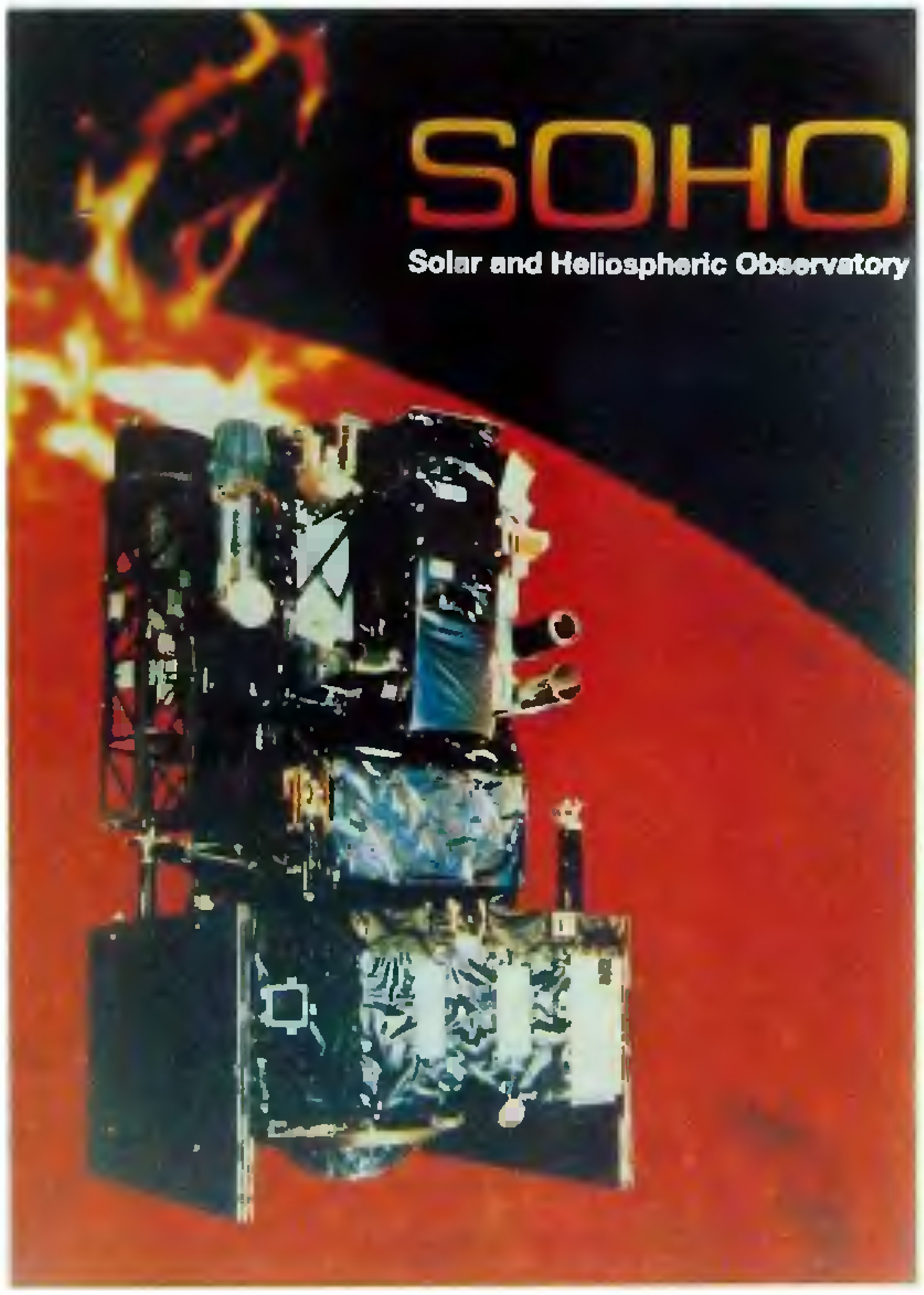
SOHO hunts elusive solar prey

B. N. Dwivedi and Anita Mohàn

The Solar and Heliospheric Observatory, SOHO, is a project of international cooperation between ESA and NASA to study the Sun from its deep core to the outer corona and the solar wind. To achieve its goals, SOHO carries a complement of twelve sophisticated, state-of-the-art instruments. In this article, we present a brief account of this ambitious project and highlight some of its achievements since the SOHO spacecraft turned an unblinking eye on a turbulent Sun from its vantage point in space on 14 February 1996.



