The Sun's Mysteries from Space – I

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This article in two parts presents a brief overview of the Sun's mysteries revealed from space observations, using recent solar spacecrafts: Yohkoh, SOHO, TRACE and RHESSI.

Among the many exotic astronomical objects in the universe, the Sun is the principal source of new physics, ranging from the nature of the neutrinos to the intricacies of the magnetohydrodynamic activity and to the geological evolution of terrestrial climate. Historically, it was the motion of the planets around the Sun that established the inverse square nature of the gravitational force. Centuries later, the precession of the orbit of Mercury provided the clue that Newton's gravitational theory needed a relativistic correction. The precession, together with the solar deflection of starlight, then provided the first quantitative proof of Einstein's theory of general relativity.

Observations of the solar atmosphere led to the development of the theory of radiative transfer in stellar atmospheres and the discovery of the element helium. Moreover, the Sun is the principal magnetohydrodynamic (MHD) laboratory for large magnetic Reynolds numbers (a measure of turbulence), exhibiting the totally unexpected phenomena of magnetic fibrils, sunspots, prominences, flares, coronal mass ejections (CMEs), the solar wind, the X-ray corona, and irradiance variations. It is the physics of these exotic phenomena, collectively making up variations of solar activity, with which we are confronted today. The activity affects the terrestrial environment, from occasionally knocking out power grids to space weather and general climate.

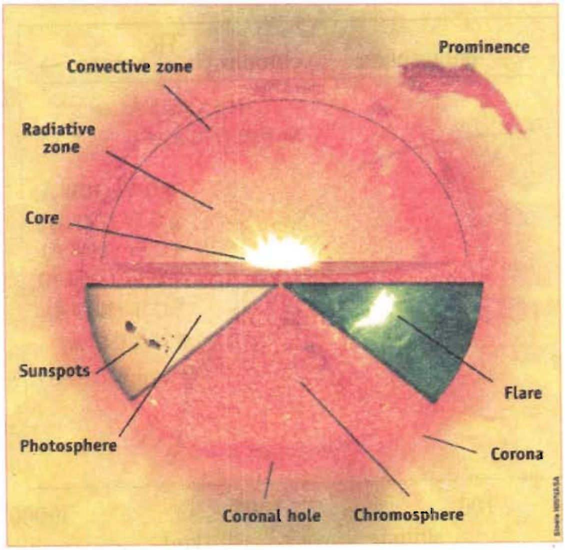


Figure 1. The chief parts of the Sun : This gives a basic overview of the Sun's structure. The three major interior zones are the core (the innermost part of the Sun where energy is generated by nuclear reactions), the radiative zone (where energy travels outward by radiation through about 70% of the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

The Sun

The Sun might seem to be a uniform sphere of gas radiating intense amount of light. In fact, it has well-defined regions which can loosely be compared to the solid part of an earth-like planet and its atmosphere (see *Figure* 1). The solar radiation that we receive on the Earth ultimately derives from nuclear reactions deep in the Sun's core. The energy gradually leaks out (first by radiation and then by convection) until it reaches the visible surface, known as the photosphere, and escapes into space. Above that surface is the Sun's tenuous atmosphere. The lowest part, the chromosphere, is normally only visible during total eclipses when it appears as a thin bright red crescent. Beyond it, as any eclipse observer has witnessed, is the pearly white corona, extending out to many times the radius of the photosphere. Further out still, the corona becomes a stream of charged particles called the solar wind which pervades the entire solar system. Journeying out from the Sun's core, an imaginary observer will first encounter temperatures of 15 MK, temperatures high enough to generate the nuclear reactions that power the Sun. Temperatures get progressively cooler en route to the photosphere, which is at about 6000 K. This is all expected from the laws of thermodynamics. But then something entirely

