Galileo's Medicean Moons: their Impact on 400 years of Discovery
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The Appearance of the Medicean Moons in 17th Century Charts and Books— How Long Did It Take?

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Abstract. Galileo's talents in perspective and *chiaroscuro* drawing led to his images of the Moon being accepted relatively quickly as the naturalistic portrayal of a truly physical place. In contrast to his resolved views of the Moon, Galileo saw the satellites of Jupiter as only points of light (as with stars). He thus used star symbols in *Sidereus Nuncius* (1610) for the moons, in constrast to an open disk for Jupiter. In this paper, I describe methods used in subsequent decades to portray objects that could not be seen in any detail but whose very existence challenged the scholastic approach to science. Within fifty years, the existence of the moons was such an accepted component of astronomy that they were depicted in the highly decorative "textbook" *Atlas Coelestis seu Harmonia Macrocosmica* by Andreas Cellarius (1660). Other symbolic methods, ranging from the routine to the dramatic, were used in subsequent centuries to portray the moons. Actual photographs using ground-based telescopes were not possible until the 20th century, just years before cameras on spaceflight missions captured the true details of the Medicean Stars.

Keywords. Atlases, History and Philosophy of Science, Planets and Satellites: Jupiter

1. Introduction

Galileo's observations of the moons of Jupiter defined what we now call "discovery-mode" astronomy. Their presence in the night sky was a completely unanticipated effect. Transient astronomical phenomena had, of course, occurred before Galileo's use of a telescope on the night of 7 January 1610. Meteors, comets and novae had been chronicled since ancient times, along with major uncertainties about their locations in the sky (atmospheric or celestial), as well as origins (natural or divine). The Galilean moons were soon accepted as permanently present bodies, objects that had escaped detection, and thus they were added to the inventory of known celestial bodies. The fact that they were not transient events required a fundamental re-thinking of what had been considered a known and stable ensemble of heavenly bodies. This led to re-appraisals of past hypotheses and the contemplation of new physical mechanisms. Pivotal to these tasks were the evaluation of evidence and the determination of the proper roles of authority: What was actually being seen? How reliable were the observations? What were their implications?

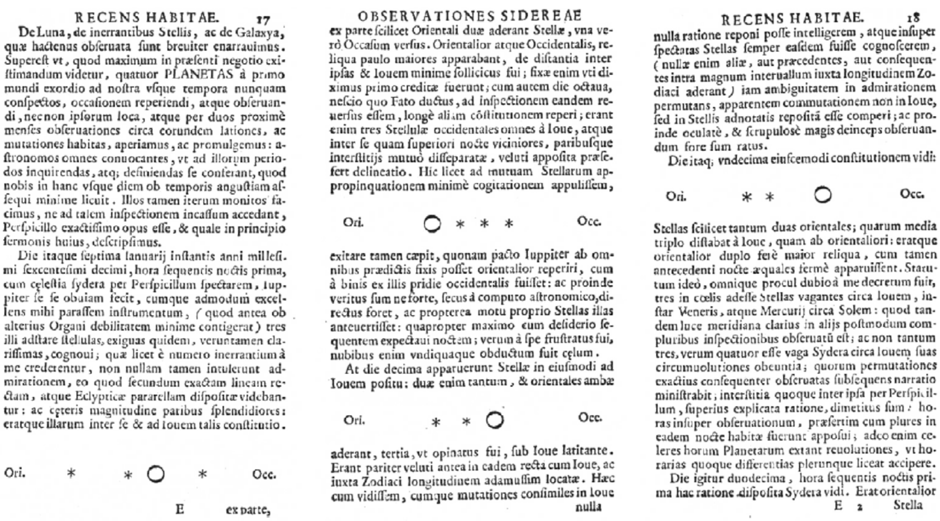
2. A New Role for Imagery

The responses from various communities to Galileo's moons were also precedent-setting aspects for new modes of discovery. They set the stage for the modern scientific requirement of experimental reproducibility by independent researchers. Verification versus falsifiability, concepts introduced later but today routine components of the scientific method, saw their origins in the announcement of *Sidereus Nuncius*.

