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Edward Gresham, Copernican Cosmology, and Planetary Occultations in Pre-Telescopic Astronomy

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Abstract

This article introduces an understudied source in the history of astronomy, the *Astrostereon or the Discourse of the Falling of the Planet* (1603). Written by the English astrologer Edward Gresham, this text presents, among other things, the earliest known set of predicted planetary occultations (for 1603–1604) and the use of these phenomena to defend the Copernican cosmology. We analyse those predictions and then briefly survey all known pre-telescopic observations of reported planetary occulations and the motivations for such observations. These data suggest that for early observers, the greater the difference in apparent brightness between the two occulting bodies, the greater the angular separation could be for an occultation nonetheless to be reported. An appendix seeks to explain this finding by considering several factors known from modern experimental analyses of human visual performance.

Keywords
Planetary occultations, Edward Gresham, *Astrostereon*, Copernican cosmology, pre-telescopic observation, human visual performance

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Introduction

An unpublished treatise by the English astrologer Edward Gresham (1565–1613), entitled *Astrostereon or the Discourse of the Falling of the Planet* (1603), contains the earliest known set of predicted planetary-stellar occultations. Although we have found some earlier observations of planetary occultations and discussions of the physical or cosmological significance of such phenomena, Gresham's prediction of 12 occultations for 1603–1604 marks a new interest in these phenomena. And Gresham's treatise is closely connected with the history of the Copernican theory in England, a history which has been intensely investigated and yet continues to exhibit some intriguing gaps. In a broader sense, the document can be located within European discussions, at the turn of the seventeenth century, concerning the new astronomy and celestial physics. It addresses also the problem of celestial influence in the new worldview and the philosophical foundation of astrology. Yet, aside from a few passing references in modern literature,[1] Gresham's text has not been examined by historians.[2]

We offer our analysis in two parts. First, we shall briefly present Gresham's manuscript, analyse his predicted occultations and explore the reasons for his interest in these phenomena. Then we shall look back at earlier interest in occultations, both in observational records and philosophical discussions about the structure of the cosmos. How did occultations, we shall ask, come to be part of the debate about heliocentric cosmology? We shall also compare earlier observations with planetary and stellar positions computed for the earlier dates by means of modern theory. What were the "actual" angular separations between pairs of objects considered, by earlier observers, as "occultations"? Can these pre-telescopic observers teach us anything about how unaided human eyes resolve relatively bright and faint light sources in close proximity against the nighttime sky? We will devote an appendix to this latter question.

Gresham's occultations

Due to scarce biographical information, Gresham remains an enigmatic figure.[3] We know nothing certain about his family background. In 1584, he probably matriculated at Trinity College, Cambridge and by 1606 earned a Master of Arts. He lived in Stainford, Yorkshire and later in London. In the years 1603–1607, Gresham published astrological almanacs.[4] Following the disclosure of the Gunpowder Plot, there were rumours that he had predicted these events in his 1605 almanac and he became implicated in the plot. Unfortunately, there are no extant copies of this particular almanac so we cannot explore this episode. However, his extant almanacs reveal that while describing seasonal changes Gresham referred to the movement of the Earth around the Sun.[5] Gresham practised also medicine and magic which would draw him into courtly intrigues such as the divorce of Robert Devereux, third Earl of Essex, and his wife Francis Howard and the poisoning of Sir Thomas Overbury. His death in 1613 spared Gresham the consequences of his involvement in the latter affair.

There are five known manuscript copies of Gresham's *Astrostereon*. Only one copy (MS Sloane 3936) is explicitly dated for 1610, but we find no reason to assume that it is Gresham's holograph. Other manuscripts were created between the 1640s and 1700s.[6]

Interestingly, we have discovered that the English astrologer John Gadbury (1627–1704) published successive fragments of the *Astrostereon* in his astrological almanacs for the years 1700, 1701, 1702, 1703 and 1705, appending a note in the first imprint: "Something touching the Planetary Bodies, from the Learned Mr. Edw. Gresham, wrote near an 100 Years since, but never printed."[7] Gadbury printed slightly more than one third of Gresham's treatise, severely editing the text.

Gresham dated the *Astrostereon* to 1 September 1603 but, as mentioned by Gadbury, the text remained unpublished at Gresham's death. In his 1607 almanac, Gresham pointed towards the existence of the *Astrostereon* and its controversial content: "And some (I heare) who (for that I am *paradoxall* in many things, but especially in the frame and *systeme* of the world, differing from all Phylosophers and Diuines in that poynt, as they thinke) absolutely condemne me of *Atheisme* and *Haeresie*." He had introduced *Astrostereon* as "a book I wrote in the hart and heate of the last great Visitation, wherein with a reuerend reconciliation of the Word, with these scrupulous *Paradoxes*, I haue neither done iniury to God nor Nature."[8]

Apparently Gresham had written the *Astrostereon* in response to an ominous prophecy circulating in London. Based on the Book of Revelation, this prophecy associated the outbreak of the plague with the prediction of the fall of a planet upon the Earth. According to Gresham, he and John Dee (1527–1608) had been accused of authoring the prophecy.[9] To defend himself against this charge, Gresham sought to show the absurdity of this prediction from an astronomical point of view.

The first part of *Astrostereon* treats the relative sizes of the planets as potential projectiles colliding into the Earth. Gresham concluded that the Moon is 39 times smaller than the Earth, Mercury is almost as large as the Earth, and the other planets are all considerably larger than the Earth (Venus 28x, Mars 2x, Jupiter 95x and Saturn 91x; all sizes in Earth volume).[10] Given such physical sizes of the planets, it becomes apparent that discussions concerning a possible location where a planet could hit Earth (e.g. land or sea) do not make much sense.

In a key passage Gresham refers to planetary occultations. He begins by liberating planets from the confines of the celestial spheres. He mocks the assumption that planets are built of the same matter as their spheres and rejects the existence of the spheres by arguing that in the models proposed so far the spheres were bound to crush against each other. Consequently, planets must be similar to the Earth "in all respects" and must move freely in space "without heavens or heavens help."[11] Invoking additional arguments that we need not rehearse here, Gresham concludes that planets are spherical, solid and opaque (for the latter Gresham employs what may well be a hapax legomenon, the otherwise unattested term "indiaphanous").[12] For planetary shapes, Gresham simply relies on the sense of sight, registering a round shape and unmottled surface. However, to argue that planets are solid and not transparent, he turns to more complex empirical data.

First, he asserts that the phenomena of solar eclipses prove that the Moon is not transparent; likewise the transits of Venus and Mercury across the Sun reveal those planets to be opaque.[13] Then, he puts forward a novel argument, *viz.*, the occultations or "eclipsations" of stars by planets prove that the latter are opaque. Gresham begins by giving an account of his own observation, on 26 October 1601, of the occultation of a star in Virgo by Venus. Then he predicts 12 similar events, between 28 September 1603 and 26

Table 1. Gresham's predicted planetary occultations and our computation of their separations according to the Copernican Prutenic Tables.

No.	Date	Planet	Star (mag)	Description	Separation in arcmins		
					Δ angle	Δ λ	Δ β
1	29-Sep-1603[a]	Venus	η Vir[b] (3)	"intercept"	8	6	–5
2	17-Oct-1603	Venus	82 Vir (4)	"near eclipse"	18	–1	18
3	29-Nov-1603	Mars	η Vir (3)	"cover"	26	–23	–12
4	26-Dec-1603	Mars	θ Vir (3)	"shroud"	31	–30	–9
5	22-Jan-1604	Jupiter	51 Oph[c] (5)	"eclipse"	12	–3	–12[d]
6	24-Mar-1604	Saturn	ξ Oph (3)	"eclipse"	36	–35	–7
7	14-Apr-1604	Saturn	ξ Oph[c] (3)	"eclipse"	15	7	–13
8	17-Jul-1604	Mars	λ Vir (4)	"shroud"	62	–17	60[e]
9	31-Jul-1604	Mars	α Lib (2)	"eclipse"	80	–6	80[e]
10	17-Sep-1604	Jupiter	51 Oph (5)	"eclipse"	16	–16	3[d]
11	15-Nov-1604	Saturn	θ Oph[c] (>4)	"eclipse"	23	–22	–8[f]
12	26-Dec-1604	Venus	θ Vir[g] (3)	"shroud"	23	–1	23

[a] Gresham specified this date as 28 September "at 4 a clocke in the morninge, or before." We assume he mistakenly took this astronomical date from an ephemerides, for the close separation occurred on the 29th day of this month.

[b] Gresham refers to "a fixed star of the third magnitude, which is in the latter partes of Virgo": for No. 3, he describes, presumably, a different star, "first of the 4 in the left winge of the Virgin." Yet, we best match his predictions by assigning η Vir to both.

[c] To match this prediction, we read "left" for "right" in Gresham's description.

[d] Apparently Gresham used for 51 Oph the positive latitude (0;45) from the Prutenic Tables (1551), Schöner (1561) or Origanus (1599) and not the negative latitude (–0;45) from *De revolutionibus*.

[e] We have not found a sixteenth-century star catalogue that lists the latitude of λ Vir as –0;30 or –α Lib as –0;40; perhaps Gresham misread his source? Making those two stellar latitudes southern would match, to the arcminute, the Prutenic predicted planetary latitudes for the dates in question!

[f] Apparently Gresham used for θ Oph the positive latitude (1;30) from the Prutenic Tables (1551), Schöner (1561) or Origanus (1599) and not the negative latitude (–1;30) from *De revolutionibus*.

[g] For this event, Gresham mentions "one of the gems of the Virgins Kirtle." According to the Prutenic Tables, Venus on 26 December 1604 was at the sidereal longitude of 211°, well beyond the final star in Virgo (μ Vir at 186°). On 8 November 1604, however, Venus passed very close to θ Vir. By assuming that Gresham's star designation is correct and that he confused the date we find the separation here specified.

December 1604, involving Venus, Mars, Jupiter and Saturn (see Table 1; the relevant text of *Astrostereon* is edited in Appendix 2.)[14]

Columns 2, 3 and 5 in Table 1 report Gresham's descriptions of the occultations. Column 4 lists our identification of Gresham's often vague descriptions of the stars that are based on the language of the *Almagest*'s star catalogue, essentially reiterated in various sixteenth-century printed versions of Copernicus's star catalogue. We follow Toomer and Graßhoff in linking Ptolemy's descriptions to modern star names. Columns 6, 7 and 8 give our computation of the angular separations between the stars and planets, taking positions of the former from the star catalogue of the 1551 Prutenic Tables (identical in the 1585 edition) and the latter as we compute them using the same source.[15] For Nos. 1 and 5 Gresham designates the time of occultation to less than a day ("morning"). In the other cases, he lists only the date; we have chosen times that yield the closest approach of the planet to the Prutenic coordinates of the star for the day in question.

Gresham does not indicate how he identified the planetary occultations listed in Table 1. He does refer, however, to two printed ephemerides, David Origanus's *Ephemerides novae* (Frankfurt a.O., 1599), based on the Copernican Prutenic Tables, and Martin Everaert's *Ephemerides novae* (Leiden, 1597), based on the author's "Belgian Tables," a work not extant. Tropical positions for the eight stars selected by Gresham do appear in Origanus's work (but not in Everaert's); tropical values for those stars also appear in a posthumous edition of Johann Schöner's *Opera* (1561) and sidereal values in the Prutenic Tables (1551, 1585). These three catalogues (all based on the Prutenic version of Copernicus's star catalogue) give identical positions for the eight stars, once precession is removed. We think it highly likely that Gresham took his stellar positions from one of these sources.

The format of Origanus's star catalogue makes us suspect that Gresham used this source. The Ptolemaic tradition of star catalogues (followed by Copernicus) lists stars by constellation. Origanus, however, separated the stars into three groups, those with latitudes greater than 8°, with latitudes less than –8°, and with latitudes between those values.[16] For each group, he listed the stars in order of increasing longitude, keeping unchanged the *Almagest's* textual descriptions and quantitative data. It would thus be easy to skim Origanus's list, looking for stars that match given planetary longitudes.

Using the Prutenic Tables, we have computed planetary positions (sidereal longitudes) for the dates in Table 1. Gresham could have worked directly with these tables or he could have copied tropical longitudes for the planets and stars from Origanus's ephemerides. We assume that Gresham denoted civil days (except for No. 1), i.e. started counting the hours from midnight. All sixteenth-century ephemerides, including Origanus's, start counting hours for astronomical time at noon. In any case, the phenomena in Table 1 are out by days if one attempts to compute planetary positions with the medieval Alfonsine Tables. Gresham obviously used Copernican positions.

If we assume that Gresham erroneously recorded positive latitudes for the stars in Nos. 8 and 9, then the average absolute values of the predicted separations would be about 13 arcminutes in longitude and 8 arcminutes in latitude (and 20 arcminutes in angle). Each of the predicted occultations would have had a separation, for at least one coordinate, of no more than 12 arcminutes. The closest predicted passage would have been No. 9, where we compute a Copernican separation of 6 arcminutes in longitude and 0 arcminutes in latitude. Gresham used three different terms (see Table 1, Column 5) to describe the separations; they do not appear to correlate with the degree of predicted separation of the bodies.

