14 Our Sun

Thus far our discussion of stellar properties has mainly used our Sun as a benchmark for key overall quantities, like surface temperature, radius, mass, and luminosity. But of course the close proximity of the Sun, and its extreme apparent brightness, makes it by far the most important star for own lives here on Earth. Other stars are so far away that even to our most powerful telescopes they appear as mere points of light, from which we can only measure the overall flux, or apparent brightness. But the Sun is close enough that we can resolve its *surface brightness*, or intensity, across its angular diameter of about 0.5^o. When its extreme brightness is suitably filtered by a dark lens, it appears to our eyes as a generally featureless disk. But even with his small, primitive telescope, Galileo was able to discover darkened blemishes we now call sunspots, and so disprove the classical ideal of the Sun as a perfect, heavenly sphere.

In modern times we have access to powerful telescopes, both on the ground and in space, that observe and monitor the Sun over a wide range of wavelength bands. These vividly demonstrate that the Sun is in fact highly structured and variable over a wide range of spatial and temporal scales, and so provide a sobering reality check on our own simple idealizations of stars as being constant, featureless, spherically symmetric balls of gas.

14.1 Imaging the solar disk

Figure 14 shows images of the solar disk made by NASA's orbiting Solar Dynamics Observatory (SDO) in 13 different wavebands, chosen to highlight different layers of the solar atmosphere, corresponding to the labeled temperatures.

In the top row the third image from the left shows the standard visual continuum, often dubbed 'white-light, formed in the layer known as the *photosphere*. As detailed in Appendix D.2, the less-bright, redder intensity toward the disk edge, known as *limb darkening*, results from the vertical decline of temperature through this photospheric layer. The sunspots below and to the left of the disk center appear dark in this visual image because, as shown in the 'magnetogram' just to its left[1], these are regions of strong magnetic field, with the light to dark

[1] Such magnetograms detect the circular and linear polarization of light induced by magnetic fields on the solar surface.

