EXPERIMENTAL SENSE IN GALILEO'S EARLY WORKS AND ITS LIKELY SOURCES

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I am going to start by declaring a number of assumptions, some of them quite old fashioned and musty, others accepted by some as commonplaces but rejected by others as outrageous, and all still open to considerable clarification, if not contention. First, something happened in Western Europe in the decades around the year 1600 which, for better or worse, we have come to know as a "scientific revolution". Certainly there had been anticipations and premonitions of such an event in the previous centuries, even antiquity. And certainly there were further, what shall we call them?, "upheavals", secondary revolutions, later on, as the new ways of investigating and understanding nature spread and became consolidated. But, and this is a second assumption, some constellation of attitudes towards nature, habits of inquiry, collections of acquired tools (both material and mathematical) and previously gathered knowledge became a coherent enough package to emerge (perhaps to condense), to take root and begin to flourish, in these years. Third, the components of this constellation, as I've called it, were not invented ex novo in the decades indicated; all had been maturing independently or semi-independently for years, in some cases for centuries. What was new was, first, the "mix", followed by a growing awareness of the power and possibilities of that mix among a restricted but significant public. Fourth, I don't believe that the touted "victories" of the period, the law of free fall, for instance, or the beginnings of the wide acceptance of the Copernican system in the hands of Tycho, Kepler, Galileo and Gilbert, were a cause of the revolution, so much as among its first fruits. Finally, as just hinted, that restricted public included many actors all over Europe, some still famous today and many, if not most, obscure or forgotten (including many only known to historians of other disciplines such as art, literature and music). If we seem to concentrate on Galileo, it is because he was one of the more visible players in the event and because we are fortunate enough to have large collections of original sources which yet reward further study.

My object here, then, is to reflect on one aspect of the beginnings in Galileo, the origins and development of his capacities as an experimental investigator. Galileo did not start his career with a fully mature notion of proper "experimental research"; in so far as he reflected on what we like to call methodology, that would only come later, and we only have limited access to what such reflections might have been. No, Galileo started by starting, using materials and tools ready at hand, off the shelf, including what was available in his Tuscan environment as he was growing up. And his "practice" only evolved or matured in the course of his investigations. So my questions then become: What can we discover in Galileo's early works of a sense of or sensibility for empirical investigation; what can we suggest about its possible sources; and what can we say about its early maturation?

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To start at the beginning, we know little of Galileo's early life, except that he was the first among several children of a father, Vincenzo Galilei, who was a professional musician, a music teacher, a composer and student of musical theory, and eventually himself an experimenter in what we would call today "musical acoustics" (we will be returning to this shortly). One consequence of this was that Galileo himself became an expert lutanist. Galileo grew up first in Pisa and then in Florence and acquired some of his early education from a member of the Vallombrosan Order, either in one of the Vallombrosan Houses in Florence itself or in the Mother House of the Order in the hills near Florence. In the fall of 1580 (not, as is usually given, 1581) he enrolled in the University of Pisa[1] and continued his formal studies until 1585 when, having "discovered" and been captured by mathematics, he left the University.

Galileo spent the next four years mostly at home in Florence, studying Euclid and Archimedes and becoming proficient enough both to take occasional jobs teaching mathematics[2] and to draft a set of theorems on the centers of gravity of solids of revolution,[3] thereby extending the reach of

[1] Del Gratta, R., "A proposito della data d'iscrizione di Galileo Galilei all'Università di Pisa [1580 settembre 5; e non 1581!]", *Bollettino storico pisano*, 46 (1977), 556-558.

[2] For instance in 1588: Schiavo, A., "Notizie Riguardanti la Badia di Passignano in Val di Pesa Estratte dai fondi dell' Archivio di Stato di Firenze", in *Benedictina*, 9 (1955), 31-92, p. 44.

[3] Galilei, G., *Theoremata circa centrum gravitatis solidorum* (ms. c. 1586-87), in Favaro, A. (ed.), *Le Opere di Galileo Galilei*, 20 Vols, Firenze, Barbèra, 1890-1909, reissued with additions: 1929-39 & 1964-66: 1, 181-208.

Archimedean techniques and (not just incidently) earning a reputation among some important contemporary mathematicians. Amid these mathematical studies he also drafted and circulated his first public work, *La bilancetta*, the *Little Balance*, in this case a balance which, he proposed, Archimedes might have used in detecting the goldsmith's fraud in the crafting of Hiero's crown[4]. [Can we think of Galileo as an experimentalist historian of science, attempting to understand Archimedes by trying to simulate some of his work?] Galileo felt that the commonly told story about Archimedes in the bath could not be correct; the implied measuring technique would have been too imprecise and certainly not worthy of the Syracusan's real capabilities. By Galileo's time, of course, balances had had a long history as tools: both in the abstract (at the core, for instance, of some of Archimedes' mathematical techniques), and in the flesh as part of the kit of everyday work and trade. In this last regard, the economic health of medieval and renaissance Florence depended in part on the reliability and precision of the balances used by goldsmiths as well as those used in the Florentine Mint, the latter organization responsible since the early 13th century for the quality and content of the gold Florin. So Galileo was not really inventing a new device. What he was doing was stretching his new Archimedean muscles and satisfying himself, if he bothered to worry about the issue at all, that with care and ingenuity one can, in fact, build very precise measuring instruments.

The Little Balance starts by being a normal equal arm balance, a longish rod, balanced in the center, with a hook at one end and a balance pan suspended at the other, these at equal distances from the center. It differs from the normal balance in that one needs to be able to move the suspension of the pan from its "home" point, back and forth along its arm. And it also differs in that it requires a special, finely divided ruler along a portion of the rod with the movable pan. To create a ruler designed, say, for the Archimedean problem, testing a possible fraud and measuring the relative amounts of gold and silver in it: 1) start by hanging a sample of pure gold from the hook, and with the pan's suspension in its "home" position bring the balance into equilibrium; 2) then immerse the gold in a container of water and slide the pan's suspension along the rod until the balance is again in equilibrium; 3) mark the position of the suspension on the rod; this will be the "gold" point; 4) repeat these three steps with a sample of pure silver thereby establishing a "silver" point; 5) finally, install the special ruler between the two established "points"; 6) To test a suspect sample, simply repeat the first two steps using that sample; if the pan's point of suspension then falls somewhere between the two previously established points, it is a mix, and its relative distances to those points will be in the ratio of the relative amounts of each component.