If Gresham did indeed prepare a list somewhat like our Table 1 as he drafted his *Astrostereon*, did he think that separations reaching up to 30 arcminutes would still yield, to the naked eye, examples of the considerably brighter planet "shrouding" or "eclipsing" the fainter star? We are unaware of any studies of how the unaided human eye distinguishes close separations of bright planetary discs and dim point-sources of starlight on the dark nighttime sky.[17] Interestingly, before describing the 12 predicted occultations, Gresham in the *Astrostereon* reported his own observation of an occultation, on 26 October 1601, of a star in Virgo by Venus.[18] The third-magnitude star, η Vir, Gresham described as "cleane couered and eclipsed." Gresham did not name the time of his

Table 2. Modern positions computed for Gresham's dates and our times.

No.	UT Hrs	Stellar errors		Separation in arcmins		
		in λ	in β	Δ angle	Δ λ	Δ β
1	5	19	–13	17	16	–7
2	6	16	–14	33	–25	23
3	1	19	–13	39	–20	–33
4	7	–15	–6	27	6	–27
5	6	–39	83	80	35	–72
6	18	–14	10	39	32	23
7	19	–14	10	77	74	21
8	19	2	–1	101	–6	101
9	24	–7	17	103	–2	103
10	18	–39	83	55	26	–49
11	17	–5	197	183	7	–183
12[a]	7	–15	–6	36	3	36

[a] For this event, we find the closest separation occurred on 9 November 1604, one day after the closest separation predicted by the Prutenic Tables.

observation, but Venus on that date was a morning star. If we assume he saw the event at 5:30 a.m. in London (Venus was near maximal elongation), our modern computations for that time indicate a separation 25 arcminutes (the closest approach, of 5 arcminutes, occurred at 9 p.m. on 25 October, when Venus would not yet have been above London's horizon). This suggests that for Gresham's eyes and sky, the separation of a bright planet and faint star by nearly half a degree appeared as an occultation! Before declaring his "observation" fraudulent, however, we shall, in the second part of this paper, compare his observational report against others made with unaided eyes, i.e., before the age of the telescope.

We must also ask what Gresham might have seen had he looked at the sky on the 1603–1604 dates listed in the *Astrostereon*. Table 2 presents the positions, computed from modern theory (JPL's DE431 planetary ephemerides), on Gresham's dates for night times that we have selected for when the occulting bodies would have been above London's horizon and at closest separation. Only in two cases are the modern separations less than 0;30°, i.e., within the width of the full moon. Would he have called these phenomena occultations? Or would he have challenged the precision of the received stellar positions or the Prutenic planetary predictions? Indeed, at several points in the *Astrostereon*, Gresham did raise doubts about planetary predictions:

> What scrupulositie, then is requisite in this case, all men maie well gather and what good use maie be made of it amongst a thousand other, the better certaintie of our yerely prognostications would quicklie manifest, But in regard it requireth better *hypotheses* and more rationall *Theoricks* then are yet extant (unles a man should minse minutes in his muse with *Origanus* and miss whole degrees in the heavens as he that conferreth the great Luggage of his *Ephemerides* with the true places of the *Plannetts* shall quickly discover) …[1]

Or concerning the famous Great Conjunction of Jupiter and Saturn in 1603, he wrote,

> But of the particuler signification of that coniunction, more shalbe said in a Treatise for that purpose[20] (if I be not prevented, or other occasions lett not) which I deferre untill I haue gotte the true tyme of the same by observation, Least with *Origanus* (curiously buildinge upon an unknowne ffoundation) I loose my laboure and the worlde the proffitte, who as in nothinge he agreeth with the heavens *Phenomenes*, so in this Accident dissenting from *Everart* no lesse then 4 daies in the tyme and one whole degree very nere in place, shall then give notable argument of his owne vanitie, and the others veritie.[21]

However, when reporting his own observation of the 1601 occultation, when "the calculation" revealed a difference in latitude of 0;30° that he did not observe, Gresham wondered whether Venus was closer to the Earth with a greater parallax than expected; he challenged neither the received position of the star nor the Prutenic predicted planetary position.[22]

We must remember, however, that Gresham's primary interest in occultations was not to test the predictions of mathematical (positional) astronomy. His goal, as noted above, was to defend the anti-Aristotelian claim that planets are comprised of the same elemental matter as Earth. In his concluding remarks about the nature of the planets, he wrote,

> Now for this lighte (I hope) I neede not saie more then that which hath ben expressed or implicatiuely deliuered in this former speeche, for seeinge that it is concluded that they are solid grosse impure and indiaphanouse bodies, theare is none so madd will attribute any natiue lighte or luminositye to theire bodilye compaction, unles a man can make a flameinge lampe of this Earthlie masse, which is not possible.[23]

For the Copernican Gresham, the Earth is a planet. Since the Earth obviously is opaque, so too are the other planets. Occultations of stars by planets further confirm this claim.

Occultations before Gresham

Although Gresham is the earliest author we know to predict planetary-stellar occultations, such phenomena had attracted some attention from earlier astronomers and philosophers. In the second part of this paper, we shall briefly survey this material, assess how pre-telescopic observers defined occultations, and consider their motivations for attending to these phenomena.

A long set of observations of occultations, preserved in Chinese dynastic histories, sheds light on the problem of how to classify certain phenomena as occultations. Hilton *et al.* examined 173 Chinese historical records of occultations and small-separation conjunctions of planets with stars, other planets, and extended objects.[24] The observations were made by imperial astronomers in various Chinese capitals. The records contain 66 events characterized as occultations (described with terms such as "conceal, "eclipse," "enter," or "not visible"), dating from 12 February 146 BCE to 3 February 1761 CE. Hilton *et al.* compared these observations with positions derived from modern ephemerides and calculated the "actual" angular separations of the pairs of bodies for the dates in question.[25]

Table 3. Events extracted from the Chinese dynastic histories that were characterized as occultations and that, by modern analysis, occurred during the night. From Hilton *et al.*, 1988.

No.	Julian Day[a]	Planet	Star (mag)	Separation in arcminutes		
				Δ angle	Δ R.A.	Δ Dec.
1	1907312	Jupiter	η Vir (4)	5	–2	5
2	1908173	Jupiter	β Sco (2)	1	0	1
3	1916266	Mars	τ Sgr (3)	4	–1	4
4	1930450	Mars	η Cnc (5)	32	5	32
5	1932759	Mars	δ Sco (3)	1	0	–1
6	1959274	Jupiter	σ Leo (4)	9	–3	–9
7	2003520	Jupiter	β Sco (2)	2	–1	–2
8	2003730	Venus	β Sco (2)	16	5	15
9	2023999	Mars	β Vir (4)	8	3	7
10	2026431	Venus	ξ Sgr (4)	28	–2	–28
11	2080729	Venus	ρ Leo (4)	5	1	5
12	2091141	Mars	ε Gem (3)	5	0	–5
13	2098259	Venus	ρ Leo (4)	18	6	17
14	2098861	Jupiter	β Sco (2)	5	–1	5
15	2111068	Venus	β Vir (4)	3	1	3
16	2121964	Mars	μ Cnc (5)	25	–3	–25
17	2122104	Mars	γ Vir (3)	4	1	4
18	2187488	Mars	ω Sco (4)	19	5	18
19	2189780	Jupiter	β Sco (2)	2	1	2
20	2197870	Jupiter	η Vir (4)	2	–1	–2
		Planet	**Planet**			
21	1858040	Venus	Mars	1	–1	1
22	1997787[b]	Venus	Jupiter	71	–14	–70
23	2096379	Mars	Saturn	4	–1	3
24	2148655	Mars	Jupiter	0	0	0
25	2307987	Mars	Jupiter	1	0	–1

[a] Recorded date converted to a Julian Day Number.

[b] We think this Julian day number (23 Aug 757 CE) is in error. On that date, the planets were separated by more than 15°. On Julian day 1997804 (10 Sept 757 CE) at UT 21;00, the planets were separated by –15 arcmins in R.A., –70 arcms in Dec, and 71 arcmins in angle.

Drawing on their analyses, we note that of the 66 records of occultations, 20 star-planet events occurred during the night, i.e. could have been observed at the Chinese locations. As can be seen in Table 3, these 20 occultations range in actual separation from 1 to 32 arcminutes; 8 had separations less than 5 arcminutes, 6 between 5 and 15 arcminutes, and another six between 16 and 32 arcminutes. We note an asymmetry between the separations in right ascension and declination, with the latter, on average, more than 4 times greater than the former. Apparently, the Chinese astronomers defined "concealment" more in terms of identical right ascensions (i.e. the coordinate changing with greater speed) than identical declinations.[26] Gresham's predicted occultations, interestingly, do not reveal such asymmetry. We also note that the Chinese recorded closer separations (of the 20 phenomena in Table 3, the average separation is only 10 arcminutes) than Gresham predicted. However, Gresham selected his phenomena from a period spanning only 2 years. The 20 Chinese occultations occurred between CE 509 and 1305, a period over which they undoubtedly observed many more occultations (at greater separations) than those recorded in the dynastic histories.

On the other hand, the fact that Chinese observers considered separations of up to 32 arcminutes to be occultations seems to confirm Gresham's understanding of the phenomena; all but one of his events show a predicted separation of less than 32 arcminutes (assuming that he erroneously reversed the signs of latitude in Nos. 8 and 9 in Table 1). Did the eyes of these pre-telescopic observers stop seeing faint stars as bright planets approached to within half a degree? We note that the 13 occulted stars appearing in the 20 Chinese records have an average magnitude of 3.4 (modern). The seven stars in Gresham's list have an identical average magnitude (Ptolemy)!

The Chinese list also includes five planet–planet occultations (Table 3), four of which had somewhat closer separations than those found in their planet–star occultations. We might wonder whether equally and unequally bright bodies, in close proximity, are seen differently by human eyes (see Appendix 1).

In contrast to the Chinese observers, ancient astronomers of the Mediterranean region apparently did not record systematic observation of occultations. The occasional discussions of such phenomena that we do find were motivated by concerns different from what Hilton *et al.* called the "astrological-political nature" of celestial events in the Chinese dynasties.[27] Aristotle's *Meteorologica* (I 343b) mentions briefly that occultations were observed in Egypt and then describes the occultation of a star in Gemini by Jupiter:

> … the Egyptians say that there are conjunctions both of planet with planet and of planets and fixed stars … we ourselves have observed the planet Jupiter in conjunction with one of the stars in the Twins and hiding it completely, but no comet resulted.[28]

It is impossible to determine when Aristotle observed this conjunction and which of the stars vanished in the light of Jupiter. A probable date is 5 December 337 BCE, when Jupiter was separated from 1 Gem by a distance of 5 arcminutes.[29] Aristotle referred to this observation of the occultation while describing a theory ascribed to Anaxagoras and Democritus, *viz.*, that comets are born in conjunctions. A more extensive description of this cometary theory appears in the commentary on the *Meteorologica* written by Alexander of Aphrodisias (2nd/3rd cent. CE):

> As regards comets, Anaxagoras and Democritus claim that the stars considered to be comets are in fact "an apparent meeting of wandering stars," these in turn being the stars of Kronos, Zeus, Aphrodite, Ares and Hermes. Hence when these stars are in close proximity, an illusion arises as if they merged and became one star called a comet. "An apparent meeting" refers to the illusion when many objects approximating each other [coming together] appear as if they were one object.[30]

In these contexts, occultations are related to the etiology of comets.

What about Aristotle's claim that Egyptians observed occultations? In *De caelo* (II 292a), Aristotle describes an observation that he had made of a lunar occultation of Mars[31] and adds that observations of lunar occultations of other stars had been made by Egyptians and Babylonians. Simplicius (6th century A.D.) in his commentary on this fragment of *De caelo* added,

> … the Egyptians and Babylonians have observed the same thing occurring with the other [wandering] stars as well (that is, with those that are higher), so that many of their observations of each of the [wandering] stars have been handed down.[32]

Both Aristotle and Simplicius (as did Diodorus Siculus and Pliny the Elder) assume that Egyptian and Babylonian sources refer to planetary occultations. Extant and deciphered Egyptian sources known today do not reference such phenomena. Babylonian sources, on the other hand, mention observed occultations of stars and planets by the Moon, passages of planets near the so-called Normal Stars and planetary conjunctions.[33]

Ancient Greeks also mentioned occultations in their discussions of the order of heavenly spheres. Aristotle used his observation of the Moon's occultation of Mars to prove that the former is the nearest celestial body to Earth. One can interpret in a similar way his reference to the observations of Egyptians and Babylonians if we consider only occultations of the planets by the Moon.[34] In the second century CE, Theon of Smyrna also linked planetary order to the phenomena of occultations in his elementary handbook for philosophy students, *Aspects of Mathematics Useful for the Reading of Plato*.[35] The discussion of occultations draws on the geometry of vision and the relative distances of the celestial spheres:

> Since we naturally see in a straight line, with the sphere of stars being the highest and the planetary spheres placed below … it is clear that the Moon, being closest to the Earth, can pass in front of all the other stars that are above it. In effect, it hides for us the planets and stars when placed in straight line between our sight and these stars, and it cannot be hidden by any of them. Mercury and Venus hide the stars which are above them, when they are similarly placed in a straight line between them and us; they even appear to occult each other, when one of the two is higher than the other, due to their sizes and the obliquity and position of their circles. These occultations are not easy to observe, however, because these planets revolve around the Sun, and Mercury, a small star close to the Sun and brightly illuminated by it, is rarely visible.[36] Mars sometimes eclipses the two planets above it, and Jupiter can eclipse Saturn. Each planet also eclipses the stars which it passes in its course (III, 37).[37]

Theon apparently did not consider whether the inner planets could also occult a superior planet.

