Istituto Lombardo (Rend. Scienze) 155, 109-134 (2021)

ROBERT GROSSETESTE: A MEDIEVAL THINKER WITH A LEGACY FOR MODERN SCIENCE

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Nota presentata dal m.e. Carlo E. Bottani
(Adunanza del 20 maggio 2021)

SUNTO. – Roberto Grossatesta (circa 1170-1253) fu uno dei primi studiosi a incorporare le idee di Aristotele, appena riscoperte, nella filosofia naturale medievale. In una serie di brevi trattati scientifici scritti tra il 1215 e il 1230 circa, si concentrò sulla spiegazione del perché, piuttosto che del come, il mondo naturale si comporti in un dato modo. Adottò un principio di riduzione per cui i fenomeni complessi possono essere compresi in termini di un comportamento sottostante più semplice che può essere verificato dall'osservazione. Ad esempio, spiegò le caratteristiche dell'arcobaleno in termini di ottica, che a sua volta può essere spiegata dalla geometria. La teoria del "Big Bang" di Grossatesta sulla formazione dell'universo, basata sull'espansione della luce da un punto, si fonda sulla necessità di spiegare la stabilità della materia solida. Sebbene i manoscritti sopravvissuti non contengano quasi nessun diagramma, è evidente che egli pensò sia matematicamente sia pittoricamente nello sviluppo di un modello unificato dei fenomeni naturali. In una collaborazione interdisciplinare unica tra storici, filosofi, paleografi, linguisti, artisti e scienziati (www.ordered-universe.com) abbiamo dimostrato come un esame dettagliato della scienza di Grossatesta possa stimolare sia la nuova ricerca scientifica contemporanea sia la creatività artistica.

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ABSTRACT. – Robert Grosseteste (ca. 1170-1253) was one of the first scholars to embed the newly rediscovered ideas of Aristotle into medieval natural philosophy. In a series of short scientific treatises written between about 1215 and 1230 he focused on explaining why, rather than how, the natural world behaves as it does. He adopted a principle of subalternation in which complex phenomena could be understood in terms of simpler under-

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lying behaviour that could be tested by observation. For example, he explained the features of the rainbow in terms of optics, which in turn could be explained by geometry. Grosseteste's "Big Bang" theory of the formation of the universe, based on the expansion of light from a point, is founded on the need to explain the stability of solid matter. Although surviving manuscripts do contain almost no diagrams, it is evident that he thought both mathematically and pictorially in developing a unified model of natural phenomena. In a unique interdisciplinary collaboration between historians, philosophers, palaeographers, linguists, artists and scientists (www.ordered-universe.com) we have shown how detailed examination of Grosseteste's science can stimulate both new contemporary scientific research and artistic creativity.

1. Introduction

The thirteenth-century polymath, Robert Grosseteste, was born probably around 1170 in the County of Suffolk in the East of England. While the village of Stradbroke does claim to be his birthplace, there is no contemporary evidence for this claim. This is even the case for attribution of his birthplace to Suffolk, it being based on the writing, between 1314 and 1320, of the historian Nicholas Trevet. Of his early life, little is known, though he may well have been educated in the cathedral school at Lincoln. The first firm evidence of his whereabouts is in the last half of the 1190s when he held a position at the court of William de Vere, the Bishop of Hereford. He evidently had considerable talent in the liberal arts, law and medicine, as emphasized in a glowing letter of commendation written to Bishop William by Gerald of Wales in 1195 [1]. From 1198, William de Vere's household being dissolved on his death, evidence of Grosseteste's location is sparse, although it can be said with some confidence that between 1198 and 1225 he spent time not only in Hereford, but also in France and probably in Paris [2]. Even in 1225, when he was appointed Rector of Abbotsley, near Cambridge, his whereabouts are a matter of debate and it is not until 1229, when he was appointed Lector to the Franciscan community, that he can be firmly placed in Oxford. Despite him being appointed to his first ecclesiastical position quite late in life, his subsequent rise within the Church was rapid. In 1231, he was appointed Archdeacon of Leicester and in 1235 Bishop of Lincoln, which was the largest diocese in the England at the time. Until his death in 1253, he was an energetic and reforming bishop, in dispute with his own Cathedral Chapter and, famously, the Papacy over matters of Church administration. He is buried in Lincoln Cathedral and several attempts at canonization during the Middle Ages all failed.

Between about 1220 and 1230, Grosseteste wrote some dozen short works on natural philosophy. These reveal a familiarity with and development of Aristotle's works in the same area, which by this stage were circulating widely in northern Europe in Latin translation, many since the 1150s at least. The great majority of Grosseteste's writings on natural philosophy are infused with the thought of Aristotle. A compilation of the probability of Grosseteste citing Aristotle either by name or as The Philosopher reveals, at first sight, an increase with time (*Fig. 1a*) over the period of his scientific writing. However, these data must be viewed with considerable caution as they reflect multiple influences and factors.

The first problem is associated with the difficulty of determining the chronology of Grosseteste's works and arises directly from the relative lack of information about his activities prior to 1229. As is also the case with other medieval scholars, dating relies heavily on textual analysis. A consequence has been wide disparities between scholars as to the dates of specific works and, for example, various writers have suggested dates for the treatise on light, *De luce,* as far apart as 1215 and 1240 [3]. The analysis in *Fig. 1* is based on Cecilia Panti's chronology of the works that she regards as authentic [4] and although it is presently regarded as the most probable sequence, it is by no means fully established. The authenticity of certain works is also in dispute. The second issue relates to the fact that in a number of works, such as the treatises *De generatione sonorum* (On the Generation of Sounds) and *De cometis* (On Comets), Grosseteste makes reference to Aristotelian concepts without specific citation [5, 6]. While use of concepts without citation was common practice, inclusion of these works into the data plotted in the graph of *Fig. 1a* would significantly flatten its shape. While there is no firm evidence that the omission in *De generatione sonorum* or *De cometis* is associated with the ban on the works of Aristotle in University of Paris in the thirteenth century, there is evidence [5] that *De cometis* may have been written in Paris around 1222, after the appearance of Halley's comet in that year. As there is also evidence that Grosseteste some spent time in France, and probably in Paris, during the period in his life when the treatises were written, circumspection in acknowledging the source might be understandable if the works in question were written or circulated in Paris.