Among the many forms of scientific revolution launched by Galileo in 1610, the one treated here is the role of visualization in astronomy. Today it is routine to consider astronomy to be the most visual of the sciences—complete with a "picture of the day" website (http://apod.nasa.gov/apod/). Yet prior to Galileo, the pictorial component of astronomy was confined almost exclusively to how one portrayed circular motion: the paths of celestial objects either circled the Earth (Ptolemaic), the Sun (Copernican), or a blend of the two (Tychonic). Indeed, one of the most reproduced figures in the history of science (Barrow 2008), perhaps second only to Leonardo's 1490 drawing of the *Vitruvain Man* (with outstretched arms and legs within a circle), was the simple but elegant drawing of the heliocentric cosmology that Copernicus put into *De Revolutionibus* (1543).

Galileo introduced a new form of celestial imagery in *Sidereus Nuncius* that went far beyond details of organization. His drawings of the Moon, a place with mountains, valleys and patterns of shadows similar to those found on Earth, contradicted the Platonic-Aristotelian doctrine of the perfection of bodies beyond the terrestrial domain. The realistic portrayal of Jupiter's moons was quite a different matter. Galileo's telescope was far too primitive to show any details on the disks of the four jovian moons. Indeed, it would take over 300 years before the ground-based telescopes at Pic du Midi gave hints of surface features upon those moons (Murray 1975, Dollfus 1998), and images from satellite missions soon followed (as discussed throughout this volume).

Galileo coined the phrase *Medicean stars* for Jupiter's satellites, and portrayed them using actual symbols of stars in *Sidereus Nuncius*. He used the terms *planet* and *star* interchangeably, and both words were correct usage within the prevailing Aristotelian terminology (Van Helden 1989). Copernicus, of course, had no reason to address the issue since the moons were unknown in his day, and it was Kepler who came up with the word *satellite* to describe objects in orbits around planets.



RECENS HABITAE. 17

De Luna, de inerrantibus Stellis, ac de Galaxya, quæ hactenus obſeruata ſunt breuiter enarrauimus. Supereſt vt, quod maximum in præſenti negotio exiſtimandum videtur, quatuor PLANETAS à primo mundi exordio ad noſtra vſque tempora nunquam conſpectos, occaſionem reperiendi, atque obſeruandi, necnon ipſorum loca, atque per duos proximè menſes obſeruationes circa eorundem lationes, ac mutationes habitas, aperiamus, ac promulgemus: aſtronomos omnes conuocantes, vt ad illorum periodos inquirendas, atq; definiendas ſe conferant, quod nobis in hanc vſque diem ob temporis anguſtiam aſſequi minime licuit. Illos tamen iterum monitos facimus, ne ad talem inſpectionem incaſſum accedant, Perſpicillo exactiſſimo opus eſſe, & quale in principio ſermonis huius, deſcripſimus.

Die itaque ſeptima Ianuarij inſtantis anni milleſimi ſexcenteſimi decimi, hora ſequentis noctis prima, cum cęleſtia ſydera per Perſpicillum ſpectarem, Iuppiter ſe ſe obuiam fecit, cumque admodum excellens mihi paraſſem inſtrumentum, (quod antea ob alterius Organi debilitatem minime contigerat) tres illi adſtare ſtellulas, exiguas quidem, veruntamen clariſſimas, cognoui; quæ licet è numero inerrantium à me crederentur, non nullam tamen intulerunt admirationem, eo quod ſecundum exactam lineam rectam, atque Eclypticæ pararellam diſpoſitæ videbantur: ac cęteris magnitudine paribus ſplendidiores: eratque illarum inter ſe & ad Iouem talis conſtitutio.

Ori. * * O * Occ.

