CAMBRIDGE

Cambridge University Press
978-1-107-05265-9 - Nearest Star: The Surprising Science of Our Sun: Second Edition
Leon Golub and Jay M. Pasachoff
Excerpt
More information

1

The Sun

ORIGINS

About 13.8 billion years ago, for reasons we do not yet understand, the Universe came into existence. Matter as we know it did not exist and even the forces by which bits of matter and radiation interact with each other were different than they are today. Our knowledge of physics is good enough now for us to calculate the conditions prevailing back to an incredible 0.000000000000000000000000000000000000000000001 seconds (10^{-45} s) after it all started. Of course, this does not get us all the way back to zero or before (if the word “before” has a meaning in this context), but we think we can speak with a fair degree of confidence about how things proceeded thereafter.

By 0.000000000001 seconds of age, the four forces of nature that now exist – gravity, strong and weak nuclear, and electromagnetic – were in place, and by the age of several hundred seconds the Universe contained the familiar matter that continues to exist today, the stuff of which ordinary atoms are made. A major turning point occurred at the age of about 380,000 years,

Cambridge University Press
978-1-107-05265-9 - Nearest Star: The Surprising Science of Our Sun: Second Edition
Leon Golub and Jay M. Pasachoff
Excerpt
More information

when the Universe cooled enough for electrons to combine with the available nucleii, which were mostly protons and helium. At this point, atoms started to form and it suddenly became possible for photons of light to travel long distances without being absorbed. Before this time the Universe was opaque, and our best telescopes will not be able to look back beyond this era.

Some time later, at an age of half a billion years, galaxies started to form. Until then, there were few stars and therefore no sources of light – the universe was in a dark age. Since galaxies consist of large numbers of stars, this implies that many billions of stars were forming, and we must assume that some fraction of them had planets as well. The Universe since then has changed only in some details – galaxies have evolved, the fraction of matter in heavy elements has increased a bit – but has otherwise looked pretty much the same as it does now.

The formation of the Sun is one extremely minute part of this history, the story of one tiny star among the trillions that have come and gone during the past 14 billion years. It is a relatively young star, only 5 billion years old and thus not of the first generation. This means that it, and the planets around it, contain heavier elements formed when earlier stars became novae and supernovae. These heavier elements – oxygen, silicon, iron, carbon, and so on – make possible certain side effects, such as organic life.

The Sun

The Sun is by far the brightest object in our sky, and the difference between its presence or absence overhead is literally like night and day. It is clearly far away, although it took centuries to figure out just how far. How is it, then, that we can know anything about an object that is far away, extremely hot, and astoundingly large?

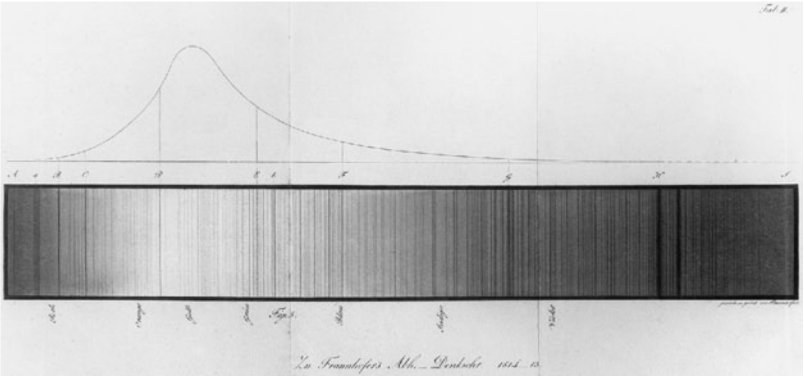

FIGURE 1.1. Fraunhofer's photospheric spectrum published in 1817. This was the first spectrum to show sharp, dark, absorption lines in the solar light. The locations and strengths of these numerous "spectral lines" provide information about the physical conditions on the Sun.

The answer is that the information is in the light. The science of spectroscopy allows us to analyze the solar light in detail (see Fig. 1.1 for an example) and thereby learn about the elements that compose the Sun and their physical states. If we then also use high resolution images of the Sun, we are able to find out what physical processes are occurring to produce the type of light that we see. We can even, with the help of new methods of measurement, now study the interior of the Sun as well.

