2. Probing the Sun

Scientists have gained much of their knowledge about the Sun from observations made on Earth over many years. However, much of our current knowledge has come from space probes that have been sent on missions to observe the Sun. These probes have provided accurate information about the Sun's temperature, atmosphere, composition, magnetic fields, flares, prominences, sunspots and internal dynamics. A knowledge of these probes and the data they collected helps us to better understand the various processes in the Sun and the effect solar radiation has on Earth. This chapter provides information about early solar space probes (pre-1990) as well as the more recent (post-1990) probes and future probes. Satellite and instrumental technology improved greatly during these periods and this is clearly evident when comparing the results obtained from recent probes to the early probes. Table 2.1 lists significant solar space probes.

Early Solar Probes

The USA launched a number of unmanned solar probes between 1959 and 1968 as part of its Pioneer program. Many of these early probes have now completed their missions but some still remain in orbit around the Sun.

Explorer Program

The Explorer program is a USA/NASA program that provided flight opportunities for solar physics and astrophysics investigations from space. The explorer program was the United State's first successful attempt to launch an artificial satellite. The program includes 92 missions since the launch of Explorer 1 in 1958. Besides being the first US satellite, it is known for discovering the Van Allen radiation

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Table 2.1 Significant solar space probes

Explorer program – USA, Launched many probes since 1958
Pioneer 5 – USA, Launched March, 1960
Pioneer 6 – USA, Launched December 1965 (still transmitting from solar orbit)
Pioneer 7 – USA, Launched August 1966 (recently turned off)
Pioneer 8 – USA, Launched December 1967 (still transmitting from solar orbit)
Pioneer 9 – USA, Launched November 1968 (still in orbit, but died in 1987)
Orbiting Solar Observatory – USA, Launched 1962–1975 (series of nine probes)
Skylab – USA, Launched May 1973 (space station in Earth orbit)
Helios 1 – USA/Germany, Launched November 1974 (came to within 44 million km of the Sun)
Helios 2 – USA/Germany, Launched January 1976 (came to within 43 million km of the Sun)
Solar Maximum Mission – USA, Launched February 1980 (monitored solar flares)
Ulysses – USA/ESA, Launched Oct 1990 (orbited sun's polar regions)
Yohkoh – Japan/USA/UK, launched 31 Aug 1991 (studied high energy radiation from Sun)
SOHO - USA/ESA, launched 2 Dec 1995 (study solar wind, corona, internal structure)
WIND and Polar – launched November 1994 (study solar wind/magnetosphere)
ACE – launched 25 Aug 1997 (study composition of corona/interplanetary space)
TRACE – USA, launched 2 April 1998 (study solar magnetic fields, corona)
Genesis – USA, Launched 8 Aug 2001 (collected solar wind particles and returned them to Earth)
Coronas-F – Russian, Launched July 2001 (monitor flares and solar interior)
RHESSI – USA, Launched February 2002 (x-ray and gamma ray imaging of flares)
Hinode – Japan/USA/UK, Launched 23 September 2006 (explore solar magnetic fields)
Stereo A/B – USA, Two probes launched Oct 2006 (study coronal mass ejections in 3D)
SDO – USA, launched February 2010 (study effects of Sun on Earth)
SOLO – ESA, due for launch 2017 (study Sun from close quarters)
Solar probe plus – USA, due for launch 2018 (study corona and solar wind)

belt around Earth. Explorer satellites have also make important discoveries about the solar wind, solar plasma, solar energetic particles, and atmospheric physics.

Pioneer Probes

Pioneer 5 was launched in March 1960 from Cape Canaveral in the USA. It was a 0.66 m diameter sphere with 1.4 m span across its four solar panels. It was equipped with four scientific instruments: a telescope to detect solar flare particles and observe terrestrial trapped radiation, a magnetometer to measure magnetic field strengths in interplanetary space, a radiation counter to measure cosmic radiation and a micrometeorite detector.

Pioneer 6, 7, 8 and 9 were the first of four identical solar orbiting spacecraft. Pioneer 6, launched in 1965 into solar orbit, is the oldest of NASA's spacecraft believed to be still active. A successful contact was made with Pioneer 6 for about 2 h on December 8, 2000 to commemorate its 35th anniversary. The probe is powered by a 79-W solar panel and consists of an aluminium cylinder 94 cm in diameter and 89 cm long. There were three magnetometer booms, and an antenna mast extending from it.

Pioneers 6–9 demonstrated the practicality of spinning a spacecraft to stabilize it and to simplify control of its orientation. Measurements made by these spacecraft provided much of the early knowledge of the interplanetary environment and the effects of solar activity on Earth. New information was gathered about the solar wind, solar cosmic rays, the structure of the Sun's plasma and magnetic fields, the physics of particles in space, and the nature of storms on the Sun that produce solar flares. Simultaneous measurements by Pioneer 6 and 8 when they were 161 million km apart allowed the most accurate determination of the solar wind density to be made up to that point.

Missions such as Pioneer 10 and 11 showed that gravity assists were possible and that spacecraft could survive high-radiation areas.

Orbiting Solar Observatory

The Orbiting Solar Observatory (OSO) was a series of nine stabilized orbiting platforms developed by the Goddard Space Flight Centre in the USA for observing the Sun and extra solar sources at ultraviolet, x-ray, and gamma-ray wavelengths. NASA launched eight successfully between 1962 (OSO 1) and 1975 (OSO 8) using Delta rockets. Their primary mission was to observe an 11-year sun spot cycle in UV and x-ray spectra. The OSO 9 probe was planned but never launched.

OSO-1 was the first satellite to carry onboard tape recorders for data storage and instruments that could be accurately pointed. Other results of the OSO series included the first full-disc photograph of the solar corona, the first x-ray observations from a spacecraft of a beginning solar flare and of solar streamers and the first observations of the corona in white light and extreme ultraviolet.

Skylab

America's first space station, Skylab, launched in May 1973, was used to study the Sun from Earth orbit. The space station included the Apollo Telescope Mount (ATM), which astronauts used to take more than 150,000 images of the Sun. Solar experiments included photographs of eight solar flares, and produced valuable results that scientists stated would have been impossible to obtain with unmanned spacecraft. The existence of the Sun's coronal holes was confirmed because of these efforts. X-ray photographs taken by Skylab showed that the corona is highly structured, containing coronal loops and holes, and bright x-ray points. However, these images were of poor quality because the telescope had low resolution and low sensitivity (Fig. 2.1).

Skylab was abandoned in February 1974 and re-entered the Earth's atmosphere in 1979. It broke up on re-entry.