'All that exists was born from Surya, the God of gods'

Rig Veda

LAUNCHED on 2 December 1995, the solar space observatory SOHO stationed itself into a 'halo orbit' around the L1 Lagrangian point (the point 1.5 million kilometers away from us at which the gravitational pull of the Earth balances that of the Sun) on 14 February 1996 (cf., Figure 1). Since then, the scrutiny of the Sun has gone on 24 hours a day, 7 days a week and will continue for another couple of years or so. SOHO was also a medieval Anglo-French hunting cry; but this time the hunt is for answers to basic questions about the Sun – from its deep core to the outer corona and the solar wind. All previous solar observations were periodically interrupted as our planet 'eclipsed' the Sun. SOHO, a most ambitious project of ESA and NASA, provides the first long, clean uninterrupted view of the Sun to answer some riddles like (i) what are the structure and dynamics of the solar interior?, (ii) why does the corona (the tenuous outer solar atmosphere that can be seen with the naked eye during eclipses and which is much hotter than the solar surface) exist and how is it heated?, and

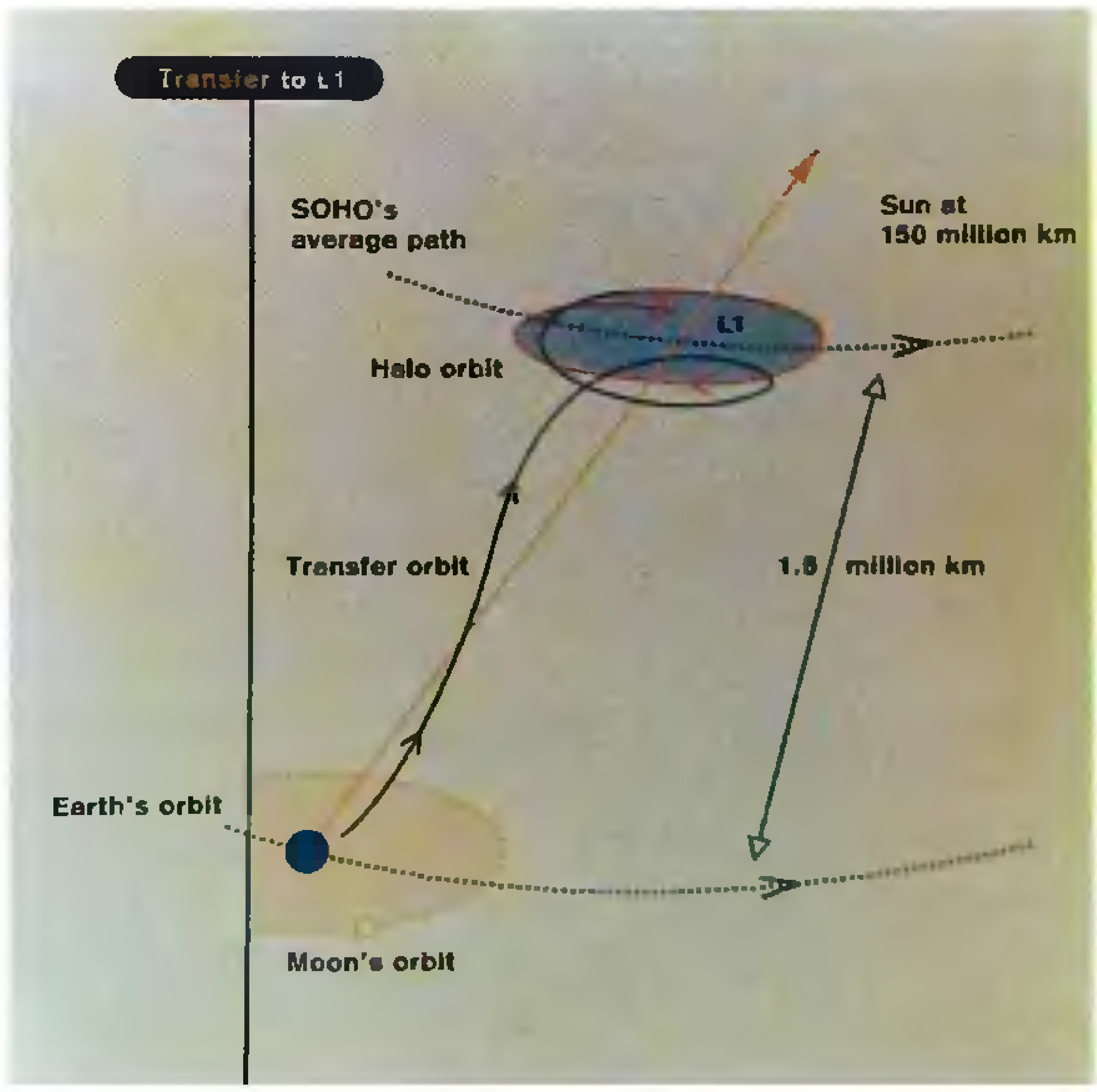


Figure 1. To the sunward station. After its launch on 2 December 1995 by an Atlas II A Centaur into a transfer trajectory to the first Lagrange point L1, SOHO arrived at its vantage point on 14 February 1996 in an orbit 1.5 million kilometers nearer to the Sun than the Earth's own orbit. At L1, or Lagrange point No. 1, the gravitational pull of the Sun is balanced by the pull of the Earth and the centrifugal force acting on a spacecraft orbiting in step with the Earth. SOHO remains hovering around that relative position, in a 'halo orbit', while it accompanies the Earth in its annual march around the Sun.

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(iii) where and how is the solar wind (the particle streams which represent the solar mass loss) accelerated? Among other tricks of the Sun (laboratory for astrophysics), for instance, it is one of the few places where observations and theoretical considerations may give us sufficient insight into a deeper understanding of the effects of magnetic field. This includes its fascinating attribute that, like a biological form, it can reproduce itself. The complexities of magnetic field are fascinating: in some cases it serves to refrigerate the gas (e.g. sunspots) while in others it serves to heat the gas to millions of degrees (e.g. active corona).