There is more than light coming from the Sun. Extremely high energy particles from large solar eruptions sometimes reach the surface of the Earth and are detected by terrestrial monitoring equipment. By putting instruments into space, we can extend the range of wavelengths available, enabling us to see solar phenomena not visible from the ground, and we can also intercept and study some of the actual solar material as it flows past the Earth at hundreds of miles per second.

Despite a rapid accumulation of new knowledge in the past 20 years, there is still a great deal we don't know about the Sun. The gaps in our knowledge have broad implications, because solar studies are relevant to almost all of astrophysics: many of the more exotic aspects of astronomy concerning distant stars and galaxies must, of necessity, be based on a foundation of theories and models developed and tested in the solar context. Our ability to explore the unfamiliar territory of intergalactic space reflects how well we understand the more familiar object close to home.

The Sun's physical parameters

This chapter and the next two will give the reader a taste of the scientific process by looking at some of the fundamentals that must be understood before more detailed discussions are possible.

A tabulation of the Sun's basic physical parameters and those of the major solar system objects is given in Appendix III. But these numbers are so far removed from our ordinary experience that they are hard to picture in a meaningful way. To make the data more accessible we will use ratios and analogies. Here are some of the basic facts:

- The ratio of the Sun's diameter to that of the Earth is: 109
- The ratio of the Sun's mass to that of the Earth is: 333,000
- The ratio of average Solar density to that of the Earth is: 1/4
- The ratio of Sun's mass to the sum of all the masses of all the planets is: 744

What do these numbers mean? The Sun is *big* by Earth standards, over a hundred times the diameter, meaning more than a million times the volume. The smallest features that we can see on the Sun with the naked eye or with low-power telescopes, such as sunspots, are typically about as big as the Earth.

The Sun is also very massive, having over three hundred thousand times more total matter than the Earth. Since we said that

Cambridge University Press
978-1-107-05265-9 - Nearest Star: The Surprising Science of Our Sun: Second Edition
Leon Golub and Jay M. Pasachoff
Excerpt
More information

the Sun is a million times bigger than the Earth, then if it had the same density as the Earth, it would be a million times more massive. But its density is low, only one-fourth that of the Earth, giving it about the same average density as water. The implication of the low density is that the Sun is not made of the same stuff as is the Earth. It is mainly made of hydrogen[1], the lightest element, followed by helium, the second lightest element.

The Earth is made mostly of heavier elements, with very little hydrogen or helium, even though modern cosmology tells us that these two light elements are the most plentiful by far in the entire universe. It would seem that during the formation of the solar system, something caused planets like Earth to end up with more heavy elements, or with less of the lighter elements. Today's explanation is that the smaller planets such as the Earth did not have enough gravitational pull to hold onto very much hydrogen; it escaped back into space and we ended up mainly with the relatively rare heavy elements – oxygen, silicon, magnesium, and iron being the most abundant. The large planets in the solar system, such as Jupiter and Saturn, have stronger gravity and were able to hold onto the light elements, so they have far lower density than the small inner "rocky" planets.

The fourth datum on the list explains why the Sun is the center of our solar system: it has over 700 times as much mass as all of the solar system planets combined, including comets and asteroids. All of these objects form a self-gravitating system: floating freely in space, they are held together by their mutual gravitational pulls and are relatively uninfluenced by other distant masses. In such a system, if one of the masses is much larger than the others, then it will be nearly unmoved by the gravitational pull that the other bodies exert on it. For our solar system, the Sun has about 99.9% of the total mass. This means

[1] That hydrogen is the most abundant element was first realized by Cecilia Payne in her 1925 Radcliffe College dissertation, but it was so contrary to the expectations of the time that, under pressure, she labelled her result "spurious."

Cambridge University Press
978-1-107-05265-9 - Nearest Star: The Surprising Science of Our Sun: Second Edition
Leon Golub and Jay M. Pasachoff
Excerpt
More information

that in the gravitational tug-of-war among all of these bodies orbiting around each other, it is a very good approximation – to an accuracy of about 0.1% – to say that the Sun remains stationary at the center of the solar system and all of the planets, asteroids, dwarf planets, Kuiper-belt objects, comets, and so on orbit around it.

The brightness of the Sun

We start by trying to figure out just how bright the Sun really is, how much energy it emits. We can get some idea by making measurements on Earth, measuring the brightness here and also figuring out how far away the Sun is.

The technique is this: assume that the Sun radiates equally in all directions[2], so our local data are representative of what anyone, anywhere, at our distance from the Sun would measure. This distance defines a spherical surface enclosing the Sun and having radius equal to 1 au (redefined by the International Astronomical Union in 2012 as exactly 149,597,870,700 meters), the distance between the Earth and the Sun. If we then take our measured value and multiply it by the surface area of this enclosing sphere, we will capture all of the radiation emitted in all directions and we will have determined the total power emitted by the Sun.

In order to make this calculation, we need to know the radius of the sphere, by finding the distance between the Earth and the Sun. The problem is that we have no obvious way of finding this number, since no direct measurement is possible. What we can do from our terrestrial location is to look around the sky at the objects out there - Sun, Moon, Venus, Jupiter, and so on - and to measure angles between them. We can use these data to figure

[2] A famous joke about using simplified models has a theoretical physicist calculating milk production by starting with the words “Assume a spherical cow....”

CAMBRIDGE
Cambridge University Press
978-1-107-05265-9 - Nearest Star: The Surprising Science of Our Sun: Second Edition
Leon Golub and Jay M. Pasachoff
Excerpt
More information

out *relative* distances: by measuring angles we can lay out the geometric pattern of objects in the solar system and determine, for instance, that the Sun is 400 times as far away as the Moon. The solution then is to know the distance to either one of them, because then we know the distance to both.

The first person known to have made such a measurement was Aristarchus in the 3rd century B.C., who measured the angle between the Sun and Moon when the Moon was exactly half full. If the Sun were infinitely far away, this angle would be 90°; with the Sun at a finite closer distance, the angle is slightly smaller, as shown in Figure 1.2. Using this method, the number we calculate for the distance of the Sun is extremely sensitive to the measured value of the angle. Aristarchus measured 87 degrees, whereas the value is really more like 89.85 degrees. His calculation said that the Sun is 18 times further away from the Earth than is the Moon, rather than 400 times further as it really

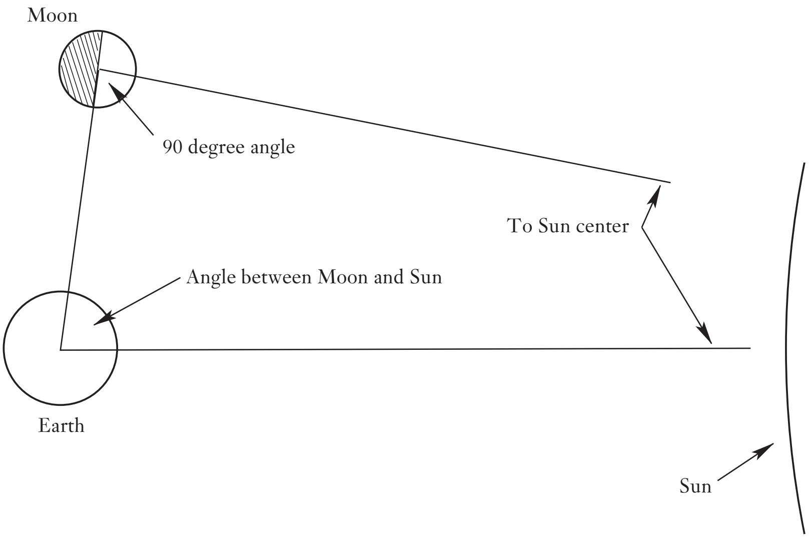

FIGURE 1.2. The geometrical relationships between the Earth, Moon, and Sun used by Aristarchus to determine the distance of the Sun.

is. Still, the method he used was sound, and with more accurate measurements of this sort we can determine the *relative* distances of the Sun, Moon, and planets quite well.

But we still do not know the true size of this pattern of relationships. How do we ever find any *absolute* distances? The answer to this problem turned out to require the invention of extremely accurate clocks.

Transits of Venus

Why clocks? Because the method used was triangulation from widely separated points on the Earth, whose size we know from measuring it directly, and the method requires an absolute determination of when the measurements are made.

