Why is the sun’s corona so hot? X-rays and ultraviolet emission from the solar atmosphere

Anita Mohan and Bholanath Dwivedi*

After half a century of puzzlement, astronomers are on the verge of figuring out why the sun’s outermost layer is 200 times hotter than it should be: a solution in terms of nanoflares, with possible contribution from MHD waves, now seems in sight.

Under ordinary circumstances, the flood of light from the bright disk of the sun overwhelms the weak emission that comes from the solar atmosphere which is thus hidden from view. However, when the sun is totally eclipsed, a white halo appears around the edge of the moon, stretching out to a distance of solar diameter (1,400,000 km) or more. This ‘halo’ is the solar corona, the Latin word for crown. Its existence and its peculiar properties, above all its extremely high temperature, have long been intriguing to astronomers who, after a half century of study, are still uncertain about the source of its energy. Over the past twenty years or so, it has become apparent that the sun is not unique in having a hot corona: many other stars have coronae too, some showing the same characteristics as that of the sun, others being quite different. Understanding the solar corona will help us gain insight into whole family of stars.

For most people, the sun might seem like a uniform ball of gas which shines constantly, day after day. This radiation has a vital role in that it is the energy that supports all life forms on earth. It derives from nuclear reactions deep in the sun’s core, where the temperatures are many millions of Kelvin; the energy leaks out very gradually throughout the sun’s interior towards the visible surface where it escapes to space and in particular to the earth. There is a steady decrease of temperature from the core (15 million K) to the surface, also known as photosphere (6000 K). Above the visible surface of the sun is a tenuous atmosphere. The part visible as a bright red crescent during eclipses, is the chromosphere. Beyond the chromosphere is the corona, which has a most surprising property: its temperature exceeds 1 million K, often much more in localized areas associated with sunspots on the photosphere (Figure 1). This fact was first recognized in the 1940s, when unfamiliar spectral lines that had been observed since the nineteenth century were identified with those emitted by iron atoms that have lost several of their normal retinue of 26 electrons, 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, which can only be observed from above the earth’s atmosphere, with rockets and satellites. Why is the corona so hot? It would be like a boiling kettle of water atop a cold stove burner. Isn’t it strange? And isn’t it ironic that the sun, the nearest and best-studied of stars harbours such a mystery?

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 the corona is also hotter where the fields are stronger. Two main possibilities are emerging from both observation 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. Magnetic reconnection effectively involves the cutting and reattachment of magnetic lines of force. The configuration that is thought to give rise to reconnection is one in which two sets of field lines, parallel but opposite to each other, are forced together so that neighbouring, oppositely-directed field lines in a sheet geometry (referred to as ‘current sheet’) diffuse if the electrical resistivity locally becomes sufficiently high. Large and sophisticated spacecrafts-like the Solar and Heliospheric Observatory (SOHO) have been launched in recent years to look for clues, particularly those associated with tiny flare-like phenomena (called nanoflares). Ground-based observations like those during eclipses also have a role to play. This has enabled video-rate electronic imaging of the corona to be done, for example, which is not possible from currently operating spacecrafts. Many such recent observations have helped us to gain a clearer picture of the processes going on. There have also been advances in our theoretical understanding of coronal heating, including how it is possible to heat a gas like the solar corona by electrical means even though its conductivity is very high.

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The authors are in the Department of Applied Physics, Institute of Technology, Banaras Hindu University, Varanasi 221 005, India

*For correspondence. (e-mail: dwivedi@banaras.ernet.in)
comparable according to a standard calculation to copper at room temperature. These advances have implications not only for solar physics, but also for studies of solar-type stars (having magnetic fields and apparently hot coronae also), for atomic and nuclear spectroscopy, cosmic magnetometry, neutrino astrophysics, seismology and space weather.

**Hot corona**

For a long time, solar eclipses offered the only opportunity for studying the corona, and astronomers about a century ago, mounted expeditions to remote areas of the earth to observe them, risking not only life and limb, but also cloudy skies. At the appropriate time – totality never lasts more than about seven minutes, usually much less – Nowadays, it is possible to observe the corona routinely from spacecrafts having X-ray and ultraviolet telescopes and even from ground-based instruments with 'coronagraphs', in which the light from the intensely bright photosphere is masked artificially by means of an opaque disk (large coronagraphs are also carried on-board the SOHO spacecraft). Although the opaque disk inside a coronagraph allows year-round observing, it cannot mask out the sun as effectively as the moon during an eclipse. The corona’s white-light emission is simply sunlight from the photo-

**Figure 1.** Solar energy derives from nuclear reactions in the core of the sun at about 15 million K, the pressure being 300 billion times the atmospheric pressure on earth. This energy (in the form of X-rays and gamma-rays) is transmitted through the solar interior, first a region known as the ‘radiation zone’ and then ‘convection zone’ (outer 200,000 km – the solar radius is 700,000 km). Because of the very high densities in the solar interior, this energy is continually absorbed and re-emitted, a process which takes about 10 million years to reach the surface or photosphere of the sun – a narrow region of the solar atmosphere where the temperature is about 6000 K, from which most of the sun’s visible radiation escapes. A slightly hotter region called the chromosphere lies immediately above the photosphere, but the bulk of the solar atmosphere consists of the corona, where the temperature exceeds one million K (much hotter locally). The rotation and convection zones in the solar interior combine to produce a dynamo action, where magnetic fields are periodically generated in a 22-year cycle. The magnetic field leads to the formation of active regions, extending from the photosphere (where sunspots appear) to the corona (regions of enhanced temperature and density), and are the sites of flares or sudden releases of energy, resulting in extremely high temperature, ionized gas (or plasma) and release of particles and mass motions (flares are frequently associated with coronal mass ejections, or giant bubbles of plasma expanding into interplanetary space).

**Figure 2.** Comparison of the white-light corona (a) seen during a total eclipse near sunspot minimum (1995) and (b) one near solar maximum (1999). The corona at minimum is much more simplified, with plumes occurring at the solar poles following magnetic field lines and streamers nearly parallel to the solar equator. At sunspot maximum, bright streamers occur all round the sun’s limb (obscured by the dark lunar disk), associated with the many sunspot regions present on the sun at the time. (Courtesy: 1995 – E. Hiei; 1999 – S. Koutchmy and J. Mouette.)
sphere which has been scattered off fast-moving free electrons in the corona, into our line of vision. The effect is similar to the scattering by tiny dust particles in a sunbeam, which renders them visible to us. The density of the corona is extremely small so that almost all the sunlight escapes without being scattered (Figures 2a, b).

The first clues that the corona might be an unusually hot environment were revealed during total eclipses in the nineteenth century. The Americans, Charles Young and William Harkness studied the corona spectroscopically during a total eclipse in 1869 and found a bright emission line at 530.3 nm (now known as the ‘green’ line, since this is the region of the visible spectrum where it is located), which could not then be identified. In the 1940s, the Swedish physicist Bengt Edlén discovered that the green line was in fact due to iron, with 13 of its electrons stripped. Such a situation is only possible if the temperature is about 1 million K, resulting in the coronal gas turning into what is called a ‘plasma’.

X-rays and ultraviolet emission

The ultraviolet emission that the hot solar corona produces was first detected by instruments built by Richard Tousey and colleagues at the US Naval Research Laboratory in the late 1940s (Figure 3). A pinhole camera built by T. R. Burnight in 1949, first detected the coronal X-ray emission. Thereafter, there was a rapid increase in our knowledge of the sun’s atmosphere from data collected by the US and Soviet spacecrafts in the 1960s and 1970s, 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 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. distant from active regions) showed that the transition region and chromosphere had a ‘network’ pattern (reflecting the shapes of giant convection or ‘supergranulation’ cells seen over the entire surface of the sun). This pattern is identical to that observed for many years previously in the light of a strong visible-wavelength spectral line due to once-ionized calcium atoms in the chromosphere. The X-ray images showed that the quiet-sun corona was characterized by diffuse large-scale arches, stretching across several million kilometres. The spatial resolution of spacecraft instruments has ever since steadily improved 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 the US and Japanese scientists; it images the sun (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). These X-ray images (Figure 4), combined with those from the radio part of the spectrum, particularly those from the Nobeyama radio telescope array in Japan (working at wavelengths of a few centimetres), show the close correspondence of emitting regions (see, Golub and Pasachoff for more details).

The ESA/NASA satellite SOHO, launched in 1995 into an orbit about an equilibrium point between the earth and the sun (the inner Lagrangian point), situated

![Figure 3](image3.png) **Figure 3.** Solar ultraviolet spectrum, obtained with a rocket-borne Naval Research Laboratory instrument launched in October 1946, showing how, as the rocket altitude increases, the spectrum extends to progressively shorter wavelengths because of the decreasing atmospheric absorption. (Courtesy: Naval Research Laboratory.)

![Figure 4](image4.png) **Figure 4.** Image of the X-ray corona taken with the Soft X-ray Telescope (SXT) on 8 May 1992. The solar surface can be made out as a dark ring. Bright structures are the most intense X-ray emission regions in the corona, and are associated with sunspots on the surface. The dark region at the top of the image is a coronal hole associated with the sun’s north pole. (Courtesy: The Yohkoh SXT team.)
some 1.5 million km from the earth on the sunward side, has on-board instruments which get an uninterrupted view of the sun, unlike the instruments on Yohkoh, which is in a low-earth orbit. Those that image the sun include the Extreme-ultraviolet Imaging Telescope (EIT), which obtains images of the solar corona several times a day in the wavelengths of lines emitted by iron ions in the transition region and corona (Figure 5). 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 in the corona 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 rise to 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 Institute for Space Research, launched in 1998 into a polar orbit round the earth. 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 kilometres wide (Figure 6).

### Heating the sun’s corona

The crucial role of the sun’s magnetic field in heating the corona has been realized only in the past decade. The fields dictate the transport of energy between the surface of the sun and the corona. Magnetic fields are thought to originate in the solar interior’s convection zone by a dynamo process associated with convection currents and the differential rotation of the sun (low latitudes have a slightly shorter rotation period than higher latitudes). The fields are buoyed up to the photosphere in the form of rope-like structures which pierce the photosphere at sites such as sunspot groups and extend outward into the solar atmosphere (Figure 7). From spacecraft images, we can make out forms like active-region loops or the larger-scale arches making up the general corona or dark regions known as coronal ‘holes’, which are funnel-shaped regions within which the field opens out into interplanetary space and along which fast solar wind streams flow. All these forms are determined by the geometry of the local magnetic field. The reason for this is that the charged particles (mostly electrons and protons) forming the corona move in helical paths up and down field lines and so are closely tied to them. The magnetic field in the general corona is about 1 milli-Tesla (10 gauss), which means that the
Figure 7. Sunspots in the solar photosphere. The solar surface consists mostly of an irregular cellular pattern caused by the temperature variations in the surface. The cells, called granules, are evidence of convection - the mechanism that transports heat to the surface. The simple round sunspot in the upper right corner of this image is about 26,000 km in diameter. The dark central portion called the 'umbrae', is about 13,000 km in diameter (about the same size as the earth). The vertical magnetic field in the umbra has a strength of about 3000 gauss. Smaller magnetic structures throughout the image show up as tiny bright points. These bright points are only about 150 km in diameter, having magnetic field strengths of 1500 gauss (about 3000 times the 1/2 gauss magnetic field strength at the earth’s poles). (Courtesy: T. Berger and G. Scharmer at the Swedish Vacuum Tower Telescope on 12 May 1998.)

Assume either that there are no electric currents flowing or, if present, they run parallel to magnetic field lines.

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 is an important clue to the corona's nature and the origin of its high temperature. Some earlier observations with rocket-borne instruments by the late G. Brueckner and his colleagues at NRL in the 1980s 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 - a stream of protons, electrons and other charged particles - which moves outward into the deepest reaches of the solar system at speeds of between 400 and 800 km/s. New results from the SUMER (Solar Ultraviolet Measurements of Emitted Radiation) spectrograph on SOHO spacecraft for the magnetic reconnection provide the best evidence to date for the existence of bi-directional outflow jets. Ultraviolet jets are only one of many sorts of dynamic phenomena occurring all over the sun, in 'quiet' (i.e. far from sunspot groups) as well as active regions. Microflares, discovered from a balloon-borne X-ray detector by Robert Lin and colleagues in 1981, are another example - in this case, impulsive bursts of very short-wavelength X-ray emission, which are like miniature versions of fully-fledged flares. Their frequency and energies would suggest that they too could participate in the heating of the corona.

**Nanoflares and magnetic waves**

Eugene Parker, at the University of Chicago who is famous for his theoretical prediction of the solar wind in the 1950s, has theorized that numerous even smaller events - nanoflares - below the detectability levels of spacecraft instruments, could explain coronal heating very effectively. There is now observational evidence from recent data which support 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 hot corona? The quiet-sun corona’s total radiative output is about $3 \times 10^{18}$ watts, with about the same amount of power being transferred to the photosphere by thermal
conduction. Present estimates of the total energy of various dynamic phenomena detected by spacecrafts like TRACE and SOHO, are about 20 per cent of this amount. The remainder could be accounted for by flare-like pulses, below the detectability thresholds of present instrumentation.

The nanoflare hypothesis for the heating of the corona thus looks a very plausible one. However, many theorists have nevertheless concentrated on the idea that heating by waves is dominant. An early theory that the corona is heated by sound waves or sonic shock fronts was discarded in the late 1970s, when it was established that shock waves would all be dissipated in the chromosphere, leaving no energy for the corona. Waves associated with the sun's coronal magnetic field are more plausibly involved in heating processes. Such waves could take the form of Alfven waves, which are like the waves which travel along elastic bands when stretched. But more generally, it is thought that the waves important for heating processes are 'magnetohydrodynamic' (MHD), i.e. they share characteristics of sound and Alfvén waves. Plasma physicists recognize two sorts of MHD waves, fast-mode and slow-mode. Theoretical predictions indicate that waves with very short periods, perhaps only a few seconds long, are the most effective in heating.

Either way, a considerable problem with magnetic field heating is the fact that it requires diffusion and therefore reconnection of magnetic field, which in turn implies that the coronal plasma has a certain amount of electrical resistivity. However, the corona is, to the contrary, highly conducting. The diffusion time for magnetic field is extremely long unless the characteristic distance over which diffusion occurs is as short as a few metres, when the diffusion time is a few seconds. Very small length-scales are thought to occur in the corona, but only in tiny regions where there are steep magnetic gradients and large electric currents. This problem applies equally to the two theories which are currently thought to explain the corona's high temperature, nanoflares and damping of magnetic waves. 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 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.

Fieldwork

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 occurring in coronal holes at each of the solar poles (since a reconnection would merely accelerate plasma, rather than heat it), 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, which may include periodic fluctuations in brightness of various structures. Some non-periodic variations in coronal brightness have been reported from the SOHO LASCO coronagraph having time scales of about 30 min. These may be a manifestation of wave-type heating, but theoretical results indicate that MHD waves having very short periods, of only a few seconds, are those of significance for coronal heating. In this respect, ground-based instruments operating during total eclipses can out-perform spacecraft instruments in terms of fast imaging, since spacecraft imaging is necessarily rather slow. Analysis of Jay Pasachoff's results indicates the presence of a small peak in Fourier spectra at frequencies of 0.5–1 Hz. This has been seen in more recent eclipses, including the 1998 eclipse in the Caribbean.

Phillips at Rutherford Appleton Laboratory in the UK, with others from Queen's University, Belfast and the University of Wroclaw, Poland have developed an instrument consisting of a pair of charge coupled device (CCD) cameras which image the white-light corona at subsecond speeds. The instrument, called the Solar Eclipse Coronal Imaging System (SEGIS), uses an adapted PC to grab the digital data from the cameras at image rates up to 44 frames a second. The data during the eclipse of 11 August 1999 at Shabla in Bulgaria, have uncovered very subtle signs of oscillatory behaviour which could be linked to MHD wave motions. The periods are between 2 and 10 s. The experiment has been successfully repeated for the eclipse on 21 June 2001, from a location near Lusaka, Zambia.

Concluding remarks

In conclusion, 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 coronal heating, waves may also play a role.

Arabian Sea oceanography and fisheries of the west coast of India

M. Madhupratap*, K. N. V. Nair, T. C. Gopalakrishnan, P. Haridas, K. K. C. Nair, P. Venugopal and Mangesh Gaun

The physical and chemical forcing, which drives the Arabian Sea production is now fairly understood. The main attributes which contribute to the productivity are (1) the boundary and open ocean processes, which manifest as upwelling during summer monsoon and (2) cooling in the northern Arabian Sea during winter. These bring in higher amount of nutrients into the upper ocean, which enhance primary productivity and we examine how these might contribute to the fisheries along the west coast of India. The highest catches are between October and March. From an oceanographic point, this region can be divided into two areas; south of 15°N and north of this latitude. Although the fish catches from these two areas are fairly equal, there is considerable difference in the composition. In the south, planktonivorous fishes dominate, whereas in the north carnivores are more abundant. This appears to be a puzzle, and not reported hitherto. Based on the lower food-web, which appears to be similar in the two regions, we seem to be unable to explain this difference.

ESTIMATES of potential fishery resources from the Exclusive Economic Zone of India (EEZ) are about 3.5 to 4.7 mt (million tonnes)\(^1\)\(^4\). The recent estimates on annual marine landings from the Indian coast show that they fluctuate between 2.2 and 2.8 mt\(^5\). Of this, about 73% of the catches originate from the west coast of India. But a close look at the catch statistics\(^5\) shows that the composition of marine landings significantly changes, not only between the east and west coasts, but also within the latter.

This and other observations, which also encompass different trophic levels, bring us to some unresolved puzzles mainly on the composition and feeding habits of the fishes, which show changes over space. Under the studies conducted during the Joint Global Ocean Flux Studies (JGOFS) programme (1992–1997), we have come to some new understanding on the physics, chemistry and basic biology of the Arabian Sea, which could be a part of the fishery biology, although interpretations of these in relation to fisheries would require a further concerted effort from all concerned. This paper is an attempt (1) to address the seasonal and spatial variability of the processes controlling the physics, chemistry and biology of the waters of the west coast of India, (2) their influence on fish composition, (3) changes in feeding habits between south and north, and (4) to speculate on the productivity and its relation to fisheries in the Arabian Sea.

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M. Madhupratap and Mangesh Gaun are in the National Institute of Oceanography, Dona Paula, Goa 403 004, India. K. N. V. Nair is in the Fishery Survey of India, Goa, India and T. C. Gopalakrishnan, P. Haridas, K. K. C. Nair and P. Venugopal are in the NIO Regional Centre, P.B. No. 1616, Kochi 682 014, India

*For correspondence. (e-mail: madhu@csio.res.nic.in)