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GALILEO'S OBSERVATIONS OF NEPTUNE

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ABSTRACT. During the years 1610 – 1613, the astronomer Galileo discovered the four largest moons of Jupiter, charted their nightly positions and even found that he was able to predict their future positions with a high degree of accuracy. His observing notebooks, now preserved at the National Archives in Florence, Italy, show his observing innovations, improving accuracies and a couple of truly startling astronomical discoveries. More than of just historical interest, his work still has important implications for present-day astronomy.

Key Words: history of astronomy – planets and satellites: Neptune

1. THE PRECEDING YEARS

In the year 1610, the astronomer Galileo had discovered a miniature solar system centered on Jupiter. He began to routinely observe these bodies, measure their positions, and carefully draw to scale the observed configurations into his notebooks. Over the next two years, he developed the ability to accurately predict the satellites' positions into the future. In fact, from these notebooks, one may see the increase in the observational accuracy as Galileo improved his telescopes and his techniques of measuring.

2. THE FIRST OBSERVATIONS OF NEPTUNE

Late in the year 1612, the planet Neptune drifted into the same field of view as Jupiter. On December 27 and again on December 28, Galileo indicated the location of what he thought was just an ordinary star. In fact, though, it was not a star; it was the planet Neptune: the first known sighting of the distant planet - 234 years before its official discovery in 1846! This startling fact was discovered and reported by Drake and Kowal (1980) and discussed further by Kowal and Drake (1980).

The two drawings are shown in Fig. 1. The satellites and their separations from Jupiter (in units of the jovian semi-diameter) are shown along with the location of the "fixed star", i.e., Neptune. The top line gives the date and time: "December 27: Hour 15.46 after noon: while Venus was rising", and the paragraph describes the configurations of the satellites: "Before sunrise 0:30. The two westerly ones were very closely joined; they were distant about 0.20 according to their longitude, but the more easterly one had such latitude that it appeared that in this conjunction it almost touched the other and at the same hour a fourth star was present and the easterly one became more remote; and the configuration was so: and the tables agreed to a nicety."

These are the first known observations of the eighth planet, made 170 years before the discovery of the seventh planet and 234 years before the discovery of Neptune itself.

3. SUBSEQUENT OBSERVATIONS

In early January 1613, Neptune approached close to Jupiter and remained in the field of view throughout the month. Drake and Kowal include photographs of many of Galileo's notebook drawings from those January nights, indicating on each the position of Neptune as predicted by present-day ephemerides. These show that on January 3 Neptune was even occulted by Jupiter. However, even though a nearby star is drawn in the notebook twice during that month, no indication of Neptune seemed to be given until January 28, by which time Neptune had almost completely departed from the field of view.

On January 28, Galileo did draw another position of Neptune. This observation is a unique one; it is shown in Fig. 2. In Fig. 2, Jupiter and three satellites (Io was hidden behind Jupiter) are connected with a solid line, and their distances, expressed in units of Jovian semi-diameters, are labeled numerically. A dashed line runs diagonally downward from Jupiter to the lefthand edge of the page where there is an asterisk labeled "a"; the distance of "a" from Jupiter is labeled as 29. The dashed line is continued from the right-hand edge of the page, coming to two asterisks, labeled "a" and "b", but with no numerical measurement given for their mutual separation. On the page Galileo writes, "Beyond fixed star a another followed in the same line, as [does] b, which also was observed on the preceding night; but they [then] seemed farther apart" (Drake and Kowal 1980). Modern catalogues show that "a" is star #119234 in the Smithsonian Astrophysical Observatory catalogue. However, there is no star anywhere near the location of "b"; Neptune was there instead.