[4] Galilei, G., *La bilancetta* (ms. ca. 1586), in Favaro, A. (ed.), *Le Opere*..., 1, 209-220; Fermi, L. & Bernardini, G.(trs. & eds.), *Galileo and the Scientific Revolution*, Basic Books, New York, 1961: Appendix.

I have taken you through these details because I think that it is important to have a feel for the material aspect of the instrument. But we have not yet finished. What did Galileo use for the special rule? Here he shows some nice opportunistic ingenuity. He used a fine wire (he did not say so, but a good guess would be a standard steel lute string) which he wound tightly and compactly around the balance arm in the space between the two points. Then, since visually counting the wires to complete a measurement would have been difficult (the eyes glaze over), he recommended drawing the point of a stiletto across the wires between the points to be measured. A combination of the slight sound resulting from the passing of the point of the knife from one wire to another and the tactile feel of that same jump through the handle of the knife would allow an accurate count. A nice touch for a musician. And one should say that the instrument, including the system of measurement, does work as proposed.

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Galileo's next public work, apart from the mentioned mathematical tract on centers of gravity (which he did circulate), was a pair of lectures he delivered to the Accademia Fiorentina on the *Shape, Site and Size of the Inferno of Dante* in 1587 or 1588.[5] This topic, not normally part of our discourses in the history of science, nevertheless shows some interesting facets. We might ask: why would anyone want to design an exact geography of an obviously fictional locale? Here it bears remembering that, whatever many others might believe, or might have believed, about the real existence of a Hell, the people we are going to be dealing with knew that this Inferno was a fiction. Today we might want to call it a sort of science fiction ante litteram, in which a created "other" world has to be given a verisimilitude consistent within its own set of rules. And that was part of the game, trying to discern the rules which Dante might have, even *must* have, used in constructing the complex geography of the circles, cliffs, pits and so on. The very complexity and vividness of his descriptions certainly prompted both a desire to have a map and a supposition that he himself must have at least sketched a diagram while composing the Inferno, even if only to keep himself from falling into contradictions in describing its fictive space. The problem for subsequent generations was that even though Dante did provide a few clues to exact dimensions in the Poem, these hardly determined a unique architecture. The Inferno was a hugely complex place, and those desiring a full map of it had to fill the gaps with their own assumptions.

The short history of those maps and assumptions begins with Antonio Manetti (1423-1497), mathematician, custodian for a while of Brunelles-

[5] Galilei, G., "Due lezioni all'Accademia Fiorentina circa la figura, sito e grandezza dell'Inferno di Dante", in Favaro, A., *Le Opere*..., IX, 29-57; also in Gigli, O. (ed.), *Studi sulla Divina Commedia di Galileo Galilei, Vincenzo Borghini ed altri*, Le Monnier, Firenze, 1855.

chi's first two perspective panels and otherwise a highly regarded student of all things Florentine. Over a number of years he had managed to construct a plausible vision of the structure of the Inferno, complete with numerical values for the important angles and vertical and "horizontal" dimensions. As it turned out, Manetti died before publishing his conclusions. Fortunately, however, his colleague and younger friend Girolamo Benivieni (1453-1542), using what he had remembered of their direct conversations, plus manuscript notes provided by Manetti's brother, composed and published a work entitled: *Dialogue of Antonio Manetti on the site, shape and measures of the Inferno of Dante Alighieri.*[6] This in 1506. The text features a hypothetical conversation between Manetti and Benivieni himself, the latter asking directed questions and Manetti describing and explaining his conclusions. The text is quite clear by itself, but Benivieni took the trouble of including a set of woodcuts clearly depicting the results, results that subsequently became the standard Florentine interpretation of Dante's intentions and which the Accademia Fiorentina eventually asked Galileo to ellucidate.

That interpretation did not go unchallenged, however. In 1544 Alessandro Vellutello of Lucca (late 15th-16th c.), in a work entitled *The Comedy of Dante with a New Exposition*,[7] offered a drastically different interpretation of the structure of the Inferno, one based on his own assumptions. Which one of these views was to be accepted?

The occasion for addressing the issue probably arrived, in 1587, both with a renewed interest in promoting Dante studies on the part of the Accademia Fiorentina and with the publication of a massive work of literary criticism by Jacopo Mazzoni of Cesena (1548-1598): *Della difesa della Comedia di Dante.*[8] Mazzoni would soon become an elder colleague and then a friend of Galileo at the University of Pisa. His *Difesa* was an effective and strongly "pro-Florentine" work, and he was quickly made a member of the important learned academies of the city. The exact connections among the events that followed are not entirely clear. We do know that Mazzoni lectured at the Accademia Fiorentina in1587-88, probably in the

[6] Benivieni, J., *Dialogo di Antonio Manetti circa al sito, forma et misure dello Inferno di Dante Allighieri*, Giunti, Firenze, 1506; also in Gigli, O., *Studi sulla Divina Commedia*..., cit. See: Vasoli, C., "Benevieni, Girolamo", in *Dizionario Biografico degli Italiani*, Istituto della Enciclopedia Italiana, Roma: 8, 550-555.

[7] Vellutello, A., *La Comedia di Dante Alighieri con la nuova espozione di Alessandro Vellutello*, Venetia, 1544; Vellutello, A., *Dante con l'espositione di Christoforo Landino, et di Alessandro Vellutello, Sopra la sua comedia dell'Inferno, del Purgatorio, & del Paradiso*, Sessa & fratelli, Venetia, 1564 & 1596. See also: Barbi, M., *Della fortuna di Dante nel secolo XVI*, Nistri, Pisa, 1890; Giambullari, P., *De 'l sito, Forma et Misure dello Infrerno di Dante*, Dortelata, Firenze, 1544; Landino, C., *Commento di Christoforo Landino Fiorentino sopra la Comedia di Dante Alighieri*, Firenze, 1481; Michelangeli, L. A., *Sul disegno dell'Inferno dantesco*, Zanichelli, Bologna, 1886

[8] Mazzoni, J., *Della difesa della Comedia di Dante*, Cesena, 1587.

