'The Moon Quivered Like a Snake': A Medieval Chronicler, Lunar Explosions, and a Puzzle for Modern Interpretation

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Abstract

Despite some scepticism, the suggestion by Hartung in 1976 that the report in the chronicle of Gervase of Canterbury corresponded to a meteorite impact with the moon in 1178, creating the Giordano Bruno crater, retains considerable support, particularly in popular scientific writing. Nevertheless, a series of studies of images of the crater from orbiting satellites, although confirming its young geological age, have indicated that it was not created within recorded human history. In this paper, we examine astronomical entries in Gervase's chronicle relating to eclipses and conclude that, despite there being descriptions of miracles elsewhere in the manuscript, he himself was a reliable reporter of astronomical events. On this basis an alternative suggestion can be put forward for the splitting of the horns and writhing of the body of the new moon, reported to Gervase: atmospheric turbulence. Although general atmospheric turbulence has been previously dismissed as too small an effect, it is possible to show that the description is consistent with viewing the new moon through a column of hot air from a fire, at a moderate distance and out of the line of sight of the observers. This interpretation of the medieval evidence as credible but unrelated to a lunar event is consistent with twenty-first century lunar studies.

Keywords: Gervase of Canterbury, Giordano Bruno Crater, Solar eclipse, Lunar eclipse, Atmospheric turbulence, Medieval science

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A Scientific Problem

In a well-publicised article, the late Jack Hartung proposed that Gervase of Canterbury's report in his *Chronicle* of a strange optical effect, namely the apparent splitting in two of the upper horn of the crescent new moon and subsequent apparent writhing of the moon in June 1178, might have been associated with the collision of a meteor with the moon, resulting in the formation of the far-side crater Giordano Bruno (Hartung 1976). This crater (Fig. 1), is in a plausible position on the moon, is geologically young, and displays the most striking ray system of any lunar crater. Calame and Mulholland (1978) subsequently calculated that such an event would have been observable from earth and, although later analysis suggested otherwise (Yoder, 1981), argued that the magnitude of the free libration in longitude in the moon's rotation was consistent with such a historical event (Calame and Mulholland, 1978). Free librations are oscillations of the moon, stimulated by impacts, that are subsequently damped by internal friction (Peale, 1976),

While the accuracy of data in the late 1970s admitted the plausibility of Hartung's suggestion, subsequent geophysical studies have all doubted that Giordano Bruno could have been formed in historic times (Kelly and Milone, 2005). From high-resolution images from the Japanese SELENE orbiter, based on crater size-frequency measurements of small craters (less than 200m in diameter) superposed on its continuous ejecta, Morota, et al. (2009) estimated the formation age of Giordano Bruno to be between one to ten million years. This value was supported by the study of the morphology of secondary craters and from optical roughness imagery (Basilevsky and Head, 2012; Shkuratov, Kaydash and Videen, 2012). There are difficulties in determining age from small crater counts (see Fig. 2), as it is difficult to separate micro-meteorite impacts from craters created by impact ejecta falling back onto solidified flow (Xiao and Strom, 2012). Nevertheless, recent impact crater counts on melt surfaces and measurement of the brightness temperatures of crater ejecta support an age of about one million years (Fritz, 2012; Williams, Sefton-Nash and Paige, 2015; Plescia and Robinson, 2019). The evidence against a lunar impact is reinforced by Withers's (2001) prediction that such an event would have subsequently caused a spectacular meteor shower on earth for at least a week, for which there is no medieval record.

The only alternative attempt at explaining what might have been seen in 1178 has been the suggestion by Nininger and Huss (1977) that the observers might have been viewing a meteor in transit of the moon and heading straight towards them. Although they carefully rejected Hartung's explanation on grounds that included the notion that an impact event is hardly likely to have repeated twelve times or more, as stated in Gervase's text, they struggled to reconcile their own model with this repetition. Multiple impacts or transits are not impossible: in 1994 twenty-one nearly equally-spaced fragments of comet Shoemaker-Levy 9 were observed to crash into Jupiter (Chapman, 1993), each impact resulting in material being lofted to about 3000km in height (Hammel, et al., 1995) above the planet's atmosphere before falling back into it. These sequential impacts were, however, rather specific to Jupiter. The comet, which had been captured by the giant planet, probably 20-30 years previously, was orbiting it in a highly eccentric orbit. It is believed to have broken apart due to Jovian tidal forces in July 1992, resulting in the twenty-one fragments impacting the planet over a period of six days in July 1994. Crater chains, as small as 50km long, that have been observed on the Moon as well as on Jovian satellites, probably also result from a similarly fragmented comet (Melosh and Schenk, 1993; Schenk et al., 1996). The time between impacts would have been much less than the several hours between Shoemaker-Levy 9 impacts, making the multiple sightings reported by Gervase's witnesses not untenable. Therefore, despite the low probability, at least one multiple cometary impact with a planetary body has been observed by humans within the past millennium.

