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The century of space science

In the course of its brilliant evolution through the twentieth century, space science brought spectacular results and led to fundamental scientific findings. In the early quest for higher altitude, cosmic rays were discovered by Viktor Hess during a balloon flight in 1912. Following the second World War, sounding rockets were used, starting in 1946, to study the structure of the terrestrial atmosphere – the threshold of space. Two landmarks of the space age stand out: the launch in 1957 of the first satellite, Sputnik 1, which sensed the near-Earth environment at orbital altitude, and in 1969 the first landing by humans on an extraterrestrial body, the Moon. Today, sophisticated space probes explore distant worlds, and space telescopes look back in time towards the early Universe.

The scientific exploration of space was at the origin and, indeed, the motivation for our first ventures away from the Earth. It is well known, however, that rockets – the enabling tools of space research – were developed with support from the military, and that the 'space race', later on, served as a substitute battleground during the Cold War. Today, fortunately, the adversities of those years have given way to peaceful global collaboration that would have been technologically and ideologically impossible during most of the twentieth century.

The experiences of the astronauts on the Moon, their pictures of the Earth from above, the visits of unmanned spacecraft and robots to the distant planets and their satellites, and the probing of the largest distances and the earliest epochs of our Universe have changed the perception of the world around us, for scientists as well as for the general public. For about a quarter of a century after the end of World War II, in what we might call the early epoch of space science, experiments in space were regarded as daring but rather extravagant. But in the course of the 1970s, the methods and techniques of space science began to enter the mainstream of science, and by the end of the century, space science had become a natural complement, and often an integral part of study in many fields of science.

The present two volumes of *The Century of Space Science* tell the story of space science as it evolved during the twentieth century. The origins of space research, the enabling technology for space transportation and the 'early epoch' of space science mentioned above, are addressed in Chapters 2–14. The chapters in the main body of this Reference Work then describe the development and results of the scientific topics that have benefited extensively from space investigations. A chronology of the space age and a list of space science missions appear as appendices.

We have had to restrict the number of fields covered, and have therefore concentrated on those topics with the most comprehensive record in space, namely the exploration of the Solar System, astronomy and gravitational physics. We note, however, that space science – far from being a coherent discipline itself – has by now become a widely used method that complements in an essential way the investigative tools of an impressive range of initially laboratory- and ground-based research fields.

We have also included three chapters on Earth science. This field is important not only because of its scientific achievements, but also because, from early on in the space

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Johan A.M. Bleeker, Johannes Geiss and Martin C.E. Huber, The Century of Space Science, 3–22

age, it started to raise humanity's awareness of the fragility of their home planet – 'spaceship Earth' – which protects them from the hostile cosmic environment. It is appropriate therefore to include here an image of 'the blue planet in space', photographed during one of the Apollo missions (Figure 1).

Rather than use this chapter to summarize the contents of the rest of the book, we instead highlight a number of results which demonstrate how space science has made major contributions to our knowledge, and sometimes has even forced us to change our concepts of nature. In outlining these results, we start with Earth System science and then proceed – roughly following the historical development – from the terrestrial environment and the Solar System to the Milky Way, and then to extragalactic space and cosmology. (Note, however, that the sequence chosen for the topics presented in the main body of this work is the opposite: it begins with gravitational physics and cosmology and ends with Earth science.)

EARTH SYSTEM SCIENCE

Space-borne observational platforms gave us, for the first time, the means to survey the many features of our planet rapidly and effectively from a global perspective. This global view of the Earth from space – together with the maturation of distinct Earth-science disciplines, such as geophysics of the solid Earth, oceanography, and atmospheric dynamics and chemistry, as well as the recognition of the human role in global change – has stimulated a new approach for studying our home world, what we might call Earth System science. In this approach the Earth System is studied in the context of a related set of interacting processes rather than as a collection of individual components. Interactions among oceans, ice, land-masses, the atmosphere and biological systems are significant but also very complex. The transport of energy and material within and among these subsystems occurs on a global scale across a wide range of time-scales. Observations from space are indispensable for present and future research,

Figure 1 The Blue Planet, with the dry lunar surface in the foreground.

whose ultimate goal is an understanding of the processes responsible for the evolution of the Earth on all time-scales.

The importance of a synoptic view of planet Earth is convincingly demonstrated by the global monitoring of stratospheric ozone (Figure 2). Ozone provides crucial protection against hard ultraviolet radiation from the Sun. The mapping and monitoring of the evolution of the Antarctic ozone hole has helped us to develop and validate representative models for ozone depletion and restoration in the upper atmosphere.

PLASMAS IN SPACE: MAGNETOSPHERE AND HELIOSPHERE

The International Geophysical Year (1957/58) was the first worldwide coordinated effort in space science. Its goal was to understand the aurorae and to map the variation of the Earth's magnetic field. Space science has indeed clarified to a large extent the relation between the two. Sounding rockets on suborbital trajectories, satellites in various orbits together with ground-based observations of geomagnetic field variations were instrumental in revealing the processes that cause auroral phenomena. These early efforts immediately led to the discovery of a magnetically trapped, collisionless particle population, namely the radiation belts and the terrestrial magnetosphere, including its extended magnetotail (Figure 3).

It was found that what is responsible for the aurorae (Figure 4) is a medium-energy particle component being injected – during magnetic substorms – from the magnetotail into the auroral zone, rather than, as had been believed, trapped high-energy particles in the radiation belts.

Space in the terrestrial neighbourhood was also exploited as a natural laboratory: *in situ* measurements led to the discovery of discontinuities in the collisionless space plasma and uncovered the phenomena of magnetic reconnection and shock acceleration, both fundamental processes throughout the cosmos. The terrestrial magnetosphere later became the prototype for modelling other planetary magnetospheres and the magnetospheres of neutron stars, pulsars and rotating black holes.

The heliosphere is formed, because the corona of the Sun is in a state of expansion, forming a continuously flowing solar wind. Because of its expansion into three dimensions, the solar wind pressure is reduced until it can no longer overcome the ambient interstellar plasma pressure. A termination shock, formed at an estimated heliocentric distance of 80–100 AU, converts the supersonic wind into a subsonic flow.

The charged particles in the external interstellar gas cannot penetrate the heliopause, the boundary of the heliosphere. However, interstellar grains and neutral atoms do enter, and

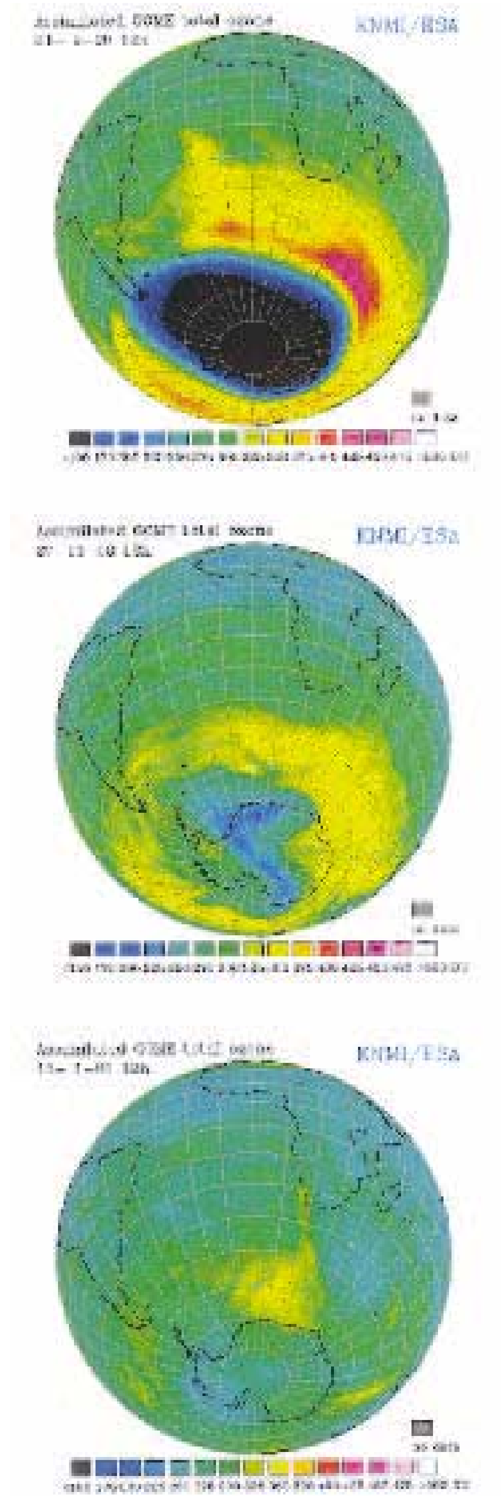

Figure 2 Assimilated total ozone maps showing the evolution of the Antarctic ozone hole between September 2000 and January 2001.

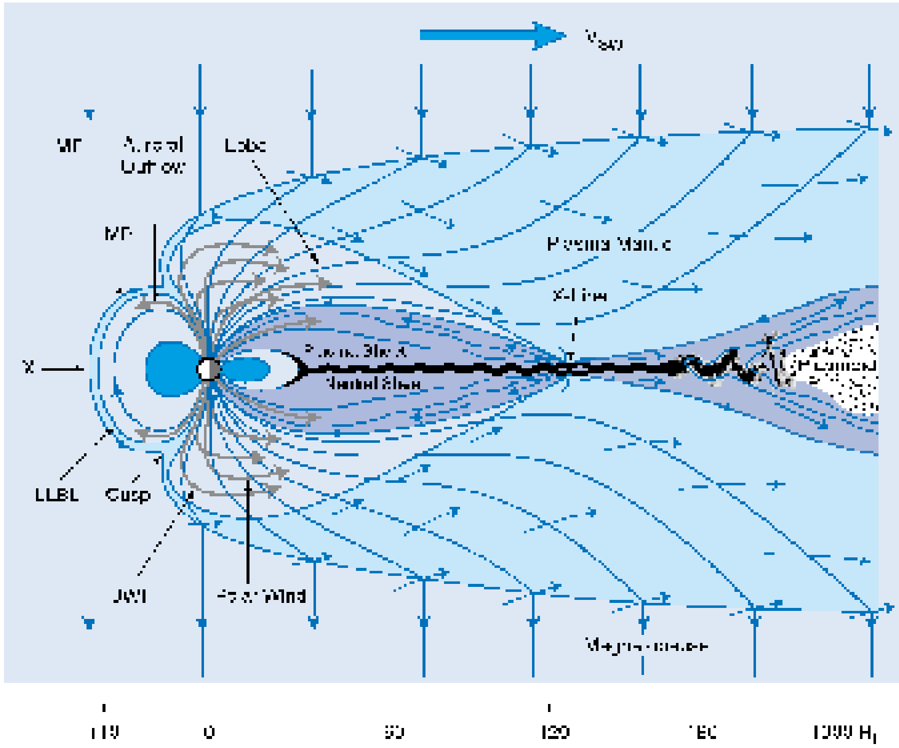

Figure 3 The terrestrial magnetosphere, which results from the interaction of the solar wind with the magnetic field of the Earth, was completely unknown before the advent of the space age. This schematic drawing gives an impression of the complexity of the interaction.

they have been found and investigated by spacecraft in the space between the planets and throughout the heliosphere, allowing a direct analysis of physical, chemical and isotopic properties of the matter in the local interstellar cloud.

A rich variety of heliospheric phenomena have been discovered, and the underlying processes are now generally well understood. And the heliosphere has become a paradigm for the interaction of a main sequence star with the interstellar medium.

THE MOON AND THE TERRESTRIAL PLANETS

The origin of the Earth–Moon system, has long been an enigma. Moons orbit many planets in the Solar System but, with the exception of those of Earth and Pluto, they are tiny in comparison with the planet they accompany. The satellite systems of the giant planets, Jupiter and Saturn, consisting of more than ten moons each were probably formed from circumplanetary disks at the time of the planets' formation. The exceptional relative size of our Moon points to a different genesis. Among the various hypotheses of the Lunar origin, there is only one – the giant impact theory – that explains all the relevant observations (Figure 5).

Evidence gathered from Lunar exploration by manned and unmanned spacecraft shows that water of crystallization and hydrogen-containing minerals are absent from Lunar material, and that other volatile elements, such as carbon and nitrogen, are virtually absent as well (Figure 6). Furthermore, neither *in situ* observations by astronauts nor pictures taken on the lunar surface or from lunar orbit revealed any traces of past water flows or sedimentation (Figure 7). The extremely high temperature of the material ejected by a giant collision can readily explain this complete lack of volatile material.

It is also remarkable that the Moon has much less iron than does the Earth or meteorites. This is indeed what we would expect if the giant impact occurred after the Earth had formed its iron core and if the impact ejected mainly material from the Earth's crust and mantle. Fractionation-corrected abundances of the three isotopes of oxygen also point to a terrestrial origin of the Moon: they are identical in all Lunar and terrestrial samples, yet differ from those of Martian rocks and all classes of meteorites.

The aggregate evidence in favour of the giant impact theory has become so strong that, at the end of the twentieth century, it is generally accepted as the proper explanation for the origin of the Moon.

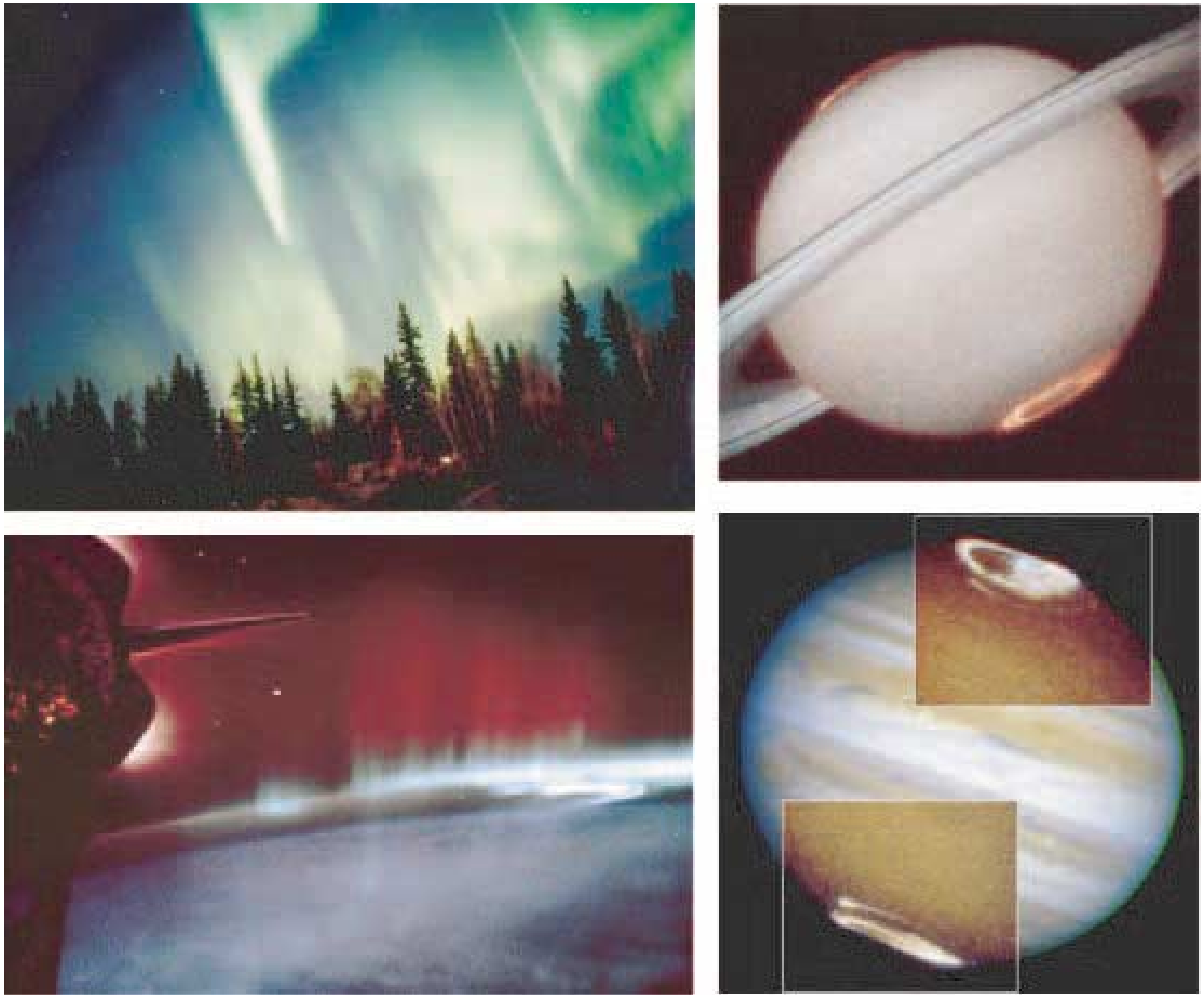

Figure 4 The aurora borealis as seen from the ground and from the Space Shuttle (note the silhouetted tail fin and engine shrouds), and pictures of aurorae on Jupiter and Saturn, as observed by the Hubble Space Telescope.