E ex parte,

OBSERVATIONES SIDEREAE

ex parte ſcilicet Orientali duæ aderant Stellæ, vna verò Occaſum verſus. Orientalior atque Occidentalis, reliqua paulo maiores apparabant, de diſtantia inter ipſas & Iouem minime ſollicicus fui; fixæ enim vti diximus primo creditæ fuerunt; cum autem die octaua, neſcio quo Fato ductus, ad inſpectionem eandem reuerſus eſſem, longè aliam cõſtitutionem reperi; erant enim tres Stellulæ occidentales omnes à Ioue, atque inter ſe quam ſuperiori nocte viciniores, paribuſque interſtitijs mutuò diſſeparatæ, veluti appoſita præſefert delineatio. Hic licet ad mutuam Stellarum appropinquationem minimè cogitationem appuliſſem,

Ori. O * * * Occ.

exitare tamen cæpit, quonam pacto Iuppiter ab omnibus prædictis fixis poſſet orientalior reperiri, cum à binis ex illis pridie occidentalis fuiſſet: ac proinde veritus ſum ne forte, ſecus à computo aſtronomico, directus foret, ac propterea motu proprio Stellas illas anteuertiſſet: quapropter maximo cum deſiderio ſequentem expectaui noctem; verum à ſpe fruſtratus fui, nubibus enim vndiquaque obductum fuit cęlum.

At die decima apparuerunt Stellæ in eiuſmodi ad Iouem poſitu: duæ enim tantum, & orientales ambæ

Ori. * * O Occ.

aderant, tertia, vt opinatus fui, ſub Ioue latitante. Erant pariter veluti antea in eadem recta cum Ioue, ac iuxta Zodiaci longitudinem adamuſſim locatæ. Hæc cum vidiſſem, cumque mutationes conſimiles in Ioue nulla

RECENS HABITAE. 18

nulla ratione reponi poſſe intelligerem, atque inſuper ſpectatas Stellas ſemper eaſdem fuiſſe cognoſcerem, (nullæ enim aliæ, aut præcedentes, aut conſequentes intra magnum interuallum iuxta longitudinem Zodiaci aderant) iam ambiguitatem in admirationem permutans, apparentem commutationem non in Ioue, ſed in Stellis adnotatis repoſitã eſſe comperi; ac proinde oculatè, & ſcrupuloſè magis deinceps obſeruandum fore ſum ratus.

Die itaq; vndecima eiuſcemodi conſtitutionem vidi:

Ori. * * O Occ.

Stellas ſcilicet tantum duas orientales; quarum media triplo diſtabat à Ioue, quam ab orientaliori: eratque orientalior duplo ferè maior reliqua, cum tamen antecedenti nocte æquales fermè apparuiſſent. Statutum ideò, omnique procul dubio à me decretum fuit, tres in cœlis adeſſe Stellas vagantes circa Iouem, inſtar Veneris, atque Mercurij circa Solem: quod tandem luce meridiana clarius in alijs poſtmodum compluribus inſpectionibus obſeruatũ eſt; ac non tantum tres, verum quatuor eſſe vaga Sydera circa Iouem ſuas circumuolutiones obeuntia; quorum permutationes exactius conſequenter obſeruatas ſubſequens narratio miniſtrabit; interſtitia quoque inter ipſa per Perſpicillum, ſuperius explicata ratione, dimetitus ſum: horas inſuper obſeruationum, præſertim cum plures in eadem nocte habitæ fuerunt appoſui; adeo enim celeres horum Planetarum extant reuolutiones, vt horarias quoque differentias plerunque liceat accipere.

Die igitur duodecima, hora ſequentis noctis prima hac ratione diſpoſita Sydera vidi. Erat orientalior

E 2 Stella

Figure 1. The pages of *Sidereus Nuncius* showing the first portrayals of the Medicean Stars on the nights of January 7^{th} (left) and 8^{th} (middle) and 10^{th} (right), 1610. (Courtesy of the Houghton Library, Harvard University, *IC6.G1333.610sa.)

Here a brief survey is offered of how Jupiter's satellites were portrayed in the years after 1610. Attention is given to the amount of time it took for other astronomers to show in graphical forms that Jupiter was a center of motion, as well as to the types of symbols they used for Jupiter and the moons. The final topic addressed is the iconographic appearances of the moons in what might be considered the 17th Century "textbook" for astronomy, i.e., in a publication not reporting new observations but meant for summarizing the status of the field to both general and technical readers.