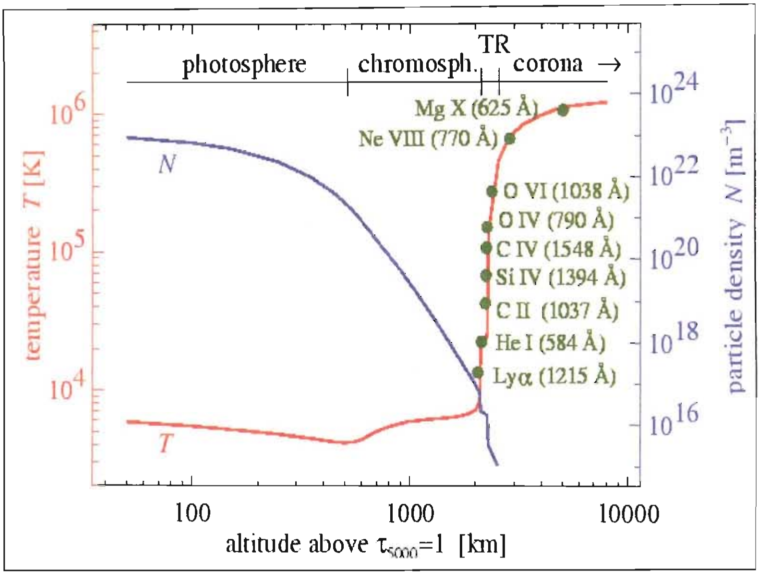


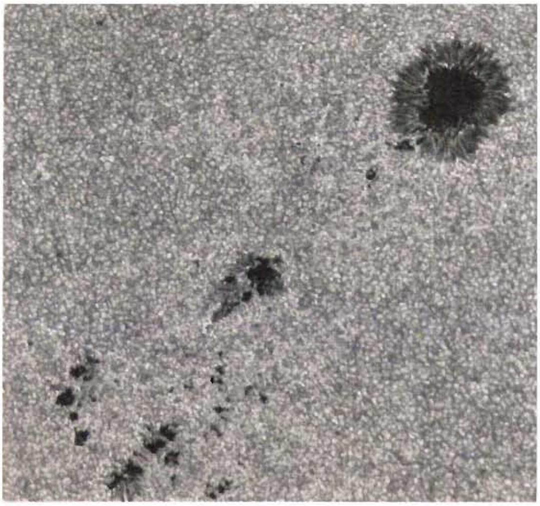
Figure 2. Empirical model of the solar atmosphere (Credit : Hardi Peter)

The neutral species of an element A is denoted by AI and its first ionized species, e.g. A^+, by AII, and so on. Thus He I refers to a neutral helium atom, C II to singly ionized carbon ion and OIV to O^{+++}. Ne VIII is a neon atom with seven electrons removed and MgX, a magnesium atom with nine electrons removed. The wavelength of the strongest line of each species is given in parentheses in *Figure* 2.

unexpected happens: the temperature gradient reverses. The chromosphere's temperature steadily rises to 10,000 K, and going into the corona, the temperature jumps to 1 MK (see *Figure* 2). Parts of the corona associated with sunspots get even hotter.

Box 1. The Sun's Surface

The solar surface is covered with 'granules' with a typical size of 1000 km. There are bright upflows of hot material, surrounded by a network of downflows of material that cooled down by radiating its energy into space. Where there are strong concentrations of magnetic field, the convection is suppressed, and the solar surface cools and turns dark (forming sunspots and pores). Small concentrations of field actually act as leaks for radiation from the interior, forming small (100 km) bright 'dots' or faculae. The field in these faculae is swept into the dark downflows, where its buoyancy keeps it afloat, being pushed back and forth as the granules evolve on a time scale of only 5 minutes.



(Credit: T Berger, Swedish Solar Observatory).

In one sense, the million-degree hot coronal gas is not as extreme as it sounds. Were the corona dense and opaque, it would emit radiation like a perfect radiator (black body) at 1 MK. If it were so, the Earth and its inhabitants would be immediately incinerated. Luckily, the corona is too tenuous for this to happen. The high temperature of the corona is, at first thought, a real paradox. How could the Sun's radiation, leaving a 6000 K surface heat the outer atmosphere to such a high temperature? Such a notion violates common sense. If we are sitting by a fire, we derive radiant warmth from it because it is hotter than we are. But if it goes out and the cinders become cold, we will no longer be warmed by it. Likewise, the corona cannot derive radiant heat from the Sun if the Sun's surface is colder than it is. But if the cold photosphere didn't radiate energy to the corona, what keeps it hot? This question remains one of the central questions in astrophysics. The understanding of coronal heating is important not only in the context of solar atmospheric physics but also in relation to the Sun-Earth connection, in examining the influence of the expanding hot solar corona on the interplanetary and near-Earth space environments. The expanding solar atmosphere forms the solar wind that during peaks of solar activity can cause magnetic storms by perturbing Earth's magnetosphere, damaging satellites, affecting communications, and even inducing power outages in ground-based electrical grids.

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Solar Eclipses and the Corona

Total solar eclipses are very rare events for any particular location on the Earth – relatively few people have ever witnessed a total solar eclipse which is one of the most beautiful spectacles in all of nature. At the time of a solar eclipse, a white halo of tenuous gas appears beyond the edge of the Moon, stretching a vast distance out into space. It is aptly termed the corona, the Latin word for crown. For a long time solar eclipses offered the only opportunity of studying the corona, but nowadays it is observed routinely with special telescopes, called coronagraphs, in which the light from the photosphere is masked artificially by means of an opaque disk. What is the source of the opalescent light that

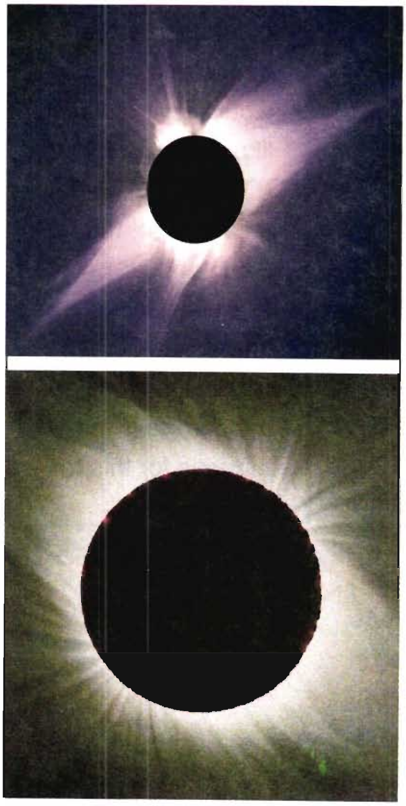


Figure 3. The white-light corona:
(Top.) The total solar eclipse of 11 July 1991 (sunspot maximum) from Mauna Kea, Hawaii. The black disk is the Moon, and the pink, feathery extensions are the solar corona. (Credit: High Altitude Observatory)
(Bottom.) Computer-processed image of the total solar eclipse of 24 October 1995 (sunspot minimum) from India. (Credit : E. Hiel)

appears during a total solar eclipse? The coronal light that we see is simply sunlight from the photosphere which has been scattered off the electrons in the corona and bent into our line of vision. The effect is somewhat 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. The corona, like the air in a dusty room, is almost perfectly transparent. Nevertheless, about one out of every million photons leaving the Sun strikes an electron in the corona and is scattered. Some of these reach our eyes and can be detected during the rare circumstance of a total eclipse when the Moon exactly covers the million times brighter solar disk. The corona then appears as a pearly white, often irregularly-shaped structure all round the Moon's limb (see *Figure* 3). From the brightness of the corona we may calculate that the electron density in the corona is about 10^8 electrons per cubic centimeter, falling off with increasing distance from the photosphere. Such densities are many trillions of times less than that of the molecules composing the Earth's atmosphere. In fact, coronal densities are low enough to be considered an almost perfect vacuum by laboratory standards.

The first clues that the corona might be an unusually hot environment were revealed during total eclipses in the nineteenth century. The Americans CA Young and W Harkness studied the corona spectroscopically during the 1869 total eclipse and found a bright emission line at 530.3 nm (now known as the 'green' line) which could not then be identified. Several more unidentified lines became evident in spectra obtained in subsequent eclipses, and a new element named 'coronium' was suspected to be the reason for these spectral lines. As the years passed, however, it became clear that coronium (as well as 'nebulium', discovered from spectral lines in certain gaseous nebulae) could not be easily admitted into the periodic table of elements and its existence as an element became discredited.

Many years later, in the 1930's and 1940's, the lines of coronium and nebulium were finally reproduced in the spectra of very hot spark sources in the laboratory. It was then realized that the corona must have a temperature of about a million degrees K as judged from the spark environments. The clinching argument was the discovery by B Edlén in Sweden that the 'green' coronal line was due, not to an unknown element, but to 13-times-ionized iron. Nebulium was identified as O III, e.g., O^{++}. These pioneering investigations revealed the two most basic properties of the corona, namely, it is a rarefied gas and that its temperature is very high. The discovery of soft X-ray and ultraviolet emission (wavelengths extending from 0.2 to 300 nm) in the post-World War II years provided further proof of the corona's high temperature (see *Figure* 4).

Solar X-rays and Ultraviolet Emission

X-rays and ultraviolet emission from the solar atmosphere is absorbed by the Earth's atmosphere. So instrumentation has to be flown on rockets or satellites to be able to view it. As already mentioned, observations were begun shortly after World War II by US groups, notably at the Naval Research Laboratory where R Tousey and his colleagues obtained the first ultraviolet spectrum of the solar atmosphere (*Figure* 4). X-ray emission was first detected by T R Burnight in 1949 using a pinhole camera pointed at the Sun on board a rocket. Spacecraft, built by the US and Soviet space agencies in the 1960's and 1970's, dedicated to solar observations, added much to our knowledge of the Sun's atmosphere; notable among them is the manned NASA Skylab

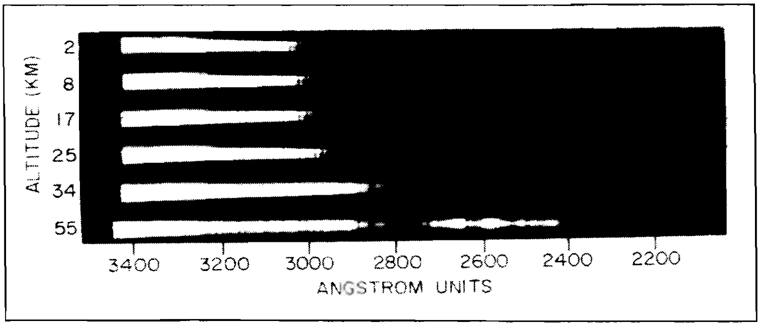


Figure 4. The first photograph of the solar ultraviolet spectrum. It was obtained with an instrument built by the US Naval Research Laboratory on a (captured German military V2) rocket launched in October 1946, and shows how, as the rocket altitude increases, the spectrum extends to progressively shorter wavelengths because of the decreasing atmospheric absorption. The broad dark lines at wavelength 280 nm (2800 Å) are the singly ionized magnesium h and k lines. (Credit: US Naval Research Laboratory, Washington, DC).

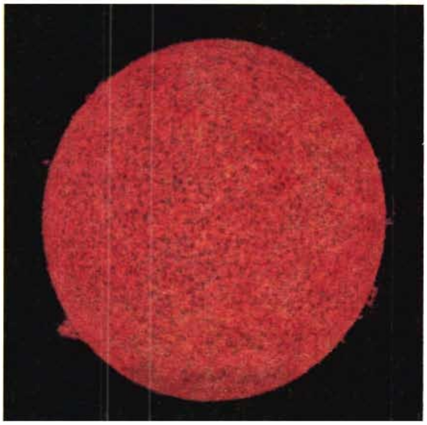
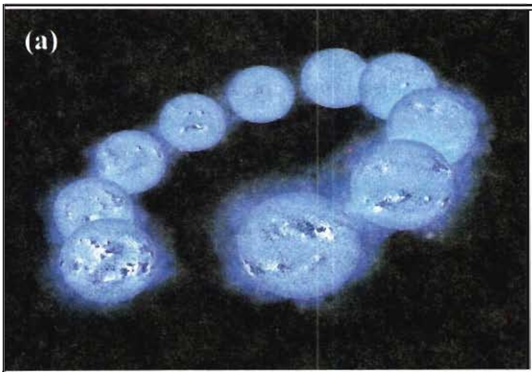


Figure 5. The Sun's image in the chromospheric emission line of neutral helium at 58.43 nm wavelength taken by the SUMER spectrograph on the SOHO spacecraft on 4 March 1996. (Credit : SUMER/SOHO, ESA-NASA).

mission of 1973-1974. Ultraviolet and X-ray telescopes on board gave the first high-resolution images of the chromosphere and corona and the intermediate transition region (temperatures between 10^4 and 10^6 K). Images of active regions (the photospheric counterpart of which are the sunspot groups) revealed a complex of loops which varied greatly over their lifetimes, while ultraviolet images of the quiet Sun showed that the transition region and chromosphere followed the 'network' character previously known from images in Ca (II) K-line at 3933Å. *Figure* 5 illustrates the chromosphere in the emission line of neutral helium at 58.43 nm formed at about 20,000 K. The X-ray images showed that the quiet-Sun corona was characterized by diffuse large-scale loops.

More recently, the spatial resolution of spacecraft instruments has steadily improved to extremely impressive levels, nearly equal to that which can be achieved with ground-based solar telescopes. Each major solar spacecraft since Skylab has offered a distinct improvement in resolution. From 1991 to late 2001, the X-ray telescope on the Japanese Yohkoh spacecraft has routinely imaged the Sun's corona, tracking the evolution of loops and other features through its 11-year cycle of solar activity (see *Figure* 6).

The ESA/NASA Solar and Heliospheric Observatory (SOHO) was launched on December 2, 1995 into an orbit about the inner Lagrangian (L1) point situated some 1.5 x 10^6 km from the Earth on the sunward side. Its twelve instruments, therefore, get an uninterrupted view of the Sun, unlike the instruments on Yohkoh. Apart from a period in 1998 when the spacecraft was temporarily out of contact, it has been in continuous operation since launch. There are several imaging instruments sensitive to wavelengths ranging from visible-light 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 the coronal ions Fe IX, Fe X, Fe XII, Fe XV (emitted in the



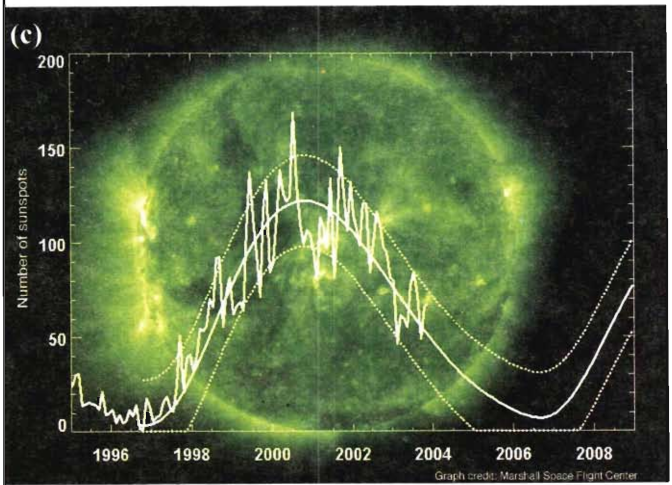


Figure 6a. The solar magnetic field in time: The magnetic maps of the Sun's surface were recorded with the Vacuum Tower Telescope at the Kitt-Peak National Solar Observatory from 8 January 1992 (lower left) to 25 July 1999 (lower right). Note the variation in pattern and strength of the field from one image to the next (taken one half to one year later than the previous). The variations in the magnetic field reflect the 11-year solar sunspot cycle.

