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SAMI K. SOLANKI* AND REINER HAMMER**

The solar atmosphere

As a typical star, and the only one that can be spatially resolved by direct means, the study of the Sun has provided an insight into many of the fundamental processes taking place in stellar atmospheres, often at small scales. A prime example is magneto-convection or the formation of coronae and the consequent emission of copious amounts of X-rays. In addition, the Sun's apparent brightness allows measurements with unprecedented accuracy. Thus the Sun is the standard against which cosmic abundances are compared. Its high apparent brightness also means that the Sun is a strong source at almost all wavelengths and thus detectable with simple, not particularly sensitive equipment such as the early instruments flown in space. Thus for many wavelengths the Sun was the first (or one of the first) cosmic source(s) detected.

However, only the lowest layers of the Sun's atmosphere, the photosphere and chromosphere, can be regularly observed from the ground over the solar disk. The transition region, corona and the solar wind are best studied from space, and even many properties of the photosphere (such as the variation of solar irradiance with time) had to await space-based observations for their determination or discovery.

1 OVERVIEW OF THE SOLAR ATMOSPHERE

Traditionally the atmosphere of the Sun is divided into four layers, starting with the photosphere at the bottom, moving up through the chromosphere and transition region to the corona. The photosphere is the layer in which the temperature drops outwards from around 5800 K at the solar surface to around 4000 K at the temperature minimum. Beyond that point it rises again, first relatively gently (forming the chromospheric plateau), but then very rapidly in the transition region (TR). The temperature profile becomes flatter again in the corona. The boundary between the corona and the TR is often drawn at approximately 10^6 K. This boundary, like that between chromosphere and TR, is not sharp or well defined. At still greater distances from the solar surface the temperature gradually decreases again, achieving values of approximately 10^5 K at 1 AU (whereby electrons and ions need not have the same temperature in the heliosphere). As we shall see in subsequent sections, the simple plane-parallel representation of the solar gas outlined above is not tenable in any layer of the atmosphere. At any given height more than one atmospheric component is present, each having its own temperature, density and velocity structure.

Features as diverse as granular convection cells in the photosphere (Figure 1) and magnetic loops in the corona (Figure 2) are now known to structure the respective layers of the atmosphere. In addition to being spatially inhomogeneous at almost all spatial scales, the solar atmosphere is also highly dynamic at almost all timescales. Much of the interesting physics to be learnt by studying the solar atmosphere is related to this structuring and dynamics and the associated heating of the chromosphere and corona.

In the following we discuss the various atmospheric layers, starting with the photosphere and moving outward. Particular emphasis is placed on the contributions made by space missions to our knowledge and understanding of the solar atmosphere. Since these contributions are largest for the transition region and corona our discussion of these layers will be more detailed than of the photosphere and chromosphere. Table 1 summarizes the space missions mentioned in this chapter.

2 THE PHOTOSPHERE

2.1 The plane-parallel photosphere

The solar photosphere is the layer that emits most of the solar radiative energy flux, with the emitted spectrum

* Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany
** Kiepenheuer-Institut für Sonnenphysik, Freiburg i/B, Germany

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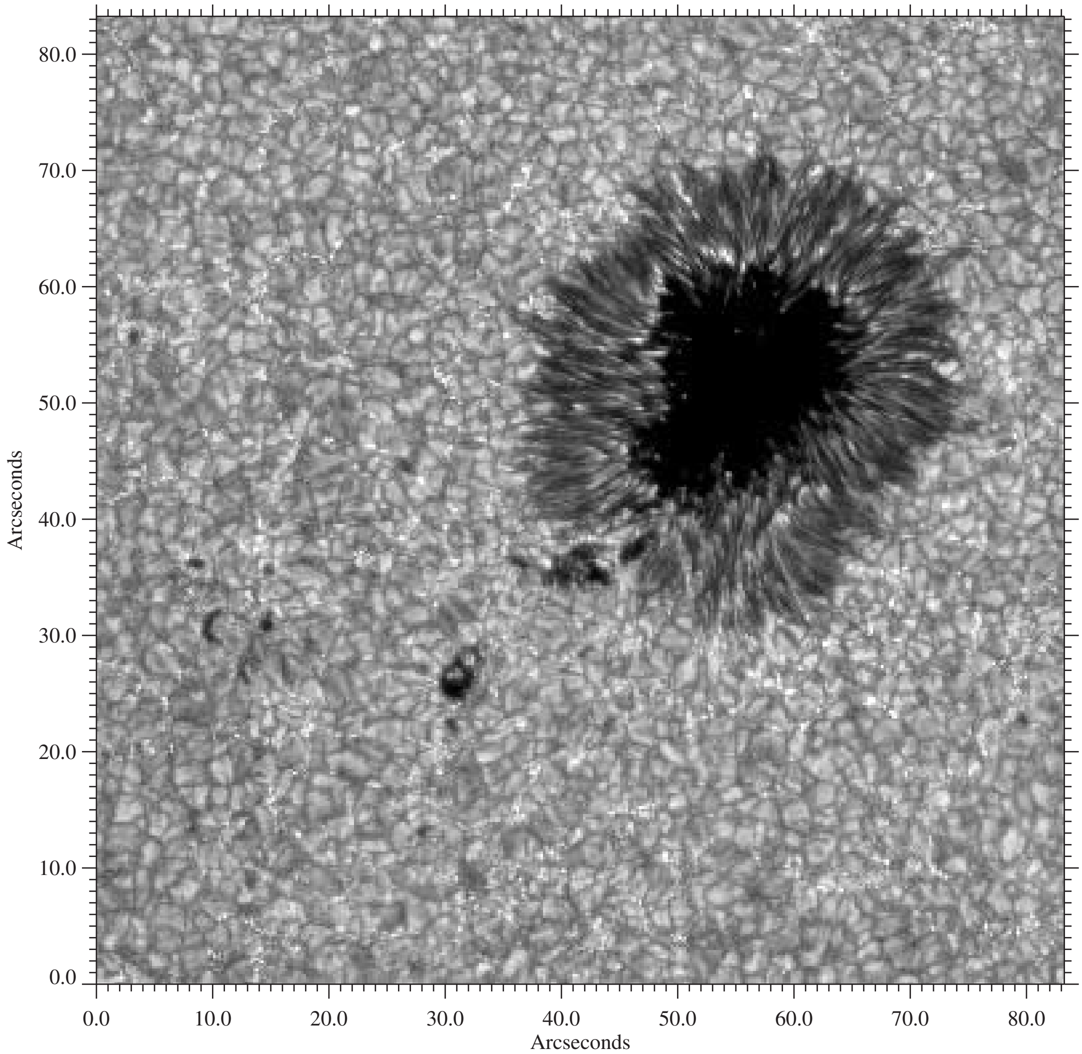

Figure 1 A snapshot of a part of the solar photosphere taken with a filter centred on the G band at 430.5 nm by T. Berger and G. Scharmer. The image covers 60 000 × 60 000 km on the Sun. The most prominent feature is a sunspot. The much smaller dark features are pores. Also visible are granules (bright cells surrounded by dark lanes) and bright points corresponding to magnetic elements. (Courtesy of T. Berger.)

having its peak in the visible (in the green part of the wavelength range). As such, the photosphere is the atmospheric layer most easily observed from the ground and consequently the one to whose investigation spacecraft have contributed the least. This, however, is changing at a rapid pace, with the ESA–NASA Solar and Heliospheric Observatory (SOHO; Fleck and Domingo 1995) providing the first glimpses of how space-based telescopes can revolutionize our understanding of the photosphere. The next major highlight is expected to be provided by the Japan–US–UK Solar B mission.

The brightness across the solar disk is not constant but rather decreases from the centre of the disk to its edge (the solar limb) at visible wavelengths. This is called limb darkening. Since at the limb the radiation is emitted at greater heights, limb darkening implies a decrease in the temperature with height. Furthermore, the spectral form of the limb darkening provides information on the continuum absorption coefficient. Such observations confirmed the proposal by Wildt (1939) that in the visible the absorption is dominated by the H^- ion in spite of its low abundance (Chalonge and Kourganoff 1946).

Traditionally the limb darkening and the shapes and strengths of absorption lines (Fraunhofer lines) have been employed to determine the temperature stratification in the solar photosphere. These diagnostics reveal that the temperature decreases outwards in the solar photosphere from over 6500 K at the deepest observable layers to around 4000 K at the temperature minimum (e.g. Holweger 1967). The advent of UV observations from space, in particular

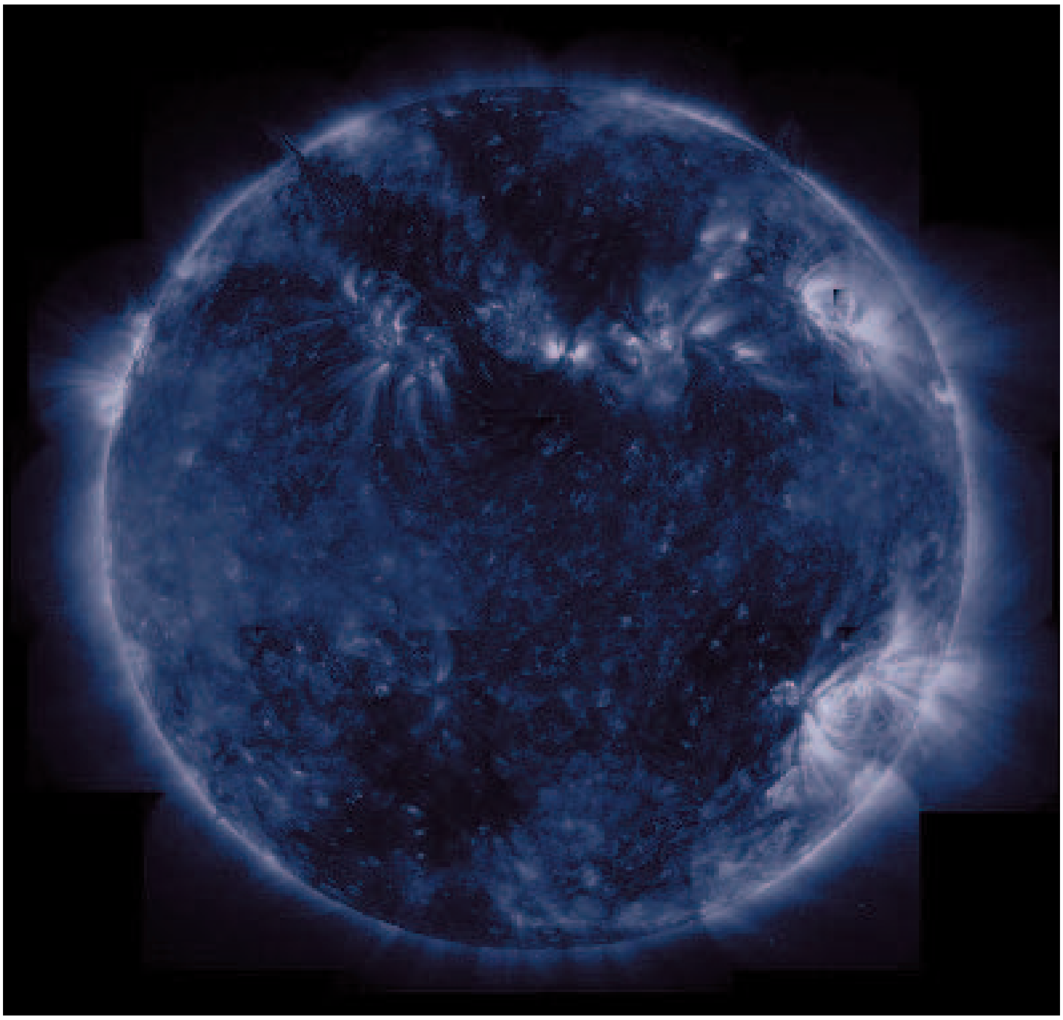

Figure 2 Composite of several high-resolution images taken with the Transition Region and Coronal Explorer (TRACE; Handy *et al.* 1999) in a spectral band near 171 Å, which is dominated by emission from eightfold ionized iron atoms (Fe IX) formed around 10^6 K. At these temperatures the network is no longer visible, and the disk emission is dominated by active regions, by coronal loops in the quiet corona (i.e. outside of coronal holes and active regions), and by numerous bright points. Plumes extend as ray-shaped density enhancements from the north and south polar coronal holes. (Courtesy of the TRACE team. TRACE is a mission of the Stanford–Lockheed Institute for Space Research, and part of the NASA Small Explorer program.)

Table 1 Space missions mentioned in this chapter

Mission	Operation period
Stratoscope	several balloon flights 1957 and 1959
OSO 4 (Orbiting Solar Observatory)	1967–69
OSO 6 (Orbiting Solar Observatory)	1969–72
Skylab	1973–74
Spektrostratoskop	balloon flight 1975
OSO 8 (Orbiting Solar Observatory)	1975–78
HRTS (High Resolution Telescope and Spectrograph)	rocket and shuttle flights since 1975
TRC (Transition Region Camera)	rocket flights 1979 and 1980
SMM (Solar Maximum Mission)	1980–89
SOUP (Solar Optical Universal Polarimeter)	experiment on Spacelab 2, 1985
NIXT (Normal-Incidence X-ray Telescope)	rocket flights, e.g. 1993
Yohkoh	since 1991
SOHO (Solar and Heliospheric Observatory)	since 1995
TRACE (Transition Region And Coronal Explorer)	since 1998
Solar B	launch scheduled for 2005

from Skylab (Tousey 1977), provided a new diagnostic, the wavelength dependence of the continuum intensity, since at shorter wavelengths the continuum radiation emanates from higher layers (e.g. Vernazza *et al*. 1973, 1981). The advantage of UV and EUV spectra is that they also contain emission lines belonging to different ions that carry information on the temperature in the solar chromosphere, transition region and corona.

A reliable knowledge of the thermal stratification is fundamental for the accurate determination of elemental abundances. The pioneering work by Russell (1929) and the seminal compilation by Goldberg *et al*. (1960) have been followed by increasingly detailed and accurate determinations of the abundances of ever more elements. The current status of our knowledge of solar abundances (from the solar core to its corona) is discussed in the volume edited by Fröhlich *et al*. (1998), with the photospheric abundances being reviewed therein by Grevesse and Sauval (1998). On the whole these abundances agree surprisingly well with the meteoritic values, although there are some minor deviations and some residual uncertainty. The latter is due partly to the inhomogeneity of the solar atmosphere (discussed in Sections 2.2 and 2.3), which has generally not been taken into account when determining abundances. However, at the level of accuracy currently being achieved such inhomogeneities begin to have a significant effect.

2.2 Convection

It was evident relatively early that a single atmospheric component cannot adequately describe the solar photosphere. The dark sunspots and the bright faculae (bright structures most prominent near the limb), already visible with a small telescope, highlight the need for multiple thermal components. Sunspots and faculae are associated with magnetic activity (Section 2.3), but even the quiet parts of the Sun are known to be inhomogeneous since the discovery by William Herschel of solar granulation, bright structures typically 1000 km in diameter separated by a dark network. Figure 1 shows a snapshot of solar granulation surrounding a sunspot. On a larger scale a bright network (most prominent in radiation coming from chromospheric and transition-region layers) is also known to exist. To account for such regions with different brightness, sets of plane-parallel models have been produced (e.g. Vernazza *et al*. 1981, Fontenla *et al*. 1993). Again, UV spectra taken outside the terrestrial atmosphere have played an important role in constructing such model families.

High-resolution observations and the modelling of spectral lines have shown that at least in the photospheric layers it is mainly inhomogeneities at scales smaller than approximately 1000 km on the Sun that are of physical relevance. For example, faculae, which have sizes of 10^4–10^5 km, are found to be composed of many small magnetic elements, each with a diameter of the order of 100 km.

The major inhomogeneity in photospheric layers is introduced by the granulation, which is the surface signature of overshooting convection. The bright granules identify hot upflowing gas overshooting from the convectively unstable layers below the solar surface into the stably stratified photosphere. These are surrounded by multiply connected cool and hence dark lanes of downflowing gas. Properties of the granulation have been deciphered using data obtained with balloon-borne telescopes (with the Stratoscope, Danielson 1961; and the Spektrostratoskop, Mehltretter 1978), in space (Solar Optical Universal Polarimeter (SOUP), Title *et al*. 1989) and from the ground (Muller 1999).

A particular success have been detailed two- and three-dimensional numerical simulations, that is computations of the radiation hydrodynamics under conditions corresponding as closely as possible to those present on the Sun, based on a minimum of simplifying assumptions. Such simulations have reproduced a wide variety of observations (e.g. Nordlund 1984, Lites *et al*. 1989), so that they are likely to include the main physical ingredients necessary to describe solar granulation. Mainly, however, they have led to a better physical understanding of solar convection and the influence of granulation on, for example, abundance determinations (e.g. Solanki 1998). Both observations and simulations suggest that the vertical velocity associated with granules decreases rapidly with height, while the horizontal velocity becomes increasingly strong, being supersonic over portions of the largest granules. This last fact is one of the rare predictions made by theory in solar physics that have been subsequently confirmed by observations.

An oscillatory velocity component is also present in the photosphere and chromosphere. In the photosphere its power peaks occur at a period of around 5 min, while in the chromosphere the power peak lies near 3 min. The 5 min oscillations are evanescent in the solar atmosphere, but propagate in the solar interior. They are used to probe the subsurface layers of the Sun (helioseismology). The amplitude of the vertical oscillatory velocity increases with increasing height and dominates over the vertical granular flow field at the top of the photosphere.

In addition to granulation three larger scales of convection are known to affect the solar atmosphere, mesogranulation (5–7 Mm in size) discovered by November *et al*. (1981), supergranulation (20–30 Mm) discovered by Simon and Leighton (1964) and giant cells (covering 40° in longitude and less than 10° in latitude) discovered by Beck *et al*. (1998) using Dopplergrams recorded by the Michelson Doppler Interferometer (MDI) on SOHO. Granulation has by far the most readily visible signature in the photosphere, followed by supergranulation, while the influence of the

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