3. 17th Century Depictions of Jupiter's Moons

Discovery and Controversy

Galileo's announcement that Jupiter had four companions in the sky was done with the simple insertion of linear drawings embedded within his published text. That is, there were no separately engraved plates (see Figure 1). He used an open disk to portray Jupiter and star symbols for the moons, presumably because he did not want to portray them as larger and smaller versions of the same types of bodies. Their reality was not accepted by all interested parties. Some simply doubted (or denied) their existence and suggested that they were merely the products of defects within the lenses used (Drake 2001). This was not classical falsification, as defined by Karl Popper (see discussions in Kuhn 1962) and as practiced today, because the rejections were made without offering evidence. I could not find an account by an experienced observer, using a telescope equal to or better than Galileo's, publishing a map of the sky showing Jupiter and fixed stars (and hence reliability), but no objects associated with Jupiter. Thus, there are no artistic renderings attesting the non-existence of the Medicean stars.

Validation is a richer field of pursuit. Van Helden (1989) points out that, unknown to Galileo, when Jupiter became visible in the Fall of 1610, his Medicean Moons were spotted by Thomas Harriot (1560-1621) in England, and by Joseph Gaultier de La Vatelle (1564-1647) and Nicolas-Claude Fabri de Peiresc (1580-1638) in Aix-en-Provence. The first to publish a book with observations was Simon Marius (1573-1625), a German astronomer who had studied with Tycho Brahe in Prague and spent the years 1602-05 as a student in Padova. He was implicated in a plagiarizing scandal with one of Galileo's former students (Baldesar Capra) concerning the publication of one of Galileo's earlier works. Returning to safer quarters in Germany for a Lutheran under investigation in Veneto, Marius became an even greater annoyance to Galileo when he published *Mundus Jovialis* in 1614. Marius claimed that he had been observing Jupiter's "four planets" since 1609 (i.e., prior to Galileo) and thus claimed the right to name them, not after the Medici family but after Jupiter's love conquests: Io, Europa, Ganymede and Callisto (a suggestion he received from Kepler). Marius' *World of Jupiter* contained tables of satellite positions but only one figure that showed the moons using star symbols in circular orbits about a solid disk representing Jupiter (Figure 2(a)). Predictably, Galileo's response was strong. In *The Assayer* (1623), he wrote:

> *"Notice the craft with which he tries to show himself prior to me.... What he neglects to mention to the reader, that since he is outside our church and has not accepted the Gregorian calendar, the seventh of January of 1610 for us Catholics, is the same as the twenty-eighth day of December of 1609 for those heretics.*
> *So much for the priority of his pretended observations."*

Thus, even if Marius' first recorded observation (29 December 1610) is accepted, it was one day *after* Galileo's! (from Drake, 1960, and The Galileo Project, Rice University).

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The astronomical community since that time has been far more gracious to Marius. Recognized as a good observer and a careful ephemeris maker, the International Astronomical Union (founded in 1919) decided in 1935 to honor him with the lunar crater named Marius, and then in 1979 by naming a feature on Ganymede photographed by Voyager *Marius Regio*.

Subsequent Findings

Rene Descartes (1596-1650) published his *Principia Philosophiae* in 1644, and in his treatment of the Copernican system of cosmology he updated the iconic image of a sun-centered system with Jupiter having four satellites. Descartes appears to be the first to use the same artistic symbol (open disk) for both the planet and its moons (Figure 2(b)) — implying, perhaps, a similarity in physical make-up (in *Il Dialogo* (1632), Galileo used an open disk for Jupiter and solid disks for the moons). Two years after Descartes, the Italian lawyer and astronomer Francesco Fontana (1602-1656) published in Naples what we might consider the first picture-book for astronomy. *Novae Coelestium Terrestrium Rerum Observationes* (1646) contained wood-cut prints of his telescopic appearances of the Moon, Mercury, Mars, Jupiter and Saturn. Fontana's observations of Jupiter and its moons started in 1630 and continued up to the year prior to publication (1643). Figure 2(c) shows an example of his jovian images: the disk of the planet is now resolved

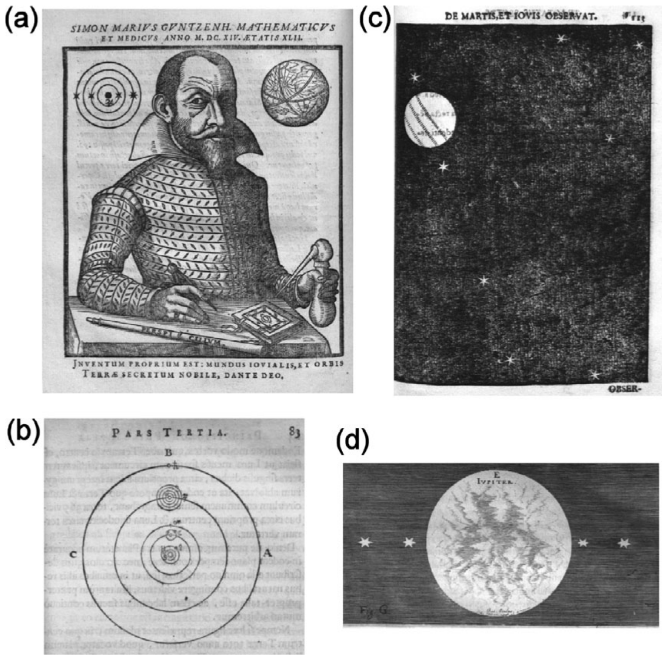

Figure 2. (a) Image of Simon Marius with Jupiter and its moons published in *Mundus Iovialis* in 1614. (b) Image from René Descartes' *Principia Philosophiæ* (1644) showing the solar system with Jupiter having four satellites. Note that both the planet and its moons are depicted using open disks. (c) Image of Jupiter and its moons from observations in 1630, published in *Novae Coelestium Terrestriumque* (New Observations of Things Celestial and Terrestrial) by Francesco Fontana in 1646. Jupiter has its atmospheric band structure and the moons are depicted using the same symbols as employed for stars. (d) Image of Jupiter and its moons from the *Selenographia* (1647) of Johnnes Hevelius. It shows a resolved disk with considerable structure, with the four moons depicted by star symbols in a symmetrical layout. (All courtesy of the Houghton Library, Harvard University: *GC6 M4552 614m, *FC6 D4537 644p, *IC6 F7342 646n, and f*GC6.H4902.647s.)

and Fontana shows that it has bands. For the moons, still points of light, star symbols are used. In his multiple plates of Jupiter spanning 13 years of observations, Fontana showed that there were changes in the banded structures (and, of course, in the positions of the moons).

Johannes Hevelius (1611-1687), the son of a wealthy merchant in Danzig (now Gdansk, Poland), created a personal observatory with some of the most advanced naked-eye and telescopic observing equipment of his time. While his *Selenographia* (1647) was primarily an atlas portraying the features of the Moon, Hevelius also used it as a way to publish his observations of the Sun and planets. Of interest here is his depiction of Jupiter and its moons (Figure 2(d)). This image shows a resolved disk of the planet that contains structure (curiously, with band-like features somewhat more meridional than the zonal patterns known to exist in its atmosphere). The four Galilean satellites are shown using star symbols — and arranged symmetrically, two to each side, and at the same distances. This image comes from a plate summarizing the appearances of three planets (Jupiter, Saturn and Mars), and thus it may well be intended to be more an illustration of characteristic patterns than a physical description on a specific night.

The famous Jesuit astronomer Giambattista Riccioli (1598-1671) championed the cosmological system of Tycho Brahe as the most acceptable to Catholic doctrine. The frontispiece to his *Almagestum Novum* (1651) is a wonderfully allegorical image that has been the subject of interpretation and speculations for centuries, mainly on the topic of hidden opinions and meanings in his portrayals of the three great world systems (Vertesi 2007). Riccioli does not include the jovian moons in any of his graphical portrayals of cosmology. However, in the upper right corner of the image [Figure 3(a)], we find Jupiter and its four moons — with the giant planet having banded structures and the moons depicted symmetrically by star symbols. The satellites are in orbits that appear polar rather than in their correct (but more difficult to show graphically) positions in the equatorial plane.