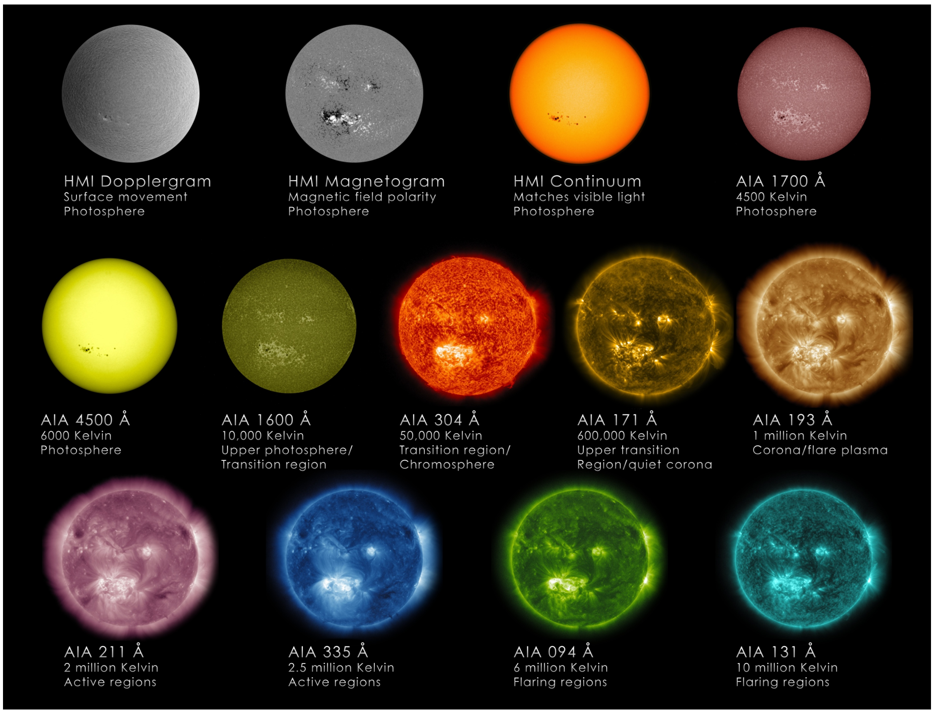

Figure 14.1 Full-disk images of the Sun at 13 different wavelengths, made by the NASA's Solar Dynamics Observatory (SDO). This includes images from both from the Advanced Imaging Assembly (AIA), which helps show how solar material moves around the Sun's atmosphere, and the Helioseismic and Magnetic Imager (HMI), which focuses on the movement and magnetic properties of the Sun's surface. Each wavelength was chosen to highlight a particular part of the Sun's atmosphere, from the solar photosphere, through the chromosphere, and up to the upper reaches of the corona. Credits: NASA/SDO/Goddard Space Flight Center. Further details at: `https://www.nasa.gov/content/goddard/how-sdo-sees-the-sun` s

switch indicating a change in the magnetic polarity; the fields are so strong that they inhibit the convective transport of energy from below, thus making sunspots relatively cool, and thus darker.

But these fields also are conduits for magnetic waves and turbulence, which when dissipated at higher layers actually add extra mechanical heating that cause the temperature in these upper layers to *rise*! Instead of the effective temperature $T \approx 5800\,\mathrm{K}$ that characterizes the photosphere, there first develops a hotter *chromosphere*, with temperature in the range $10,000 - 50,000\,\mathrm{K}$. This is followed by an abrupt jump across a narrow *transition region* to temperatures of *millions* of Kelvin (!) in the solar *corona*.

In the more-opaque UV wavebands that are formed in these higher layers, the regions above sunspots, known as *active regions*, are thus actually *brighter* than the surrounding areas. For example, in the central panel of the middle row, which is tuned to 304 Å emission from ionized Helium at temperatures of 50,000 K in the upper chromosphere, the active regions are bright, though there is still emission over the entire solar disk. But as one moves to the *far* UV and X-ray diagnostics (right middle and bottom row) that are formed at the MK temperatures of the corona, the contrast becomes greater, with some nearly dark regions that have little or no emission, known as *coronal holes.*

Figure 14.1 provides a schematic summary of these various layers and features of the solar atmosphere.

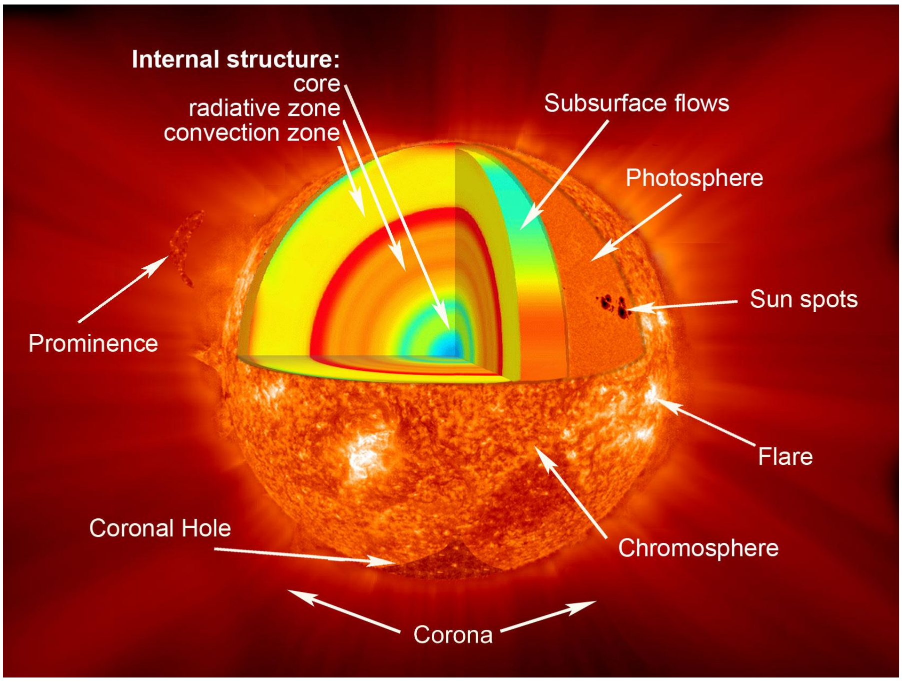

Figure 14.2 Schematic summary of key regions and features of the solar atmosphere, along with interior cutout showing the Sun's nuclear-burning core, intermediate radiative diffusion region, and near-surface convection zone. Image credit: NASA