In astronomy we speak of *parallax*, rather than triangulation, to denote the well-known phenomenon that two objects line up differently along the line of sight for one observer than for another. For example, during a solar eclipse an observer at one location might see the Sun and Moon line up perfectly, so that the eclipse is total. But an observer some distance off to the side might be able to see past the edge of the Moon for a partial view of the solar disk; for her, the eclipse will not be total.

We have known the relative distances among the planets for quite some time – the values have not changed much since the days of Copernicus. We have also known how fast the planets move around in their orbits, so that the angles between them and how these angles change with time has been known for many years. But in order to progress from a relative diagram to one whose absolute size is determined, we need to know the true length of any one piece of the figure; we will then know all of the lengths. Parallax can be used to make this measurement.

We do have access by direct measurement to one length: the size of the Earth, or more to the point, the distance from one side of the Earth to the other. All we need then is to line up two objects from one side, then from the other, and measure the size of the angle between these two perspectives, and we know the absolute scale of the solar system. But what to use?

In 1716, Edmond Halley – who not only plotted the orbit of the comet that bears his name, but who also was the first accurately to predict the path of a total solar eclipse – pointed out that the passage of the planet Venus across the face of the Sun could be used to provide the needed marker. There had been a pair of transits of Venus in 1631 and 1639; the first went unobserved and the second, though observed, did not lead to useful measurements. The next pair of transits would occur in 1761 and 1769 and Halley, knowing he would not live to see them, urged future astronomers to make the extraordinary efforts needed to obtain the crucial measurements from widely separated parts of the Earth.

Time enters into the measurement because the contact between Venus and the bright disk of the Sun occurs at different times at the two separated sites. If we imagine that the line joining the edge of the Sun to Venus is continued out until it hits the Earth, then this line sweeps across the Earth as Venus moves across the face of the Sun. First it hits one edge of the Earth (observer number 1), then it sweeps across until it hits the other edge of the Earth (observer number 2). From our scale model – whose absolute size we are trying to determine – we know the rate at which this line is sweeping around. A measurement of the time between the transits seen at the two sites therefore tells us how much angle has been swept out in the time it takes to sweep from one side of the Earth to the other. Knowing that angle and the size of the Earth, which is one side of the triangle, allows us to calculate the size of the side of the triangle formed by the distance between the Earth and Venus. The key is for the two observers – who in those days could not communicate with each other – to both have highly accurate clocks that tell the same time if only one contact is measured, or, by Halley's

Cambridge University Press
978-1-107-05265-9 - Nearest Star: The Surprising Science of Our Sun: Second Edition
Leon Golub and Jay M. Pasachoff
Excerpt
More information

original method, clocks measuring time at the same rate so as to determine the duration of the transit.

The entire business of getting to the appropriate sites, bringing accurate enough clocks, avoiding hostile natives, obtaining the data, and getting home safely was a major international undertaking[3] but it was accomplished and the distance from Earth to Sun was determined though not as accurately as desired.

The nature of the orbits of the Earth and Venus is such that transits of Venus come in pairs with 8 years between them, and then over a hundred years until the next pair. There weren't any transits of Venus since 1874 and 1882 (Fig. 1.3) until the pair of transits on June 8, 2004, and on June 5-6, 2012 (Plate XV). The 2004 transit was visible from all of Europe, with part of it visible from the Eastern United States, and entirely visible in western Siberia and in progress at sunrise in eastern Russia. A whole transit of Venus observed from Earth, from immersion of Venus onto one side of the Sun until emersion on the other side, lasts over 6 hours. The following pair of transits won't occur until December 11, 2117, and December 8, 2125. None of these transits are dramatic to see the way eclipses are, but intellectually they are superb.

Transits of Mercury also occur. They are more frequent than those of Venus, coming about 13 times per century, but are more difficult to observe because Mercury is so small. The TRACE satellite observed such a transit toward the end of 1999 (Fig. 1.4)

---

[3] The story of the transit expeditions in the 18th century is told in the delightful and often hair-raising book *The Transits of Venus*, by Harry Woolf, Princeton University Press, 1959. See also the series of articles by Don Fernie in *The American Scientist*, and books by Sheehan and Westfall, Maor, and Lomb listed in the bibliography at the back of this book. The two authors of this book and Glenn Schneider solved the problem of the black-drop effect that diminished the accuracy of transit measurements, reported in the journal *Icarus* in 2004.