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Leon Golub and Jay M. Pasachoff
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Introduction

The corona is a high-temperature portion of the Sun's outer atmosphere, beginning slightly above the visible surface and extending hundreds of thousands of kilometers, or further, into interplanetary space. A precise definition of the term "corona" is to some extent dependent on one's theoretical bias: if the solar atmosphere is viewed as spherically symmetric and homogeneous ("plane-parallel"), then the corona is easily defined as the portion of the atmosphere above a certain height, with perhaps some small variation from place to place.

As we shall see, the corona is far from homogeneous and such models are of limited applicability. One may then choose instead to focus on coronal structures, which seem to be omnipresent and which are found to be relatively independent of each other. The observed structuring takes the form of long, thin loops or strands either extending out into interplanetary space or curving back and reentering the photosphere.

Both hot and cool structures are seen in the outer solar atmosphere. The "footpoint" of such a loop is defined as the portion of the structure that is anchored in the photosphere, and footpoints are generally cooler than the coronal portion. This implies that there is a horizontal interface between low and high temperature regions of atmosphere. However, with both hot and cool structures present in the outer solar atmosphere, in some locations there may be loops of different temperature situated next to each other. The interface between the hot and cool regions is therefore not always horizontal. Thus, height alone is not an adequate defining coordinate for coronal conditions. In this type of "loop model atmosphere," the corona is built up from an assemblage of relatively isolated[a] structural building blocks, which must then be joined together to form a coherent whole.

The extent to which the corona departs from a spherically symmetric, plane-parallel atmosphere may be seen in Fig. 1.1, an image taken by the *TRACE* satellite in the highly ionized Fe IX/X emission lines near the 173 Å central wavelength of this channel. These lines emit EUV radiation at ≈1 million K

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[a] Discussions of the term "relatively isolated" in this context will be found in Ch. 7.

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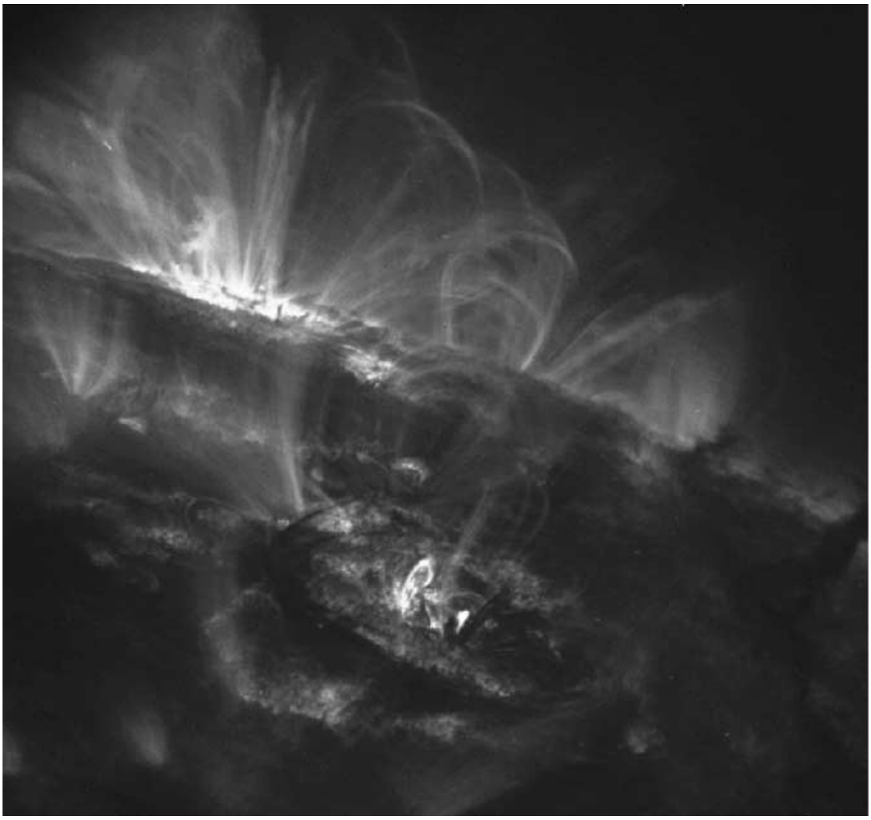