14.2 Corona and solar wind

Though very hot, the corona has a very low density, even above active regions. At visual wavelengths it is thus nearly transparent, and so generally hard to see. Fortunately, by an amazing coincidence, Earth's moon has nearly the same angular size as the Sun, and so in rare and brief instances, there occurs a *solar eclipse*, during which the moon just covers up the bright solar disk. As shown in

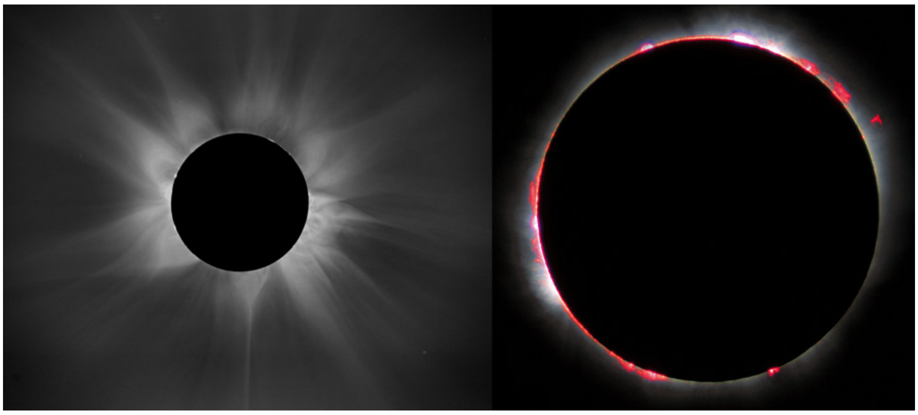

Figure 14.3 Left: Eclipse image of the solar corona during time of extensive active regions on the sun. Right: Image of the red Hydrogen emission from chromospheric active regions during the same eclipse. Credit: NCAR's High Altitude Observatory (corona) and Luc Viatour (chromosphere)

the left panel of figure 14.1, this allows us to see the corona as visible solar light scattered by electrons in the corona's tenuous, but highly ionized gas. In the right panel, the rim of red light comes from the chromosphere[2], via the magnetic suspension of hot gas in active regions, leading to Hydrogen Balmer-α ($n = 3$ to $n = 2$; see Appendix A.) emission at the red wavelength 6563 $\mathring{A}$. The magnetic fields from these active regions rise up into the corona, forming closed magnetic loops that connect footpoints of opposite magnetic polarity on the surface.

The corona is so hot that the Sun's gravity cannot, by itself, keep the gas bound against a pressure-driven outward expansion known as the *solar wind*. But in regions with closed magnetic loops, the magnetic field tension holds the gas back against this expansion, allowing such regions to keep a high pressure and density, and thus making them more visible in both white light and X-ray signatures.

Coronal holes arise in *open* field regions between such closed loops, allowing the gas to escape into the outward solar wind expansion. This gives then a lower coronal density and relatively low brightness in both scattered white-light, and X-ray emission. The coronal magnetic field is thus the key cause of the coronal structure seen in figure 14.1.

The radial streamers[3] at the tops of the coronal loops show that wind expansion wins out in the outer corona, effectively pulling open the closed field lines there. The resulting solar wind expands outward, past the Earth and even all the other planets, extending to distances > 100 au, until it is finally stopped

[2] This red color led to the name 'chromosphere', from the Greek *chroma* for color.
[3] Sometimes referred to as "helmet streamers", due their resemblence to German WWI army helmets.

by running into the local interstellar medium. The full region within this wind-termination sboundary is referred to as the *heliosphere*.

As illustrated below in figure 24.2, the magnetosphere formed by Earth's own magnetic field shields our planet and its atmosphere from a direct hit by the solar wind, instead just channeling any solar wind plasma toward the magnetic poles, where interaction with the atmosphere forms the aurora, a.k.a. the norther and souther lights. In contrast, the lack of a strong field on Mars has allowed the solar wind to gradually erode its now much thinner atmosphere. As discussed in section 24.3, this can affect the habitability of extra-solar planets around cool stars with coronal winds.