Three hundred years later, Proclus, who presumably knew Theon's treatise, also referred to occultations while discussing the order of planets. His *Outline of Astronomical Theories* does not offer detailed information about such phenomena and mentions only three planets; Venus was observed to run beneath Mars, just as Mercury was observed running beneath Venus.[38] In his *Commentary on Plato's* Timaeus, Proclus linked the phenomena of occultations to his rumination on the nature of heavenly bodies. Arguing that heavenly matter is composed in a specific way of all four elements (i.e. earth, water, air and fire, with the latter dominating), Proclus evokes, in a fairly general way, the argument about the Moon and other stars obscuring other stars.[39] If celestial bodies were transparent, they would not occult each other.

Ptolemy, on the other hand, did not bring together his discussions of occultations and planetary order. There are no references to planetary occultations in the *Planetary Hypotheses*, where Ptolemy orders the planets from Moon, Mercury, Venus, Sun, Mars, Jupiter, to Saturn.[40] Ptolemy mentions only that the passage of Mercury and Venus across the solar disc has not yet been observed, but he does not offer this fact as an argument against positioning the spheres of these planets below the Sun's sphere.

In the *Almagest*, Ptolemy mentions three phenomena reported by earlier astronomers as occultations, viz., of η Vir by Venus on 12 October 272 BCE (*katalambanein*=to overtake), of β Sco by Mars on 18 January 272 B.C. (*epiprostithenai*=to add in, to cover, to impose on) and of δ Cnc by Jupiter on 4 September 241 B.C. (*epikaluptein*=to cover or shroud).[41] Drawing on modern recomputation, Toomer and Jones assert that an occulation could not have occurred on 12 October 272 BCE. Our recomputation confirms their computed positions; for η Vir – Venus, the modern separation was 13 arcminutes. However, based on what we have learned from the Chinese reports and Gresham's predictions, we might conclude that Ptolemy's predecessors thought they had witnessed an occultation. For the second event, modern computations place the occultation two days earlier; for the stated time of that day (UT 3:00), we compute a separation of 12 arcminutes, again well within the tolerances for naked-eye observation. Toomer and Jones also claim that the third event "was not an occultation," given the computed separation of 17 arcminutes. Yet, the Chinese and Gresham also would have called this an occultation, as did Ptolemy's sources. In any case, in the *Almagest*, these occultations provided quantitative, empirical information on planetary positions at given dates, material Ptolemy used to set the mean motions for his planetary theories.[42]

Ptolemy does not tell us why his predecessors recorded the occultation observations. The first record (Venus) he attributes to Timocharis, a comparatively well-known astronomer, presumably working at Alexandria. (In the *Almagest* Ptolemy reports also on 4 lunar occultations of stars and 12 stellar declinations that were observed by Timocharis.) The Mars and Jupiter occultations are not attributed by Ptolemy and were made by unknown Hellenistic astronomer(s) using the Dionysian calendar.[43] It is possible that these early occultation observations were part of a larger observational project of tracking the motions of the planets relative to stars near the ecliptic, similar to Babylonian Normal Stars, a project not necessarily motivated by theoretical concerns arising from mathematical astronomy.[44] However, Jones has argued that Ptolemy's source for the early Jupiter occultation may have been the author of P. Oxy. LXI 4133, a papyrus fragment which reports an observation of Jupiter in A.D. 104/105, a date selected to explore the anomalistic period of that planet's orbit (i.e. 344 years after BCE 241). Jones' argument seems quite plausible to us. Presumably the early Hellenistic occultation observations were motivated by the need to set parameters in mathematical astronomy and not simply to explore the phenomenon as an aspect of natural philosophy.

Interestingly, however, the only extant observational report from late antiquity lists occultations or near conjunctions from the years CE 475 and 510. Attributed to the fifth-century Alexandrian Neoplatinist Heliodorus, the list includes three lunar occultations

Table 4. Heliodorus's observations of close conjunctions, A.D. 475–510.[46]

No.	Date	Bodies		Description	Separation in arcmins		
					Δ angle	$\Delta\lambda$	$\Delta\beta$
1	1-May-475	Mars	Jupiter	"in contact … nothing between them"	4	–2	–3
2	27-Sep-508	Jupiter	α Leo	"less than 3 fingers to the north and … least distant"	1	1	1
3	13-Jun-509	Mars	Jupiter	"into conjunction … 1 finger ahead and 2 fingers to the south"	14	–7	12
4	21-Aug-510	Venus	Jupiter	"ahead by about 8 fingers … no difference in latitude"	17	–17	–5

(of Venus, Saturn, and Aldebaran) and four close conjunctions. The text, bound ("accidentally," according to Neugebauer) in three of the earliest extant manuscripts of the *Almagest* and copied with Ptolemy's *Canobic Inscription*, has recently been re-edited, translated, and analysed by Jones. Table 4 summarizes Jones' analysis of the close conjunctions. Heliodorus did not employ any of Ptolemy's terms for "occultation." The scale of his separations roughly match those of the Chinese astronomers. Heliodorus compared two of the close conjunctions with predictions he computed from the Handy Tables, the *Almagest*, and "the ephemerides." Yet Jones earlier suggested that "it is difficult to discern in them [Heliodorus's observations] any systematic effort to check the tables' accuracy"[45] and we do not finally know why Heliodorus recorded these events.

Interest in occultations remained very sporadic during the Latin Middle Ages. An interesting example of such observation, apparently free of any philosophical implications, surfaces in a chronicle by the twelfth-century monk Gervase of Canterbury, who recorded that on 12/13 September 1170:

> … on the Ides of September, in the middle of the night, two planets were seen in conjunction to such a degree that it appeared as though they had been one and the same star; but immediately they were separated from each other.[47]

Based on modern calculations, we presume that Gervase of Canterbury described the occultation of Jupiter by Mars (we compute a separation of less than 6 arcseconds!), a phenomenon which is also recorded in the Chinese sources.[48] Interestingly, however, the Latin medieval observer described this phenomenon as a merger of two sources of light rather than the occultation of one source by the other, perhaps related to the fact that this event has the closest computed separation of any occultation event we discuss in this article.

The first systematic Latin astronomical observers, Johannes Regiomontanus (1436–1476) and Bernhard Walther (1430–1504), made planetary observations from the 1460s through Walther's death in 1504. Like Ptolemy, their goal appears to have been mathematical astronomy, observing to test predictions of the Alfonsine Tables.[49] The preserved records of their observational activity reveal no interest in planetary distances or the structure of the cosmos.[50] The more than 600 individual planetary observations they recorded include no phenomena denoted as occultations. In the first decade, before acquiring large angle-measuring instruments, they occasionally used stars to visually estimate planetary positions. For example, on 5 December 1461, Regiomontanus writes that clouds prevented him from seeing a conjunction of Mars and Saturn; on 2 December, the date of the conjunction predicted by the Alphonsine Tables, he had observed a separation of 2° in longitude.[51] On 16 October 1462 in the morning at the "12th hour of the night" he observed Mars separated by "an estimated four diameters of Venus" from the fourth-magnitude star, σ Leo. According to our computation, at that time (UT 5:00) Mars and σ Leo were separated by 22 arcminutes, which implies that Regiomontanus estimated the apparent diameter of Venus to be about 5 arcminutes.[52]

Walther recorded several other close conjunctions. For example, on 19 September 1494 at 5 a.m. he saw Venus "conjuncted" with Regulus, noting that the planet was 10 arcminutes west and 13 arcminutes south of the bright star (our recomputation places the planet 12 arcminutes west and 28 arcminutes south; the actual conjunction occurred around 9:30 a.m., well after sunrise). The Chinese observers and Gresham might well have called this observed phenomenon an occultation; Walther, however, did not. On 8 September 1503 at 4 a.m., Walther observed a "conjunction" in longitude of Jupiter and δ Gem,[53] with a separation in latitude of 2 "digits" or about 7 arcminutes (our recomputation shows a separation in longitude of 5 arcminutes, in latitude of 8 arcminute). Finally, only 2 months before his death, on 28 March 1504 at 7 a.m. Walther described the "closest" (propinquissimus) path of Saturn past 8 Gem (we think the actual star was 12 Gem = δ Gem), separated by "2 or 3 digits" (7–10 arcminutes) in both longitude and latitude (at that time, we find a separation of 7 arcminutes in longitude and 10 arcminutes in latitude). The following night, the planet was "closer" (propinquior) to the star, so that their conjunction (in longitude and latitude) "was to be judged at almost the same instant" (sic que coniunctio iudicanda fuerat eodem instanti fere). We compute the separations at 7 a.m. on 29 March to have been 5 arcminutes in longitude and 10 in latitude, for an angular separation of 11 arcminutes.[54] Never announcing an actual occultation, Walther's criteria for this phenomenon apparently required closer separations than did those of Gresham or the Chinese astronomers.

It would not be until the 1570s, with Michael Maestlin's (1550–1631) interest, that occultations began to attract more systematic attention. Maestlin not only observed occultations in the second half of the sixteenth century but also searched for historical descriptions and interested his student, Johannes Kepler (1571–1630), in these phenomena.

Like Walther, Maestlin was a systematic observer of heavenly phenomena. From the 1570s through the 1620s, he observed most of the lunar and solar eclipses and many lunar occultations.[55] He earned a reputation as a careful observer from the publication of two early treatises, one on the new star of 1572 in Cassiopeia[56] and another on the comet of 1577.[57] The observations included in these books helped establish the position of the nova and comet relative to the stars by means of a thread held at arm's length.[58] Maestlin observed his first planetary occultation in the period between the appearance of the nova and the 1577 comet. On 16 September 1574, he saw Venus occulting Regulus. Maestlin subsequently observed Venus eclipsing Mars on 13 October 1590 and Mars occulting

Jupiter on 19 January 1591. We compute the actual separations to have been smaller than the resolution of the human eye for these three events, i.e., less than 1 arcminute (1574 at 22:30 UT, 1590 at 5:00 UT, 1591 at 5:30 UT).

A broader context for Maestlin's interest in occultations may be provided by some intriguing notes in copies of *De revolutionibus* linked with the figure of Paul Wittich (fl. 1563–1586). This mathematician was based in Wrocław and held at least four copies of *De revolutionibus*, two of the 1543 edition and two of the 1566 edition.[59] The books owned by Wittich carry numerous marginal notes. In both first editions (the Liége and Vatican copies) we find information about two conjunctions: Jupiter–21st star of Pisces, dated 8 November 1572, and Venus – Regulus, dated 16 September 1574. Both notes are recorded at relevant places in Copernicus's star catalogue, i.e., beside Regulus (f. 54r) and at the end of the constellation of Pisces (f. 57v).[60] Palaeographic analysis of the notes appears to confirm Wittich's hand in both cases.[61]

We translate the first note:

> On 8 November 1572 Jupiter occulted [*tegere*] the 21st star in Pisces. And Jupiter, according to computations, was in 21°07' Aries. Thus the longitude of the star amounts to 353°18' from the beginning of Aries.[62]

This longitude of Jupiter (21;07°) was computed according to the Prutenic Tables.[63] The precession for November 1572 given by the Prutenic Tables amounts to 27;49°. Copernicus's star catalogue lists the longitude of 21st star in Pisces as 353;30° relative to the first star in Aries. If we add the Prutenic precession, this places the stellar longitude at 21;19°, which exceeds Jupiter's longitude by 0;12°. Deducting this amount from the star's longitude gives a revised sidereal longitude of 353;18°, matching Wittich's annotation.

Hence, the note appears internally coherent and can be read as an attempt to verify the longitude of 21st star in Pisces on the basis of Copernicus's planetary theory. The description of the observation features the verb *tego* (to hide or bury), which is used in Latin to refer to occultations. Yet, if we identify the 21st star in Pisces (5th magnitude) with π Psc,[64] on 8 November 1572 that star was separated from Jupiter in latitude by almost three and one-half degrees and in longitude by nearly half a degree, hardly an occultation by the criteria emerging in our survey. If, however, we consider the 20th star in Pisces (o Psc, 4th magnitude), the planet and star on said date would be separated by 24 arcminutes in longitude and only 10 arcminutes in latitude. But the longitude for this star does not match the revised value Wittich specified in the marginal note. We speculate that he observed Jupiter near the 20th star in Pisces, but then confused the coordinates for the 20th and 21st stars in Pisces when using Copernicus's star catalogue.

Wittich's note pertaining to the meeting of Venus and Regulus is somewhat shorter:

> On 16 September 1574 at 8 hour Venus occulted [*eclipsare*] Regulus. By the tables Venus was in longitude 23°27' of Leo, in southern latitude 48'.[65]

Here, the identification of the occulted star is unambiguous. If we assume that the observation was recorded, as the 1572 occultation, to check a stellar position, the following computations would be necessary. The sidereal longitude of Regulus in the catalogue of Copernicus is 115;50°. If we increase it by the value of the procession based on the Prutenic Tables, i.e., 27;50°, we arrive at a tropical longitude in September 1574 of 143;40°. This value exceeds Wittich's computed longitude of Venus by 0;13° which would imply that the sidereal longitude of the star is too large by 0;13°. Wittich does not comment on the discrepancy.

Yet, the coordinates of Venus that Wittich cited "ex Tabulis" remain puzzling. According to the Prutenic Tables, Venus was at Leo 23;27° at 3 hours after midnight (Königsberg meridian) on 16 September 1574. By 8 a.m., the Prutentic Venus is at Leo 23;42°. (Maestlin had described the time of his observation as 4 hours after midnight.)[66] Furthermore, according to the Prutenic Tables, Venus was positioned 20 arcminutes above the ecliptic which does not match the southern latitude Wittich states. At that time, however, Jupiter had a Prutenic latitude of −0;45°. Perhaps Wittich confused the latitudes of Jupiter and Venus in his ephemerides?