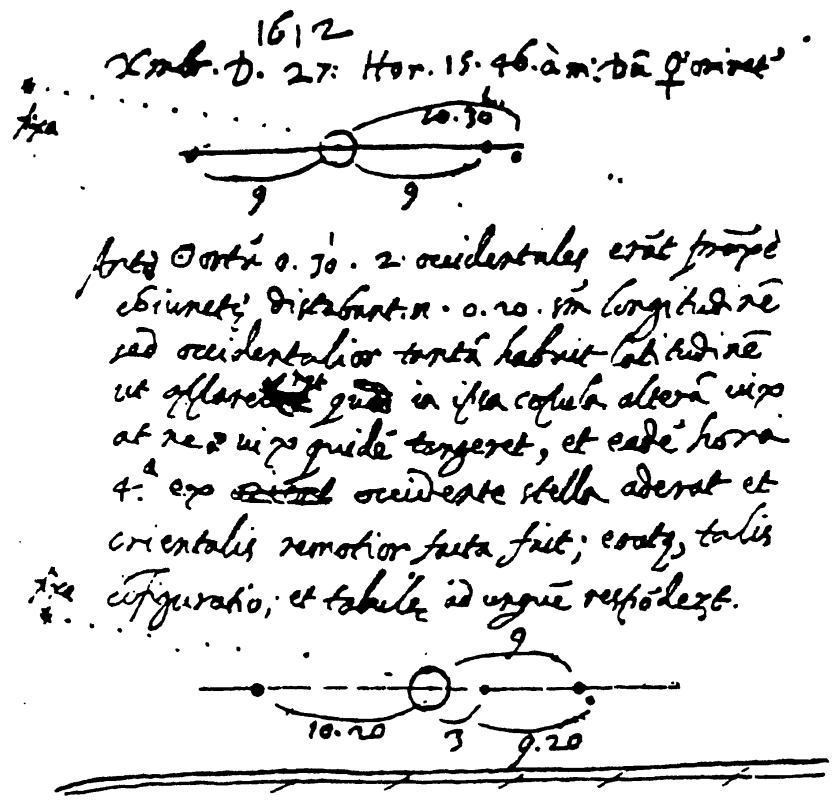

Fig. 1. Galileo's notebook from the 27th of December, 1612. These historic drawings show the satellites and their separations from Jupiter, but more importantly, the locations of a "fixed star", which, in reality is Neptune - the first known observations of that planet.

4. AN ASTROMETRIC POSITION OF NEPTUNE

Present-day computations, using modern satellite ephemerides (Lieske, 1980), show that Galileo's measurements of the satellites' separations from Jupiter are accurate to 0.1 Jovian semi-diameters or better(!), after accounting for a consistent 10% scale factor (Galileo's measurements at this time were too small by about 10%. Evidently, he over-estimated the semi-diameter of Jupiter by that amount.) Furthermore, by actually measuring his diagrams with a ruler, we find that the separations are drawn to scale with an accuracy of 0.2 semi-diameters or better - an accuracy smaller than the width of the dots with which he indicated the satellites' positions!

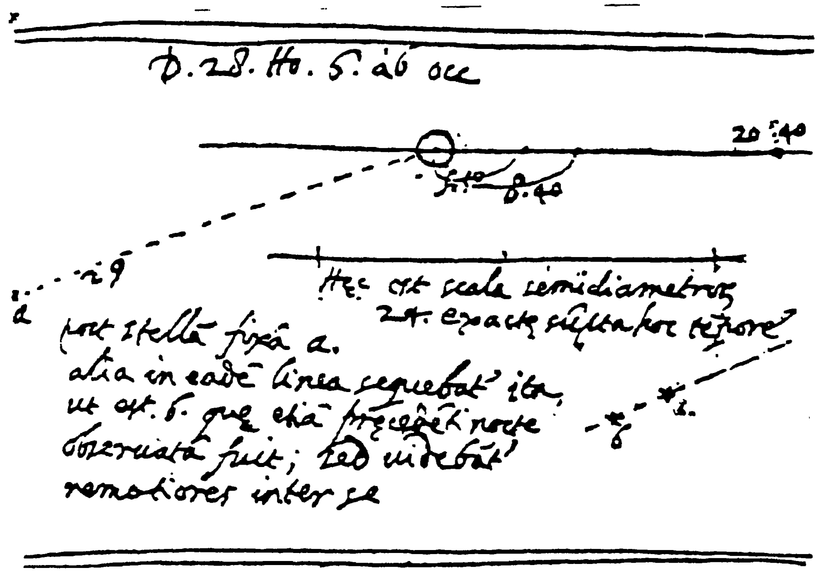

Fig. 2. Jupiter, three satellites, SAO star #119234 ("a") and Neptune ("b") were drawn by Galileo on this diagram of January 28, 1613. Galileo thought that Neptune was just a "fixed star", but he did notice that the stars seemed to have moved since the preceding night.