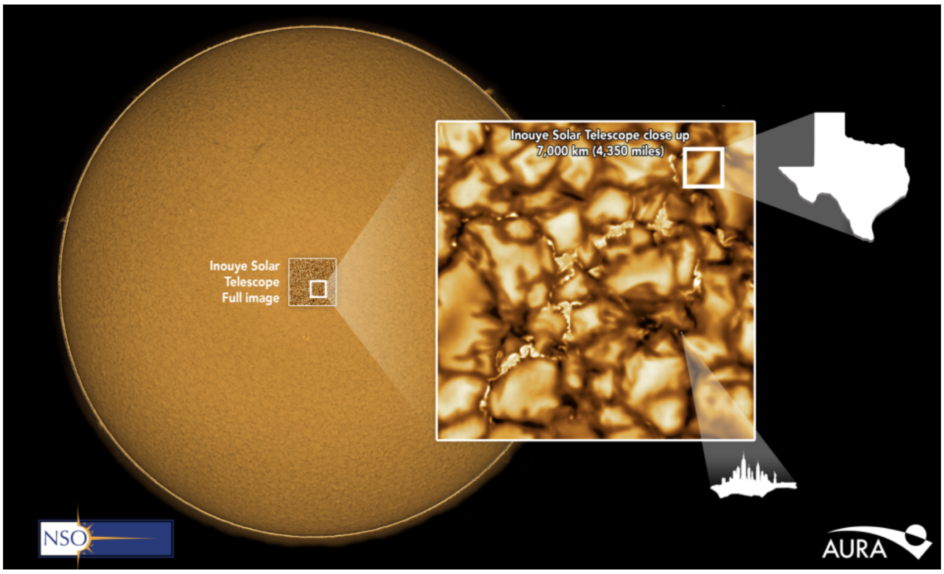

Figure 14.4 Illustration of how the DKIST telescope allows us to zoom in to image structure on the solar surface down to a resolution of ∼0.1 arcsec, or ∼ 70 km, only about twice the size of Manhattan. The irregular granulation structures have typical size of ∼2 arcsec, or ∼1500 km, about the size of Texas. They represent cells of convection, with brighter center upwelling from the hotter interior, bounded by narrow lanes of cooler darker downflows. Image credit: NSO/NSF/AURA; visit `www.nso.edu`

14.3 Convection as a driver of solar structure and activity

The angular diameter of the solar disk is

$$\alpha_\odot = \frac{2R_\odot}{\mathrm{au}} \approx 0.01\,\mathrm{rad} \approx 0.5^o \approx 1800\,\mathrm{arcsec}. \tag{14.1}$$

This means the roughly 1 arcsec resolution limit from atmospheric seeing allows for about 1800 resolution elements across the solar disk, representing a physical size of $s = \text{au} \times \text{arcsec} \approx 2R_\odot/1800 \approx 700\,\text{km}$. With special techniques to correct for atmospheric seeing, it is possible to reach a factor 10 higher resolution, so down to 0.1 arcsec, or a physical size $s \approx 70\,\text{km}$.

As illustrated in figure 14.2, such resolution is achieved by DKIST[4], the currently most advanced ground-based solar telescope. Its primary mirror has a diameter $D = 4\,\text{m}$, which from eqn. (13.3) gives a diffraction-limit resolution $< 0.1\,\text{arcsec}$ in the visible. Its site at an altitude of about 3000 m atop the Haleakala volcano on the island of Maui, Hawaii was chosen for its relatively stable air and so good, sub-arcsec seeing, which with adaptive-optics correction allows resolution that approaches this diffraction limit.

Zooming in to a small segment of the disk, figure 14.2 shows the Sun's *granulation* pattern, with central bright cells bounded by narrow, darker lanes. This is characteristic of a systematic gas motion called *convection*. Hotter gas in the interior wells upward in the cell centers, making them hotter and thus brighter. After this gas cools by radiation into space, it falls back downward in the narrow lanes that bound the cells, which being cooler also appear darker. As detailed below in section 17.3, such convection arises in the near-surface layers of relatively cool stars like the Sun, from the blocking of radiative diffusion by the enhanced opacity associated with ionization of neutral Hydrogen. An animation of the dynamical variation of this convective structure is given in `https://www.youtube.com/watch?v=4nieF-e0OOs`.

