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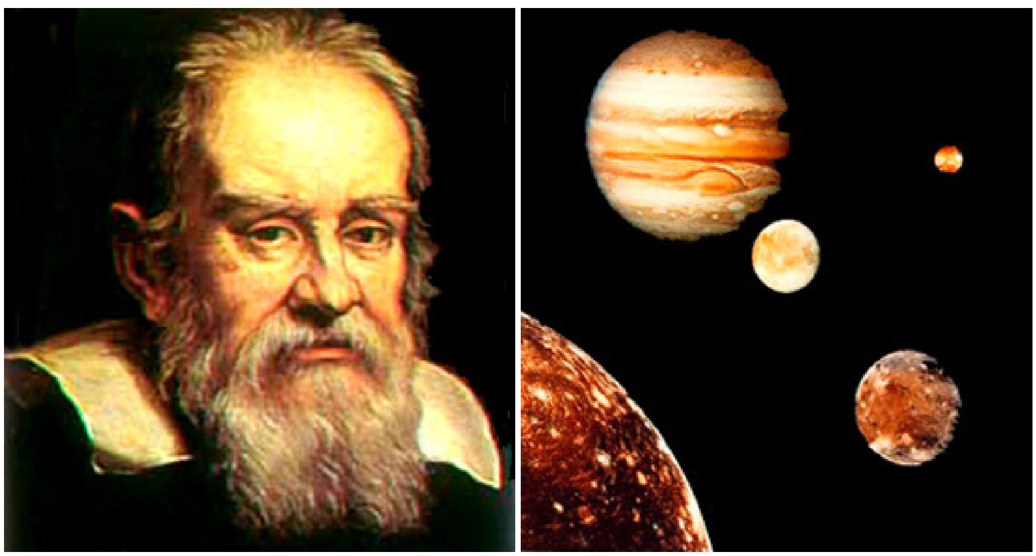
Galileo's Stars: Distance and Diffraction

by Chris Larson

In the early 17th century, almost overnight the universe grew larger, stranger and more wonderful — for that was when (around 1610) Galileo Galilei started investigating the heavens with telescopes he built himself. (The telescope was invented in the Netherlands in 1608, and Galileo drew upon Dutch descriptions of the invention to build his own instruments.) The roster of astronomical discoveries made by **Galileo** is staggering: he saw moons circling Jupiter and rings around Saturn, areas of roughness on the Moon and sunspots on the Sun, and resolved the blur of the Milky Way into a host of stars too faint to be seen with the unaided eye. Not only did he see these wonders, he made precise measurements of positions — measurements that confirmed his belief in the essential correctness of the theory that planets orbited around the Sun, rather than the Sun and planets circling the Earth. [See Jupiter's Moons Surprise Astronomers, September 1996].



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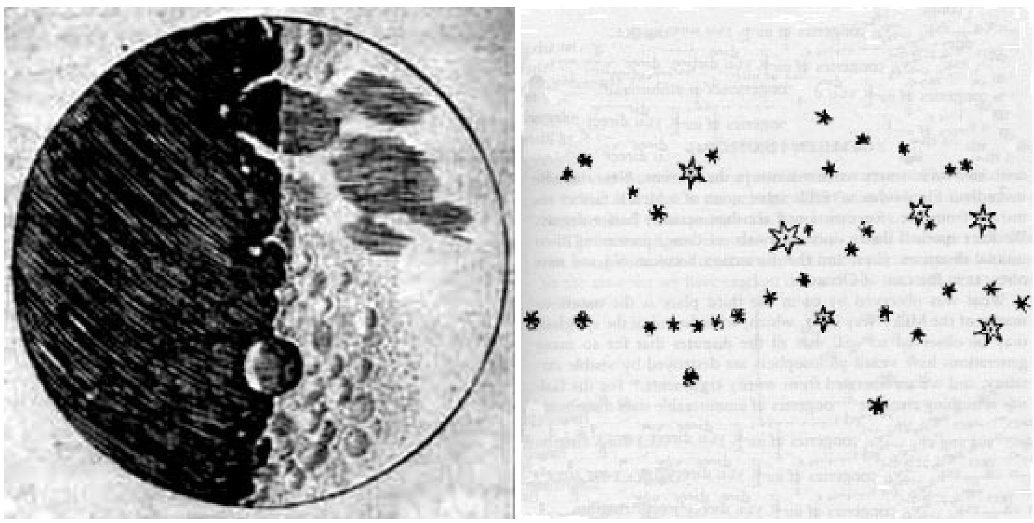
Top Left: NASA/Justus Sustermans; Top Right: NASA; Bottom: Science Museum/Science & Society

By 1610, Italian physicist and astronomer Galileo Galilei (top left) had built telescopes of 20 times magnification (center). Here are several of his many subsequent astronomical achievements: he saw moons circling Jupiter (top right), areas of roughness on the Moon (bottom left), and star systems, like Pleiades, in the Milky Way (bottom right).