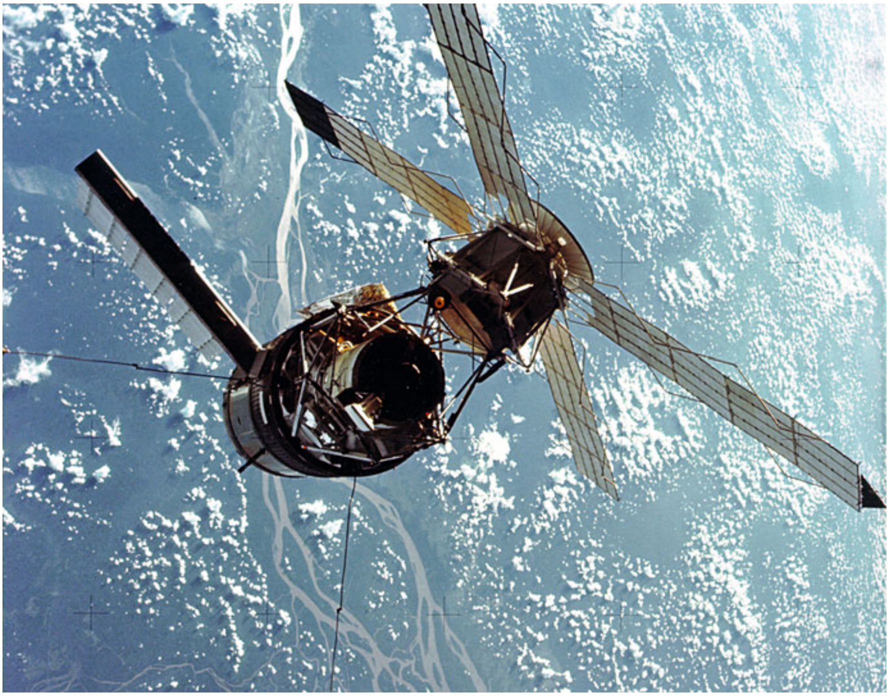

Fig. 2.1 Although it remained in orbit around Earth, the USA's first space station, Skylab, was used to take more than 150,000 images of the Sun. It confirmed the existence of coronal holes on the Sun (Credit: NASA).

Helios 1 and 2

Helios-A and Helios-B (also known as Helios 1 and Helios 2) was a pair of probes launched into orbit around the Sun for the purpose of studying solar processes. A joint venture of the Federal Republic of Germany (West Germany) and NASA, the probes were launched from the John F. Kennedy Space Centre at Cape Canaveral, Florida, on Dec. 10, 1974, and Jan. 15, 1976, respectively.

The probes are notable for having set a maximum speed record among spacecraft at 252,792 km/h. Helios 2 flew to within 44 million km of the Sun (slightly inside the orbit of Mercury). Data was obtained about the velocity and distribution of the solar wind, the intensity of the solar magnetic field and distribution of cosmic rays. Energy transported in the solar wind was found to be carried by protons. Measurements from Helios showed the solar wind has two main velocities. When the wind speed is high, the proton density is relatively low. When the wind speed is low, the proton density is high. In the high-speed wind, heavier particles also have a higher temperature; but it is the other way around in the slow wind, where lighter particles are hotter.

The Helios space probes completed their primary missions by the early 1980s, but they continued to send data up to 1985. The probes are no longer functional but still remain in their elliptical orbit around the Sun. The trajectory of the probes is shown in Fig. 2.2.

Solar Maximum Mission

The Solar Maximum Mission (SMM) was a solar probe launched by the USA on 14th February 1980. The craft was designed to monitor solar flares during a period maximum solar activity. Instruments on the craft were also used to measure solar irradiance. The probe excelled in x-ray and gamma ray spectroscopy of solar flares, as well as making observations of white light emissions from coronal mass ejections. A gamma ray spectrometer was used to detect energetic solar neutrons near the Earth following a solar flare, which occurred on 21 June 1980.

The probe suffered a failure during orbit of the Sun and had to be repaired by space shuttle astronauts in 1984. SMM collected

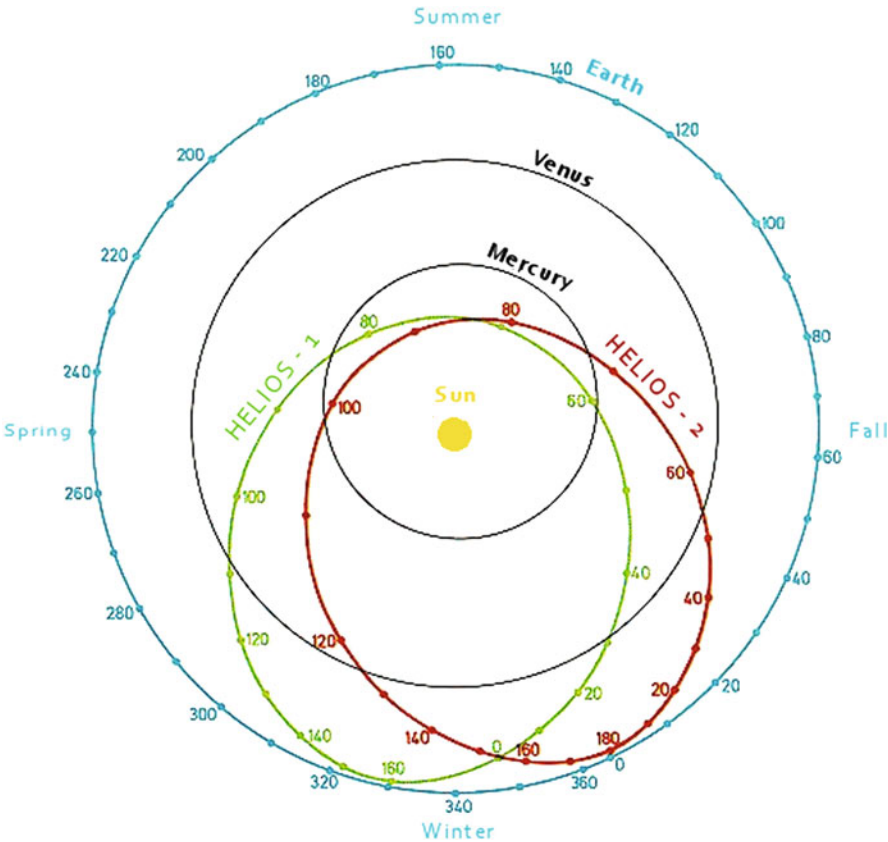

Fig. 2.2 The trajectory of the Helios probes was unusual because they were designed to make measurements in the medium between the inner planets as well around the Sun (Credit: NASA).

data about the Sun until 24th November 1989, and re-entered Earth's atmosphere on 2nd December 1989.

Ulysses

The Ulysses spacecraft, launched on 6th October 1990, was a joint venture between NASA and the European Space Agency (ESA) project designed to study the poles of the Sun and interstellar space around the poles. The first solar polar passage was in June 1994. In February 1995 the craft passed the solar equator in June of that year the craft flew over the Sun's north pole. The spacecraft made a second pass over the Sun's poles between September 2000 and January 2001. At this time, the Sun was close to the peak of its activity cycle. The main objective of the Ulysses mission is to study the properties of the solar wind as a function of latitude, solar magnetic field, solar radio bursts, plasma waves, solar x-rays, solar and galactic cosmic rays. Its instruments found that the solar wind blows faster at the poles than at equatorial regions. Ulysses is now heading back out to the orbit of Jupiter on the long leg of its 6-year circuit around the Sun.

Recent Solar Probes

Yohkoh

Yohkoh means ‘sunbeam’ in Japanese and is one of the most productive solar space missions conducted by the Institute for Space and Astronautical Sciences in Japan with collaboration with American and British scientists. The spacecraft is in a slightly elliptical low-earth orbit, with an altitude ranging from approximately 570 to 730 km. The orbital period is 90 min.