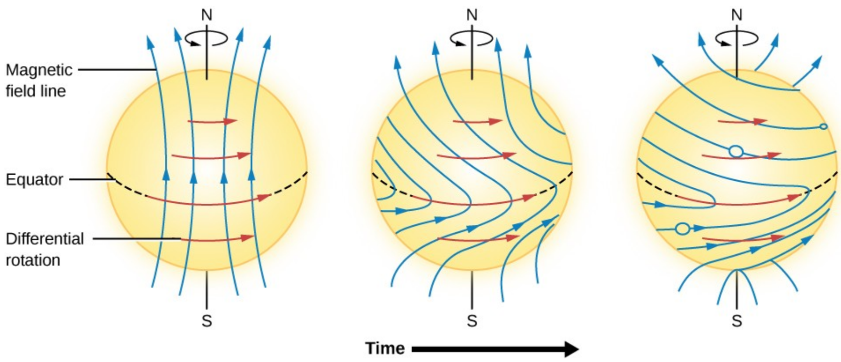

Figure 14.5

Such convection combines with the Sun's rotation to generate magnetic fields through a "rotation-convection magnetic dynamo". Although hydrogen gas in the solar atmosphere is mostly neutral, other elements lose a sufficient number of their less tightly bound electrons to make the overall gas behave like an

[4] For *Daniel K. Inouye Solar Telescope*, named in honor of the Hawaii senator who championed funding for the project in the US congress.

ionized plasma, with a high electrical conductivity. Such a conducting plasma makes any magnetic field "frozen-in", or effectively stuck to the local plasma. Near and below the stellar surface, where the gas energy density dominates over that associated with the magnetic field, the stretching and compression of any embedded magnetic field acts to amplify that field. For example, in granulation convection cells, the dense material upwelling in the center tends to sweep any magnetic field lines to the cell edges, thus concentrating the field in the narrow dark lanes. The small-scale bright regions in the dark lanes in figure 14.2 are sites of such locally concentrated magnetic field.

Above the solar surface, the rapid decrease in gas density and pressure with height means that in the upper layers of the Sun's atmosphere, in the *chromosphere* and extending up into surrounding *corona*, it is the magnetic field that dominates and channels the gas, leading to the extensive coronal structure shown in the eclipse image in figure 14.1.

Finally, as illustrated in figure 14.3, larger-scale interior generation of magnetic fields occurs through the interaction of convection with the Sun's *differential rotation*. The latter refers to the fact that the Sun does not rotate as a solid body, like the Earth or any planet, but instead actually has a faster angular rotation (shorter rotation period) at its equator than at higher latitudes towards its poles. As field lines are stretched azimuthally, they eventually form kinks that pop up through the solar photosphere, forming sunspot pairs with opposite magnetic polarity. With increased strength and complexity of the field, coupled with foot-point wandering induced by convection, can lead to localized regions of *magnetic reconnection*. The sudden release of magnetic energy leads to a localized *flare* in brightness in wavebands from the visible to X-ray, as shown in several panels on the bottom row of figure 14. Over time this reconnection dissipation leads to an overall decline in magnetic field strength and complexity, and so an associated decline in solar activity till this reaches a relatively quiescent minimum, whereupon the cycle restarts with winding up of the large-scale residual field by differential rotation. This is the origin of the 11-year cycle seen in, e.g. sunspot number, as well as other signatures of solar activity.

Through monitoring spectroscopic signatures of activity, including coronal X-ray emission, activity cycles have been inferred in other cool, solar type stars, albeit with varying periods ranging from about a year to many decades. This illustrates again how the Sun provides us with benchmark for complex structure and activity in stars that we only see as points of light, reminding that they too are far more complex than our idealized steady, spherically models would imply.

14.4 Questions and Exercises

Quick Question 1: