JHA, xxxviii (2007)

SOLAR ECLIPSE OBSERVATIONS IN THE TIME OF COPERNICUS: TRADITION OR NOVELTY?

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In Western astronomy before Tycho Brahe and Kepler, only a handful of astronomical observations were actually used to derive parameters in a theory or to test the structure of a theory. Those observations, usually quoted in scientific treatises, such as the *Almagest* or *De revolutionibus*, have been analysed by historians of astronomy who want to know how observations are to be tied to a theory. Not surprisingly, those records give us a very general picture of historical observational practice. However, there are still not fully explored series of observations that allow us to understand details of the observational methods used in the medieval and early modern period and the transmission of these methods. This paper will offer an examination of such a series of observations made in Frauenburg by Nicolaus Copernicus. The series was recorded by Copernicus in his copy of Johann Stoeffler's *Calendarium Romanum magnum* (Oppenheim, 1518), and concerns four partial solar eclipses that occurred in 1530, 1536, 1540, and 1541. It will be argued that Copernicus employed the *camera obscura* (pinhole camera) to measure the magnitude of these eclipses. This conclusion will allow us to strengthen a thesis previously proposed by Ludwik A. Birkenmajer, that the astronomical use of images formed through an aperture, which spread among European astronomers in the second half of the sixteenth century, may have its source in eclipse measurements made by Copernicus during the later years of his scientific activity.

1. *The Observations*

Stoeffler's *Calendarium* contains predictions of solar and lunar eclipses for the years 1518–73, and Copernicus made the notations in twelve eclipse diagrams of this book (Figure 1).[1] Among them there are four solar eclipses with the magnitudes estimated by Copernicus. Their dates are 29 March 1530, 18 June 1536, 7 April 1540, and 21 August 1541, and information given by Copernicus is as follows:

29 March 1530
obseruata varmie puncta 8
principium 17.58
finis 19.50
medium 18.54[2]

18 June 1536
[*puncta*] *quasi 9 a borea*
durauit ad finem hore tertie[3]

7 April 1540
[*puncta*] *11*
finis h. 18.40. varmie
defecit ab austro[4]

21 August 1541
[*puncta*] *fere 4 1/2*
a borea
in fine medium celi XV Librae, hor. 2.24[5]

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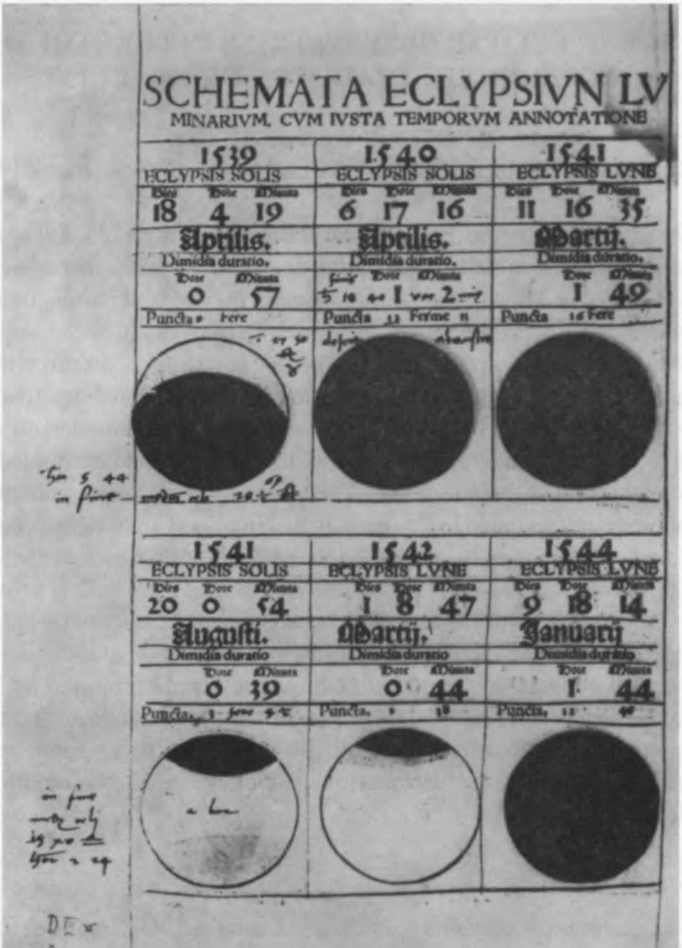

SCHEMATA ECLYPSIVN LV
MINARIVM. CVM IVSTA TEMPORVM ANNOTATIONE

1539 ECLYPSIS SOLIS	1540 ECLYPSIS SOLIS	1541 ECLYPSIS LVNE
Dies Hore Minuta 18 4 19	Dies Hore Minuta 6 17 16	Dies Hore Minuta 11 16 35
Aprilis.	Aprilis.	Martij.
Dimidia duratio. Hore Minuta 0 57	Dimidia duratio. Hore Minuta 1 2	Dimidia duratio. Hore Minuta 1 49
Puncta 9 fere	Puncta 12 Ferme 11	Puncta 16 fere

1541 ECLYPSIS SOLIS	1542 ECLYPSIS LVNE	1544 ECLYPSIS LVNE
Dies Hore Minuta 20 0 54	Dies Hore Minuta 1 8 47	Dies Hore Minuta 9 18 14
Auguſti.	Martij.	Januarij
Dimidia duratio Hore Minuta 0 39	Dimidia duratio Hore Minuta 0 44	Dimidia duratio Hore Minuta 1 44
Puncta, 3	Puncta, 5	Puncta, 12

FIG. 1. Eclipses for the years 1539–44 from Stoeffler's *Calendarium* (Oppenheim, 1518), with the notes of Copernicus referring to the observations of three solar eclipses of 18 April 1539, 7 April 1540, and 21 August 1541. Library of the Uppsala Astronomical Observatory, Coll. Hjörter, G I, 51, f. D3v. Photograph courtesy of the Institute for the History of Science, Warsaw.

Although it is not stated explicitly, we may safely assume that these four observations were made in Frauenburg. The estimates of magnitude were expressed in digits (*puncta*) or twelfths of the solar diameter (Figure 2). Table 1 presents information about these eclipses according to modern computations.[6]

Eclipse measurements constitute an important part of Copernicus's astronomy. In the *Narratio prima* Georg Joachim Rheticus wrote: "For nearly 40 years in Italy

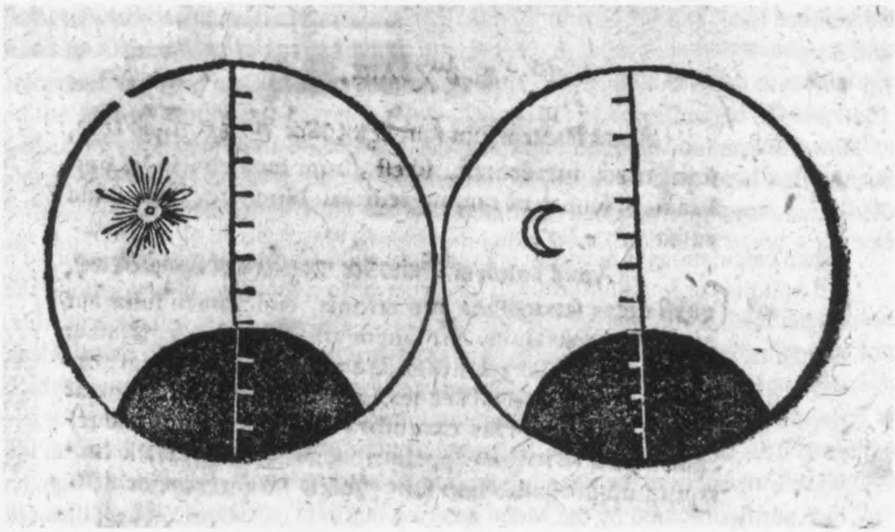

FIG. 2. Following ancient practice eclipse magnitude was given in digits — twelfths of the solar or lunar diameter. *Erasmi Reinholdi Salueldensis Theoricae novae planetarum Georgii Purbachii ... recens editae et auctae novis scholiis* ... (Wittenberg, 1580), f. 194r. Courtesy of the Warsaw University Library.

TABLE 1. Solar eclipses observed by Copernicus in Frauenburg (modern computation).

Date	Time of maximal eclipse (UT)	Altitude	Magnitude
1530 Mar 29	5^h40^m	14°	0.72
1536 Jun 18	13^h30^m	46°	0.87
1540 Apr 7	4^h44^m	9°	0.96
1541 Aug 21	12^h08^m	41°	0.41

and here in Frauenburg, he observed eclipses and the motion of the Sun."[7] This statement follows Copernicus's words from *De revolutionibus* III,20: "Accordingly, even in putting the [solar] apogee at 6 2/3° within the Crab, I was not satisfied to trust the time-measuring instrument, unless my results were also confirmed by solar and lunar eclipses."[8] However, Copernicus did not describe how he measured eclipse magnitudes (it is also not known how Copernicus made his time measurements). In 1900, Birkenmajer hypothesized that Copernicus used in his eclipse observations a pinhole camera.[9] To support his conjecture, Birkenmajer pointed out that a presentation of this method appeared in Erasmus Reinhold's edition of Peurbach's *Theoricae novae planetarum*, published posthumously (Reinhold died in 1553) in 1580. Birkenmajer noticed that the presentation is absent in the first edition of Reinhold's work (Wittenberg, 1535) and that Reinhold's preface was written in April 1542.[10] An obvious link between Frauenburg and Wittenberg (Reinhold was the senior professor of mathematics and astronomy in the latter town) Birkenmajer saw in Rheticus, who was staying with Copernicus throughout most of the period from May 1539 to

September 1541. Indeed, Rheticus could have observed solar eclipses in April 1540 and August 1541 together with Copernicus, since he returned to Wittenberg from his stay with the Warmian canon only for a short period of time between the end of 1540 and the beginning of 1541.[11]

However Reinhold in his description of the new observational technique, published for the first time in 1542 in the second edition of his commentary on Peurbach's *Theoricae*, says nothing about its source. Without going into details, he explains:

> When calculations indicate an approaching solar eclipse, climb to the attic of a tall building or to a not-too-lowly chamber or to a room on an upper-floor, the higher the better for the task. Your observation post should be, as far as possible, devoid of all light. Yet even if you close every opening and block every crack, the solar rays will surely find a fissure or hole of whatever shape through which to penetrate into the room. Failing that, make yourself a small opening for the rays. This done, you will notice that the spot of sunlight on the floor or on the brick wall opposite the opening, most amazingly, takes the shape of the Sun, its face partly obscured by the Moon entering our field of vision. You can thus see with your own eyes what proportion of the 12 digits of the Sun's luminous face has been concealed … even if you watch the earth, rather than the sky. Such an ephemeral image will allow an apt observer to understand much more, make better estimates etc.[12]

The suggestion that Copernicus used in his eclipse observations a pinhole camera should be strengthened by independent evidence. As we shall see, this evidence can be found in Copernicus's observational data. But to understand its meaning, we have to enter into the history of astronomical use of pinhole images in the medieval and early modern periods.

2. *Pinhole Images and Eclipse Observations*

The problem of images formed through an aperture was an important element of study into the nature and propagation of light in medieval science. This problem had an interesting practical aspect which referred to the possibility of casting images of the full or eclipsed solar disc through an aperture onto a screen.[13] Thus among works dealing with the theory of pinhole images we find purely theoretical treatises that offer an idea of using an aperture to study nature, and technical fragments that try to give a method of measuring an image on the screen. In both cases a correct explanation of the formation of images was dependent upon the geometrical competence of the scholar discussing the subject.

The case of the pinhole images formed during a partial solar eclipse was first analysed by Ibn al-Haytham (Alhazen, died *c.* 1040) in his *Maqāla fī Sūrat al-kusūf* (*Treatise on the form of the eclipse*).[14] However, his work and commentaries on it were available only in Arabic and it seems that Latin medieval authors were unacquainted with al-Haytham's analysis. In the Western scientific tradition, the problem of pinhole images was considered a number of times in the thirteenth century, by scholars such as Roger Bacon, Witelo, and John Pecham. However, a thorough understanding of the use of a finite aperture to determine the apparent diameter of the Sun or magnitude of the solar eclipse was achieved by the next generations of medieval scholars.

A correct and detailed description of the astronomical use of a pinhole camera is given in the introductory text (*Prologue*) to William of Saint-Cloud's *Almanach planetarum*, composed in 1292 and preserved in several manuscripts.[15] William of Saint-Cloud gives technical information about how to observe using a pinhole camera:

> Let there be made an aperture in the roof or in a window of a closed house towards that part [of the sky] in which the eclipse of the Sun is to happen. Let the size of the aperture be like that through which wine is drawn from barrels. Once the light of the Sun passes through the aperture, let there be placed at a distance of 20 or 30 feet from the aperture something flat, as for example a panel, in such a way that light of the Sun falls perpendicularly on the surface of that flat object.[16]

He knows that the image of the Sun will be round, even if an angular aperture is used. And he understands that if the aperture has a finite diameter, the angle corresponding to the apparent diameter of the Sun must be measured from the intersection before the aperture of the outermost rays casting the solar image on the screen (Figure 3). William of Saint-Cloud also knows that, when the luminous source is the partially eclipsed Sun, the image on the screen will be inverted and it will reproduce the relative dimensions of eclipse in the sky:

> And when the eclipse begins, that light [falling on the screen] will be seen proportionally lacking according to the lack [of light] in the Sun. And it will increase in size according to its increasing and it will decrease according to its decreasing. The only difference will be that the part lacking in the light will be opposite to the part lacking in the Sun, in such a way that if the eastern part of the Sun is lacking, in the light the western part will be lacking, and vice versa.[17]

However, although William's analysis is correct, his text does not give any explicit instructions on how to measure the magnitude of the solar eclipse, taking into account the finite diameter of the aperture. This problem was solved for the first time by Levi ben Gerson (1288–1344).

About 35 years after William of Saint-Cloud, Levi sought to measure the variation of apparent solar diameter by means of a pinhole camera and in this way to investigate the solar eccentricity from the inverse proportion between the distances and the angular dimensions. In astronomical fragments of his *Milhamot Adonai*, written in Hebrew in 1328, Levi showed that the pinhole image of the Sun on the screen was a measure of the apparent size of the luminary, provided the diameter of the aperture was subtracted from it.[18] He also formulated a principle of finding the magnitude of the partially eclipsed Sun:

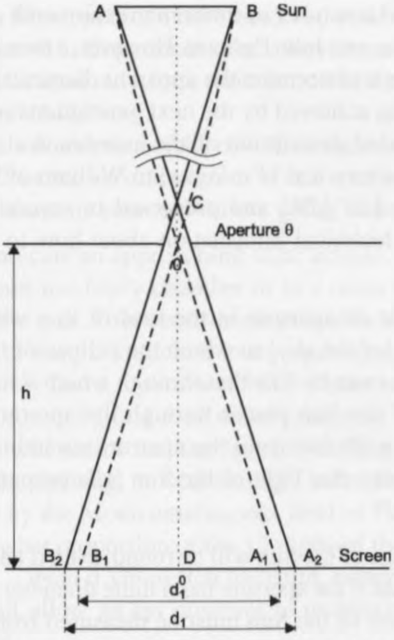

FIG. 3. A pinhole camera with a finite aperture used for measurements of the apparent diameter of the Sun (*AB*). The aperture with the centre in point *O* has a diameter θ. The solar image B_2A_2 observed on the screen has the linear diameter d_1 and corresponds to $\angle B_2CA_2 = \angle ACB$, where *C* is the point of the intersection before the aperture of the outermost rays casting the solar image on the screen. The linear diameter d_1^0 corresponds to the known distance *h* between the aperture and the screen (and to $\angle B_1OA_1 = \angle AOB$). Since *h* is negligible in comparison with the distance between the Sun and the aperture, we can assume that CB_2 is parallel to OB_1 and CA_2 to OA_1. Hence $d_1^0 = d_1 - \theta$.

> It is best for the hole of the window to be very small, for then the rays that arrive at the wall that receives the light take on the shape of the Moon according to the amount of the eclipse. If you subtract the amount of the window from the diameters of the greatest and the smallest ray, you will find in the remainder the ratio of the eclipsed part to the body of the luminary, for it is equal to the ratio of the surplus of the greatest diameter over the least diameter to the greatest diameter, or to the ratio of the least diameter to the greatest diameter.[19]

The geometry of a pinhole camera with a finite aperture and the conditions of solar eclipse observation according to Levi's solution are illustrated in Figures 3 and 4.

Levi's astronomical fragments were translated into Latin in 1342, but it seems that his theory of pinhole images had no influence on the subsequent discussions of this technique and its use in observing eclipses in the Latin West.[20] Explicit recommendations that the *camera obscura* could be used for observations of the apparent diameter of the Sun occurred in a handful of other Latin manuscripts, for example in works written by Egidius of Baisiu[21] and Henry of Hesse,[22] and later in print, especially after publication in 1542 of the second edition of Erasmus Reinhold's commentary on Peurbach's *Theoricae novae planetarum*. But the definitive solution of the problem of the formation of images behind small apertures, from which the right method of eclipse measurements could be deduced, was found by Johannes Kepler in 1600.[23]

Kepler's study had grown out of Tycho Brahe's attempts to measure the apparent diameter of the Moon during a solar eclipse and to achieve consistency between observations and his lunar theory. Tycho realised that the width of the aperture should be somehow involved in calculations, but he failed to find the right solution.[24] Kepler's theory explained the reasons for subtracting the diameter of the aperture from the image of the Sun, as earlier was postulated by Levi. Kepler included the new theory of pinhole images in his *Ad Vitellionem paralipomena* published in 1604. In this treatise he also described in rich detail the observational technique developed on the basis of Reinhold's crude instruction:

> This problem is from my teacher Maestlin. We went up under the roof of the church, and, the doors being shut against the light, someone climbed up into the highest beams, in order to remove a roof tile in a suitable place so that a very slight crack could make an allowance for light, now one tile, now another, according to

FIG. 4. The pinhole image of partially eclipsed Sun observed on the screen. The aperture has the finite diameter θ. According to the Levi's principle: $d_{1,2} = d_{1,2}^{0} + \theta$, where d_1 and d_2 are, respectively, "the greatest" and "the least" diameters of the crescent-shaped solar image, whereas d_1^{0} and d_2^{0} are values not disturbed by the width of the aperture.

> the way the beams were intercepting one or another way.... He received this ray, eclipsed along with the Sun, on paper.... And because the whole radiation is a right cone, whose vertex is about at the opening, it is obvious that the ray formed on the paper does not come out circular, unless the paper be perpendicularly opposed to the radiation, by Apollonius I, 9. Therefore, he drew upon the paper a number of circles of different sizes, about as many as he saw that the ray was going to take up, and, after drawing the diameters, divided them into 12 equal parts, or digits. Next, he received the ray with the marked circles set opposite, in such a way that the edge of the ray should coincide everywhere with the circumference of one of the circles, by changing the circles or by putting them nearer or farther from the opening until this should happen. This was evidence that the cone of radiation was cut perpendicularly by the paper. Now he directed the divided diameter by rotating the paper so that it should bisect the horns of the Sun. The interior arc of the deficient ray, where it cut the divided diameter, thus then showed digits of the eclipse. This teaching, presented by Reinhold, he refined with greater care, following the advice of the author.[25]

As we shall see, it is quite possible that Copernicus conducted his observations of solar eclipses in a similar way.