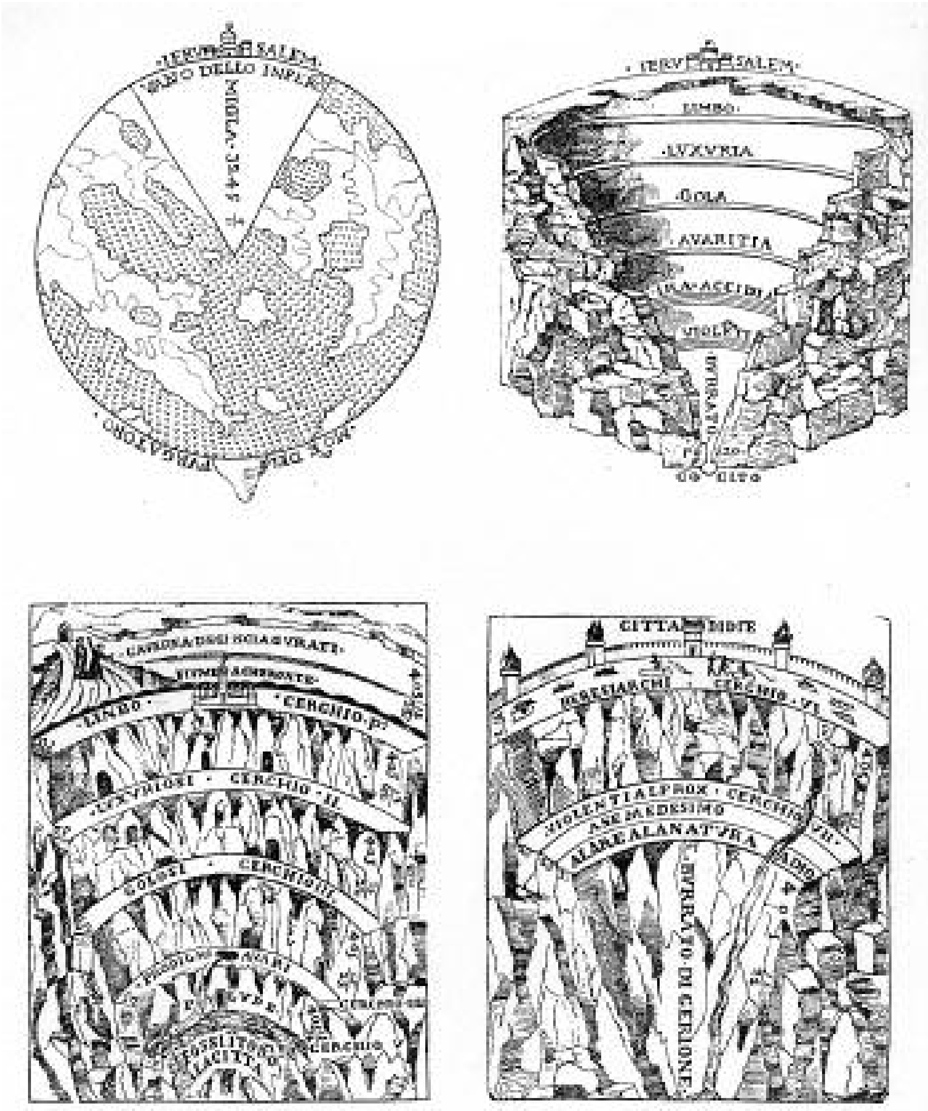

Fig. 1 (from Benevieni, G., Dialogo di Antonio Manetti..., in the edition of Gigli, O., Studi sulla Divina Commedia, di Galileo Galilei, Vincenzo Borghini ed altri, 37-132: 120, 121, 123, 124)

weeks or months before and after Galileo's two lectures and presumably on literary-linguistic topics. And in 1587, Giovanni Stradano (1523-1605), a well known and highly regarded artist connected with the Medici Court, was commissioned to do a series of scenes depicting the damned in the several circles of the Inferno along with a set of illustrations and maps of its architectural geography, all but one of the latter illustrating the Manetti

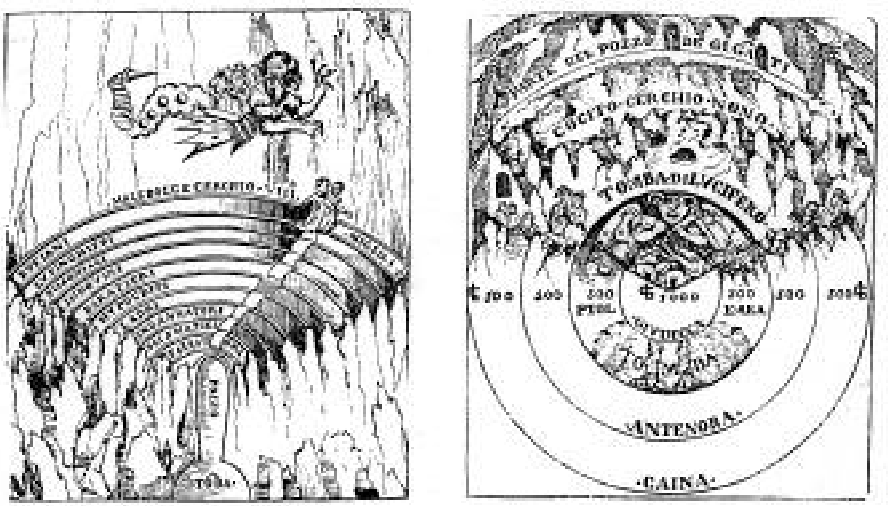

Fig. 2 (from Benevieni, G., Dialogo di Antonio Manetti..., in the edition of Gigli, O., Studi sulla Divina Commedia, di Galileo Galilei, Vincenzo Borghini ed altri, 37-132: 125, 127)

views, that one showing the Vellutello scheme.[9] It would be nice at this point to say that the young Galileo helped or advised Stradano with the laying out of the illustrations, especially a few of the very abstract ones, or even that he had these with him when he gave his lectures, but we simply do not know that. We do know, however, that he accompanied his lectures with illustrative drawings; he says as much. My own feeling is that if he did not use the Stradano drawings, he used their substantial equivalent; the forms and numbers in his texts match those of Stradano exactly. In any case, both were illustrating the canonical Manetti. And shortly after, in 1594, he is linked indirectly to one Luigi Alamanni and a related precision rendering of the Manetti scheme.