Galileo, Sidereus Nuncius, 1610

Galileo's conception of the stars that we see in the night sky is essentially the one that we hold now — that they are bodies similar to the Sun, but located at distances so great that we see them only as a pinprick of light. He even made estimates of how far away the stars were. The numbers he came up with did represent the stars as extremely distant — nevertheless, he underestimated their true distance by a factor of roughly a thousand.

It might be thought that his numbers did not mean anything terribly specific — he was simply trying to give an idea of great distance, and, if he was off by a factor of a thousand, people at the time were not used to dealing with such magnitudes and it didn't matter. However, according to a study done by Christopher Graney, a physicist at Jefferson Community College in Louisville, Kentucky, Galileo's numbers reflect fairly precise measurements — measurements that did not, however, measure what Galileo thought they were measuring. Graney presents his arguments and calculations in a preprint that was posted in late August to the online archive arXiv.

Nature of Light and Nature of Stars

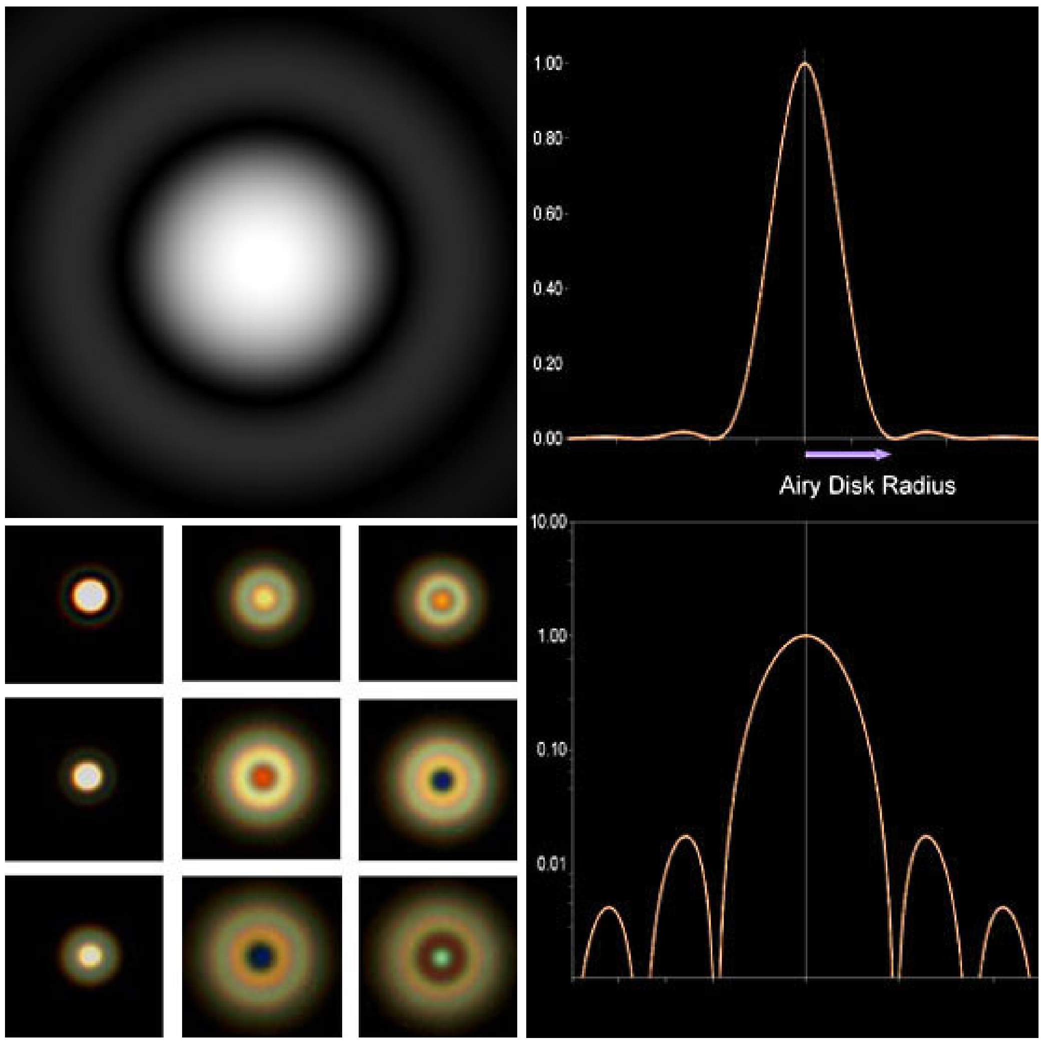
According to Graney, Galileo did a pretty good job estimating the distance of stars, based on the tools and theories he had available to him. At root, two wrong ideas — one having to do with stars, and the other with light — account for the mistake he made.