The scientific objective of Yohkoh is to observe the energetic phenomena taking place on the Sun, specifically solar flares in x-ray and gamma ray emissions.

Yohkoh was launched in August 1991 and contains two spectrometers and two x-ray telescopes (one for hard x-rays and the other for soft x-rays). Each is designed to observe a limited range of wavelengths emitted by the hot plasma produced during solar flares. Observations of spectral lines provided information about the temperature and density of the hot plasma, and about motions of the plasma along the line of sight. Information about temperature and density of the plasma emitting the observed x-rays is obtained by comparing images acquired with different filters. Flare images can be obtained every 2 s. Smaller images with a single filter can be obtained as frequently as once every 0.5 s.

Yohkoh data showed that solar flares and coronal mass ejections can be triggered by magnetic reconnection, where oppositely directed magnetic fields merge together, releasing the necessary energy at the place where they touch. The soft x-ray telescope also showed that the flares or ejections are triggered when the bright x-ray emitting coronal loops become twisted into a helical or S-shape. The probe also found that the corona is ever-changing and has no permanent features.

During each orbit, about five or six times a day, Yohkoh passes over Japan and data is down and up loaded at these times. In addition, Kennedy Space Centre in the USA also receives data from the spacecraft. At other locations in the orbit, the data gets sent to ground stations in the NASA Deep Space network.

Yohkoh collaborated with NASA's High Energy Solar Spectroscopic Imager (HESSI), providing crucial calibration data for its high-resolution hard x-ray images. Solar-B is the Japanese follow-up mission, again with involvement from the US and the UK. It will look at the Sun in soft x-rays, as Yohkoh did, but it will also make very high-resolution images in visible light.

SOHO

The Solar and Heliospheric Observatory (SOHO) another joint NASA/ESA mission launched in December 1995 provided valuable information about the solar atmosphere, solar wind and the Sun's internal structure. SOHO weighs nearly two tonnes and flies in a halo orbit around the Lagrangian point L1. This point is about 1.5 million km from Earth towards the Sun. The L1 Lagrangian point is a location in space where gravitational pull of the Sun and Earth cancel or balance each other. From this vantage point SOHO is able to 'hover' and observe the Sun continuously for 24 h a day, 7 days a week.

In June 1998, ground controllers lost contact with SOHO due to telemetry error. Intense efforts to restore contact paid off 6 weeks later when the spacecraft responded to commands sent from ground stations (Figs. 2.3 and 2.4).

One of SOHO's instruments, called the Large Angle and Spectrometric Coronagraph (LASCO) routinely monitors a huge region of space around the Sun. LASCO is able to take images of the solar corona by blocking the light coming directly from the Sun with an occulter disk, creating an artificial eclipse within the instrument itself. Occasionally, coronal mass ejection can be seen moving away from the Sun. Although not designed for the purpose, the coronagraph instrument on SOHO has detected over

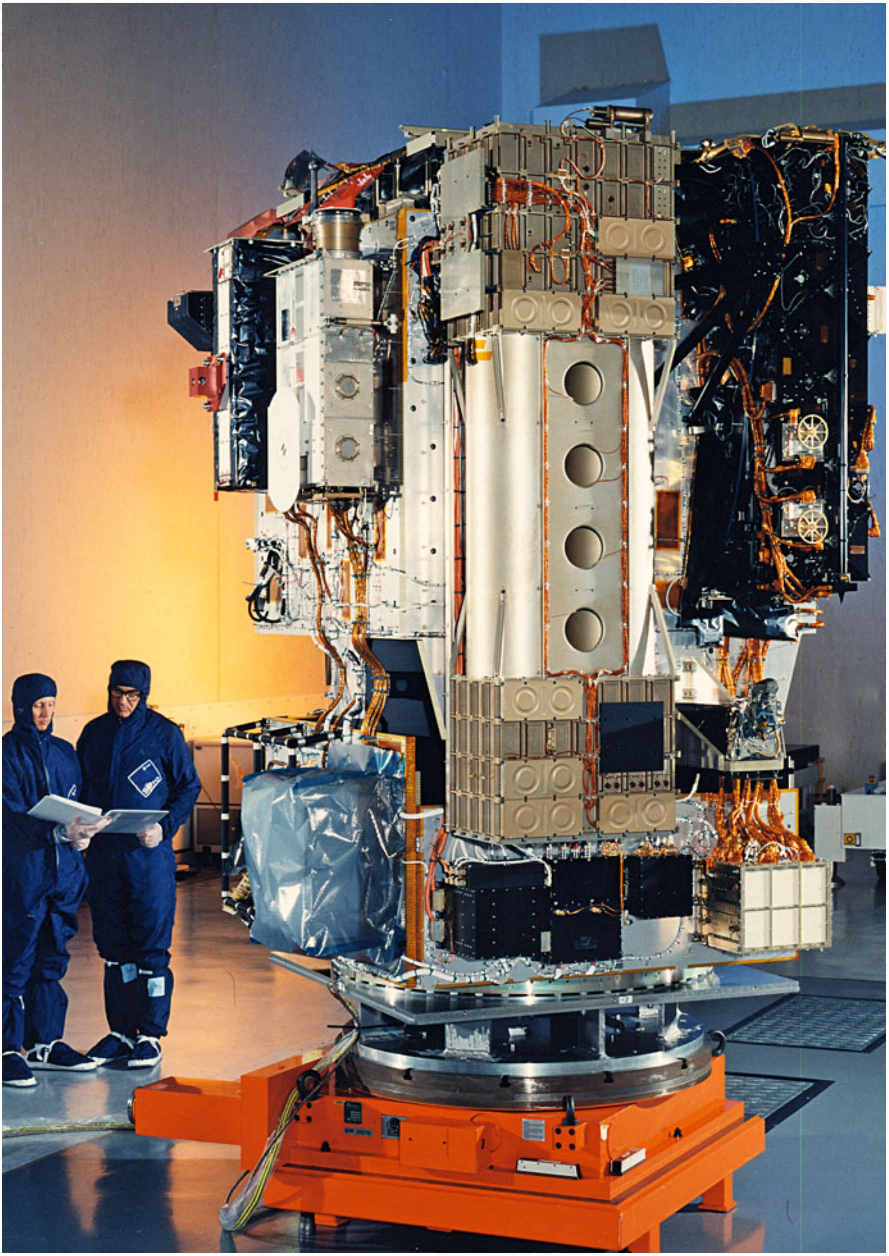

Fig. 2.3 This picture taken prior to launch, shows some of the sophisticated technology on board SOHO (Credit: NASA).

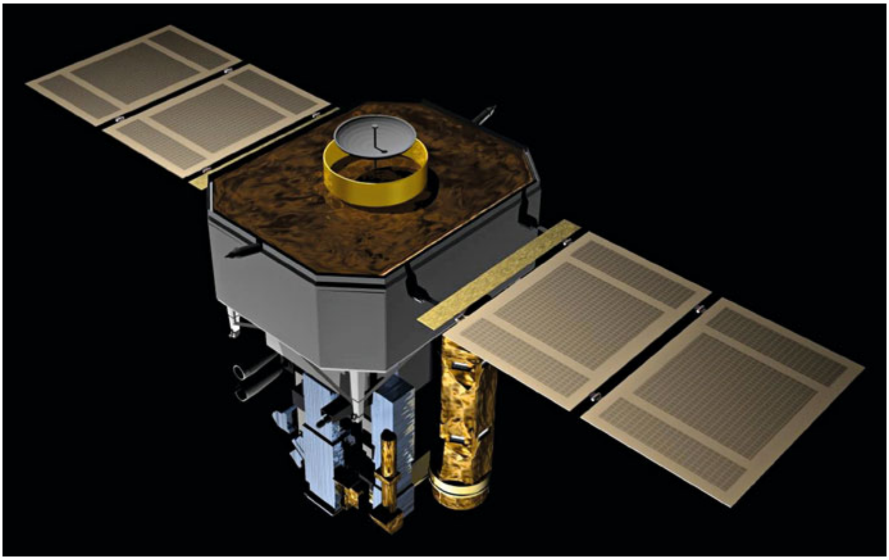

Fig. 2.4 The SOHO space probe contains a total of 12 scientific instruments used to monitor different parts of the Sun (Credit: NASA).

2,000 different comets passing close to the Sun. Of course, it is not SOHO itself that discovers the comets – that is the province of the dozens of amateur astronomer volunteers who daily pore over the fuzzy lights dancing across the pictures produced by the LASCO cameras. Over 70 people representing 18 different countries have helped spot comets over the last 15 years by searching through the publicly available SOHO images online. See Fig. 2.5.

Two other instruments on board the SOHO spacecraft, the Solar Wind Anisotropies (SWAN) and the Michelson Doppler Imager (MDI), allow scientists to 'see' what is happening on the far side of the Sun.

The Extreme-ultraviolet Imaging Telescope (EIT), aboard SOHO takes full-disc images of the Sun's transition region and lower corona at three lines of ionised iron, Fe IX, Fe XII, and Fe XV, and one line of ionised helium, He II. See Table 2.2.

One of SOHO's most important discoveries has been in locating the origin of the solar wind at the corners of honeycomb-shaped magnetic fields near the Sun's poles. Data obtained from SOHO enabled scientists to compare the behaviour of sunspots during low and high activity periods. The space probe has also

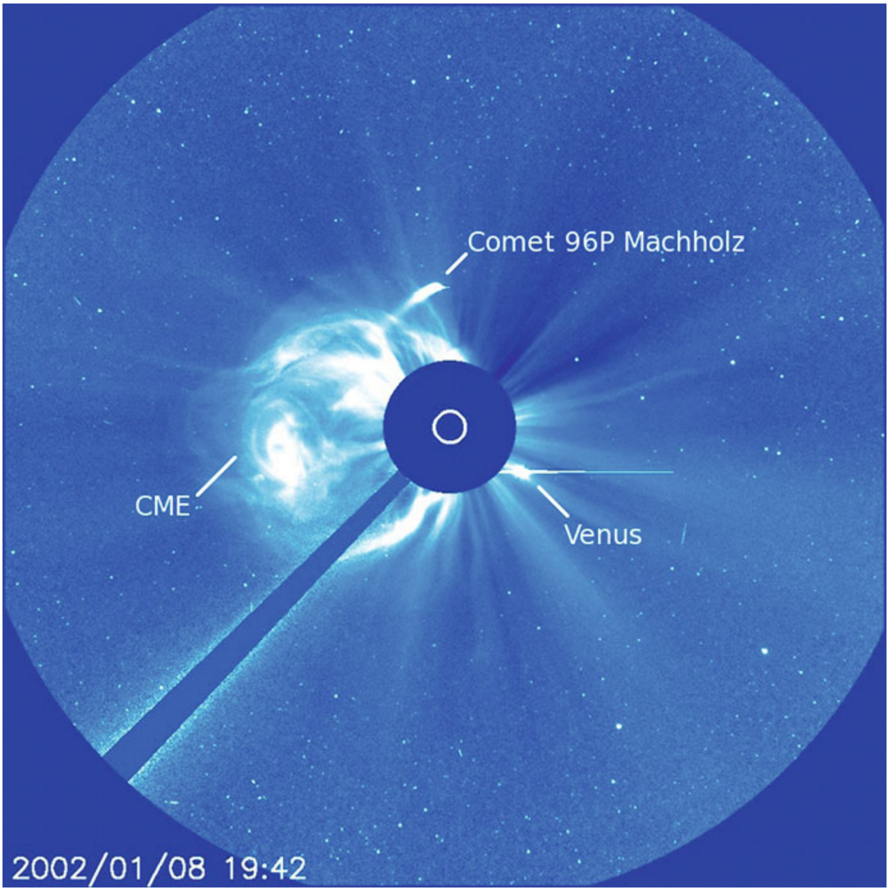

Fig. 2.5 One comet discovered by SOHO is Comet 96P Machholz. The comet orbits the Sun approximately every 6 years and SOHO has seen it three times. Up until January 2011, SOHO had detected over 2,000 comets in orbit around the Sun. A coronal mass ejection (*CME*) and the planet Venus are also shown in this picture (Credit: NASA/ESA/SOHO).

Table 2.2 Wavelengths used by EIT to take images of the Sun's disc

Wavelength (A)	Emitting ion	Formation temperature (°C)
171	Iron, Fe IX and Fe X	1,000,000
195	Iron, Fe XII	1,400,000
284	Iron, Fe XV	2,100,000
304	Helium, He II	60,000

provided an unprecedented breadth and depth of information about the Sun, from its interior, through the hot and dynamic atmosphere, to the solar wind and its interaction with the interstellar medium.

Some of the key findings include:

- Revealing the first images ever of a star's convection zone (its turbulent outer shell) and the structure of sunspots below the surface.
- Providing the most detailed and precise measurements of the temperature structure, interior rotation, and gas flow in the Sun's interior.
- Measuring the acceleration of the slow and fast solar wind.
- Identifying the source regions and acceleration mechanism of the fast solar wind in the magnetically 'open' regions at the Sun's poles.
- Discovering new solar phenomena such as coronal waves and solar tornadoes.
- Revolutionizing our ability to forecast space weather, by giving up to 3 days notice of Earth-directed disturbances, and playing a lead role in the early warning system for space weather.
- Monitoring the total solar irradiance as well as variations in the extreme ultra violet flux, both of which are important to understand the impact of solar variability on Earth's climate.

SOHO was designed for a nominal mission lifetime of 2 years. Because of it's amazing results, the mission has been extended five times (in 1997, 2002, 2006, 2008, and 2010). These extensions allowed SOHO to cover an entire 11-year solar cycle (number 23) and the rise of the new cycle (number 24). SOHO is currently approved through to the end of 2012.

Wind and Polar

Wind and Polar are sister spacecraft used to measure the mass, momentum, energy flows and time variability, throughout the solar wind-magnetosphere-ionosphere system near Earth. Wind was launched in November 1994. It was initially sent into a lunar swing-by orbit in which the Moon's gravity helped propel it through Earth's magnetosphere on its sunward side, at the Lagrange L1 location in space.

Wind observations compliment those of the Polar spacecraft, which looks down at the Earth's magnetic polar regions.