Figure 6b. The solar corona in time: This image shows the corona in X-rays as observed by Yohkoh's Soft X-ray Telescope (SXT). The series of images are mostly on the same day as of the magnetic maps in Figure 6a from 8 January 1992 (lower left) to 25 July 1999 (lower right). The X-ray images show much more striking changes in patterns and intensities, driven by the changes in the magnetic field. The Sun's surface is hot enough to produce X-rays, so it shows up as a dark ball. The hot corona extends hundreds of thousands of kilometers above it and is shaped into complex forms by magnetic fields. (Credit : SXT/Yohkoh).

Figure 6c. Checking on the sunspot cycle: Scientists track solar cycles by counting sunspots. The current 11-years solar cycle reached its peak level in July 2000. Since then, the number of sunspots and general solar activity has gradually declined, though it did attain a second peak around January 2002. Inevitably, the number of sunspots will continue to go down until the numbers bottom out during the period of solar minimum, sometime around 2006. This chart is projected onto an extreme ultraviolet image of the Sun taken on 16 December 2003 that reveals only a few areas of solar activity. The jagged and heavier white line represents the monthly sunspot numbers observed. The solid curve is an estimate of the monthly mean sunspot numbers, and the dotted curves represent the limits within which the real sunspot numbers are expected to fall. (Credit: EIT/SOHO, NASA/MSFC).

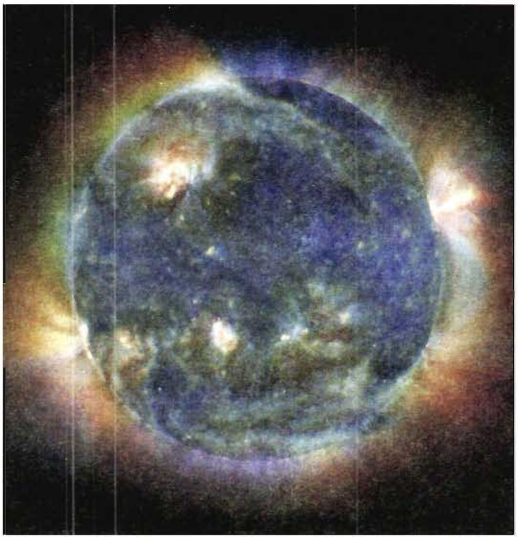


Figure 7. This is the delightfully detailed, brightly coloured image of the active Sun. From the EIT instrument on board the space-based SOHO Observatory, this tantalizing picture is a false colour composite of three images, all in extreme-ultraviolet light. Each individual image highlights a different temperature regime in the Sun's hot atmosphere and was assigned a different colour: red at 2 x 10^6 K, green at 1.5 x 10^6 K and blue at 10^6 K. The combined image shows bright active regions strewn across the solar disk, which would otherwise appear as dark groups of sunspots in visible light images, along with some magnificent plasma loops and an immense prominence at the right hand solar limb. (Credit: EIT/SOHO, ESA–NASA).

temperature range 600 000 K to 2500 000 K) as well as the chromospheric He II 30.4 nm line (see *Figure* 7). 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 (solar radius = 700,000 km) from the Sun's center, determining empirical values for densities, velocity distributions and outflow velocities of hydrogen, electrons, and several minor ions. An intriguing observation with the UVCS has shown that particular ions, specifically highly ionized oxygen atoms, have temperatures in coronal holes, of some 100 MK, that are much higher than those characterized by electrons and protons making up the bulk of the plasma. There seems to be some directionality to the oxygen temperatures – they are higher perpendicular to the magnetic field lines than parallel to them, a result that is in agreement with interplanetary spacecraft sampling of the particles making up the solar wind. The observation seems to call for high-

