.

In the following Salviati shows, on the basis of a series of calculations relying on the reasoning of Copernicus, that what is really false in the arguments of the anti-Copernicans is the accepted values of apparent diameters of the stars. The main authority and reference being Tycho Brahe, an astronomer generally noted for the precision of his celestial measurements. According to Salviati (and of course to Galileo) a star of the first magnitude has an apparent diameter of only 5″, and one of the sixth magnitude of 50′″ (one minute third being 1/60 of a second), these values being 240 or 360 times smaller than those of Tycho.

Among Galileo's manuscripts at the Biblioteca Nazionale of Florence there are some loose papers with astronomical observations or annotations, some of which have to do with the apparent diameters of stars and with the distance of the sphere of fixed stars (collected in the *Analecta astronomica* of OG III, pp. 872–880). In some of these annotations Galileo assumes that a star of the first (or, alternatively, of the second) magnitude is as great as the sun. On the basis of the apparent diameter of the star, of the sun, and of the estimated distance between earth and sun, he tries to deduce the distance of the fixed stars. In one case he concludes that this distance is as great as 360 radii of the Great orb. In another case he concludes that the distance of the fixed star is 67,800 times the radius of the sun. The difficulty with these calculations is that the available values of the earth–sun distance and of the diameter of the sun (generally given with reference to the diameter of the earth) were definitely wrong. For instance, in Galileo's time the earth–sun distance was estimated to be about 1000–1200 earth radii (against an average modern value of 23,455). As to the diameter of the sun, in the *Dialogue*, Galileo assumes that it is 11 times the radius of the earth, while modern values are of about 218 earth radii. Using the modern values, Galileo's estimate of the distance of the fixed stars would be above 5 billion km in the first calculation (360 radii of the Great orb), and a little less than 50 billion km for the second calculation (67,800 radii of the sun). Even this last value is a gross underestimation of the distance of the nearest star, Proxima Centauri situated at 4.2 light years (1 light year being 9.4607×10^{12} km). Sirius (referred to as *Canicola*, i.e. the Dog Star) repeatedly mentioned by Galileo is a relatively near star at about the double of the distance of Proxima Centauri.

Galileo was interested in the problem of the apparent size of the stars until the last years of his life as is clear from an unfinished manuscript *Operazioni astronomiche* that he wrote in 1637 (OG VIII, pp. 449–464). He describes in detail the cord method for the measurement of the visual angle of luminous stars (and particularly the Dog Star). Moreover, he contrived other methods based on the calculation of the time a star is occulted by an appropriate device, also applicable to the measurement of Sirius. He described them in 1638 to a friend, Niccolò Arrighetti, so that they would not be lost 'in the case he passed away'. These methods, annotated by Arrighetti among his recollections, have been published in the works of Galileo (OG VIII, pp. 464–466). We will discuss them in Chapter 14.

In the *Dialogue* Sagredo invites Salviati to explain the reasons and justifications for the large discrepancies between the commonly accepted values of the angular sizes of the stars and those provided by his reference, a person indicated as 'our Academician', i.e. Galileo himself. Salviati does that by making reference to an argument that we have been considering in the previous chapters with regard to the mountains of the moon, that of the adventitious irradiation emanating from luminous bodies, and of influence in the visibility of small bright objects:

SAGREDO. Then their error consists in their having been very much deceived in taking the apparent diameter of the fixed stars.

SALVIATI. That is the error, but not the only one. And truly I am quite surprised at the number of astronomers, and famous ones too, who have been quite mistaken in their determinations of the sizes of the fixed as well as the moving stars, only the two great luminaries being excepted. Among these men are al-Fergani, al-Battani, Thabit ben Korah, and more recently Tycho, Clavius, and all the predecessors of our Academician. For they did not take care of the adventitious irradiation which deceptively makes the stars look a hundred or more times as large as they are when seen without haloes. Nor can these men be excused for their carelessness; it was within their power to see the bare stars at their pleasure, for it suffices to look at them when they first appear in the evening, or just before they vanish at dawn. And Venus, if nothing else, should have warned them of their mistake, being frequently seen in daytime so small that it takes sharp eyesight to see it, though in the following night it appears like a great torch. I will not believe that they thought the true disc of a torch was as it appears in profound darkness, rather than as it is when perceived in lighted surroundings; for our lights seen from afar at night look large, but from near at hand their true flames are seen to be small and circumscribed. This alone might have sufficed to make them cautious. To speak quite frankly, I thoroughly believe that none of them—not even Tycho himself, accurate as he was in handling astronomical instruments and despite his having built such large astronomical instruments and despite his having built such large and accurate ones without a thought for their enormous expense—ever set himself to determine and measure the apparent diameter of any star except the sun and moon. I think that arbitrarily and, so to speak, by rule of thumb some one among the most ancient astronomers stated that such-and-such was the case, and the later ones without any further experiment adhered to what this first one had declared. For if any of them had applied himself to making any test of the matter, he would doubtless have detected the error. (DIALOGO, p. 353; transl. pp. 360–361)