In Fig. 2, the satellite measurements are very accurate as usual; for the "stars", however, the accuracy is noticeably less. The important feature of this observation, however, is the distance separating Neptune from the star: according to modern ephemerides, that should be about 7.1 Jovian semi-diameters, but in Galileo's drawing, after applying the scale factor, the separation is only about 4.0 semi-diameters - a very different number. The difference in positions corresponds to about 53 seconds of arc in Neptune's orbital longitude and, more importantly, about 26 seconds of arc in latitude. Clearly, this disagreement is unacceptable for a modern ephemeris of Neptune Did Galileo carefully draw the star-Neptune separation to scale? If yes, then the ephemeris of Neptune is seriously in error. If no, then one may conclude that the ephemeris of Neptune is quite accurate, for it does place Neptune on the line connecting Jupiter and the star.

There is no way that the Neptune ephemeris could be off by 26 arcseconds in latitude at the time of Galileo's observations. Throughout the 20th century, Neptune has been measured over an arc covering 110 to 285 degrees in longitude, i.e., encompassing its position of January 28, 1613, longitude 176 degrees. An error of a single arcsecond in the orbital plane (i.e., latitude) would barely be tolerable; an error of 26 arcseconds would be grotesque. The only other explanation would be some unknown influence - a different law of gravity? Planet X?

5. NEPTUNE PERTURBED BY PLANET X?

To test the Planet X hypothesis, numerical experiments were performed whereby Neptune was perturbed by 500 randomly selected perturbers. A hypothetical Planet X with a mass equal to that of the earth, was placed in an orbit whose perihelion distance was randomly chosen to lie between 25 and 35 au's and whose eccentricity was randomly chosen to lie between 0.0 and 0.9; the other (orientation) elements were all randomly chosen. The orbit of Neptune was then integrated from the present epoch backward to the time of Galileo's drawing. The directions and distances of the departures from the original unperturbed ephemeris are drawn in Fig. 3.

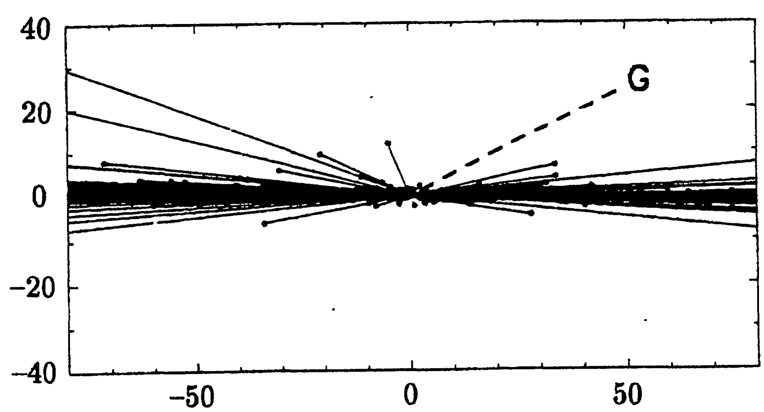

Fig. 3. Perturbations of Neptune on January 28, 1613, caused by randomly chosen Planet X's of one earth mass. Most of the cases show Neptune perturbed in the direction along the orbit (longitude). For virtually all of the out-of-plane cases, the perturbation is small, indicating that a perturbation large enough to agree with Galileo's measurement (denoted by the letter "G") would require tens of earth masses - a Planet X as large as Neptune itself!

In nearly all of the 500 cases, Neptune was perturbed along the orbital (longitude) direction. Further, of the few that were perturbed away from the orbital plane, most were very small in magnitude. For these smaller few, it would require a much larger mass to push Neptune all the way up to the position drawn by Galileo, denoted in the figure by the letter "G". In fact, most would require 20 or more earth masses, implying a Planet X larger than Neptune itself! The conclusion is that if Neptune were perturbed to where Galileo drew it, the perturbation was a rare one - pathological in nature.

6. A POSSIBLE FOURTH OBSERVATION OF NEPTUNE

Why didn't Galileo observe Neptune at other times during the month of January, especially when it was close to Jupiter? A study of the observations taken during those days of close approach shows that Neptune was almost invariably located either near another satellite,or near to the disk of Jupiter, or actually occulted by Jupiter. Since the magnitude of Neptune is about 7.9 while those of the satellites are between 5.5 and 6.0, it could also have been the case that hazy observing conditions prevented Neptune's detection while allowing the observations of the satellites.