The error having to do with stars is easier to describe. Galileo thought — reasonably enough, given what was known at the time — that all stars were alike, and all like the Sun. Thus, fainter stars would simply be more distant. In fact, as we now know, stars vary in size and brightness, and these factors — as well as distance — will affect how bright they appear to us.

The second problem Galileo faced is somewhat more subtle, and has to do with the nature of light, which propagates like a wave in many situations. In particular, the wave nature of light means that diffraction occurs; diffraction is a term for the bending or spreading that waves (of light, for example) exhibit on meeting an obstacle or passing through an opening.

How does this affect what **Galileo** saw? Essentially, diffraction made the stars look bigger. Stars are, in fact, so distant that it's reasonable to think of them as a point in the night sky. To make this a bit clearer, think of looking at a tennis ball. At a distance of 10 feet, the ball certainly has a perceptible width — more technically, it subtends roughly one degree in your field of view at that distance. (It's not hard to figure this out more accurately. A circle of radius 10 feet has circumference $2\pi r$, or 2 x 3.14 x 10, which equals about 63 feet, or 756 inches. Divide this by 360 — the number of degrees in a full circle — and we see that one degree, at this distance, will cover just over 2 inches. So, if a tennis ball is about 3 inches in diameter, it will cover about 1 ½ degrees at a distance of 10 feet.) But if the tennis ball is moved not 10 feet away but 10 miles away, it will of course become effectively invisible — at that distance, its width in our field of view has narrowed to a point. The same occurs with stars. They have, of course, a diameter much greater than a tennis ball's, but the distances are so vast that they are reduced to a point source of light.

The great astronomer did, however, see stars as a disk, and this was because of diffraction — the bending of light from the star as it passed through the aperture or opening of the telescope. The effect of a circular aperture (as in a telescope) is to diffract light so that it creates a circular region of high intensity, followed by subsequent circles of light and dark — but most of the light appears in that central disk, called an Airy disk in tribute to the 19th century British astronomer George Biddell Airy, who provided a mathematical equation (based on diffraction effects) describing the central disk.



Top Left and Right: Courtesy of Christopher Graney; Bottom Left: Tom Pope/Jim Mosher

The effect of a telescope circular aperture is to diffract light so that it creates a circular region of high intensity, followed by subsequent circles of light and dark — but most of the light appears in that central disk, called an Airy disk. TOP and BOTTOM LEFT: Circular aperture diffraction patterns. TOP and BOTTOM RIGHT: Intensity plots for diffraction patterns.

Graney gives the equation that describes, in this situation, the radius of the Airy disk, or central maximum of the diffraction pattern of light. That equation is:

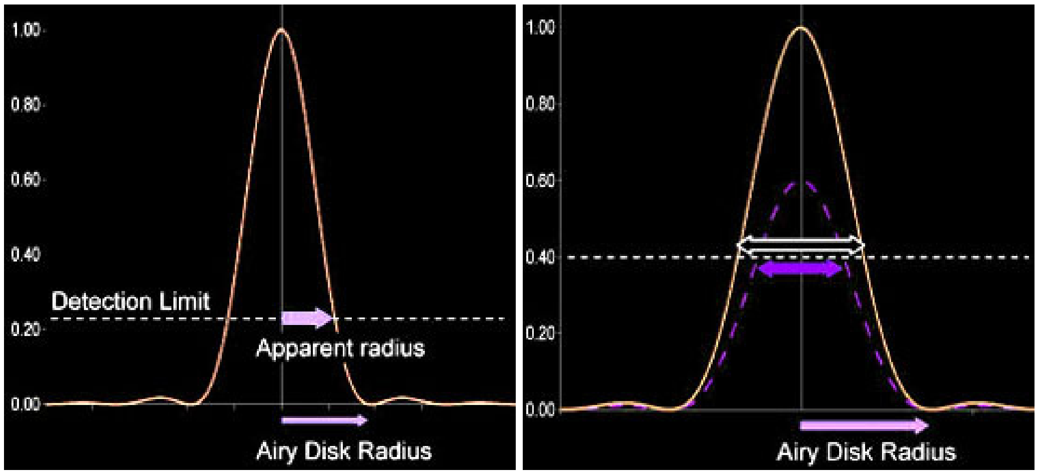
$$\theta_A = 1.22\lambda/D,$$

where the θ_A stands for the radius of the Airy disk, the Greek letter λ (lambda) for the wavelength of light, and the D for the diameter of the aperture — in this case, the opening of the telescope through which light enters. Diffraction effects do yield outer rings (light alternating with dark), but in the case of **Galileo**'s observations of stars, these outer rings would have been too faint to be visible.

A Further Complication

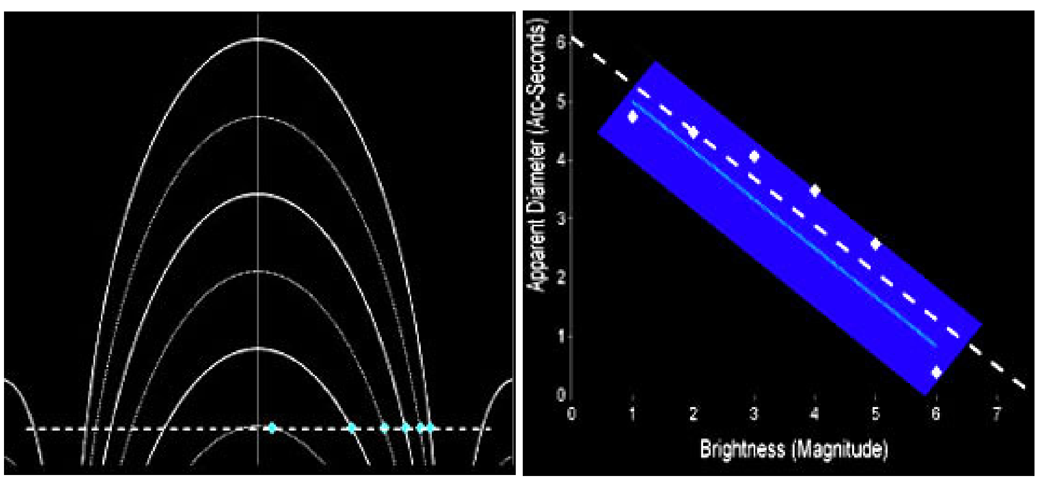
Diffraction, and the Airy disks that result, explain why **Galileo** thought he was actually seeing a perceptible disk for a star, instead of a pinprick of light, and thus why he believed that stars are much closer than they actually are. However, Graney points out that there is more to the story than that. "In theory all stars have the same diameter image because all have the same Airy disk radius," he notes. Remember, the equation that gives the radius of the Airy disk depends on two variables — the diameter of the telescope's aperture (which will certainly not change whichever way the telescope is pointed), and the wavelength, which will be more or less the same for different stars. However, **Galileo** did see substantial differences in the sizes of what he took to be the diameters of the stars he was looking at. Why was that?

The answer lies in the fact that **Galileo** did not observe the full Airy disk of the stars he was looking at, but only a portion of it, Graney concludes. He explains it this way: "The star image diameter seen by a telescope user like **Galileo** depends not just on the Airy disk radius, but also on factors that set a limit on the intensity of light that can be detected, such [as] sky conditions and the sensitivity of the human eye. This detection limit means that the apparent star diameters **Galileo** sees will be smaller than twice the Airy disk radius." Dimmer stars, Graney notes, will seem to have smaller diameters than brighter stars.



Courtesy of Christopher Graney

TOP LEFT and RIGHT: Diffraction pattern detection limitations due to sky conditions, human vision and variation in the brightness of stars. BELOW LEFT: An intensity plot for stars of magnitude 1 to 6. The size of each star, marked by diamonds, is determined by the detection limit. BOTTOM RIGHT: The plot of star diameters versus magnitude with the aqua line representing the relationship between magnitude and size, the bright blue area indicating the arc-second "error," and from the graph left, the diamonds pinpointing the star diameters with the line dash matched to the diamonds.



Courtesy of Christopher Graney

The upshot was that "diffraction tricked **Galileo** into believing that a linear relationship existed between the magnitudes and apparent sizes of stars." Since he also thought that all stars were essentially alike (and like our Sun), this meant he believed there was a similar correlation between the magnitudes and distances of the stars, and this led him to his erroneous calculations.