Since launch, Wind has investigated shocks generated by coronal mass ejections, using radio signals to track them from launch in the corona through interplanetary space to the Earth. The most powerful shocks where found to produce a wider wavelength range of radio emission. Radio signals produced by these shocks are triangulated using instruments aboard the Wind, Ulysses, Cassini and twin Stereo spacecraft, permitting a three-dimensional determination of their trajectory.

One of Wind's instruments showed that the slowest solar winds contain the greatest amount of helium, while faster winds have the least amount of helium. Scientists are now using data from Wind to determine where the solar energetic particles originate from, how they are accelerated, and how they escape and propagate from solar flares or coronal mass ejections.

ACE

The Advanced Composition Explorer (ACE) was launched in August 1997 into an orbit around the L1 Langrangian point between the Sun and Earth. The main objective of ACE is to determine the composition of several samples of matter in the solar corona and interplanetary space. It also provides real time solar wind data and monitors solar particles as they bombard Earth. The probe therefore contributes to forecasts of space weather. ACE carries a set of nine instruments to measure the charge state composition of the nuclei from hydrogen to nickel from the solar wind and galactic cosmic rays. One recent discovery of the Wind and ACE spacecraft was of solar wind magnetic fields that merge and join together near the Earth's orbit, in long, steady reconnection layers that stretch out for hundreds of Earth radii. This magnetic reconnection was previously thought to occur only within very small regions in a very short, patchy manner.

TRACE

In April 1998, NASA launched a satellite into sun-synchronous polar orbit around Earth at an altitude of 625 km. The probe called Transition Region And Coronal Explorer (TRACE) is a computerised satellite launched from a Pegasus XL rocket dropped from a jet aeroplane flying high above the Pacific Ocean. The main instrument on TRACE is a Cassegrain telescope of diameter 30 cm and length 160 cm. TRACE is one of several small satellites in NASA's Small Explorer (SMEX) project.

TRACE observes the Sun in extreme-ultraviolet radiation of specific spectral lines sensitive to a wide range of temperatures; but unlike EIT (onboard SOHO), which images the entire solar disc, TRACE observes specific regions on the Sun with higher resolution, detecting fine details that could not be seen from previous spacecraft. The main regions studied by TRACE are the solar photosphere, transition region and corona at temperatures between 4,000 and 5 million °C at wavelengths of 171, 195, 284, 1,216, 1,550, 1,600, 1,700 and 2,500 A.

TRACE is also used to study the connection between the Sun's magnetic field and the heating of its corona. It particular it has provided new insights into the magnetised coronal loops that shape and constrain the hot plasma in solar active regions. The magnetised loops stretch up to 500,000 km from the visible solar disc, spanning up to 40 times the diameter of planet Earth. These magnetic loops also oscillate, or move back and forth, with periods of between 2 and 7 min, appearing when flares excite the oscillations (Fig. 2.6).

TRACE has also provided new information about the quiet corona and transition region, away from solar active regions. Bright, extreme-ultraviolet, flare-like events, known as nanoflares, appear to flash on and off but with insufficient energy to heat the corona. Trace has also observed the jet-like spicules that emerge upwards from the photosphere into the lower corona. More than 10,000 spicules can be seen at any moment on the Sun, rising and falling every 5 min or so, and carrying a mass of 100 times that of the solar wind into the lower corona.

TRACE provided images at five times the magnification of those taken by the Extreme Ultraviolet Imaging Telescope Instrument aboard SOHO. Many details of the fine structure of the corona were observed for the first time. Early in its mission, TRACE discovered the fine-scale magnetic features where enhanced heating occurs at the foot points of coronal loop systems in solar active regions, which later became known as 'coronal moss.'

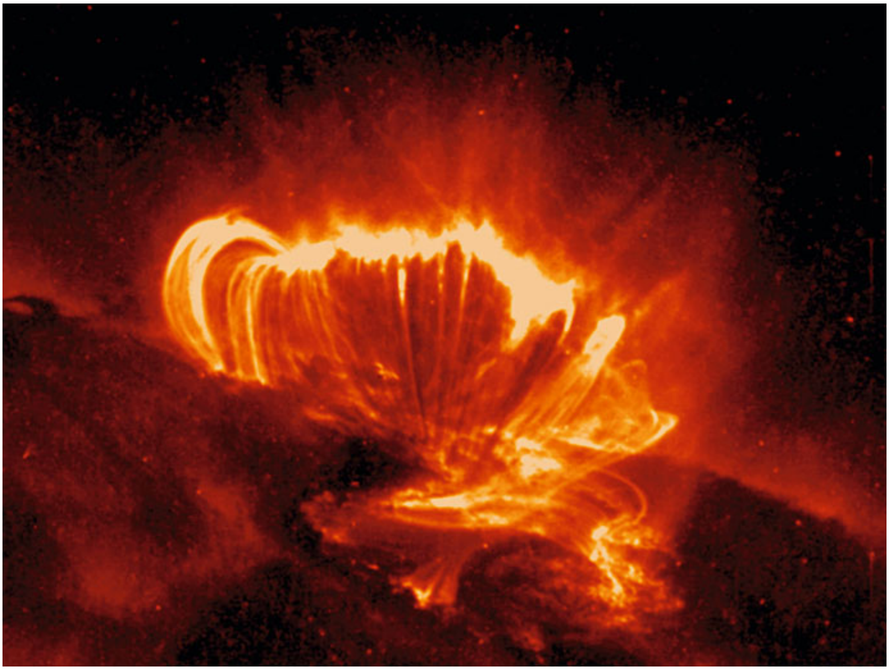

Fig. 2.6 EUV image taken by TRACE on 21st April 2002, of plasma gas being channelled by magnetic fields into bright, thin loops stretching high into the corona (Credit: NASA/TRACE).

In 2001, TRACE observations of astonishing coronal activity were highlighted in the IMAX movie SolarMax.

Genesis

The Genesis space probe launched by NASA in August 2001 was designed to collect samples of solar wind particles and return them to Earth for analysis. The spacecraft collected solar wind particles from the L1 Langrangian point over about 2.5 years. On its return to Earth in September 2004, a capsule containing the samples was ejected from Genesis but its parachutes did not open and the capsule hit the Utah desert floor at nearly 320 km/h. Several hours after the landing, scientists retrieved the collection canister after the wreckage was made safe. Although the crash left the solar particles open to contamination, scientists were still hopeful of obtaining useful data about the composition of the particles in the solar wind. Scientists wanted a sample from our Sun because a preponderance of evidence suggests that the outer layer of the Sun preserves the composition of the early solar nebula. Knowing the exact elemental and isotopic composition of the outer layer of the Sun is effectively the same as knowing the elemental and isotopic composition of the nebula. The data could help scientists understand how planets and other solar-system objects formed; this would also aid in understanding stellar evolution and the formation of solar systems elsewhere in the universe.

Initial tests showed Genesis collected about 0.4 mg of solar particles, equal only to a few grains of salt. Scientists involved in the research announced on 10th March 2008 that analysis has shown that the Sun has a higher proportion of oxygen-16 than does the Earth. The measurement was made after the upper 20 nm of a collection wafer was removed with a beam of caesium ions. This implies that an unknown process depleted oxygen-16 from the Sun's disk of protoplanetary material prior to the coalescence of dust grains that formed the Earth. See Fig. 2.7.

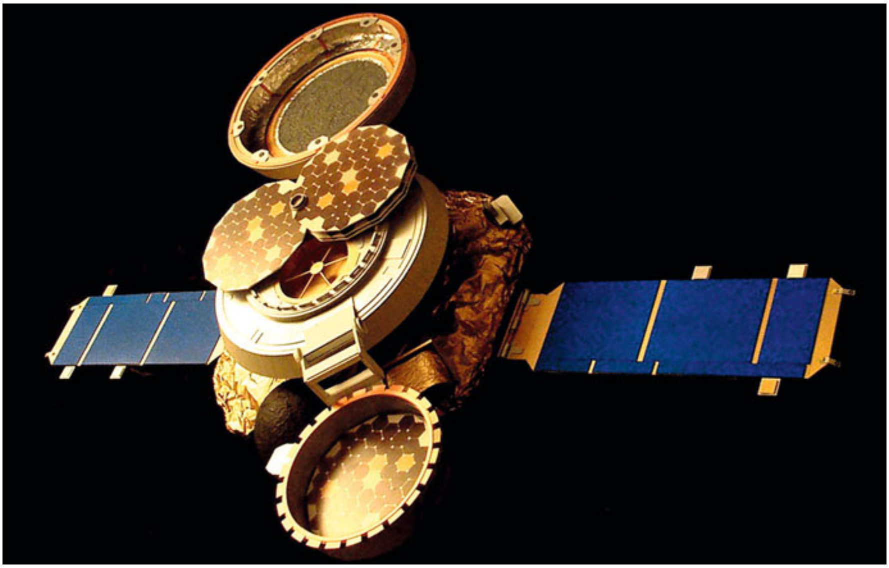

Fig. 2.7 The Genesis spacecraft was used to collected samples of the solar wind from space. Some samples were collected on its hexagonal wafers and special foils (Credit: NASA/Genesis).

CORONAS-F

The Complex ORbital near earth Observations of the Solar Activity (CORONAS-F) is a Russian space probe launched on 31st July 2001 on a cyclone rocket from Russia's Northern Cosmodrome in Plesetsk. It orbits Earth in a polar orbit at an altitude of 500 km. The main objective is to collect data about solar flares and the solar interior. The craft contains 15 instruments, including ten x-ray spectrometers and imagers, two UV instruments, a radiometer, a coronagraph and several full disc photometers. Being Russian, little information is known about the results from the mission.

RHESSI

The Rematy High Energy Solar Spectroscopic Imager (RHESSI) is a NASA mission aimed at exploring the particle emission and energy release of solar flares. This mission was launched in February 2002. It contains two imaging spectrometers and has the ability to provide high-resolution images of solar flares over a broad spectral range from soft x-rays to gamma rays. It takes full disc solar images. The probe provided scientists with enough data to enable them to calculate far more precisely the exact roundness of the Sun. These measurements indicated that the Sun is not exactly spherical; instead there are small differences between the equatorial and polar radii that result in an oblate shape. The Sun was found to have a thin, rough skin, with bright, magnetic ridges arranged in a network pattern, as on the surface of a cantaloupe.

Hinode (Solar-B)

Hinode (formally Solar-B) is a Japanese Aerospace Exploration Agency solar mission in collaboration with the USA and United Kingdom. It is the follow-up mission to the Yohkoh and it was launched from Japan on 23rd September 2006 and placed in a sun-synchronous orbit.

Hinode was planned as a 3-year mission to investigate the solar magnetic fields and their role in heating the chromosphere and corona. It consists of a 50 cm solar optical telescope and spectrophotometer, an extreme ultraviolet (EUV) spectrometer, and an x-ray telescope.

Hinode's x-ray telescope has provided new information about the energy source of the Sun's corona. It discovered twisted and tangled magnetic fields that are able to store huge amounts of energy. When the complicated magnetic structures relax to simpler configurations, a huge amount of energy is released. This energy heats the corona and powers solar eruptions like flares and coronal mass ejections. The x-ray telescope also discovered gigantic arcing magnetic structures surrounding the active regions of sunspots.

How the solar wind is formed and powered has been the subject of debate for decades. Data from Hinode also showed that powerful magnetic 'alfven' waves play a critical role in driving the solar wind into space. In the past, alfven waves have not been able to be seen because of limited resolution in available instruments. With the help of Hinode, scientists have been able to see direct evidence of alfven waves, which will help them unravel the mystery of how the solar wind is powered.

Unlike instruments on TRACE and other dedicated solar observatories, the x-ray telescope on Hinode, is a 'grazing incidence' telescope capable of studying so-called 'soft' x-rays. Most solar telescopes observe lower-energy radiation. The x-ray telescope also photographs the Sun faster and with better resolution and greater sensitivity than previous grazing-incidence x-ray instruments.

The Hinode solar optical telescope was the first to be able to measure small changes in the Sun's magnetic field. The data collected will be used to study how these changes evolve and coincide with dynamic events seen in the corona.

The EUV imaging spectrometer has been designed to measure the flow velocity or speed of solar particles, and diagnose the temperature and density of solar plasma. The EUV imager provides a crucial link between the other two instruments because it can measure the layers that separate the photosphere from the corona.

STEREO A/B

The Solar TErrestrial RElations Observatory (STEREO) is a solar mission launched by NASA on 26th October 2006. It consists of two nearly identical spacecraft, one orbiting ahead of Earth (A) and the other behind Earth (B). Observations are made simultaneously of the Sun and then combined to provide a 3D stereo image of the Sun. Spacecraft A takes 347 days to orbit the Sun while spacecraft B takes 387 days. Because the A spacecraft is moving faster than B, they are separating from each other and A is orbiting closer to the Sun than B. The images are adjusted to account for this difference.

Each of the spacecraft carries cameras (a EUV imager and two coronagraphs), particle experiments and radio detectors in four instrument packages. STEREO is used to image the inner and outer corona and the space between Sun and Earth, detect electrons and other energetic particles in the solar wind, study the plasma characteristics of protons, alpha particles and heavy ions, and monitor radio wave disturbances between the Sun and Earth (Fig. 2.8).

From February 2011, the two Stereo spacecraft will be 180° apart from each other, allowing the entire Sun to be seen for the first time. Such observations will continue for several years. By combining images from the STEREO A and B spacecraft, with images from NASA's Solar Dynamic Observatory (SDO) satellite, a complete map of the Sun can be formed. Previous to the STEREO mission, astronomers could only see the side of the Sun facing Earth, and had little knowledge of what happened to solar features after they rotated out of view. In 2015 contact with the two spacecraft will be temporarily lost for a few months as they both pass behind the Sun. After this, they will continue to operate again and approach Earth.

