

This astronomy project will focus on the work of Galileo Galilei, perhaps the most famous astronomer of all time. Galileo became famous for his observations with a telescope. His most important discoveries with the telescope were:

- The Moon has rough topography (mountains, craters, etc.)
- Discovery of the four largest moons of Jupiter (Io, Europa, Ganymede, Callisto)
- Discovery of the phases of Venus
- Discovery of the rotation of the Sun on its axis through study of sunspots

Your project will be to make observations, similar to Galileo, and establish for yourself that the Moon has rough topography, that Jupiter has four moons easily seen in a telescope, that Venus goes through phases and that the Sun rotates on its axis. **WARNING! LOOKING AT THE SUN WITHOUT PROPER PROTECTION CAN DAMAGE YOUR EYES, EVEN CAUSING BLINDNESS.** If you want to include observations of the Sun in your project, this can be done **ONLY** under the direct supervision of Jeff La Favre.

Jupiter is currently visible in the early evening hours but will move to the day time sky at the end of August. On April 29 Jupiter sets 8 hours and 3 minutes after the Sun, on May 29 it sets 5 hours and 42 minutes after the Sun, on June 29 it sets 3 hours 55 minutes after the Sun and on July 29 it sets 2 hours after the Sun. Therefore, you should try to complete your observations of Jupiter by the end of July (sooner is better).

First, we should study some history about Galileo and the telescope. Our story starts in the year 1609 in Padua, Italy (not far from Venice) where Galileo was employed as a professor at the University of Padua. At this time in history, Italy was not a country yet, but was a collection of “city-states.” Padua was part of the Republic of Venice and the central government was located in Venice. This is important to know because the University of Padua was supported by the government and therefore, Galileo was an employee of the Republic of Venice (they paid his salary, which was 480 Florin a year).

In June of 1609, Galileo was not feeling well and was bedridden. Piero Duodo, an important man from Venice, happened to visit Galileo during this time. Galileo asked Duodo if it was possible that his salary could be increased. From this incident, we know that Galileo was not happy with the amount of money he earned as a professor. Duodo returned to Venice and talked to someone in the government about Galileo’s pay. On June 29 he wrote a letter to Galileo, informing him that it was very unlikely that his pay could be increased. Galileo then started to think about other ways in which he could earn extra money.

In July, Galileo was feeling better and he traveled to Venice. During his visit, Galileo heard rumors about a wonderful new invention; an optical device that allowed distant things to appear as if they were nearby (the telescope).

On August 3, Galileo returned to Padua and that night devised a design for a telescope after some thought. The following day he constructed his first telescope, using lenses that he presumably obtained

from some optician (a maker of eyeglasses). His first telescope had a magnifying power of about three, more or less the same as other telescopes that were starting to appear in Europe for sale. Galileo believed that he could make some money by selling telescopes of his own design. In order to be successful, Galileo needed to produce a telescope more powerful than any other available at the time. The problem was that the specific lenses needed could not be purchased from an optician. Galileo needed to learn how to make his own lenses.

Six days after Galileo produced his first telescope, he had finished his second telescope, containing lenses that he made himself. The telescope had a power of about eight (made things look 8 times larger). Now Galileo had the telescope he believed he could sell. He wanted to sell it to the government of the Republic of Venice, in the hope that they would increase his salary.

Galileo traveled back to Venice on August 21 to demonstrate his telescope to government officials. At the top of the bell tower in St. Mark's Square, Galileo set up his telescope and allowed important government officials to take a look. Out on the sea, Galileo and his guests observed ships on the distant horizon. Those ships were headed to Venice, but could only be seen without the telescope 2 hours later. Galileo's telescope was considered by the government officials as a very important invention. The telescope could be useful in military operations, where one could see their enemy approaching much earlier than with just the naked eye. Other uses for the telescope may have also come to mind to those government officials. At the time however, the officials and Galileo himself were not thinking about the usefulness of the telescope for observing celestial objects (stars, planets, etc.).

Galileo offered his telescope invention to the government and in return, the government raised his salary to 1,000 Florin per year. In addition, they gave him a lifetime appointment as professor at the university. In his invention of the telescope, Galileo had improved his financial condition, which was one of his goals.

Not long after, probably sometime in October of 1609, Galileo started using his telescope to look at things in the night sky. He discovered that the Milky Way was composed of untold numbers of stars, stars that could only be seen with a telescope. He also observed the Moon and discovered its rough topography. Then, in early January of 1610, Galileo started to observe Jupiter and discovered the four largest moons of Jupiter, known today as the Galilean moons (Io, Europa, Ganymede and Callisto).

Galileo was so excited about his discovery of the moons of Jupiter, that he published a book in March of the same year, describing in detail his observations to date with the telescope, especially his observations of the moons of Jupiter. The title of this book is *Sidereus Nuncius*. The book is written in Latin, which at the time was the preferred language for scientific works (all European scholars could read Latin regardless of their native language). We are fortunate that Galileo's book has been translated into English (actually several times). The translation by Albert Van Helden is currently in print and I have purchased a copy of this book for you. I hope you will find it interesting.

In the following pages I have provided to you part of the text from *Sidereus Nuncius*, specifically, the text covering observations of Jupiter for the period of January 7 to 24. Along with the text, I have included the drawings made by Galileo. The text from the book is in *Italics* font. I have included comments of

my own to help you understand Galileo's writing and these comments are not in Italics. I have used my astronomy software (SkyX version 10) to plot out the positions of the Galilean moons for the days and times listed for Galileo's observations. These are located just below Galileo's drawings. In addition, I have provided the distances from the moons to Jupiter as determined with SkyX. These are all helpful in evaluating the information in Galileo's book and allow us to better understand what Galileo could see with his telescope.

During Galileo's life, time was kept according to the old Italian hours, which set the day to begin at sunset. The first hour of night begins at sunset, and we shall take the center point of each hour, which means that for the first hour of night, we shall use the time of 30 minutes after sunset (unless the exact time after sunset is given). In measuring the distance (separation) of the moons from Jupiter, Galileo used the degree system (there are 360 degrees in a circle, there are 60 minutes in one degree and there are 60 seconds in one minute – in the SkyX data, I provide the separations in minutes and seconds – for example: 2 minutes and 30 seconds is written like this 2' 30").

In reading Galileo's book, we should keep in mind the model of our solar system that was most popular at the time. That model is known as the **geocentric model** (Earth in the center of the solar system), which today we know is wrong. Galileo already believed in the **heliocentric model** (Sun in the center), the correct model, at the time he started using his telescope. His observations further convinced him that the Sun was in the center of our solar system and that the planets orbited around the Sun, not the Earth. When you read Galileo's words, see if you can find places where he suggests that the heliocentric model is the correct one.