Box 2. Ion-cyclotron Resonance

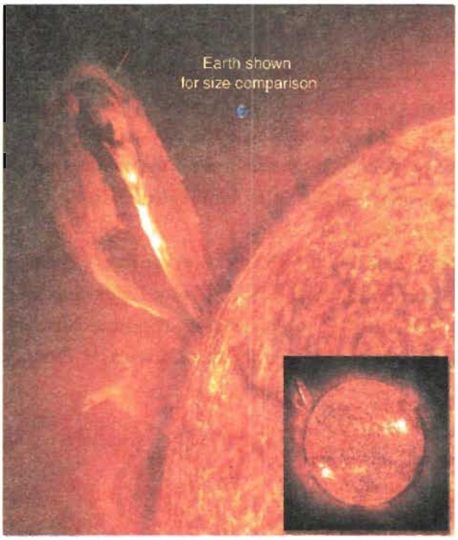
In the presence of magnetic fields, the particles have no restriction moving parallel to the magnetic field B, but cannot move freely perpendicular to it. Lorentz forces cause them to orbit around the field lines with the gyro-frequency (qB/m). Due to the magnetic field strength B decreasing with height, high-frequency torsional or transverse Alfven waves with their velocities given by

$$V_A = \frac{B}{(\mu\rho)^{1/2}}$$

propagating along the field lines will come to regions where the wave frequency becomes equal to the gyro-frequency of protons and ions like five-times ionized oxygen, e.g. O VI. Here ion-cyclotron resonance heating takes place.

Box 3. Coronal Mass Ejection

Coronal Mass Ejections (CMEs) are observed as localized increases in the brightness of white-light coronagraph images. Integration of the brightness increase (which depends only on the electron density, N_e) permits evaluation of the total mass, m, of the ejection. For a sphere of radius r, we have : $m = 4\pi r^3 N_e m_p/3$, where m_p is proton mass 1.67×10^{-27} kg. For a fully ionized plasma $N_e = N_p = 10^{13}$ electrons m^{-3}, and taking $r = 6.96 \times 10^8$ m, we have $m = 10^{13}$ kg = 10 billion tons. If we take one ejection per day, and 10^{13} kg per ejection, it amounts to a mass flow rate of about 10^8 kg s^{-1}. The kinetic energy of a CME with $m = 10^{13}$ kg and $v = 4 \times 10^5$ m s^{-1}, is KE = $\frac{1}{2} mv^2 \approx 10^{24}$ Joule = 10^{31} ergs, which is comparable to the energies of large flares. Assuming $v = 4 \times 10^5$ m s^{-1}, the time to travel from the Sun to the Earth (1.5×10^{11} m) will be T = distance/speed = 3.75×10^5 sec = 4.34 days.



Large, eruptive prominence in He II 304 Å, with an image of the Earth added for size comparison. This prominence from 24 July 1999 is particularly large and looping, extending over 35 Earths out from the Sun as judged from the comparison image. The inset fall-disk solar image indicates that the eruption looped out for a distance almost equal to the Sun's radius. Erupting prominences (when Earthward directed) can affect communications, navigation systems, even power grids, while also producing auroras in the polar skies. (Credit: EIT/SOHO).

frequency ion-cyclotron waves that are produced lower down in the atmosphere as low-frequency waves but which through some cascade process end up at the observed frequencies. Whether this is important for the heating of the corona as a whole remains to be seen.

The three coronagraphs making up the Large Angle and Spectroscopic Coronagraph (LASCO) view the white-light corona with high resolution out to distances of 30 solar radii. Movies of the corona from LASCO show the large-scale structures in the corona as they rotate with the rest of the Sun (the 'synodic' solar rotation period, i.e. as viewed from the Earth, is 27 days or so, with slight latitude dependence), but more particularly they show the large ejections of coronal mass in the form of huge bubbles, moving out with velocities of several km/s 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.

Suggested Reading

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