A different approach to Gervase's testimony was taken by Nockolds (2002) who questioned the veracity of the whole report, suggesting that the entry is nothing more than propaganda connected to the last decade of the Latin Christian Kingdom of Jerusalem, and the pressure within Christian Europe to send reinforcements. (For an authoritative account of this period, see Hamilton [2000]). Nockolds (2002) questioned the scientific reliability of Gervase's reports on the grounds that elsewhere in the *Chronicle* atmospheric and celestial phenomena are described and interpreted as portents of political and military events, largely doom-laden, for example linking atmospheric phenomena seen four days earlier to the defeat of the army of the Kingdom of Jerusalem at Ramleh in 1177. While noting the caution with which medieval chronicles should be approached, there are, however, grounds for accepting the reliability of Gervase's description, if not the interpretation, of the lunar effect reported to him. Taken in the context of the other astronomical entries in Gervase's chronicle, especially after 1180, his reporting of solar and lunar eclipses from 1175, and in particular his description of a partial solar eclipse, which he himself saw later in 1178, do, in fact, possess the hallmarks of credible scientific narrative.

Here an alternative interpretation of the historical events is presented in the context of the current scientific evidence of the age of formation of the Giordano Bruno crater on the moon. It is proposed that the splitting of the horns and writhing of the body of the new moon, reported to Gervase, arose from viewing the moon through a column of hot air. Mathematical calculation indicates that the change in refractive index associated with hot air rising from a house fire, metal working or bell casting, at a moderate distance from and out of the line of sight of the observers, is sufficient to account for the phenomena reported. An examination of astronomical entries in Gervase's chronicle relating to eclipses leads to the conclusion that he himself was a reliable reporter of astronomical events and that the report of the lunar contortions, if not its interpretation, can be taken as a believable record of what was seen and perceived. Gervase was a learned monk of his age, operating within a conceptual framework of the universe that, in all probability, owes much to the older Greco-Roman traditions of astronomy and astrology inherited by Latin Europe, established by the Carolingians, and transformed by new translations from Arabic and Greek natural philosophy (Aristotle, Ptolemy, the Islamicate thinkers they inspired) over the course of the twelfth century (Gasper, et al., 2019). Although there is no indication that Gervase was particularly influenced by the new learning, he was certainly versed in the old.

The *Chronicle* of Gervase of Canterbury

Gervase of Canterbury was a noted historian and chronicler during the later twelfth and early thirteenth centuries. Born in about 1145, little is known about his earlier years, although he may well have been from Kent, and his family appear to have been of some means with property in Canterbury (Martin, 2004). There he became a Benedictine monk at Christ Church Cathedral Priory. Gervase passed his adult life in the priory's service, from taking his final vows as a monk in 1163, and holding the office of sacristan in 1193-1197. The monastery formed the focal point for his intellectual interests as well as devotional life; the history of the house, especially its contemporary history including disputes with neighbouring houses and an Archbishop of Canterbury, provided the foundation for his writing career (Staunton, 2017).

That career, occupying the period from about 1180 until about 1210, the probable date of Gervase's death, was wide-ranging, creative as well as careful. He produced a number of historical works, beginning, probably in the mid-1180s, with the *Imaginationes* and *Responsiones*, which rehearse various positions in a lengthy dispute between the monastic community and Archbishop Baldwin (reigned 1185-1190), and a dispute between Richard, Archbishop of Canterbury and Roger, Abbot of St Augustine's Abbey, also in Canterbury (Gervase of Canterbury, 1879, I: xviii-xxii). *De combustione et reparation Cantuariensis ecclesiae*, a description of a fire at Canterbury Cathedral in 1174 which destroyed the choir, and its rebuilding which took until 1184, is dated, traditionally, to the same period (Gervase of Canterbury, 1879, I: xv). Famous especially amongst historians of art and architecture for the description of the building process, the text is not without its controversies, for example, whether it was composed to hide the fact that the fire in 1174 was a result of arson (Frankl, 1960; Kidson, 1993). More convincing is the re-dating of the text by Cragoe to 1199 or so, in the context of the dispute with Baldwin over whether the Archbishop could break his connection with the Cathedral (Cragoe, 2001). Whatever his political purpose in writing, the accuracy and detail of his description is worth noting. Three works that seem to post-date 1199 include the *Acta pontificum Cantuariensis ecclesie*, which provided short lives of the Archbishops of Canterbury up to death of Hubert Walter in 1205, the *Mappa mundi* [*Map of the World*], which records in textual, and tabular, rather than pictorial form, the monasteries, castles and waterways of every English county, and the *Gesta Regum—Deeds of the Kings* (Gervase of Canterbury, 1879, I: xxvii-xxx). This final work traces the histories of the Kings of England up to King John, but Gervase seems to have stopped in 1210, the remainder completed (presumably after his death) by another author.