SOHO carries a complement of twelve sophisticated, state-of-the-art instruments: Global Oscillations at Low Frequency (GOLF), Variability of solar Irradiance and Gravity Oscillations (VIRGO), Solar Oscillations Investigation/Michelson Doppler Imager (SOI/MDI), Solar Ultraviolet Measurements of Emitted Radiation (SUMER), Coronal Diagnostic Spectrometer (CDS), Extreme-ultraviolet Imaging Telescope (EIT), Ultraviolet Coronagraph Spectrometer (UVCS), Large Angle Spectroscopic Coronagraph (LASCO), Solar Wind Anisotropies (SWAN), Charge, Element and Isotope Analysis System (CELIAS), Comprehensive Suprathermal and Energetic Particle analyser (COSTEP) and Energetic and Relativistic Nuclei and Electron experiment (ERNE). For a detailed description of all these instruments, see ref. 1. The spacecraft maintains contact with the ground through the NASA Deep Space Network (DSN). The DSN is a network of three radio antennas spread around the world – the first is in Goldstone, USA; the second near Madrid, Spain and the third in Canberra, Australia. Together, these antennas provide continuous links to spacecraft wherever they happen to be in relation to the Earth. Planning, co-ordination and operation of the spacecraft and the scientific payload is conducted from the Experiment Operation Facility (EOF) at NASA Goddard Space Flight Center (GSFC).

SOHO probes the Sun's interior

The Sun sings to itself and the SOHO makes a hi-fi recording of the Sun's song with its three instruments on board: GOLF, VIRGO and SOI/MDI. These instruments record widespread throbbing motions of the Sun's visible surface. They detect rhythmic variations in the intensity of light or in its wavelength. The oscillations are caused by sound waves reverberating through the Sun. Just as seismology reveals the Earth's interior by the study of earthquakes, or seismic waves, so helioseismology looks below the Sun's surface. SOHO's helioseismology experiments, conducted from a steady platform in space, provide greater clarity than the ground-based stations (e. g. GONG).

SOI/MDI observes a million points on the Sun's visible surface once a minute. It can detect subtle, short-range oscillations due to sound waves penetrating only a short distance into the Sun. And it has generated the first chart of horizontal motions of gases just below the visible surface, indicating shallow flows. Ground-based instruments have detected motions deep inside the Sun. That can be done with SOHO too, but it also provides the missing link to motions at the visible surface. With the help of first movies of the Sun's interior and by relating them to the measurements of surface magnetic fields, we may begin to solve the mystery of dark blemishes on the Sun: why do sunspots occur and why do they become most numerous every eleven years or so?

The instrument VIRGO monitors large-scale oscillations that penetrate all the way to the centre of the Sun. It shows that the variation of the sound-speed with depth is smoother than in the theoretical models[2]. Theoretical prediction is that the speed of sound should show jumps corresponding to layers of different compositions deep in the Sun. This suggests that the distribution of helium abundance is smoother than in the theoretical models. A smoother distribution of helium would have a profound effect on models of nuclear fusion in the core of the Sun. And such a change in the understanding of the Sun's internal engine could help solve one of the most nagging problems in solar physics: why do detectors on Earth pick up fewer neutrinos than predicted – a discrepancy known as the solar neutrino problem.

SOHO tunes in the Sun's atmosphere

The solar atmosphere is studied by five SOHO instruments. Three of them, viz. SUMER, CDS and EIT, study the chromosphere and the transition region into the corona. Two other instruments, viz. UVCS and LASCO, examine the middle corona between 1.3 and 10 and 1.1 and 30 solar radii from the Sun-centre. The imaging instruments have already yielded surprises, including spectacular solar images that are suggestive of a turbulent Sun. Even though the Sun is currently in the quietest phase of its eleven-year cycle of activity, members of the SOHO team have recorded vigorous action going on in the Sun every day. Short, hair-like jets of strong emissions decorate the solar atmosphere, not clearly seen before. Recorded by EIT, these spicules of various kinds tell of energetic upheavals that may be responsible for heating the outer atmosphere to more than a million degree temperature Celsius. Also visible in the ultraviolet images are plumes-like ropes, stretching far into space from the north and south poles of the Sun. Figure 2 shows the image of the Sun taken in extreme-ultraviolet light at 195 Å from Fe XII ion by the EIT on 9 May 1996. This figure shows solar plasmas at 2 million degrees, confined by magnetic structures. Movies

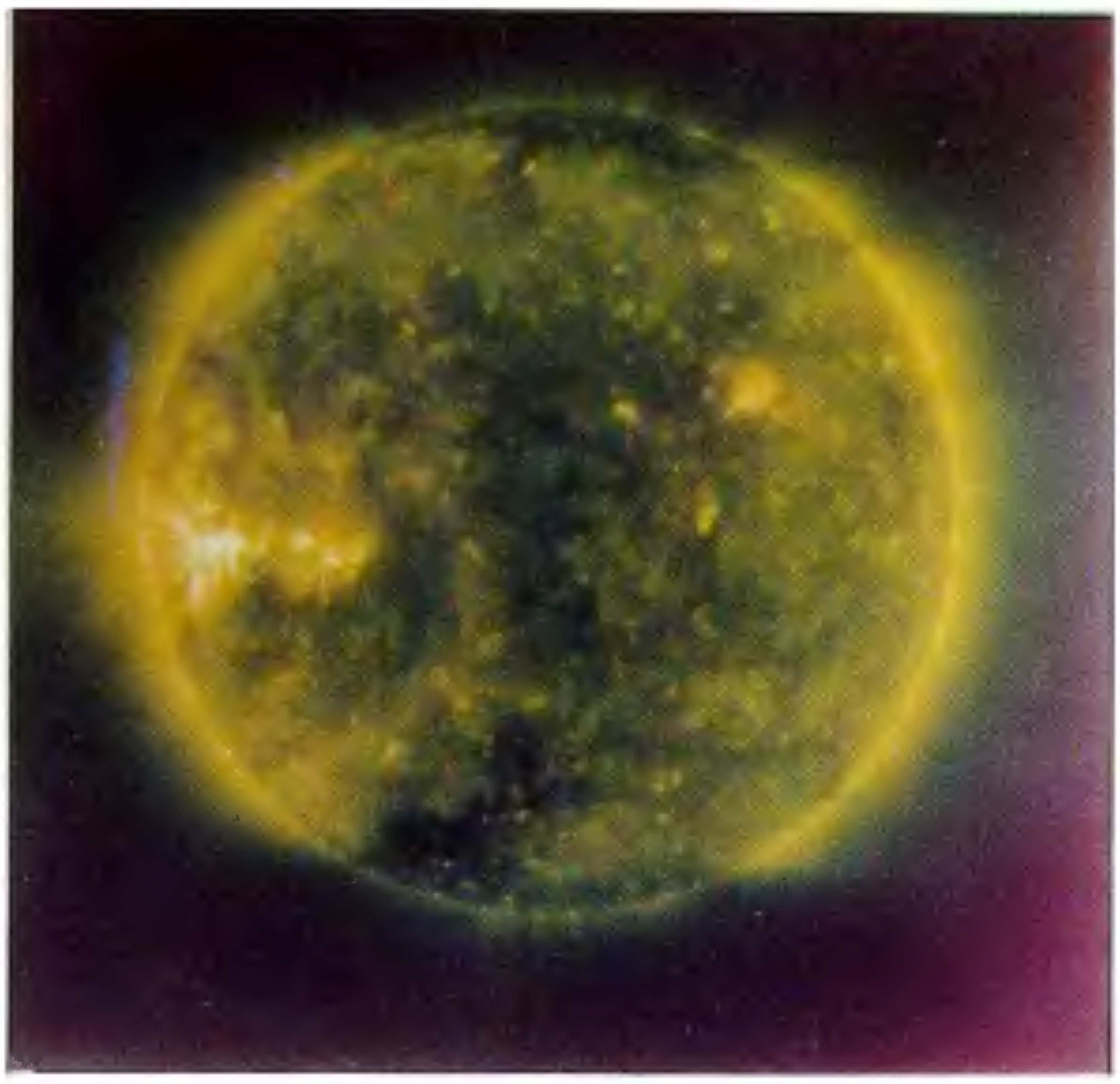

Figure 2. The image of the Sun in the extreme-ultraviolet light at 195 Å from Fe XII ion taken by the EIT on 9 May 1996. This image shows solar plasmas at 2 million degrees, confined by magnetic structures (courtesy, EIT/SOHO team).

Figure 3. This image was taken using the LASCO on 1 May 1996. The white circle shows the location of the Sun, hidden behind an occulting disc, to allow observation of the diffuse outer layers of the Sun's atmosphere. The image shows an enormous eruption, known as a coronal mass ejection (CME), emanating from the left hand edge of the Sun and travelling out at a speed of several hundred kilometers per second. Also captured on the image (at the top) is the comet Hyakutake on its approach to the Sun (courtesy, LASCO/SOHO team).

of such images have revealed that the solar atmosphere is extremely dynamic, even though it is currently in its 'minimum' state.

Images obtained with SOHO's visible-light coronagraph, LASCO, show the Sun releasing billions of tons of gas into the solar system that can affect the Earth's own space environment. Although the Sun is relatively very quiet, a couple of outbursts have already been recorded by LASCO. Repeated observations over several hours, made from SOHO's vantage point in space where the Sun never sets, results in impressive movies of the events. The coronagraph masks the glaring light from the Sun's visible surface to make the corona observable. LASCO has a particularly wide field of view, out to fifteen times the solar diameter on either side. As it is a composite instrument, LASCO can also observe the atmosphere quite close to the solar surface. This capability of LASCO is helping the interpretation of the mechanism of the coronal mass ejections. For the first time, we see the Sun preparing itself for a mass ejection. In the days preceding such an event, multiple magnetic loops appear in the images of the inner corona. They tell us that the Sun is reorganizing its magnetic field. This destabilizes the solar atmosphere and causes the mass ejection. This observation would enable us to work in advance solar outbursts, endangering low-flying satellites, and may harm power distribution systems on the Earth. Figure 3 shows the LASCO image with an enormous eruption on 1 May 1996. Also captured on the image (at the top) is the comet Hyakutake on its approach to the Sun. Tracking comets by a solar spacecraft reminds us of the fact that the solar wind was discovered by the study of comet tails.