Whatever the case for Wittich and his annotation, observation of the 1574 occultation of Regulus by Venus obviously inspired Maestlin to look for historical records of similar phenomena. He found Aristotle's description of the occultation of Mars by the Moon and the passing reference to Mercury occulted by Venus and Venus by Mars in Proclus's treatise, as well as references to Mercury visible against the solar disc. This collection of earlier events, along with his own observation of 1574, was presented in the final section of his discussion of eclipses in his *Epitome astronomiae* published in 1582.[67]

In the early 1590s Maestlin witnessed two further planetary occultations. On 13 October 1590, he observed the occultation of Mars by Venus (we compute the separation to have been 0.2 arcminutes at 5:00 UT) and on 19 January 1591, he saw Mars occulting Jupiter (we compute a separation of 0.6 arcminutes at 5:30 UT). These two observations supplemented the list of the examples he collected, both historical and his own. He included this list in his *Disputatio de eclipsibus Solis et Lunae* (1596)[68] and in the fourth edition of *Epitome astronomiae* (1597).[69] In the former text, he linked his two most recent observations to a claim about the order of the planets. After discussing well-known cases of solar eclipses and lunar occultations of stars, Maestlin added,

> In a similar way each lower star on the sky may obscure another higher star which is passing by… It could be clearly seen that in one case Mars, and in another case Venus were lower due to the white colour of Venus and the fiercely red colour of Mars.[70]

Since in a total occultation, it must be the closer body that remains visible, the colours of occulting planets allowed Maestlin to draw conclusions about their relative distances from the Earth.[71] We have not found, in the earlier discussions, any suggestion that observed colours might yield clues about planetary distances.

For our final pre-telescopic example, we turn to Johannes Kepler. In 1590–1591, he was studying in Tübingen and probably had observed the occultations of those years with Maestlin. In a section in his *Optics* (1604) on "the mutual occultations of the other [non-luminary] heavenly bodies," Kepler repeated his teacher's conclusions: for 1590, "… the brilliant colour of Venus again indicat[ed] that Venus was the lower," for 1591, "The fiery ruddy colour of Mars argued that Mars was the lower."[72] Kepler also described the occultation of Regulus by Venus that had occurred on 25 September 1598 and the occultation of Mercury by Venus at the turn of June in 1599. Unlike the previous rather brief reports by Maestlin, these references include fuller descriptions of observational conditions. Kepler had seen Regulus covered by Venus:

> … at Graz on 15/25 Sept. 1598 at hour 3 in the morning, when Venus had barely risen. At the fourth hour, more than one [diameter of] Venus could have fit in between; nevertheless, the line from Venus to Cor [Regulus] fell a little below Jupiter.[73]

Our computations show that Venus was closest to Regulus on 25 September 1598 at half an hour after midnight (Graz time) when the bodies were separated by 2 arcminutes. At 3 a.m. in Graz, the bodies were separated by 7.5 arcminutes, at 4 a.m. by 13 arcminutes. Hence, Kepler's eye on that morning estimated the apparent diameter of Venus, seen close to the horizon, as about 10 arcminutes! The JPL ephemerides computes the apparent physical diameter of the planet at that date to have been 14 arcseconds.

Kepler's report of a very close encounter of Venus and Mercury at the turn of June 1599 is even more detailed:

> … on 21/31 May 1599, Mercury was about one degree beyond Venus, it was nearly the same amount further north … on 29 May or 8 June … looking with greatest care at Venus, I nevertheless saw no Mercury, while I saw the Twins and Capella. I was in fact persuaded that I saw certain rather long and thin rays from the eastern part of Venus; Venus, however, did not change colour.[74]

In fact, the planets came closest to each other in the early evening on 4 June 1599 when the minimum separation was 9 arcminutes. By the evening of 8 June, the planets were separated by more than 2 degrees. It is not clear to us what Kepler saw that evening; Mercury was elongated from the Sun by 23 degrees, Venus by 25 degrees.

In any case, Kepler's *Optics* became the most widely circulated printed source of occultory observations from ancient times to the 1590s.[75] Similar to Maestlin's *Epitome*, Kepler's list appears after a detailed discussion of lunar and solar eclipses.[76] And occultations provided Kepler with the opportunity to speculate on the structure of the cosmos. The opening paragraph recalls Kepler's earlier claim that planets have their own light.[77] This would mean that occultations involving planets cannot be understood in the same way as lunar eclipses. Kepler notes that "the star Mars will seem not to be entirely free of the suspicion that it may run into the earth's shadow." This seems to echo the discussion concerning the parallax of Mars.[78] He hypothesizes a chain of planetary shadows that would create a kind of plenum resulting from the spacing of the planets and physical diameters:

> … since the point of the lunar shadow falls exactly on the earth, it seems fitting that the point of Venus's shadow come to an end at the moon, when nearest the sun, the point of the Mercurial shadow at Venus; likewise, again, the earth's shadow at Mars, Mars's at Jupiter, and Jupiter's at Saturn.[79]

Kepler does not mention that to test this chain empirically the observer would need to visit the surface of each planet! And he does not draw any cosmic conclusions from planet-star occultations.

On the other hand, Kepler offers a variety of arguments to support his claim that planets have their own light. He refers to several earlier authors (Cleomedes, Albategnius, Witelo) and presents conclusions drawn from his own observations of the light and colour of stars and planets.[80] He recalls his 1601 treatise, *On Giving Astrology Sounder Foundations*,[81] wherein he had argued that

> … the five planets do not only make use of light borrowed from the Sun but also add something of their own – which, indeed, there are also other reasons to believe. For, if many of the natural bodies on the Earth have intrinsic light, what is there to prevent other celestial globes besides the Sun having the same? Then, if the planets lacked light of their own, they should show a changing face, as the Moon does. Finally, it is plausible to consider brightness and twinkling as evidence for intrinsic light, and cloudiness and steadiness as evidence for illumination from another source.[82]

In 1601, Kepler's views were congruent with the long-established and multi-faceted discourse on the nature of the light of the planets.[83] Kepler would change his view on this question only after learning of Galileo's telescopic observations. In a 1610, letter to Galileo, Kepler wrote,

> Your second highly welcome observation concerns the sparkling appearance of the fixed stars, in contrast with the circular appearance of the planets. What other conclusions shall we draw from this difference, Galileo, than that the fixed stars generate their light from within, whereas the planets, being opaque, are illuminated from without …[84]

Here, Kepler did not turn to the example of planetary occultations to discuss the nature of the planetary light.

Conclusions

This survey enables us to draw several conclusions about the role of planetary occultations in the history of pre-telescopic astronomy. First, despite the rarity of known observations of planetary occultations in the second half of the 16th century, it was this period that witnessed a heightened interest in such phenomena. Apparently inspired by his own 1574 observation of the occultation of Regulus by Venus, Maestlin sought to systematize records of these phenomena from Antiquity to his own time. In successive editions of his *Epitome astronomiae*, he recalled the enigmatic opinion of Proclus about the mutual occultations of Mercury and Venus, but it was only in *Disputatio de eclipsibus Solis et Lunae* (1596) that Maestlin mentioned the phenomena of 1590 and of 1591 and linked them to the question of planetary order.

Second, we note that many observers reported occultations for bodies that, according to our modern computations, were significantly separated, i.e., by angles of 10 arcminutes or more. Clearly, the experience of occultations, as mediated by the human eye gazing at the nighttime sky, differed from the geometry of straight light rays passing bodies of given physical dimensions and distances. Our survey suggests that the difference in brightness between the occulting bodies was related to the actual separations we computed for phenomena reported as occultations. When two bright bodies were reported as occulted, e.g. two planets or a planet and a first-magnitude star like Regulus, the actual separations were significantly less than when a bright planet and a faint star (magnitudes greater than 3) were reported as occulted. In these latter cases, actual separations of up to half a degree could be reported as occultations.

Third, we note that none of the sources surveyed in this section suggest that the observed planetary occultations were predicted with the help of astronomical tables. Living with the nighttime sky, our scattered observers seem to have recorded the sporadic occultations they noticed, just as they recorded comets or other unusual phenomena when they appeared. It would not be until 1601, at the very end of the pre-telescopic period, that Edward Gresham would systematically study a Copernican ephemerides (or tables) and star catalogue and draft a list of predicted occultations for the next 2 years.

Finally, we have seen that pre-telescopic astronomers turned to occultations for various reasons. For some, occultations provided the occasion to "measure" planetary positions to a precision of arcminutes without use of angle-measuring instruments, provided one knew stellar positions to a given precision. Or as we saw in the case of Wittich, one could use a theoretically predicted position of a planet to confirm the location of a star. For others, the phenomena of occultations could offer evidence for arguments about the relative distances of celestial bodies from the Earth, about the self-illumination of planets, or about their material constitution. For Gresham, occultations supported the idea of planets' "indiaphanouse" nature, a claim that, in turn, he wielded to defend the Copernican heliocentric cosmology. We are unaware of any other example in which the phenomena of occultations entered debates about Copernicanism.

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Notes

1. F.R. Johnson, *Astronomical Thought in Renaissance England: A Study of the English Scientific Writings from 1500 to 1645* (Baltimore: The Johns Hopkins Press, 1937), pp. 250–1, places Gresham among the English followers of Copernicus but refers only to traces of such views in Gresham's astrological almanacs. B. Capp, *Astrology and the Popular Press: English Almanacs 1500–1800* (London: Faber and Faber, 1979), p. 191, concludes that Gresham endorsed the Copernican system "in an unpublished but widely-known tract written in 1603" but did not specify why he considered *Astrostereon* to be widely known. Capp adds that Gresham also declared that the Moon is habitable (p. 198). This latter comment prompted one of us (JW), who was then working on the first critical edition of the Polish translation of Kepler's *Somnium*, to investigate the *Astrostereon* manuscripts. The results of the investigation proved to be far more interesting than the enigmatic references.
2. Currently, JW and Barbara Bienias are preparing a critical edition of *Astrostereon*.
3. B. Capp collected the extant information on Gresham's biography in the *Oxford Dictionary of National Biography*. M.S. Dawson, "Astrology and Human Variation in Early Modern England," *The Historical Journal*, 56(1), 2013, pp. 31–53, notes that the British Library holds a manuscript collection of individual horoscopes, dated April–October 1605, referring to thefts, robbery, marital problems and so on. Dawson suggests that they may have been cast by Gresham since his local London address (Thames Street) is close to those of the clients who came to the astrologer.
4. Copies of Gresham's almanacs for those years, excepting only 1605, are extant.
5. He is most explicit about a moving Earth in his almanac for 1606: "Our orb (as any other) obliquely circling the globouse body of light, is variablie affected with the light and darkenesse, and in uttmost limits with greatest difference." Cf. E. Gresham, *A new Almanacke and Prognostication for the Yere of our Lord God 1606* (London, 1606), f. B7v.
6. These conclusions have been reached with the assistance of Dr. Susan Davies, palaeographer from the University of Aberystwyth, who proved immensely supportive in our early investigations.
7. J. Gadbury, *ΕΦΗΜΕΡΙΣ: Or, a Diary Astrological, Astronomical, Meteorological for the Year of our Lord 1700* (London, 1700) and for the following years. In the year of his death Gadbury did not publish an almanac for 1704, but he prepared for publication the almanac for 1705, as suggested by the relevant title page. Interestingly, Gadbury did not mention the title of Gresham's treatise in any of his editions. It seems that Gadbury found in Gresham's text support for his own proposals on the reform of astrology; for a discussion of this reform cf. Patrick Curry's entry for Gadbury in the *Oxford Dictionary of National Biography*.
8. Gresham, *A new Almanacke and Prognostication for the Yere of our Lord God 1607* (London, 1606), f. B2v.
9. Gresham, *Astrostereon*, MS Sloane 3936, f. 4r–v. So far we have not identified any source other than *Astrostereon* which refers to such a prophecy. A brief comment on this affair can

be found in G. Parry, *The Arch-Conjuror of England: John Dee* (New Haven: Yale University Press, 2013), p. 265.