Finally, attempts to trace the development of Grosseteste's thought are complicated by his steady change in citation practice over time (*Fig. 1b*). This could reflect a different engagement with the text and a different level of access to his sources, for example, use of a personal copy for sustained reading. It could also indicate a change in audience, such as a greater emphasis on teaching. While the distribution of citations across the later works is not uniform, there is a dramatic change in practice between the periods 1210-1220 and 1220-1230. In these later works, not only is the source author named, but also specific works are cited. The reason for this change in approach is not evident, but in the increased frequency of citations there is a greater probability of specific citation of Aristotle in the later works.

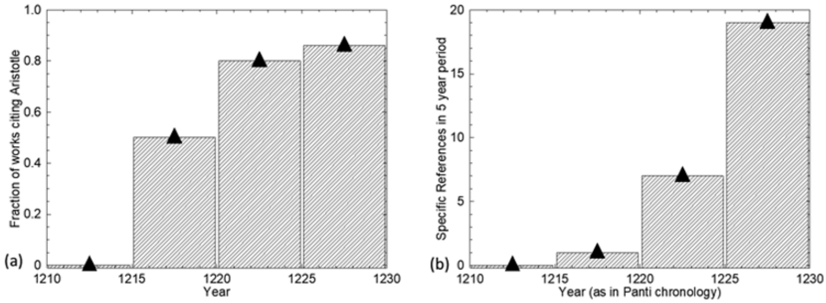

Fig. 1. (a) Fraction of Grosseteste's scientific works specifically citing Aristotle as a function of time. (b) Total number of specific references to any author as a function of time. Both plots are in 5-year data bins.

2. Experience or Experiment

There is no doubt that Grosseteste was familiar not only with the physics of reflection of light from polished surfaces, but also the refraction of light at interfaces between media of different refractive index. This is evident in the first part of the treatise *De iride* (On the Rainbow) where he states that:

> 'The first part [of optics] is fulfilled in the science we say deals with sight; the second in that which we call 'on mirrors'; the third part has remained untouched and unknown among us until the present time. Nonetheless, we know that Aristotle brought this third part to completion, which is much more difficult than the other parts on account of its intricacy, and which, on account of the profundity of natures [concerned] stands out as much more worthy of wonder.' [7,8]

The implication of Grosseteste's statement is that the studies of reflection (catoptrics), presumably of (Pseudo-)Euclid and/or Ptolemy, were known in northern Europe at the time but that the principles of refraction (dioptrics) were not so clearly established. It is not clear what were Grosseteste's sources on dioptrics; his only specific reference to refraction is to the experiment of the object in the cup of water (*Fig. 2*) which, somewhat bizarrely, is posited as a principle in the book *De speculis* (On Mirrors) of pseudo-Euclid, the book being otherwise entirely concerned with catoptrics.

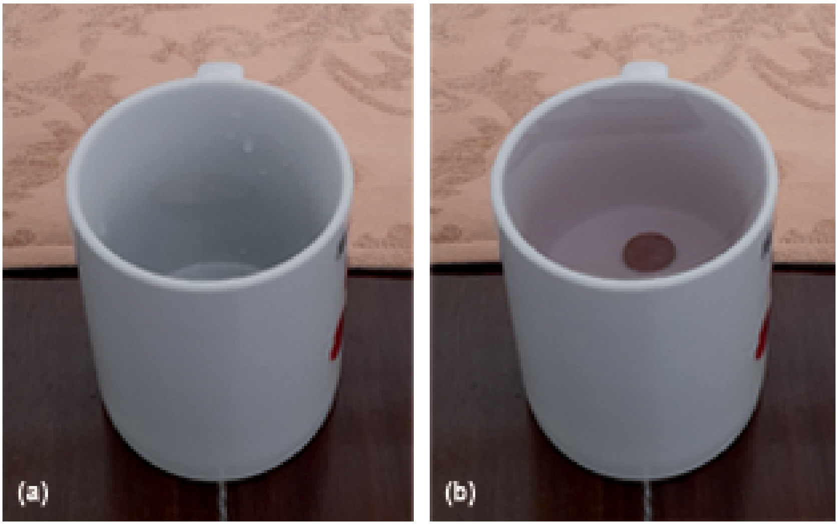

Fig. 2. The 'object in cup' experiment described by Grosseteste. (a) With no water in the cup, the coin, (as the object is described in one manuscript), is invisible at the chosen angle of sight while (b) it becomes visible, at the exact same angle of sight, when water is poured into the vessel.

While the reference to *De speculis* does not reveal whether Grosseteste actually carried out such an experiment himself, there are several instances where he encourages his readers to experiment for themselves. In the treatise *De natura locorum* (On the Nature of Places), during discussion of the focusing of light rays through refraction at the interfaces of a full, round glass body, Grosseteste comments that refraction can be beautifully observed in an example that will be familiar to his readers. He asserts that anyone can verify that, if a urine flask is held in the light from the sun, the rays run together to a point where something easily flammable can be set on fire. This direct appeal to action is echoed in the treatise *De impressionibus elementorum* (On the Impression of the Elements). Here, in describing the properties of bubbles, he explicitly explains how to undertake the experiment (*Fig. 3*) that he envisages.