The instrument SUMER is equipped with a normal incidence spectrometer to study plasma flows, temperatures, densities and wave motions from the chromosphere to the corona from ten thousand to over a million degrees with high spatial (1.5 arcsec, 1 arcsec = 725 km) and high temporal (~ 10 sec) resolution. Earlier it was not possible to have a consistent view of the solar atmosphere by measuring line profiles and intensities, Doppler shifts and line broadenings with such a high accuracy from the chromosphere to corona by a single instrument. The SUMER is providing an enormous amount of excellent high-resolution EUV data to address such basic questions in solar physics as the existence of corona and the acceleration of solar wind. Image of the Sun in the EUV light (C IV line at 1548 Å) taken by the SUMER (cf. Figure 4) reveals the million-degree corona. The first results from SUMER will shortly appear in *Solar Physics*[3]. Analysis of the high-quality EUV data from SUMER seem to pinpoint processes that maintain the corona and accelerate the solar wind[4]. Plasma diagnostics applicable to CDS and SUMER instruments have been discussed earlier[5] and hence will not be repeated here. The early indications of SOHO's performance amply justify the creation of a Sun-grazing spacecraft capable of observing ultraviolet

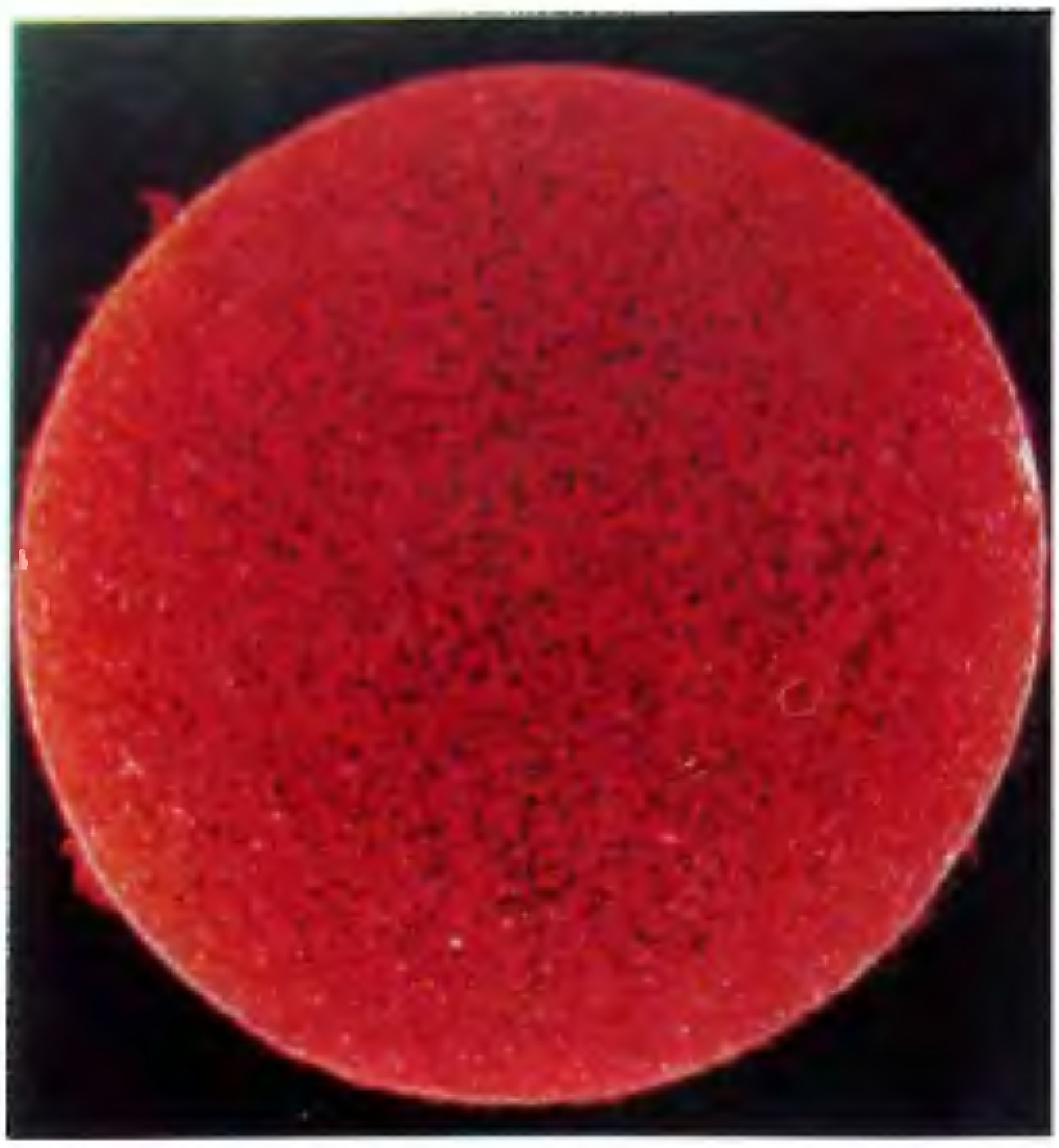

Figure 4. The Sun in the EUV light (C IV line at 1548 Å) reveals the million-degree-temperature corona (courtesy, SUMER/SOHO team).

emissions that are blotted out by the Earth's atmosphere. The imager EIT, ultraviolet spectrometers SUMER and CDS, and the ultraviolet coronagraph UVCS (an imager for the outer atmosphere) are being used to analyse the violent processes on the Sun at a wide range of wavelengths. Interpretation of these observations is likely to give us a much better insight of the Sun.

SOHO probes the solar wind *in situ*

The hot solar atmosphere is expanding into interplanetary space, filling the solar system with a perpetual flow of electrified matter called the solar wind. Spacecraft have made *in situ* measurements of the solar wind near the Earth, showing that it manifests itself in two ways, either as wind moving at a relatively slow speed of 300 to 400 km/s, or as high-speed streams of 600 to 800 km/s. What forces propel the solar wind to these supersonic speed with such tremendous energy, and where do the components of the solar wind come from? This is one of the