The proof of uniqueness, is, without doubt, the significant part of the above result. Kruzkov proved the same for equation (18) among solutions of bounded variation assuming entropy condition. His proof is quite complicated and ingenious because one has to play with inequalities (6). Assertion in Theorem 8 (ii) is much stronger. However, the proof given in ref. 7 is surprisingly not very complicated.

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Some publications of P-L. Lions

On kinetic equations and transport theory

1. (with DiPerna, R. J.) On the Cauchy problem for Boltzmann equations. Global existence and weak stability, *Ann. Math.*, 1980, **130**, 321–366.
2. (with DiPerna, R. J.) Global solutions cf Boltzmann equations and the entropy inequality, *Arch. Rat. Mech. Anal.*, 1991, **114**, 47–55.
3. (with DiPerna, R. J.) Global weak solutions of Vlasov–Maxwell systems, *Comm. Pure Appl. Math.*, 1989, **42**, 729–757.
4. (with DiPerna, R. J.) Ordinary Differential Equations, Sobolev spaces and transport theory, *Invent. Math.*, 1989, **98**, 511–547.
5. (with Golse, F., Perthame, B. and Sentis, R.) Regularity of the moments of the solutions of a transport equation, *J. Funct. Anal.*, 1988, **76**, 110–125.
6. (with DiPerna, R. J.) Solutions globales d'équations du type Vlasov–Poisson, *C. R. Acad. Sci., Paris*, 1988, t307, Série I, 655–658.

On viscosity solutions

7. (with Crandall, M. G.) Viscosity solutions of Hamilton–Jacobi equations, *Trans. Am. Math. Soc.*, 1983, **277**, 1–42.
8. (with Crandall, M. G. and Ishii, H.) User's guide to viscosity solutions of second order partial differential equations, *Bull. Am. Math. Soc.*, 1992, **27**, 1–67.

On the theory of concentration – compactness

9. The concentration–compactness principle in the calculus of variations, The locally compact case:

   Part 1. *Ann. I.H.P., Anal. Nonlin.*, 1984, **1**, 109–145.
   Part 2. *Ann. I.H.P., Anal. Nonlin.*, 1984, **1**, 223–283.

10. The concentration–compactness principle in the calculus of variations, The limit case:

    Part 1. *Riv. Mat. Ibero – americana*, 1985, **1**, 145–201.
    Part 2. *Riv. Mat. Ibero – americana*, 1985, **1**, 45–121.

On the theory of compensated compactness

11. (with Coifman, R., Meyer, Y. and Semmes, S.) Compacité par compensation et espaces de Hardy, *C. R. Acad. Sci. Paris*, 1989, t309, Série I, 945–949.

On viscous compressible flows

12. Lectures on viscous compressible flows given at International Centre for Mathematical Sciences, Edinburgh, November 1995.

Viewing solar mysteries from space

Bhola N. Dwivedi

The solar atmosphere presents a rich tapestry, providing astrophysics with new, unexpected designs of great intricacy. And for millennia we have based our views of the Sun (and the universe) in the narrow visual window of the electromagnetic spectrum. Over the last fifty years or so, this has been extended to the radio, ultraviolet, X-ray, gamma-ray and other parts of the spectrum. This article presents solar mysteries viewed from major space programmes in the past and future space missions underway to unravel these mysteries.

FOR millennia, the Sun (and the universe) has been viewed in the visual light that unaided human eyes are capable of seeing. As the bestower of light and life, the ancients made God out of the Sun. There was consternation, therefore, back in the seventeenth century when Galileo demonstrated that the Sun was not the immaculate object as supposed by ancient philosophers. Since then, interests in our nearest star, the Sun, with its sunspots and related magnetic phenomena (see Figure 1), have been passing gently from the consternation of philosophers to the fascination of astronomers and astrophysicists. Therefore, the observations of the Sun and their interpretations are of universal importance for at least two fundamental reasons. First, our Sun is the source of energy for the whole planetary system including our own planet and almost all aspects of our life have direct relations to what happens on the Sun; and second, our Sun

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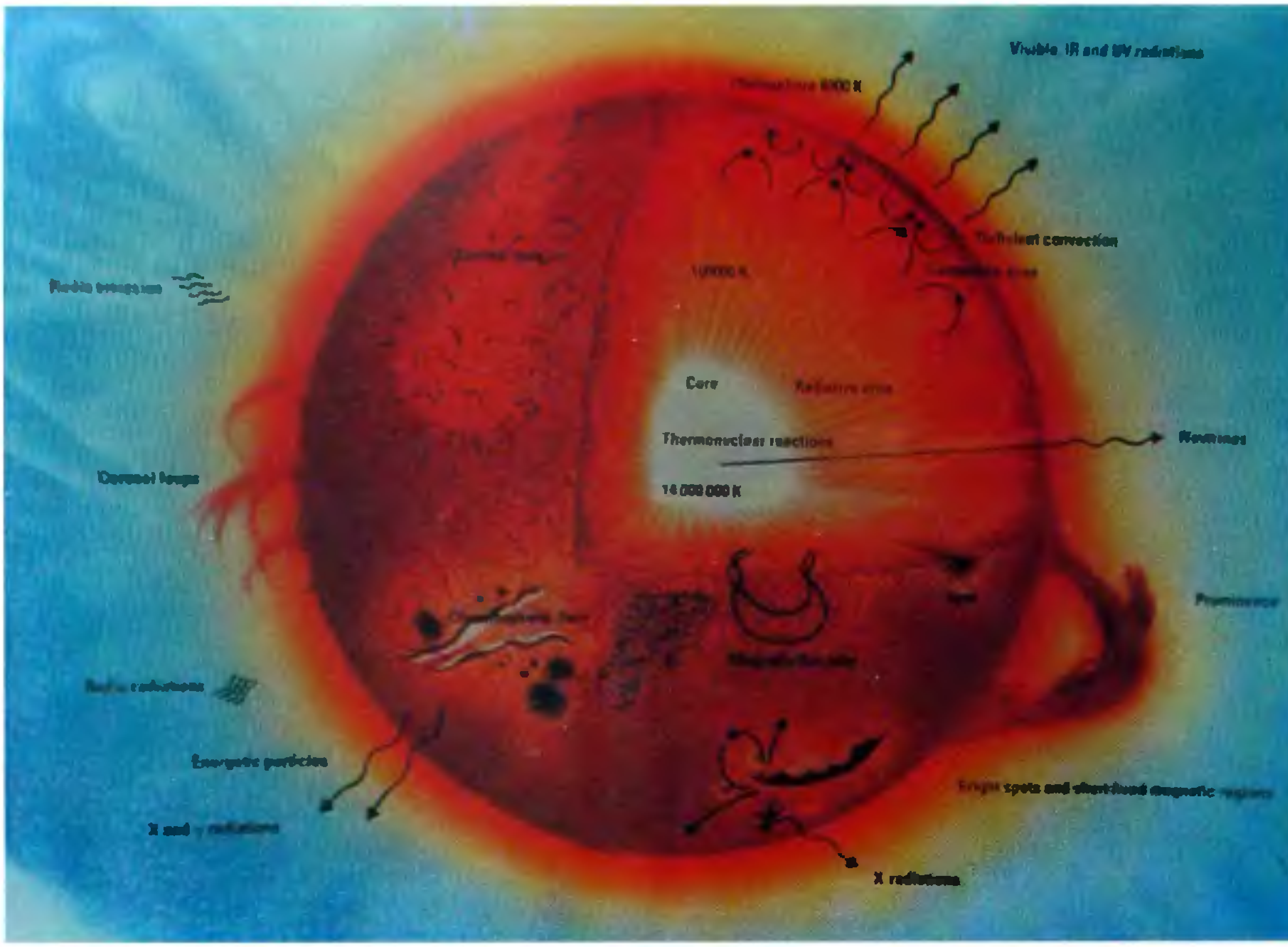

Figure 1. Brief view of our star the Sun: Solar energy derives from nuclear reactions in the core of the Sun at about 16 million degrees, the pressure being 300 billion times the atmospheric pressure on the Earth. This energy (in the form of X- and gamma-rays) is first transmitted through the radiation zone and then the convection zone (outer 200,000 km out of a total solar radius of 700,000 km). Because of tremendous pressure, this energy is continually absorbed and re-absorbed and may take 10 million years to reach the surface of the Sun. The rotation and convection combine to produce dynamo action, where electric currents and magnetic fields are generated and change with a 22-year cycle. The magnetic field leads to the formation of sunspots that combine to form active regions together with the surrounding gas. Such regions often explode into flares which produce intense local heating and energetic particles, and can cause coronal transients which expand into space, envelop the Earth, and generate magnetic storms, including auroral displays. Visible solar radiation comes from the thin cool (about 6000 degrees) layer called photosphere, which is a 'barrier' for observing both the Sun's interior and its outer atmosphere. SOHO will use special techniques to open a window into the Sun's interior and out into its extended atmosphere. The chromosphere is somewhat hotter (about 10,000 degrees), while corona is so hot (greater than a million degrees) that it remains as one of the unresolved problems of solar science. (Courtesy, ESA.)

is the only star among the billions of stars in our sky, of which we can resolve surface details and see astrophysical processes at work – processes on enormous scale, which occur not only on other stars but also in other astrophysical contexts throughout the universe.

When viewing the Sun from the surface of the Earth, all the observations are unfortunately restricted to the visible and the radio windows of the solar radiation. All the other windows of the electromagnetic spectrum, namely, infrared, ultraviolet, extreme-ultraviolet, X-rays and gamma-rays are completely absorbed by the Earth's atmosphere and never reach the surface of our planet (see Figure 2). Likewise, the streams of plasma (known as solar wind), continuously flowing from the Sun and high-energy particles emanating from the acceleration processes on the Sun do not reach the Earth's surface, since they are deflected by the Earth's magnetic field. Both these facts are surely a boon to life on Earth which could not survive without shielding from the damaging ultraviolet radiation, X-rays, gamma-rays and energetic particles. But from the viewpoint of astronomers, confined to the surface of the Earth, it is indeed frustrating not to be able to see the short-wavelength, high-energy, universe. Thus, the most important physical processes on the Sun (and of course, anywhere in the universe) which are best understood via the analysis and interpretation of these

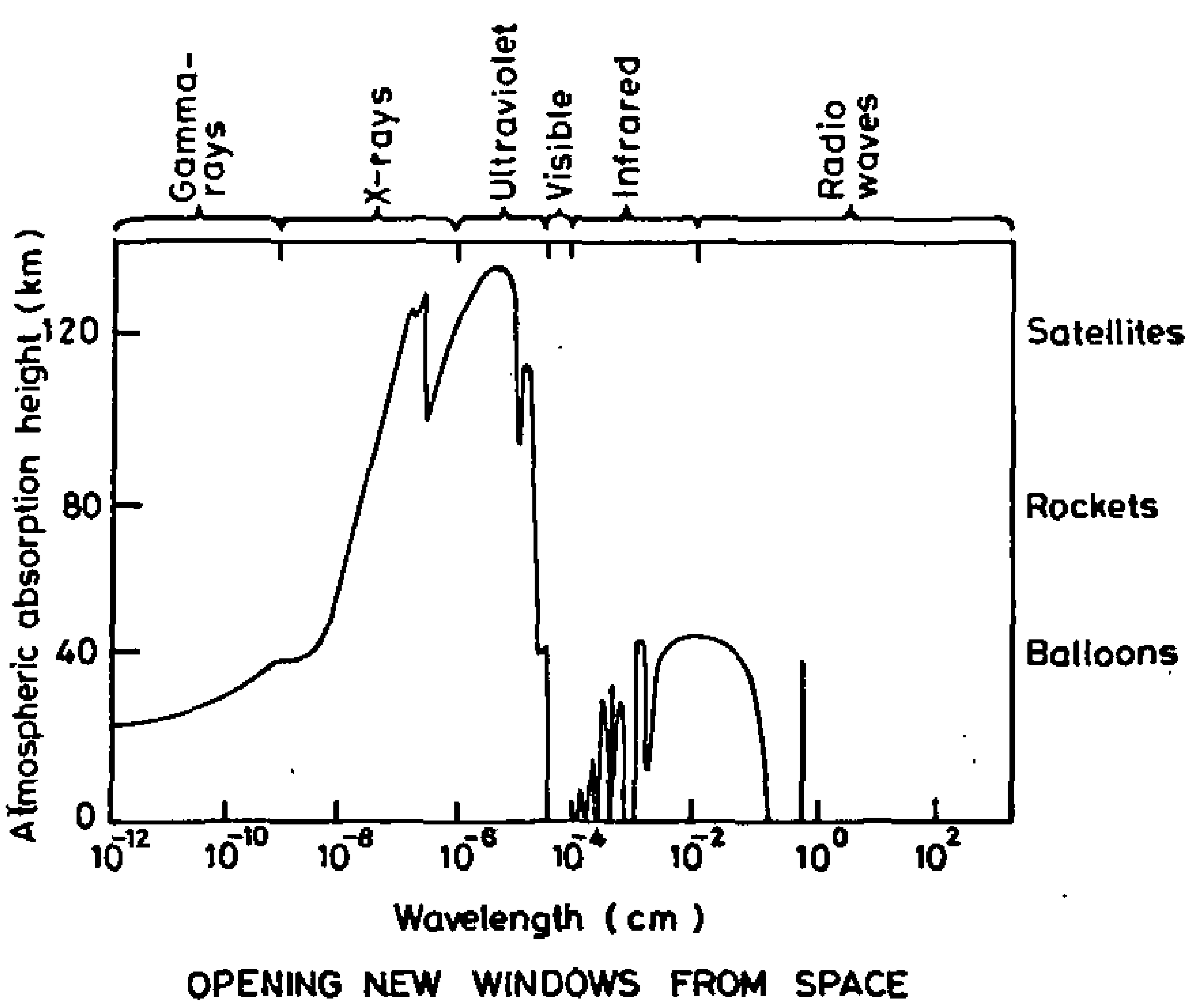

Figure 2. Modern astronomy uses all regions of the electromagnetic spectrum. The Earth's atmosphere absorbs most infrared light as well as gamma-rays, X-rays, and ultraviolet light. To observe this radiation, we must go above our atmosphere. This plot depicts the atmospheric absorption of electromagnetic radiation showing the spectral regions accessible by balloons, rockets and satellites.

high-energy radiations, cannot be observed at all by the ground-based experiments. Fundamental solar processes are also being studied on ground (e.g., GONG: Global Oscillation Network Group) and underground (neutrino telescopes), while solar radio astronomy has attained enough sophistication to compete with space probes for coronal studies.

To observe the X-ray and EUV corona or solar energetic particles, therefore, instruments must be flown on balloons, rockets or satellites to altitudes above our atmosphere which is opaque to these radiations and out of the Earth's magnetic envelop (magnetosphere) which deflect energetic particles. Thus, the progress in this area had to await the arrival of the space age. As a result of space-borne instruments, we now have a much better understanding of the solar atmosphere. Chromosphere is the region of the solar atmosphere above the photosphere and temperature minimum characterized by a rise in temperature with height and much fine structure, mostly in the form of a network of bright patches; the transition region lies between the chromosphere and the corona characterized by a steep rise in temperature; and the corona is the high-temperature region extending high above the Sun consisting of almost fully ionized plasma in closed magnetic field loops or of plasma expanding outwards along open magnetic field lines. The X-ray and EUV corona appear to be highly structured consisting of loops, streamers and holes, the shapes of which are controlled by magnetic field (see Figure 3). Variations of this magnetic field cause flares and accelerate particles up to cosmic-ray energies. We also record all kinds of particles in interplanetary space that continuously stream out or intermittenly eject from the Sun[1].

Some of these observations are carried out by balloons flying at high altitudes. We have then much better visibility in the infrared, and observations can extend farther into the ultraviolet light. If launched at higher geomagnetic latitudes, balloons can also record energetic particles which penetrate to lower altitudes close to the geomagnetic poles. Rockets, of course, go significantly higher, carrying instruments which are capable of observing the entire electromagnetic radiation. Although the stabilization and accurate pointing of a rocket carrying such experiments have reached a high degree of sophistication, the brevity of a rocket flight lasting typically ~5 minutes during which it is capable of accumulating the scientific data is an obvious disadvantage. Thus, the entire electromagnetic spectrum and energetic particles from the Sun are best recorded by instruments on board satellites orbiting the Earth or by space-probes orbiting the Sun.

There are, in principle, two different modes for solar observations that one can carry out in space. The easier and simpler one records the radiation of the whole Sun at selected wavelengths and energies without spatial resolution. Many satellites and space probes have been doing this for over three decades, looking towards the Sun and recording the ultraviolet, extreme-ultraviolet, soft and hard X-ray, gamma-ray or energetic particle emissions from the Sun into the interplanetary space. This kind of observation was made by most sophisticated instruments at the three ISEE (International Sun–Earth–Explorer) satellites, of which two were orbiting the Earth and the third was staying near the libration centre between the Earth and the Sun. For X-ray and gamma-ray energies, and particle radiation, this is the easiest mode to be accomplished. However, we need to know from where on the Sun and how the radiation has been emitted, in order to understand the structure of the emitting source and the physical processes that produce the radiation. This is achieved by the other mode of solar observations – the imaging of the Sun.

To accomplish this second mode is much more difficult (and expensive). In the first mode, a detector with a wide field of view (several degrees of arc) looking in the direction of the Sun (the angular diameter of which is half-a-degree of arc) gives us all the information we need. If we want to image the Sun, however, we must point the satellite detector all the time exactly at the place we want to image. For example, if we want to image a part of the solar surface with a spatial resolution of one arcsecond (about the best resolution we get at the Earth; one arcsec = 725 km), we must keep the instrument pointed at the Sun all the time with this extremely high precision, which is not easy to achieve. Moreover, the high-energy radiation cannot be imaged by means of the optics commonly used in the optical

Figure 3. Stanford/MSFC Rocket X-ray Telescope image of the Solar Corona, taken on 23 October 1987 at 18:08 UT (64 second exposure). The million-degree-corona, photographed by a multi-layer Cassegrain X-ray telescope in the 171–175 Å, is dominated by Fe IX and Fe X emission lines. (Courtesy, A. B. C. Walker, Jr.)

range at ground-based observations. One has to use special optical materials in the ultraviolet, quite different optical arrangements in soft X-rays, and completely new imaging methods (collimators), without any use of optical surfaces, at still higher energies. To achieve high resolution with these equipments is not easy. All this makes good imaging of solar features from a satellite a difficult and expensive task.

The first attempts to image the Sun were made aboard the Orbiting Solar Observatories (OSOs), consisting of a rotating wheel structure and a section permanently pointed at the Sun, carrying several imaging instruments. However, their spatial resolution was much worse than that of instruments in the optical range based on the Earth. Although we learned a lot from the OSO observations about the physical processes on the Sun, the spectacular success came only with the launch of the NASA spacecraft, Skylab, in May 1973. It was the first manned observatory, with crews of astronauts being ferried up to the spacecraft for periods of several weeks on three occasions during the nine-month-long mission. An array of instruments called the Apollo Telescope Mount (ATM) onboard Skylab was designed to study the Sun in various wavelengths: soft X-ray, extreme-ultraviolet, ultraviolet and white-light. Observations from these instruments gave us an enormous amount of completely new information about the Sun. For the first time, we got high-resolution (2 arcsec) images of the solar corona all over the disc in soft X-rays; frequent high-quality images of the corona above the solar limb up to a distance of several solar radii; images of the Sun in many spectral lines of different elements throughout the whole solar spectrum, and profiles of these lines in various features of the solar atmosphere[2]. This set of instruments discovered the existence of coronal holes (regions of substantially reduced radiation), and demonstrated that these parts of the solar corona, where the magnetic field-lines go straight out of the Sun, are the sources of the high-speed solar wind. Everywhere else ('non-hole' corona), the magnetic field is closed and the whole corona is thus composed of a variety of loops. The magnetic field in these loops confines hot and dense coronal plasma and makes it thus visible in the X-ray and extreme-ultraviolet images. Another Skylab discov-