The most significant of Gervase's historical writings was the *Chronica* [*Chronicle*], which moves chronologically from the final years of Henry I (d. 1135) to the death of Richard I in 1199. It seems to have been composed from around 1188 onwards (Gervase of Canterbury, 1879, I: xx-xxvii). For the earlier sections Gervase made use of previous authors. These include, in particular, Henry of Huntingdon's *Historia Anglorum* [*History of the English People*], the *Chronicle of John of Worcester* which incorporated the dating system of Marianus Scotus, and the *Gesta regis Henrici secondi* [*Deeds of Henry II*] attributed to Benedict of Peterborough which chronicles the reigns of Henry II and Richard I. The *Lives* of Thomas Becket, notably that by Herbert of Bosham are also evident (Gervase of Canterbury, 1879, I: xxi; Staunton, 2017). As he approached the period of his own maturity, however, Gervase seems to rely far more on his own experience or the testimony of members of his community. As suggested by William Stubbs, the *Chronicle* has the air of a contemporary composition from 1188 or a few years before (Gervase of Canterbury, 1879, I: xxi). That the *Chronicle* might draw on earlier experience, at least to the late 1170s, is indicated in the record of the celestial phenomena from 1178 to be discussed below. In the case of the solar eclipse, Gervase's record is articulated as from his own experience. In the case of the lunar explosions, where his account explicitly follows the testimony of eyewitnesses, Gervase is the only chronicler to record the incident. It is not, for example, recorded in the *Deeds of Henry II*, which gives more weight to the position that these are from Gervase's own memory. As Stubbs put it "Either these facts were noted at the time, or they must have made such an impression on our author's memory that, when he began to write several years later, he could fix the dates" (Gervase of Canterbury, 1879, I: xv).

Reports of Lunar and Solar Eclipses

The *Chronicle* contains a number of astronomical reports which range from those with a similar modern identification such as lunar and solar eclipses, and comets, to more interpretative reports of visions in the sky. Examples of the latter include the wonders of October 12, 1188, in which three men, two with mitres, one without, appeared over Canterbury and were seen with great clarity. Nockolds (2002) suggests that this entry is an interpretation of a sighting of the aurora borealis, a phenomenon that is extremely rare at the latitude of Canterbury. The defensive purpose of Gervase's *Chronicle* should be born in mind here, against Archbishop Baldwin's attempts to re-define the status of the Cathedral Priory and its community vis-à-vis the Archbishopric; 1188 marked a significant downturn in relations between the two. Gervase was also clear about the differences between a chronicle and a history. He notes in the prefatory remarks to his *Chronicle*:

> To some extent the historian and the chronicles have the same aim and subject matter, but their way of dealing with it is different, as is the form. They share a common aim, since both strive for truth. The form of their work is different, because the historian proceeds at length and in an elegant way, while the chronicler in a simple and brief manner.[1]

A chronicle, he goes on to state, deals with the computation of time, the deeds of kings and princes, and the record of miracles and portents, and it does so succinctly. This is then a necessary context in which to hold Gervase's record of celestial/astronomical phenomena and their meaning; one that allows both for accuracy of observation and a wide valence of interpretation.

It is the eclipse records which will be examined in detail here, especially those after 1178 when it can be more confidently assumed that the entries are original to Gervase. These reports have indications of personal experience and observation, rather than derivation from earlier accounts. Given his description of the task of the chronicler it is perhaps no surprise to find him recording celestial phenomena. The accuracy of his account is, however, striking. Three lunar eclipses reported in the *Chronicle*, and tabulated below (Table 1), have dates, for example, which

[1] 'Historici autem et cronici secundum aliquid una est intentio et materia sed diversus tractandi modus est et forma varia. Utriusque una est intentio, quia uterque veritati intendit. Forma tractandi varia, quia historicus diffuse et eleganter incedit, cronicus vero simpliciter, graditur et breviter' (Gervase of Canterbury 1879, I: 87). Translated from the original by Giles Gasper.

are entirely accurate when compared with those calculated and listed in the Five Millenium Eclipse Catalog of the United States National Aeronautics and Space Administration Goddard Space Flight Center (Espenak, 2016a). The dates in Gervase's *Chronicle* and the NASA catalogues are based on the Julian calendar.

Although there are some discrepancies, the reporting of solar eclipses in the *Chronicle* is also convincing (Table 2). The Eclipse Atlas of the NASA GSFC website reveals that in the period 1161-1180, only two solar eclipses would have been visible in Canterbury. The first is the September 1178 eclipse which was described in detail and is discussed below. The second occurred on January 28, 1180. There is no report in the *Chronicle* of this 1180 partial eclipse, which will have had 80% obscuration in Kent. However, it will have been visible between about 15.30 and 18.00 hours UT (Universal Time), and particularly if the sky was overcast as is not uncommon in mid-winter, it could well have been confused with sunset.

In the next decade 1181-1190, an unusually large number of five partial eclipses could have been visible from Canterbury. The first, in 1181, only had an obscuration of 12%, which may explain why it was not recorded by Gervase. That on May 1, 1185 was recorded, as was another partial eclipse a year later, although Gervase dates this as May 1, 1186, whereas calculation shows that a partial eclipse, that would have been visible to Gervase, occurred on April 21 of that year. In contrast, the 64% obscuration eclipse of September 4, 1187 was reported correctly and Gervase noted that it was partial eclipse. The rapid succession of eclipses is connected by Gervase to the actions of Archbishop Baldwin, in a negative fashion, which is consistent with the emphasis on the task of the chronicler to record visions and portents, especially in this case when they could be related to the chief antagonist of the Canterbury community. The obscuration of the 1190 eclipse was small, but it is, however, curious that the 1191 eclipse which will have been annular in places such as York and Lincoln, although only partial in Kent, does not get mentioned. So, with one exception, the dates of the solar eclipses in the *Chronicle* are accurate, and of the omitted eclipses only two could be thought to be unexpected from a modern perspective.

Solar Eclipse of 1178

The most detailed astronomical entry to be found in the *Chronicle* relates to a partial eclipse of the sun in September 1178, the same year that Gervase describes being told about the splitting of the moon image. He states that:

In September [1178], on the vigil of the feast of the Holy Cross, Wednesday, the 27th [day] of the moon, about the sixth hour, an eclipse of the sun took place in Kent, not total but partial.[2]

Reference to the Feast of the Holy Cross gives a date of September 14. As seen in Fig. 3, an eclipse of the sun is indeed calculated to have occurred on September 13, 1178, the day of the vigil of the two-day feast (Espenak, 2016b). This date is close to the equinox; sunrise in Canterbury, Kent, will have been about 05.30 hours UT–approximately Greenwich Mean Time (GMT) on that day. The medieval day was divided into twelve equal hours of daylight starting from sunrise. Therefore, on September 13, the hour will have been very close to that based on one twenty-fourth of the full solar day. According to the NASA Eclipse Web Site, the partial eclipse seen from Kent will have started at 10.08 hours UT, reaching its maximum at 11.22 hours UT. In this way "about the sixth hour" will have been about 10.30 hours UT, which is indeed when the partial eclipse will have become sufficient to be noticeable to naked eye observation in Kent.

Gervase continues his description as follows:

Now the body of the sun appeared to be horn shaped, the horns stretching towards the west, as the moon customarily is in the twentieth [day of the lunar cycle]. Nothing more was seen of the rest of the sun's rotundity. For a certain black disc covered the remaining light of the sun, which, descending gradually, rotated around itself in its higher part that horn-shaped light, until both horns were suspended, as if pointing towards the ground on both sides. And as this black object gradually proceeded, the abovementioned horns, which at first pointed towards the west, at length were turned towards the east as when the moon is new. In this way, as this small black disc disappeared, the sun regained its brilliance.[3]

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[2] 'Mense Septembri, vigilia Sanctae Crucis, feria iiii, luna xx vii hora quasi sexta, facta est eclipsis solis in Cantia, non universaliter sed particulariter' (Gervase of Canterbury 1879, I: 277). Translated from the original by Giles Gasper and Sigbjørn Sønnesyn.

[3] 'Corpus enim solis corniculatum apparuit, ad occidentem cornua tendens, ut luna solet cum vicesima est. De reliqua solis rotunditate nichil amplius videbatur. Nam quaedam nigra sperula solis reliquum texit splendorem, quae paulatim descendens splendorem illum corniculatum circa se in parte superiore rotavit, donec utraque cornua penderent, utrimque quasi in terram respicientes. Cumque illud nigrum paulatim procederet, cornua supradicta tandem ad orientem versa sunt ut in novilunio, quae prius erant ad occidentem. Sicque sperula illa nigra paulatim transeunte, suam sol receipt claritatem'. (Gervase of Canterbury 1879, I: 277). Translated from the original by Giles Gasper and Sigbjørn Sønnesyn.

As is illustrated in Fig. 4, Gervase's account is a remarkably good description of how an opaque circle of diameter 5% greater than the apparent diameter of the sun moves across it on a 23.5° inclined path. In particular, it should be noted that the horns of the sun, produced by the obscuring disc, are initially pointing westwards as the sun is viewed from Kent. He likens these to the horns of the moon in the 20th day. If he was using the ecclesiastical lunation, the 20th day would have corresponded approximately to the 23rd day of the lunar cycle, at which time the moon changes from Gibbous to crescent, the horns then pointing westwards. Fig. 4 shows that as the eclipse continues, the sun's horns appear to turn to point downwards towards the ground, finally pointing eastwards as is the case for a New Moon. Modern images of partial eclipses with horns pointing downwards are common (Solar Eclipse, 2020).

Gervase's final comments are strikingly descriptive.