principal objects of the SOHO mission through its three instruments on board, CELIAS, COSTEP, and ERNE. By analysing the solar wind, SOHO investigators have learnt that the relative abundances of different isotopes of magnesium in the solar wind are close to those found on Earth. This indicates that the Sun's cool surface probably preserves a good sample of the primordial solar system's makeup.

SWAN instrument on SOHO surveys the sky around the Sun to examine the ultraviolet glow from hydrogen atoms lit by the Sun. These atoms come on a breeze from the stars that blows through the solar system. But the competing wind of charged particles from the Sun breaks the incoming atoms, so that they no longer emit their characteristic wavelength. The result is a hole in the pattern of emissions downstream from the Sun. The surviving emissions are brightest upstream, and far above the plane of the Sun's equator. Accordingly, it appears that the solar wind blowing from high-latitude regions of the Sun is less strong than from lower latitudes, at least during the present quiet phase of the eleven-year cycle of solar activity. The Earth is also visible in the maps being produced by SWAN because a cloud of hydrogen gas called the 'geocorona' envelops it and glows in the ultraviolet light. The 'geocorona' would hamper observations of the interstellar glow by satellites close to the Earth. As SOHO sees the geocorona from the outside, it can monitor the effects of solar activity on the Earth's outer atmosphere. At the present time of a quiet Sun, the sky maps clearly indicate a situation of increased solar wind around the Sun's equator. What will happen when the Sun becomes stormier remains to be seen. This will then enable to study important changes in the solar wind's impact on the interstellar gas, revealed by the changes in the sky maps.

SOHO makes sense of the moody Sun

Observing the Sun in different ways, SOHO will link events in the Sun's atmosphere and solar wind to activity beneath the visible surface and the Sun's strange song – to understand the Sun better, and to learn how it rules the interplanetary space and the Earth's environment. In the next two years or so, SOHO will unravel some of the mysteries of the Sun. And William Butler Yeats says, 'I will . . . pluck till time and times are done . . . the golden apples of the Sun', the enthralled SOHO scientists have only just started.

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