Figure 5 All evidence indicates that our Moon was created by a collision between Earth and a Mars-sized object that had formed in a nearby orbit. This painting by William K. Hartmann depicts the situation five hours after the collision.

The Apollo programme and unmanned lunar orbiters and landers have given us a remarkably complete picture of the evolution of the Moon as a geological, geophysical and geochemical entity. Its anorthositic crust indicates complete melting in its early history. Later, between about 600 and 1500 million years after the birth of the Moon, iron- and titanium-rich lava rose from below and filled the large basins that had been excavated a few hundred million years

Figure 6 A thin section of basaltic rock collected by Neil A. Armstrong and Edwin E. Aldrin in the Lunar Mare Tranquillitatis. The Moon is virtually free of hydrogen, carbon, nitrogen and other volatile elements; accordingly, the minerals in this sample of lunar rock do not contain these elements.

Figure 7 The dry Lunar landscape in the Mare Imbrium. Like everywhere else on the Moon, there is no trace of past water flows. The rocks are dry, devoid of hydrogen, carbon and nitrogen, although nearby there is a valley that at times in the past had been considered to be a dry riverbed.

earlier by large impacts during the last stages of accretion in the Solar System. The lava-filled basins are the dark basaltic planes on the Moon that were called maria by Galileo.

The other surface features are younger and are mostly due to more recent impacts, because by about 3 billion years ago the interior of the Moon had cooled to the point where geological activity came to a standstill, and the surface of the Moon was only occasionally changed by impacts. On Earth, the intrinsic geological activity goes on to this day. Impacts have only a small influence on shaping surface features of our planet. However, towards the end of the twentieth century it became more and more apparent that impacts play a major role in the evolution of life.

The space age has also completely transformed planetary science. This field has evolved from a branch of astronomy into a multidisciplinary field that now embraces astronomy, geology, geophysics, geochronology, geochemistry and atmospheric science.

Concepts developed over centuries of Earth science can be extended to those objects not too dissimilar from the Earth, namely the terrestrial planets and the Moon. Although an interplanetary traveller would perceive Earth, Moon and Mars (Figure 8) as entirely different worlds, these members of the Solar System have important similarities: their sizes, chemical compositions and distances from the Sun are rather similar, and so comparative studies can further our understanding of their origin and evolution. Moreover, we note that these three are the only objects in the Universe for which, by the end of the twentieth century, detailed geological surveys had been conducted and of which we possess rock samples for laboratory analysis.

It should be stressed, however, that comparative planetology is not just a matter of transferring experience and information from Earth science to planetology. Quite the contrary: much has been learned about the origin and the early history of the Earth from comparisons with the Moon. The methods used to derive the relative abundances of chemical elements in the Earth and other planetary bodies were developed by comparing results of chemical analyses of rocks from the Earth, Moon and meteorites, including some meteorites from Mars. Comparisons of the molecular and isotopic compositions of the extremely different atmospheres of Venus, Earth, the Moon and Mars have also improved our knowledge of fundamental atmospheric processes such as outgassing and loss by escape, and of factors that determine planetary climates, such as the greenhouse effect. And our

