

Galileo's miraculous year 1609 and the revolutionary telescope

Introduction

In 1987, when I was a postdoc at Caltech, I visited the Caltech sister laboratory just up the road which was having an open day. That sister laboratory was the Jet Propulsion Laboratory and a highlight of the visit for me was seeing the Galileo spacecraft being assembled in the huge clean rooms. The atoms of that spacecraft are now dispersed somewhere in the atmosphere of Jupiter following its entry into the Jovian atmosphere in 2003 after a 14 year mission which included 8 years orbiting and observing Jupiter.

Naming the spacecraft after Galileo, commemorates the revolutionary discoveries made by Galileo 400 years ago this year that set humanity on a new path of understanding. As a consequence of this anniversary, 2009 has been declared the International Year of Astronomy¹ by the General Assembly of the United Nations.

Galileo's discovery of the moons of Jupiter were only one part of an avalanche of remarkable discoveries made by a telescope, simple in concept but masterful in construction and application, that overturned widely held views of Earth's place in the cosmos. In part, Galileo's discoveries were made possible by a new way of thinking that represented a turn away from received wisdom and towards discovering and observing directly from nature. In this, Galileo stands at the boundary between the medieval world and the modern world.

This short article reviews the great discoveries made in the first few years of the astronomical telescope starting in the last few months of 1609. Remarkably, the notes from Galileo's observations reveal he unwittingly observed the planet Neptune 234 years before its official discovery. As I will discuss, evidence that Galileo realised he had seen a new planet could still be hidden deep in his notebooks.

by Professor David Jamieson

Credit NASA/JPL

The Discoveries

Galileo Galilei was born in 1564 in Pisa. He had a position as a professor of mathematics in Pisa before moving to the University of Padua in 1592. There, in late 1608 or mid 1609, he heard² of a "spyglass" invented in the Dutch republic. He quickly designed his own version from first principles and by November of 1609 was making observations of the night sky. After clearing up any doubt that what he was seeing was real and not artefacts in the glass of the lenses, he published his first comprehensive book of astronomical observations in March of 1610. Although Galileo is not the first to observe the sky, he was the first to publish.

So great was the interest in his work (rumours must have already been spreading widely prior to 1610) that Sir Henry Wotton, English Ambassador to the Republic of Venice obtained a copy and sent it to the King of England, on the day of publication, with a cover letter³ stating that the author "*runneth a fortune to be either exceedingly famous or exceedingly ridiculous*". The book was "*Sidereus Nuncius*"⁴ which translates to "*Starry Messenger*". It was published in the lingua franca of science in the 17th Century: Latin.

This slim tome contains an astonishing list of discoveries. The

Moon was found to have dramatic surface texture including mountains and craters casting long shadows if the phase was right. Familiar constellations were found to have vast numbers of new stars invisible to the unaided eye but clearly seen through the telescope. More than 34 stars were visible in the constellation of the Pleiades, many more than the nine or so visible to the unaided eye⁵. Even more astonishing was the report that Jupiter was seen to have four tiny moons in orbit around it. These four moons were discovered between 10 and 16 January 1610⁶.

Galileo named them the "Medicean Stars" in hope of getting financial support from Cosimo II de' Medici, the Grand Duke of Tuscany. The discovery of moons orbiting Jupiter was very radical because this was the first time objects had been observed orbiting a planet other than Earth.

After publication of *Sidereus Nuncius* in March 1610 Galileo continued to make discoveries. He observed that there was something odd about Saturn. At the limit of resolution of his telescope, he saw two "lobes" sticking out each side of the planet. He established the primacy of his discovery by sending an anagram to Kepler shortly after 25 July 1610 that reads

.....
"smaismrmilmepoetaeumibunenugttauiras"

and then rearranged as

"Altissimum planetam tergeminum observavi"

translates to⁷:

"I have observed the highest of the planets [Saturn] three-formed".

Much later, in 1616, these lobes were observed to vanish, until the idea of thin rings around the planet explained these puzzling observations.

In September of 1610 was the discovery of the astonishing phases of Venus⁸. Although Venus just looks like a very bright star to the unaided eye, telescopic observations showed it to exhibit phases like the Moon. Galileo again established the primacy of his discovery by sending an anagram (in Latin) to Kepler⁹:

"Haec immatura a me jam frustra leguntur oy"¹⁰

This too may be rearranged to read:

"Cynthiae figuras aemulatur mater amorum"

and then translates to:

"The mother of love (Venus) imitates the shape of Cynthia (the Moon)".

Sadly, we no longer report important scientific discoveries in such poetical terms. The variations of the visible phase of Venus and the correlations with the observed size of the planet in the eyepiece of Galileo's telescope could only be explained if Venus orbited the Sun and not Earth. Later, he discovered sunspots¹¹ (as had many other people by then) and began demonstrating them to other people in 1611.

The Telescope

All this was made possible by a telescope of unprecedented power and quality, fabricated by Galileo's own hand. Indeed Galileo's telescope was of such high quality that for more than 20 years after 1609 he had a monopoly on the supply of high quality astronomical telescopes. His access to the products of the great glass industries of Venice, his knowledge of optics and his high manual skills were the key factors in his success. The key innovation in his astronomical telescope was a high-precision plano-convex objective lens which was combined with a plano-concave objective lens in the now immortal "Galilean telescope configuration". Convex lenses were already in mass production to combat presbyopia¹² (from the Greek for "old person"). Likewise

concave lenses to combat myopia¹³ were also in use. It was Galileo's genius that saw the potential of combining these lenses, with carefully selected focal lengths, to make a workable astronomical telescope.

The actual objective used in some of the important discoveries is on display¹⁴ at the Museum of Science in Florence, which I had the pleasure of visiting in December of 2008. In fact I was obliged to purchase a set of +1.5 Dioptre spectacles from a supermarket in Florence to allow me to read the fine print in the museum guidebook.



Roland Szymanski (left), occasional telescope maker, and David Jamieson (right), author, inspect Roland's replica of Galileo's 1609 x20 telescope made with modern materials in May 2009 at the School of Physics, University of Melbourne.

When looking at Galileo's original objective lens in the museum display cabinet, now unfortunately broken in several pieces, I was amazed that so slight a piece of glass could have been responsible for so many revolutionary discoveries. Galileo's telescope incorporated many innovations, not just the lenses, as revealed by people today seeking to make replicas as close as possible to the original¹⁵.

Then, as now, Galileo had to keep a close eye on the financial support for his research. So in a letter to the Duke of Tuscany, a potential funding agency, he wrote¹⁶:

"Most Serene Prince. Galileo Galilei most humbly prostrates himself before Your Highness, watching carefully, and with all spirit of willingness, not only to satisfy what concerns the reading of mathematics in the study of Padua, but to write of having decided to present to Your Highness a telescope ("Occhiale") that will be a great help in maritime and land enterprises. I assure you I shall keep this new invention a great secret and show it only to Your Highness. The telescope was made for the most accurate study of distances. This telescope has the advantage of discovering the ships of the enemy two hours before they can be seen with the natural vision and to distinguish the number and quality of the ships and to judge their strength and be ready to chase them, to fight them, or to flee from them; or, in the open country to see all details and to distinguish every movement and preparation."

He tried a number of lens combinations, aiming for the highest possible magnification with the sharpest view. The most successful combination appeared to consist of a hand-ground plano-convex objective with a focal length of 980 mm and a diameter of 37 mm teamed with a plano-convex eyepiece of focal length of -47.5 mm and diameter of 22 mm. The objective was stopped down to 12 – 25 mm to limit aberrations and the combination gives a magnification of about 20. The magnification is handy, but the benefits of

collecting light through a 25 mm diameter lens and focussing it through the 6 mm diameter human iris should not be overlooked! The telescope allowed Galileo to see objects with a brightness of about 9th magnitude compared to the unaided eye's limit of about 6th magnitude. For comparison, the moons of Jupiter have a brightness between 5th and 6th magnitude.

A significant difficulty with the Galilean telescope for astronomy is that the field of view is very narrow. For example the 20 magnification telescope has a field of view of only about 0.13° which is about one quarter of the full Moon. This would have made it difficult to get an overview of the Moon, to say nothing of the need to constantly tweak the telescope to compensate for the rotation of the Earth!

The Moons of Jupiter and the heliocentric model

Following his discovery of the four Galilean moons of Jupiter from 7 - 10 January 1610, Galileo spent many years tracking their orbits. Page after page of his notebooks record his meticulous observations¹⁷. Reproductions of most of these notebooks are now available online at the Institute and Museum of the History of Science in Italy^{18, 19}.

By 1612 he was using a fully quantitative and precise technique, now lost, to measure the distance of each of the four moons from the centre of Jupiter in units of the diameter of Jupiter. He also took great care to record "fixed stars" that drifted through the field of view during his observations as he tracked Jupiter's movement across the sky.

The discovery of objects orbiting a planet other than Earth created severe difficulties for one of the primary justifications of the geocentric model

of the solar system that required everything to orbit Earth. The observed variations in the phases of Venus could really only be explained by the heliocentric model. But the most salient feature of the heliocentric model was that the Earth moved relative to the Sun AND the stars. Therefore stars, if assumed to be at varying distances from the Earth, should exhibit parallax as the Earth changes position in its orbit over the course of a year. Galileo was well aware of this feature of the heliocentric model and made several attempts to detect this parallax. He did this by making assumptions about the distances to the stars and calculating the magnitude of the expected parallax.

He made the very reasonable assumption that stars were suns like our own and therefore that the size and brightness of the star disk observed in his telescope could be used to estimate their distance. In the case of the double star Mizar he estimated that the two stars were 300 and 450 Astronomical Units (AU) distant from the Earth, with the consequence that the annual parallax should be significantly larger than their angular separation^{20, 21} than he observed in January 1617. Unfortunately his assumptions about the distances to the stars were significantly underestimated.

Wave optics was unknown to Galileo and so he did not recognise that the star diameters he measured were due to diffraction through the collimators of his lenses (and other effects), not the true magnified star diameters.

Over the years, the two stars of Mizar did not show any parallax that Galileo could observe. Of course no such parallax of Mizar, true distance around 5 million AU, or any other closely spaced pair of stars, could be observed with Galileo's telescope or any other technology before the 18th century. Indeed it was the observation of stellar aberration²² by James Bradley in 1725 that first detected Earth's orbit around the Sun. This is an effect that arises from the changing direction of Earth's velocity vector and produces a shift in the positions of the stars an order of magnitude larger (and 3 months out of phase) compared to stellar parallax.

Galileo's failure to observe stellar parallax must have puzzled him. Especially as critics of the heliocentric model demanded this hard evidence²³ before abandoning the geocentric model. Perhaps he realised there was something wrong with his assumptions? In any case his observations of Mizar and other closely spaced stars do not appear to have made it out of his notebooks and into any of his publications.

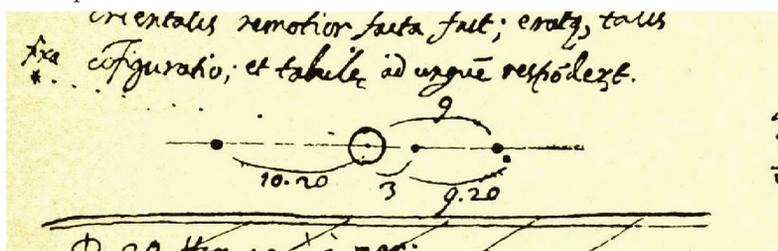


Fig 1 Galileo's notebook for December 28 1612. The object labelled "fixa" on the left is Neptune. Image credit by kind permission of the Ministero per i Beni e le Attività Culturali della Repubblica Italiana/Biblioteca Nazionale Centrale di Firenze.

Galileo's Observations of Neptune

Just about all of the "fixed stars" he records in his notebooks while observing Jupiter appear in modern star catalogues. However one of those "fixed stars", seen in December 1612 and January 1613 does not appear in any catalogue. This particular "fixed star"

turns out to be something entirely different: Galileo was actually observing the planet Neptune. These observations were made 234 years earlier than the official discovery of Neptune in 1846²⁴. It is remarkable that Neptune has yet (in 2009) to complete one orbit around the Sun since its official discovery, because its orbital period is 165 years. The first orbit will be completed in 2011.

The story of Galileo's observations of Neptune is remarkable, and a striking example of his skill and care making quantitative observations with very simple apparatus that have stood the test of time. Galileo's observations of Neptune were discovered by Kowal and reported in the journals *Nature*²⁵ and *Scientific American*²⁶ in 1980. Kowal also provides a commentary on the circumstances of the discovery and the aftermath in a short essay²⁷ posted on the web site of *DIO: The International Journal of Scientific History* in 2008.

Galileo's notes show he made several observations of the planet Neptune in December 1612 and January 1613. He uses the label "fixa" where he plotted the position of Neptune in his notebook, indicating, at least initially, that he believed he was observing a fixed star and not a planet (Fig 1).

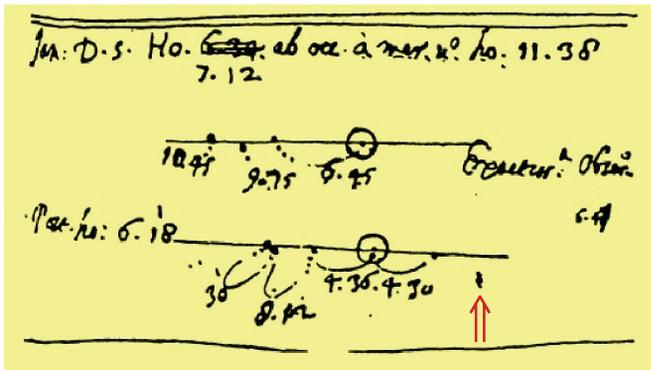


Fig 2 Galileo's notebook from 6 January 1613: The unlabelled mark to the lower right (identified by the red arrow) is Neptune. The mark is not present in the on-line images of Galileo's notebooks. Reproduced from Standish and Nobili. Image credit by kind permission of the Ministero per i Beni e le Attività Culturali della Repubblica Italiana/Biblioteca Nazionale Centrale di Firenze.

Even more remarkable is that Galileo's notes of 28 January 1613 suggest he saw Neptune move when it passed in close conjunction to an actual star. Yet it appears he did not follow up this observation, and no further entries in his notebooks have been identified that suggest Galileo was aware of the possibility of a new planet. If Galileo had used his observations to propose the discovery of a new planet, it would have been the first time a planet had been discovered by humanity since deep antiquity, and would be without precedent in recorded history.

The first two of three observations of Neptune identified by Kowal were both made on 28 December 1613. The third observation was on 28 January 1613. On 4 January 1613, in between these two dates, Neptune was actually occulted by Jupiter.

The reason why Neptune was visible in close proximity to Jupiter over a time span of a month was that Jupiter and Neptune executed a retrograde loop (direction reversal) on 13 January 1613 as the Earth overtook them in orbit. This maximises the amount of time they are visible in close proximity in the sky.

A further article by Standish and Nobili²⁸ report a possible additional observation of Neptune that is represented by an unlabelled mark in Galileo's notes from 6 January 1613. This mark, which is not reproduced in images of Galileo's notebooks posted on the web, is clearly seen to be a deliberate record of an observation because of the physical evidence of the page itself. This reveals, as reported by Standish and Nobili, a dimple in the page made by the deliberate press of the nib of an ink pen into the paper.

As pointed out by Kowal and Drake, the observations made by Galileo on 28 January are quite remarkable. First, Neptune appeared in close proximity to an actual star. Second, although the actual star could be plotted in Galileo's notebook on the same page as Jupiter and its satellites, Neptune could not because it lay further from Jupiter beyond the position of the actual star. So Galileo included an inset drawing of the actual star with Neptune included as well.

Galileo's notes on his observations, as pointed out by Kowal and Drake, indicate that Galileo recalled seeing both Neptune and the actual star the previous night, but he did not record them in his notebook. However he notes on his 28 January observations that "After the fixed star *a*, another was following in the same line in the same way as *b* did, which was also observed on the night before; but they seemed to be further away relative to each other"²⁹ (here *a* is an actual star and *b* is Neptune). Kowal and Drake point out that from 27 to 28 January Neptune would have moved 2.5 Jovian radii closer to the actual star. Clearly Galileo had seen this motion.

The absence of follow-up observations is puzzling. Kowal and Drake speculate that bad weather or difficulties relocating Neptune once it moved out of the field of view when the telescope was trained on Jupiter prevented further observations. There is no evidence yet found that Galileo formed the hypothesis that he had seen a new planet on the nights of 27 and 28 January.

However, I suggest the unlabelled mark on 6 January might be a retrospective record made by Galileo after he made the remarkable observation on 28 January. Given he depended only on his memory of the observations made, but not recorded, on 27 January to identify the motion of Neptune (*b*) relative to the fixed star (*a*), then it is possible the mark on 6 January was made from memory AFTER he made the observations on 28 January. If so, this would suggest he did indeed form the hypothesis that he had seen a new planet which had moved right across the field of view during his observations of Jupiter over the month of January 1613.

This particular "fixed star" turns out to be something entirely different: Galileo was actually observing the planet Neptune.

Therefore it would be very interesting to see if trace element analysis of the unlabelled spot from 6 January could identify the date on which it was recorded. 6 or 28 January? If the latter, I would propose this could construe evidence that Galileo was thinking about the possibility he had discovered a new planet.

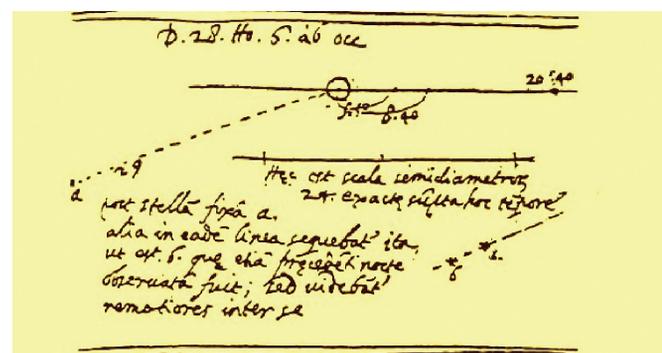


Fig 3 Galileo's notebook from January 28 1613: The object labelled "b" on the inset lower right is Neptune. Image credit by kind permission of the Ministero per i Beni e le Attività Culturali della Repubblica Italiana/Biblioteca Nazionale Centrale di Firenze.

Trace Element Analysis of Galileo's Inks

This proposal arises from prior use of trace element analysis of Galileo's inks establishing the dates of some of his undated writings. The National Institute of Nuclear Physics at the University of Florence has had considerable experience in the analysis of Galileo's inks using Proton Induced X-ray Emission (PIXE). Manuscripts from the years 1600, 1605-09, 1617 and 1636 have been analysed³⁰. The analysis covered both the background parchment and the inks employed in the writing. On the PIXE evidence, the relative concentration of K, Ca, Fe, Cu, Zn and Pb allow, in some cases, identification of the date at which a document was written to a precision of three months (see for example a case study in the development of Galileo's theories of mechanics³¹).

The challenge of using trace elements to identify the date of the unlabelled spot on the page for 6 January, 1613, is much greater than using trace elements to date a manuscript. This is because when two manuscripts are compared, the entire surface area of each manuscript can be used for comparison. Here we seek only to compare the composition with a single spot to the composition of the writing ink in the remainder of the manuscript. However, the Florence group have identified large variations in the composition of the ink in a single manuscript³². These variations that are larger than the accuracy of the PIXE measurements themselves, suggest real variations in the ink composition are responsible.

It would be very interesting to see if the ink composition could be employed to link the unlabelled dot of 6 January, 1613, with the ink used on 28 January, 1613. If such a link could be established, this could be interpreted that Galileo understood he was seeing something unusual that was, perhaps, a new planet.

But I would suggest another intriguing possibility presents itself. Galileo's habit of sending cryptic anagrams to his correspondents to establish the primacy of his discoveries has already been explained here. It is therefore possible that there remains, undiscovered in the Galileo literature, an anagram put there by Galileo to establish the date of his discovery of Neptune. However, as yet no such anagram has been uncovered. Perhaps there is such an anagram hidden in his notebooks or in his voluminous correspondence revealing that he considered the possibility he had discovered a new planet. This would indeed be an even more remarkable addition to the already impressive list of discoveries that make the 400th anniversary of Galileo's telescope worth celebrating!

Obviam Valens Tamen Pavor³³

Footnotes

- 1 <http://www.astronomy2009.org.au/>
- 2 A. Carugo, Galileo in Venice, *Microchemical Journal* 79 (2005) 7-14.
- 3 M.B. Hall, *The Scientific Renaissance 1450-1630*, Dover 1994 p 320.
- 4 http://en.wikipedia.org/wiki/Sidereus_Nunciuss
- 5 [http://en.wikipedia.org/wiki/Pleiades_\(star_cluster\)](http://en.wikipedia.org/wiki/Pleiades_(star_cluster))
- 6 http://galileo.rice.edu/sci/observations/jupiter_satellites.html

- 7 <http://www.mathpages.com/home/kmath151.htm>
- 8 http://en.wikipedia.org/wiki/Galileo_Galilei
- 9 <http://www.physics.rutgers.edu/~croft/ANAGRAM.htm>
- 10 Translation: "This was already tried by me in vain too early" from <http://www.physics.rutgers.edu/~croft/ANAGRAM.htm>
- 11 <http://galileo.rice.edu/sci/observations/sunspots.html>
- 12 <http://en.wikipedia.org/wiki/Presbyopia>
- 13 <http://en.wikipedia.org/wiki/Myopia>
- 14 <http://brunelleschi.imss.fi.it/telescopiogalileo/index.html>
- 15 <http://www.pacifier.com/~tpope/index.htm>
- 16 <http://www2.jpl.nasa.gov/galileo/ganymede/discovery.html>
- 17 <http://www2.jpl.nasa.gov/galileo/ganymede/discovery.html>
- 18 http://www.pacifier.com/~tpope/Accessing_Manuscripts.htm
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- 20 C.M. Graney, Letter to the editor of *Sky and Telescope* concerning Galileo's observations of Mizar, May 2006.
- 21 C.M. Graney, On the accuracy of Galileo's Observations, *Baltic Astronomy*, 16 (2007) 443-449.
- 22 http://en.wikipedia.org/wiki/Aberration_of_light
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- 24 http://en.wikipedia.org/wiki/Discovery_of_Neptune
- 25 C.T. Kowal and S. Drake, Galileo's observations of Neptune, *Nature* 287 25 Sept 1980 pp 311-313
- 26 S. Drake and C. T. Kowal, Galileo's Sighting of Neptune, *Scientific American* Dec 1980 pp 52-59.
- 27 C.T. Kowal's history of his discovery of Galileo's observations of Neptune: <http://www.dioi.org/Kowal-Galileo.pdf> (Dio: The International Journal of Scientific History, Vol 15, December 2008)
- 28 E. M. Standish and A. M. Nobili, Galileo's Observations of Neptune, *Baltic Astronomy* 6 1977 pp 97-104
- 29 Translation by Sonya Wurster, University of Melbourne 2009
- 30 L. Giuntini, F. Lucarelli, P.A. Mando, W. Hooper, P.H. Barker, Galileo's writings: chronology by PIXE, *Nuclear Instruments and Methods in Physics B* 95 (1995) 389-391.
- 31 F. Lucarelli, P.A. Mando, Recent applications to the study of ancient inks with the Florence external-PIXE facility, *Nuclear Instruments and Methods in Physics B* 109/110 (1996) 644-652.
- 32 P. Del Carmine, L. Giutini, W. Hooper, F. Lucarelli, P.A. Mando, Further results from PIXE analysis of inks in Galileo's notes on motion, *Nuclear Instruments and Methods in Physics B* 113 (1996) 354-358.
- 33 Anagram by David Jamieson 2009, translation of the anagram by Dr Alberto Cimmino: "I Boldly Follow The Path Even Though Scared".

Professor David Jamieson is the Head of the School of Physics at the University of Melbourne and is a member of ARC Centre of Excellence for Quantum Computer Technology. He served as the President of the Australian Institute of Physics in 2005-6, and has presented popular lectures on fundamental topics in physics around Australia.