3. *Copernicus and Eclipse Measurements*

An astronomer who has not learnt the method for subtracting the size of the aperture from the image of the partially eclipsed Sun will introduce into his measurements of eclipse magnitude a systematic error. Let d_1 and d_2 denote, respectively, the diameter of the solar disc and the width of the crescent-shaped solar image, measured on the screen of the *camera obscura* during the maximum phase of the eclipse (Figure 4). This leads to an erroneous magnitude

$$M_E = d_1 - d_2/d_1.$$

According to the Levi-Kepler principle, a proper value of magnitude could be obtained through the formula

$$M = d_1^0 - d_2^0/d_1^0,$$

where $d_1^0 = d_1 - \theta$ and $d_2^0 = d_2 - \theta$ are values not disturbed by the width of the aperture θ. Since $d_1 - d_2 = d_1^0 - d_2^0$ and $d_1 > d_1^0$, we always have

$$M_E < M.$$

In other words, if we calculate magnitude from the diameters of solar image without subtracting the width of the aperture, we will always underestimate eclipse magnitude.

Let us now return to Copernicus's eclipse measurements and compare his estimates of magnitude with modern calculation. As seen in Table 2, the magnitudes measured by Copernicus during four solar eclipses have errors (observed magnitude minus

TABLE 2. Magnitudes of partial solar eclipses observed by Copernicus (Frauenburg) and Ibn Yūnūs (Cairo).

Date	Observed magnitude (digits)	Computed magnitude (digits)	$O - C$ (digits)
Copernicus			
1530 Mar 29	8	8.6	$8 - 8.6 = -0.6$
1536 Jun 18	almost 9	10.4	$8.9 - 10.4 = -1.5$
1540 Apr 7	11	11.5	$11 - 11.5 = -0.5$
1541 Aug 21	almost 4.5	4.9	$4.4 - 4.9 = -0.5$
		Mean value of the error:	$O - C_{\text{Copernicus}} = -0.8$
Ibn Yūnūs			
977 Dec 13	~8	7.2	$8 - 7.2 = +0.8$
978 Jun 8	5.5	6.0	$5.5 - 6.0 = -0.5$
979 May 28	~5.5	5.4	$5.5 - 5.4 = +0.1$
985 Jul 20	3	3.4	$3 - 3.4 = -0.4$
		Mean value of the error:	$O - C_{\text{Ibn Yūnūs}} = 0.0$

magnitude computed from modern theory) that vary from –1.5 to –0.5 digits; the mean error is –0.8 digits. This result suggests that all these eclipse measurements were conducted in similar conditions and the obvious explanation of the negative systematic error is the use of a pinhole camera without the necessary reduction of measured values.

To test this hypothesis in another way I looked for an ancient series of eclipse observations similar to Copernicus's, but presumably made without the use of the *camera obscura*. Happily, such a set of observations is contained in the *al-Zīj al-Kabīr al-Hākimī* compiled by the great Cairo astronomer Ibn Yūnūs, who died in 1009 (whereas Ibn al-Haytham's *Treatise on the form of the eclipse* was written after 1027[26]). Ibn Yūnūs's reports were recently translated and compared with modern computations by S. S. Said and F. R. Stephenson.[27] Among Ibn Yūnūs's records one can find a consistent group of four solar eclipse observations, together with measurements of magnitude. All of them were made in Cairo; three of them (in 977, 979, and 985) were conducted by Ibn Yūnūs himself, whereas the fourth (in 978) was witnessed by him.[28] Table 2 shows the results of analysis of eclipse magnitudes recorded by Ibn Yūnūs. The errors vary from –0.5 to +0.8 digits; the mean error amounts to 0.0 digits. It should be pointed out that Ibn Yūnūs does not explicitly describe the method of observation. However in his work he recorded the eclipse measurement made in 928 in Baghdad by Banū Amājūr. According to preserved description, the Sun was observed by reflection in water.[29]

The data from Table 2 are presented graphically in Figure 5. We can see that Copernicus's magnitudes are systematically low in comparison with Ibn Yūnūs's, and that might suggest that we are dealing with two different observational techniques.

If we accept the claim that Copernicus used the pinhole camera for his eclipse observations, we could try to reconstruct possible conditions of measurements. The important point is that the erroneous magnitude M_E is in a simple way dependent

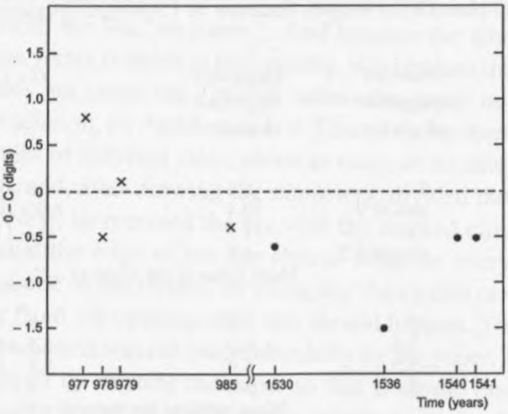

FIG. 5. The error in the measured magnitudes of partial solar eclipses (observed – calculated) recorded by Ibn Yūnus (years 977–985) and Copernicus (years 1530–41). For details see Table 2.

TABLE 3. Width of aperture θ in mm, computed from errors in Copernicus's eclipse magnitudes (Table 2) for three assumed values of *h*.

Distance aperture – screen *h* (m)	4	6	9
1530 Mar 29	3	4	6
1536 Jun 18	6	9	14
1540 Apr 7	2	2.5	4
1541 Aug 21	4	6	9.5

on the width of aperture θ, the distance *h* between the aperture and the screen, the correct value of magnitude *M*, and the apparent diameter of the Sun $D_{\odot}$. If we apply simple trigonometric transformations to the situation shown in Figure 3, the following relation holds true:

$$\theta = 2 \tan (D_{\odot}/2) (M/M_E - 1) h.$$

With the mean value of $D_{\odot} = 0;31,59^{\circ}$ we can use this formula to obtain pairs of θ and *h*, corresponding to the relevant magnitude M_E measured by Copernicus. The results are presented in Table 3.

It must be stressed that Table 3 contains only approximate values of θ and *h*, since they were calculated under the assumption that the geometry of the pinhole camera was the only factor that influenced the process of magnitude measurements. (However, it should be also noticed that the values of θ presented in Table 3 are rather consistent and very reasonable.) Bearing this in mind, we could also estimate a diameter of the solar image on the screen of Copernicus's *camera obscura* for the distance between the aperture and the screen proposed by William of Saint-Cloud in his *Almanach planetarum*. William suggested "a distance of 20 or 30 feet", or 6–9 meters. If we take *h* = 6m, we have for the diameter of the solar image value 56mm + θ; for *h* = 9m, the diameter is equal to 84mm + θ.

4. *Copernicus and the Astronomical Use of Pinhole Images in Europe*

Because of the case of systematically underestimated magnitudes of partial solar eclipses observed by Copernicus in years 1530–41, it is highly probable that the Warmian canon used in his measurements a pinhole camera. This conclusion raises two interesting questions.

First, how might Copernicus have learned of the astronomical use of a pinhole camera? With appropriate reservation some comments may be offered. The Jagiellonian Library in Cracow, where Copernicus studied, has a rich collection of fifteenth-century optical manuscripts.[30] This collection includes copies not only of Pecham's *Perspectiva communis*, where the problem is simply mentioned, but also the only known copy of the work by Egidius of Baisiu, whose contribution to the problem of pinhole images can be considered superior to that of any other medieval scholar in Europe before Kepler, with the exception of Levi ben Gerson.[31] The manuscript with the treaties composed by Egidius (presumably of French origin) belonged to the library of Matthew of Miechow (Maciej z Miechowa), a Cracow professor of medicine and a historian. (In the catalogue of this library, dated 1 May 1514, was also listed a handwritten treatise maintaining that the Earth moves while the Sun is at rest — the first known description of Copernicus's planetary theory, probably his *Commentariolus*.[32])

As is well known, Martin Biem of Ilkusch (Marcin Biem z Olkusza), a Cracow professor of astronomy and astrology, was a close associate of Copernicus in lunar eclipse observations linking Cracow and Frombork.[33] Although the subjects studied by Copernicus at the University of Cracow during the period 1491–95 are not known, it is certain that in winter term of 1492–93 Martin Biem taught optics and it is very probable that Copernicus attended his astronomy lectures. Biem observed in Cracow and Ilkusch at least three partial solar eclipses, those of 1 October 1502, 8 June 1518, and 29 March 1530 (the last eclipse was also observed by Copernicus in Frauenburg). He recorded his observations in his copy of the *Almanach nova in annos 1499–1531* (Ulm, 1499) published by Johann Stoeffler and Jacob Pflaum, including notes about eclipse magnitudes.[34] Unfortunately, Biem says nothing about his method of measurements, although he admitted that the observation of 1518 was made with great care ("*iuxta verissimam obseruacionem*"). According to modern computation,[35] Biem recorded the magnitude of the 1502 eclipse with good accuracy. However, his observed magnitudes for the eclipses of 1518 and 1530 he listed in an inconclusive way: "the part of the Sun to be eclipsed is 11 digits, but in Ilkusch it was nearer to 10 digits" (1518); "7 digits and slightly more" (1530). Therefore although Martin's eclipse magnitudes observed in 1518 and 1530 have negative errors (see Table 4), comparable with the errors in Copernicus's observations, we cannot draw from this any firm conclusion.