Also keep in mind that at the time, all objects seen in the night sky were considered stars (even the planets and the Moon). The stars were divided into two categories: 1) the fixed stars [which we know today are the true stars] and 2) planets, the wandering stars. Without a telescope the planets and stars look very similar. The main difference is that the planets wander around the night sky over long periods of time (due to the fact that they orbit the Sun). Do not be surprised to read that Galileo calls the moons of Jupiter stars or planets, for those were the names he thought should apply at that time. Of course today we know much more about the moons of Jupiter and we know they are not true stars or planets.

Now, you can read about Galileo's observations of Jupiter!

It remains for us to reveal and make known what appears to be most important in the present matter: four planets never seen from the beginning of the world right up to our day, the occasion of their discovery and observation, their positions, and the observations made over the past 2 months [7 January to 2 March 1610] concerning their behavior and changes. And I call on all astronomers to devote themselves to investigating and determining their periods. Because of the shortness of time, it has not been possible for us to achieve this so far. We advise them again, however, that they will need a very accurate glass like the one we have described at the beginning of this account, lest they undertake such an investigation in vain.

Here Galileo informs us that he has discovered four moons of Jupiter and asks astronomers to make observations so that more can be learned about them, especially their orbital periods. He warns other astronomers that they must have a good telescope to see the moons, one like he has been able to make.

*Accordingly, on the **seventh day of January** of the present year 1610, at the **first hour of the night**, when I inspected the celestial constellations through a spyglass, Jupiter presented himself. And since I had prepared for myself a superlative instrument, I saw (which earlier had not happened because of the weakness of the other instruments) that three little stars were positioned near him – small but yet very bright. Although I believed them to be among the number of fixed stars, they nevertheless intrigued me because they appeared to be arranged exactly along a straight line and parallel to the ecliptic, and to be brighter than others of equal size. And their disposition among themselves and with respect to Jupiter was as follows:*



Figure 1. Galileo's drawing - east is on the left, west on the right - the same applies to all of Galileo's drawings

That is, two stars were near him on the east and one on the west; the more eastern one and the western one appeared a bit larger than the remaining one. I was not in the least concerned with their distances from Jupiter, for, as we said above, at first I believed them to be fixed stars.



Figure 2 SkyX chart for January 7, 1610, 5:17 pm for Padua, Italy

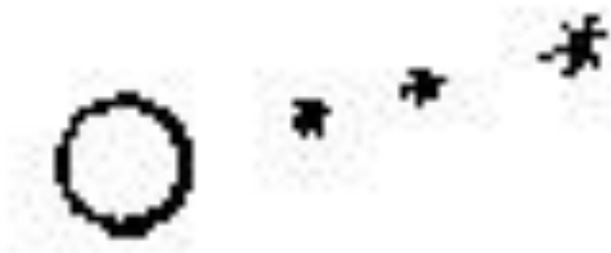
January 7, 1610 at the first hour of night
sunset is at 4:47 pm, first hour = 5:17 pm
Callisto 9' 8" east of Jupiter
Europa 2' 27" east of Jupiter
Io 2' 17" east of Jupiter
Ganymede 5' 23" west of Jupiter

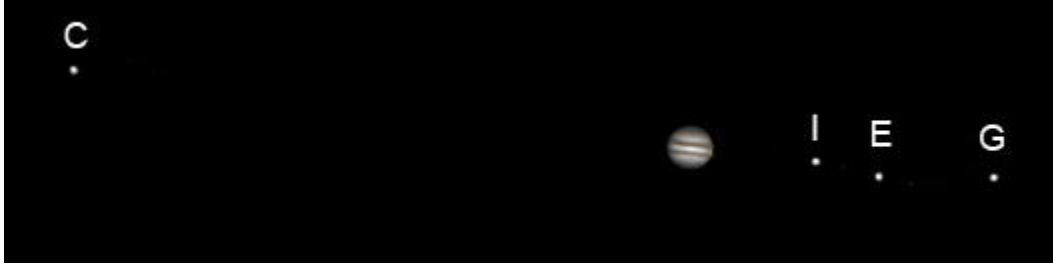
On his first observation, Galileo believes that the moons of Jupiter he sees are really just background stars that happen to be near Jupiter at the time. Yet, he finds it very interesting that they all form a straight line. So maybe something special is going on here? We should continue to investigate!

Here we can also see a limitation in Galileo's telescope. The moons Io and Europa were very close together and Galileo saw them as one moon. Thus, he thought there were three instead of four. Nearly all modern telescopes, even the kind you might have, are superior to Galileo's telescope and in this case would probably allow you to see Io and Europa as two separate moons.

Galileo made many telescopes after the one he demonstrated in Venice. Recall that the telescope he took to Venice had a magnifying power of about eight. As he continued to make telescopes, one of his objectives was to increase the power. The telescope he used in January of 1610 had a power of about twenty. In his text above, he tells us "*And since I had prepared for myself a superlative instrument, I saw (which earlier had not happened because of the weakness of the other instruments)...*" The superlative instrument was his twenty power telescope and here he is saying that his earlier telescopes (for example the eight power one) did not have enough magnification to reveal the moons of Jupiter.

But when, on the eighth, I returned to the same observation, guided by I know not what fate, I found a very different arrangement. For all three little stars were to the west of Jupiter and closer to each other than the previous night, and separated by equal intervals, as shown in the adjoining sketch.





January 8 (first hour of night?)

sunset is at 4:48 pm, first hour = 5:18 pm

Callisto 10' 4" east

Europa 3' 3" west

Io 2' 1" west

Ganymede 4' 54" west

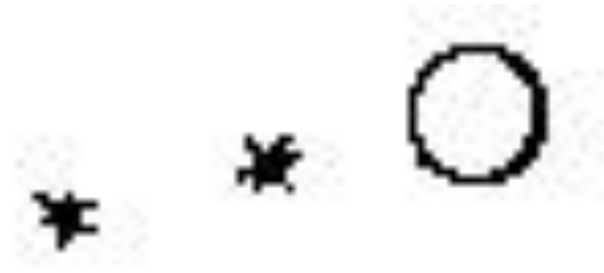
On his second observation, Galileo is perhaps caught by surprise. Now all three moons he saw were on the west side of Jupiter and closer together than the previous night. He knew that Jupiter moved compared to the background stars but thought something was wrong here, as we shall read soon from his own words. Also notice that on this day, Galileo missed seeing Callisto, which was now more distant from Jupiter to the east.

Here I should also note how different the arrangements of the moons are comparing them on January 7 and 8, separated by just one day in time. Both Io and Europa have moved from the east side of Jupiter to the west side. Io is the closest moon to Jupiter and orbits around the planet in 1.8 days; Europa is the next closest and orbits in 3.6 days; then Ganymede, which orbits in 7.2 days; and lastly, Callisto, which orbits in 16.7 days.