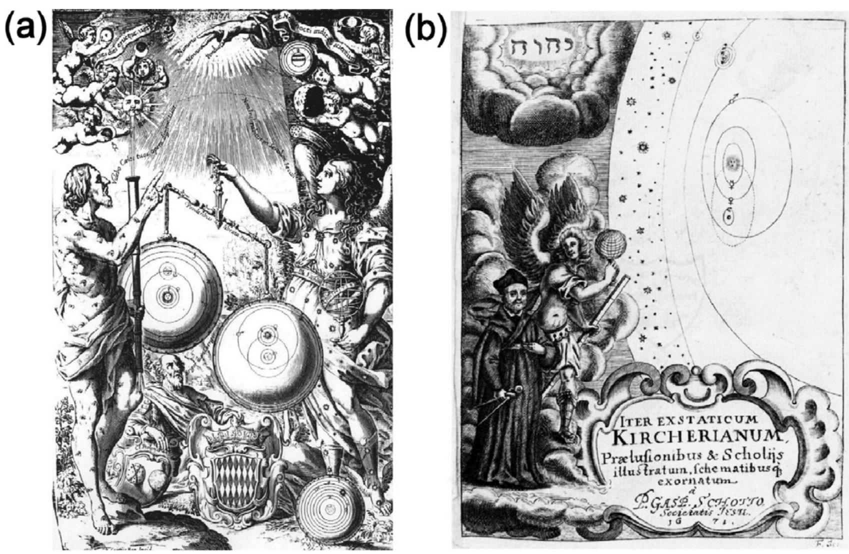

Figure 3. (a) Frontispiece of Riccioli's *Almagestum Novum* (1651). Jupiter and its moons appear in the upper right (from The Library of the Department of Astronomy, University of Bologna.). (b) Frontispiece of Athanasius Kircher's *Iter Exstaticum Coeleste* (1671) showing the system of Tycho Brahe, updated with the telescopic discovery of Jupiter's four moons, depicted as stars orbiting a resolved disk with banded structures (from Department of Special Collections, Stanford University, Green Library.).

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Given the decorative nature and rich symbolism of this particular frontispiece, the jovian system's portrayal is consistent with the theme of a representational-only illustration.

Athanasius Kircher (1602-1680), that most remarkable and controversial polymath of the Society of Jesus (Findlen, 2004), offered his views on cosmology via a dream-dialogue in 1656, with later editions in 1660 and 1671 under the title *Iter Exstaticum Coeleste* (The Celestial Ecstatic Journey). The frontispiece (Figure 3(b)) depicted the Church-approved Tychonic system with a specificity that goes beyond Riccioli — dramatically having a telescope point towards Jupiter — with its revelation of four moons, portrayed by tiny star symbols (Godwin 2009). Father Kircher's intended message to the reader of his dream has long been suspected as being pro-Copernican (De Santillana 1955).