> '… some [bubbles] remain in the water, and some ascend above the water. Let us first, then, talk about those that ascend. If anyone should like to see this with his own eyes, let him put clear water in a clear bronze dish, and he will clearly see ascending bubbles being generated by the heat of a fire placed underneath the dish.' [9]

These appeals to experience, although providing important lessons for the teaching of physics today [10], cannot be described as controlled experiments in the modern sense. Grosseteste was, seemingly, an acute observer and interpreter of natural phenomena even though A. C. Crombie's original claims concerning the extent of such contributions to the structure and methods of modern experimental science were subsequently substantially softened by the author in the second edition of his book on Grosseteste's scientific works and their legacy [11].

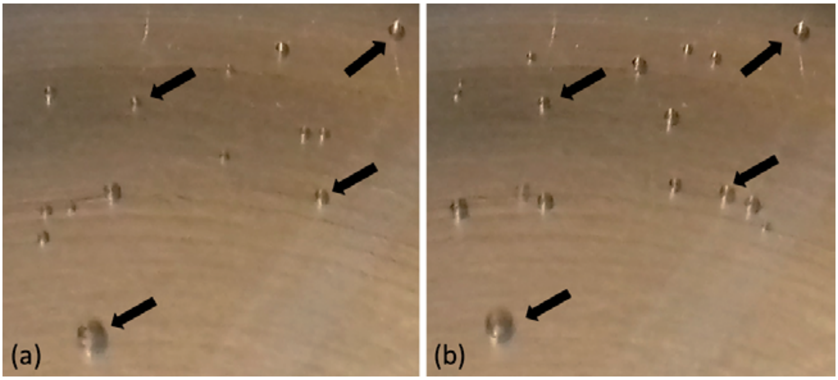

Fig. 3. A modern realization of the experiment described by Grosseteste. Adjacent frames from a video of bubbles in a polished pan of boiling water showing examples of bubbles that do not ascend to the surface.

It is in his treatment of refraction at interfaces that doubts as to the extent of his experimental approach become evident. Grosseteste had assimilated the concept of light travelling in straight lines into his thinking and he accurately discusses in the first part of *De iride* how light is refracted abruptly at an interface between different transparent media. He correctly explains the optics of the coin-in-cup demonstration (*Fig. 1*) in terms of the change in the position of the virtual image [12]. The conclusions are reached logically, predicated on the premise that light travels in straight lines, and they are not the interpretation of quantitative measurements. Indeed, if Grosseteste had undertaken such measurements, it is doubtful that he would have put forward his assertion that the angle of refraction is half the angle of incidence with respect to the normal to the interface. He states in *De iride*:

> 'I say, then, that the entry of the ray into this second diaphanous [medium] is according to the path of a line dividing into equal parts the angle enclosed by the ray, conceived as extending continuously and straight, and the line extended, at a right angle over the surface of the second diaphanous [medium] at the point at which the ray meets the diaphanous [medium], and into its depths. Furthermore, experiences similar to those through which we learn that the reflection of a ray over a mirror is at an angle equal to the angle of incidence show us that the size of the ray's angle of refraction is determined in this way. This same fact is made manifest to us by that principle of natural philosophy, "that every operation of nature is in the most complete, most ordered, shortest, and best way possible for it." ' [7,8]

The argument that nature's operations are the most ordered and the shortest, while foreshadowing William of Ockham's later principle, leads here to a wrong conclusion, as does the appeal to the similarity with the equal angles of incidence and reflection from a mirror. Grosseteste does not appear to have known the work on optics of Ibn al-Haytham (d. c. 1041 CE), which was to have considerable influence on European optics from the late thirteenth century. It had been translated into Latin in the late twelfth or early thirteenth century but its early circulation remains unclear. [13]. If Grosseteste had done so, it is likely that he would have appreciated Ibn al-Haytham's comment that

> ' … the angles of refraction do not maintain the same ratio with the angles [of incidence] that the first line forms with the normal: rather these ratios vary in the same transparent body.' ([14] p 251).

Although Ibn al-Haytham did not give values for the angle of refraction as a function of the angles of incidence, he did formulate seven general rules [15] for the variation and gave detailed instructions on how to fabricate the apparatus and use it to measure the pairs of angles systematically under controlled conditions. These instructions are based on the briefer instructions found in Ptolemy's fifth book of his On Optics, written some time in the second century CE. Unlike Ibn al-Haytham, Ptolemy does give the measured angles of incidence and refraction, in tabular form, for transmission of light from air to water, air to glass, and water to glass [16]. Further, unlike Ibn al-Haytham and subsequently Witelo around 1270, Ptolemy does not discuss refraction from a denser to a less dense medium and neither does he indicate that such measurements were even attempted. While there are grounds for doubting whether either Ibn al-Haytham [15] or Witelo [12] actually performed all the refraction measurements described, Ptolemy's data do match very well those that a modern experimenter can obtain and, with one exception, lie close to the curve predicted by Snell's Law[1] (*Fig. 4a*).

