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Probing the Sun's hot atmosphere : Views from Yohkoh, SOHO and TRACE

B.N. Dwivedi

Department of Applied Physics, Institute of Technology, Banaras Hindu University, Varanasi 221005, India

Abstract. This article reviews some recent progress in our understanding of the Sun's hot atmosphere, using data from spacecraft (Yohkoh, SOHO and TRACE) and from ground-based eclipse experiments.

1. Introduction

From afar, the Sun does not look very complex. To most people, it is just a uniform ball of gas, the essence of simplicity. In actuality, it has well defined regions, like a planet's solid part and atmosphere (see Figure 1). In keeping with physical expectations, the Sun's temperature drops steadily from its core, 15 million K, to the photosphere, a mere 6000 K. But then a surprising thing happens. The temperature of the chromosphere steadily rises to 10,000 K. Even more startling, the temperature of the corona jumps to 1 million K. Parts of the corona associated with sunspots are even hotter. This fact was first recognized in the 1940's, when unfamiliar spectral lines that had been observed since the nineteenth century were identified with those emitted by Fe X and Fe XIV, a situation that could only exist at temperatures of 1 million K or more. The temperature of the corona is in fact so high that it emits copious amounts of x-ray and extreme ultraviolet radiation. In view of the fact that the energy must originate beneath the photosphere, how can this be ? Heat should not emanate from a cold object to a hotter one any more than water should flow uphill. Researchers have hunted for the elusive coronal heating mechanism for more than half a century. It is particularly strange that a puzzle like this should exist for the only star we can study at close hand, for which we might expect to have a complete and detailed knowledge. Nor is the mystery confined to the Sun: many stars with properties like the Sun's appear to have x-ray-emitting atmospheres where the temperature is at least as hot as the solar corona (Dwivedi and Phillips, 2001). Over the years there has been a steady improvement of our understanding about the heating of the solar corona. It is known that magnetic fields observed and measured in the photosphere are implicated, since where the fields are stronger the corona is also hotter. Two main possibilities are emerging from both observations and theory : either the field converts its energy into heat by many small-scale reconnections (the same involved in major explosive energy releases called solar flares) or by damping of magnetic waves of various sorts.

Figure 1. The chief parts of the Sun: This gives a basic overview of the Sun's structure. The three major interior zones are the core (the innermost part of the Sun where energy is generated by nuclear reactions), the radiative zone (where energy travels outward by radiation through about 70% of the Sun), and the convection zone (in which convection circulates the Sun's energy to the surface) The flares, sunspots and photosphere, chromosphere, corona, coronal holes, and the prominence are all clipped from actual SOHO images of the Sun. Courtesy of Steele Hill and SOHO/ESA-NASA.

2. X-rays and ultraviolet emission from the solar atmosphere

The solar ultraviolet emission was first detected by R. Tousey and colleagues at the U.S. Naval Research Laboratory in the late 1940's using captured German rockets. A pinhole camera built by T.R. Burnight in 1949 was the first time coronal x-ray emission was detected. Thereafter there was a rapid increase in our knowledge of the Sun's atmosphere from data collected by U.S. and Soviet spacecrafts in the 1960's and 1970's, dedicated to solar observations, particularly the manned NASA Skylab mission of 1973-1974. Ultraviolet and x-ray telescopes on board Skylab gave the first high-resolution images of the corona as well as the chromosphere (a highly structured part of the atmosphere between the photosphere and corona where the temperature is about 10,000 K) and an intermediate 'transition region' (thought by some to be a thin layer separating the chromosphere and the hot corona). Images of active regions (the photospheric counterparts of which are the sunspot groups) showed a complex of loops which varied greatly over their several-day lifetimes, while ultraviolet images of the 'quiet' Sun (i.e. distinct from active regions) showed that the transition region and chromosphere resembled a 'nétwork' appearance previously known from images in the light of a strong visible-wavelength spectral line from Ca II in the chromosphere. The x-ray images showed that the quiet-Sun corona was characterized by diffuse large-scale arches, stretching across several million kilometers. The spatial resolution of spacecraft instruments has steadily improved ever since to extremely impressive levels, not far short of that which can be achieved with ground-based solar telescopes. The Japanese Yohkoh spacecraft, launched in 1991, has on board a soft x-ray telescope made jointly by U.S. and Japanese scientists; it images the Sun and in particular, flares in wavelengths of 0.2 to 2 nm with an angular resolution of about 2 arcseconds (equivalent to 1450 km on the Sun: the mean solar diameter is 32 arcminutes, or just over half a degree).

The ESA/NASA satellite SOHO, launched in December 1995 into an orbit about the inner Lagrangian point situated some 1.5 million km from the Earth on the sunward side, has on board twelve instruments which get an uninterrupted view of the Sun, unlike the instruments on Yohkoh which is in a low-earth orbit. There are several imaging instruments, sensitive from visible-light wavelengths to the extreme-ultraviolet. The Extreme-ultraviolet Imaging Telescope (EIT), for instance, uses normal incidence optics to get full-Sun images several times a day in the wavelengths of lines emitted by coronal ions Fe IX/Fe X, Fe XII, Fe XV (emitted in the temperature range 6×10^5 to 2.5×10^6 K), as well as the chromospheric He II 30.4 nm line. The Coronal Diagnostic Spectrometer (CDS) and the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) are two spectrometers operating in the extreme – ultraviolet region, capable of getting temperatures, densities and other information from spectral line ratios. The Ultraviolet Coronagraph Spectrometer (UVCS) has been making spectroscopic observations of the extended corona from 1.25 to 10 solar radii from the Sun's centre, determining empirical values for densities, velocity distributions and outflow velocities of hydrogen, electron, and several minor ions. The striking difference in the width of line profiles seen on the disc and in a polar coronal hole from UVCS and SUMER instruments, is a new observational fact. This led to the discovery of the large velocity anisotropy observed in coronal holes and its interpretation as solar wind acceleration by ion-cyclotron resonance.

The extremely broad O VI line yields velocities upto 500 km s^{-1}, which corresponds to a kinetic temperature of 200 million K (Kohl et al., 1998; Wilhelm et al., 1998). The Large Angle and Spectroscopic Coronagraph (LASCO) instrument observes the white-light corona with high resolution out to distances of more than 20 million km. Movies from LASCO show the large-scale coronal structures as they rotate with the rest of the Sun (a period of about 27 days as seen from the Earth), as well as the large ejections of coronal mass in the form of huge bubbles, moving out with velocities of up to 1000 km per second that, on colliding with the Earth in particular, give the well-known magnetic storms and associated phenomena that have become a matter of widespread concern for telecommunications in recent years. Another recent spacecraft which has given us spectacular images of the corona is the Transition Region and Coronal Explorer (TRACE), operated by the Stanford–Lockheed Institue for Space Research, launched in 1998. It is able to resolve coronal structures in the ultraviolet down to about 1 arcsecond (725 km). Images from TRACE have revealed that active-region loops are often thread-like features no more than a few hundred km wide. There is a clear relation of these loops and the large arches of the general corona to the magnetic field measured in the photospheric layer. The crucial role of this magnetic field has only been realized in the past decade. The fields dictate the transport of energy between the surface of the Sun and the corona. The loops arches and holes appear to trace out the Sun's magnetic field (see Figure 2).

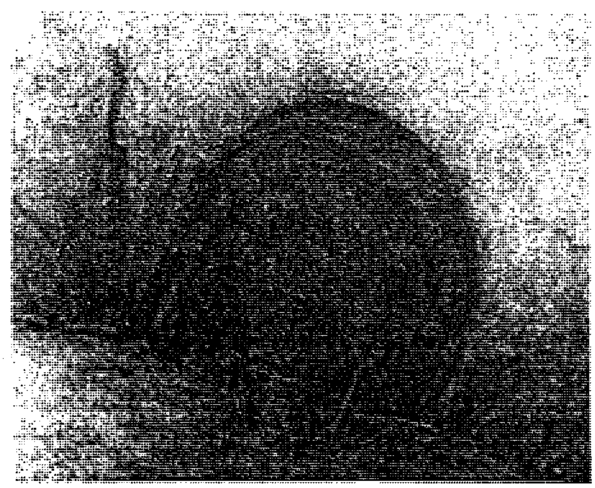

Figure 2. Coronal loops, seen in the ultraviolet light (Fe IX 171 A) by the TRACE spacecraft, extending 120,000 km off the Sun's surface.

3. Coronal heating : Theory

The entire corona (as revealed in x-ray and EUV images) is pervaded by magnetic field and in fact the various forms of the corona are determined by the geometry of the local magnetic field loops, giant arches, coronal holes (funnel-shaped regions within which the field opens out into interplanetary space and along which fast solar wind streams flow). One vital piece of information that we are still unable to measure is the corona's magnetic field strength. We can measure, with considerable accuracy, the photospheric magnetic field. For vector magnetographs, all three components of the photospheric magnetic field can be deduced. Although, eventually, infrared measurements may give important information, in practice the only way at present in which the coronal field can be deduced is through extrapolations of the photospheric field through the assumption, for example, of a potential ($\nabla \times \mathbf{B} = 0$, i.e. current-free) or force-free ($\mathbf{J} \times \mathbf{B} = 0$) field. It is clear, however, from photospheric magnetograms that the field in active regions is more complex than in quiet regions. It is also known that the active region corona is appreciably hotter (typically 4×10^6 K, depending on the nature of the active region) than in quiet regions (2×10^6 K, less in the coronal holes at the poles). There does seem, then, to be a qualitative relation between field strength and heating.

A considerable theoretical problem with magnetic field heating is the fact that it requires the diffusion of the magnetic field, which implies a resistive plasma. The coronal plasma is, on the contrary, highly conducting. Using Spitzer's classical expression for plasma resistivity ($1/\sigma$) at temperature T (K),

$$1/\sigma = 10^3 \times T^{-1.5} \text{ ohm m} \quad (1)$$

we find for $T = 2 \times 10^6$ K,

$$1/\sigma = 4 \times 10^{-7} \quad \text{ohm m} \quad (2)$$

only a factor 20 or so higher than a highly conducting solid like copper at room temperature. To illustrate the effect of this high conductivity, we use the induction equation of magnetohydrodynamics (MHD),

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \quad (3)$$

where $\eta = 1/(\mu\sigma)$ If the first term be neglected, (i.e. if v, the plasma velocity, is very small), the diffusion time τ for a magnetic field is given by :

$$\tau = \frac{L^2}{\eta} \quad (4)$$

With $\mu \simeq \mu_0 = 1.26 \times 10^{-6}$ H m^{-1} (the permeability of free space) and L of the order of the dimensions of the visible structures in the corona, we find that the time τ is extremely long (many years). Only if the characteristic distance L over which diffusion occurs is as short as a few metres then the diffusion time is a few seconds. Expressed another way, the first (advection) term in the induction equation (3) is generally much larger than the second (diffusive) term. Defining the magnetic Reynolds number R_m, by

$$R_m = \frac{|\nabla \times (\mathbf{v} \times \mathbf{B})|}{|\eta \nabla^2 \mathbf{B}|} \quad (5)$$

and measuring how tied the magnetic field is to the plasma, R_m is normally 10^6-10^{12} for the corona unless the length scales are very small. Only then can magnetic reconnection be achieved.

It is known that very small length scales do occur in the region of neutral points or current sheets, where there are steep magnetic field gradients which give rise to large currents. It is thought, then, that such geometries are important for coronal heating if this is by very small energy releases, known as nanoflares (Parker 1988). Some 10^{16} J would be released in a nanoflare, i.e. 10^{-9} of a large solar flare, and many energy releases such as this occurring all over the corona, quiet regions as well as active regions, could account for heating of the corona. Most likely this mechanism would not apply to coronal hole regions where the field lines are open to interplanetary space. In the competing wave heating, magnetohydrodynamic waves generated by photospheric motions (e.g. granular or supergranular convection motions) are damped in the corona. In this case, we need conditions such that the magnetic field changes occur in a shorter time than, say, the Alfvéwave transit time across a closed structure like an active region or quiet Sun loop.

4. Coronal heating by nanoflares

Movies made by concatenating TRACE images of active regions reveal a vast wealth of detail, with coronal loops showing continual brightenings and motions. The rapid variability of coronal structures uncovered recently and indeed since Skylab is an important clue to the corona's nature and the origin of its high temperature. Some earlier observations with rocket-borne instruments by Brueckner and Bartoe (1983) showed the presence of localized dynamic events in the transition region in which material is accelerated with velocities of up to 400 km per second. The energy contained in some of the more important of these so-called jets amounts to a millionth of that of a strong flare, or about 10^{19} Joules. It is possible that shock waves generated by jets could contribute to the heating of the corona. Enough energy and mass are contained in the jets, assumed to occur over the whole Sun, to satisfy the requirements of not only the corona but also its dynamic extension, the solar wind. Ultraviolet jets are only one of many sorts of dynamic phenomena occurring all over the Sun, in 'quiet' as well as active regions. Microflares, discovered from a balloon-borne x-ray detector by Lin et al. (1984), are another example. Shimizu (1995), in studies of the Yohkoh SXT data for active regions, finds numerous small brightnenings in active region loop structures having energies of the order 10^{20} J, i.e. comparable to microflares. Parker (1988) has theorized that numerous even smaller events, nanoflares, could explain coronal heating very effectively. There is now observational evidence from recent data which supports this idea, since tiny flare-like events with energies of down to 10^{17} Joules, or about ten times the energy of a nanoflare, have now been observed. Could their combined energy over the whole solar corona be sufficient to explain the corona ? The quiet-Sun corona's total radiative output is about 10^{19} Watts, with about the same amount of power being transferred to the photosphere by thermal conduction. Present estimates of the total energy of various sorts of dynamic phenomena actually detected by spacecraft like TRACE and SOHO, although very rough still, are 20 percent of this amount. The remainder could be accounted for by flare-like pulses, below the detectability thresholds of present instrumentation.

5. Coronal heating by waves

The literature for wave heating of the corona is very considerable, but we may briefly summarize it by stating that the waves, generated by turbulent motions in the solar convection zone or at the photosphere, may be surface waves in a loop geometry, or body waves which are guided along the loops and are trapped. The work of Porter et al. (1994) shows that short-period fast-mode and slow-mode waves (periods less than 10 s) could be responsible for heating since only for them are the damping rates high enough. Theoretical predictions indicate that waves with very short periods, perhaps only a few second long, are the most effective in heating. The other suggestion, of course, has been that small-scale reconnection occurring in the chromospheric network creates high-frequency Alfvén waves, and that these waves may represent the main energy source for the heating of the corona and generation of the solar wind (Axford and McKenzie, 1997). It can be calculated that the diffusion time for a magnetic field is a few seconds when the length scale is as short as a few metres. Very small length scales do occur in the corona where there are steep magnetic gradients which give rise to large currents. A key observation was made in 1999 when a fine loop was seen by the TRACE spacecraft to perform damped oscillations as a result of a nearby powerful flare. The period of the oscillations indicated that indeed the conductivity is not nearly as high as would be calculated on the usual classical assumptions, and so the conductivity of the solar plasma may not be the problem it was once thought to be (cf., Nakariakov et al., 1999).

Although the nanoflare hypothesis of coronal heating may be observationally plausible, MHD waves may well contribute significantly. It is, for example, unlikely that nanoflares could heat the corona in the regions of open field lines such as occur in coronal holes at each of the solar poles, yet it appears that the corona is still hot in these open field regions. It is, therefore, important to look for signatures of wave motions, particularly short-period MHD waves as these are probably the most important in heating processes. Ground-based instruments operating during total eclipses can out-perform spacecraft instruments in terms of fast imaging since spacecraft imaging is necessarily rather slow. Some non-periodic variations in coronal brightness have been reported from the SOHO LASCO coronagraph over periods of about 30 minutes. However, theoretical results indicate that MHD waves having very short periods, of a few seconds, are the only ones significant for coronal heating. If such short-period waves are important, there must still be considerable interest in observing the visible-light corona during total eclipses from the ground, since one can use high-speed electronic cameras to obtain rapid imaging of particular coronal structures.

6. Concluding remarks

The reason for the Sun's hot corona is almost certainly due to either wave heating or heating by nanoflares. Although the evidence now favours nanoflares for the bulk of coronal heating, waves may also play a role. At present this can only be investigated using ground-based instruments since the periods of MHD waves effective for coronal heating are likely to be very small (a few seconds). Spacecraft imaging is too slow to search for such periodicities.

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