Fig. 1.1 The extent to which structures dominate the lower corona is seen in this EUV image from the *TRACE* satellite, showing an extreme departure from a plane-parallel atmosphere. (Photo courtesy TRACE/NASA)

and the atmosphere is seen to be highly structured, departing radically from a uniform, plane-parallel configuration.

It is thus a matter of some controversy to define exactly what is meant by *the corona*. The definition we choose is based on a fundamental physical consideration: the visible surface of the Sun, the *photosphere*, is at a temperature of ≈5,800 K. In the absence of any special circumstances the atmosphere above the photosphere should *drop* in temperature as one moves higher. However, the most important physical fact about the corona is that it reaches very high temperatures, more than 10^6 K. Thus, for whatever reason, the outer atmosphere of the Sun shows a steep rise in temperature. Moreover, this temperature increase is found to occur over very short distances, with the rise from $<10^4$ K to $>10^6$ K occurring within ≈500 km, *i.e.*, less than a thousandth of the solar radius.

If we pick a temperature well above that of the Sun's surface, such as 10^5 K, then we may define any portion of the atmosphere above this temperature as *corona*. This very rough definition will be further refined in subsequent chapters.

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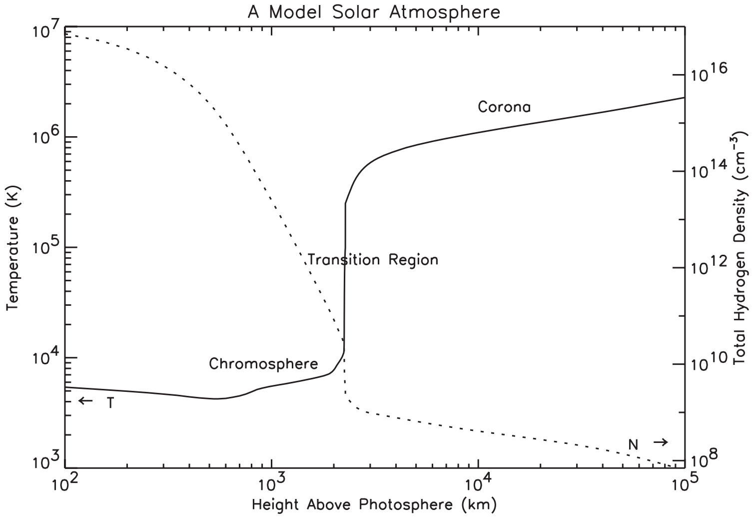

Fig. 1.2 Plane-parallel model of solar atmospheric temperature (solid line) and density (dotted line) vs. height. (Courtesy G. Avrett)

The basis for this choice can be seen in Fig. 1.2 (after Fontenla *et al.*, 1993 and Gabriel, 1976), which is a schematic representation of the temperature of the solar atmosphere as a function of height above the surface, keeping in mind again that "height" is not a unique determinant.

The key feature of interest in this figure is the sharp rise in temperature between 2,000 km and 3,000 km above the surface, labelled "transition region." The height of the transition region will vary from one place in the atmosphere to another because of the inhomogeneous nature of the corona, and it may even be oriented vertically rather than horizontally in some places, with hot coronal structures penetrating downward below the upward reach of nearby cooler spicules (see Daw *et al.*, 1995). However, the existence of such an interface region, whatever its shape, is thought to be universal throughout the solar outer atmosphere and it serves as a natural demarcation of the changeover to "corona." Because the rise in temperature is so dramatically steep, the choice of 10^5 K is adequate for our purposes, since a large change in this cutoff value will correspond to only a very small change in actual physical location.

Defining the outer extent of the corona is somewhat easier, because there is a natural criterion given by the physics of an expanding corona (Ch. 9). The high temperature and high thermal conductivity of the coronal gas insure that it is continually expanding outward, reaching supersonic speeds and extending far into the sphere surrounding the Sun. The particle density and flow speed of the solar wind are such that the gas pressure is higher than that of the interstellar medium, which implies the existence of a dynamical interaction between the solar and interstellar plasmas in order to attain pressure equilibrium.

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The result of the coronal expansion is the formation of a cavity, called the "heliosphere," carved into the interstellar medium. Theory predicts that there is a shock front known as the "termination shock" where the outflowing supersonic solar wind is no longer able to push back the interstellar gas. Beyond the shock is the heliosheath, where the two gas types mix, and finally the interstellar plasma itself exists beyond the "heliopause." The two *Voyager* spacecraft have crossed the termination shock: *Voyager-1* crossed in December 2004, at a distance of 94 AU (Stone *et al.*, 2005), and *Voyager-2* crossed several times (the termination shock is dynamic) between 30 August and 1 September 2007 at a distance of 84 A.U. (Richardson *et al.*, 2008). The heliopause is estimated to be in the range 130–150 A.U. (1 A.U. = 1 astronomical unit = 1.496×10^{11} m, the mean semimajor axis of the Earth's orbit) from the Sun. The heliopause provides the natural definition of the outer extent of the solar corona (see, *e.g.*, review article by Holzer, 1989).

1.1 The solar corona

The appearance of the solar corona during a total solar eclipse is shown in Fig. 1.3. The corona is extremely faint relative to the visible disk of the Sun, having a maximum brightness ratio of $\approx 10^{-6}$, decreasing to $\approx 10^{-9}$ within a single solar diameter away from the visible limb. On a good day at ground level the sky brightness exceeds that of the corona by 3 to 5 orders of magnitude, so that the corona is completely invisible to the naked eye. However, due to the extraordinary coincidence that the Moon is very nearly the same angular size as the Sun, the bright disk of the Sun is sometimes completely covered, while portions of the sky near the Sun are still visible. In addition to blocking direct vision of the disk, the lunar obscuration also produces a cone of darkness that lowers the sky brightness by ≈ 4 orders of magnitude and the corona becomes briefly visible.

As indicated in Fig. 1.4, there are three main components to the coronal light, distinguished by the mechanisms which produce the light. They are labelled, respectively, the K- (kontinuierlich), F- (Fraunhofer) and E- (emission) corona. These three components are formed by very different mechanisms and have very different properties; recently, it has also become common practice to identify a fourth component, the T- (thermal) emission.

The K-corona displays a continuous emission spectrum and is found to be strongly polarized. It arises out of photospheric light that is scattered by the electrons of the coronal gas. The K-corona is thus dependent on the presence of coronal gas, but it is actually photospheric light that is scattered toward us by the corona. This light would be 100% polarized if the visible Sun were a point source and the scattering occurred at an angle of $\frac{\pi}{2}$ to the line of sight. However, because of the complicated geometry of the actual coronal structures,

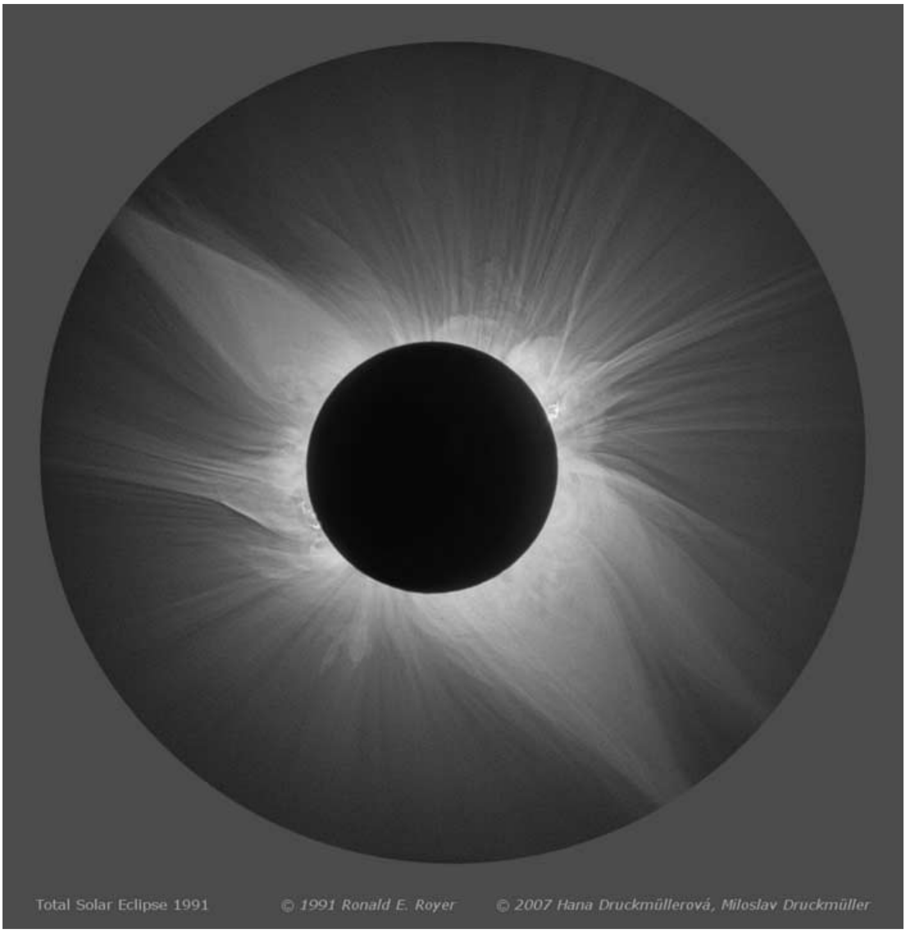

Fig. 1.3 The solar corona observed during the total eclipse of 1991, a time of maximum magnetic activity on the Sun. (Courtesy H. Druckmüllerová and M. Druckmüller)

the polarization of the K-corona is considerably less than 100% and varies from place to place in the corona.

The F-corona, so-called because it shows the same dark absorption lines that Fraunhofer found in the on-disk spectrum (see Ch. 3), is actually unrelated to the corona *per se*. It arises out of scattering of the photospheric light by small dust particles in the ecliptic plane, and it may more accurately be thought of as the inner zodiacal light. Thus, the F-corona is again not true coronal light, but a reflection (literally) of the bright photospheric light.

The Fraunhofer spectrum is visible in the F-corona because the Doppler shifts due to the velocities of the dust particles are small compared with the widths of the Fraunhofer lines. They are therefore not significantly broadened in the scattering process and remain visible in the light that reaches us. In contrast, these lines are nearly impossible to detect in the K-coronal spectrum, because the high temperature of the corona makes the thermal velocities of the scattering electrons quite large ($\frac{v}{c} > 1\%$). The Fraunhofer lines in the scattered light are therefore broadened enough to be "washed out," although sensitive instrumentation can be used to observe the faint absorption from the overlapping, broadened spectral lines. The F-corona is relatively unpolarized, which is useful in helping to determine the absolute brightness of the variable K-corona.

The T-corona is caused by thermal (largely infrared) emission of interplanetary dust, usually the same dust that is causing the F-corona. It has become detectable with improvements in infrared techniques. Since it is thermal emission, it adds to the continuum in all infrared measurements; it can, in principle, be distinguished by the shape of its Planck curve.

The E-corona represents the only component thus far mentioned that arises out of true emission of light by the actual coronal gas. It consists of emission in isolated spectral lines formed by the high-temperature coronal ions (Ch. 3). At the end of the nineteenth century, the identification of these emission lines presented an enormous challenge, which some called "*the* outstanding problem in all of astrophysics" (Swings, 1939). It required half a century for the correct explanation to be found and coronal physics was revolutionized in the process.[1] Once the major breakthrough had been made by Grotrian and Edlén in 1939–40, the solution to the coronal spectral-line problem became one of the great triumphs of astrophysics (Ch. 2).

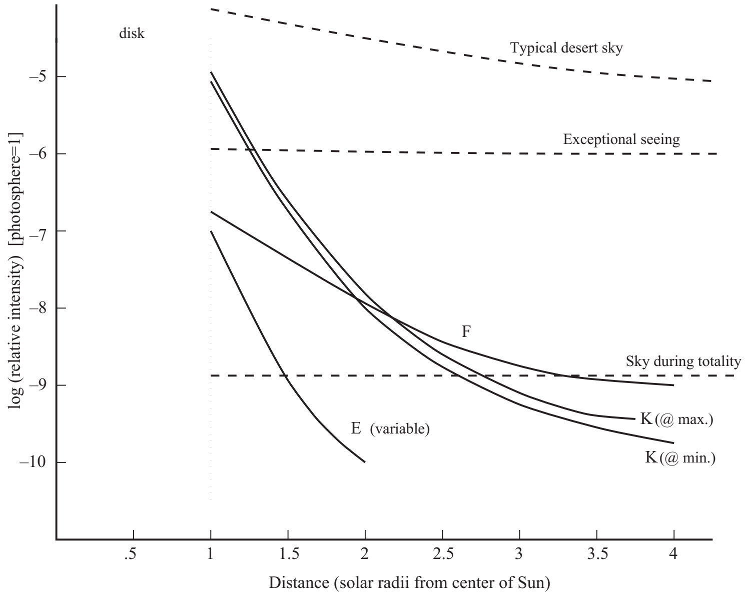

Fig. 1.4 Brightness variation of the main components of the solar corona as a function of radial distance.

Although the total integrated light of the E-corona is relatively small, the fact that the emission is concentrated into spectrally isolated lines makes it possible to view many of these lines quite clearly by using a narrow-band filter centered on the desired wavelength. The continuous emission from the K- and F-coronae dominates the E-corona in broadband observations because the K- and F-components emit over a wide range of wavelengths and their total emission over this range is large. The emission lines of the E-corona are strong relative to the local background level of K- and F-continuum emission, although they are hard to detect in broadband observations because the total number of photons collected from the background overwhelms the number collected from the narrowband emission line. The contrast between the strong emission line and the weaker, but broader in wavelength, K- or F-component can be increased by using a narrow bandpass filter which cuts down on the width of continuum which can enter the instrument without cutting the line emission as much. Thus, the overall image becomes fainter, but the *relative* contribution from the emission line has increased. By taking longer exposures or using a larger aperture camera, the coronal emission in the line becomes visible.

We close by noting that, although the emission-line corona was first discovered at visible-light wavelengths, *the primary emission of the corona is in the UV and soft x-ray region of the spectrum.* This is due to the high temperature of the coronal plasma, as we will discuss in Ch. 3.

1.2 Solar magnetism and the corona

Figure 1.3 shows a highly structured corona, consisting mainly of outwardly directed streamers at large radial distances from the solar surface and more complex structures closer in to the surface. The structure of the corona out to a few tenths of a solar radius above the limb consists to a large extent of bright, helmet-shaped structures, with long "helmet streamers" extending radially outward above them. These tend to be found near mid-latitudes and are hardly ever seen near the poles of the Sun. The same is true of sunspots, and the two phenomena are indeed related. Both sunspots and x-ray bright coronal regions are caused by the emergence of magnetic fields from inside the Sun; the weaker large-scale structures of the corona, as well as the long streamer structures, are also intimately related to the solar magnetic field.

Because the corona is optically thin at visible-light wavelengths (*i.e.*, these wavelengths are not strongly absorbed in traversing the corona; see Sec. 3.3), many distinct features can add together along the line-of-sight when structures are viewed at the limb, as they are during eclipses. With the advent of spaceborne instrumentation, it became possible to view the corona on-disk, as shown in Fig. 1.5. At the x-ray wavelengths used to obtain this image the corona is also optically thin, so that we see the x-ray emission integrated along the line-of-sight down to the solar surface.[2] However, the regions responsible for the coronal

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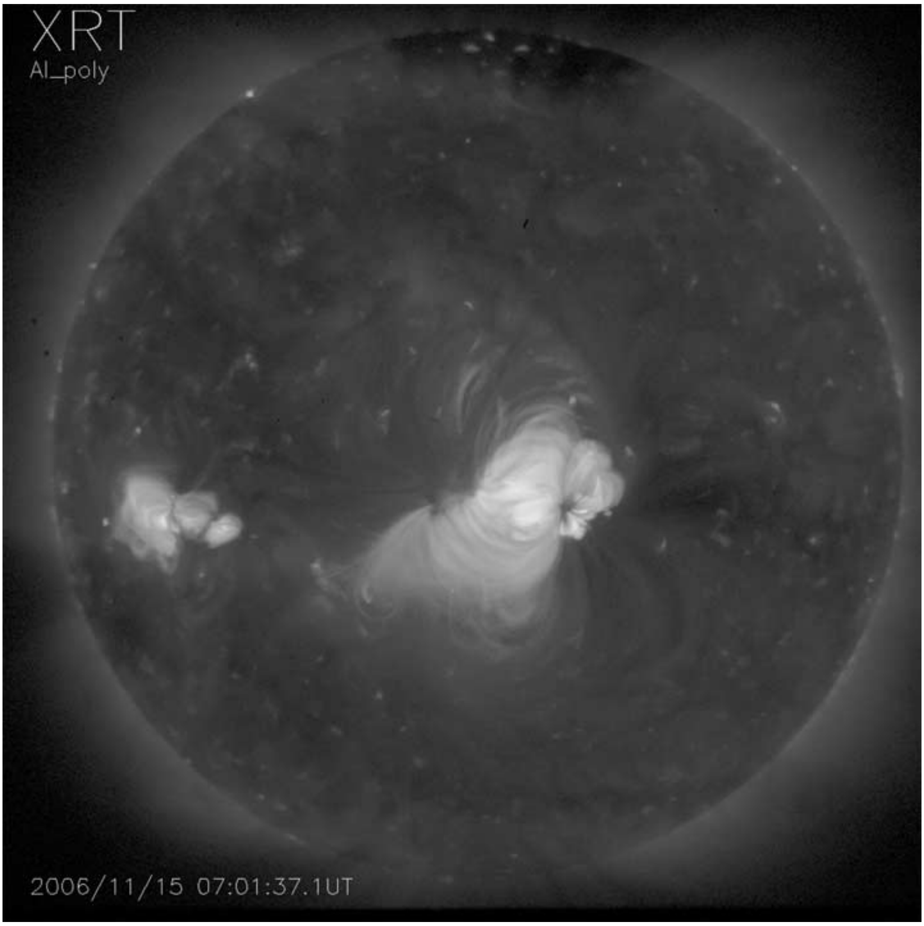

Fig. 1.5 View of the on-disk x-ray corona, taken from the *Hinode* XRT, November 15, 2006. (Photo credit JAXA/NASA/SAO)

emission are seen more clearly because they are now spread out horizontally in the image rather than piled up at the limb. We still view the corona integrated along the line of sight to the surface but, as we will discuss in Ch. 6, the length scale for this vertical integration turns out to be substantially shorter than the horizontal scale over which limb structures are integrated.

Figure 1.6 shows a superposition of both on-disk and limb observations. It was obtained during a total solar eclipse in 2005 by Fred Espenak aboard a ship in the Pacific, and processed by Miloslav Druckmüller with the addition of images taken at the same time from the *SoHO* satellite. The ground-based eclipse permitted the white-light photo of the outer corona to be obtained, while the *uneclipsed* Sun was viewed at the same time from telescopes in orbit. The combination of observations obtained during eclipses has shown that the streamer structures originate at the solar surface, typically in the brighter places called "active

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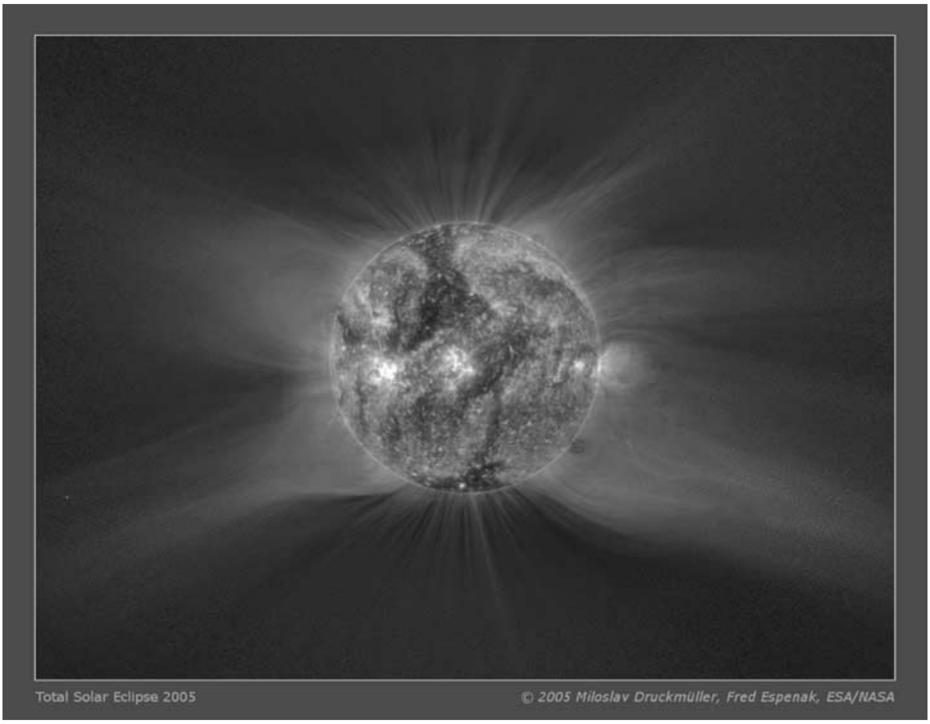

Fig. 1.6 Composite photo showing the white-light corona seen from the ground at the April 8, 2005, eclipse and the on-disk EUV corona observed from the *SoHO* EIT (195 Å + He 304 Å) at the same time. (Courtesy M. Druckmüller)

regions." This type of comparison brings home clearly the point that the corona is three-dimensional, with its roots at or below the solar photosphere and outer extension far into interplanetary space.

The highly structured nature of the outer solar atmosphere seems to be intimately linked to the presence, at the solar surface, of magnetic fields that have been generated inside the Sun and have emerged to the surface. Figure 1.7 shows clearly that the corona is brightest (and also hottest) at just those locations where magnetic field has emerged from inside the Sun. Dynamo theory (Ch. 4) predicts that strong magnetic fields will be generated deep in the solar interior and that bundles or "ropes" of magnetic flux will float to the surface. When this happens, a magnetically bipolar region will become visible, extending above the surface in a three-dimensional structure. As a rough approximation, we may imagine that there is a bar magnet located just below the surface, oriented horizontal to the surface. The field lines of the magnet will thus penetrate the surface, showing two magnetic poles, and will also exhibit a three-dimensional structure above the surface, with field lines running out of one pole and reentering at the other.

The figure shows the solar magnetic field measured at the photospheric level, corresponding to a horizontal slice through the bottom of the 3-D structure.

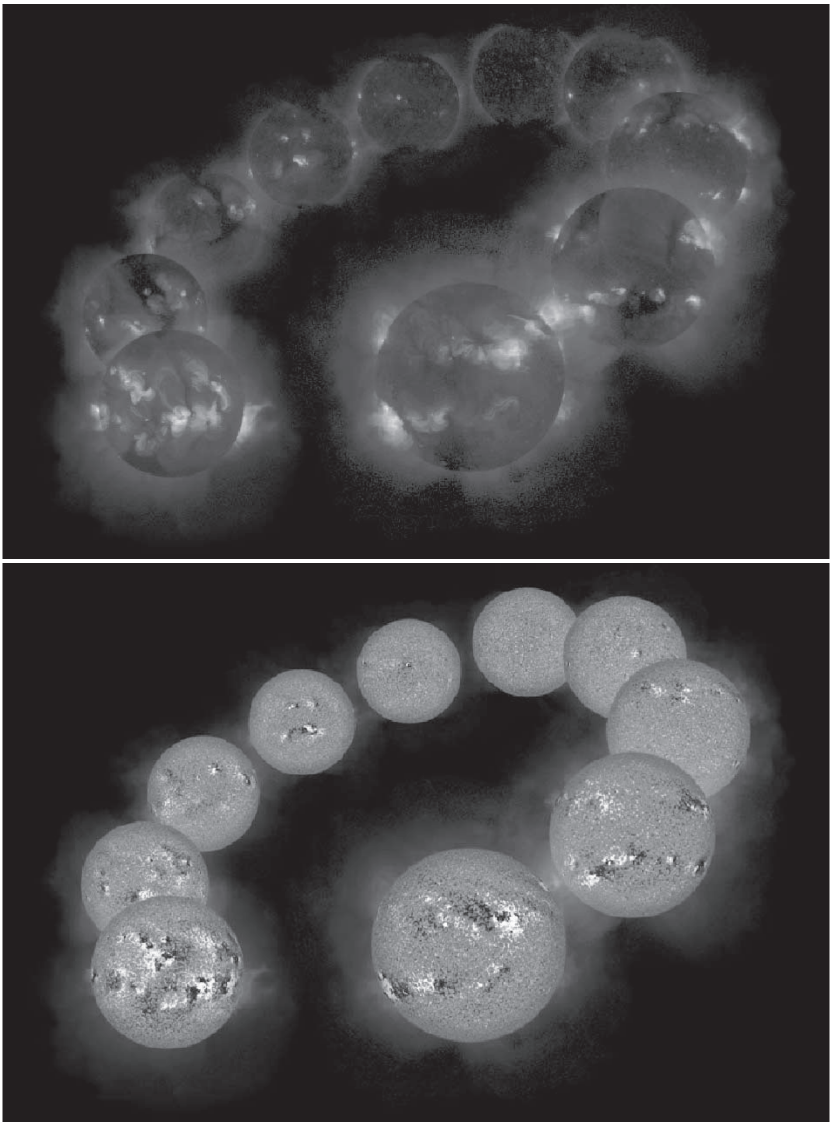

Fig. 1.7 Observations over the course of a solar cycle of the x-ray corona (top, from SXT on Yokkoh) compared with measurements of the magnetic field at the solar surface (bottom, U.S. National Solar Observatory). (Courtesy JAXA/NASA/NSO)

In this representation, the direction of the magnetic field is shown as either black or white, depending upon whether it is oriented away from or toward the line-of-sight; a magnetically bipolar region would therefore appear as a pair of closely spaced black and white patches. Several such regions are visible in the figure. If we could observe the corona above such a magnetic region, we would then expect to see magnetic field lines leaving the solar surface in one part of the region and returning into the surface in another part. This is just what is