Even though at this point I had by no means turned my thought to the mutual motions of these stars, yet I was aroused by the question of how Jupiter could be to the east of all the said fixed stars when the day before he had been to the west of two of them. I was afraid, therefore, that perhaps, contrary to the astronomical computations, his motion was direct and that, by his proper motion, he had bypassed those stars. For this reason I waited eagerly for the next night. But I was disappointed in my hope, for the sky was everywhere covered with clouds.

When a planet is in direct motion, it drifts to the east with respect to the background stars. But at the time when Earth is nearest to Jupiter, Jupiter drifts to the west with respect to the background stars (known as retrograde motion). Galileo tells us that according to astronomical computations, Jupiter should be in retrograde, that is moving to the west (and in fact it was). But if that was the case, why did he find the "stars" to the west of Jupiter on the 8th while 2 were to the east on the 7th? That would not happen if Jupiter was in retrograde motion, so Galileo wonders if in fact it is in direct motion.

Then, **on the tenth**, the stars appeared in this position with regard to Jupiter.



Only two stars were near him, both to the east. The third, as I thought, was hidden behind Jupiter. As before, they were in the same straight line with Jupiter and exactly aligned along the zodiac. When I saw this, and since I knew that such changes could in no way be assigned to Jupiter, and since I knew, moreover, that the observed stars were always the same ones (for no others, either preceding or following Jupiter, were present along the zodiac for a great distance), now, moving from doubt to astonishment, I found that the observed change was not in Jupiter but in the said stars. And therefore I decided that henceforth they should be observed more accurately and diligently.



January 10 (first hour of night?) 5:20 pm

Ganymede and Europa separated by 18"

Callisto 7' 45" east

Europa 3' 34" east

Io 39" west

Ganymede 3' 49" east

Here is an important point in Galileo's observations. The moons are now back on the east side of Jupiter. How can these be fixed stars?

Note here again the limitations of Galileo's telescope. Ganymede and Europa are close together and Galileo saw them as one. In addition, Galileo thought Io had moved behind Jupiter, but in actuality, it was just too close to Jupiter to be seen in his telescope. Galileo has yet to discover that Jupiter has four bright moons.

And so, **on the eleventh**, I saw the following arrangement:



There were only two stars on the east, of which the middle one was three times as far from Jupiter than from the more eastern one, and the more eastern one was about twice as large as the other, although the previous night they had appeared about equal. I therefore arrived at the conclusion, entirely beyond doubt, that in the heavens there are three stars wandering around Jupiter like Venus and Mercury around the Sun. This was at length seen clear as day in many subsequent observations, and also that there are not only three, but four wandering stars making their revolutions about Jupiter. The following is an account of the changes in their positions, accurately determined from then on. I also measured the distances between them with the glass, by the procedure explained above. I have added the times of the observations, especially when more than one were made on the same night, for the revolutions of these planets are so swift that the hourly differences can often be perceived as well.



January 11 (first hour of night?) 5:21 pm
Callisto 4' 50" east
Europa transiting Jupiter
Io transiting
Ganymede 5' 43" east

Galileo has discovered the four largest moons of Jupiter!!! At this particular time, Europa and Io happen to be right in front of Jupiter and Galileo could not see them. Thus, his drawing has only two moons. In the description above, Galileo tells us that he has found all four moons, but we will have to wait until later to see all four on his drawings.

Thus, **on the twelfth**, at the **first hour** of the following night, I saw the stars arranged in this manner.



The more eastern star was larger than the western one, but both were very conspicuous and bright. Both were two minutes distant from Jupiter. In **the third hour** a third little star, not at all seen earlier, also began to appear. This almost touched Jupiter on the eastern side and was very small. All were in the same straight line and aligned along the ecliptic.



Figure 3 SkyX chart for January 12, 5:23 pm

January 12 first hour 5:23 pm

Callisto 1' 18" east

Europa 3' 26" west

Io 1' 9" east

Ganymede 3' 31" east

Apparently, Galileo felt that on this night, it was only necessary to provide one drawing, which could suffice for the first and third hours. The drawing shows three stars but his words indicate that only two were seen in the first hour.

Once again, two moons were close to each other and seen as one by Galileo. In his descriptions, Galileo provides the size and brightness of the moons. His telescope was not powerful enough to actually see the diameters of the moons, but he thought he could actually see them as very small circles. Therefore, it is difficult to understand what he means by the size of a moon. He was probably influenced by how bright a moon appeared to him and when brighter, he may have thought it was larger in size. When a moon is closer to Jupiter, its brightness is overwhelmed by the brilliance of Jupiter. It is no surprise then, that Galileo would sometimes see a moon close to Jupiter and say that it was not very bright then.



Figure 4 SkyX chart for January 12, 7:23 pm

January 12 third hour 7:23 pm

Callisto 1' 0" east

Europa 3' 15" west

Io 1' 40" east

Ganymede 3' 10" east

On the thirteenth, for the first time four little stars were seen by me in this formation with respect to Jupiter.



Three were on the west and one on the east. They formed a very nearly straight line, but the middle star of the western ones was displaced a little to the north from the straight line. The more eastern one was 2 minutes distant from Jupiter; the intervals between the remaining ones and Jupiter were only 1 minute. All these stars displayed the same size, and although small they were nevertheless very brilliant and much brighter than fixed stars of the same size.



January 13 (first hour of night?) 5:24 pm

Callisto 2' 30" west

Europa 1' 38" east

Io 1' 48" west

Ganymede 1' 15" west

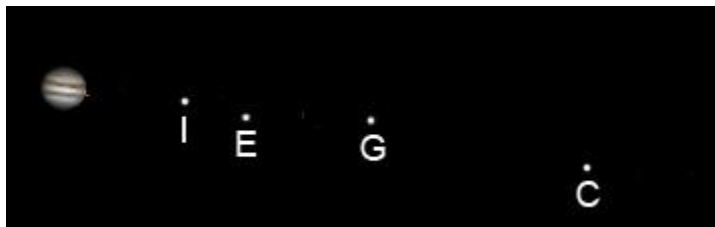
Finally, after 6 days of observations, Galileo sees all four moons. It just so happens that on this day, all moons were sufficiently removed from Jupiter but not very far from the planet, so all four could be noticed by Galileo.

On the fourteenth, the weather was cloudy.

On the fifteenth, in the third hour of the night, the four stars were positioned with respect to Jupiter as shown in the next figure.



They were all to the west and arranged very nearly in a straight line, except that the third one from Jupiter was raised a little bit to the north. The closest one to Jupiter was the smallest of all, and the rest consequently appeared larger. The intervals between Jupiter and the next three stars were all equal and of 2 minutes; and the most eastern one was 4 minutes from the closest one to it. They were very brilliant and did not twinkle, as indeed was always the case, both before and afterward.



January 15 third hour of night 7:26 pm

Callisto 8' 32" west

Europa 2' 58" west

Io 1' 56" west

Ganymede 4' 57" west

Here Galileo noticed that Ganymede was slightly north in the alignment of the moons, just as the SkyX chart shows them. Keep in mind that we are looking at the orbits of the moons slightly removed from

their planes of orbit. It is only when they reach the far west or far east point in their orbit that we see them exactly lined up in a straight line. At other times they will be slightly higher (north) or lower (south) as they circle the planet. Also note that Galileo says the moons don't twinkle. In fact, that is a distinction between true stars, which do twinkle, and planets (and moons), which don't twinkle. Stars twinkle in our turbulent atmosphere above Earth because they are point sources of light. Planets can be seen as circles in the telescope and thus are not point sources of light. That is why they don't twinkle.

*But in **the seventh hour** only three stars were present in the arrangement with Jupiter.*



They were indeed precisely in the same straight line. The closest one to Jupiter was very small and removed from him by 3 minutes; the second was 1 minute distant from this one; and the third from the second 4 minutes and 30 seconds.



January 15 seventh hour 11:26 pm

Callisto 8' 49" west

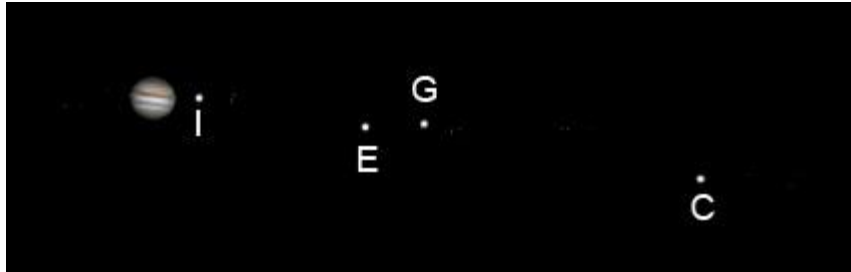
Europa 3' 23" west

Io 1' 1" west

Ganymede 4' 31" west

In the space of just four hours, Io has moved closer to Jupiter, to such an extent that at 11:26 pm, Io was too close to Jupiter to be seen by Galileo. Keep in mind that Io orbits around Jupiter in 1.8 days, the fastest of the Galilean moons. In fact, it moves so fast that we can notice the change in a matter of a few hours.

After another hour, however, the two little stars in the middle were still closer to each other, for they were removed from each other by barely 30 seconds.



January 15 eighth hour (12:26 am January 16)

Callisto 8' 53" west

Europa 3' 26" west

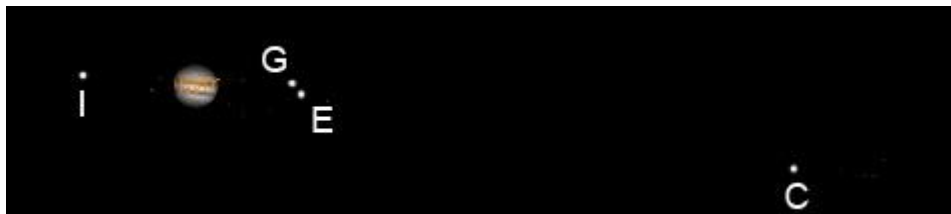
Io 43" west

Ganymede 4' 23" west

On the sixteenth, in the first hour of the night, we saw three stars arranged in this order.



Two flanked Jupiter, 40 seconds removed from him on either side, and the third was 8 minutes from Jupiter in the west. The one closer to Jupiter appeared not larger but brighter than the farther one.



January 16 first hour 5:28 pm

Callisto 9' 43" west

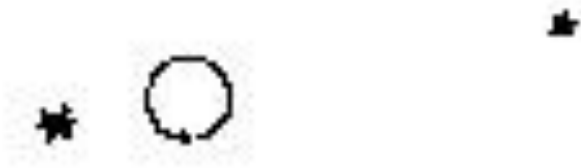
Europa 1' 41" west

Io 1' 50" east

Ganymede 1' 32" west

Ganymede – Europa separation 14"

On the seventeenth, 30 minutes after sunset, the configuration was thus.



There was only one star on the east, 3 minutes from Jupiter. Likewise, one was 11 minutes from Jupiter to the west. The eastern one appeared twice as large as the western one. There were no more than these two.



January 17 30 minutes after sunset 5:29 pm

Callisto 9' 42" west

Europa 3' 24" east

Io 1' 7" west

Ganymede 3' 13" east

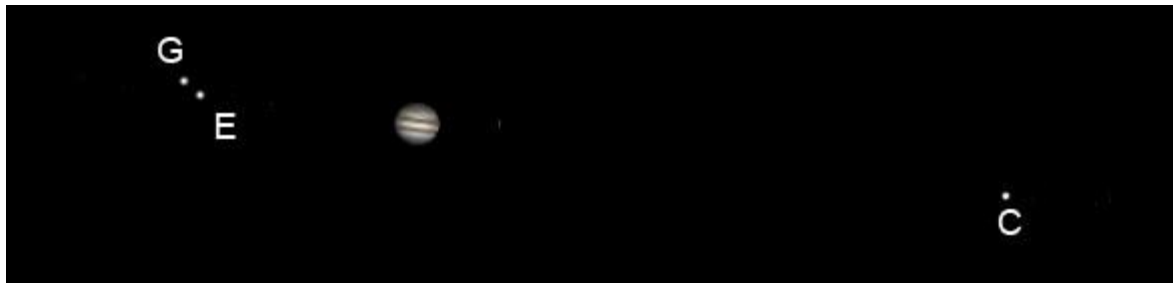
Ganymede – Europa separation 15"

Here again, Io was too close to Jupiter to be seen by Galileo. Also, Ganymede and Europa were close to each other and seen as one.

But after 4 hours, that is, around the fifth hour of the night, on the eastern side a third began to emerge, which, I suspect, had earlier been united with the first one. The formation was thus.



The middle star, extremely close to the eastern one, was only 20 seconds from it, and it was displaced a little bit to the south of the line drawn through the outermost stars and Jupiter.



January 17 4 hours later (the fifth hour of night) 9:29 pm
Callisto 9' 33" west
Europa 3' 32" east
Io behind Jupiter
Ganymede 3' 51" east
Ganymede – Europa separation 21"

At 5:29 pm Ganymede and Europa were separated by 15 seconds and at 9:29 pm by 21 seconds (note that Galileo says the separation was 20 seconds, a very close agreement). With a slightly increased separation at 9:29 pm, Galileo was now able to see the moons separately. Also note that Galileo observed that Europa was slightly south (below) the line drawn between Callisto and Ganymede, just as seen in the SkyX chart.

On the eighteenth, 20 minutes after sunset, the appearance was thus.



The eastern star was larger than the western one and 8 minutes distant from Jupiter, while the western one was 10 minutes from Jupiter.



