The Sun's Mysteries from Space – II

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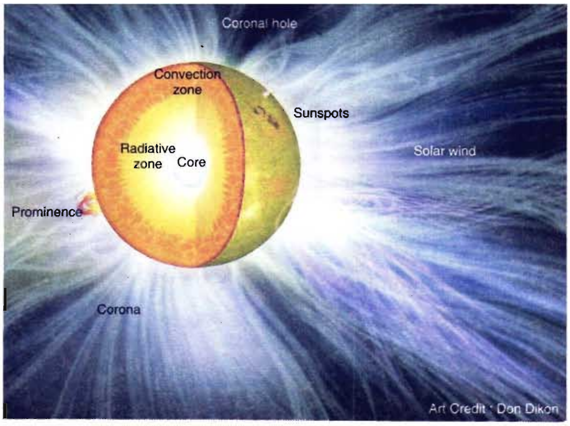
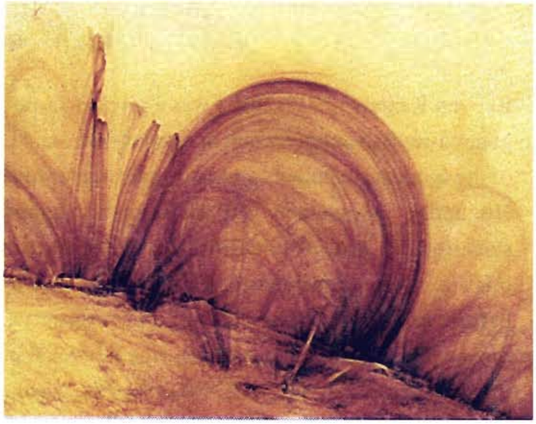
In the concluding part of our article we discuss problems of coronal heating and coronal holes and solar winds.

The Transition Region and Coronal Explorer (TRACE) satellite, operated by the Stanford-Lockheed Institute for Space Research, went into a polar orbit around Earth in 1998 and has extremely impressive imaging capabilities. The spatial resolution is of the order of 1 arcsecond (725 km), and there are wavelength bands covering the Fe IX, Fe XII, and Fe XV lines which EIT observes as well as the Ly-alpha line at 121.6 nm. Its ultraviolet telescope has obtained images containing tremendous amount of small and varying features – for instance, active region loops are revealed to be only a few hundred kilometers wide, almost thread-like compared to their huge lengths. Their constant flickering and jouncing hint at the corona's heating mechanism. There is a clear relation of these loops and the larger 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).

The latest in the fleet of spacecraft dedicated to viewing the Sun is the Ramaty High Energy Solar Spectroscopic Imager (RHESSI), launched in 2002, which is providing images and spectra in hard X-rays (wavelengths less than about 4 nm). As until recently solar activity has been very high, much attention has been paid to data from intense flares. But now at the solar minimum, investigators using RHESSI's data are more and more interested in tiny microflares which are a clue to the coronal heating mechanism. *Figure* 3 shows a microflare seen by RHESSI and TRACE on 6 May 2002 at 09:01 UT.





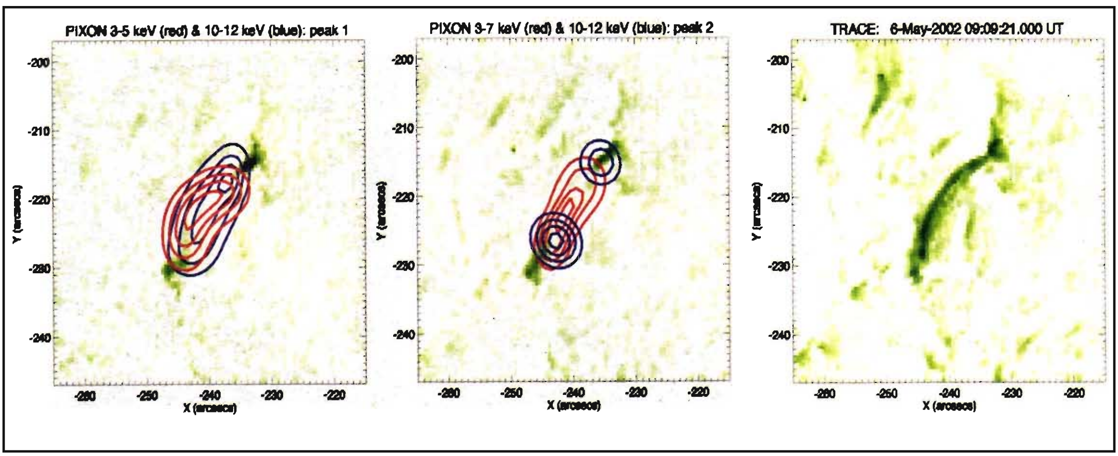
Coronal Heating

An early theory that the corona is heated by sound waves and their associated shock fronts was discarded in the late 1970's when it was established from spacecraft observations that shock waves were all dissipated in the chromosphere (a region a few thousand km thick, immediately above the photosphere), leaving no energy for the corona itself. The corona is a magnetically dominated environment consisting of a variety of plasma structures including X-ray bright points, coronal holes and coronal loops or arches (see *Figure* 4).

Figure 1 (left). A cut-away view of the Sun-regions of the solar core and atmosphere.

Figure 2(right). Coronal loops, seen in the ultraviolet light (Fe IX 171 Å) by the TRACE spacecraft on 6 November 1999, extending 120,000 km off the Sun's surface.
(Credit: TRACE/NASA)

Figure 3. RHESSI contours, processed with PIXON (red-thermal : 3-6 keV, blue-nonthermal : 10-12 keV) overlaid on TRACE (195 Å) images for peak 1, peak 2 and post-event. Footpoints and loop emission is clearly visible during peak 2. Cooling postflare loops can be seen in TRACE after the RHESSI. (Credit : S. Krucker)



Box 1. Reuven Ramaty

Reuven Ramaty (1937-2001) was a pioneer in the fields of solar physics, gamma-ray astronomy, nuclear astrophysics, and cosmic rays. He was one of the founding members and a co-investigator of NASA's HESSI mission. His active involvement and enthusiastic support were critical for the selection by NASA of HESSI as the sixth Small Explorer (SMEX) mission. Quite unfortunately, Ramaty passed away in April 2001, months before the launch of the mission on 5 February 2002. The mission was renamed in his honour and became the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), the first such mission named after a NASA scientist.

Box 2. Solar Flares

Solar flare appears as a sudden, rapid and intense variation in brightness. A flare occurs when magnetic energy that has built up in the solar atmosphere is suddenly released. Radiation is emitted across virtually the entire electromagnetic spectrum, from radio waves at the long wavelength end, through optical emission to X-rays and gamma rays at the short wavelength end. The amount of energy released is the equivalent of millions of 100-megaton hydrogen bombs (one megaton of TNT is 4.2×10^{22} ergs) exploding at the same time!

Solar flares are classified according to their X-ray brightness in the wavelength range 1 to 8 Å. The Sun releases energy in transient outbursts, ranging from major flares ($\sim 10^{32}$ to 10^{33} ergs) down to microflares and even nanoflares. The energy releases often appear to be dominated by accelerated ~10s of keV electrons and sometimes ~1 MeV nucleons. Hard (> 20 keV) X-ray microflares, tiny bursts with $\sim 10^{27}$ to 10^{28} ergs in >20 keV electrons, were discovered with a balloon-borne hard X-ray detector in 1984 by R P Lin and his colleagues. This led to the speculation that the energy released in accelerated electrons, summed over hard X-ray bursts of all sizes, might contribute significantly to the heating of the active corona.

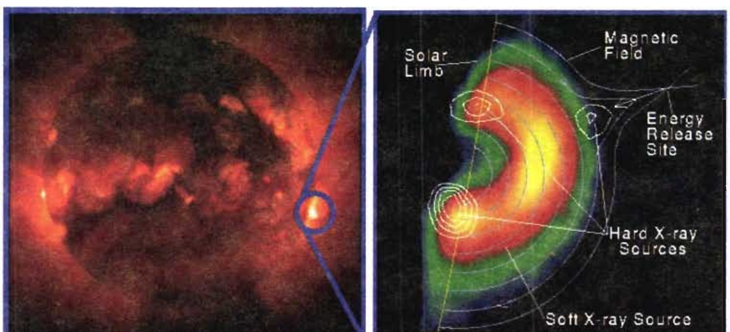


Figure A. Yohkoh X-ray image of a solar flare, combined image in soft X-rays (left) and soft X-rays with hard X-ray contours (right) observed on 13 January 1992.
(Credit : SXT/Yohkoh)

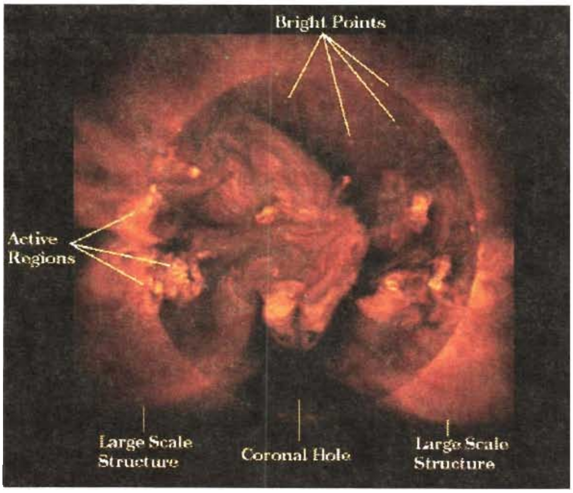


Figure 4. The X-ray Sun showing variety of plasma structures.
(Credit : SXT/Yohkoh)

There is strong but indirect evidence to suggest that the corona is heated by magnetic fields. 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, using magnetographs that work on the principle of the Zeeman effect (magnetic splitting of lines). This can be done for small regions so that a complete magnetic field map (known as a magnetogram) of the Sun's visible hemisphere can be constructed. Although, eventually, infrared measurements may give important information, practically the only way at present in which the coronal field can be deduced is through the particular assumption: either that there are no currents flowing in the plasma (current-free) or that currents, if they exist, run parallel to magnetic field lines (force-free). These predict that the magnetic field of the corona generally has a strength of about 10 gauss which is 20 times the Earth's magnetic field strength at its poles. In active regions, the field may reach 100 gauss. It is to be noted, however, that vibrating magnetic structures in the solar atmosphere are opening up a new way to study the Sun. By fitting the observed oscillations from the TRACE spacecraft with MHD wave theory, Valery M Nakariakov has determined the magnetic field strength in a coronal loop to be of about 13 gauss. The photospheric field in an active region corona is more complex than in quiet regions and

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also the active region corona is appreciably hotter. Thus there seems to be a relation between magnetic field strength and complexity and heating.

A considerable problem with magnetic field heating is the fact that it requires diffusion, and therefore reconnection, of the magnetic field which implies a resistive plasma. The coronal plasma is, on the contrary, highly conducting. The corona's electrical conductivity is not too unlike that of solid copper, a familiar example of an almost perfect conductor, at room temperature. Using the induction equation of magnetohydrodynamics (MHD), we find that the diffusion time for a magnetic field is extremely long. If the characteristic distance over which diffusion occurs be as short as a few meters, then the diffusion time is a few seconds. Put another way, the magnetic Reynolds number R_m, measuring how tied the magnetic field is to the plasma, is typically 10^6 to 10^{12} for the corona, indicating that the field is completely 'frozen in' to the plasma. However, reconnection requires R_m to be very small, much less than one in fact. Thus, only if the length scales are very small can one achieve magnetic reconnection. 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. Some 10^{16} J are released in a nanoflare, i.e. 10^{-9} of a large solar flare, and many energy releases like this occuring all over the Sun, quiet as well as active regions, could account for the heating of the corona. However, it is doubtful whether this mechanism would apply to coronal hole regions where the field lines are open to interplanetary space.

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The above reasoning applies equally to the competing wave heating hypothesis of coronal heating, in which MHD waves generated by photospheric motions (e.g. granular or super-granular 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 Alfvén wave transit time across a closed structure like an active region or a quiet Sun loop. The waves, generated by turbulent motions in the convection zone or at the photosphere, may be surface waves, or body waves which are guided along the loops and are trapped. Theoretical work 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. It is possible that (and would certainly be simpler if) X-ray bright points, coronal holes and the different types of coronal loops (see *Figure* 4) are heated by the same mechanism, but it is also possible that they are heated by different mechanisms. The debate on coronal heating centers on whether the field energy is dissipated via numerous small magnetic reconnections ('nanoflares'), or damping of MHD waves which emerge from the interior and pass through the Sun's surface layers to the corona.

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The overriding problem for both theories is the way reconnections or MHD waves manage to dissipate current energy into heat energy in view of the fact that the corona is highly conducting. TRACE observations and analysis of damped coronal magnetic loop oscillations provide evidence that the resistivity of the corona is not in fact as low as it would seem classically. But, rather, there are anomalous processes in which heat dissipation occurs via particle-wave interactions instead of particle-particle collisions. If the resistivity were enhanced (or the resistivity and the viscosity are enhanced), then it would support the dissipation of waves and magnetic reconnection mechanisms for coronal heating.

Although the weight of observational evidence generally points to a nanoflare mechanism for providing the bulk of coronal heating, MHD waves probably contribute significantly. It is, for example, unlikely that nanoflares could have much effect in coronal holes. In these regions, the field lines open out into space rather than loop back to the Sun, so a reconnection would accelerate plasma rather than heat it. Yet the corona in holes is

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still hot. Astronomers have therefore scanned coronal holes as well as closed field regions for signatures of wave motions, which may include periodic fluctuations in brightness. The difficulty is that the MHD waves involved in heating probably have very short periods, just a few seconds. At present, spacecraft imaging is too sluggish to capture them. For this reason ground-based instruments operating during total eclipses are still important.

Coronal Holes and the Solar Wind

In 1950's Waldmeier first recognized persistent depressions in the intensity of the monochromatic corona (outside the polar caps) as observed by ground-based coronagraphs and called them 'holes' (Löcher in German). Observations from the Skylab firmly established that the high-speed solar wind originates in coronal holes which are well-defined regions of strongly-reduced ultraviolet and X-ray emissions. More recent data from Ulysses show the importance of the polar coronal holes, particularly at times near the solar minimum, when the dipole field dominates the magnetic field configuration of the Sun. The mechanism for accelerating the wind to the high values observed, of the order of 800 km s^{-1}, is not understood quantitatively. The Parker model is based on a thermally-driven wind. To reach such high velocities, temperatures of the order 3 to 4 MK would be required near the base of the corona. However, other processes are available for acceleration of the wind, for example, the direct transfer of momentum from MHD waves, with or without dissipation. This process results from the decrease of momentum of the waves as they enter less dense regions, coupled with the need to conserve momentum of the total system. If this transfer predominates, it may not be necessary to invoke very high coronal temperatures at the base of the corona.

Prior to the SOHO mission, there was very little information available on the density and temperature structure in coronal holes. Data from Skylab was limited, due to the very low intensities in holes and poor spectral resolution, leading to many line bends. High-resolution ultraviolet observations from instruments on SOHO spacecraft provided the opportunity to infer the density and temperature profile in coronal holes. Comparing the electron temperatures with ion temperatures, it was concluded that ions are extremely hot and the electrons are relatively cool. Using the CDS and SUMER instruments on the SOHO spacecraft, electron temperatures were measured as a function of height above the limb in a coronal hole. Observations of two lines from the same ion, O VI 1032 Å from SUMER and O VI 173 Å from CDS, were made to determine temperature gradient in a coronal hole. This way temperature of around 0.8 MK close to the limb was deduced, rising to a maximum of less than 1 MK at 1.15 $R_\odot$ ($R_\odot$ = 700,000 km), then falling to around 0.4 MK at 1.3 $R_\odot$. These observations preclude the existence of temperatures over 1 MK at any height near the center of a coronal hole. Wind acceleration by temperature effects is, therefore, inadequate as an explanation of the high-speed wind, and it becomes essential to look for other effects, involving the momentum and the energy of Alfvén waves.