So should we take **Galileo** off his pedestal in the history of science? That would be a big mistake — as Graney observes, "Since an understanding of wave optics lay almost two centuries in **Galileo**'s future, he can certainly be forgiven for not grasping that diffraction was creating spurious results!"

Christopher Graney: From the Ground Up

Christopher Graney is a professor of physics at Jefferson Community and Technical College in Louisville, *Kentucky. As an astronomer and teacher, he oversees the operation of the Otter Creek Observatory, the only public observatory in the state of Kentucky. Below are Graney's September 15 responses to questions posed to him by Today's Science.*

Courtesy of Christopher Graney

"I like to be able to teach from the ground up — to teach not just 'here is what we know' but also 'here is how we know it and why we got to where we are now'."

Q. Where did you grow up and go to school? Was your school particularly strong in science?

A. I grew up in Owensboro Kentucky. I graduated from Owensboro Catholic High School, the U of Dayton (undergraduate), and the U of Virginia (graduate).

Q. Were there any individuals who were especially important in your choosing a scientific career? What did you most like besides science in school?

A. I think my mother encouraged an interest in the stars. Someone gave me a toy telescope when I was very young, and I remember my mother waking me up late at night to go out and see a lunar eclipse. Besides science in school I liked cars — I bought a beat-up Triumph Spitfire convertible 2-seat sports car when I was 16, and spent an enormous amount of time messing with it.

Q. What do you find most exciting/interesting about your present work? What is least appealing?

A. There's not much I don't like — there's always some politics in the academic world and I don't like that. I really like teaching my classes. My studies of **Galileo** grew out of an interest in doing a better job of teaching my astronomy classes. I read a paper by Owen Gingerich of Harvard, one of the leading historians of science, that made me question so much of what I had been teaching out of a standard textbook. What Gingerich was saying and what the textbook said were very different — and Gingerich really made sense. That set me on a path of investigating the history of science for myself. I like to be able to teach from the ground up — to teach not just "here is what we know" but also "here is how we know it and why we got to where we are now".

*Q. What are you working on now? What problem would you most like to solve? Are there other famous astronomers/physicists of the past whose work you have looked at and analyzed, as you did with **Galileo**?*

A. There is no one I've analyzed like **Galileo**. Right now I'm still working on trying to understand **Galileo**'s observations of stars. There are a lot of interesting questions to be answered about his observations. For example, the distances **Galileo** calculated were large, but they were still short of the real distances by a factor of 1000 and more. The distances he calculated turn out to be incompatible with other ideas he had about the nature of stars and the motion of the earth, so what was he thinking? It's interesting because had **Galileo** chosen to do so, he could have used his observations of stars to claim that some stars were closely paired (really closely — like nearly touching), or to claim that stars were not like the sun, but were far larger, or even to claim that the Earth did not move! But instead he was very careful in reporting his observations — the stuff he chose to report we know today was generally correct — stars ARE suns, the Earth moves, etc. So he really set science on the right path. How did he know which observations to trust and which ones to keep to himself? And what about his colleagues? What did he share with them? These are all things I would like to know.

Q. What are you most proud of, scientifically speaking? What do you most regret not learning *more about?*

A. I'm most proud of offering some interesting classes. I would never claim to be a great teacher, but I've got some great material in my classes — you'll learn stuff in my class that you won't find in textbooks — I use a lot of the scientists original words and writings in my class, so students can really see what these guys were thinking.

Q. What do you think will be the big scientific challenges and accomplishments of this century-in physics in particular?

A. That I can't speculate on. Things change rapidly. A lot will depend on how technology progresses, because my opinion is that technology plays a big role in how science progresses. Tycho Brahe was a scientist who came right before Galileo and probably had all the talent **Galileo** had, but he didn't discover what **Galileo** discovered because **Galileo** had the telescope, and Tycho didn't.

Discussion Questions

Diffraction effects occur when waves pass objects — for example, entering the aperture of a telescope or passing through a slit (or multiple slits) in a paper or grating, but they are significant only when the wavelength (of light, sound, water or whatever is involved) is comparable in size to the openings in the barriers to the waves. Thus, diffraction effects involving light typically involve systems with small apertures (because wavelengths of visible light are small), while water waves will exhibit diffraction effects on much larger scales — as you can see if you watch the effect on ocean waves of an indentation in the coastline. What other natural examples of diffraction can you think of?

If you play music in your home, which sounds — the high notes or the bass notes — are more audible in other rooms, and why is that?

Study Abstract and Text

(Researchers' own descriptions of their work, summary or full-text, on scientific journal websites).

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