It is extremely unlikely that Grosseteste had access to Ptolemy's On Optics as it survived only in a single manuscript in Latin from the mid-twelfth century, associated with Eugenius of Sicily, translated from Arabic, itself translated, presumably, from the Greek original [16]. In the context, Grosseteste's postulate that the angle of refraction is half the angle of incidence is not at all unreasonable. This proves to be even more nearly a sound approximation if one examines the variation of incidence and refraction angles for glass of composition available in medieval Europe (*Fig. 4a*). Classical glasses were manufactured using a flux of natron, a naturally occurring mixture of sodium carbonate decahydrate and sodium bicarbonate found in Lower Egypt, resulting in high sodium content glass [17] of refractive index typically about 1.49 [12]. The natron deposits became exhausted in the ninth century CE and use of plant ash as the flux became more common as the medieval period progressed. The composition of a thirteenth-century clear glass from Sienna Cathedral corresponds to a refractive index of 1.52 [12]. Inspection of *Fig. 4b* reveals that the deviation from Grosseteste's 'half-angle' law is less than 5° across the whole angular range for both types of glass. On the other hand, only for angles of incidence nearly perpendicular to the interface does this criterion hold for transmission of light

1 Snell's Law of Refraction states that, with respect to the surface normal, the angle of incidence *i* is related to the angle of refraction *r* by $\sin i / \sin r = n$, where *n* is a constant called the refractive index.

from air to water. One can be totally confident that Grosseteste did not test his hypothesis against quantitative experiments.

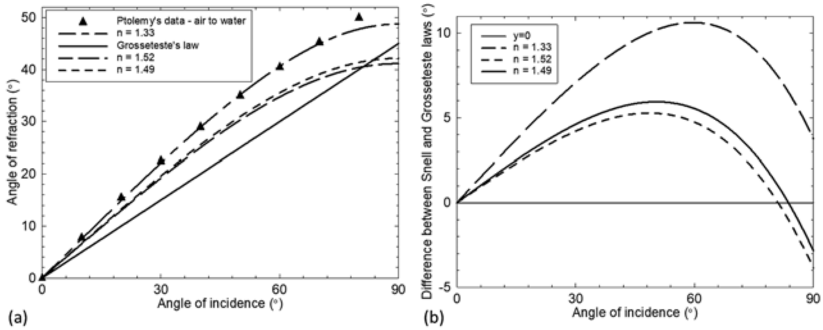

Fig. 4. (a) Comparison between angles of incidence and refraction according to Snell's law and Grosseteste's law of refraction. The curves for n = 1.49 and 1.52 represent the typical limits for air to medieval glasses, while the n = 1.33 curve represents refraction from air to water. Triangles are the data points given in Ptolemy's Optics. (b) Deviation of Grosseteste's law from Snell's law for air to water and glass.

On the other hand, Grosseteste could possibly have applied his knowledge of optics to the magnification of objects and also visualization of objects at a distance, that is, telescopic observation. He states in *De iride*:

> 'For if known perfectly, this part of optics shows us the way in which we may make things very far away appear as though placed very close by, and in which we may make large things placed close by appear very small, and in which we may make small things placed far away appear as large as we please, so that it becomes possible for us to read very small letters at an incredible distance, or count [grains of] sand, or seeds, or [blades of] grass, or whatever you might want.'

and

> ' It is also evident to these same [who know optics perfectly] how to shape diaphanous [objects] so that these diaphanous [objects] will receive the rays emitted from the eye according to an angle, made in the eye, of whatever size they want' [18].

There is debate as to whether lenses were in use in the high medieval period and if so to the extent of their use, but it can be demonstrated that all the effects described by Grosseteste can be obtained with a single lens [18]. This includes single-lens telescopic observation without recourse to the twin-lens spy-glass that appeared only in the early seventeenth century. Roger Bacon (1214-1292), in the Sixth Part of his *Opus Majus*, which was sent to the Pope in 1267, described how use of the smaller part of a glass sphere enabled those with weak eyes to see magnified letters.

> 'If a man looks at letters or other small objects through the medium of a crystal or of glass or of some other transparent body placed above the letters, and it is the smaller part of a sphere whose convexity is toward the eye, and the eye is in the air, he will see the letters much better and they will appear larger to him. … Therefore this instrument is useful to the aged and those with weak eyes. For they can see a letter, no matter how small, sufficiently enlarged' ([19] p 574.)

Bearing in mind that Bacon copied parts of Grosseteste's work for his own purposes without attribution, it is not beyond the realms of possibility that the optical devices referred to by Grosseteste were plano-convex lenses such as described by Bacon. Use of lenses in the thirteenth century is difficult to prove, though by the first few years of the fourteenth century there are references to *vitreos ab oculis ad legendum* [20].

Invention of a device for magnification of text, referred to as a 'reading stone', has been accredited to the Islamic scholar and innovator, Abbas ibn Firnas (c. 809/810 – 887 CE) although this ascription is open to interpretation. A reading stone produced using a glass-blowing pipe such as would have been available in the thirteenth century is shown in *Fig. 5a*. A cylinder of glass 76 mm in diameter, with an approximately hemispherical end, was blown in 2018 by Colin Rennie at the National Glass Centre, Sunderland, U.K. After allowing the cylinder to cool, its end was cut and polished to form a flat surface perpendicular to the cylinder axis, at a distance 50 mm from the end. While the reconstruction was cut with a diamond saw and polished with proprietary grit, such a surface could have been produced more slowly with a wire saw and sand. The remaining cylindrical section determines the minimum distance that the curved surface can be located with respect to the object, for example letters and characters on a page of writing (*Fig. 5b*). In other respects, the magnifying optics of the curved part of the reading stone are equivalent to those of the smaller part of the sphere that Bacon described. As the radius of curvature of the section of the hemisphere was measured to be

40 mm, ray tracing indicated that making the cut at the distance of 50 mm would result in a magnification of just under two. This proved to be the case experimentally (*Fig. 5b*).

Whatever the interpretation of Grosseteste's reference to the shaping of diaphanous objects, the quotation above from *De iride* indicates that he understood that the magnification of an object is determined by the angle which rays make at the eye. Elsewhere in the treatise he states that it is the narrowness of the angle at which an object is seen that makes it invisible, not the distance [12].