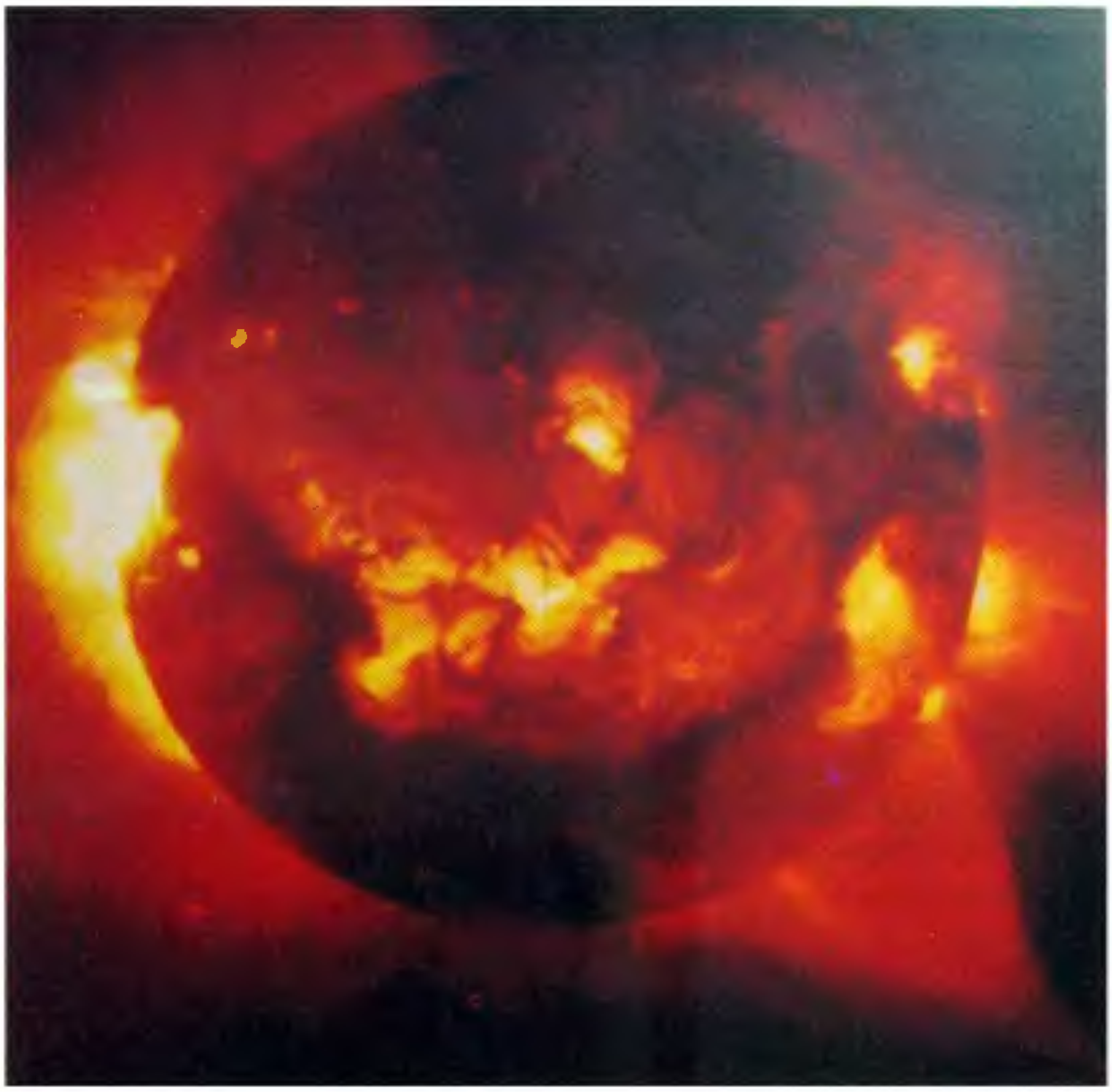

Figure 4 *a*. Soft X-ray image of the Sun on 25 January 1992, taken with the Soft X-ray Telescope (SXT) aboard Yohkoh using a red temperature colour in which the bright part corresponds to high-intensity regions, while the dark-red part corresponds to low-intensity regions. The picture shows active regions with thread-like structures as well as a number of small X-ray bright points in dark coronal holes. (Courtesy, D. Alexander.)

ery was that of the 'X-ray bright points', small magnetic dipoles emerging in high numbers to the surface of the Sun. Skylab also discovered the existence of coronal transients (which we now call coronal mass ejections), enormous clouds of plasma expanding from outbursts near the solar surface through the outer corona into interplanetary space.

The next highly sophisticated solar satellite, the Solar Maximum Mission (SMM) was launched into an orbit around the Earth on 14 February 1980. This satellite carried seven different experiments, primarily designed to observe flares or associated phenomena in a wavelength range extending from white-light to gamma-rays. As the spacecraft was unmanned, the data had to be recorded electronically and telemetered down to ground stations. A large number of flares was observed as this satellite operated at times of high solar activity. Study of hard X-ray emission revealed the extremely high temperatures in flares, e.g. up to 30 million degrees Kelvin for the largest outbreaks. The presence of upward-flowing hot gas, with velocities of several hundred kilometres per second, was detected at the onset of the flares. These flows seemed to occur simultaneously with bursts of energetic, hard X-rays with wavelengths much less than 0.1 nanometres.

Other satellites operating over the period of solar cycles 21 and 22 included the US satellite P78-1 and the Japanese Hinotori satellite. The P78-1 spacecraft carried the SOLWIND coronagraph and soft X-ray spectrometers which obtained the first observations of the broadening and shifts of soft X-ray lines emitted during the solar flare impulsive phase. Hinotori carried a soft X-ray spectrometer, obtaining the highest-resolution spectra, and an imaging hard X-ray instrument. Spacelab 2 was a week-long mission on the Challenger Space Shuttle in the summer 1985. A large number of scientific instruments – biological, astronomical and solar – filled the bay of the Shuttle, and were operated by astronauts. The solar instruments included an extreme ultraviolet spectrometer (CHASE) to measure the coronal helium abundance, an ultraviolet high-resolution telescope and spectrograph (HRTS) and a high-resolution optical