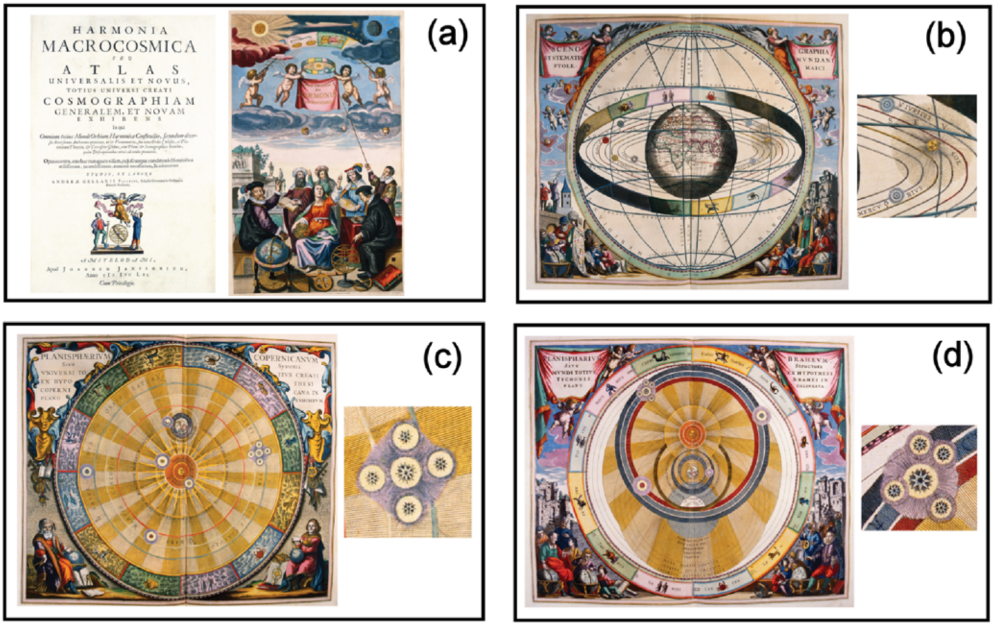

Figure 4. Images from Andreas Cellarius' *Harmonia Macrocosmica* (1661). (a) Title page and frontispiece, (b) The Ptolemaic system, with detail showing Jupiter without its four Galilean moons. (c) The Copernican system showing Jupiter surrounded by four moons, with detail showing all five objects depicted using star symbols. (d) The system of Tycho Brahe with Jupiter and its satellites all displayed using star symbols, with the satellites at variable distances from the planet. (from Mendillo Collection).

4. The *Harmonia Macrocosmica* of Andreas Cellarius

Andreas Cellarius (1596-1665) produced his exquisite "Harmony of the Great Cosmos" in 1660 (with a second printing in 1661), a volume that clearly signifies the high point of celestial cartography. It was published in Amsterdam by the great firm of Johannes Janssonius. Cellarius was an educator, and thus this elaborate atlas may be taken, not as the work of a practicing astronomer, but as a compendium of all knowledge about astronomy from antiquity to his day (Kanas 2007). Its publication date is, conveniently, 50 years after *Sidereus Nuncius*, and thus serves as an appropriate answer to the question posed for this study: it took 50 years for Galileo's starry message to get into the textbooks.

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The *Harmonia* contained 29 copper engraved plates, individually hand colored, and often with gilding for stars or points of emphasis. Eight of the plates included information about Jupiter, with three showing its four moons. Figure 4 shows the title page, frontispiece and three of its plates. Panel (b) describes Ptolemy's geocentric system and, keeping with all celestial objects encircling only the Earth, Jupiter is shown without its satellites. Clearly an update would have been logically inconsistent. Panel (c) displays the famous plate *Planisphaerium Copernicanum*. The heliocentric system of Copernicus has golden rays extending from a humanized Sun to the stellar sphere indicated by the signs of the zodiac. Jupiter has its four moons in a representational fashion (i.e., with star symbols all equidistant from the planet). Elaborate cartouches frame the Latin title and astronomical instruments hang nearby. The two astronomers below appear to be Ptolemy (in an Eastern turban) and Copernicus, sitting with their globes and tools gazing out at the viewer.

Panel (d) of Figure 4 gives one of two depictions of the compromise cosmology of Tycho Brahe — ones that include Jupiter with four moons. The planets encircle the Sun, and the Sun with its brood circles the Earth. This modification of Ptolemy kept the system geocentric, but allowed for objects (other than the Moon) to orbit the Sun. Consistent with that approach, Cellarius has Jupiter depicted by a large star symbol with its four moons shown using smaller stars. Not only are these Medicean stars not all the same size, they are also at slightly different distances from the planet. This, then, is the most dramatic departure from Ptolemy that could be tolerated by the Church.

5. Later Depictions of Jupiter's Moons

Following Galileo's discoveries of 1610, astronomers continued to scan the skies for new objects, and cartographers continued to create atlases with updated astronomical content. Limitations of space allow only a few to be mentioned. First to come was the discovery of moons around another planet (e.g., Christian Huygens discovered Saturn's moon Titan in 1655, and G. D. Cassini found four more between 1671-1684). Even more astounding were the discoveries of new planets (e.g., William Herschel's discovery of Uranus (1781) and LeVerrier's discovery of Neptune in 1846). These advances were due to rapid developments in the technologies of telescope design and construction in the later half of the 17$^{\text{th}}$ Century and beyond. Yet, actual photographs of the disks of the jovian moons did not occur until the mid-years of the 20$^{\text{th}}$ Century (e.g., see images taken in 1962 in review by Dollfus (1998)). During the intervening centuries, prints and paintings had no choice but to show Jupiter with only tiny disks for its moons. Examples occur in *Four Systems of Cosmology* by Alexis Hubert Jaillot (Paris, 1690), *Descriptions de l'Universe* by Alain Manesson Mallet (Paris, 1683), Systems of Cosmology in *Atlas Historic* by Nicolas de Fer (Paris, 1705), and in the *Papal Astronomical Paintings* by Donato Creti (Bologna, 1711). The series of atlases by Dopplemayer and Homann (1720) contained many images of Jupiter with bands and of Saturn's rings, but the moons still remained as points of light. Examples can be seen in McCarroll (2005). Perhaps the most unusual depiction of Jupiter's moons in the 18$^{\text{th}}$ Century was offered by Carel Allard (1648-1709). His chart of the southern sky appeared in the *Atlas Minor* of N. Visscher in 1717, and later in an atlas by Covens and C. Mortier in 1759. Allard was known for innovative publications in which border decorations contained additional items of scientific information related to the central image, rather than the usual depictions of angels, philosophers or astronomers (as in the Cellarius images in Figure 2). One of Allard's side-bar inserts is shown in Figure 5. This rare, and perhaps unique, depiction of the four moons of Jupiter that Galileo named after the Medici family actually shows

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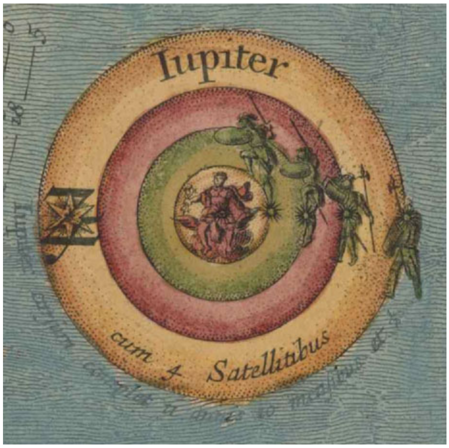

Figure 5. A side-bar item from the star chart *Planisphærii Coelestis Hemisphærum Meridionale* by Carel Allard (1759) that has Jupiter's four Medicean moons depicted by four armed men—assumed to be the four Medici brothers, Cosimo, Francesco, Carlo and Lorenzo. (Courtesy of the Pusey Library, Harvard University).

the four Medici brothers (Cosimo, Francesco, Carlo and Lorenzo) in combat gear. Galileo never used their specific names in his writings about the moons, instead referring to them simply and Medicean moons I, II, III and IV. It is thought that the French astronomer Nicolas-Claude Fabri de Peiresc (1580-1637) may have made the suggestion to use their actual names in this way (see Galileo Project, Rice University).

6. Conclusions

Galileo's announcement of the Medicean Moons created a new way to do astronomy and, indeed, natural science. One of his innovations was the introduction of astronomical art— and visualization has played an increasingly prominent role in science and education ever since. In this brief summary that focused on how the Medicean Stars were portrayed in the half century following publication of *Sidereus Nuncius*, we pass from Galileo's simple drawings embedded within lines of text to the sumptuous illustrations of Cellarius. For centuries, no one knew what these bodies looked like, and yet they caused a sensation, led to a trial, and to the validation of Newtonian physics beyond Earth. They offered a scheme for finding longitudes in distant lands and upon the seas. Upon closer inspection, the images we now have challenge our models for volcanism, magnetism and, most surprisingly, for potential host sites for life.

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