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That the solar wind is emanating from coronal holes (open magnetic field regions in the corona) has been widely accepted since the Skylab era. But there was little additional direct observational evidence to support this view. Don Hassler and his colleagues found the Ne VIII emission blue shifted in the north polar coronal hole along the magnetic network boundary interfaces compared to the average quiet-Sun flow (see *Figure* 5). These Ne VIII observations reveal the first two-dimensional coronal images showing velocity structure in a coronal hole, and provide strong evidence that coronal holes are indeed the source of the fast solar wind. The apparent relationship with the chromospheric magnetic network, as well as the relatively large outflow velocity signatures at the intersections of network boundaries at mid-latitudes, is a first step towards a better understanding of the complex signature and dynamics at the base of the corona and the source region of the solar wind.

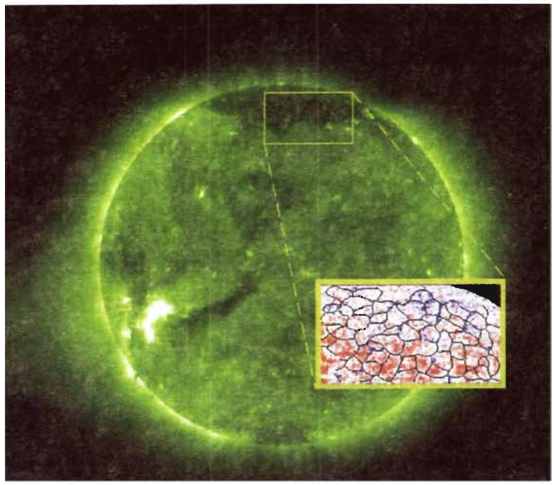

Figure 5. The Solar corona and polar coronal holes observed from EIT and SUMER instruments on SOHO. The 'zoomed-in' or 'close-up' region in the image shows a Doppler velocity map of million degree gas at the base of the corona where the solar wind originates. Blue represents blue shifts or outflows and red represents red shifts or downflows. The blue regions are inside a coronal hole or open magnetic field region, where the high-speed solar wind is accelerated. Superposed are the edges of 'honeycomb'-shaped patterns of magnetic fields at the surface of the Sun, where the strongest flows (dark blue) occur. (Credit: Don Hassler and SUMER-EIT/SOHO).

Concluding Remarks

A large amount of information concerning the physics of the Sun's atmosphere has been made available in recent years from highly successful spacecraft and ground-based instruments. We have made a tremendous progress in pinpointing the processes that maintain the Sun's hot corona and accelerate the solar wind

Box 3.

Using data from the LASCO coronagraph on board the SOHO spacecraft, the first three-dimensional (3D) views of massive solar eruptions, called coronal mass ejections CMEs have been produced. This new result is critical for a complete understanding of these dramatic phenomena. To fully understand the origin of these powerful blasts and the process that launches them from the Sun, we need to see the structure of CMEs in three dimensions. Views in three dimensions will help us to better predict CME arrival times and impact angles at the Earth. J Davila (NASA-GSFC, Greenbelt, MD) and T Moran (Catholic University, Washington) have analysed two-dimensional images from the ESA/NASA Solar and Heliospheric Observatory (SOHO) in a new way to yield 3D images. Their technique is able to reveal the complex and distorted magnetic fields that travel with the CME cloud and sometimes interact with the Earth's own magnetic field, pouring tremendous amounts of energy into the space near Earth.

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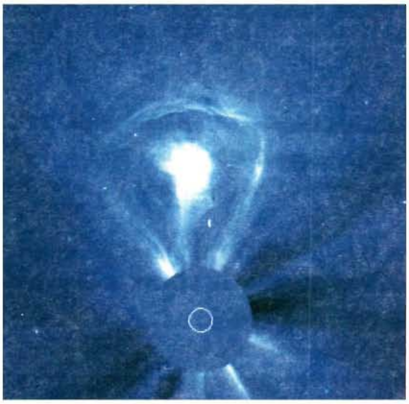

Figure A: A classical three-part CME inside the LASCO C3 field of view, showing a bright frontal loop (shaped like a lightbulb) surrounding a dark cavity with a bright core. This CME is headed roughly 90 degrees away from the Earth. The uniform disk in the centre of the image is where the occulter is placed, blocking out all direct sunlight. The approximate size of the Sun is indicated by the white circle in the middle.
(Credit: LASCO/SOHO, ESA-NASA)