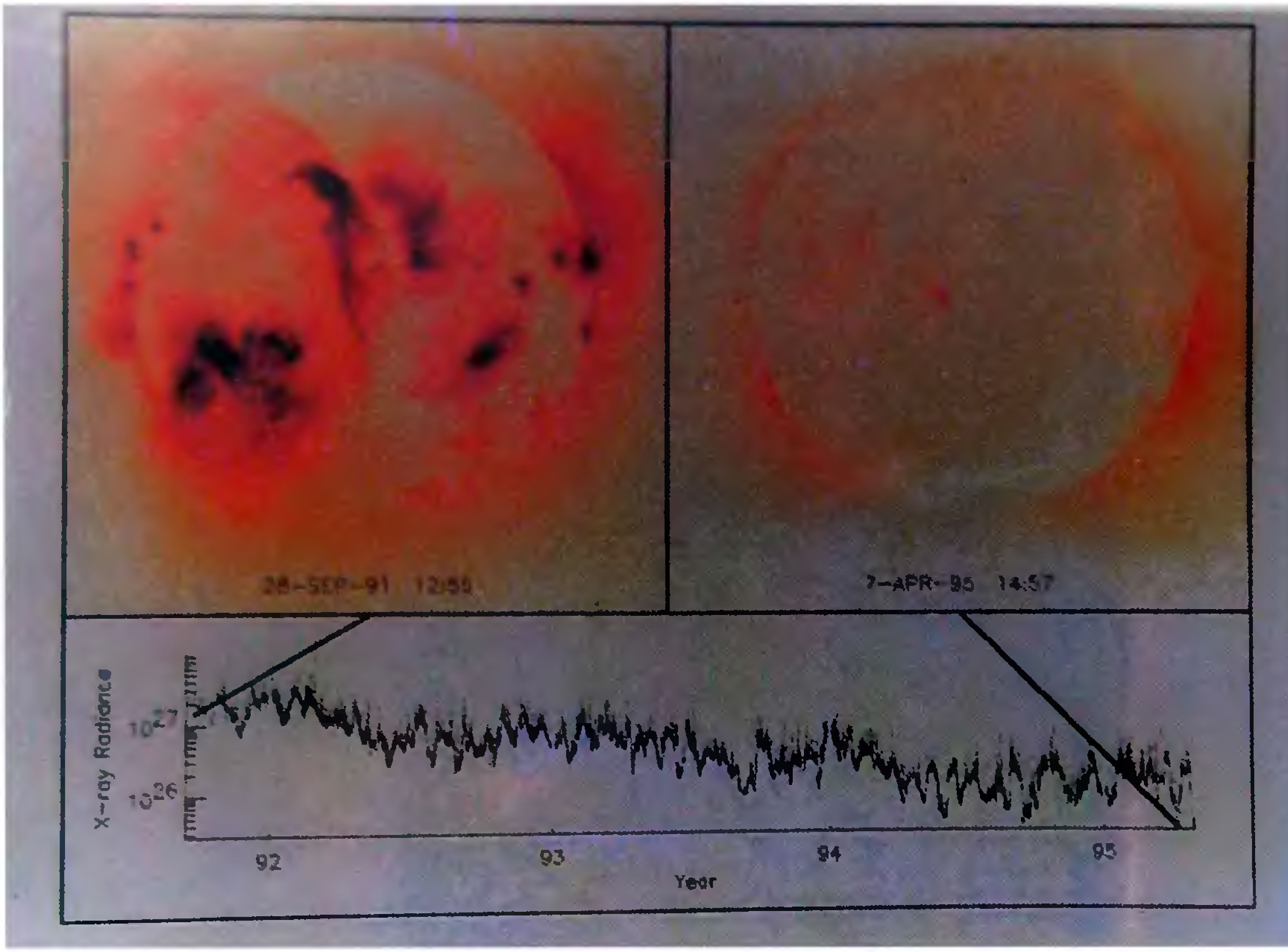

Figure 4 *b*. X-ray image of the Sun obtained from Yohkoh spacecraft on 28 September 1991 (Solar Maximum) and on 7 April 1995 (Solar Minimum) showing the evolution of the corona quite clearly over a three and half year period. (Courtesy, D. Alexander.)

imaging polarimeter (SOUP). The success of the mission promoted the possibility of a second flight of the solar instruments, but the disastrous Challenger accident in 1986 led to an indefinite postponement of this project[3].

The most recent Japanese Yohkoh spacecraft, launched on 30 August 1991 is observing flares with hard and soft X-ray imaging instruments, in addition to a sensitive X-ray crystal spectrometer observing lines of very hot ions. The images (see Figure 4 *a*) obtained by the Soft X-ray Telescope (SXT) on Yohkoh satellite are capable of showing coronal structures with a spatial resolution of 2.5 arcsec that is better than on Skylab and much better than on SMM. The SXT images of the full-Sun, obtained at intervals of few hours have been put together to form 'movies' which show the complexity of the various fascinating phenomena taking place all over the Sun. Huge streamers on the solar limb are carried on to the disc by solar rotation, where they may appear as arcades of loop structures. Sometimes there is a sudden expansion of a large loop-like coronal structure, with apparent ejection of coronal material, leaving the Sun at speeds higher than the escape velocity (618 km/s). Giant post-flare arches behind such ejections expand with slow constant speeds for tens of hours up to altitudes of ~300,000 km. Coronal holes appear as dark voids at either pole and as narrow regions at lower latitudes. Bright points constantly flicker, with lifetimes of less than a day over the entire solar surface. X-ray 'jets', a phenomenon then observed for the first time, appear as columns of fast-moving material with velocities of 100 km/s or more. The SXT images of flares show the loop-like structures previously observed by Skylab and SMM. In addition, many of them show a bright, point-like structure at the loop apex, a puzzling phenomenon because heat conductivity is so large for a hot coronal gas that one would expect such point-like sources to be rapidly dissipated along the length of the loops in which they occur. Instead, they persist for a long time in some flares. It is possible that they are blobs of hot, ionized gas that are pinched by the magnetic field. This picture, if correct, might require some change in our perception of solar flares, which were considered to result from the reconnection of magnetic field lines[4]. Recent X-ray data from Yohkoh also reveal a striking dimming of the corona (about 30 times dimmer) between 1991 and 1995 (see Figure 4 *b*). This change reflects the fluctuations of the 11-year