What can we learn from these illustrations? The first Benevieni-Manetti woodcut shows the most general configuration of the Inferno, a cone whose apex is at the center of the earth and whose base (a section of a spherical surface) has at its center Jerusalem (Fig. 1); Manetti used an accepted value for the circumference of the earth and therefore its radius (and 22/7 as the value of π); the apex angle of the cone is sixty degrees. The second illustration shows the layout of the upper part of the Inferno; the lower part, the

[9] Biagi, G., *Dante illustrato da Giovanni Stradano: Illustrazioni alla Divina Commedia dell'artista fiammingo Giovanni Stradano 1587, riprodotte in fototipia dall'originale conservato nella R. Biblioteca Medicea Laurenziana di Firenze*, Alinari, Firenze, 1893; Gizzi, C., *(ed.), Giovanni Stradano e Dante, Catalogo della Mostra tenuta a Torre de'Passeri nel 1994*, Electa, Milano, 1994.

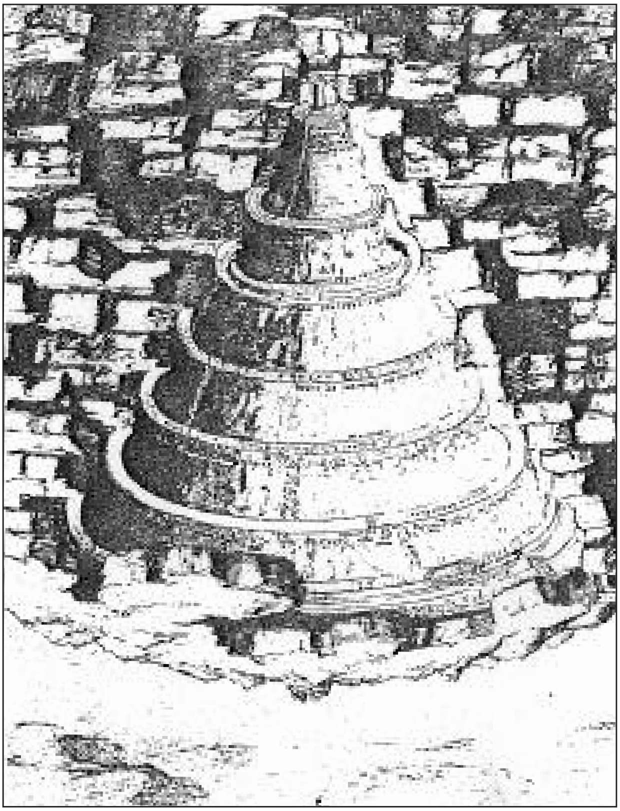

Fig. 3 (from Gizzi, C. (ed.), Giovanni Stradano e Dante, Milano, Electa, 1994: 143)

Malebolge and below, cannot be shown on the same scale. The third and fourth illustrations show that upper part in two sections; while not exact scale drawings, they do show the intended vertical distances between the levels and the "horizontal" widths of those levels, both in miles (note that there is an error in the figure for the vertical drop of the "Burrato di Gerione"; this ought to be 730 5/22 miles). The last two show images of the lower Inferno, the Malebolge and the icy spheres at the center, each to a different scale (Fig. 2; the measues given in the last are in Florentine braccia).

The first of the Stradano images (one among several) shows a general, qualitative view of the Manetti scheme, including Jerusalem at the top and the several levels of Dante's Circles down to the center of the earth (Fig. 3). He does not include the dimensions and he distorts the relative scale of the Malebolge and the space at the bottom with Lucifer; but he provides a strong sense of the physical geography from the earth-cover to the vast open volume of the enclosed space.

In contrast, the second Stradano image is a precise scale rendering of a portion of that space (Fig. 4). The curved line at the top represents the sur-

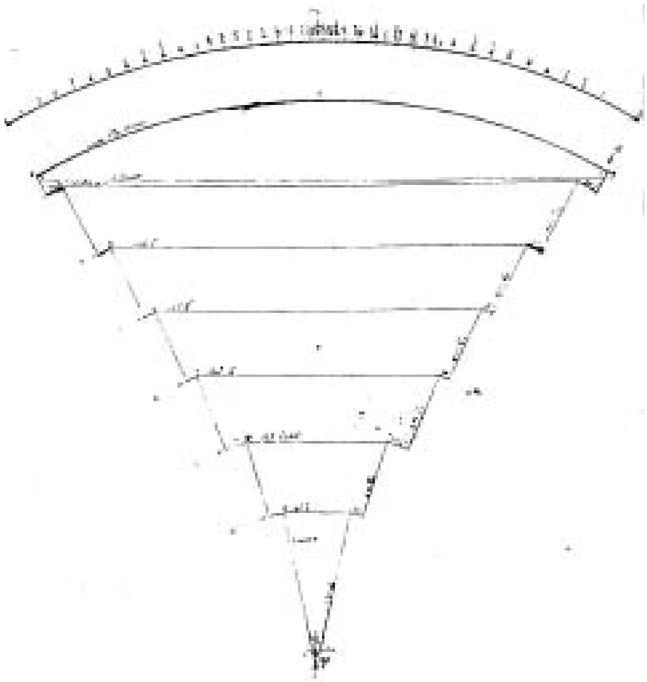

Fig. 4 (from Gizzi, C. (ed.), Giovanni Stradano e Dante, Milano, Electa, 1994: 150)

face of the earth; it is marked with roman numerals increasing from the edges towards the center. Under it is a curve delimiting the bottom of the earthly cover of the Inferno, and immediately under it, on each side, there is a ledge, the locus of the first level and first Dantean Circle, Limbo. That level is shown to be 405 15/22 miles down from the surface (the numbers are hard to read in the reproduction but they are there in the original). Under it the next levels drop by equal intervals down to the sixth level, seventh Circle (the fifth level has two Circles). The next drop, through the Burrato di Gerione to the Malebolge, is by 730 5/22 miles. The Malebolge and the Pozzo down to the center could only be indicated, not rendered. The ledges or levels also have a precise construction. Manetti had calculated that the curved radius on the surface of the earth measured from Jerusalem to the projected edge of the cone was 1700 miles. He divided this distance, first into ten 100-mile segments, and then into smaller segments adding up to 700 miles. From several designated points he imagined vertical (radial) lines to the center of the earth; these lines were used to construct the levels. And the geometry was such that he could specify the widths of those levels; these figures were already given in the Manetti-Benevieni woodcut. In the Stradano drawing the roman numerals on the surface of the earth mark the divisions of the 1700 miles on either side of Jerusalem. The construction lines are not shown,

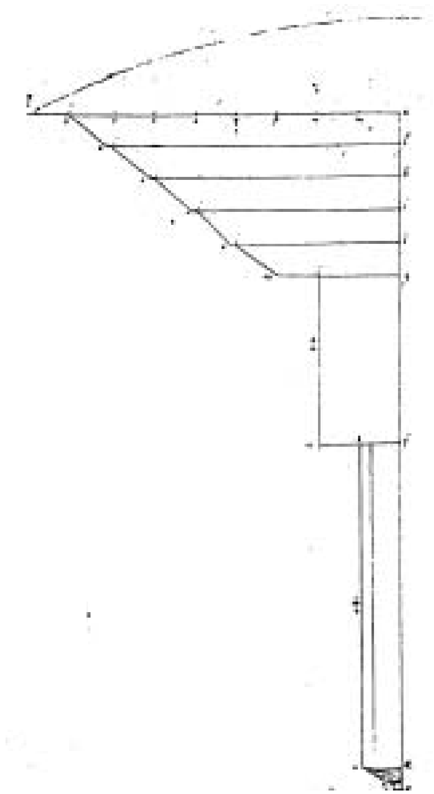

Fig. 5 (from Gizzi, C. (ed.), Giovanni Stradano e Dante, Milano, Electa, 1994: 149)

but if one lays a straight edge from the center of the earth to the 'M' on the surface, one finds that the line it defines passes up the edge of the Burrato. In other words, that line marks the inner edge of the sixth level, seventh Circle, and thereby defines the section of a cone which constitutes the Burrato. And so on for the rest of the levels, including the ten bolge of the Malebolge, level 7, eighth Circle, not shown in this image. To be noted is the fact that in this construction the Inferno is not, strictly speaking, a cone; it is a nested set of truncated cones[10] whose walls, in an overall sense, bulge in to the centerline. Given the intricacy of developing a map of the Inferno with precise shapes and measures, one might even suppose that Manetti had realized a diagram fairly similar to this one. Did Stradano work out this geometry on his own? If not, who gave him a hand?

[10] It is perhaps worth noting that the geometry inherent in the planning and constructing of the Cupola by Brunelleschi also involved a set of nested cones; could Manetti have had a germ of his idea from that source? For further details and additional sources on the Cupola see: Settle, T. B., "Brunelleschi's horizontal arches and related devices", in *Annali, Istituto e Museo di Storia della Scienza*, 3 (1978, fasc. l), 65-80, plus figures.

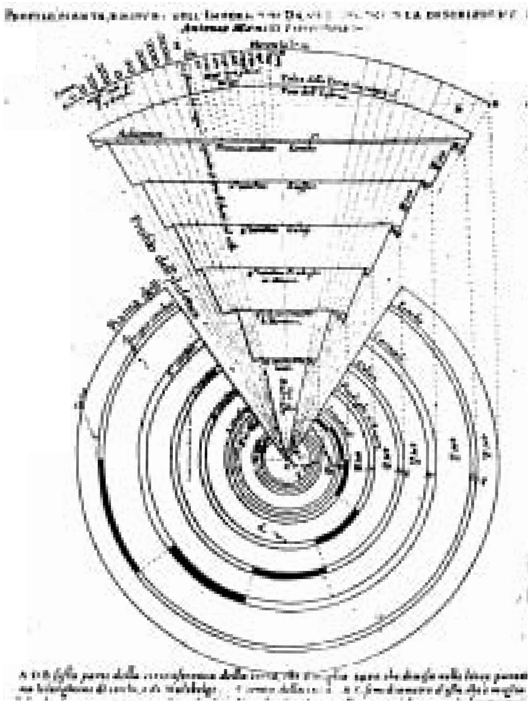

Fig. 6 (from Allighieri, D., Divina Commedia, Edizione della Accademia della Crusca,in 8.avo, Firenze, 1595: foldout)

The last Stradano drawing shows an attempt to provide an image of Vellutello's Inferno (Fig. 5). There are many problems with it, some having to do with the fact that Vellutello was not always consistent in his own suppositions. In one major departure from Manetti, he makes the depth of the Inferno to be only 295 1/4 miles, not 3245 5/11 miles, while not strictly speaking an impossible assumption, a very small and cramped space, indeed. And none of his vertical transitions are by radial lines; the ones in the upper part are sloping, allowing Dante and Virgil to climb down them as they might climb down the scarp of a mountain. And in the lower part his "vertical" lines are parallel, not converging to the center. This was one of the aspects very heavily criticized by Galileo in his second Lecture; this made no architectural-engineering sense; masses of earth would be unsupported vertically and all would have come tumbling down long ago. In other words, Galileo objected both to the mathematics and to the physics of Vellutello's construction. And I suspect that he also was repulsed aesthetically. Manetti's space has a certain architectural grandeur, whereas Vellutello's is simply ugly. So Galileo concluded for Manetti, as was supposed he would when invited to speak.

Our last image comes from the 1595 octavo edition of the *Divina Commedia* published by the Accademia della Crusca (Fig. 6). It is a composite of the one we have seen already, this time with a set of construction lines making the geometry and the dimensions obvious, and another of the Stradano drawings not considered here. This was a copper plate rendering of an illustration used by Luigi Alamanni (1558-1603) in lecture he gave in February of 1591. Alamanni had been one of those behind the original commissions to Stradano in 1587.[11] There is no direct evidence that it was he who was behind the invitation to Galileo or the completion of these abstract plans, but it is not too difficult to imagine that he had some part in the events. That he knew and in some measure "kept track" of Galileo we know from a letter in 1594 in which he mentions that Galileo had passed from the University of Pisa to that of Padua.[12]