SDO

The Solar Dynamics Observatory (SDO) is the most advanced spacecraft ever designed to study the Sun and its dynamic behavior. SDO is providing better quality, more comprehensive science data faster than any NASA spacecraft currently studying the Sun. The probe is aimed at providing data on the processes inside the

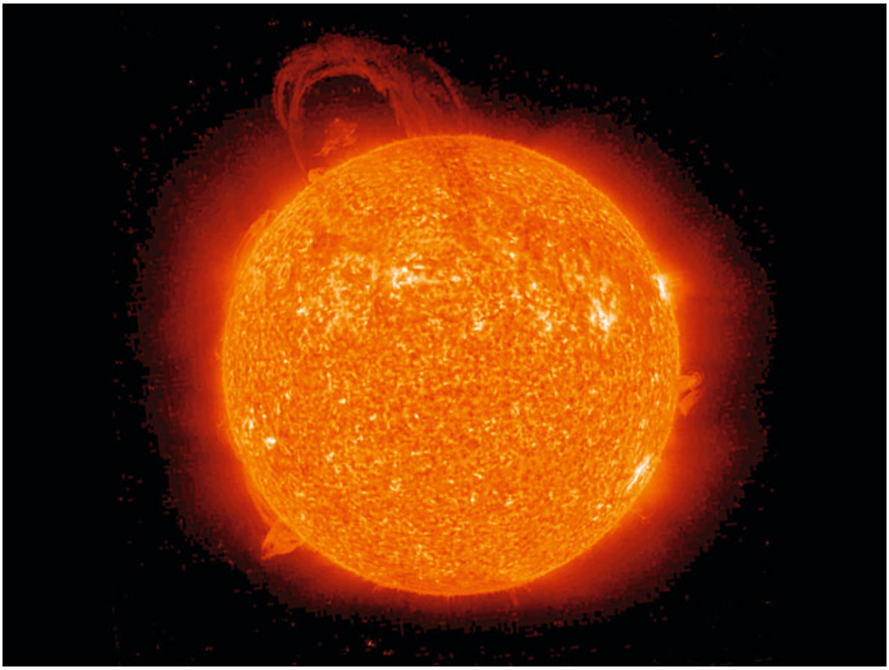

Fig. 2.8 The STEREO (Ahead) spacecraft caught this spectacular eruptive prominence in extreme UV light as it blasted away from the Sun (12–13th April 2010). This was certainly among the largest prominence eruptions seen by either the STEREO or SOHO missions. The length of the prominence appears to stretch almost halfway across the Sun, about 800,000 km. Prominences are cooler clouds of plasma that hover above the Sun's surface, tethered by magnetic forces. They are notoriously unstable and commonly erupt as this one did in a dramatic fashion (Credit: NASA/STEREO).

sun, the sun's surface, and its corona that result in solar variability. SDO will help scientists to better understand the Sun's influence on Earth and near-Earth space through the use of many wavelengths simultaneously. SDO will also investigate how the Sun's magnetic field is generated and structured.

SDO was launched from Cape Canaveral Air Force Station in the USA on 11th February 2010. After launch, SDO was placed into an orbit around Earth at about 2,500 km. It then underwent a series of orbit-raising maneuvers that placed it in a circular, geosynchronous orbit at altitude 36,000 km. It has a 5-year science mission and carries enough fuel to operate for an additional 5 years. At launch its mass was 3,100 kg with a payload of 290 and 1,450 kg of fuel. The solar panels cover an area of 6.6 m^2 producing

Fig. 2.9 The Solar Dynamics Observatory (*SDO*) is the most advanced spacecraft ever designed to study the Sun (Credit: NASA/SDO).

1,450 W of power. The overall length of the spacecraft along the Sun-pointing axis is 4.5 m, and each side is 2.22 m. See Fig. 2.9.

The SDO has three main instrument packages:

- The Atmospheric Imaging Assembly (AIA) is an array of four telescopes that observes the surface and atmosphere of the sun. The AIA filters cover ten different wavelength bands that are selected to reveal key aspects of solar activity. For example, wavelengths of 1,600 and 1,700 A are used to monitor the photosphere and transition regions; 304 A is used to monitor the chromosphere, while 171 and 193 A are used to monitor the corona.
- The Extreme Ultraviolet Variability Experiment (EVE) measures fluctuations in the Sun's ultraviolet output. Extreme ultraviolet (EUV) radiation from the Sun has a direct and powerful effect on Earth's upper atmosphere; it provides heat and inflation, and inserts enough energy to break apart atoms and molecules.
- The Helioseismic and Magnetic Imager (HMI) maps solar magnetic fields and peers beneath the Sun's opaque surface using a technique called helioseismology. A key goal of this experiment is to decipher the physics of the Sun's magnetic dynamo.

Did You Know?

The rapid cadence and continuous coverage required for Solar Dynamics Observatory (SDO) observations led to placing it into an inclined geosynchronous orbit. This allows for a nearly continuous, high data-rate contact with a single, dedicated ground station. Nearly continuous observations of the Sun can be obtained from other orbits, such as low Earth orbit. If SDO were placed into a lower orbit, it would be necessary to store large volumes of scientific data onboard until a downlink opportunity was available, and multiple sites around the globe would be needed to downlink the data. However, no space-qualified data recorder with the capability to handle this large data volume exists. This lack of a data recorder, the large data rate of SDO, and the ability to continuously stream data from the spacecraft if a geosynchronous orbit was selected, led to the selection of the inclined geosynchronous orbit. The disadvantage of this inclined geosynchronous orbit includes higher launch and orbit acquisition costs and eclipse (Earth shadow) seasons twice annually. During these 2–3 week eclipse periods, SDO experiences a daily interruption of solar observations, and these interruptions have been included in SDO's data capture budget. There will also be three lunar shadow events each year from this orbit.

The inclined geosynchronous orbit is located on the outer edges of Earth's radiation belt, where the radiation dose can be quite high. Additional shielding was added to reduce the effects of exposure to this ionizing radiation. Because the potential for damage due to space radiation effects is a 'space weather' effect, SDO is affected by the very processes it is designed to study (Fig. 2.10).

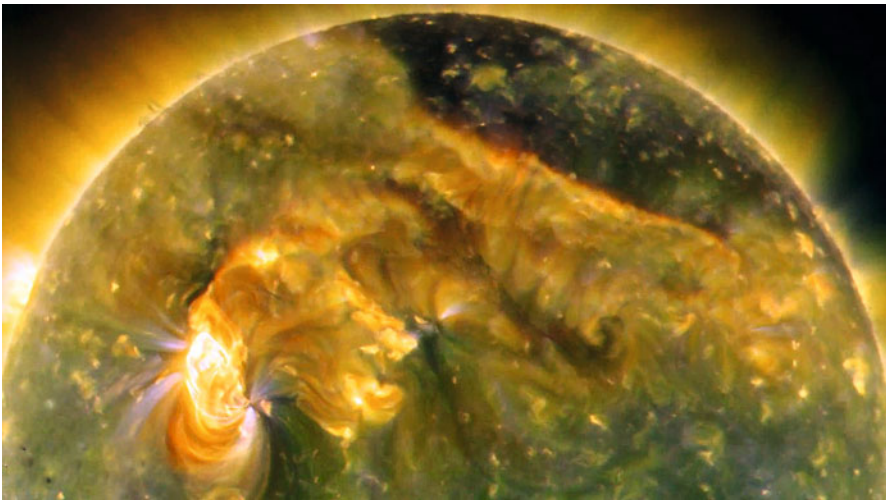

Fig. 2.10 On 1st August 2010, almost the entire Earth-facing side of the Sun erupted. There was a huge solar flare with multiple filaments of magnetism lifting off the Sun's surface, and large-scale shaking of the solar corona, radio bursts, a coronal mass ejection and more. This extreme ultraviolet snapshot from the Solar Dynamics Observatory (*SDO*) shows the Sun's northern hemisphere in mid-eruption. Different colours in the image represent different gas temperatures ranging from 1 to 2 million °C (Credit: NASA/SDO).