This passage reveals some of the typical aspects of Galileo's reflection on the tendency of humans, sometimes even of great scholars, to take for granted what is generally considered true, without any critical analysis or personal verification. It contains the essence of his justification that the apparent diameter of small luminous bodies (like stars and the planets with the exception of the moon) is much larger than the effective geometrical angle subtended at the level of the observer's eye. Galileo's argument is based on two main elements: on one side, the comparison of the visual appearances in two different conditions of average illumination and on the other, the correspondence between the observation of a celestial body (Venus) and of a terrestrial light source (the flame of a torch). As we have seen in section 8.2, it is under conditions of high ambient light that the spatial resolution gets better and the perceived size of a small light source is less distorted with relation to its real geometrical dimension. In the case of Galileo, however, there was no reason a priori for assuming that the image of Venus seen in daytime corresponded more accurately to the geometrical image of the planet than the much bigger globe shining in the night sky. The difficulty was, however, rapidly resolved with reference to the terrestrial light source. From afar we overestimate the size of a torch when it is seen under conditions of 'profound darkness' compared to its aspect perceived 'in lighted surroundings'. This is one of the arguments why, in the absence of a specific knowledge of the phenomena and mechanisms of light and dark adaptation, Galileo could conclude that the image of Venus seen in daylight is a better indication of its true size.

8.5 Measuring the stars with a cord

Against the common views of great astronomers, Galileo had other elements for supporting his conclusion that the visibility of stars and planets can be greatly distorted by the subtleties of vision processes. His reasoning was also based on experimental evidence. We will follow how Salviati responds to Sagredo's remark which was intended as an excuse for the doubtful perspicacity of previous astronomers:

SAGREDO. But if they lacked the telescope (for you have already said that our friend came to know the truth of the matter by means of that instrument), they ought to be pardoned, not accused of negligence.

SALVIATI. That would be true if they could not have obtained the result without the telescope. It is true that the telescope, by showing the disc of the star bare and very many times enlarged, renders the operations much easier; but one could carry them on without it, though not with the same accuracy. I have done so, and this is the method I have used. I hung up a light rope in the direction of a star (I made use of Vega[4] which rises between the north and the northeast) and then by approaching and retreating from this cord placed between me and the star, I found the point where its width just hid the star from me. This done, I found the distance of my eye from the cord, which amounts to the same thing as one of the sides which includes the angle formed at my eye and extending over the breadth of the cord. This is similar to, or rather equal to, the angle made in the stellar sphere by the diameter of the star. From the ratio of the thickness of the cord to its distance from my eye, using a table of arcs and chords, I immediately found the size of the angle—taking the customary precaution, used in determining such very acute angles, not to put the intersection of the visual rays at the center of my eye, where they would not go if they were not refracted, but beyond the location of the eye where the actual width of the pupil would permit them to converge.[5] (pp. 353–354; transl. 361–362)

The subsequent objection by Sagredo allows Salviati to stress a fundamental point of Galileo's view of the problem that justifies the basic validity of the method of the cord:

SAGREDO. I understand this precaution, though I somewhat question it; what bothers me most in this operation is that if it is made in the dark of night, it seems to me that one is measuring the diameter of the irradiated disc and not that of the true and naked star.

SALVIATI. Not a bit; for the cord, by covering the bare body of the star, takes away the halo belonging not to it but to our eyes; of this it is deprived the moment the true disc is hidden. In making the observation you will be astonished to see how thin a rope will cover that great torch which seemed incapable of being hidden except by a much larger obstacle. (pp. 354; transl. 362)

This was a fundamental justification for the validity of Galileo's visual experiment (and of all his conceptions about the sizes of small luminous points) which is repeatedly reasserted when he returns to this theme. In his view, the halo, the adventitious rays (which he refers to by different

[4] *Lira* in the original, i.e. Lyra, the constellation of which Vega is the most brilliant star.

[5] The precaution to which Salviati alludes, and that will return in an unfinished treatise written by Galileo in 1637, is not justified in view of the modern knowledge of image formation on the eye. In the framework of modern physiological optics the point from which to calculate the angle subtended by a visual object is the posterior nodal point, which is situated before the centre of the eye (i.e. nearer to the cornea) and not, as implied by Galileo, beyond the eye. As a matter of fact, even in the late years of his life Galileo seemed to have no clear idea of the mechanisms of the image formation in the eye despite the previous studies of Kepler and Scheiner that had clarified the basic process by which the optics of the produce a real image (*pictura*) on the eye's fundus (see Chapters 13 and 14).

Figure 8.7 Galileo's *Discourse*.

terms) are produced mainly within the eye, and are not an objective feature of the luminous object.

The idea is expressed in a particularly clear way in *Discorso delle comete* ('Discourse on the comets') read in 1619 at the Accademia Fiorentina by Galileo's student, Mario Guiducci, and published in the same year under Guiducci's name, but largely due to the pen of Galileo himself (Figure 8.7). In this discourse the problem of the apparent size of star and planets is considered mainly with reference to telescopic observations. Concerning the site of adventitious irradiation this is what we find in this text:

> Here it is necessary first that we upset a false opinion about the nature of this same irradiation, if indeed anyone has put faith in what some philosophers have written to the effect of stars, torches, and all kinds of luminous bodies of all kinds light up and brighten a part of the surrounding air also, which

> in turn at a suitable distance shows its splendor more vividly and more definitely, and that is why the whole torch appears much larger to us. This reasoning is false. The truth is, first, that the air is neither lighted nor brightened; next that this irradiation is not around the luminous object anyway, but is so close to us that if indeed it is not actually within our eyes, it is upon their surfaces; perhaps it is caused by the principal light from the object being refracted in that moisture that is always maintained upon the pupil of the eye by the eyelid. Several things support this. (COMETE, 1619, pp. 31–32: transl. p. 47)

Before continuing the reading of the *Discorso* let us consider the conditions and problem inherent in Galileo's experiment with the cord for measuring the angular size of stars. First, we must be aware the true angular sizes of stars are not only much smaller than those given by Tycho and his followers but are also definitely smaller than those resulting from Galileo's measurements. For instance, Vega, the brightest and apparently largest star of the Lyra constellation, estimated by Galileo to be about 5″ is actually a little less than 1‴ (1 third or 1/60th of 1″), that is, more than 1000 times smaller than the value given by Galileo. This value (precisely 3.28±.06 milliarcseconds as ascertained by modern interferometric techniques) is not only below any possible estimate made by the unaided eye, but was certainly well below the resolution limit of Galileo's telescope. Moreover, as is the case for most of stars, it is also below the diffraction limits of any conventional modern light telescope, and can be measured only with sophisticated techniques (like those based on interferential procedures). In the case of Venus, Jupiter, and Saturn, the existence of a planetary atmosphere made Galileo's telescopic observations even more complex.

In addition to the optical limitations of the telescope (and the physical constraints due to the undulatory nature of light), another measurement problem is the influence of earth's atmosphere. Because of the existence of this atmosphere it is only partially true that the halo or irradiations surrounding the true image of a star is exclusively produced within the eye. A part of it is indeed produced by the atmospheric diffraction of the light rays coming from the star and by atmospheric turbulence. This is, however, a very small portion of the halo visible with unaided eyes and not large enough to influence the outcome of Galileo's cord experiment (in modern astronomy the consequences of atmospheric turbulence can be reduced by using the methods of the so-called 'adaptive optics'). The main difficulty is that, despite Galileo's repeated assertion that the experiment was made in a very precise way, it is nevertheless unrealistic to avoid an important source of error due to the impossibility of keeping the eye totally immobile during the measurement. In addition to possible accidental movements (both of the eye in the orbit and of the head), it is impossible to avoid the rapid involuntary movements of the eyes; microsaccades can span a spatial extent of several minutes of arc, i.e. a value much larger than the apparent visual angle of the stars. The fact that, despite the complexities and intrinsic limits of the method, Galileo was able to reduce by more than 200 times the value of the size of Vega and other stars is further evidence of his extraordinary experimental and logical perspicacity.

Returning to the *Discorso* we can see how the authors justify the idea that the adventitious irradiation issuing from small luminous bodies arises mainly within the eye rather than from the illuminated air surrounding the light source:

> The irradiation appears greater to moist and teary eyes; also if you partially close and compress the eyelids, the rays appear very long, an evident sign that the brilliance is established in the eye and resides there. And what finally shows that it is in the eye is that if we interpose our hand or some other opaque body between the eye and the light, and gently move it as if we wanted to cut out the light, the irradiation is never completely hidden until the actual flame is concealed, but the rays appear quite unaltered between the hand and the eye. This would not occur if the rays were close to the light; that is, between it and the hand. As the hand begins to cut off part of the actual light, parts of the same rays also commence to disappear, namely those which seemed to stem from the opposite part of the light. Thus if

> in raising the hand the lower part of the flame is hidden, those rays will begin to be lost which seem to burst forth from the upper part; and on the contrary, if the hand is placed above the light and is lowered to hide the upper part, then the lower rays will be lost. (COMETE, p. 32; transl. pp. 47–48)[6]

Soon afterwards, another simple experiment is mentioned to support the origin of the adventitious rays emanating from the flame of the candle within the eye:

> The same thing is proven by another most evident experiment. If looking at those rays we lean our head either toward the right or left shoulder—and thus tilt our eyes in the same way, we shall behold the same tilt occurring in the rays, but not in the small flame of the candle, which remain fixed. This is an argument which so much show that those rays are in the eyes, as it demonstrates that the flame is outside and far from them. (COMETE, pp. 32–33; transl. p. 48, modified)

It is worth comparing this passage with that of a modern text of visual science, *The first steps in seeing* by Robert William Rodieck. Interestingly, in order to discuss the image seen when the eye looks at an extremely small light spot, the author considers the vision of a star, and particularly Solaris, the North pole star. In this context he refers to the concept of the point spread function. In order to show that the radiating pattern visible with this type of stimuli originates within the eye and not in the outside world, Rodieck proposes to the reader a simple experiment:

> You can observe point spread function of one of your own eyes whenever you see a radial pattern caused by sunlight reflected from a small bright object. If you tilt your head to the side, the radiate pattern rotates as well, demonstrating that this phenomenon is due to the optics of the eye. Every eye shows these effects, which are due to the arrangements of cells within the lens. But, like fingerprints, every eye differs in the exact patterns. (Rodieck, 1998, p. 82)

There is indeed an amazing correspondence between the writing of a modern retinal physiologist and the words written more than two centuries ago by Galileo (and Guiducci) with, perhaps, an element of greater precision in the old text where it is stated that the movement of the rays occur in the same direction of the head movement, and that there is no tilt of the proper image of the small flame.[7]

In many passages of the *Dialogue* Galileo considers the problem of the adventitious irradiation with reference to both stars and terrestrial light sources. Salviati mentions the origin of this irradiation in the context of the experiment of the mirror that we have dealt with in detail in Chapter 5. He tries to explain to Simplicio why a light beam coming out from the surface of a spherical mirror contributes imperceptibly to the ambient light while it appears large and brilliant when looked at directly. He compares its appearance to that of a flame and to the appearance of Sirius:

> SALVIATI: First of all, that brilliance which you see so vividly on the mirror, and which seems to you to occupy such a large part of it, is not such a big piece. It is really very tiny, but its extreme brightness causes an adventitious irradiation of your eyes through the reflection made in the moisture at the edges of your eyelids, which extends over the pupil. It is like the little hat that seems to be seen around the flame of a candle at some distance; or you may want to compare it with the apparent rays around a star. For example, if you match the little body of the Dog Star as seen in the daytime through the telescope, when it is

[6] As we shall see in Chapter 14, Galileo was probably inspired from Leonardo in placing the main cause of the irradiation at the level of the eye.

[7] Hermann von Helmholtz is among the scientists who have studied the phenomenon of irradiation from small light sources; he devoted several pages to the phenomenon in the first volume of his *Handbuch der physiologischen Optik* (1867).

without irradiations, with the same seen at night by the naked eye, you will perceive beyond all doubt that with its irradiations it with the same seen at night by the naked eye, you will perceive beyond all doubt that with its irradiations it appears thousands of times larger than the bare and real starlet. A similar or larger augmentation is made by the image of the sun which you see in that mirror; I say larger, because it is more vivid than that of the star, as it is obvious from one's being able to look at the star with less injury to one's vision than at this reflection in the mirror. (DIALOGO, p. 69; transl. p. 76)

Simplicio replies with an argument based on the visual appearance of a gilded plate struck by the sun, to which Salviati responds by alluding to how the image of a bright light source seen from afar can depend on phenomena taking place in the eye. The observation can be considered as complementary to that of the cord capable of obstructing the vision of an object even when it subtends an angle much smaller than that subtended by the distant light source. In this case, as we shall now see, the attempted obstruction is made around the light source, where the adventitious rays appear. Surprisingly it proves to be largely ineffective in hiding their splendour:

SALVIATI: In order to explain better, let us take a very large gilded plate exposed to the sun; it will show to a distant eye the image of the sun occupying only a part of the plate, that from which the reflection of the incident solar rays comes. It is true that on account of the vividness of the light such an image would appear crowned with a much larger part of the plate than it really did. To verify this, one might note the exact place on the plate from which the reflection came, and likewise figuring how large the shining space appears, cover the major part of this space leaving only the middle revealed; the size of the apparent brilliance would not be a whit diminished, but it would be seen widely spread over the cloth or other material used for the covering. So if anyone, seeing from a distance a little gilded plate shining all over, should imagine that the same phenomenon would have to occur with a plate as large as the moon, he would be as much deceived as if he were to think that the moon is no larger than the bottom of a vine vat. (DIALOGO, p. 71; transl. 78–79, revised)[8]

It should be noted that even though this reasoning is justified for the case of the irradiation issuing from a torch or a candle, it is less so for a star or a planet. This is because in the case of stars and planets part of the irradiation is due to the diffraction of light by the earth's atmosphere, a phenomenon which is amplified by impurities in the air, whereas in the case of a close light source the effect of the interposed layer of air is much less pronounced.

It is to Galileo's great merit that, despite the many possible errors intrinsic to the procedure of his visual experiment, he succeeded in showing how previous measures of the stars (that had been accepted by astronomers of great authority) were greatly overestimated.

8.6 **A telescope-assisted visual experiment**

In the case of *Discorso* (as well as a similar discussion in *Saggiatore*), the central problem regarding adventitious irradiation was concerned mainly with telescopic observations. It is with reference to another telescope experiment that Galileo provided an important piece of evidence pointing to the small size of celestial bodies. The problem raised by Galileo's anonymous adversary (actually Horatio Grassi, the Jesuit who was also his opponent in the debate over *Saggiatore*; see Chapter 1) concerned the reason why the telescope, which was so powerful when magnifying the moon and the sun, seemed much less capable of magnifying the diameter of

[8] As we shall see in Chapter 14, Galileo's experiment correspond to one described by Giovanni Battista della Porta in his *De refractione* published in 1593.

other planets, and totally ineffective for the stars. Galileo's explanation was based on the idea that, while the telescope magnified the real external image of the object, it did not magnify the adventitious irradiation because this came mainly from inside the eye. Without entering into the details of his discussion with Grassi, we report here another of Galileo's important experiments supporting his idea that the apparent size of small luminous sources is grossly overestimated by the unaided eye. This experiment described in *Discorso delle comete* involves the phenomenon of light and dark adaptation. Galileo intuitively grasps the fundamental significance of this phenomenon in his astronomical observations, despite having no explicit and clear knowledge about it. The new experiments involve the most brilliant star in the sky, Sirius, referred to by Galileo/Guiducci as *Cane* and three of the most visible planets of the sun, Venus, Jupiter, and Saturn:

> In confirmation of what I am saying, let the telescope be fixed upon the Dog Star, for example, before dawn: it will not appear much larger than if seen without the telescope. Now let us follow it until the sun rises. We shall see it remain the same size through the telescope, but to the unaided eye it will seem gradually to diminish in such a way as to be seen smaller than the least visible of the night stars. And finally the sun rises, it will be made infinitely smaller and it will be completely lost; yet it will still be seen very well through the telescope, looking always the same. Venus, Jupiter and in sum all the stars observed though the instrument appear to us no larger by night than by day, yet the same stars seen with the naked eye are very large in the dark and very small in the lighted sky. This is a sure argument that that which is seen through the instrument is the pure object robbed of its alien rays. The same is deduced from its perfect and sharp figure, sometimes horned [*falcata*] in Venus, oval in Saturn, and circular in the other stars. (COMETE, pp. 28–29; transl. pp. 44–45)

With reference to a passage of the *Dialogue* on the different shape and size of Venus in daytime and at night, Galileo had more faith in observations made in daylight. This was based on the comparison with what happened with the shape and size of a flame seen at different distances and in different condition of illumination. A similar type of argument is made in *Discorso delle comete* where the visibility of terrestrial light sources is invoked on several occasions to support arguments about celestial bodies.

As discussed in sections 8.1 and 8.2, among the relevant factors are the various optical aberrations of the eye (chromatic, spherical, astigmatic, and those due to the imperfect transparency of ocular media). These aberrations play a progressive role as the pupil size increases in response to the dimming of ambient light. As a consequence, the blur of the retinal image increases as the optical point spread function becomes broader, with a relative increase in peripheral light intensity. The increased light sensitivity due to the shift from cones to rods of the predominantly active photoreceptors (as well as other functional adaptations of the neural circuits of the retina) make the eye sensitive not only to the light of the central lobe corresponding to the main image of a luminous point, but also to the surrounding zones. This results in a substantial increase of the size of the perceived image. The actual dimensions of the perceived image depend on the luminance of the source, because the lateral spread of the light would produce an excitation of photoreceptors only if its intensity is sufficiently high for their activation. One of the consequences of the blur would be loss of detail of the shape of the luminous body (in the case of Venus it would appear spherical even when it is falciform due to its phases).

As the ambient light increases with the rising sun, the pupil diameter decreases, thereby reducing the effects of optical aberrations. Consequently, the image of a luminous point on the retina would become more precise, with a narrowing of its lateral extension. The shift from rods to cones would result in only the more central parts of the light distribution being effective in triggering a visual response. The consequence is a substantial reduction of the perceived size of a point source; in Galileo's case it can be assumed to be Sirius, whose true angular size is less the 6/1000 of a second of arc, a value largely below the resolution limit of both the naked eye and the telescope. With a larger, non-spherical luminous body, there would also be a better correspondence between the apparent and physical size.[9]

Telescopic observations would be less affected by the factors considered here. This is because of the larger size on the retina of the image of the point source and also because of the light capturing properties of the instrument (resulting in more light adaptation). The actual size and shape of the image on the retina would depend on the magnification of the telescope and the quality of its optics and also on the quantity of light that the telescope could capture. The physical aperture of the telescope is larger than that of the human pupil. As remarked in the *Discorso*, in the case of the telescopes used by Galileo the interplay of these factors resulted in a perceived size of a luminous point source only slightly larger than that seen with the naked eye. Moreover, because of the light collecting property of the telescope, the visibility of a very bright star like Sirius (indeed the brightest star in the sky with an astronomical magnitude now estimated to about −1.4, i.e. more than four times brighter than Vega) is likely to be due to light adaptation of the eye, irrespectively of the changes in the ambient illumination. This is probably the reason why the Dog Star was 'seen very well through the telescope, looking always the same' when observed both in the night and day.

In *Saggiatore* Galileo mentions an experiment similar to that on the Dog Star made by observing Jupiter during the night and day with both the naked eye and a powerful telescope. He writes:

> With the telescope, its disc will be seen as always of the same size, but as seen by the naked eye it will progressively shrink as the dawn brightens. Near sunrise Jupiter—which in the dark surpasses all the stars of the fifth magnitude—is reduced to a smaller appearance than a star of the fifth or sixth magnitude, and finally at sunrise it is reduced to an indivisible point and becomes completely lost. Yet after that it has disappeared to the naked eye, it continues to be seen through the telescope large and round all the day. (SAGGIATORE, pp. 219–220; transl. p. 326)

The telescope used in observing Jupiter was one capable of magnifying the surface of the object seen by about 600 or 1000 times (i.e. one having approximately 20 or 30 times linear magnification) and—according to Galileo—it caused the planet 'to swallow up its coiffure of rays, and makes it similar to the full moon'. With a comparable telescope this is what happened to the appearance of Sirius:

> But the very tiny disc of the Dog Star, though enlarged a thousand times by the telescope, cannot equal its irradiation size as to appear completely shorn. Yet since the rays near the outer edges are somewhat weak and separated, the disk is very easily seen amid the discontinuity of the rays. The more the telescope enlarges this, the more distinct and the less irradiated it appears. (p. 218; transl. p. 325)

It seems as if, with more powerful and improved telescopes, in 1623 Galileo was near to separating, in the case of Sirius, the central images of the stars from the surrounding annular illumination due to light diffraction and optical aberrations. It would seem that for Galileo there was nothing definitely peculiar about the stars as stars but simply the fact that they were tiny luminous

---

[9] In exceptional circumstances, and particularly with a very clear atmosphere, people with extremely acute eyesight can almost see the falciform shape of the crescent of Venus. This is because the phase of thin crescent subtends a visual angle of about 60″, a value not very far from the resolution limits of particularly good eyes.

visual objects. As he remarks in *Saggiatore*, essentially similar visual phenomena would occur with any terrestrial object seen under conditions making it appear as a minute shining body:

> For candles shine, and blazing torches seen from distance, and any small pebbles, and bit of wood or other small bodies [*qualunque sassetto, legnuzzo o altro piccolo corpicello*], and even the leaves of plants or drops of dew struck by the sun; and from certain viewpoints these are irradiated as much as the most refulgent star, and when seen through the telescope they show the same type of enlargement [*tenore*] that stars do. (p. 86; transl. pp. 230–231)

8.7 Driving a car in the night with Galileo's thoughts

If Galileo were to live in modern times, it could easily be surmised that he would find other examples, besides candle flames, as analogies to the problem of the visual appearance of stars. Suppose, for instance, that we are driving during the night on a relatively solitary country road and Galileo is seated by us. All is dark until a car approaches with its headlights appearing initially as small light sources shining. Surely our companion would direct our attention to the appearance of the light, and especially to the adventitious rays spreading in all directions from the light bulbs, and varying in their extension and directions as we move our eyes and/or the car approaches. Perhaps he will ask us to stop for just a little, while the car is still distant and take a pencil or a small screwdriver to show how completely that broad brilliance is obliterated when the object hides the head lights. Perhaps he would also remark that our pupil is wide when looking at the distant headlights.[10] As the car approaches the brightness of the headlight increases and can even become somewhat disturbing, until it is at few tens of metres from us. If we, and the other driver, do not proceed at fast speed, we will have the time to notice a rather unexpected phenomenon.

Rather suddenly, at the moment we can see the headlights distinctly we will realize that the irradiation appears to decrease substantially. Galileo would remark then that we would still see a glare around the headlamps, but this is clearly less luminous than the light issuing directly from the bulbs, and that it is clearly distinguishable from the image of the main light sources. Perhaps he would also tell us that our pupils became narrower while looking at the headlights while nearer to them. If we doubted him he would ask us to stop the car and demonstrate what happens if we look at the headlamps of our car by alternatively turning the lights on and off.

Surely he would use particularly colourful expressions to describe the phenomenon by which, when seen from near, lights are stripped of their adventitious rays, or are sheared of their luminous covers as luminous lambs, or swallow their shining coiffure. And surely he would tell us, somewhat proudly, that he can do the same with the stars and planets, simply by looking at them with the new glass that he invented (or at least considerably improved) 'some years ago'.

The problem of irradiation surrounding a light source is amply discussed by Galileo in *Saggiatore* with reference to both celestial bodies and terrestrial lights. In particular, in chapter 49 he differentiates between a fainter and ampler irradiation belonging to the illumination of the air surrounding light sources (and easy to distinguish perceptually from the main light source, even with the unaided eye), and a more intense and more restricted luminosity, indistinguishable from

---

[10] The phenomenon of the constriction and dilatation of the pupil with changes of ambient light is considered by Salviati and Sagredo in the *Dialogue* in the context of the discussion of the visibility of stars (DIALOGO, p. 355; transl. p. 363). Galileo was well aware of it because it had been thoroughly studied in the circle of his friend Paolo Sarpi, and by Fabricius ab Aquapendente, his colleague at the University of Padua, and also his physician. (See Chapter 13.)

the light source when this is viewed from a distance. The telescope could help in separating visually this second irradiation from the main image of the light source, an effect that Galileo denotes metaphorically as 'to undress', 'to strip out', 'to shear'.

It is, of course, a fiction to place Galileo in a modern automobile but it is not very far from truth, inasmuch as every moment of ordinary life provided the opportunity for Galileo to exercise his 'acute' vision. Indeed the experience of the car headlights at night presents us with a way to appreciate how Galileo succeeded in reducing the estimated size of stars and thus strongly contributed to make more plausible the universe of Copernicus.

8.8 **New Jesuit assaults and the disruption of the eighth orb**

The importance of the discussion on the apparent size of the fixed stars with reference to the cosmological and mathematical plausibility of the Copernican system has been remarked upon. With relatively simple visual experiments, Galileo had succeeded in demonstrating that the angular size of the stars was much smaller than previously supposed. This enabled him to defend the heliocentric system from criticisms of the conservative cultural milieu, and from Jesuits who had fully endorsed the anti-Copernican politics of the Vatican authorities, especially after the official censure of Copernicus by the Holy Office in 1616.

The pro-Copernican aspect of the new-found dimensions of the stars, derived from the cord experiment, is clearly expressed in the *Dialogue* through the words of Salviati, in refuting the anti-Copernican arguments of Scheiner and Locher. It is also asserted in others texts by Galileo dealing with the relationship between the size of the Great orb and of the sphere of the fixed stars (as, for instance, a long letter addressed in 1624 to Francesco Ingoli: OG VI, pp. 502–561; see also the legend to Figure 8.5).

As noted in Chapter 7, the Catholic Church was obliged to abandon the traditional cosmology of Ptolemy and was inclined to endorse the system of Tycho Brahe against that of Copernicus. After the death of Galileo, this project was pursued by Giovanni Riccioli with his *Almagestum novum*, published in 1651, i.e. less than 10 years after Galileo died. The importance of the angular sizes of stars as support for Copernicus makes it little wonder that in his monumental work Riccioli questioned the validity of Galileo's method in measuring the size of stars. Moreover, on the basis of his own measurements, the Jesuit proposed substantially larger values than those of the Tuscan scholar (although not as large as those of Tycho Brahe and his followers). For instance, Riccioli concluded that Sirius had a diameter of 18″ and Sirius of a little more than 17″, based on his observations, made in collaboration with Grimaldi and some other brothers. The method used by Riccioli and Grimaldi was a telescopic comparison of the apparent diameter of the star with those of other celestial bodies (like Saturn and Jupiter). Unlike Galileo's method, it did not involve a procedure of occultation. Because of that, it suffered from the errors that Galileo had pointed out repeatedly. The values found by Riccioli and Grimaldi were smaller than those of Tycho only because of the use of a telescope (and one surely improved with respect to that of Galileo). Due to these smaller estimates, Riccioli was obliged to assume a value of the radius of the sphere of the fixed star much greater than those accepted by previous authors (210,000 times the radius of the earth instead than the 20,110 of al-Ferghani and that of 14,000 of Brahe). This made the Copernican hypothesis a little less absurd than Scheiner's and Locher's assertions about it 40 years earlier.

Despite Galileo's experimental and logical efforts to account for the presumed absurdities of the Copernican system with respect to the distance of the fixed stars, he was far from trusting the existence of the sphere of fixed stars. In other words, he did not believe that the stars were all at approximately the same distance from earth. This emerges in the letter addressed in 1624 to Francesco Ingoli, a stubborn adversary of the Copernican system. In the well-established astronomical tradition, Ingoli had asserted (in 1616) the necessity of locating the earth at the centre of the universe, i.e. at the centre of the eighth sphere or firmament. This was also because during their supposed revolution around the earth, the stars always appear the same size, which would be impossible if they were not moving together along a circular orbit centred on the earth. This is Galileo's refutation of Ingoli's argument:

> As to the second [argument] by which you pretend, together with Sacrobosco, to be capable of demonstrating that the earth is at the centre of the firmament, because the fixed stars, situated in whatever part of the sky, always appear to us the same size. I tell you that it lacks not only one, but all the conditions needed for a correct conclusion. First, you suppose that the stars of the firmament are all in the same orb: *this is so doubtful to be known, that neither you nor others would ever be capable of demonstrating it*. (OG VI, p. 523, our emphasis)

In another passage, Galileo deals with the orbits of the satellites of Jupiter that he had discovered with his telescope. The existence of satellites which rotate around a globe different from the earth made less cogent one of the fundamental assumptions of the Ptolemaic system—the need to have an absolute centre of the universe. This centre was both the site around which all satellites and stars rotated and also an absolute reference point. In this context Galileo remarked:

> If it would then be necessary to assign to the totality of the stars an inferior site, that is a centre, and superior one, that is toward the external parts, this is doubtful to determine; in the [existing] ambiguity it seems to me more reasonable to assume that it is no rather than yes, because (as I have already said) *I do not believe that the stars are placed all on a spherical surface, such that they would be equally distant from a given point*. (p. 536, our emphasis)

These two passages make clear that Galileo did not trust the existence of a sphere of the fixed stars, nor that those stars (either fixed, or freely moving), were at one and the same distance from the earth. A criticism of the fixed-stars orb conception is developed in the Second Day of the *Dialogue* in the context of a general censure of the Ptolemaic system. Galileo, was not, however, too explicit in such type of assertions.[11] This was likely because it implied the possibility of an infinite universe, with a plurality of worlds and without an absolute centre. Such statements had physical and religious dimensions and were considered heretical by the Catholic Church. A similar conception had been one of the imputations addressed to Giordano Bruno and a justification for his condemnation by the tribunal directed by Cardinal Roberto Bellarmino which was followed by his execution by burning at the stake in Rome in 1600.

In Galileo's age, the idea of the existence of an eighth orb, although strongly asserted by the conservative milieu and by Jesuits, was already being questioned, particularly after the various observations that had made the idea of the existence in the sky of solid orbs problematic. Independently of Bruno, criticism of the existence of the eight spheres was particularly strong among British Copernicans. The first cosmological image of a universe with stars spreading outwards, towards a potentially infinite space was published in an English text by Thomas Digges; he was an important astronomer and mathematician, the son of Leonard Digges who was also an astronomer (and astrologer). This image was inserted by Thomas Digges as an appendix to an astrological work by his father, having an impressively long title beginning with *A Prognostication euerlasting of right good effect*.... Thomas's appendix, also with a long title and a strong Elizabethan style, *A Perfit*

[11] A short and somewhat ironical allusion to the problem of the infinity of Universe is contained in a letter addressed by Galileo to Fortunio Liceti on 20 September 1639 (OG XVIII, pp. 106–107).

Description of the Cælestiall Orbes according to the most aunciente doctrine of the Phythagoreans, latelye reuiued by Copernicus and by Geometricall Demonstrations approued, appeared starting from the 1576 edition of Leonard's *Prognostication*. Interestingly, as seen in the text referring to the disrupted sphere of 'starres fixed' written by Thomas, and reported in the legend to Figure 8.8, the modernity

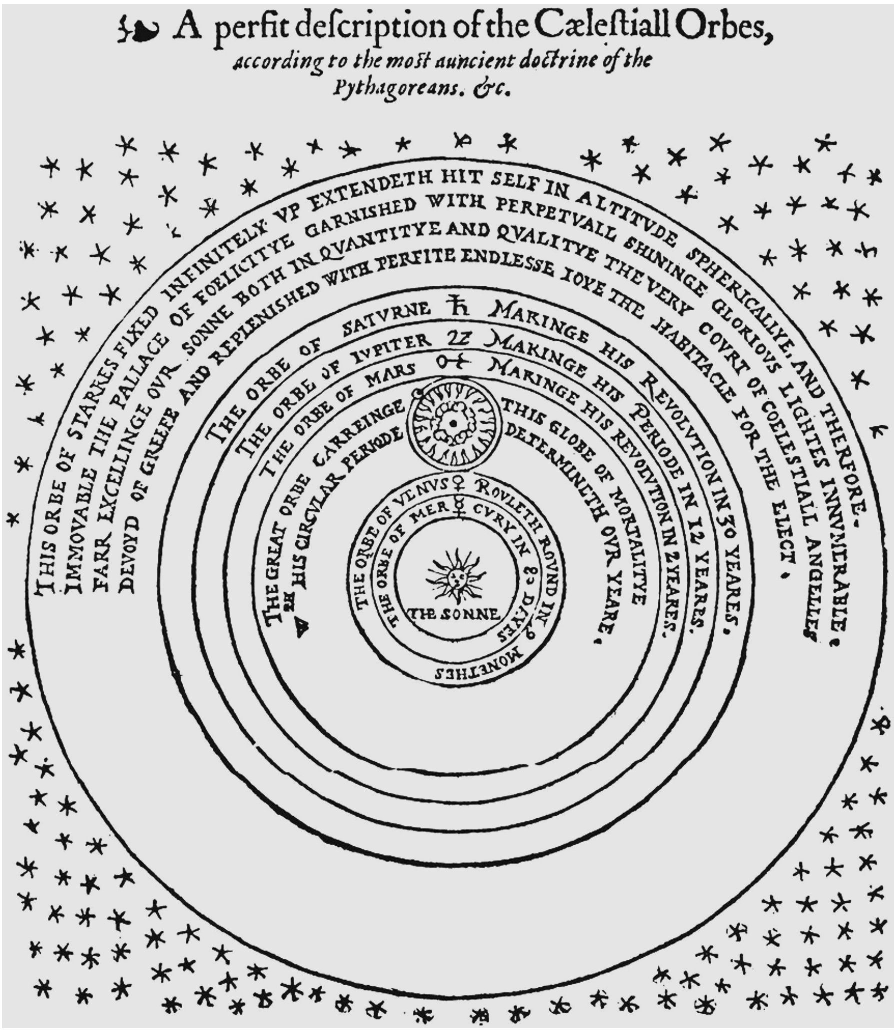


Figure 8.8 The first published image with a representation of the Copernican system based on the idea that stars spread in the far regions of the cosmos at variable distances from the sun, without being inserted in a specific orb. The text referring to the stars reads as follows: 'This orbe of starres fixed infinitely up extendeth hit self in altitvde sphericallye, and therefore immovable the pallace of foelicitye garnished with the perpetvall shininge gloriovs lightes innvmerable farr excellinge ovr sonne both in qvantitye and qvalitye the very covrt of coelestiall angelles devoyd of greefe and replenished with perfite endlesse ioye the habitacle for the elect'. Reproduced from Digges, L. and Digges, T., *A prognostication euerlasting of right good effect fruitfully augmented by the auctor, contayning plaine, brief, pleasaunt, chosen rules to iudge the weather by the sunne, moone, starres, cometes, rainebow, thunder, cloudes*, 1576, Aldbrough, St John Publications.

of Digges's ideas went along with a religious attitude with strong implications of an esoteric and astronomical character.

8.9 The monkey and the mirror

Galileo did not believe that there were sound physical and logical arguments to assume the existence of a sphere of fixed stars. Nor did he trust his sensory impressions sufficiently to provide evidence of its existence. This was because he was well aware that all remote objects appear to be at the same distance, and thus the stars in the sky would be visually located on one and the same hypothetical sphere, regardless of their actual distance.

Horatio Grassi (addressed by the pseudonym of Sarsi) stressed the importance of visual appearances in order to establish the physical nature of comets. In *Saggiatore*, Galileo replied to his adversary (through Virginio Cesarini) in this way:

> As your Excellency will note, Sarsi has such a confidence in the sense of sight that he deems it impossible to be deceived any time that a spurious object may be set aside a real one. I confess that I do not have such a perfect discriminatory faculty, but resemble the monkey that firmly believed he saw another monkey in a mirror, and so live and real did the image seem to him that he did not discover his error until he had run behind the mirror four or six times to catch her. Assuming that what Sarsi sees in his own mirror are not true and real men at all, but are mere images [*vani simulacra*] like those the rest of us see in ours, I should like to know what those visual differences are by which he so readily distinguishes the true from the spurious. For my part, I have countless times been in one room with closed shutters and have seen on the opposite wall the reflection of sunlight coming through some tiny hole, and as far as vision could tell I have judged it to be a star, no less bright than Venus and the Dog Star. When we walk over a field toward the sun, in how many thousands of straw and pebbles, little polished or moistened, will the reflection of the sun be seen in the aspect of the most splendid stars? Sarsi has but to spit upon the ground, and undoubtedly he will see the aspect of a natural star from that point toward which the sun's rays are reflected. Furthermore, any body placed at a great distance and struck by the sun will appear as a star, particularly if placed so high as to be seen as the other stars are seen. And who could distinguish the moon seen in daytime from a cloud touched by the sun? Surely, no one. Finally, if simple appearances can determine the essence of a thing, Sarsi must grant that the suns, moons, and stars seen in still water or in a mirror are true suns, real moons, and actual stars. (SAGGIATORE, pp. 89–90; transl. pp. 232–233, slightly revised)

We close this chapter centred on the illusory appearance of the size of stars with this strong statement on the possible fallacy of vision by Galileo. We will return to the problem of seeing stars in the last chapters of our book, and particularly in Chapter 14.

In Chapter 9 we will move to consider other aspects of Galileo's reflection on visual appearances, characterized by more decidedly geometrical considerations.