Thus the scientific community at Cracow seems the most obvious environment where Copernicus might have learned about the astronomical use of a *camera obscura*, although we cannot exclude another scenario.

Table 4. Solar eclipses observed by Martin Biem in Cracow (1502 and 1530) and Ilkusch (1518).

Date	Time of maximal eclipse (UT)	Observed magnitude (digits)	Computed magnitude (digits)	$O-C$ (digits)
1502 Oct 1	6.30	10.8 (10 digits and 46 minutes)	10.9	–0.1
1518 Jun 8	5.07	~10	10.5	–0.5?
1530 Mar 29	5.35	7.1 (7 digits and slightly more)	8.1	–1.0?

The root of the second question is the hypothesis formulated by Birkenmajer. We have the series of four observations that strongly suggest that Copernicus used in his eclipse measurements a pinhole camera. We may safely assume that Rheticus witnessed two of four Copernicus eclipse observations. We also know that Rheticus, during his sojourn with Copernicus, twice returned to Wittenberg and to his colleague Erasmus Reinhold — at the end of 1540 and in autumn 1541. There is no doubt that Rheticus would have had an opportunity to communicate Copernicus's observational method to Reinhold, since the short description of the method appeared in the second edition of Reinhold's commentary on Peurbach's *Theoricae novae planetarum*, published in the middle of 1542.

Reinhold's note appears to have been very influential. Tycho's career in observational astronomy began with the acknowledgement that the best method for eclipse measurements is the use of a pinhole camera.[36] Tycho learned about this technique from Reiner Gemma Frisius's *De radio astronomico et geometrico liber* (Antwerp and Louvain, 1545), in which Gemma Frisius described his observation of a solar eclipse in 1544 by the method recommended by Reinhold.[37] As we have already seen, the "teaching, presented by Reinhold" was "refined with greater care" by Michael Maestlin. Kepler witnessed eclipse observations conducted by his teacher and was aware of problems Tycho had with reduction of his own measurements made by the pinhole camera. Eventually Kepler built his own pinhole camera and used it in solar eclipse observations. As Stephen Straker claims, it was the need for solving the enigma of Tycho's eclipse observations that led Kepler to a theory of pinhole images and to his foremost treatise in optics, *Ad Vitellionem paralipomena*.[38] Hence, if this article's reconstruction of Copernicus's method of eclipse observations and of the route of its dissemination through Reinhold's work is plausible, then the Warmian canon not only "had taught astronomers how to use a compass to measure the magnitudes of solar eclipses",[39] but also sowed the seeds from which modern optics flourished.

Acknowledgements

I wish to express my gratitude to José Chabás, Richard Kremer, and José Luis Mancha for their valuable suggestions and comments.

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2. Birkenmajer, *op. cit.* (ref. 1), 552.
3. *Ibid.*, 554.
4. *Ibid.*, 555.
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6. Paweł Sobotko, "O zaćmieniach Słońca i Księżyca obserwowanych przez Mikołaja Kopernika", *Kwartalnik historii nauki i techniki*, xxxvi (1991), 153–74.
7. *Three Copernican treatises*, transl. by Edward Rosen (New York, 1971), 125.
8. Nicholas Copernicus, *On the revolutions*, transl. by Edward Rosen (Warsaw and Cracow, 1978), 162.
9. Birkenmajer, *op. cit.* (ref. 1), 296–7.
10. Between 1535 and 1580 the book had at least eight editions. They were published as reprints of the first edition (Wittenberg, 1551; Basel, 1569 and 1573) or the second edition, which appeared in Wittenberg in 1542 (reprinted in Wittenberg, 1553; Paris, 1557; Wittenberg, 1580). Birkenmajer did not state it explicitly, but the method was already described in the edition of 1542.
11. Jesse Kraai, "The newly-found Rheticus lectures", *Beiträge zur Astronomiegeschichte*, i (1998), 32–40.
12. Erasmus Reinhold, *Erasmi Reinholdi Salueldensis Theoricae novae planetarum Georgii Purbachii ... recens editae et auctae novis scholiis ...* (Wittenberg, 1542), f. Z8.
13. The history of this problem has been described in a series of articles: David C. Lindberg, "The theory of pinhole images from Antiquity to the thirteenth century", *Archive for history of exact sciences*, v (1968), 154–76; *idem*, "A reconsideration of Roger Bacon's theory of pinhole images", *Archive for history of exact sciences*, vi (1970), 214–23; *idem*, "The theory of pinhole images in the fourteenth century", *Archive for history of exact sciences*, vi (1970), 299–325; Bernard R. Goldstein, *The astronomy of Levi ben Gerson (1288–1344)* (New York and Berlin, 1985), 48–50, 140–3; José Luis Mancha, "Egidius of Baisiu's theory of pinhole images", *Archive for history of exact sciences*, xl (1989), 1–35; *idem*, "Astronomical use of pinhole images in William of Saint-Cloud's *Almanach planetarum* (1292)", *Archive for history of exact sciences*, xliii (1992), 275–98.
14. Eilhard Wiedeman, "Über die Camera obscura bei Ibn al Haitam", *Sitzungsberichte der Physikalisch-medizinischen Sozietät in Erlangen*, xlvi (1914), 155–69; *The optics of Ibn al-Haytham*, transl. and comment. by A. I. Sabra (London, 1989), ii, pp. xxxiii, xlix–li.
15. See Mancha, "Astronomical use" (ref. 13).
16. *Ibid.*, 282.
17. *Ibid.*
18. Goldstein, *op. cit.* (ref. 13).
19. *Ibid.*, 49–50.
20. *Ibid.*, 142–3.
21. Mancha, "Egidius of Baisiu's theory" (ref. 13), 9–10. Egidius's treatise was presumably written before Levi's work; see *ibid.*, 30–31.
22. Lindberg, "The theory of pinhole images in the fourteenth century" (ref. 13), 314–15; Mancha, "Astronomical use" (ref. 13), 286–8. Henry's work, a commentary on Pecham's *Perspectiva communis*, had been printed in 1500.
23. The solution was formulated independently at the end of the sixteenth century by the Sicilian scholar Francesco Maurolico, but it was published no earlier than in 1611. The conditions under which Kepler provided his solution of the problem are presented in a classical paper by Stephen Straker, "Kepler, Tycho, and the 'Optical part of astronomy': The genesis of Kepler's theory of pinhole images", *Archive for history of exact sciences*, xxiv (1981), 267–93.

24. Straker, *op. cit.* (ref. 23), 269–85.
25. Johannes Kepler, *Optics*, transl. by W. H. Donahue (Santa Fe, 2000), 362–3. This quotation is from chap. 11, problem 7 of *Ad Vitellionem paralipomena*.
26. *The optics of Ibn al-Haytham* (ref. 14), p. xxxiii.
27. S. S. Said and F. R. Stephenson, "Solar and lunar eclipse measurements by medieval Muslim astronomers, II: Observations", *Journal for the history of astronomy*, xxviii (1997), 29–48.
28. *Ibid.*, 37–38, 40. There are two other solar eclipse observations reported by Ibn Yūnus (of 993 and 1004); however in these cases magnitude was not given in linear digits but in digits of area (a fraction of the area of the solar disk). See S. S. Said and F. R. Stephenson, "Solar and lunar eclipse measurements by medieval Muslim astronomers, I: Background", *Journal for the history of astronomy*, xxvii (1996), 259–73, pp. 266–8.
29. Said and Stephenson, "Solar and lunar eclipse measurements" (ref. 27), 35.
30. Grażyna Rosińska, *Fifteenth-century optics: Between medieval and modern science* (*Studia Copernicana*, xxiv; Wrocław, 1986), 181.
31. Mancha, "Egidius of Baisiu's theory" (ref. 13), 32.
32. Ludwik Antoni Birkenmajer, *Stromata Copernicana* (Cracow, 1924), 201–2.
33. Birkenmajer, *Mikołaj Kopernik* (ref. 1), 449–74. Copernicus referred the parameters of his theory to the meridian of Cracow, which he considered to be identical with that of Frauenburg. In Book IV, chap. 7 of *De revolutionibus* he wrote: "For Gynopolis, which is commonly called Frombork, where I generally made my observations, is located at the mouths of the Vistula River and lies on the meridian of Cracow, as I learn from lunar and solar eclipses observed simultaneously in both places." See Copernicus, *On the revolutions* (ref. 8), 191. Unfortunately, details of this collaboration between Frauenburg and Cracow are unknown.
34. *Ibid.*, 459–60, 471, 473.
35. I owe the modern data to Marek Zawilski.
36. Straker, *op. cit.* (ref. 23), 269.
37. *Ibid.*, 269–70. Gemma's work became widely known when it was reissued together with a modified edition of Peter Apian's *Cosmographia* (Antwerp, 1584). Kepler, incidentally, noticed that Gemma's estimation of magnitude (10 digits) was incorrect: the eclipse was greater. Apparently Gemma Frisius also did not know about the error introduced by a finite aperture. See Kepler, *op. cit.* (ref. 25), 308.
38. Straker, *op. cit.* (ref. 23), 293.
39. Kepler, *op. cit.* (ref. 25), 57. Kepler used these words to praise Reinhold, Gemma Frisius, and Maestlin.