10. Gresham, *Astrostereon*, MS Sloane 3936, f. 17r. Since this problem is linked closely with Gresham's discussion of the distances and sizes of the planets and raises another range of astronomical issues, a separate article shall be devoted to this aspect of his treatise.
11. Gresham, *Astrostereon*, MS Sloane 3936, f. 6r. There is an extensive literature which attempts to reconstruct in detail the process by which the celestial spheres were eliminated in Western astronomy. Cf., e.g., W.H. Donahue, *The Dissolution of the Celestial Spheres, 1595–1650* (New York: Arno Press, 1981), W.G.L. Randles, *The Unmaking of the Medieval Christian Cosmos, 1500–1760* (Brookfield: Ashgate, 1999) and M. Lerner, *Le monde des sphères*, 2nd ed. (Paris: Les Belles Lettres, 2008).
12. The form 'undiaphanous' is first recorded in 1666 <http://historicalthesaurus.arts.gla.ac.uk/category-selection/?qsearch=undiaphanous>
13. In the fragment of the *Astrostereon* dedicated to planetary occultations, Gresham refers also to the prediction of Venus's transit across the solar disc, a problem closely linked to Gresham's discussion of cosmic dimensions (see n. 10).
14. While publishing the fragments of *Astrostereon*, Gadbury retained the description of the observation of the occultation in 1601 but removed the entire passage with the predictions of the occultations.
15. We compute Prutenic positions using a spreadsheet, prepared by Lars Gislén and one of us (RK), that replicates each step of a manual computation, including linear interpolation, from the Prutenic Tables.
16. David Origanus, *Ephemerides novae annorum XXXVI* (Frankfurt a.O., 1599), i:74–85. Origanus also abridged Ptolemy's catalog, including only 404 stars.
17. J.L. Hilton, P.K. Seidelmann and C. Liu, "Analysis of Ancient Chinese Records of Occultations between Planets and Stars," *Astronomical Journal*, 94, 1988, pp. 1482–93, at 1483, suggest that poor seeing or irradiation within an observer's eye "may have caused an observer to record an occultation when the objects were actually several minutes apart." Gresham's "occultations" are separated by significantly greater distances. J. Meeus, "Mutual Occultations of Planets," *Journal of the British Astronomical Association*, 80(4), 1970, pp. 282–7 considers planet–planet occultations, but calculates apparent sizes only by geometry, disregarding the optics of human eyes. See Appendix 1.
18. Significantly, only in one of the extant manuscripts, MS Sloane 3279, has the year been corrected from 1602 to 1601. In the remaining five manuscripts, the date is 1602. Gadbury printed the date as 1601.
19. Gresham, *Astrostereon*, MS Sloane 3936, f. 39v.
20. We do not know whether Gresham compiled this treatise, but if he did, it is not extant. Interestingly, Gadbury in his *Collectio Geniturarum* (London, 1662), pp. 179–80, printed, together with Gresham's nativity horoscope, this accusation:

> This is the Nativity of Mr Edward Gresham a most ingenious Person & good Artist, as the severall Almanacks he wrote sufficiently testify; as also an ingenious & learned Discourse upon a Conjunction of <Saturn> and <Jupiter> which by him was never published; but since his Death printed by another under the title of *England's Propheticall Merlin*: and that Book-pirate, which published the same, hath never so much as once named Mr Gresham therein, but after an usurping of his Pains, hath endeavoured to obliviate his Name for ever. Of which Iniustice and Plagiarsim, unless I would consent to and winck at, I could not but give the World notice; that the ashes of this Worthy (though much abused) Person, might not rise up in Judgment against me, for my silence therein.

Gadbury had in mind William Lilly's pamphlet *Englands Phrophetical l Merlin, Fortelling to all Nations of Europe until 1663 the Actions depending upon the influence of the Conjunction of Saturn and Jupiter, 1642/3* (London, 1644). To resolve this question, Lilly turned to Elias Ashmole for help and he found proof that Gresham could not have written what Lilly published; the pamphlet incorporated the comet of 1618, which appeared five years after Gresham's death. Cf. C. Blackledge, *The Man Who Saw the Future: A Biography of William Lilly* (London: Watkins Publishing, 2015), pp. 150–1.

21. Gresham, *Astrostereon*, MS Sloane 3936, f. 43v.
22. Gresham, *Astrostereon*, MS Sloane 3936, f. 8v. For a London time of 5:30 (ca. 7 a.m. in Königsberg), we find a separation of 19 arcminutes in longitude between the Prutenic longitude for Venus and the star's position in the Prutenic Tables and a separation of 26 arcminutes in latitude. Interestingly, Gresham did not mention the discrepancy in longitude.
23. Gresham, *Astrostereon*, MS Sloane 3936, ff. 14v–15r.
24. Hilton *et al.*, "Analysis of Ancient Chinese Records," pp. 1482–93.
25. *Ibid.*, Table 1, pp. 1485–6.
26. It seems that in Babylonian astronomy (5th century B.C. – 1st century B.C.), observations of the transits of planets near Normal Stars were made in a similar way. Cf. G. Graßhoff, "Normal Star Observations in Late Babylonian Astronomical Diaries," in N.M. Swerdlow (ed.), *Ancient Astronomy and Celestial Divination* (Cambridge and London: The MIT Press, 1999), pp. 97–147; A. Jones, "A Study of Babylonian Observations of Planets Near Normal Stars," *Archive for History of Exact Sciences*, 58(6), 2004, pp. 475–536.
27. Hilton *et al.*, "Analysis of Ancient Chinese Records," p. 1482.
28. Aristotle, *Meteorologica*, trans. by H.D.P. Lee (Cambridge: Harvard University Press, 1952), p. 47.
29. S.M. Cohen and P. Burke, "New Evidence for the Dating of Aristotle *Meteorologica* 1–3," *Classical Philology*, 85(2), 1990, pp. 126–9.
30. H. Diels and W. Kranz, *Die Fragmente der Vorsokratiker* (Berlin: Weidmann, 1952), 55 A 92. The opinion about comets being optical phenomena resulting from the conjunction of planets was cited also by Seneca (1st century A.D.) in his *Naturales questiones*, 7.12.1 and 7.19.1. On the first occasion Seneca mentions only "some of the ancients;" the second ascribes this theory to Zeno of Citium (335–263 B.C.), founder of Stoicism. In the first fragment Seneca lists several arguments against this theory. One of them refers to the order of the spheres:

    Saturn is sometimes above Jupiter, and Mars looks down vertically on Venus or Mercury, but a comet is not created by their conjunction, when one passes below the other. Otherwise they would be produced every year, for every year some stars are together in the same sign of the zodiac (7.12.3).

    See Seneca, *Natural Questions*, trans. by H.M. Hine (Chicago: University of Chicago Press, 2010), p. 122. Seneca's description implies that the concept of conjunction was used rather broadly. Aristotle, Seneca and Aëtius (1st century A.D.) were probably the primary sources for sixteenth-century authors such as Joachim Camerarius, Antoine Mizauld and Christoph Rothmann. Cf. M.A. Granada, A. Mosley and N. Jardine, *Christoph Rothmann's Discourse on the Comet of 1585: An Edition and Translation with Accompanying Essays* (Leiden: Brill, 2014), pp. 146–7, n. 145. See also S. Schechner Genuth, *Comets, Popular Culture, and the Birth of Modern Cosmology* (Princeton: Princeton University Press, 1997), Table 1, p. 18.

31. For attempts to date this observation, see F.R. Stephenson, “A Lunar Occultation of Mars Observed by Aristotle,” *Journal for the History of Astronomy*, 31, 2000, pp. 342–4; D. Savoie,“Problèmes de datation d’une occultation observée par Aristotle,” *Revue d’histoire des sciences et de leurs applications*, 56, 2003, pp. 493–504; A.C. Bowen, *Simplicius on the Planets and Their Motions* (Leiden: Brill, 2013), pp. 186–7, 224–5.
32. Bowen, *Simplicius on the Planets*, p. 121.
33. *Ibid.*, pp. 225–6.
34. Cf. *ibid*., p. 226.
35. Cf. O. Neugebauer, *A History of Ancient Mathematical Astronomy* (Berlin: Springer, 1975), pp. 949–50.
36. For an eighteenth-century telescopic observation of Venus occulting Mercury, see J. Ashbrooke, “John Bevis and an Occultation of Mercury by Venus,” *Sky and Telescope*, 16(2), 1956, p. 68.
37. Theon of Smyrna, *Exposition des connaissances mathématiques utiles pour la lecture de Platon*, trans. by J. Dupuis (Paris: Hachette, 1892), pp. 311–13.
38. *Procli Diadochi Hypotyposis astronomicarum positionum*, K. Manitius (ed.), (Leipzig: Teubner, 1909), pp. 224–5 (*Hypotyposes* 7.22).
39. *Procli Diadochi in Platonis Timaeum commentaria*, E. Diehl (ed.), (Leipzig: Teubner, 1904), ii:44, 12–13; Proclus, *Commentary on Plato’s* Timaeus, Vol. III, Book III, Part 1, *Proclus on the World’s Body*, trans. with introduction and notes by D. Baltzly (Cambridge: Cambridge University Press, 2006), p. 92. Baltzly’s introduction offers a detailed account of Proclus’s arguments on the composition of the heavens.
40. B.R. Goldstein, “The Arabic Version of Ptolemy’s Planetary Hypotheses,” *Transactions of the American Philosophical Society*, 57(4), 1967, pp. 1–12. A condensed summary of Ptolemy’s arguments can be found in J. Evans, *The History and Practice of Ancient Astronomy* (New York: Oxford University Press, 1998), pp. 348–9.
41. G.J. Toomer, *Ptolemy’s Almagest* (London: Duckworth, 1984), pp. 477 (X.4), 502 (X.9), 522 (XI.3). For background, see B.R. Goldstein and A.C. Bowen, “The Introduction of Dated Observations and Precise Measurements in Greek Astronomy,” *Archive for History of Exact Sciences*, 43(2), 1991, pp. 93–132; A. Jones, “Ptolemy’s Ancient Planetary Observations,” *Annals of Science*, 63(3), 2006, pp. 255–90; R.L. Kremer, “Experience and Observation in Hellenistic Astronomy,” in A.C. Bowen and F. Rochberg (eds), *Hellenistic Astronomy: The Science in its Contexts* (Leiden: Brill, 2018), pp. 158–82.
42. See Jones, “Ptolemy’s Ancient Planetary Observations,” pp. 267–8. The *Almagest* also includes reports of 7 observations of stars being occulted by the Moon, material recently analyzed by L.V. Morrison, C.Y. Hohenkerk and F.R. Stephenson, “The *Almagest* Greek and Roman Occultations Re-Visited,” *Journal for the History of Astronomy*, 48(4), 2017, pp. 405–16. In not all cases did the lunar limb actually cover the star, a finding that supports our hypothesis, presented below, that for naked-eye observers, the greater the difference in brightness between the two bodies the greater the angular separation can be for events nonetheless to be reported as occultory.
43. See A. Jones, “A Likely Source of an Observation Report in Ptolemy’s *Almagest*,” *Archive for History of Exact Sciences*, 54(3), 1999, pp. 255–8.
44. For further discussion, see Goldstein and Bowen, “The Introduction of Dated Observations, pp. 97–8; Jones, “Ptolemy’s Ancient Planetary Observations,” pp. 276–8, 289–90; Jones, “A Study of Babylonian Observations,” pp. 475–536. There has been also a suggestion that Ptolemy’s fragmentary record of ancient planetary occultations is part of Aristarchos’s systematic testing of the astronomical distance scale; see D. Rawlins, “Aristarchos Unbound: Ancient Vision,” DIO, 14, 2008, pp. 13–32, 27–8.

45. A. Jones, "Later Greek and Byzantine Astronomy," in C.B.F. Walker (ed.), *Astronomy before the Telescope* (London: British Museum Press, 1996), p. 103. Cf. Neugebauer *A History of Ancient Mathematical Astronomy*, pp. 1038–41.
46. We take these data from the recent edition and translation in A. Jones, "Ptolemy's Canobic Inscription and Heliodoros' Observation Reports," *Sciamus*, 6, 2005, pp. 80–83.
47. W. Stubbs (ed.), *The Historical Works of Gervase of Canterbury: The Chronicle of the Reigns of Stephen, Henry II and Richard I*, vol. 1 (London: Longman, 1879), p. 221: "Idus Septembris, nocte media, duo planetae sic conjungi videbantur, ut quasi una eademque stella fuissent appareret; sed ilico abinvicem separati sunt." English translation, slightly modified by us, in D.W. Olson, R.L. Doescher, and S.C. Albers, "A Medieval Mutual Planetary Occultation," *Sky and Telescope*, 84(2), 1992, pp. 207–9.
48. Olson *et al.*, "A Medieval Mutual Planetary Occultation," pp. 2017–9. It must be noted that this phenomenon was identified earlier as the conjunction of Mars and Jupiter by Th. Streete, *Astronomia Carolina* (London, 1661), p. 107. See also Hilton *et al.*, "Analysis of Ancient Chinese Records," p. 1485, No. 51.
49. N.M. Swerdlow, "Regiomontanus on the Critical Problems of Astronomy," in T.H. Levere and W.R. Shea (eds), *Nature, Experiment, and the Sciences* (Dordrecht: Kluwer, 1990), pp. 165–95; R.L. Kremer, "War Bernard Walther, Nürnberger astronomischer Beobachter des 15. Jahrhunderts, auch ein Theoretiker?" in G. Wolfschmidt (ed.), *Astronomie in Nürnberg* (Hamburg: Tredition Science, 2010), pp. 156–83.
50. M.H. Shank, "Regiomontanus versus George of Trebizond on Planetary Order, *Distances, and Orbs (Almagest 9.1)*," in press.
51. According to the Parisian Alfonsine Tables, these planets had identical longitudes on 1 December 1461 at 13;40 hours past noon at the meridian of Toledo. The Toledan Tables indicate a separation in latitude of only 0;09° at that time.
52. Johannes Schöner, *Scripta clarissimi mathematici M. Ioanis Regiomontani* (Nuremberg, 1544), ff. 39r–v, 41v.
53. Walther names the star 8 Gem, which, he adds, has a latitude of 2;40° according to Ptolemy; yet Walther measured zero latitude with his armillary sphere. Presumably, Walther confused 8 Gem and 12 Gem, listed in Ptolemy's catalog with a latitude of −0;30° (both stars are listed with the same longitude). We have used 12 Gem = δ Gem for our recomputation.
54. Schöner, *Scripta*, ff. 55v, 56r, 60r.
55. Cf. R.A. Jarell, "The Life and Scientific Work of the Tübingen Astronomer Michael Maestlin, 1550–1631" (Ph.D. thesis, University of Toronto, Toronto, 1971), pp. 87–127; *idem*, "Mästlin's Place in Astronomy," *Physis*, 17(1–2), 1975, pp. 5–20; M. Schramm, "Zu den Beobachtungen von Mästlin," in G. Betsch and J. Hamel (eds), *Zwischen Copernicus und Kepler – M. Michael Maestlinus Mathematicus Goeppingensis 1550–1631* (Frankfurt am Main: Harri Deutsch, 2002), pp. 64–71.
56. M. Maestlin, "Demonstratio astronomica loci stelle novae," in N. Frischlin (ed.), *Consideratio novae stellae, que mense Novembri anno salutis 1572* (Tübingen, 1573), pp. 27–32. This work was reprinted by T. Brahe in his *Astronomiae instauratae progymnasmata* (Prague, 1602), pp. 544–8.
57. M. Maestlin, *Observatio & demonstratio cometae aetherei astronomica, qui anno 1577, et 1578, constitutus et sphaera Veneris, apparuit* (Tübingen, 1578).
58. For observing the comet Maestlin employed both a quadrant and his transversal method with a thread.
59. O. Gingerich, *An Annotated Census of Copernicus' De Revolutionibus* (*Nuremberg, 1543 and Basel, 1566*) (Leiden: Brill, 2002), pp. 8–15 (1543 Liége), 105–8 (1543 Vatican 1–Ottoboniana 1902), 23–28 (1566 Prague 3), 178–80 (1566 Wrocław 4). Cf. also O. Gingerich

and R.S. Westman, "The Wittich Connection: Conflict and Priority in Late Sixteenth-Century Cosmology," *Transactions of the American Philosophical Society*, 78(7), 1988, pp. 27–41.

60. Owen Gingerich erroneously interpreted the note from 1572 as referring to the conjunction of Jupiter and Fomalhaut; cf. Gingerich, *An Annotated Census*, p. 105; Gingerich and Westman, "The Wittich Connection," pp. 32, 33.
61. Cf. Gingerich and Westman, "The Wittich Connection," p. 12; Gingerich, *An Annotated Census*, p. 8.
62. Anno 1572 D[ie] 8 Novemb[ris] / tegebat <Iuppiter> Stellam 21 <Piscium>. / Fuit aut[em] Long[itudo] <Iovis>, se[cu]nd[u]m Supputatione[m] / in 21° 7' <Arietis>, Ergo Longitudo / fixae 353. 18'. ab <Arietis> fixo. The Liège copy, f. 57v. Triangular brackets show the deciphered symbols from the note.
63. The Prutenic Tables, computed for the meridian of Königsberg, noon, give for the longitude of Jupiter 21;06°.
64. J. Dobrzycki, "Katalog gwiazd w *De revolutionibus*," *Studia i Materiały z Dziejów Nauki Polskiej. Seria C*, 7, 1963, pp. 109–53, 139; Toomer, *Ptolemy's Almagest*, p. 380.
65. Anno 1574 D[ie] 15 Sept[embris] H[ora] 8 Eclipsabat <Venus> Regulu[m]. Long[itudo] <Veneris> ex Tabulis 23 23' <Leonis> Lat[itudo] 48' M[eridionalis]. The Liége copy, f. 54r. Triangular brackets show the deciphered symbols from the note.
66. For meridian of Tübingen, for 16 September 1574, 4 hours after midnight, we find the Prutenic Venus at Leo 23;33°.
67. M. Maestlin, *Epitome astronomiae* (Heidelberg, 1582), p. 471. In this edition Maestlin dates the occultation still for 16 October. The same information appears in the second edition, *Epitome astronomiae* (Tübingen, 1588), p. 484.
68. M. Maestlin, *Disputatio de eclipsibus Solis at Lunae* (Tübingen, 1596), pp. 17–18.
69. M. Maestlin, *Epitome astronomiae* (Tübingen, 1597), p. 484. This addition is missing from the third edition of the *Epitome* (Tübingen, 1593).
70. Maestlin, *Disputatio*, pp. 17–18.
71. Interestingly, a similar argument to prove that comets are celestial objects was used in 829 A.D. by Albategnius (Abū Ma'shar): "For I saw with my own eyes a comet beyond Venus. And I knew that the comet was above Venus, because its color was not affected." Quoted in L. Thorndike, "Albumasar in Sadan," *Isis*, 45(1), 1954, p. 29. Maestlin was familiar with Albumasar's observation; see Jarell, "The Life," p. 114.
72. J. Kepler, *Optics: Paralipomena to Witelo & Optical Part of Astronomy*, trans. by W.H. Donahue (Santa Fe: Green Lion Press, 2000), p. 316.
73. *Ibid.*, p. 315.
74. *Ibid.*, p. 316.
75. It was used, for example, by Streete, *Astronomia Carolina*, pp. 114–16. Streete verified the ancient observations he had collected by making computations on the basis of his own tables. Cf. S.J. Johnson, "Occultations of and by Venus," *Astronomical Register*, 12, 1874, pp. 268–70.
76. Kepler, *Optics: Paralipomena*, p. 315, Chapter 8 Section 5.
77. *Ibid.*, Chapter 6 Section 12.
78. "For, concerning the length and breadth of the shadow belonging to earth, and the sun's parallax, if you look at the quantity, there is even now grounds for cautious consideration," he comments. Cf. Kepler, *Optics: Paralipomena*, p. 314.
79. *Ibid.*, pp. 314–15.
80. *Ibid.*, pp. 271–4.
81. J. Kepler, *De fundamentis astrologiae certoribus* (Prague, [1601]), theses XXV–XXIX; cf. Kepler, *Optics: Paralipomena*, p. 272.

82. J.V. Field, "A Lutheran Astrologer: Johannes Kepler," *Archive for History of Exact Sciences*, 31, 1984, pp. 189–272, at 243.
83. For an overview of relevant opinions and arguments, from the Middle Ages to the seventeenth century, see E. Grant, *Planets, Stars, and Orbs: The Medieval Cosmos, 1200–1687* (Cambridge: Cambridge University Press, 1996), pp. 393–413.
84. E. Rosen, *Kepler's Conversation with Galileo's Sidereal Messenger* (New York and London: Johnson Reprint Corporation, 1965), p. 34.
85. F.W. Campbell and R.W. Gubisch, "Optical Quality of the Human Eye," *Journal of Physiology*, 186, 1966, pp. 558–78.
86. S. Hecht, S. Schlaer and M.H. Pirenne, "Energy, Quanta and Vision," *Journal of General Physiology*, 25, 1942, pp. 819–40.
87. W.A.H. Rushton, "The Sensitivity of Rods under Illumination," *Journal of Physiology*, 178, 1965, pp. 141–60.
88. S. Hecht, "Rods, Cones and the Chemical Basis of Vision," *Physiological Reviews*, 17, 1937, pp. 239–90.
89. R.M. Pritchard, W. Heron, and D.O. Hebb, "Visual Perception Approached by the Method of Stabilized Images," *Canadian Journal of Psychology*, 14, 1960, pp. 67–77; M. Rucci and J.D. Victor, "The Unsteady Eye: An Information Processing Stage, Not a Bug," *Trends in Neurosciences*, 38, 2015, pp. 195–206.
90. The following fragment is based on a semi-diplomatic transcription of an excerpt from a manuscript copy of Edward Gresham's *Astrostereon* (1603), MS Sloane 3936, f. 8v–10v (British Library, London). For convenience of reading our transcription, raised letters have been lowered (e.g., "w^{ch}" into "which"), contractions and special signs have been expanded, "thorn" has been replaced by "th," and terminal -es graph with "es." Otherwise, original orthography has been preserved. Some missing letters and words have been put in square brackets. Words which appear in the manuscript in italics have been italicised in the transcription. Original punctuation has been preserved, although at times it had to be supplemented with modern conventions of sentence and clause division (all additions in square brackets).
91. See n. 18 above.
92. Latin "If the calculation is correct."

Appendix I

On the resolution of occultations viewed with the naked eye (Howard C. Hughes)

Introduction. We wish to briefly compare the pre-telescopic occultation observations with what is known about the limits of human visual performance as observed in carefully controlled laboratory experiments. Do these visual reports of occultations appear compatible with the abilities of the human visual system, or are some of the reports surprisingly accurate or inaccurate? First, we consider the optical quality of the human eye, since it sets an absolute limit on the ability to distinguish one point source from two distinct sources in close spatial proximity. Then, we consider additional factors that degrade spatial resolution, especially under the dark-adapted conditions that star-gazing requires. We conclude that the pre-telescopic observations appear surprisingly compatible with modern measures of visual performance made in laboratory studies using carefully specified stimulus conditions.

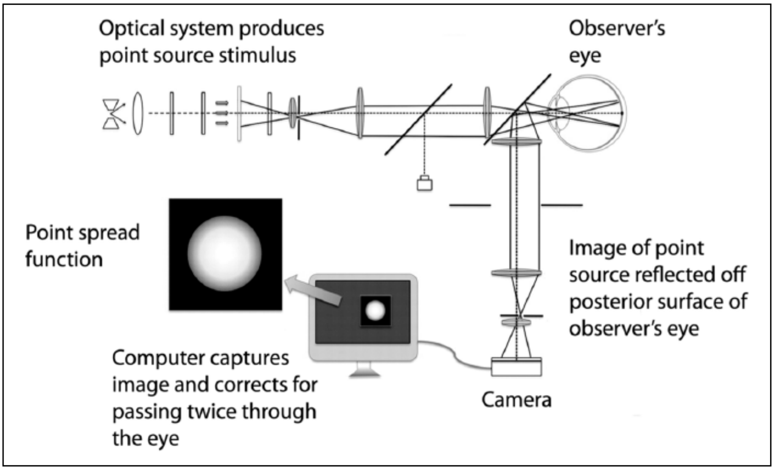

Figure 1. Schematic diagram of apparatus used to obtain the point spread function of the intact eye. The image obtained from reflection off the back surface of the eye is captured by the camera and analysed by the computer.
Adapted from Figure 2 of H. Ginis, *et al.*, "The wide-angle point spread function of the human eye reconstructed by a new optical method," *Journal of Vision* 12(3), 2012, 20, 1–10.

Visual acuity depends on the optical quality of the retinal image. Vision results from processing within neural networks that extract information from images projected onto the retina, the thin layer of cells that line the posterior surface of the eye. The absolute limit of spatial resolution is determined by the quality of that retinal image. No optical system is perfect; they vary greatly in the objective quality of the images they can produce. The optical quality of a raptor's eye is better than ours, and that of a cat is much worse (by a factor of about 10). The optical quality of our cell phone cameras is better than our eyes – otherwise, the pictures would look blurred.

How can we (noninvasively) measure the quality of the optics in a human eye when we cannot directly observe and measure the image formed in the retinal plane? Not all of the light that forms the retinal image is absorbed within the eye; some passes through the retina, is reflected off the back surface of the eye, and exits from the eye via a path similar to the incoming path. Thus, if we project a very narrow beam of photons all following parallel paths into the eye of an observer, the optical surfaces of the eye would bend (refract) them so that they would all converge at a small patch of retina, and form an image of a bright point of light – like a very intense star. The light that exits from the eye is the retinal image of that point after it has passed through the optics a second time. Once we compensate for the second passage through the optical system, it is equivalent to the retinal image of the original point source. Such measurements were first reported by F.W. Campbell and R.W. Gubish[85] using a specialized optical apparatus schematically illustrated in Figure 1.

This image, the point spread function, is a blurred replica of the original stimulus. The amount of blur is a measure of the quality of the retinal image. The point spread function sets an upper limit on visual acuity – the "width" of the function reflects the magnitude

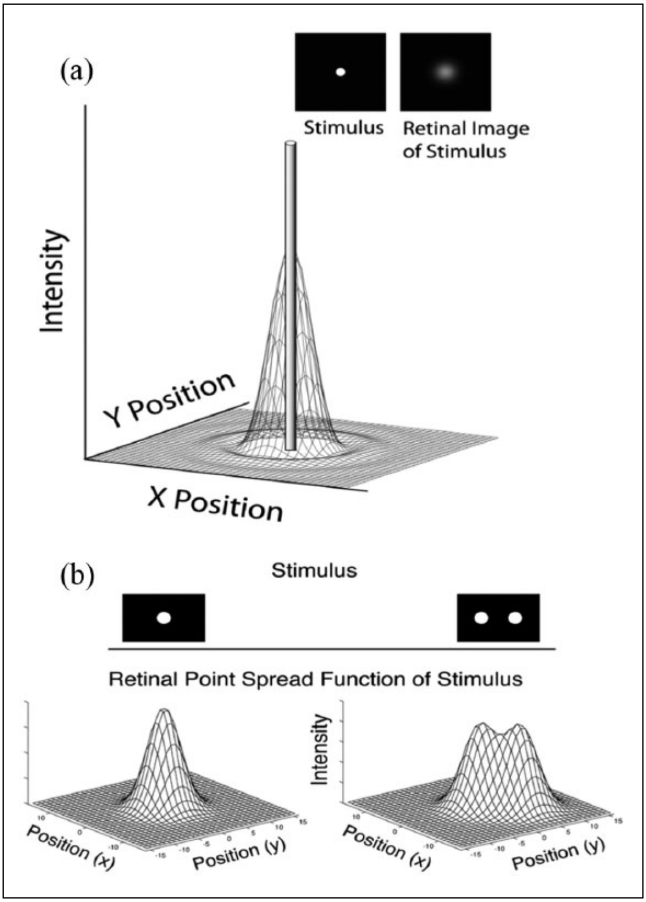

Figure 2. The point spread function sets an upper limit on the "two-point discrimination" threshold.

Panel (a) modified from https://astronomy.stackexchange.com/questions/2398/is-the-moon-only-60-pixels.
Panel (b) modified from http://foundationsofvision.stanford.edu/chapter-2-image-formation.

of the blur: as the width increases, visual acuity decreases, and minimum separation needed necessary to distinguish two objects in close proximity increases. Figure 2 illustrates how the point spread function applies to the problem faced by naked eye observers attempting to document celestial occultations.

As illustrated in Figure 2(b), the problem of distinguishing two point sources from one depends upon the topography of two superimposed point spread functions. If the retinal image of the sources has a resolvable depression between two peaks of retinal illumination, then the two points may be distinguishable. Having distinguishable peaks within the retinal image of two points in close spatial proximity is necessary, but not sufficient to resolve the stimulus into two distinct sources. Other factors will come into play, especially during night vision.

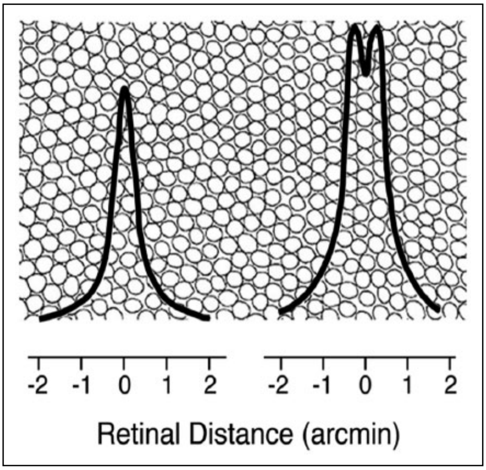

Figure 3. Superimposition of line spread functions on the foveal cone mosaic at the limits of human visual resolution.
Modified from http://webvision.med.utah.edu/book/part-iii-retinal-circuits/midget-pathways-of-the-primate-retina-underly-resolution/.

Of course, observers cannot directly evaluate their own retinal images. Rather, the retinal image provides the input to the visual nervous system, which performs extensive neural processing of that image. The image must first be transformed from spatial (and temporal) patterns of light intensities to spatio-temporal patterns of neural activity. This transformation is accomplished by the photoreceptors, a population of 126,000,000 specialized cells that contain pigments that absorb a proportion of the light that rains down upon them. The photoreceptors convert the energy in those absorptions into bioelectric signals which are then transmitted via synaptic interactions to retinal neurons (which are embryonically and functionally a part of the central nervous system). Each photoreceptor obtains a discrete sample of the image (one picture element, i.e. one pixel). The Nyquist-Shannon sampling theorem states that, in order to resolve spatial separations of 1 arcmin, receptor cells must subtend no more than 30 arcsec (2 receptors/arcmin).

Figure 3 illustrates the one-dimensional cross sectional profiles of the retinal images of single fine bright line and a pair of bright lines separated by 1 arcmin, all superimposed on the photoreceptor mosaic of the central fovea (the region of the fovea that possesses the highest density of photoreceptors and is therefore the region of greatest visual acuity). This is the only region of the retina where the cones are small enough to provide the sampling density (as specified by the sampling theorem) needed to recover all the detail in the retinal image.

The central fovea contains only cones, the photoreceptors that support colour vision and detail vision. They only work when ambient levels of light are high, so night vision is inherently more "grainy." It is also colour-blind.

The top panel in Figure 4 illustrates the visibility of grating patterns that vary in both their "spatial frequency" (the units of spatial frequency are "cycles per degree" [cpd], which is simply the number of light/dark pairs that are packed into 1 degree) and their

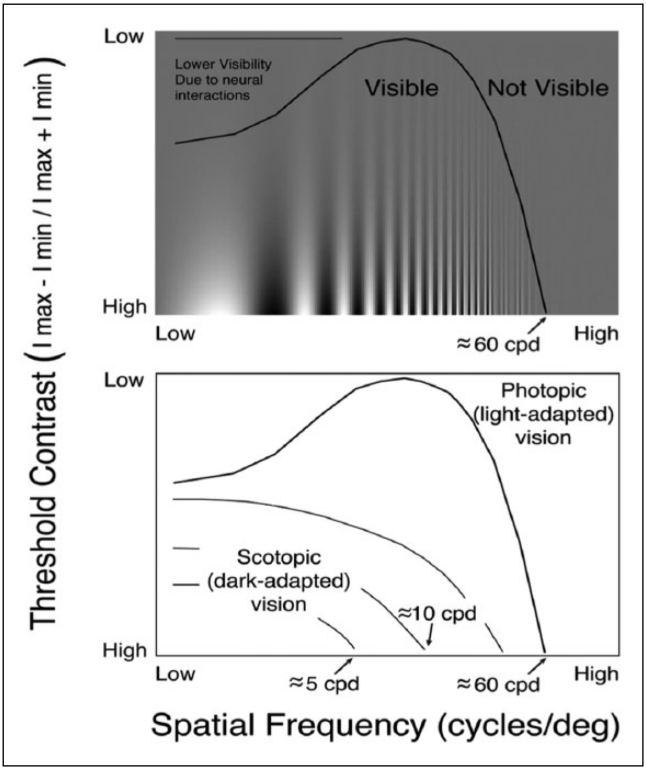

Figure 4. An illustration of the Spatial Contrast Sensitivity Function, which provides a comprehensive summary of the analysis of spatial patterns, including a measure of visual acuity. The bottom panel illustrates how the Contrast Sensitivity of human observers changes as we adapt from daylight to nighttime vision. See text for additional details.
Adapted from http://www.telescope-optics.net/images/eye_contrast.PNG.

contrast (a measure of the brightness difference between the light and dark bars). The top panel shows the appearance of sine wave gratings, patterns whose brightness changes as a sinusoidal function of horizontal position. The contrast of all the patterns in greatest at the bottom of the graph and gradually diminishes as you go up. All the contrast values on any horizontal line are equal, but it is clear that the visibility of all the bars along any horizontal is not the same. Inspection of the grating pattern confirms that the visibility of the bars in greatest at intermediate spatial frequencies (those bars are seen to extend higher) and visibility falls at both higher and lower spatial frequencies. We also see that the bars are less visible at low spatial frequencies. The quality of the retinal image of the lower spatial frequencies is just as good as those for intermediate spatial frequencies, but we are actually less sensitive to the lower frequency patterns. This is not a consequence of optics, but rather the result of neural processes within the retina designed to accentuate neural responses to abrupt changes in brightness over space (sharp contours) and attenuate very gradual changes (i.e. soft shadows and shading). Thus, Figure 4 illustrates that some high-fidelity retinal images are rendered invisible by neural filters designed to enhance visibility of specific aspects of the retinal image (i.e. edges). We turn now to consider the major anatomical and neural factors that further limit visual resolution under the adverse conditions of night vision.

Properties of scotopic (dark-adapted) vision. We have already noted that there are two different types of photoreceptors: rods and cones. One of the great early discoveries of vision science was the discovery that rods are the receptors specialized for night vision and cones mediate day vision. Thus, the rods are much more sensitive than cones to very dim lights presented on dark backgrounds. In fact, rods can signal the absorption of a single photon.[86] Rods are also much larger than cones, and their outputs are combined into larger "pools" of retinal neurons via synaptic convergence that occurs in cone pathways. As a result, rod signals reflect absorptions summed over larger areas of the retina surface than corresponding cone pathways. All these factors contribute to the greater absolute sensitivity of scotopic vision, but at a cost of dramatically reduced spatial acuity (the increased granularity of night vision). This is an unavoidable tradeoff – sensitivity to low-light levels is incompatible with spatial resolution in any image processing system, as anyone who as attempted night photography with the cellphone camera knows quite well.

This fundamental tradeoff between absolute (as opposed to relative) sensitivity and spatial resolution is illustrated in the bottom panel of Figure 4, which compares the spatial contrast sensitivity function for light-adapted (photopic) and dark-adapted (scotopic) vision. The reduction in visual acuity is apparent in the "high frequency cut-off" of the illustrated curves, which falls from 60 cpd in the light-adapted eye to about 5 cpd in the dark-adapted eye (a reduction in the threshold of two-point discrimination thresholds from 1 arcmin to 12 arcmin).

Light and dark adaptation. Anyone who has carefully viewed the transition from night to dawn, or from dusk to night knows that stars disappear with the dawn and reappear as the night sky darkens. Visual sensitivity is relative, not absolute. This is but one well-known example of Weber's Law, which states that a just noticeable difference (JND) in stimulus intensity is not constant, but is a constant proportion of the background

$$\begin{aligned}&\text{JND} = k = \Delta I/I, \text{ where k is known as the Weber fraction,}\\&\text{I is the background intensity,}\\&\text{and } \Delta I \text{ is the just detectable change in the intensity background.}\end{aligned} \tag{1}$$

Thus, a star whose brightness is 1 (arbitrary units) that is barely visible when the background sky is 10 units will not be visible if the background increases to 100. With a background of 100, only stars whose intensity were 10 or greater would be visible against the brighter sky (if $k = 10$).

Weber's Law is a ubiquitous property of sensory sensitivity. It is an adaptation seen in systems that must operate over a very wide range of ambient intensities. We say our eyes must "adapt" to large changes in average light levels and this adaptation takes time. The

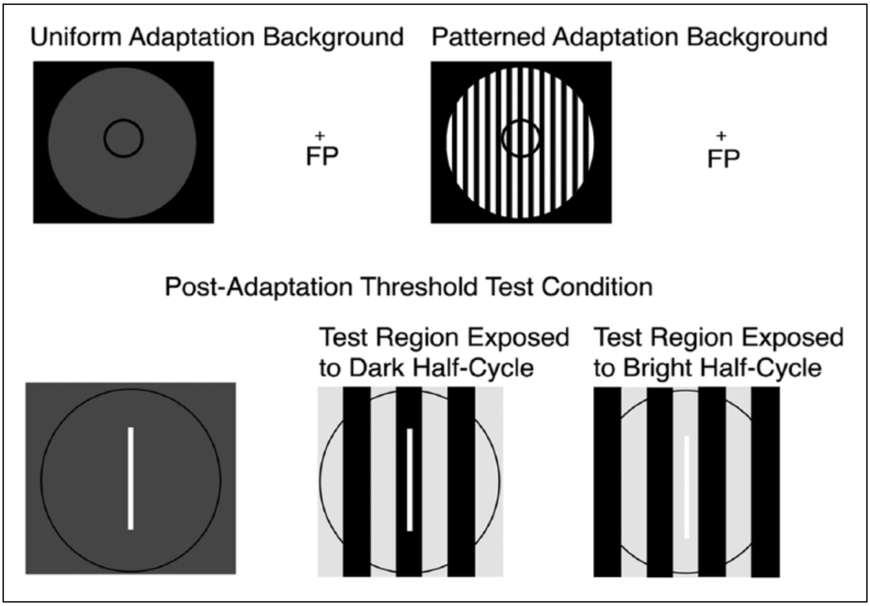

Figure 5. A conceptual illustration of Rushton's experiment on the spatial spread of light adaptation. FP stands for fixation point. The adaptation and test fields were located in near-peripheral vision because there are no rods in the fovea. See text for details.

increase in sensitivity with time in the dark is dark adaptation and corresponding "adjustment" to increases in background illumination is called light adaptation. Light and dark adaptation allow our vision to operate efficiently under different illumination conditions. Our visual apparatus has an operating range of at least 100,000,000,000,000/1–from the dimmest nighttime conditions to a snow-covered mountain top on the most brilliant winter's day.

The importance of light adaptation for the present discussion concerns the interactive effects between two sources that may be expected as the source converge in space, especially if the objects differ substantially in brightness. This is because light adaptation is not restricted to the area of the retina that is directly exposed to the changing background. Rather, the effects of light spread from light-exposed areas of the retina to adjacent areas that have remained in the dark.

The "diffusion" of light adaptation was discovered by William Rushton and colleagues in the mid 1960s.[87] This discovery contrasted with the prevailing view of the mechanism of light adaptation at that time, which held that light adaptation was a phenomenon entirely attributable to properties of the photochemical properties of the visual receptors.[88] When a pigment molecule absorbs a photon, it changes its molecular conformation and this begins a cascade of intracellular events which ultimately result in the flow of ionic currents across the receptor cell membranes which then initiates neuronal processing in the retina. Upon the absorption of a photon, the new conformation renders the molecule transparent – light is said to "bleach" the pigments and only "unbleached" pigments can absorb light. Thus, the photochemical theory stated that light adaptation

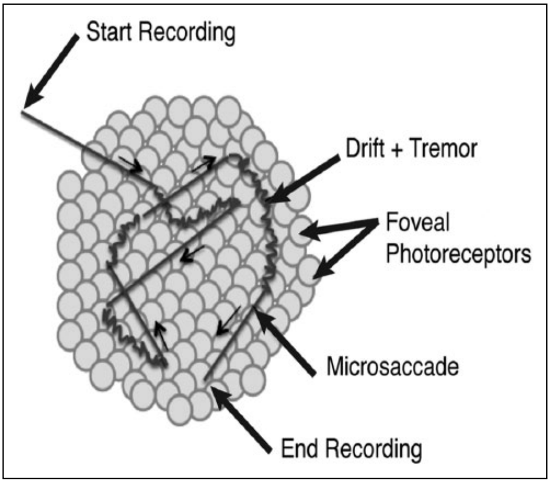

Figure 6. Schematic illustration of the various of eye movements that occur during "steady fixation." These movements are involuntary and we are not aware of their occurrence. The overlapping circles represent the outer segments of foveal cones and provide an indication of the scale of these movements, whose cumulative effect can extend 10 or more arcmin during several seconds of attentive fixation.

Modified from https://en.wikipedia.org/wiki/Fixation_(visual)#/media/File:Two_Types_of_Fixational_Eye_Movement.png.

occurs because increasing the background illumination increases the proportion of pigment molecules in the bleached state, leaving a smaller proportion in the unbleached state, p, which elevates the photoreceptor threshold.

There were reasons to doubt that photopigment bleaching was completely (or perhaps even the primarily) the consequence of pigment bleaching, but it was Rushton who performed the clever experiment to prove it. Figure 5 is a schematic, conceptual illustration of the logic of Rushton's experiment.

The experiment is designed to evaluate the photochemical theory of light adaptation. It proposes to do this by comparing the consequences of light adaptation using two different adaptation stimuli. The first is a uniform field, the second a patterned grating. In the experiment, the spatial frequency of the adaptation grating (i.e. the width of the bars) can vary, but the total luminous flux of both types of adaptation field was equated; the exposed region of the retina was exposed to the same density of photons/unit time. If light adaptation occurs exclusively in the photoreceptors then the three testing conditions illustrated in the bottom half of the figure should lead to very different effects on the light-adapted threshold for the thin, vertical test flash. The uniform test adaptation field should produce an intermediate elevation in threshold, because the photoreceptors that must detect the test flash are exposed to an intermediate intensity of adapting light. The test case in the right panel should produce a greater threshold elevation than the uniform adaptation field, because those receptors are exposed to a bright half-cycle of the grating, which is brighter than the uniform field (whose brightness is the average of the brightness of the light and dark bars). Note however, that the test case illustrated in the centre test condition should show no adaptation, since those photoreceptors were only exposed to the dark bars during the adaptation phase of the experiment (the adaptation field was presented 1 second before the test flashes). Rushton reasoned that the results should depend on the spatial frequency of the patterned adaptation field. If the lines were too fine, then eye movements (discussed in detail in the next section) would "smear" the effects by sweeping the pattern across the retina and the effects of the patterned and uniform adaptation fields would produce equivalent threshold elevations (even if adaptation is restricted to the photoreceptors exposed to light). On the other hand, if the spatial frequency was too coarse, then the experiment would not provide a critical test of the photochemical theory since in this case it is possible that the bar width was much greater than the spatial spread of light adaptation, thresholds during the dark half-cycle test might not appear elevated, and that might be mistaken for positive evidence for the photochemical account.

The results indicated that a patterned grating produces the same level of light adaptation as the uniform field – in both the dark-phase and light-phase tests – if the spatial frequency of the adaptation field is 2 cpd (cycles/deg). The width of the light/dark bars of a 2 cpd grating is 0.25 deg (15 arcsecs), so the provisional conclusion is that light adaptation spreads laterally more than 15 arcsecs from the photoreceptors that were exposed to light. Even a very weak adaptation field can more than triple the threshold. Thus, as a brighter object approaches a much dimmer one, the spread of light adaptation from the brighter object could render the dimmer one invisible, thus giving the impression of an occultation. Eye movements would "smear" these effects over an even greater region of the retina, so we explore those effects next.

Fixational eye movements. The experiments introduced in the previous section rely critically on the precision with which a stimulus can be delivered to a precise location on the retina. To provide a sense for the scale of retinal distances, the diameter of the foveal cone outer segments in Figure 6 is 2.5 μ (0.0025 mm). The scale of movements portrayed in Figure 6 cannot be seen or measured without elaborate devices capable of resolving very tiny movements of the eyes. Usually, a contact lens fitted with a small mirror must be affixed to the eye and held on the cornea with suction.[89] Alternatively, very brief exposures can insure that no stimulus movement occurs on the retina during the actually adaptation phase, but that does not allow precise replications of the retinal position of test stimuli, as is required in these tests of the spatial spread of light adaptation. In any case, none of these techniques were used or available to early pre-telescopic astronomers, so the viewing conditions under which they made his observations surely involved an unsteady gaze. These movements would sweep the images of celestial bodies as pre-telescopic astronomers viewed their movements and would therefore spread the effects of their light over an even larger area of the retina, adding further difficulties to the problem of observing an occultation with the naked eye. These effects would add to those produced by light adaptation of retinal neurons, suggesting possible reasons why separations of 20 arcmin or more might be mistaken for occlusion of one celestial body by another.

Atmospheric aberrations – "twinkle, twinkle, little star ...". Everyone has noticed the fact that stars do not appear to be constant, unchanging point sources. As the well-known

Table 5. The four possible outcomes in a two-alternative forced-choice signal detection experiment.

	Signal State	
Report	Signal Present	Signal Absent
"Present"	Hit	False Alarm
"Absent"	Miss	Correct Rejection

children's poem reminds us, we see stars twinkle ("stellar scintillation"). These variations in brightness (and position) result from atmospheric disturbances (wind, differences in air temperature) that change the refractive index in different depths of the atmosphere. They cannot be avoided with land-based observations and would further degrade the resolution of a faint source into two closely adjacent sources.

Observer expectations. We consider one last factor that would surely have introduced honest errors into pre-telescopic observations: one that relates to the observer's expectations. Consider a simple situation in which an observer makes an observation and must decide whether the observation provides evidence for one of two states, such as one object or two. Let us require that the observer report which state they observed – either one object or two. The observer must choose; it is called a two-alternative force-choice task (2AFC). The 2AFC task is the most efficient way to study the detection of weak signals because it is a simple world in which the event of interest only has two states (one star or two?) and you must choose one of them (i.e. report "one" or "two"). Thus, the task only permits the four possible outcomes indicated in Table 5.

Those four outcomes are percentages (or estimated probabilities) of trials in which each outcome actually occurs in a large number of observations in a given experimental setting. Two of those reports (hits and correct rejections) are correct, and the other two (miss and false alarm) are incorrect. Note, however, that the entire table can be reconstructed from only two outcomes, since

1. p (Miss) = 1–p (Hit) and
2. p (Correct Rejection) = 1–p (False Alarm).

The entire outcome of this experiment is therefore summarized by two values. By convention, p (Hit) and p (False Alarm) are reported (the outcomes associated with positive reports – the "yes" responses).

Signal Detection Theory provides a way of completely specifying the objective performance for detecting weak signals in the context of a noisy background, exactly the situation we are concerned with here. If p (Hit) = p (False Alarm), then the signal is not detectable (the observer is no more likely to report a signal when it is presented than they are when the signal is not presented). If the signal is detectable, then p (Hit) > p (False Alarm). How much greater p (Hit) is than p (False Alarm) reflects the sensitivity to the signal.

Signal Detection Theory also holds that there are non-sensory factors that contribute to detection performance. These are factors such as the apriori probability that a signal will be presented. Knowing that 80 percent of the trials will contain a signal will bias an observer to report that a signal was indeed presented. Critically, however, this will appear in the data as an increase in both the hit and the false alarm rate (unless the task is trivially easy). Of course, we cannot recover all the information needed to perform such an analysis on the pre-telescopic occultation reports, but if any of these observers were looking for occultations they would be biased observers with a tendency to report them if they felt an observation provided supporting evidence. This would lead to false alarms, of which there are many in the records. The important point is that this is not because of any dishonesty (or at least it need not be). Rather, it is in the nature of any situation in which we are trying to detect weak signals in the presence of noise. Thus, we are not surprised that there do not appear to be any claims that they could resolve near misses less than 1 arcmin, not only because 1 arcmin is below the resolution threshold but also because they were searching for occultations, not near-misses. Rather, we surmise that our observers had a bias to report occultations, so many of the reports are appropriately categorized as false alarms. Because of light adaptation, poor resolution of night vision, instabilities of fixation and stellar scintillation, those "false alarms" are much more likely to be the result of honest and understandable decision criteria than willful miss-reporting of observations.

Conclusion. Under ideal conditions, a separation between 2 dim point sources of illumination could be discerned at separations as little as 1 arcmin. But the pre-telescopic occultation observations were made under conditions far from ideal. The combined effects of dark-adaptation, spread of the effects of the light adaptation from brighter objects, and effects of involuntary eye movements that occur during the most intense and careful scrutiny would combine to reduce the minimum resolvable separation by as much as a factor of 30. Thus we conclude that there is nothing to indicate that the pre-telescopic observations were systematically biased in any way that these observers could have ever anticipated. Rather than disparaging these important observations from pre-telescopic astronomy, we are left with admiration for the care and objectivity that they brought to these unaided observations of celestial occultations.

Appendix 2

Edward Gresham on planetary occultations[90]

So hath *Venus* eclipsed *Mercurie* and both of them at seuerall tymes haue ben sene to eclipse the Sunne (accordinge to theire greatnes) makeinge apparance of blacke spottes theirein, which was nothinge but the true shewe of theire naturall bodies beinge nowe voyde of lighte and castinge theire shadowes towardes us[,] which thinge[,] if theare had ben any diaphaneitie or puritie of bodys in them, they could not haue done, beinge obiected so neare to so greate a lighte and of such penetracion. And for myne owne parte Anno 1602.[91] Oct: 26 I observed the firste Starre of the 4 in the left winge of the *Virgin* cleane couered and eclipsed from my sighte by the interception of *Venus* goeinge betwixte me and the said Starre, and yet her North latitude exceeded the Starrs 30 minutes or half a degree (*dummodo non fefellit Calculus*)[92] which was no smale argument of great paralax in *Venus*, and consequentlie that she is nearer the earth then hath hitherto ben imagined.

And that euery one maie the better conceave theire grosse opacitie[,] let him consider what bodies here under his senses are transparant or admitte lighte to peirce thorowe them and he shall finde such to be all *glassie* and *waterie* bodies as yce congealed, christaline bodies and moste sorte of pretious stones, the Water and Ayer selues. And so consequentlie all pure and simple bodies, and the more pure, the more diaphanouse, the more grosse lesse transparant, and consequentlie the Earth-selfe and all bodies of like impure compaction to admitte no vision of lighte thorow them, if then the more pure the bodie is, the more diaphanouse, the more impure and grosse, lesse transparent, and the bodies of all the *Planetts* be most indiaphanouse, it followeth that they be most impure and grosse and as grosse as this Earthlie masse we tread upon, And so consequentlie naturallie darke, opacous and voide of all lighte.

But if any man thinke this Stellicall eclipsation to be a ffable, or hold it as a iest, or some brainesicke illudement, let them looke up the 28 of this moneth towardes the Easte at 4 a clocke in the morninge, or beefore[,] and he shall see *Venus* goeinge towardes a fixed starre of the third magnitude, which is in the latter partes of *Virgo*, and the next morninge he shall see her very neare it, the Starre beinge still Easte frome hir, and on the 29 daye in the morninge [-] if he looke for the same Starre [-] his laboure is in vayne, for *Venus* will be betwixte the same and his eye, and so intercepte the sighte thereof, which shee coulde not doe if she weare diaphanouse. The 17 of *October* she will also verie neare Eclipse a Starre of the *Square* in the left *ham* of *Virgo*. Likewise the 26. 27. and 28 daies of *November* nexte towardes the eleven a clocke place aboute 6 in the morning who so will vouchsafe to looke up shall see *Mars* a red fiery planet goeinge towardes the verye same starr the first of the 4 in the left *winge* of the *Virgin*, but the 29 daie the Starre shalbe couered by *Mars* his bodie from his sighte.

But if theare be any (as I doubte to many) whose wittes will not reache to the disouerye of theis said apparances by this discription, let them the third and fourth of December next looke what they shall see in the Sunne[,] for that they know wheare to finde and which is it, and I doubte not but they will be on my side, f[o]r that goodlye planet *Venus* [-] which at this tyme is our beautifull and glorious morning Starre [-] shalbe then a blacke specke in the Sunnes bodie eclipsinge or hideinge so much of the same bodie frome us, as her bodie amounteth unto, which she could not doe if the Sunns-beames or lighte could be seene thorowe her. Againe on Christmas-even in the morninge from one a clock till seaven shall *Mars* be sene goeinge towardes the last of the 4 starres in the left *winge* of *Virgo*. But on S^{t} *Stephens* daie in the morninge *Mars* will shroude him from our sighte, and on *Innocents* daye in the morninge the Starre shall appeare againe *West* frome *Mars*. Also the 22 of Ianuary next in the morninge *Iupiter* shall eclipse a Starre standinge in the righte foote of *Serpentarius* or *Ophiuchus*. The 24 of Marche shall *Saturne* eclipse another Starre of the same constellation preciselye in longitude and latitude, and so shall the Starre remaine unsene for the space of 7 daies before and 7 daies after for the slow motion of *Saturne* who will in the end leaue the starre behinde him towardes the Easte for the apparance of his retrogradation, wheareas in truth neither he nor any other ever was or shall be retrograde, but of that in a discourse of more moment[.] Also the 14th of Aprill 1604 will *Saturne* eclipse another Starre in the righte foote of the same *Ophiucus*. The 17 of Iulie will *Mars* kisse the *Virgins* lefte foote and shroude the same from thie sighte. The 31^t^ of the saide moneth he will eclipse a brighte Starre in the *South ballance* (if thou lookest 2 or 3 daies before the same daie, thou shalt see *Mars* on the west hande (of)Starre, but as many daies after he shall appeare Easte from the same(.) The 17 of September shall *Iupiter* eclipse a litle Starre in the lefte ffoote of *Ophiuchus*(.) *Saturne* eclipse one of the 4 Starres in the righte foote of the same *Ophiuchus*. And about S^t^ *Stephens* daye in the same yeare 1604 *Venus* shall shroude one of the gemms of the *Virgins Kirtle*.