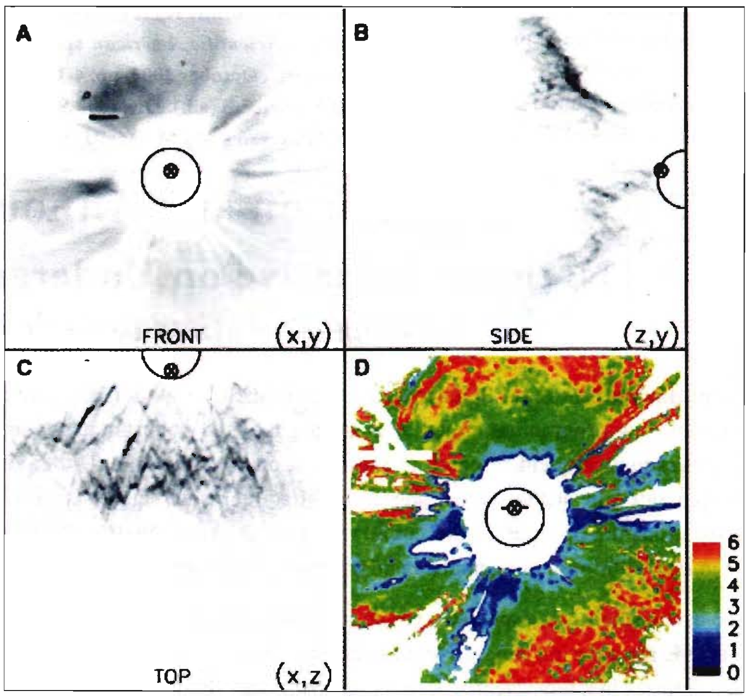

Figure B: A similar CME heading almost directly towards Earth, observed by LASCO C2 which has a smaller field of view than C3. The size of the Sun is indicated by the larger circle, and the x-marked circle on the Sun shows the origin of the CME. Panel (a) shows the total intensity (darker means more intensity) as imaged directly by LASCO. Only the narrow lower end of the 'lightbulb' shape is visible – the widest portion has expanded beyond the field of view, whereas the front part and the core are too dim to be seen or hidden behind the occulter. Panel (d) is a topographic map of the material shown in panel (a). The distance from the plane of the Sun to the material is colour coded – the scale in units of solar radii is shown on the side. Panels (b) and (c) show the intensity as it would have appeared to an observer positioned to the side of the Sun or directly above it, respectively. (Credit : J Davila and T Moran)

This is a landmark development in our quest for understanding CMEs and space weather.

as well as other solar mysteries. And the search goes on to unlock the tricks our Sun is performing.

Suggested Reading

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Information and Announcements

National Initiative on Undergraduate Science

Calling Scientists to visit HBCSE

Homi Bhabha Centre for Science Education (HBCSE), a National Centre of TIFR, Mumbai, has launched a major new programme aimed at nurturing talented undergraduates in basic sciences and promoting undergraduate student research in India. National Initiative on Undergraduate Science (NIUS) is to be implemented in academic collaboration with interested scientists of TIFR, BARC and other leading institutions/universities in the country. It is a natural sequel to the Olympiad programme in physics, chemistry, biology, mathematics and astronomy for which HBCSE is the nodal Centre of the country.

We invite scientists, especially young physicists, chemists, biologists (and those in allied fields) to visit HBCSE for a period ranging from a month to a year. The Centre is developing undergraduate research laboratories in a few selected areas. Likewise, some theoretical areas and problems will be identified that are suitable for review and protoresearch by undergraduate students. We expect visiting scientists to contribute to this effort. Interested scientists from national institutes, university and college teachers may write to Prof. Arvind Kumar, Centre Director, HBCSE, Tata Institute of Fundamental Research, VN Purav Marg, Mankhurd, Mumbai 400 088, stating (a) the period of intended visit, (b) the nature of work they propose to do at HBCSE, (c) names of two referees (for visits exceeding 3 months), and attaching a copy of CV. **Visit our websit: http://www.hbcse.tifr.res.in for more details.**

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