Fig. 5. Modern reconstruction, for the author, of a medieval reading stone by Colin Rennie, University of Sunderland. (a) Glass cylinder with end section which is a part of a hemisphere. (b) Magnification of text when the reading stone is slid over the page.

3. Subalternation

3.1 De iride (On the Rainbow)

An important feature of Grosseteste's scientific thinking is his adoption of Aristotle's principle of subalternation. Aristotle, and Grosseteste after him, was concerned with understanding the reasons why phenomena occurred (science *propter quid*), not just how phenomena happened (science *quia*) [11]. Grosseteste, in understanding the formation of the rainbow, states that the knowledge of the mechanisms producing the rainbow is to be found in the science of optics, which itself is explained by geometrical figures pertaining to sight. The science of the rainbow is subalternated to optics, which itself is subalternated to geometry. Therefore, says Grosseteste at the beginning of *De iride,* although inquiry into the mechanism by which the rainbow is formed falls within the remit of both the student of optics and the student of physics, the student of physics wishes to know that various things happen, while the student of optics is concerned with understanding why these things occur. Although unspoken, such a strategy results in breaking down a complex problem into explanation of simpler phenomena which can be observed and tested. The formation of the rainbow is explained by studying how light is refracted at interfaces between the air, the cloud and the collection of droplets falling from it. The behaviour of light refracted at interfaces is understood through the science of dioptrics.

Although, as seen in section 2, Grosseteste's axiom that the angle of refraction is half the angle of incidence does not stand up to detailed experimental scrutiny, nevertheless, his grasp of the science of optics was sufficient to postulate a plausible and testable mechanism for the formation of the rainbow based on refraction, a major step forward in its understanding. In his model, the cloud and drops of rain falling from it is in the form of an inverted cone with a curved base. Sunlight initially refracted at the interface between the air and the cloud, is further refracted at the interface between the cloud and droplets. Grosseteste then proposes that the light is focused within the cone and its refraction at the air-droplet interfaces spreads the light out onto a conical surface, the light rays having the shape of an arch. The concentrating of the light enables him to explain the rainbow colours in terms of his theory of colour based on combinations of three sets of opposite qualities, developed within the short treatise *De colore* (On Colour) [21]. Two of the pairs of qualities, bright-dim (*clara-obscura)* and copious-scarce (*multa-pauca*), are of the light itself while the third, pure-impure (*purum-impurum*), is determined by the material through which the light shines. The colour extreme of white comprises *clara, multa* and *purum* qualities, while that of black is *pauca*, *obscura* and *impurum*. Using a combinatorial approach, Grosseteste argues that there are thus 7 (i.e. 2^3-1) colours close to white and 7 colours close to black and no more [22]. In *De colore,* Grosseteste explicitly states that *multa* does not relate to a large amount of diffuse light, but that it is equivalent to the concentration of light through focusing by a concave mirror [20]. Focusing of light in the inverted cone of falling raindrops therefore influences the colour of the light in different parts of the rainbow.

The model was criticized by Roger Bacon. Amongst his arguments against the rainbow resulting from refraction is that refraction in a cone will not generate a figure corresponding to the surface of a cone [19]. While it is tempting to agree with Bacon, experience of

Grosseteste's writing suggests that the introduction of the inverted cone and its generation of the arch of coloured light as on a conical surface was deliberate and may have been based on an underlying observation. A chance observation by the present author of colouration in a caustic formed by ceiling lights at the base of a conical wine glass filled with water (*Fig. 6*) led to an experimental and ray-tracing investigation into the generation of caustics in liquid-filled conical vessels.

Both experimentally and computationally, it was found that under certain illumination angles, white light entering the top surface of the conical vessel was refracted into a curved, coloured caustic resembling a rainbow [23]. Because of the low symmetry of refraction through a conical object, the optics had not been explored in detail before this work. The results do provide an example of where new science was stimulated by the study of the medieval texts, suggesting that Southern's sweeping assertion that the study of medieval science 'is a historical experience, and scarcely an avenue to scientific or theological truth' ([24 p lxvi]) may deserve a little nuancing.

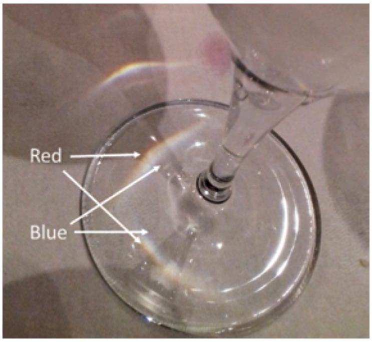

Fig. 6. Coloured caustics from two halogen ceiling lights formed at the base of a conical wine glass full of water at a dinner table in January 2017. Such an observation is fully in the spirit of perception through common experience, evidenced by Grosseteste's texts.

3.2 *De luce* (On Light)

Perhaps the most well-known of Grosseteste's scientific writings is his late treatise *De luce* (On Light) [25,26]. Probably written about 1225, and perhaps almost contemporaneously with *De colore*, it contains the bold assertion that light (*lux*) is the first corporeal form and that it multiplies itself infinitely, expanding instantaneously from a point into a sphere. Not only is light the first corporeal form, but it is light that gives extension and dimension to all matter. This dimensionality arises despite neither corporeal form (corporeity) nor matter themselves having any dimension and is achieved because of the ability of light to multiply itself instantaneously an infinite number of times.

The leap of thought made by Grosseteste is to move from consideration of the stability of immediately observable solids to a model for the formation of the entire universe. Critical to his thought is that, because light is the first corporeal form and because form and matter are inseparable, by its expansion into all directions, light introduces the three dimensions into matter. In the beginning, light extended matter, pulling it out into a sphere the size of the material universe. This issue of the beginning of the universe will have been important to Grosseteste in that, as a Christian cleric, the Biblical account of creation will have been paramount. On the other hand, within the Aristotelian framework which he had espoused, there was no beginning and no end to the universe; it extended infinitely in time. There is no hint in the *De Luce* as to whether or not Grosseteste set up the model to attempt to reconcile Aristotelian and Christian cosmogenesis or whether he simply wanted to explore within the Aristotelian framework the consequences of his hypothesis that light is the first form. What he does succeed in doing is to provide an elegant and logical mechanism for the formation of the universe in Aristotle's scheme of nested spheres with the Earth at the centre. It is even more striking that this is an initially expanding universe. The result is a strikingly original approach to explaining the structure of the heavens and the Earth, based on a central concept of light. To a modern scientist, careful reading of the clearly laid out text suggests that it can be interpreted as being based on a single set of physical laws, which are unitary across the universe.

Grosseteste recognized that as light instantaneously drags matter outwards, the density must decrease as the radius increases if the amount of matter within the sphere of light remains conserved. As a vacuum is impossible within Aristotle's structure, Grosseteste postulated that there must be a minimum density, (or maximum rarefaction), beyond which matter cannot be further rarefied. At this radius, there is what we might now refer to as a phase change of the coupled light and matter into a state of perfection within which no further change is permissible. This is the outermost sphere of the universe. At this point, because light must continue multiplying itself, he asserts that this most rarified of bodies, consisting only of first form (*lux*) and first matter, itself emits light of a different kind (*lumen*) towards the centre of the sphere contained within the perfected first shell. Because the *lumen* is coupled and intrinsic to matter, it sweeps up and compresses the matter inside the sphere as it propagates inwards. As there is no creation of new matter, that in the outer region is rarefied. At a certain critical ratio of lumen to matter, the matter becomes perfected and can no longer undergo change. This generates the second of the celestial spheres, that of the fixed stars. *Lumen* is emitted from this newly perfected sphere, and again compresses matter until the further rarefaction and compression results in a third perfected sphere. Below the ninth sphere, that of the moon, the *lumen* is not sufficient to perfect the material of the elements (fire, air, water, earth) and these thus do not allow natural circular motion, which pertains only to perfect bodies, but just natural radial motion. They also permit decay and violent motion.

Despite containing no mathematical symbols, the text of *De luce* is nevertheless carefully structured in a mathematically logical sequence. This provided the intriguing possibility not just of translating from the edited Latin text into modern English, but of translating the English text into the language of mathematics. Having achieved that, it proved possible, though not without some unexpected computational challenges, to calculate numerically the structures predicted within Grosseteste's text [27]. It was necessary to assume an inverse power law distribution of initial density in the model universe, as the text does not describe the initial expansion process in any detail, but conservation of matter results in the standard continuity equation and the inward propagation of lumen is described by a differential propagation equation with terms for the geometric concentration of light in a spherical geometry, the absorption of light as it passes through matter and the generation of *lumen* by perfected matter [28]. The mathematical terms in the equations are faithful to the words in the text. For example, in Grosseteste's discussion of diurnal motion, he argues that the lower spheres are lower in purity and therefore they receive diurnal motion in a weakened state because the first corporeal light in them is weaker. As the text makes it clear that perfected matter is the source of lumen, the term in the propagation equation governing the change in intensity of *lumen* is set proportional to the density of perfected matter. There is some ambiguity in the text as to the conditions for perfection of the inner spheres, but it can be interpreted as equivalent to *lumen* being necessarily in multiples of the intensity of *lux*, and that a critical ratio of matter to intensity was required for perfection.

The remarkable result was that such a scheme did produce a sequence of concentric perfected spheres in the manner that Grosseteste described. Without opacity of the perfected spheres, the number of spheres generated did not converge and by continued running of the calculation any number of spheres could be generated. This was corrected by assuming that *lumen* is absorbed by the already perfected spheres and then, with different combinations of lumen generation and absorption in both perfected and unperfected matter, various numbers of spheres could be generated.

The nine perfected and one imperfect sphere, the latter comprising four sub-spheres of fire, air, water, and earth, required in the Aristotelian scheme was justified by Grosseteste though a geometric argument based on the perfection of the number ten, that is, nine plus one. This last part of *De luce* has received criticism, for example, from Southern, who stated that 'it must also be observed that, like much else that he [Grosseteste] wrote, it tails away into a rather chaotic and unintelligible sequel in its final paragraphs' [24]. However, despite changing his approach, Grosseteste's argument is no less taut and lucid than in the earlier part of the treatise. He starts by using ideas associated with the Arabic scholar Abu Ma'shar al-Balkhi (whose Latin name is Albumasar) and Daniel of Morley, stating that

> 'in the highest body – which is the most simple of bodies – we can find four things; namely, form, matter, composition, and the composite' [27].

Form is assigned to the number one, matter to the number two, composition to the number three and composite to the number four, each with a corresponding number of qualities. The sum of these numbers is ten, which is argued to be the perfect number of the universe. If they ever existed, no diagrams survive in any of the extant manuscripts, all of which are later copies of Grosseteste's original work. Nevertheless, it has been suggested that Grosseteste was thinking geometrically when reaching this conclusion [29]. As illustrated in *Fig. 7*, placement of circles in contact with one another results in a pyramid having important geometrical symmetries. There is evidence for this form of thought in a somewhat later work, from about 1235, the commentary of the first six days of Creation known as the *Hexaemeron*. There, in Book 9, chapter 1, paragraph 2, Grosseteste writes:

> 'The perfection of the world follows from the perfection of the number six as an effect from its cause. One should consider, moreover, that taking the number six step by step according to its parts it builds up a triangle, fixing one at the vertex, then two arranged in a line, and then three arranged in a line equidistant to the two, drawn in such a way that from the one first placed in a perpendicular line can be drawn down to the middle unit of the three. Thus, according to Augustine, the construction of this world arises in a similar laying down of a triangle. On the first day, as if in the first and highest place, light was made, like the first unit. In the two following days the firmament and the earth was made, like the two-unit line put after the unit. On the three following days the adornments of the fabric of the world were made, and ordered in a three-unit line, since on the fourth day the heaven was adorned with stars, on the fifth day the liquid element, i.e. air and water, were adorned with fish and birds (though both were brought forth from the water) and on the sixth day the earth was adorned with the earthly animals that rose from the earth.' ([30] pp. 269-270).

The construction described in the second sentence of this quotation is illustrated in *Fig. 7a* where the perfection of the number six is demonstrated by the three-fold rotation symmetry and three-fold mirror symmetry of the arrangement of circles. *Fig. 7b* sets out geometrically Grosseteste's laying out of the features associated with the first six days of creation in the manner described in the *Hexaemeron* text. In setting out to establish the importance and perfection of the number six, there can be little doubt that he was imagining perfection of ideas as being associated with the perfection of geometrical symmetry. There is no hint as to whether or not the three-fold symmetry appealed through its theological association with the Trinity.

Fig. 7c illustrates how the qualities of form, matter, composition, and the composite can be arranged in a similar triangular fashion. Such a triangle is simply an extension by another row of the touching circles of *Fig. 7a*, and as seen in *Fig. 7d*, it has equivalent symmetry. The geometrical perfection of these arrangements is mapped onto the perfection of the numbers ten and six, a perfectly constructed Universe created in a perfect number of days.

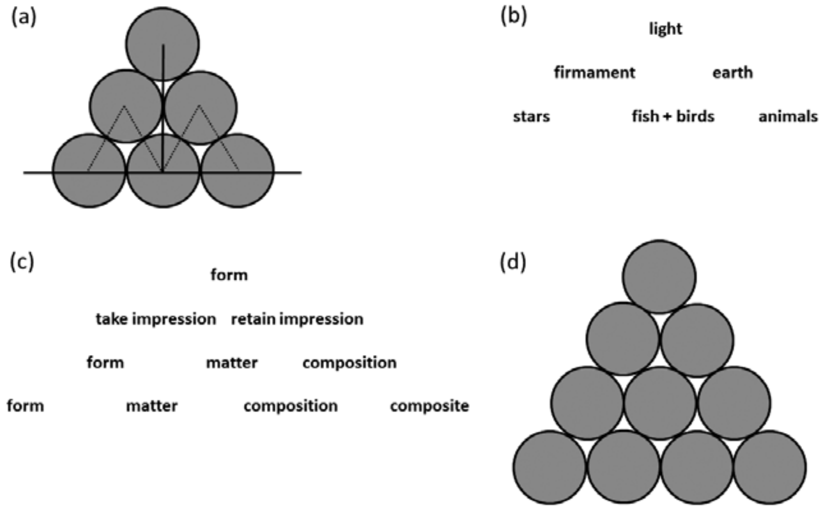

Fig. 7. (a) Arrangement of six touching circles exhibiting a symmetric geometric structure as described in the *Hexaemeron*. Note that the three circles in the third row are all equidistant (dotted lines) to the circles in the second row as stated in the text. (b) Attributes of each of the six days of Creation set out in the geometric arrangement described. (c) Qualities of form, matter, composition and composite arranged in a similar triangle. (d) Similar arrangement of ten touching circles exhibiting three-fold symmetry.

4. The Ordered-Universe project and the response of creative artists

The beauty of Grosseteste's thought has led to unexpected creative stimuli. In the Ordered Universe project to re-examine, edit, translate, and assess from a scientific viewpoint Grosseteste's shorter scientific works (opuscula) on natural philosophy, Giles Gasper assembled an extended team of medievalists, linguists, philosophers, paleographers, physicists, engineers, and psychologists (www.ordered-universe.com). With the important caveats that "there are no stupid questions" and "that trespassers are welcomed", the team set out to study the texts by reading them line by line, word by word, as a group. Although time-consuming and expensive, this method paid dividends: because each member approached the material from a totally different perspective, insights have emerged that might have been missed by any individual alone. For example, the dimensionality and combinatorial qualities of Grosseteste's theory of colour had been missed, not least because Ludwig Baur's critical edition of *De colore* [31] was based principally on a corrupt 16th century manuscript. Insistence on a logical scientific argument resulted in the identification of the loss in the later manuscripts of the word *obscura* from the pairs of opposites *clara-obscura, multa-pauca*, *purum-impurum.* A search in the earliest manuscript now in Madrid, unknown to and therefore not used by Baur, revealed the missing word.