Is any of this of more than anecdotal interest? I think that it tells us that, at least from the 15th century on, cultured Tuscans had certain expectations about the material world (expectations about the possibilities of the precise mapping and representation of it, that is), and expectations about the possibility of completeness and closure in that mapping. Here I mean "closure" in two senses. The first is the business-accounting sense. At the end of the day or month the books have to close; the numbers have to add up. This would have been obvious in a Tuscany which saw the invention of double-entry bookkeeping. The second sense is a material-structural one, also obvious at least to those of Manetti's generation, which saw Brunelleschi complete the construction of the Cupola of the Florentine Duomo. Had that planned structure not "closed" after 16 years of work, the Cupola would not have stood; there would be no Cupola, only a pile of rubble. In the case of the Inferno, there was the expectation that behind the surface chaos of the graded tormenting of sinners was a mathematical order which could be discerned and depicted in precise images and that the invented structure had to make architectural-engineering sense. And whether or not the Florentine Accademicians consciously ever reflected in these terms, everyone, including Vellutello, expected to be able to find that order. Everyone, that is, outside of the philosophy faculties of the universities, which still taught the irrelevance and essential extraneity of mathematics to knowledge of the material world. Recall that 40-odd years after his two lectures Galileo still felt that he had to argue the point against his Aristotelian Simplicio in the *Dialogue on the Two Great Systems*.[13] As a young man, in this fertile peri-

[11] Brunner, M., "Alcune note sulla commissione dei disegni danteschi di Giovanni Stradano", in Gizzi, C., (ed.), *Giovanni Stradano e Dante*..., cit., 123-132.

[12] Letter from Alamanni to G. B., Strozzi, 7 August, 1594, in Favaro, A., *Opere* ..., X, 66; see also the comments by Favaro, A., IX, 7-8, 10. That Alamanni knew Galileo in 1587 is clear; in December of that year he, along with Conte Giovanni Bardi, G. B. Strozzi and Barone G. B. da Ricasoli, testified that Galileo's Theorems on Centers of Gravity were indeed by him: Favaro, A., *Opere*..., I, 183.

[13] Galilei, G., *Dialogo... sopra i due massimi sistemi del mondo tolomaico, e copernicano*, Fiorenza, 1632, in Favaro, A., *Le Opere*..., VII, 232-234; Drake, S. (tr. & ed.), *Dialogue on the Two Great Systems-Ptolemaic & Copernican*, 2nd ed., U. California Press, 1970, 206-208.

od at home between 1585 and 1589, Galileo obviously already felt quite at ease finding and depicting precision in the stuff of the world.

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And so he proved in yet another venture, this one putting him in effective collaboration with his father, Vincenzo (1520-1591). The story is hard to put together because of the relative lack of sources, but a general outline is beginning to emerge. It involves the discovery on the part of Galileo of the isochronous properties of swinging bodies, pendula, on the one hand, and the empirical investigations of Vincenzo and then Galileo himself into the nature of musical harmony, on the other.[14]

When precisely Galileo discovered isochronism or whether he discovered the several properties all at once or only over a period of time are yet open questions. According to several versions of the story by Vincenzo Viviani, Galileo made the discoveries while still a student at Pisa in or around 1583. Viviani tells us that in the Pisan Duomo one day, a swinging chandelier caught Galileo's attention; he noticed that as the arcs of the swings diminished, the period of the swings seemed to remain the same, initially checking this impression by using the beat of his pulse and by "counting" against his well developed sense of musical time. Then, returning to his rooms, he and some friends devised ways to verify the original impression and eventually discover the remaining properties.

Exactly what it was that had caught his attention, of course, we don't know. But we can imagine that once focussed on the lamp he could well have checked the swings in the ways suggested; and we can also imagine that he even tried to recall, without success, if he had ever encountered any mention of such equality-of-swinging in his books or lectures on the various properties of motion. Nor do we have any explicit record of how exactly he and his friends may have tried verifying the original observation. They would have known that the human pulse and existing mechanical clocks were unreliable at best and that under the circumstances even counting against a trained sense of musical beat would not give a satisfactory answer. But if they had gone to the trouble of hanging a couple of weights on strings from an overhead beam in the room, they may have stumbled on the only possible solution: checking pendulums against themselves. Alternatively, after trying these "imperfect" solutions for a while, Galileo may have come to the realization that, if a swinging body had an oscillating motion which intrinsically retained a constant rate of swing, i.e., if it were a "natural timekeeper", or even only the best timekeeper then available, then the only way

[14] For a fuller treatment see: Settle, T. B., "La rete degli esperimenti galileiani", in Baldo Ceolin, M. (ed.), *Galileo e la scienza sperimentale*, Dip. di Fisica "Galileo Galilei", Universsità di Padova, Padova, 1995, 11-62; also published as: "Galileo's Experimental Reaearch, an Experimental Approach", in *Preprint 52*, Max Planck Institute for the History of Science, Berlin, 1996.

to test the possibility would be, again, to test several against themselves. In any case, however Galileo arrived at this solution, he indirectly indicated that he understood the point when, in several passages in the First Day of the *Discorsi*, many years later, he discussed a pendulum analogue for understanding some properties of musical harmonics.[15] A possible set of steps for testing for isochronism would be as follows:

Start with two pendulums of equal length. First set them in motion on equal arcs; then on arcs with different excursions; then set one in motion and, a few seconds later, set the other in motion while the first is still swinging; as so on. In whatever sequence or configuration one can think of, the result that is most impressive is that in each case the pendulums keep pace with one another. With a little reflection there would be no other conclusion to draw: by their inherent nature pendulums of a given length beat equal intervals of time, no matter what the lengths of the excursions.

Then having taken this first step, the rest is relatively easy. By substituting bobs of different weight and density one learns that the period is independent of those variables.

Finally, by setting two pendulums in motion, one of which, say, is four times the length of the other and watching them swing in a sort of syncopated harmony, one discovers the proportionality between the length of a pendulum and its period.

If we recall that in the 1580s there had been no previous discussion of these properties and no theoretical base for even imagining their existence, the only way Galileo could have discovered them was through some sort of empirical exploring, culminating, in effect, in performing the above steps. From what we know, these were the first of the many truths he discovered about the physical world which were unknown to and even unimagined by Aristotle or any subsequent natural philosopher.

Now it is possible that Galileo completed the discovery of isochronism, in the sense of passing from the initial observation and suspicion to an empirical certainly in the indicated way, while still a student at Pisa. On the other hand, those passages from the *Discorsi*, showing that he associated pendular isochronism with certain effects in musical acoustics, hint that he may only have reached that completion in Florence, after giving up his university studies in 1585, and witnessing or even participating in his father's own investigations.

As musicologists are well aware, modern musical acoustics began with the investigations of Vincenzo Galilei.[16] Towards the middle of his life,

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[15] Galilei, G., *Discorsi e dimostrazioni matematiche intorno à due nuove scienze*..., Elsevir, Leiden, 1638: in Favaro, A., *Le Opere*..., VIII, 146-150; Crew, H. & de Salvio, A. (trs. & eds.), *Dialogues Concerning Two New Sciences*, New York, Dover, 1954, 102-108; Drake, S. (tr. & ed.), *Galileo, Two New Sciences*, U. Wisconsin Press, Madison, 1974, 102-108.

[16] Palisca, C., "Scientific Empiricism in Musical Thought", in Rhys, H. H. (ed.), *Seventeenth Century Science and the Arts*, Princeton, 1961, 91-137; Palisca, C., *The Florentine Camerata, Documentary Studies and Translations*, New Haven, Yale University Press, 1989; Palisca, C.,

already a well known musician and musical theorist, he was given the opportunity of going to Venice and studying with Gioseffo Zarlino (1517-1590), the maximum expert of the day. Zarlino, out of his own studies of ancient and medieval authors as well as his own practical knowledge, had proposed a theory of harmony based on the existence of "sonorous numbers". According to him, ratios composed of pairs of the first six natural numbers, the "senario", were harmonic ratios and gave pleasing tonal combinations by their very nature; ratios using other numbers were inherently discordant. Here Zarlino was implicitly alluding to musical effects demonstrable on the monocord. The ratio two-to-one is that of a full octave, as is obvious when one stops the string of a monocord at its half-point: if the full length of the string sounds a certain note, the half-length sounds a full octave higher. But for Zarlino, the cause of the harmony was in the ratio of the sonorous numbers and had nothing to do with the material properties of the string or the instrument or with the mechanisms of the generation, transmission, or perception of sound. The listener simply apprehended the essential "two-to-oneness" and was pleased.

Initially Vincenzo had accepted these ideas but then he was led to reject them and even vigorously attack them.[17] When he began to doubt, he did so from the empirical stance of the composer and performer. First examine the way singers actually modulate their voices and performers actually tune their instruments, he wrote, and then find the ratios. But the ratios of what? Not of pure numbers, but of some measurable physical characteristic. He was led to investigate the variety of conditions in which one could produce and combine tones, looking at known musical instruments as well as other sources of identifiable notes. He tested stretched cords of brass (ottone), steel (accaio) and gut (minugia), for instance, initially on the lute and the monocord, and later simply by suspending them in the vertical with weights attached. He confirmed that the ratio two-to-one, when referred to the lengths of stretched strings, did describe the means for producing an octave; but he also found that the same musical interval could be generated by increasing the tension on the string by a factor of four. So what was the "true" or "essential" numerical ratio for the octave, two-to-one or four-to-one? And the ratio for the musical interval the fifth, commonly and correctly taken to be three-to-two when referred to the lengths of strings, became nine-to-four when referring to relative tensions. Then in the case of organ pipes, if a given pipe sounded a certain note, one with all its dimensions doubled sounded an octave lower. But doubling all the dimensions meant that the ratio producing the interval was eight-to-one. In short, Vincenzo showed that these and other empirically recognized harmonic ratios

"Was Galileo's Father an Experimental Scientist?", in Coelho, V. (ed.), *Music and Science in the Age of Galileo* (Univ. of Western Ontario series in Philosophy of Science, 50), Dordrecht-Boston, 1992, 143-151.

[17] Galilei, V., *Dialogo della musica antica et della moderna*, Firenze, 1581.

could be generated "using" numbers well outside the senario, thus destroying Zarlino's attempt to unite and explain harmonic phenomena within a system of ideal, Platonic, numbers. He could provide a set of empirical rules for generating harmonies in different circumstances and could illustrate the difficulties in tuning different types of instrument and in composing for voice, but he had destroyed all previous theoretical underpinnings for the phenomena and had provided no replacement, least of all based on the properties of the material world.

When did the son, Galileo, enter this scene? His own early apprenticeship in music and musical research would have followed closely the progress of his father's investigations, which perhaps can be divided into two phases. Vincenzo began, even before Galileo went to Pisa as a student in 1580, by looking for the empirical distinctions among the principal methods of construing musical scales and tuning instruments; and Galileo would have absorbed both his father's early results and his radically empirical attitudes while he himself was becoming an accomplished lutanist. Then, sometime after 1585, the year of Galileo's return, Vincenzo began looking more closely at the logic of the senario and the several ways of generating harmonic intervals just mentioned. Now, if Galileo had already completed his discovery of isochronism in Pisa in about 1583, he may have also noticed that a given pendulum string, made with a lute cord and with a sufficiently heavy weight on the end, will sound a note when plucked, and that different weights generated different notes. Did he bring this knowledge back to Vincenzo in Florence thus initiating the latter's own further research? Or alternatively, did Vincenzo initiate his own work independently, thus providing Galileo, by and large based in Florence after 1585, with the weights on the ends of lute strings which he then used to complete the discovery of isochronism? For the present, there is no way of judging. But either way, by at least about 1589 or 90, Galileo could hardly have failed to be impressed by the fact that a single device, a weight on the end of a fine cord, seemed to yield two types of natural oscillator: the pendulum itself with the properties already defined, and the vibrating string.

For Galileo, one of the essential properties of the pendulum was that its rate of oscillation did not change as the amplitude of the swing diminished. In the case of the vibrating string, the pitch of the tone remains the same as the visible amplitude of its vibrations diminish and as its resulting strength or loudness decreases. Was it possible that the essential feature distinguishing musical tones was the rate of the vibration of the sounding body and hence the medium transmitting the sound? If this were so, the dependence of pitch on a rate of vibration could provide the link re-uniting the musical phenomena left adrift when Vincenzo demolished Zarlino's theory. This suggestion had been made previously, but with little in the way of corroborating physical evidence. For Galileo, however, the analogy was compelling, even if he realized that it did not constitute unequivocal proof. What he lacked was a direct way of counting the vibrations per unit time of each of several lute strings tuned to identifiable notes or some effective substitute procedure. But then, for a while at least, one such procedure seemed to offer a possibility.

We know that among the sources of musical tones which Vincenzo had explored was what we might call the call "singing glass", a "footed glass" or goblet, which can be made to emit a tone by rubbing a damp finger around its rim.[18] He mentioned it twice in his writings, and he recognized that different sized goblets gave different tones and that the tone emitted by a single glass could be changed by varying the depth of liquid in it. We have nothing on the subject by Galileo from this period. But later, in the First Day of the *Discorsi*, he mentions exploring the effect.[19] There, he started by reflecting on the nature of resonant phenomena, noting that, among other things, a clean, well-made goblet can be made to resonate by placing it near a sounding viola cord tuned to the goblet's natural pitch. Moreover, with the same goblet one can show that the vibrating source provokes tremors and waves in a surrounding medium. If we put some water in it and then rub its rim with the end of a moist finger, it will produce a clear tone with a definite pitch. It will also produce a pattern of wavelets on the surface of the water. And if we put the goblet into a large container filled with water almost up to the rim of the goblet and again rub its rim, we will see similar patterns of waves radiating out over the surface of the water and away from the glass. Finally, an effect which Galileo says that he had produced many times: every so often, he wrote, while thus sounding a tone with a fairly large goblet almost filled with water, the pitch would jump a full octave while simultaneously the wavelets divided into two. For him this showed that the "form of the octave was double", the inference being that doubling the number of wavelets in the same space meant that the frequency of the vibrations had also doubled. Hence the ratio of two-to-one did apply to the octave after all, referring not to the senario of Zarlino, but instead to the rates of vibration of the sources of the tones.

We have no way of knowing when Galileo did this work or even whether he did it all at once or in several bursts over a period of time. My guess, however, is that he started playing with singing goblets in this same four year period of working in concert with his father, in the context both of searching for a natural basis for harmonic phenomena in music and of extending his understanding of natural oscillators. We should note that all the phenomena he reports can be reproduced, save one. Some, not all, goblets can be made to emit a tone an octave above an original or base tone. In

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[18] Galilei,V., *Dialogo*..., cit., 133; Galilei,V., "Discorso particolare intorno, alla diversità delle forme del diapason [1589/90], Firenze, Bibl. Naz. Centrale, ms. Gal. 3, ff. 44r-54v: transcription and English translation in Palisca, C., *The Florentine Camerata*..., cit., 180-197.

[19] Galilei, G., *Discorsi e dimostrazioni*..., cit., in Favaro, A., *Le Opere*..., VIII., 141-143; Crew, H. & de Salvio, A., *Dialogues... Two New Sciences*, cit., 98-99; Drake, S., *Galileo, Two New Sciences*, cit., 99-100.

the test, however, the wave packets produced on the surface of the liquid do not double, they jump from four to six. Of course, Galileo may have seen some effect that we have not yet been able to observe or reproduce. On the other hand the "flavor" of these passages is that, while he was convinced of his conclusion, that tone depends on frequency of vibration, he realized that this evidence was not really convincing. What is impressive, however, if our own attempts to reproduce the phenomena are any indication, is the amount of effort he must have expended in the original work. The few lines regarding the wavelets in the singing goblets did not come automatically or easily. Galileo did not have an established fund of theoretical knowledge to guide him. At some point he, or he and his father together, decided to look more closely at the known but otherwise banal mode of producing tones by rubbing the rims of goblets, seeing them as another, controllable source of musical sounds. To try to diagnose and make sense out of a lot of confusing phenomena (and perhaps find mathematical underpinnings?) would have required persistent work, glasses of many sizes and shapes, varied experimental conditions, luck, and (not the least) an extended period of time. In the end, for reasons of a lack of means at his disposal, this was one line of investigation which he did not complete. But by 1589, even before initiating the investigations documented in the manuscript *De motu antiquiora*, he was already capable of and used to practicing serious and sustained empirical research.

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Had Galileo become a reasonably mature "experimental researcher" by this time. Let's try to list some of the characteristics of his "practice" which we have found in these early ventures:

— It would seem that Galileo had early and thoroughly adopted what might be called a mechanical-mathematical view of nature.
— For him it was perfectly natural to investigate and understand natural phenomena in precise, even mathematical, terms.
— And in consequence, there was no objection to representing those phenomena in abstract diagrams and maps, which then became carriers of information.
— It is also clear that Galileo had a natural manual capacity.
— He had no terrors about getting his hands dirty.
— He saw no problems with designing and building appropriate measuring devices and probably had a good instinct for their limits.
— He also built abstract material models of natural phenomena, otherwise known as experimental devices.
— He had no difficulty seeing these material models and their corresponding abstract diagrams in reciprocal relation to one another.
— He was at peace manipulating these material models, subjecting

them to varying circumstances in the course of an investigation.
— And he had a primary respect for nature, a capacity for "listening" to nature rather than imposing on the phenomena ready made notions of what nature ought to be like.
— Clearly, then, for him this manuality was a thinking manuality, not a rote one. That is, when building devices or actually experimenting he did not turn his mind off; always under consideration was a continual tri-partite interchange among: the original natural phenomenon "in the raw", as we might say; the abstract formal model being proposed; and the experimental manipulation in process.

(Which is not to say that he did not make mistakes: he did. Later in the *De motu antiquiora* there is ample evidence that he was or became capable of correcting them.)

(Nor is there evidence so far for an appreciation of the problem of experimental artifact; again, the DMA manuscripts show ample evidence for such an awareness.)

— And he had also acquired the habit of persisting in the pursuit of an investigation, not necessarily being satisfied with initial, apparently easy results, but pushing for better, more precise information.

If we can admit these on the basis of the evidence we have seen, then if Galileo had not reached full maturity as an experimental researcher, he was certainly very close to the lip of it.

At this point perhaps one final comment needs be made. How much had Galileo reflected on what he had done, on what he was doing, by 1589? Had he developed anything we might call a theory or justification for these activities? My own impression is: no. He seems simply to have done them, having taken the several components I have listed from his cultural environment, perhaps embellished them and condensed them into a personal stance, a mode of investigating and understanding the material world.