January 18 20 minutes after sunset 5:20 pm

Callisto 8' 20" west

Europa 27" east

Io transiting Jupiter

Ganymede 5' 36" east

On the nineteenth, at the second hour of the night, the formation was like this.



There were three stars exactly on a straight line through Jupiter, one to the east, 6 minutes distant; between Jupiter and the first western one was an interval of 5 minutes, while this star was 4 minutes from the more western one. At this time I was uncertain whether between the eastern star and Jupiter there was a little star, very close to Jupiter, so that it almost touched him.



January 19 second hour of night 6:32 pm

Callisto 5' 38" west

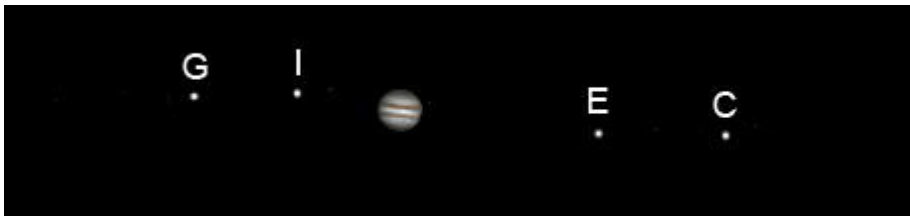
Europa 3' 25" west

Io 57" east

Ganymede 3' 49" east

Callisto – Europa separation 2' 14"

And at the fifth hour, I clearly saw this little star now occupying a place precisely in the middle between Jupiter and the eastern star, so that the formation was as follows:



January 19 fifth hour 9:32 pm

Callisto 5' 15" west

Europa 3' 13" west

Io 1' 42" east

Ganymede 3' 21" east

At 6:32 pm Io was separated from Jupiter by 57 seconds and was too close to the planet to be seen by Galileo. Just three hours later (9:32 pm), Io had moved farther away from Jupiter, with a separation of 1 minute 42 seconds and could now be seen by Galileo.

*Further, the newly perceived star was very small; yet by **the sixth hour** it was almost equal in magnitude to the others.*



January 19 sixth hour 10:32 pm

Callisto 5' 7" west

Europa 3' 6" west

Io 1' 54" east

Ganymede 3' 11" east

On the twentieth, at 1 hour, 15 minutes, a similar configuration appeared.



There were three little stars so small that they could hardly be perceived. They were not more than 1 minute from Jupiter and each other. I was uncertain whether on the west there were two or three little stars.



January 20 1 hour 15 minutes (after sunset) 6:18 pm

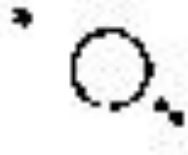
Callisto 2' 19 west

Europa 1' 16 east

Io 1' 43" west

Ganymede 44" west

Around **the sixth hour** they were arranged in this manner:



The eastern one was twice as far from Jupiter as before, that is, 2 minutes; the middle one to the west was 40 seconds from Jupiter but 20 seconds from the western one.



January 20 sixth hour 11:33 pm

Callisto 1' 32" west

Europa 2' 24" east

Io 2' 10" west

Ganymede 1' 44" west

At length, in **the seventh hour**, three little stars were seen to the west; the nearest was 20 seconds from him; between this one and the westernmost one there was an interval of 40 seconds; and between these another was seen, displaced a little to the south and not more than 10 seconds from the westernmost one.





January 20 seventh hour(12:33 am January 21)

Callisto 1' 23" west

Europa 2' 35" east

Io 2' 8" west

Ganymede 1' 56" west

On the twenty-first, at 30 minutes, there were three little stars to the east, equally spaced from each other and Jupiter. The intervals were estimated to be 50 seconds. There was also a star to the west, 4 minutes from Jupiter. The closest one to Jupiter to the east was the smallest of all. The rest were somewhat larger and equal to each other.



January 21 30 minutes (after sunset) 5:34 pm

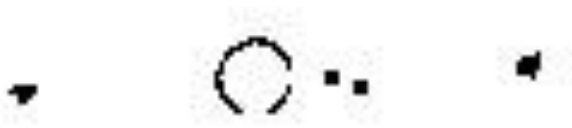
Callisto 1' 18" east

Europa 3' 4" east

Io 1' 59" east

Ganymede 4' 35" west

On the **twenty-second, at the second hour**, the configuration was similar.



The distance from the eastern one to Jupiter was 5 minutes; the distance from Jupiter to the westernmost one was 7 minutes; the two western stars in the middle were 40 seconds from each other while the nearer one was 1 minute from Jupiter. The little stars in the middle were smaller than the outermost ones, but they were on the same straight line extended along the length of the zodiac except that of the three western ones the middle one was displaced a bit to the south.



January 22 second hour 6:36 pm

Callisto 4' 54" east

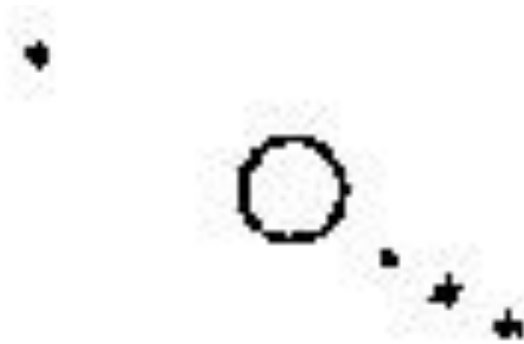
Europa 2' 23" west

Io 2' 9" west

Ganymede 5' 12" west

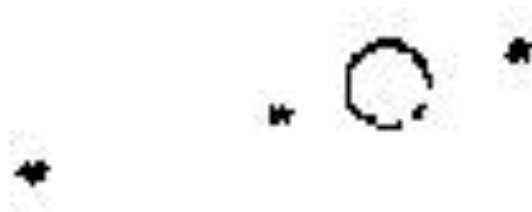
Europa and Io separated by 16" and at 7:06 pm they were separated by 22", and at 8:06 pm they were separated by 37"

But at the **sixth hour** of the night they appeared in this arrangement. The eastern one was very small and, as before, 5 minutes distant from Jupiter; the three western ones were separated equally from Jupiter and each other, and the spaces were nearly 1 minute, 20 seconds each; and the star closer to Jupiter than the other two appeared smaller; and they all appeared to lie exactly on the same straight line.



January 22 sixth hour 10:36 pm
 Callisto 5' 25" east
 Europa 3' 0" west
 Io 1' 39" west
 Ganymede 4' 53" west

On the **twenty-third, 40 minutes after sunset**, the configuration of stars was about like this:



There were three stars in a straight line with Jupiter along the length of the zodiac, as they have always been; two were to the east and one to the west. The easternmost one was 7 minutes from the next one, this one 2 minutes, 40 seconds from Jupiter, and Jupiter 3 minutes, 20 seconds from the western one; and they were all about equal in magnitude.



January 23 40 minutes after sunset 5:47pm

Callisto 7' 34" east

Europa 2' 6" west

Io 2' 2" east

Ganymede 2' 6" west

Europa and Ganymede separated by 8"

*But at the **fifth hour** the two stars which earlier were closest to Jupiter were no longer visible, hiding behind Jupiter in my opinion; and the appearance was as follows:*



January 23 fifth hour 9:37 pm

Callisto 7' 55" east

Europa 1' 14" west

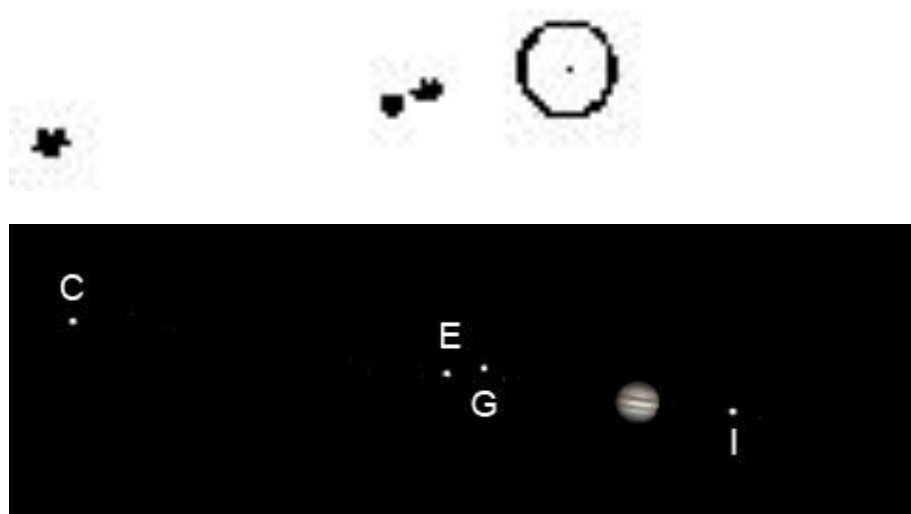
Io 1' 16" east

Ganymede 1' 23" west

Europa and Ganymede separated by 11"

Here Galileo suggests that the two moons he saw earlier (actually three) were now behind Jupiter. In fact, they were not behind Jupiter, but just too close to the planet to be seen by Galileo.

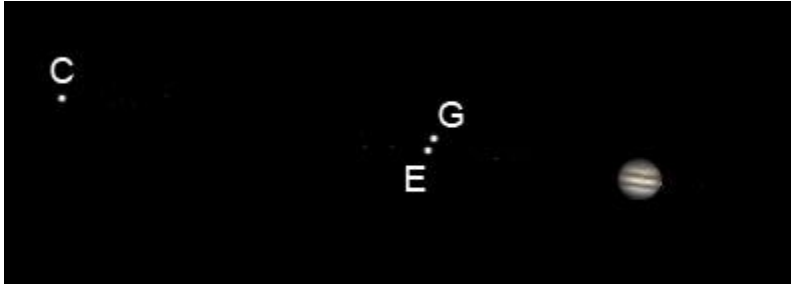
*On the **twenty-fourth**, three stars appeared, all to the east, and nearly in the same straight line with Jupiter, for the middle one deviated slightly to the south. The star closest to Jupiter was 2 minutes from him, the next one 30 seconds from this one, and the easternmost one 9 minutes from that one; and all were very bright.*



January 24 (first hour?) 5:38 pm
Callisto 9' 15" east
Europa 3' 7" east
Io 1' 31" west
Ganymede 2' 34" east

*But at the **sixth hour** only two stars presented themselves in this arrangement, that is, precisely on a straight line with Jupiter. The nearer one was removed from Jupiter by 3 minutes while the other one was 8 minutes from this one. If I am not mistaken, the two middle little stars observed earlier had united into one.*





January 24 sixth hour 10:38 pm

Callisto 9' 26" east

Europa 3' 28" east

Io behind Jupiter

Ganymede 3' 24" east

Europa and Ganymede separated by 12"

In Galileo's description for the sixth hour he was correct on two facts: 1) Io had moved behind Jupiter and 2) Europa and Ganymede had moved closer together, so close that Galileo saw them as one.

Here ends the text of Galileo's book and my analysis of the results. On the next page you will find a copy of Galileo's drawings, all together. Then on the second page following, some suggestions for your observations.

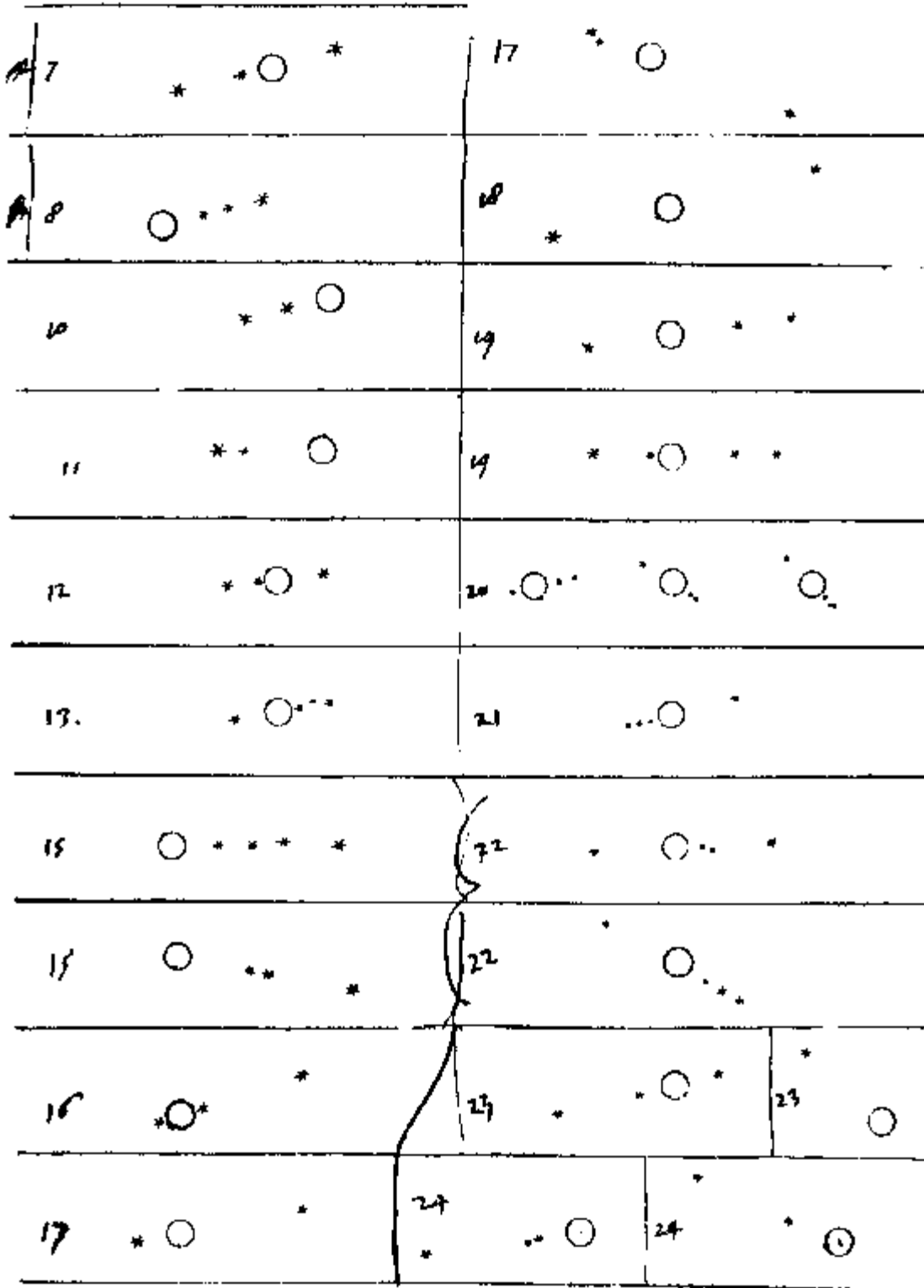


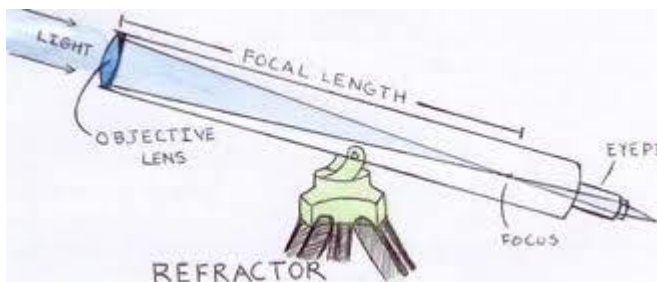
Figure 5 Galileo's Jupiter drawings, January, 1610

Suggested observation program for the moons of Jupiter

Jupiter is currently visible in the early evening hours but will move to the day time sky at the end of August. On April 29 Jupiter sets 8 hours and 3 minutes after the Sun, on May 29 it sets 5 hours and 42 minutes after the Sun, on June 29 it sets 3 hours 55 minutes after the Sun and on July 29 it sets 2 hours after the Sun. Therefore, you should try to complete your observations of Jupiter by the end of July (sooner is better).

- 1) Make a series of drawings of the moons and Jupiter on several different nights to show that the moons change position with respect to Jupiter
- 2) Make a series of drawings during the same night, separated by a few hours....can you see a change in position of any moons?
- 3) Identify the moons by name on your drawings - use a program available online:
<http://www.skyandtelescope.com/observing/objects/javascript/jupiter>
- 4) Determine the orbit period of one or more of the moons – an advanced task
- 5) Measure the separation of the moons from Jupiter– an advanced task

Here are some things to keep in mind. Depending on the type of telescope you use, your view of the sky may be inverted (upside down) or flipped right to left. You need to keep that in mind when making drawings. There are methods you can use to correct a drawing so that it matches the true arrangement in the sky. For an inverted image, just turn the paper upside down and then make the drawing. For flipped images, you can use tracing paper and then view the drawing from the backside. If you want, just draw the image as you see it, without any corrections. If you don't correct your drawing, make sure you write a note on your drawing indicating the kind of telescope you used and whether the image is inverted or flipped right for left.



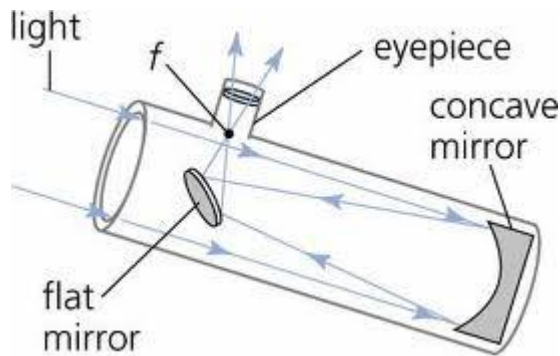
A refractor telescope produces an inverted image.

Figure 6 Refractor telescope



When a mirror diagonal is attached to a refractor, the image is upright but flipped right to left (the left side appears on the right, right on the left).

Figure 7 Refractor with attached mirror diagonal



A Newtonian reflector delivers an image that is inverted and possibly rotated. The rotation depends on the eyepiece orientation and how you look into the eyepiece. If you are using a Newtonian, I suggest you use it in the day to look at an object that is familiar to you. Then you will be able to determine how the image is oriented. **CAUTION: NEVER POINT THE TELESCOPE ANYWHERE NEAR THE SUN.**

Figure 8 Newtonian reflector telescope

Make sure that you record the date and time of each observation that you make. The moons of Jupiter move quickly, so we need to know when you made your observations! You should also record the focal length (f) of the telescope and the focal length of the eyepiece (these are usually printed somewhere on the telescope and eyepiece and usually in millimeters – an eyepiece marked with 25 is a 25 mm eyepiece).

Project 1

Make a series of drawings of the moons and Jupiter on several different nights to show that the moons change position with respect to Jupiter. Try your best to draw what you see accurately. It is important that the moons are drawn at the correct distances from Jupiter. Use the sheet on the next page or insert the drawings you have already made into this project book.

Drawings of Jupiter and its moons (project 1) – for orientation enter “upright”, “inverted” or “flipped” (right to left)

Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm
Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm
Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm

Project 2 - Make a series of drawings during the same night, separated by a few hours....can you see a change in position of any moons?

Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm
Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm
Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm	Date _____ Time _____ Orientation _____ Telescope fl _____ mm Eyepiece fl _____ mm

Project 3 - Identify the moons by name on your drawings for project 1 and/or 2. If you have noted the date and time on each of your drawings, you should be able to identify the names of the moons on your drawings by using this program available online:

<http://www.skyandtelescope.com/observing/objects/javascript/jupiter>

You can label the moons on the drawings using one letter for each moon, like this: I = Io, E = Europa, G = Ganymede, C = Callisto.

Project 4 - Determine the orbit period of one or more of the moons – an advanced task. You will need to complete project 3 first in order to identify the moons on your drawings. Look for a set of two drawings where a moon is in the same position or close to the same position. For example, suppose you made two drawings that have Ganymede in the same position. One drawing was made on May 1 at 9:00 pm and the other on May 8 at 11:30 pm. The difference in time between the two drawings would be 7 days and 2.5 hours. But how many times did Ganymede go around Jupiter in 7 days and 2.5 hours? In order to determine that, you would need to have additional drawings between the two selected drawings. Suppose after looking at all of your drawings, it is evident that Ganymede has gone around Jupiter 2 times in 7 days and 2.5 hours. Then we need to divide 7 days and 2.5 hours by 2 to get the orbit period. The answer in this example is 3.55 days (the correct value is actually 3.551 days).

Compare your value(s) for orbital periods to these: Io = 1.769 days, Europa = 3.551 days, Ganymede = 7.155 days, Callisto = 16.69 days.

Project 5 - Measure the separation of the moons from Jupiter– an advanced task. By measuring the separation of the moons from Jupiter, we can derive some knowledge about the orbits (that is, the relative distances of the moons from Jupiter). However, we must make these measurements at a time when the moon is at its maximum distance from Jupiter, as seen here on Earth. You could determine the correct time to make your measurements by using the same program used to identify the moons (<http://www.skyandtelescope.com/observing/objects/javascript/jupiter>). To find the time of maximum separation of a moon, just enter different days and times into the program until you find a day and time when the moon reaches its most distant point from Jupiter. Then make your measurement at that time.

Astronomers commonly measure separation between celestial objects in degrees. We can draw an imaginary great circle across our sky, which continues under the Earth, to make a complete circle. A complete circle contains 360 degrees. To give you an idea of the size of a degree, consider that both the Moon and Sun appear in our sky with an apparent diameter of approximately one half degree. That is, the left edge of the globe is one half degree distant from the right edge. Since a degree is a relatively large unit of measurement, astronomers divide it into smaller units. One degree is divided into 60 minutes (don't confuse this with minutes of time, which are different). If two objects in the sky are separated by an angle of 1 minute, they are also separated by $1/60^{\text{th}}$ of a degree. For objects that are very close to each other, minutes can be divided into seconds. There are 60 seconds in each minute (again, don't confuse seconds with the time unit seconds, which is different). In the case of the moons

of Jupiter, astronomers usually use minutes of angle for separation between a moon and Jupiter. However, you can also use degrees if you wish, which may be less confusing for you.

There are several methods that could be used to measure the separation of the moons from Jupiter. A common method that astronomers use (at least historically) utilizes a special eyepiece with a ruled reticle (this is like having a ruler inside your eyepiece). Then you can use this special ruler to measure the distance between two objects seen in the field of view. Since you don't have this special eyepiece, you would need to use another method.

I will suggest an alternative method (the drift method). The Earth spins at a constant rate on its axis, which means that objects in our night sky move at a constant rate (well, more or less). We know that a day is 24 hours long. And most people think the Earth spins one time on its axis in 24 hours. Well, that is almost correct, but not quite. If we use the stars as our guide, then the Earth turns on its axis one time in 23 hours and 56 minutes. Astronomers call this **sidereal** time (http://en.wikipedia.org/wiki/Sidereal_time). We can draw a great circle across the sky, midway between the north and south celestial poles. Astronomers call this great circle the celestial equator. And we can divide the celestial equator into 360 degrees (a complete circle). The Earth turns 360 degrees in 23 hours and 56 minutes (which is the same as 1436 minutes). Then how far does the Earth turn in one minute of time? We divide 360 degrees by 1436 minutes, which equals 0.25 degrees per minute (or 15 minutes of angle per minute of time).

If an object is on the celestial equator, we can use the information above to directly calculate angular separation by drift. However, what can we do if the object is not on the celestial equator? Suppose for example we were watching a star that was located exactly at the north celestial pole. In that case, the star would not move at all over time and we could not use the drift method to measure separation. In between the poles and the equator, objects will move at rates dependent on their declination (declination is similar to latitude on Earth, a measurement in degrees from the equator). Currently, Jupiter is located at declination + 7 degrees. At that declination, celestial objects move at an angular speed nearly the same as at the equator, so we can just use 15 minutes of angle per minute of time.

Now suppose we watch Jupiter and one of its moons in the telescope, being very careful not to move the telescope as we watch. We wait until the moon or Jupiter disappears from the field of view and note the time on our watch. Then we wait until Jupiter or the moon disappears from the field of view and note the time again. Suppose we observe that Jupiter disappears from our view in the telescope at exactly 9:02 pm and then Ganymede disappears at exactly 9:04 pm. The time difference would be 2 minutes, which means that Ganymede was 0.50 degrees or 30 minutes of angle from Jupiter ($2 \times 15 = 30$ minutes of angle).

Jupiter will not change much in declination over the next six months (only about one degree). Therefore, you can use a rate of 15 minutes of angle per minute of time for this year for Jupiter and its moons.

For more information on the moons of Jupiter, check the Internet, like this:

http://en.wikipedia.org/wiki/Galilean_moons

Questions you might be asked at interview judging

What is the difference between a “fixed star” and a planet? Without a telescope, planets and stars look very similar, like pin-points of light in the night sky. Before the telescope was invented, astronomers named the true stars “fixed stars” and wandering stars were named planets. To ancient astronomers, the only difference between fixed stars and planets was the fact that planets move across the sky over long periods of time in relation to the fixed stars. Today we understand that the fixed stars are like our Sun; very hot, very large spheres of gas that burn by nuclear fusion. Planets are much cooler and smaller than stars and don’t burn. Planets orbit around their parent star, which is why they appear to move compared to the “fixed stars.”

What is the Heliocentric Solar System model? The model of our Solar System that places the Sun in the center with all planets orbiting around the Sun. This is the correct model of our Solar System, the model that Galileo believed was correct.

What is the Geocentric Solar System model? The model of our Solar System that places the Earth in the center with the planets and the Sun orbiting around the Earth. This model was believed to be correct by many ancient astronomers and even many scientists during Galileo’s time. Today we know it is not the correct model.

Which moon orbits the fastest around Jupiter? Io

Which moon orbits the slowest around Jupiter? Callisto

Which moon orbits closest to Jupiter? Io

Which moon orbits farthest from Jupiter? Callisto

Why did Galileo miss some of the moons of Jupiter when first observing with his telescope? The quality of Galileo’s telescope was relatively poor. When two moons were close to each other, he sometimes could only see them as one object. In addition, if a moon was fairly close to Jupiter, Galileo could not see it. The field of view of Galileo’s telescope was very restricted (he could only see a small part of the sky). Sometimes, when a moon was far from Jupiter (especially Callisto), Galileo missed seeing it.

What is retrograde motion? Most of the time, the planets move across the background of stars in an easterly direction, known as direct motion. However, there are times when the apparent motion of a planet reverses and goes in a westerly direction. The westerly movement of a planet is known as retrograde motion. In the case of the outer planets (those farther from the Sun than Earth), retrograde motion occurs when the Earth passes by a planet due to its faster orbit around the Sun. The outer planet only appears to move backwards because of the faster movement of the Earth.