However, one of us [EMS] did notice a mark on the page of Galileo's notebook for the second drawing of January 5, shown in Fig. 4. The mark is near to where Neptune should have been at that time, below the line of satellites on the right-hand side of the drawing. Is the mark a real ink spot or is it a blemish on either the photograph or on the manuscript? If it is really ink, was it intentionally made by Galileo? If intentionally made, does it represent a carefully measured position of Neptune?

One of us [AMN] went to the National Library in Florence to examine Galileo's original manuscripts. The reports came by fax:

> "I have seen the man from the restoration department of the National Library .... a chemical test is not allowed. What he suggested - and we did it on the spot - was to use a microscope and look at the mark both in direct and backward light (I mean, with a light bulb from behind). We have no doubt that it is ink. ... With the light bulb we could see more details. It was more evident that it was ink and also it was possible to distinguish the point where the pen went."

> "From yesterday's visit to the Biblioteca Nazionale ...With a UV lamp I could only use a little lens because the manuscript (about 10 by 30 cm) is very hard to handle, and it was impossible to use the UV lamp in combination with the microscope. In any case, UV light is very useful because it shows much neater signs (this seems to be due to some particular refraction properties of the ink used at the time). It confirms

that we are looking at an ink spot and not at a paper irregularity."

Thus, it seems a certainty that the mark is ink and that it was made directly by Galileo's pen. Furthermore, there is a good possibility that the mark was intentionally made and that it was a measurement by Galileo of Neptune.

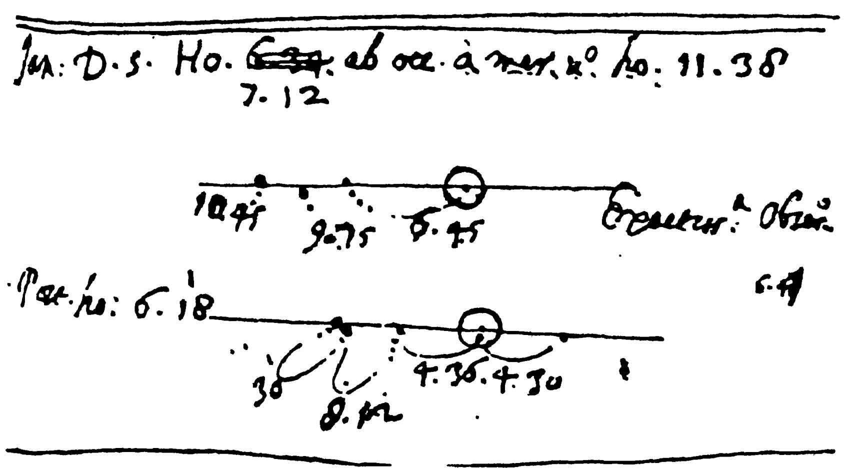

Fig. 4. Galileo's drawings of January 5 - 6, 1613. In the second, the spot to the lower right is just where Neptune was at that time. Magnification of the spot shows that it was an intentional mark, made with ink.

It is interesting to note that the mark in question does not exist in "Le Opere di Galileo Galilei" (1907), the compilation of Galileo's works, in which his drawings were reproduced by some sort of lithographic process. Evidently, during that process, an editor must have "cleaned up" the reproductions, thereby erasing the mark along with some other (much smaller) blemishes on the paper. Fortunately, the figures in the paper by Drake and Kowal were actual photographs of the original manuscript. Otherwise, the spot would have gone unnoticed.

Both co-authors have marveled at the seeming coincidence that Galileo's accuracy reached a crescendo at just the right time - the appearance of Neptune. Only a month or so after Neptune had receded from the field of view, Galileo's interest in accurately measuring the satellites' positions seems to have waned. Before long, this great scientist became involved with other pursuits.

8. CONCLUSIONS

Galileo observed Neptune in 1612 and 1613 - an amazing fact discovered by Drake and Kowal. However, the implications for the ephemeris of Neptune are ambiguous; some have interpreted the observation of January 28 as indicating a problem. Now, though, it seems that there is an additional intentional measurement of Neptune by Galileo, one which agrees closely with the position given by modern-day ephemerides - ephemerides created under the assumption that the force model of the solar system is complete and correct.

No change to the law of gravity is therefore indicated, nor do Galileo's observations give a reason to invoke the presence of a tenth planet in the solar system.

ACKNOWLEDGMENTS

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