The approach of the scientists has tended to be much more pictorial than that of the historians. In trying to understand Grosseteste's arguments the scientists invariably reached for the whiteboard and marker pen to sketch the realization in a two-dimensional space of the ideas being put forward in words. After a decade of working together it is easy to forget how radical was such an approach. Distinguished medievalists, familiar with the *De iride* text, were astonished at seeing the coin-in-cup experiment (*Fig. 2*) live for the first time

Perhaps the most unexpected result of the Ordered Universe project has been the impact on the creativity of artists who have become part of the project team. As well as stimulating Tom McLeish to explore the parallels between scientific and artists creativity [32], there have been a significant number of art-works, from sound and light projection, to temporary multi-media installations, multi-media sculpture, photography, film, and glass art, specifically inspired by the Grosseteste texts. The most spectacular, and viewed by over one million people, have been the sound and light-art works of Ross Ashton and Karen Monid of The Projection Studio (www.theprojectionstudio.com). Their initial interaction with the Ordered Universe resulted in 'World Machine', projected onto Durham Cathedral as part of the Lumière festival of 2015, which incorporated imagery from 13th century and 21st century cosmologies. A subsequent work, 'Spiritus' drew on Grosseteste's thinking on light and body, and played at the 2016 Berlin Light Festival and e-Luminate 2017 in Cambridge (*Fig. 8*). Another projection, 'Horizon', which was shown in Napa, California and Poole, U.K. in 2019, directly incorporated material from Grosseteste's *De sphera* (On the Sphere). This was combined with satellite imagery from NASA in a reflective piece concerning our place in the world and the limits of our horizons. Alexandra Carr's dynamic sculpture 'Empyrean' (www.alexandracarr.co.uk), which formed the centerpiece for an international exhibition on Dante's Divine Comedy, was also inspired by the nested spheres described in *De luce* and *De sphera*.

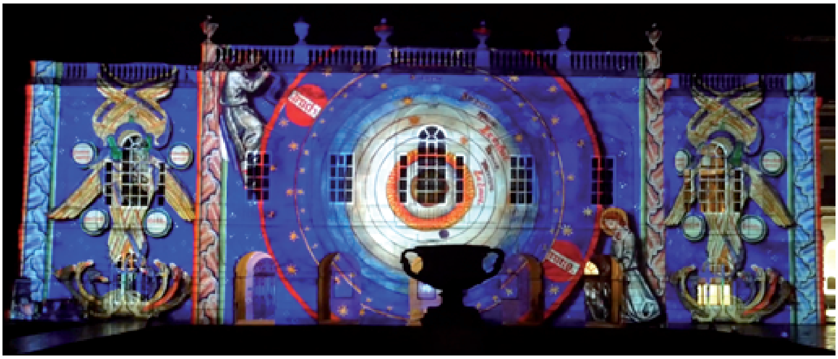

Fig. 8. The Projection Studio's 'Spiritus: Light and Darkness', at e-luminate, Cambridge, 2017 was based around the work of Robert Grosseteste. *(Photograph reproduced by permission of Ross Ashton and Karen Monid).*

The study of *De iride* stimulated pieces of glass art from Colin Rennie and Cate Watkinson of Sunderland University, which featured in the exhibition 'Illuminating Colour' 21 Oct 2017 - 11 Mar 2018, U.K. National Glass Centre, Sunderland. Colin Rennie's glass dish, shown in *Fig. 9*, was inspired by the colour-space spirals corresponding to variations in rainbow colour [33] and contains three orthogonal coloured spirals, created sequentially by picking up the ball of viscous glass in three orthogonal directions and trailing thin spiral lines of coloured glass in each direction. The final piece was then spun out to a bowl form before cooling.

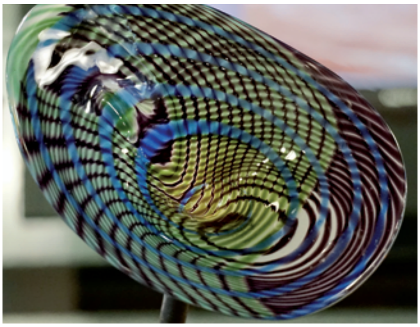

Fig. 9. Blown glass vessel in process, with colour applied on 3 axes. Created by Colin Rennie, University of Sunderland. *(Photograph reproduced by permission of Colin Rennie and Giles Gasper).*

5. Conclusions

At the outset of the Ordered Universe project, it had been hoped that new scientific results would be generated as a result of inspiration found in the study of the thirteenth century works. Surprisingly, this was indeed achieved. Examples include development of new computational methodology to overcome the challenge of modelling the creation of the perfected spheres in *De luce* [28], development of ray tracing to study of refraction in materials with little symmetry [23] and simulation of rainbows produced under different conditions of drop size and spectral characteristics using Mie theory [33]. What was completely unanticipated was the creative stimulus given to the practitioner artists which arose from their collaboration in the project including active engagement in Ordered Universe reading symposia and other knowledge-exchange workshops.

Southern's assertion that

> 'I do not think that any medieval scientific work, or even many scholastic theological works, are read, or can profitably be studied, for the information which they contain about the structure of the physical universe or the truths of the Christian religion.' ([24] pp. lxiv-lxvi).

is hard to dispute. However, the study of the medieval scientific texts can result in motivation to explore new aspects of science and also use modern science to examine the validity of the texts in the context of their day. An example of the latter was the use of modern psychophysical techniques to demonstrate the coherence of Grosseteste's formulation, in *De generatione sonorum*, of vowel sounds in an auditory, mental and visually representational framework based on a combinatorial approach from geometric figures [34]. It raised questions pertinent to our own time about the role of experimentation, observation and modelling, and what constitutes permissible evidence for supporting or rejecting hypotheses. These, plus the extraordinary artistic responses, provide ample justification for the detailed study of the medieval science itself and constitute a fascinating part of the legacy of one of the world's greatest polymaths and the world in which he lived.

Acknowledgments

Grateful thanks are expressed to Giles Gasper (Durham), Tom McLeish (now York) and Hannah Smithson (Oxford) for enabling the author to be part of the core research team of the Ordered Universe project which was funded by the U.K. Arts and Humanities Research Council (Grant: AH/N001222/1). Thanks are extended to the whole team (www.ordered-universe.com) for their friendly collaboration and particularly to Giles Gasper for his superb mentoring, commenting on and suggesting amendments to this manuscript, and steering a naïve physicist away from (at least some of) the traps into which amateur historians are apt to fall.

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