support for basic research on supercomputers and their applications. Also, new antitrust legislation could make more secure new companies such as SRC (Semiconductor Research Corporation) and MCC (Microelectronics and Computer Technology Corp.), which want to pool scarce talent and resources in the semiconductor and computer technology fields. Finally, multiyear authorization bills would greatly aid the planning of research in supercomputing, as in other fields of science.

We believe that measures such as those outlined above will produce a climate conducive to progress in supercomputing. They will permit the United States to marshal its impressive strengths in this area—an entrepreneurial supercomputer industry, a robust and innovative academic research establishment, and a large and growing base of experience in supercomputer applications—to maintain its leadership in supercomputer design, and to make further impressive strides in the application of supercomputing to scientific and engineering problems.

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Galileo, Planetary Atmospheres, and Prograde Revolution

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Summary. Early in March 1610 Galileo was preoccupied with curious brightness variations of the newly discovered satellites of Jupiter. In formulating an incorrect explanation he advanced important generalizations about the existence of planetary atmospheres and counterclockwise circulation within the solar system.

The first serious scientific conjecture that planetary atmospheres exist quite generally was made by Galileo in March 1610 in the concluding paragraphs of his *Starry Messenger*. Analysis of Galileo's data shows that he developed this hypothesis from his misinterpretation of an optical illusion and from an unmentioned assumption about the counterclockwise sense of revolution for motions within the solar system.

The hypotheses of planetary atmospheres and prograde revolution were employed by Galileo to account for certain appearances of the system of four satellites that he had recently discovered around Jupiter. Records of his early telescopic observations of the Galilean satellites consist of their apparent configurations and relative brightnesses. Because these data are of good quality, their detailed analysis elucidates the manner in which Galileo reached his correct but unfounded conclusions.

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Orbital Brightness Variations

A striking feature of the relative brightness information recorded in the *Starry Messenger* is the frequent dimness of the satellite nearest to Jupiter. Galileo recognized this variation of apparent brightness with orbital position and was preoccupied with its explanation in his conclusion of the *Starry Messenger*. Reconstruction of the satellite configurations shows that Galileo regularly underestimated satellite brightness at small separation angles (*1*). In Fig. 1 records from the *Starry Messenger* are reproduced for some of the observations in which the brightness of the innermost satellite is underestimated. This brightness diminution occurs in approximately half of Galileo's brightness data.

Reconstruction of the satellite configurations shows that the probability of Galileo's underestimating the relative brightness of the nearest satellite varies inversely with separation angle and approaches 100 percent for the smallest separations detected (*1*). Figure 2 shows this probability compared with the judgments of eight contemporary scientists viewing a simulated Jovian star field in the laboratory. In the simulation, a viewer in a darkened room directly views three colinear light sources that mimic Galileo's telescopic view of Jupiter and two satellites (*2*). The viewer controls the brightness of the closer "moon." The separation of this moon is varied by the experimenter, while the viewer matches the brightness of the two moons. The electrical power which a viewer delivers to the inner moon is measured as a function of its separation. Two viewers can differ considerably in the power provided at a given separation, and it is impossible to know which viewer's perception would be most similar to Galileo's. Nevertheless, a clear pattern emerges: all viewers decrease the supplied power as separation is increased. For each viewer there is a separation beyond which the inner satellite is reduced no further. The fraction of viewers who underestimate the inner satellite is plotted in Fig. 2 as a function of separation angle. The good agreement between the variations in brightness perceived by Galileo and modern viewers suggests that the principal orbital brightness variations in Galileo's data are illusory (*1*).

Galileo's Explanation

Galileo often recorded correct relative brightnesses for satellites far from Jupiter, and he recognized that the satellites likely differed in intrinsic brightness. (Their intrinsic differences are in fact comparable to Galileo's estimates of the perceived differences that he sought to explain.) By March 1610 Galileo had estimated an orbital period for Callisto only (*3*). It was the correlation of perceived brightness differences with orbital position that encouraged Galileo to conjecture on their origin even though he could not identify individual satellites.

In his interpretation Galileo first ruled out an origin for the brightness variations in terrestrial atmospheric effects or in cyclic changes of the distance between a satellite and the earth during each satellite orbit. Considering celestial objects close to the horizon, he noted "that when atmospheric mists intervene . . . the fixed stars and planets [appear] less than they really are" (*4*). Galileo

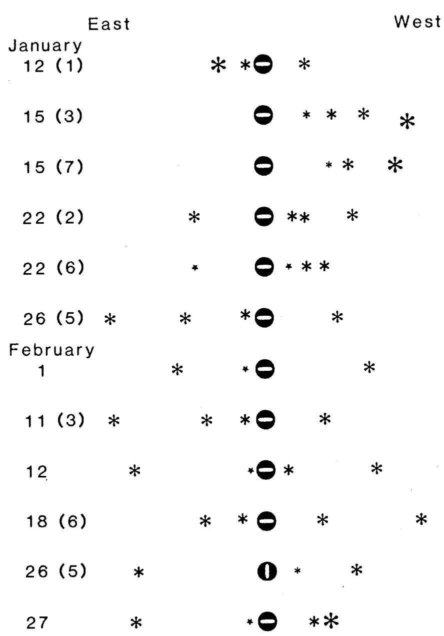

Fig. 1. Observations by Galileo in which he underestimated the relative brightness of the satellite nearest Jupiter. Satellites appear along a line because their nearly circular orbits are viewed edge on. The calendar date in 1610 and the hour of night in parentheses are shown.

Table 1. Orbital position and assumed sense of revolution consistent with satellite apparent motion at small separation.

		Sense of revolution	
		Clockwise (retrograde)	Counterclockwise (prograde)
Orbital position	Apogee	East to west	West to east
	Perigee	West to east	East to west

then recalled arguments advanced earlier in the *Starry Messenger* for a lunar atmosphere to account, in part, for the apparent smoothness of the lunar limb. He concluded:

> . . . it is certain that not only Earth, but also the Moon, has its own vaporous sphere enveloping it . . . and we may consistently decide that the same is true with regard to the rest of the planets (*4*).

The atmosphere inferred for Jupiter would make the satellites

> appear smaller when they are in apogee; but when in perigee, through the absence or attenuation of that atmosphere, they appear larger (*4*).

The puzzle of this explanation is that small separations occur at both apogee and perigee, while only near apogee would Jupiter's atmosphere intervene between the satellite and the earth. (Here apogee and perigee refer to the orbital positions where the satellite-to-earth distance is a maximum and minimum, respectively.) Galileo had no way to ascertain whether a particular satellite at small separation was near apogee or near perigee.

If the assumed Jovian atmosphere were to encompass a satellite orbit, perigee would correspond to a minimal thickness of intervening atmosphere. In this case both maximum (perigee) and minimum (apogee) brightness would be identified with small separations. But Galileo recorded no instance of brightness enhancement at a small separation. On the contrary, he underestimated the brightness of the innermost satellite on 22 out of 45 occasions (*1*). A review of his data would have prompted Galileo to visualize an atmosphere smaller than the satellite orbits. Satellite brightness would then be constant except near times of apogee, when diminution would occur. Galileo's hypothesis predicted the occasional occurrence of both diminution (apogee) and constant brightness (perigee) at small separations. With the sense of revolution of each satellite unknown, Galileo may have reasoned about diminution no further before publishing. There is evidence, however, that Galileo used his recorded observations to test his model.

The Key Observations

Identifying the orbital position corresponding to an observed separation is complicated by the fact that the earth is very nearly in the orbital plane of the satellites. The satellite orbits are in fact nearly circular, as Galileo assumed, but their movements appear from the earth to be along a straight line. Thus, there are in general two possible orbital positions corresponding to each separation. Near apogee, where dimming by the hypothesized atmosphere was predicted, clockwise revolution implies east to west motion, while counterclockwise revolution implies west to east motion. Table 1 summarizes the relationships among assumed sense of revolution, inferred orbital position, and observable eastward or westward motion.

To test his theory, Galileo would segregate those observations in which the nearest satellite appeared unusually dim. Nights of only one observation would be discarded because they can contain no record of eastward or westward motion. Among the nights of multiple observations, the 12 occasions on which a satellite seemed to merge with or separate from Jupiter between two observations

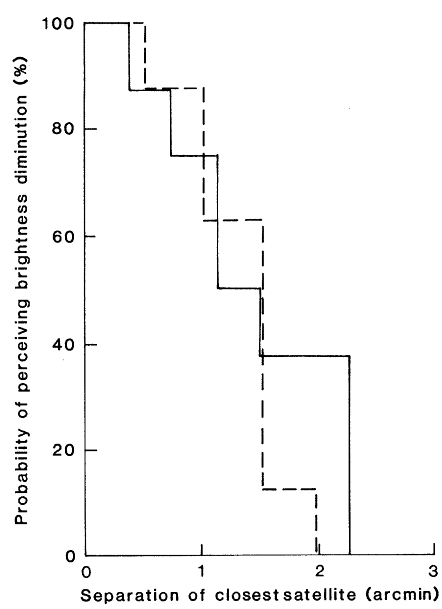

Fig. 2. Probability of underestimating the brightness of the nearest satellite for Galileo (solid line) and modern observers (dashed line) (*1*). The probability decreases with increasing angular separation.

are not useful because a relatively dim satellite at small separation could be intrinsically dim.

The key observations with which Galileo could test his hypothesis required records of the relative brightness of a single satellite at more than one position close to Jupiter. There were four such records (Table 2), and in all four instances a satellite observed at two separations was dimmer when closer to Jupiter.

If Galileo assumed prograde revolution for all four satellites, Table 2 shows that his explanation for satellite brightness variations is appropriate to the observations of 19 January, 4 February, and 11 February but not to those of 17 February. While this assumption of counterclockwise revolution is not stated explicitly in the *Starry Messenger*, it is clear from Galileo's records for 26 February. On this night, at one half hour after sunset, there were two satellites visible, one on each side of Jupiter. At the fifth hour, however, a third dim satellite was in view to the west of Jupiter (Fig. 1). This third satellite had formerly been merged with Jupiter and had in fact moved from perigee into view on the west of Jupiter. Galileo's manuscript for this night records this satellite as having been "concealed by Jupiter" in his first observation. This wording is altered to "concealed beneath Jupiter" (*5*) in the *Starry Messenger*, a modification by Galileo made between 26 February and the publication date of 12 March. Prograde revolution is required by this assertion that westward motion corresponds to perigee (Table 1). Galileo, therefore, postulated general prograde revolution sometime after 26 February (Table 3).

Galileo's modification of his original manuscript was occasioned by his desire to add to it observations of the motion of Jupiter and the satellites with respect to a fixed star. These additional observations commenced on 26 February and continued to 2 March, the last day of all observations in the *Starry Messenger*. Insertion of the reference star observations provided the occasion for Galileo to review what he had written for 26 February and change "by Jupiter" to "beneath Jupiter" to reflect his later conclusions.

The contradiction of 17 February remained a stubborn fact confronting Galileo's theory. Perhaps Galileo discounted the 17 February data as spurious or due to an unknown special circumstance. A better possibility is evident from examination of his manuscripts.

An important factor influencing the final sections of the *Starry Messenger* is Galileo's haste in its preparation, a circumstance reflected in its last sentence: "Want of time prevents my going further into these matters; my readers may expect further remarks upon these subjects in a short time" (*4*, p. 72). In preparation for publication of his work, Galileo made a neat copy of his observations through 16 February (*6*). After that day, a cross is found as an editorial mark, apparently to designate the location of an insertion. In his notebook of observations (*7*), there is a continuous record of his observations through 16 February, followed by an extensive gap that ends with the resumption of recorded observations on 9 March.

Apparently Galileo was hurried enough when preparing the manuscript for printing that he removed two or three pages from his notebook to save time. In the manuscript, beginning with 17 February, there is a general decrease in the neatness of the text, drawings of configurations are sometimes boxed as in the notebook, and the days of the month are given in numerals rather than written out, as they are earlier in the manuscript. Other editorial marks for insertions follow 1 and 2 March and help us picture an author scrambling to ready his manuscript for printing. Finally, after the 2 March observations, a very messy text summarizes Galileo's conclusions regarding the Jovian satellites.

When this final section was written, the data most on Galileo's mind must have been the observations he had recently copied for the printer—that is, the observations through 16 February. For these data, there were exactly three nights of a satellite being observed at two

Table 2. Key observations for testing Galileo's hypotheses.

Date	Location of nearest satellite with respect to Jupiter	Motion of nearest satellite	Location for prograde revolution
19 January	East	West to East	Apogee
4 February	East	West to East	Apogee
11	East	West to East	Apogee
17	East	East to West	Perigee

Table 3. A chronology of Galileo's conjectures in 1610.

7 January	Noticed satellites near Jupiter for the first time.
15 January	Conceived of orbital motions for the satellites (*12*).
16 January	Began writing text of the *Starry Messenger* describing observation procedures and observations of the moon, stars, and Milky Way (*13*).
17 February	Recorded the only observations clearly in conflict with his later conjectures.
26 February	Observed a dim satellite separate from Jupiter on the west; later described this satellite as being near perigee on the basis of its apparent westward motion, despite its dimness.
2 March	Last Jupiter observation included in the *Starry Messenger*.
3 March onward	Wrote portion of text introducing the Jupiter observations, completed the copying and annotating of observations from his notebook through 16 February.
	Hurriedly added notebook pages for observations beginning 17 February.
	Conceived of hypotheses of a Jupiter atmosphere and prograde satellite revolution.
	Added observations of Jupiter's motion with respect to a fixed star for 26 February through 2 March and, as he did so, modified the record of 26 February in accord with presumed prograde revolution.
12 March	Added a dedication to and published the *Starry Messenger*.

elongations, and dimmer at the smaller. For all three, the satellite motion was west to east, indicating the satellite was behind Jupiter. All three observations could be accounted for if Jupiter had an atmosphere to attenuate the light coming from the satellite. The explanation which Galileo advanced for the brightness variations was well suited to three of the most definitive observations at hand, with those of 17 February being overlooked.

Conclusion

Galileo's search for concepts with which to interpret his measurements led him to pioneering insights in solar system physics which, although valid, cannot be justified on the basis of his data. The final paragraphs of the *Starry Messenger* are conjectural and were advertised by Galileo to be on a much less sure footing than the data and much of the discussion presented earlier in his book. This structure of the *Starry Messenger* firmly established its kinship with modern scientific papers where the most speculative remarks are presented after a description of data and analysis have justified the author's claim to an informed opinion on matters bordering his investigation.

Galileo ultimately confirmed the prograde sense of revolution when, in 1612 (*8*), he recognized the need to account for Jupiter's shadow in predicting and reconstructing satellite configurations accurately. His keen interest in refining the orbital parameters of the satellites must have led him to recognize also the occurrence of brightness diminution for satellite position near perigee. That he never retracted or modified his atmospheric theory for diminution despite its incompatibility with his data calls for explanation.

In May 1612, Galileo wrote that the Jovian satellites "show themselves constant, like any other star, and they are always light except when they run into the shadow of Jupiter" (*9*, p. 101). Early in 1610, these same satellites had appeared "sometimes to be twice as large as at other times" (*9*, p. 57). Galileo's general awareness of an illusory effect is reflected in the *Starry Messenger* in a discussion of earthshine on the crescent moon and later in *Letters on Sunspots* (1613) in descriptions of sunspots and of Venus (*9*, pp. 42, 92–93, 130–131). In a postscript to *Letters on Sunspots*, Galileo notes that (*8*)

> stars very close to the body of Jupiter, because of its brightness, are not easily seen without sharp vision and a good instrument; but upon their becoming more distant, getting away from this irradiation and accordingly revealing themselves better, they show that they shortly before were really close to Jupiter.

Throughout these first years of telescopic observation, Galileo must have refined his observational judgment of relative brightness. By May 1612 the satellites would "show themselves constant" if Galileo were adjusting his perceptions for a presumed illusion. Without investigating the phenomenon of illusion itself in some detail, however, Galileo was never able to substantiate a reason for variations in satellite brightness at small separations (*10*). He therefore did not know whether or not variations of satellite brightness provided evidence for a Jovian atmosphere.

Except for the phenomenon of brightness diminution near perigee, Galileo's many observations between 7 January and 2 March, 1610 were consistent with his hypothesis of a Jovian atmosphere. Within a few years Galileo must have understood the weakness of this explanation of diminution and recognized the brightness contrast illusion in his earliest satellite data. Although Galileo did not resolve the role of illusion in satellite diminution, his exhaustive efforts to model the satellite orbits led him well beyond his important, lucky generalizations concerning planetary atmospheres and prograde revolution. His private confrontation with illusion gave him special insight into the significance to astronomy of Euclid's warning: "By means of sight alone we can not reach certain knowledge" (*11*). Certainly Galileo came to understand Euclid's remark more deeply than his adversaries, who cited Euclid in their arguments against the very existence of the Jovian satellites.

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