In May 2010, the AIA instrument on the SDO observed a number of very small flares that generate magnetic instabilities and waves over a large fraction of the Sun's surface. The instrument is capturing full disc images in eight different temperature bands that span 10,000 to 36 million °C. This allows scientists to observe entire events that are very difficult to discern by looking in a single temperature band, at a slower rate, or over a more limited field of view.

The data from SDO is providing a lot of new information and spectacular images of the Sun. Scientists are gaining a better understanding of how even small events on the Sun can significantly effect the operation of technological infrastructure on Earth (such as GPS systems, cable TV, radio and satellite communications).

Future Solar Probes

SOLO

The SOLar Orbiter (SOLO) is a solar mission proposed by the European Space Agency (ESA). The mission is planned for launch in January 2017. SOLO will perform detailed measurements of the inner heliosphere and solar wind, and perform close observations of the polar regions of the Sun. At its closest point, the spacecraft will be closer to the Sun than any previous spacecraft (one fifth the distance between Earth and the Sun or within 60 solar radii). It will be able to almost match the Sun's rotation around its axis for several days, and so will be able to see solar storms building up over an extended period from the same viewpoint. It will also deliver data of the side of the Sun not visible from Earth.

SOLO is specifically designed to always point to the Sun, and so its Sun-facing side is protected by a sunshield. The spacecraft will also be kept cool by special radiators, which will dissipate excess heat into space.

SOLO will carry a number of highly sophisticated instruments:

- Solar wind analyser – to measure solar wind properties and composition.

- Energetic particle detector – to measure charged and energetic particles.
- Magnetometer – to measure magnetic fields using high resolution.
- Radio and plasma wave analyser – to measure magnetic and electric fields.
- Polarimetric and Helioseismic imager – to provide high-resolution images of the photospheric magnetic field.
- EUV imager – to image various layers of solar atmosphere.
- EUV spectral imager – to examine surface and corona.
- X-ray spectrometer – to image Sun using x-rays.
- Coronagraph – to image the corona.
- Heliospheric imager – to image flow of solar wind.

SOLO will take about 3 years to reach the Sun using gravity assists from Venus and Earth. These swing-bys will put the spacecraft into a 168 daylong orbit around the Sun from which it will begin its scientific mission. During the course of the mission, additional Venus gravity assist manoeuvres will be used to increase the inclination of SOLO's orbit, helping the instruments to see the polar regions of the Sun clearly for the first time. Solar orbiter will eventually see the poles from an angle higher than 30°, compared to 7° at best from Earth.

Solar Probe Plus

Solar probe plus is planned for launch by NASA by July 2018. On its 6-year mission, the probe will perform 24 close-pass manoeuvres, using several 'slingshots' around Venus to get progressively closer to the Sun. At its closest approach, the probe will be within six million km of the Sun. To protect it from the Sun's heat, the probe will be tucked away behind a 2.7 m diameter, 15 cm thick shield made from a carbon foam composite; that will withstand over 1,400°C and intense radiation. The probes closest approach will be around December 2024.

The aims of the mission are to:

- Determine the structure and dynamics of the magnetic fields at the sources of solar wind.

- Trace the flow of energy that heats the corona and accelerates the solar wind.
- Determine what mechanisms accelerate and transport energetic particles.
- Explore dusty plasma near the sun and its influence on solar wind and energetic particle formation.

Did You Know?

A number of spacecraft used to monitor the Sun make use of a spectroscope or spectrograph.

Spectroscopes traditionally consist of a prism and several lenses that magnify the spectrum so that it can be examined. After photography was invented, scientists preferred to produce a permanent photographic record of spectra. A similar device for photographing a spectrum is called a spectrograph.

In its basic form a spectrograph consists of a slit, two lenses, and a prism arranged to focus the spectrum of an astronomical object, such as the Sun or a star, onto a photographic plate. See Fig. 2.11.

The spectrograph mounts at the focal point of a telescope and the image of the object being examined is focused on the slit. After the spectrum has been photographed, the spectrum is compared to the spectrum of known elements. Each element produces its own unique set of spectral lines. This method allows scientists to determine what elements are present on the object being examined. Scientists can also determine the velocities of objects from any shift in spectral line wavelengths (the Doppler shift).

A better device for breaking light into a spectrum is the diffraction grating – this device replaces a prism (see Fig. 2.12). In recent years charge coupled devices (CCDs) connected to a computer have replaced photographic plates to record spectra. CCDs produce a spectral graph that plots light intensity against wavelength. Dark spectral lines appear as dips in the graph, while bright lines appear as peaks. CCDs can be used for both visible and UV light. The exact choice of detector depends on the wavelengths of light to be recorded.

The forthcoming James Webb Space Telescope will contain both a near-infrared spectrograph (NIRSpec) and a mid-infrared spectrometer (MIRI).

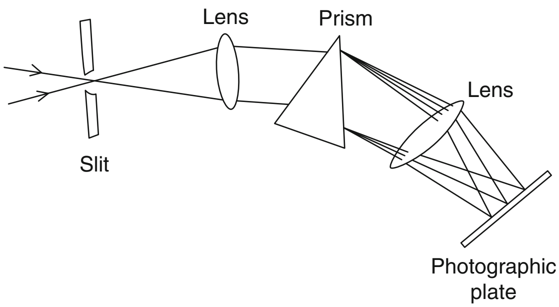

Fig. 2.11 A prism spectrograph.

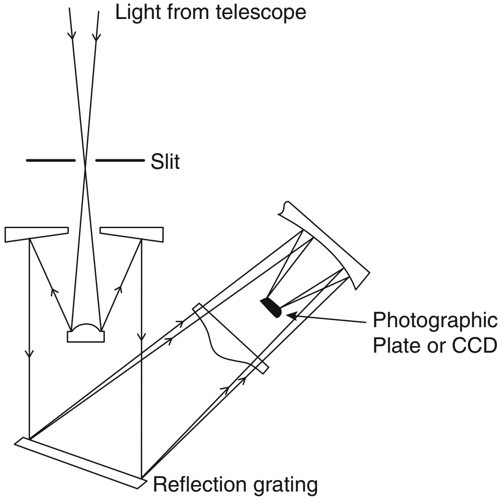

Fig. 2.12 A grating spectrograph.

Web Notes

For information on the Helios space probes see: http://www.honeysucklecreek.net/dss44/helios.html
For information on the Ulysses space probe see: http://ulysses.jpl.nasa.gov/
For information on SOHO see: http://sohowww.nascom.nasa.gov
For information about Hinode see: http://www.isas.jaxa.jp/e/enterp/missions/hinode/
For information on the SDO see: http://sdo.gasfc.nasa.gov
For information on SOLO see: http://sci.esa.int/solarorbiter
For information on Solar probe plus see: http://solarprobe.gsfc.nasa.gov/

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