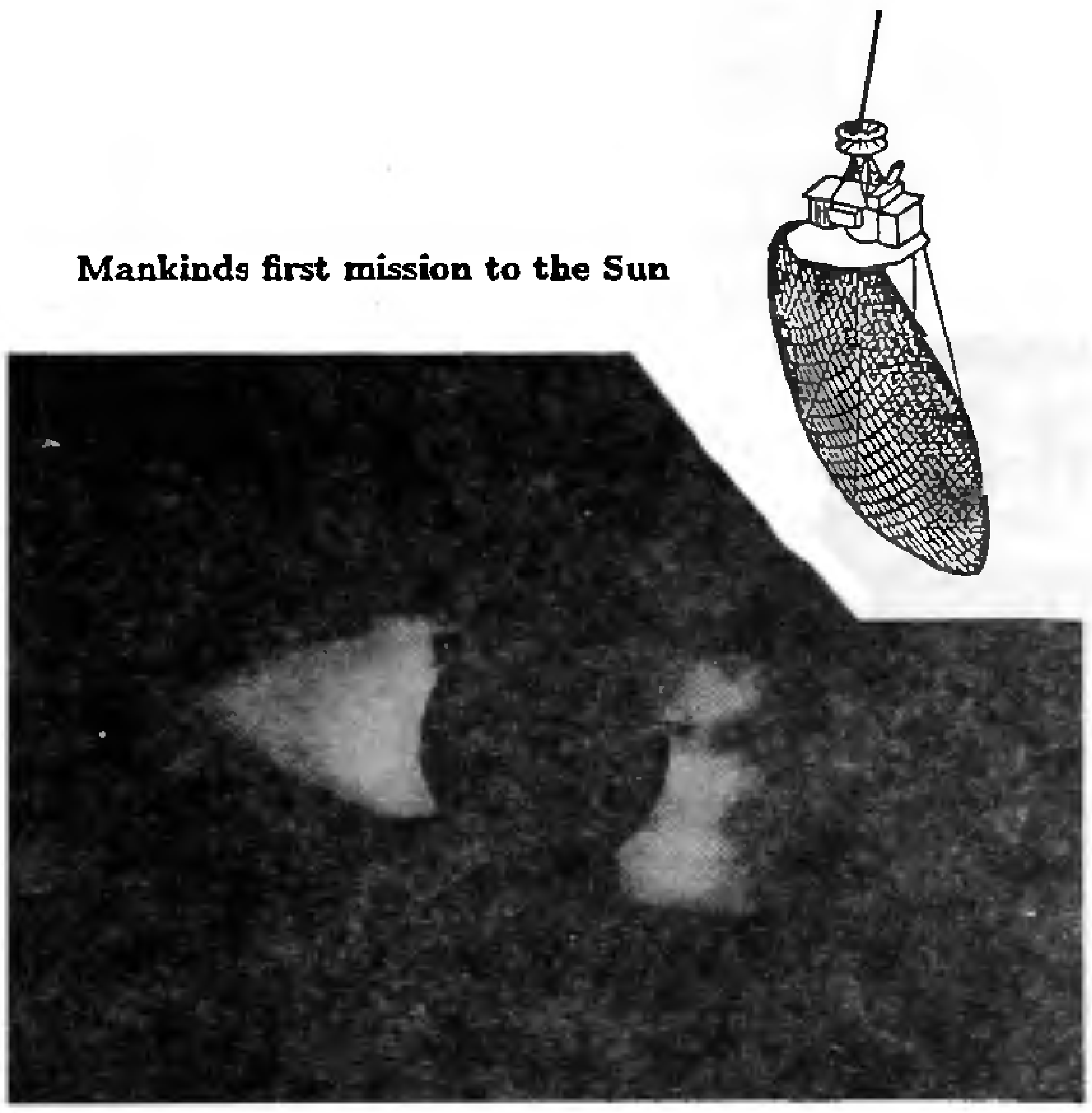

Figure 5. The ambitious Solar Probe Spacecraft is shown with white light solar corona in the background (with expected perihelion at a distance of 4 solar radii, corresponding to 2.8 million km). The shape is dominated by thermal shield which serves as an antenna at the same time. (Courtesy, E. Marsch.)

solar cycle, as it evolves from its period of maximum activity in 1991 to one of its minimum in 1997.

In order to study the solar-terrestrial relations, several spacecraft have explored the terrestrial and other planetary magnetospheres and the interplanetary medium, not only near the Sun but also at the edge of the solar system, notably Pioneers 10 and 11 and Voyagers 1 and 2. Our knowledge of the nature of interplanetary space has largely come from instruments on these and other spacecraft which have measured energies and compositions of the charged particles making up the solar wind as well as magnetic and electric fields. Much information has come from instruments imaging the terrestrial auroral zone, like the Dynamic Explorers and an experiment on the Swedish Viking spacecraft, all launched in 1980s. The goal of the Ulysses mission was to escape the confines of the solar equator where all previous measurements had been made, and to reach the vicinity of the Sun's poles. The spacecraft Ulysses, launched on 6 October 1990 from the Space Shuttle, used three upper stages to escape the Earth's gravity en route to Jupiter. The encounter with Jupiter on 11 February 1992 rotated the orbit 80° relative to the solar equator. The resulting flight path passed under the south pole of the Sun, returned to the ecliptic (March 1995) and passed over the north pole (June through September 1995). The spacecraft again heads out toward the orbit of Jupiter at 5.3 AU. The orbital period of Ulysses is 6.3 years, so that on the next revolution around the Sun, the spacecraft will pass over the south and north polar regions during the coming solar maximum in 2000 and 2001. Ulysses has already explored the field and particle environment of the Sun's polar region. The solar wind speed was fast and nearly constant about ~50° latitude. Compositional differences were observed in slow (low-latitude) solar wind and in fast (high-latitude) solar wind. The radial magnetic field did not change with latitude, implying that polar cap magnetic fields are transported toward the equator. The intensity of galactic cosmic rays was nearly independent of latitude. Their access to the polar region is opposed by outward travelling, large amplitude waves in the magnetic field[5].

Solar spacecraft for the 1990s – The Solar and Heliospheric Observatory (SOHO) successfully launched on 2 December 1995 will observe the Sun from an equilibrium point between the Sun and the Earth, while the CLUSTER group of four satellites will investigate the three-dimensional structure of the Earth's magnetosphere and surrounding solar wind. Both these projects are jointly undertaken by NASA and European Space Agency (ESA) within the frame of the Solar Terrestrial Science Program (STSP). The STSP, in turn, forms part of ESA long term science plan known as 'Space Science: Horizon 2000' and NASA collaborative International Solar-Terrestrial Physics (ISTP) program with ESA and ISAS (Institute of Space and Astronautical Science, Japan). The main objectives of SOHO include the study and understanding of solar coronal phenomena and of the solar structure and interior dynamics from its core to the photosphere. The primary goal of the coronal and solar wind studies is to understand the coronal heating mechanism and its expansion into the solar wind. These goals will be achieved both by remote sensing of the solar atmosphere with high-resolution spectrometers and telescopes and by *in-situ* measurement of the composition and energy of the resulting solar wind and the energetic particles that propagate through it. The structure and interior dynamics will be studied by helioseismological methods and the measurement of solar irradiance variations[6].

SOHO will also collaborate with other space missions. For instance WIND and CLUSTER, when outside the magnetosphere, will provide solar plasma parameters that will complement the coronal and solar wind measurements of SOHO. When CLUSTER is inside the magnetosphere, SOHO will be a useful monitor for the conditions of the environment external to the magnetosphere. Some common scientific objectives and cross-fertilization aspects between CLUSTER and SOHO are also expected. For example, plasma transport into and out of regions of closed magnetic field lines occurs near the Sun and in the Earth's magnetosphere, as well as in many astrophysical contexts. Explosive releases of energy occur both on the Sun (coronal mass ejection) and in the geotail (plasmoid). Magnetic field line merging is a fundamental process that occurs on the Sun and in the magnetosphere and perhaps also in the solar wind. It is particularly associated with extended, thin current sheets, which are observed in the Earth's magnetosphere and are inferred to exist at the Sun. Joint studies by these two missions will illustrate the roles of the different parameter regimes and the limits of the analogy. This will throw light on the attempts to extrapolate and apply knowledge gained in solar-system studies to remote astrophysical objects.

Finally, it should be emphasized that the SOHO mission, being the first 'cornerstone' of ESA long-term programme, 'Space Science – Horizon 2000', will play a profound role in the pursuit of space science and plasma physics research from a coordinated approach between *in-situ* observations by CLUSTER, Ulysses, Geotail, Interball, Wind, or Polar and the remote and *in-situ* measurements taken by SOHO.

A number of other spacecraft are currently being defined and planned. These include the NASA Orbiting Solar Laboratory, which will have imaging and spectral instruments covering the range from X-rays to white light, and the ambitious 'Solar Probe' which will measure small solar structures from an orbit with an expected perihelion at a distance of four solar radii, corresponding to 2.8 million kilometers from the solar surface; the shape is dominated by thermal shield which serves as an antenna at the same time (see Figure 5). European Space Agency hopes to provide a solar physics element for the Columbus Space Station, which may consist of a set of instruments, including an imaging high-resolution spectrometer in the extreme-ultraviolet spectrum to study the chromosphere, transition region and the corona.

Thus, indeed, we are fascinated to accomplisl the beauty of our star, the Sun, in the entire ele netic light, thanks to the great technological ment. We wish to understand and appreciate 'w the corona?', 'what accelerates the solar wi many other questions. Seek simplicity and dis 'so is the case of the corona, like life: the c look, the more detail we see. And exploration o will continue with our quest of knowledge to u it substantially if not fully. Shall we ever ful stand our Sun?

How did the Sun get in her place
with her round and shiny happy face?
Who cast the shadows, high and low?
I do not know, I do not know!

With good science, vision, wisdom and re should be optimistic!

1. Noyes, R. W., *The Sun, Our Star*, Harvard Unive 1982, pp. 164–180.
2. Dwivedi, B. N., *Space Sci. Rev.*, 1994, **65**, 289–316.
3. Phillips, K. J. H., *Guide to the Sun*, Cambridge Unive 1992, pp. 343–352.
4. Svestka, Z., Private communication, 1995.
5. Smith, E. J., Marsden, R. G. and Page, D. E., *Science*, 1005–1006.
6. *The SOHO Mission – Scientific and Technical Asp Instruments* (Domingo, V., Scientific Coordinator), SP-1104.

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The Charles Stark Draper Prize

John R. Pierce and Harold A. Rosen were awarded the $400 000 Charles Stark Draper Prize – the world's largest award exclusively for engineering achievement. Pierce was responsible for designing and launching Telstar 1, the world's first active communication satellite. Rosen devised an ingenious method of placing the Syncom II satellite in geosynchronous orbit. The Draper Prize is endowed by the Charles Stark Draper Laboratory Inc., Cambridge, Mass.