> The air, being partly obscured by clouds, provided assistance to human sight so that people could see the above mentioned more easily. In the meantime, the air was tinged with different colours at different places, that is, red, saffron, green, and pallid. This was seen by me along with practically everyone in Kent. Elsewhere, however, the eclipse was universal, so that midday seemed like dark night, and one friend could not see another right next to him. This eclipse was also seen in France.[4]

The partial obscuring of the sun by clouds explains why he was able to give such a clear description of events without being blinded by looking directly into the sun. The report of the changed colours in different directions is very characteristic of a partial eclipse. As well as personal testimony of the 1999 solar eclipse viewed from Luxembourg by one of the authors (B. K. Tanner), there are modern reports of colour change. E. C. Krupp watched the partial phase of the total Pacific eclipse of 2005 without optical aid from the bridge of the ship *Discovery*. He noted that the twilight colours encircling the horizon were brighter than usual and more yellow than orange or red (Feinberg, 2005). Unlike the earlier report of strange lunar phenomena, there is a clear statement that the partial eclipse was seen by Gervase himself, together with many others in Kent. The comment about a total eclipse elsewhere is also consistent with the path of the total eclipse, which tracked over Bordeaux, under Angevin lordship, from which it is possible that

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[4] 'Aer vero nubibus paulisper obtectus, visibus humanis praebuit adjutorium quo facilius supradicta viderentur. Diversis interea locis, coloribus variis aer tinctus erat, videlicet rubeo, croceo, viridi et pallido. Haec a me et fere ab omnibus in Cantia constitutis videbantur. Alibi autem eclipsis fuit universalis, ut in meridie nox videretur tenebrosa, et socius socium juxta se positum non videret. In Francia quoque eclipsis ista visa est.' (Gervase of Canterbury 1879, I: 277). Translated from the original by Giles Gasper.

Gervase may have received reports. In the September 13, 1178 eclipse, the moon was close to the earth and its apparent diameter was 0.552°. It will have fully covered the sun (diameter of only 0.533°) and obscured much of the corona. It will indeed have been very dark. The final comment that the eclipse was *also* seen in France, may not relate to the total eclipse, but to the fact that in the region around Paris, the [partial] eclipse was also seen.

The Report of the Splitting and Writhing of the Image of the Moon in 1178

The evidence of the eclipse reports in the *Chronicle* suggests accurate reporting of these phenomena from the perspective of modern scientific credibility, unaffected by Gervase's tendency to relate these to the major theme of his narrative, namely the injustice of Archbishop Baldwin's actions towards the community at Christ Church, Canterbury. That being the case there appears to be no reason to suppose that the report of the splitting and writhing of the image of the moon in June 1178 was a fabrication, despite the observation not being witnessed by Gervase himself. That it was a second-hand report, means that its susceptibility to misinterpretation of a genuinely observed, but unusual, optical phenomenon rather than a spectacular lunar event should be acknowledged. In this connection, it is worth noting that there are no reports of such an observation in other contemporary chronicles. In terms of interpretation, aside from Hartung's (1976) original suggestion of a lunar meteorite impact, the only alternative proposal proffered is that of Nininger and Huss (1977), namely a meteorite in transit of the moon seen head-on. Both explanations are weak, though not implausible, in respect to a key statement in the record, which is that the phenomenon was repeated 'twelve or more' times.

The episode is recorded by Gervase as follows:

> In this year [1178], on the Sunday before the nativity of Saint John the Baptist [June 18], after sunset, on the first day of the moon, a wondrous sign appeared, while five or more people were seated facing it. For the new moon was shining, in accordance with its phase [it had] horns projecting eastwards; and, behold, suddenly the upper horn divided into two. From the middle of this division a burning torch leapt out, throwing out flames, embers, and sparks. At the same time [part of] the body of the moon, which was lower was twisted up as though anxiously, and, using the words of those who related to me what they saw with their own eyes, the moon quivered like a snake that has been stabbed. After this it returned to its proper state. This fluctuation repeated twelve times or more, that is to say, that the fire kept up various projections as mentioned above and returned again

> to its previous state. After these fluctuations, from one horn to another, that is along its length, it became semi-dark as a consequence. This was told to me, who writes this, by those men who saw this with their eyes, [each] prepared to give his guarantee or oath, that they added nothing untrue to what is mentioned above.[5]

A close reading of the text immediately corrects a misconception in some of the scientific commentary (Hartung, 1976; Fritz, 2012), namely that the phenomenon recorded was observed by monks. There is, strictly speaking, nothing in the *Chronicle*'s account to support this. Moreover, if those who reported the incident were Canterbury monks, Gervase is perhaps unlikely to have been vague in their number, which is recorded as "five or more," not specifically five. Further, it is unlikely that monks would have been seated facing the moon after sunset, as the Office of Vespers and then Compline would have demanded their presence inside the abbey building. The status of the 'five or more' men is not specified, unlike their willingness to give guarantees or oaths which does imply a certain knowledge of legal procedure and social expectation. They were perhaps attached to Canterbury estates, given the fact that it was they who spoke to Gervase about what they had witnessed. Although, then, the witnesses were probably not book-learned, the details that Gervase emphasises, for example, that the horns of the crescent new moon projected eastwards would have been evident to anyone, whether educated or not.

The writhing of the image of the moon, quivering "like a snake that has been stabbed," is very suggestive of atmospheric turbulence. A particularly good example of the edge of a new moon "wriggling" in this way, when viewed telescopically close to the horizon above the Manchester area conurbation, was filmed in 2012 (Richard 1983, 2012). Such an explanation for the phenomenon reported to and by Gervase has received only cursory attention and indeed, natural atmospheric turbulence after sunset, even in June, would be expected to be small (Hartung, 1976; Withers, 2001). That said, a different, but related, proposition can be put

[5] 'Hoc anno, die Dominica ante Nativitatem Sancti Johannis Baptistae, post solis occasum, luna prima, signum apparuit mirabile, quinque vel eo amplius viris ex adverso sedentibus. Nam nova luna lucida erat, novitatis suae more cornua protendens ad orientem; et ecce subito superius cornu in duo divisum est. Ex hujus divisionis medio prosilivit fax ardens, flammam, carbones et scintillas longius proiciens. Corpus interim lunae quod inferius erat torquebatur quasi anxie, et, ut eorum verbis utar, qui hoc michi retulerunt et oculis viderunt propriis, ut percussus coluber luna palpitabat. Post hoc rediit in proprium statum. Hanc vicissitudinem duodecies et eo amplius repetiit, videlicet ut ignis tormenta varia sicut praelibatum est sustineret, iterumque in statum rediret priorem. Post has itaque vicissitudines, a cornu usque in cornu scilicet per longum seminigra facta est. Haec michi qui haec scribo retulerunt viri illi qui suis hoc viderunt oculis, fidem suam vel jusjurandum dare parati, quod in supradictis nichil addiderunt falsitatis' (Gervase of Canterbury 1879, I: 276). Translated from the original by Giles Gasper and Sigbjørn Sønnesyn.

forward: that what Gervase's witnesses observed arose from air turbulence associated with the hot column of air above a local fire, either human-made or natural. That sunset was mentioned suggests that it was not long after dark, and the background light level could have been quite high. A fire out of the line of sight of the observers, for example hidden by trees or below the crest of a hill, need not have been evident if there was little or no smoke. As shown below, refraction in the turbulent column of hot air above the fire could have resulted in the apparent double image of the almost vertical 'horn' of the crescent moon, when combined with the image from the direct line of sight to the side of the hot air column.

In order to determine quantitatively whether such an explanation is plausible, a modest amount of mathematics is required. With reference to Fig. 5(a), it is straightforward to show, from Snell's Law[6], that the angle of deviation Δ of a horizontal light ray entering a vertical cylindrical column of hot air is given by

$$\Delta = 2\delta n \tan i \qquad \text{Equation 1}$$

where i is the angle of incidence of the ray with respect to the surface normal of the cylinder and δn is the (small) difference in refractive index between the cool and hot air. A useful approximation to the refractive index of air $n(p,t)$ is

$$n(p,t) = 1 + 7.86\times10^{-4}\left(\frac{p}{273+t}\right) \qquad \text{Equation 2}$$

where p is the pressure in kPa and t the temperature in °C. In the context of a substantial fire, we might reasonably take the temperature of the hot air as 300°C and if the normal air temperature was 20°C, this gives a value of 1.3×10^{-4} for δn. The incidence angle varies with position and the exact shape of the column, but taking $i = 72°$, $\tan i = 3$. The deviation angle Δ is then 0.05°. As the angular diameter of the moon is about 0.55°, this represents a splitting of the horns of the crescent moon of about one tenth of the moon's diameter. For such a deviated ray to reach the eye of the observer together with that un-deviated by the hot column it would require the observer to be distant $D \approx 500$ m from the fire if the separation d of the rays at the edge of the column was about 0.5 m.

[6] Snell's Law of Refraction states that the angles θ_1 and θ_2 between the normal and the light rays on either side of an interface are related to the respective refractive indices n_1 and n_2 by $\sin\theta_1/\sin\theta_2 = n_2/n_1$

Refraction in such an idealised cylindrical column would result in a broadening rather than a splitting of the image. Such a simple splitting could be achieved if the moon were viewed at glancing angle through a rectangular cross-section column of hot air, for example above a hearth as in Fig 3(b). The angles i and i' between the rays and the perpendiculars to the surfaces shown there are related to the deviation angle Δ by

$$\Delta = \frac{\pi}{2} - i - i' = \theta - i' \qquad \text{Equation 3}$$

where θ is the glancing angle between the incident light ray and the edge of the hot air column. By reference to Fig 3(b) and use of Snell's Law, it is straightforward to show that, in the small angle limit,

$$\Delta \approx \delta n / \theta . \qquad \text{Equation 4}$$

In this moderately small angle approximation, this is half the value of Δ derived from Equation 1, where there are two glancing angle interfaces. For a value of $\theta = 9°$, the angular splitting of the lunar image, Δ, is 0.05°. A not unrealistic value of 3° gives a splitting of 0.15°, which would be readily visible.

However, to retain a sharp image of the lunar horn and hence a clear splitting rather than blurring, it is necessary that the refractive index be uniform across the cross-sectional area of the hot rectangular column above the hearth. This is unlikely to be fulfilled. However, if the glancing angle θ becomes smaller, a point is eventually reached at which the ray refracted by the first interface runs along the surface. The glancing angle θ at which this occurs is called the critical angle θ_c. For this to occur, in Fig 3(b) $r = \pi/2$ and so from Snell's Law

$$\frac{\sin i}{\sin r} = \frac{\cos\theta}{\sin\frac{\pi}{2}} \approx 1 - \frac{\theta_c^2}{2} = \frac{n_2}{n_1} . \qquad \text{Equation 5}$$

As $n_1 - n_2 = \delta n$, one has

$$\theta_c = \sqrt{2\delta n} \qquad \text{Equation 6}$$

If the hot fumes are at 300°C and the ambient air temperature is 20°C, the critical angle θ_c is very close to an angle of 1°. For glancing angle values of θ less than 1°, Equation 4 breaks down and total reflection occurs, the hot gases acting as a mirror; see Fig 3(c).[7] The deflection

[7] The total reflection is defined variously as total internal reflection or total external reflection. For example, when X-rays of typically 10keV energy are incident at angles below typically 0.5° on atomically flat and smooth surfaces the total reflection observed is termed total external reflection. This type of grazing incidence X-ray scattering, where the refractive index in the material is slightly less than unity, is used as a means of characterizing thin films in the semiconductor and magnetic data recording industries (Bowen and Tanner, 2006).

angle Δ jumps to 2θ, that is just under 2°, giving a huge angular displacement of the lunar image. There is no distortion in the image, because specular reflection occurs irrespective of the hot gas temperature or its uniformity, provided that the refractive index difference between the gas and the ambient air is such that the viewing angle is less than the local critical angle. A sharp splitting of the horns of the moon will have been prominent. Although the curvature of the horn which is the mirror image will have been opposite to that of the direct image, the flower-like opening out of these two images will have aided the identification of the sparks arising from the "middle of the division." There is no comment on the curvature of the images in the medieval account. The writhing of the main image may relate to turbulent refraction effects, although such an effect could also be produced in total reflection by the boundary between hot and cold gases distorting, thereby changing the effective reflection, and hence displacement, angles.

It is worth noting that such total (usually termed internal) reflection from layers of hot air just above the ground is the standard explanation for the formation of mirages in hot climates. The lunar splitting might be thought of as a "vertical mirage" from the boundary between the hot and cool gases. This kind of localization of hot gases is possible from a house fire, where part of the building is engulfed by flames and the hot air is emerging from just part of the building, and though perhaps it is unlikely to have been repeated "twelve times or more," this repetition could have occurred if the conditions for total reflection were being fulfilled intermittently. Such a configuration could also be found in relation to metalworking. If focused on Kent, where the majority of Christ Church's property lay, iron-smelting might come into consideration, although this is not without some interpretative difficulty. While the Weald of Kent had been a rich source of iron ore under Roman rule, and would become so again in the Early Modern period, this was not the case for the intervening centuries (Geddes, 1991; Clere and Crossley, 1995). The most important sources of iron ore in the medieval period were the Forest of Dene, the Midlands, south Yorkshire, Cumbria, Durham, and Northumberland. This does not preclude smelting in other regions, trade in iron across England appears to have been easy and frequent, and the considerable import of iron ore, for example from Sweden, should be taken into account also in this connection (Geddes, 1991). Processing of iron took place in bloomeries, with a well-documented example from the middle third of the fourteenth century, at Tudely in Kent (Geddes, 1991; Giuseppi, 1913). How far back this activity in the region around Canterbury can be dated, and whether specifically to the later twelfth-century, is not possible to establish. Examples of shaft and bowl furnaces, the latter no more than a metre in width and 50 cm deep, with a bellow system, are to be found in the twelfth century, but in Durham rather than Kent (Geddes, 1991; Tylecote,1959).

Medieval smelting techniques could not reach the melting point of iron itself (1538°C), but use of the blooming process enables production at about 1000°C. Although speculative, it is not too difficult to imagine, perhaps following installation of new bellows or an over-enthusiastic operator, that the air forcing process could have become uncontrolled, blowing red hot charcoal into the air. The blast of extremely hot air combined with the burning material ejected from the projecting hearth edge would send up "flames, embers and sparks" in a turbulent column of air that would have resulted in both the splitting of the image and the apparent twisting of the body of the crescent moon. At each release of hot gas, the refractive index difference would have increased, thereby causing total external reflection and apparent splitting of the lunar image at a fixed angle of observation. Ceasing operation of the bellows would have returned the image again to normal as the refractive index difference dropped, for the sequence only to be repeated again as new fuel was added to the hearth and the bellows again operated to force the burning. Eventually, after twelve or more such sequences, the fire may have started smoking, the smoke obscuring and hence darkening the image of the moon. By this time, the darkening sky will have made direct detection of the smoke difficult or impossible.

A further possibility for a fire producing a narrow column of hot gases is also connected to metal-working but of copper alloys, and in particular in the process of bell-casting (Blair and Blair, 1991; Elphick, 1988). While this process could take place within churches, highlighting the liturgical significance of the act, for example at ninth century Vreden (Germany) and fourteenth century Sola (Norway), it was not exclusively so (Arnold and Goodson, 2012; Hommedal, 1986a; Hommedal, 1986b). The methods of casting recorded in the remarkable early twelfth century treatise on metal-working, glass, and stone, *De diversis artibus* [*On the Divers Arts*] by a German monk, Roger of Helmershausen, known to posterity as Theophilus Presbyter, seems, with a few variations, to have been standard (Theophilus, 1967). The description of the process includes a pit dug out to hold the mould, with a furnace built up around, a fire is then lit around the mould as the furnace is finished, leaving a small aperture, the fire then kept alight for 24 hours, with the bell bronze heated separately (Blair and Blair, 1991). This procedure would also, if managed inopportunely, be capable of creating the atmospheric conditions that, together with the requisite sight lines of the observers, might have led to the phenomenon described to Gervase.

Church bells and bell towers were increasingly common across Europe from the later tenth century; from the mid-eleventh century bell towers were frequently built within churches in Britain. The Normans also developed a particular type of bell tower over the course of the twelfth and thirteenth centuries (Christie, 2004; Arnold and Goodson, 2012). Christ Church, Canterbury was exemplary of this process (Gibson, 1995). Prior Conrad (1107-1126) was remembered for having commissioned five extremely large bells: "The first took ten men to ring it, as did the second; the third took eleven men, and the fourth eight, but the fifth needed twenty-four" (Wharton, 1691).[8] Within Gervase's lifetime Prior Wibert (reigned 1153-1167) created a free-standing bell tower in 1167, south of the choir, which housed a great bell "which took 32 men to ring it."[9] While the fire of 1174 did no lasting damage to the bell collection, as the damage and repairs focused on the choir, bells played an important part in the life of the community.

Concluding Comments

It can be stated confidently that whatever the men who made their report to Gervase of Canterbury saw, it was not the creation of the crater Giordano Bruno. Modern scientific analysis of the lunar surface reveals no evidence that the crater was formed within human history, and the connection to the entry in the *Chronicle* should be identified as the nostrum it most certainly is. Nevertheless, the wonders seen in the night sky in June 1178 and their record within Gervase's *Chronicle* provoke stimulating questions as to how and why he included the material that he did, alongside the broader methodological implications of interpretation and analysis of the incident using the research insights of modern science in tandem with humanities. There is no need either to postulate an extraordinary lunar event or discredit the whole report as fabrication. Careful analysis of the text reveals much about Gervase's intentions and a more prosaic origin for the incident described.

Despite his biases, directed in particular towards Archbishop Baldwin, and, more positively, to the notion of the collective will of the monastic community at Christ Church, Canterbury, Gervase's record of astronomical phenomena is noteworthy, as it describes effects in considerable and accurate detail. The description of the writhing moon throwing out sparks and embers should perhaps be taken, then, at face value. Taking that line of approach, it is possible, as shown above, to provide a coherent and cogent explanation for the incident as the result of atmospheric turbulence deriving from a hot column of air produced by a fire. Although speculative the explanation is plausible. That Gervase chose to include the episode in his *Chronicle* is evidence in its own right that he attached to it some significance. The record aligns to and illustrates aptly his description of a chronicler's purpose: the computation of time, the

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[8] "quinque signa permaxima, quorum primum X. similter secundum X. tertium XI. quartum VIII. quintum vero XXIV homines ad sonandum, trahunt" (Wharton, 1691, 137). Translated from the original by Giles Gasper.

[9] "Signum quoque magnum in clocario posuit, quod triginti duo homines ad sonandum trahunt" (Wharton, 1691, 138). Translated from the original by Giles Gasper.

deeds of kings and princes, and the record of miracles and portents, and all of this within a compass short and succinct. He would not in this way have felt it necessary to analyse the phenomenon, which he notes as wondrous, in any further detail. Modern scholarship on the episode does not share such reticence. That Gervase's moon should have prompted interest from modern scientists is striking, but the limitations of a mono-disciplinary approach to this history, and this 'science', are clear. By employing a collaborative methodology, a fuller interpretation is possible, that retains the integrity of Gervase's account while at the same time exploring its physical implications.

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