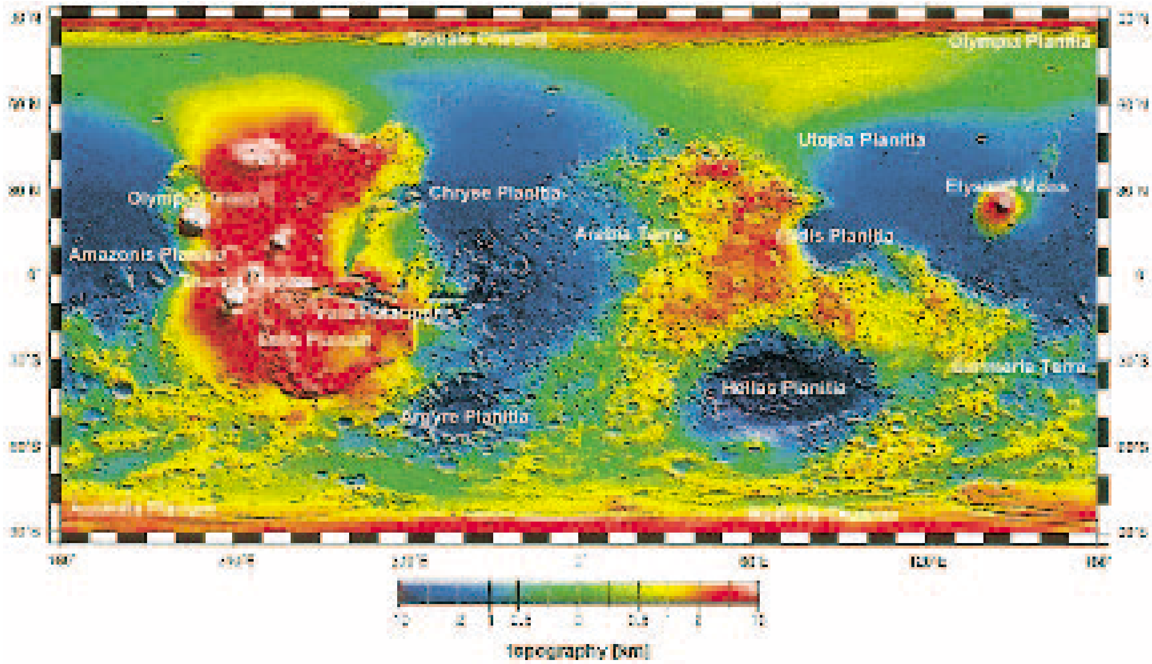

Figure 8 Topographic map of Mars. Low levels are shown in blue, as a reminder that in the past there was probably extensive flooding on Mars.

understanding of the role of impacts in surface geology and in biological evolution on Earth has been greatly advanced by the study of craters and other surface features of the terrestrial planets and the Moon.

The technique of remote sensing from orbit permits us to investigate not only the atmospheres but also the surfaces of the Moon and the planets, including the Earth. Moreover, depending on the thickness of the atmosphere, the surface chemistry and mineralogy of these bodies can be probed by using parts of the electromagnetic spectrum other than the visible, for example gamma rays for Mars and X-rays and gamma rays for the Moon (Figure 9). The atmosphere of Venus, on the other hand, is so thick that surface features can be sensed only by radio and radar techniques (Figure 10). Similarly on Earth, radar can ‘see through’ the clouds.

Information about the interiors of planets is obtained from seismic data and from measurements of gravity, heat flow and magnetic field. Strong magnetic fields, implying an ongoing dynamo effect inside the Earth, Jupiter and other large planets, have been observed. Magnetic field measurements now also indicate that Mars possessed a dynamo in its early history.

The exploration of Mars gained momentum towards the end of the twentieth century, largely because indications of

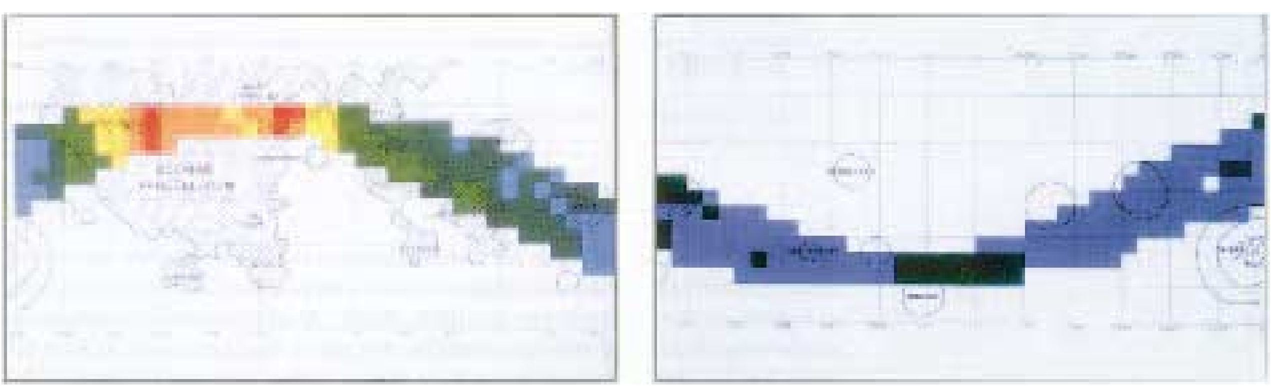

Figure 9 A compositional map of the Lunar surface as determined by the Apollo 15 gamma-ray spectrometer. High concentrations of radioactive elements (red and yellow regions) are found in the maria and other regions on the nearside.

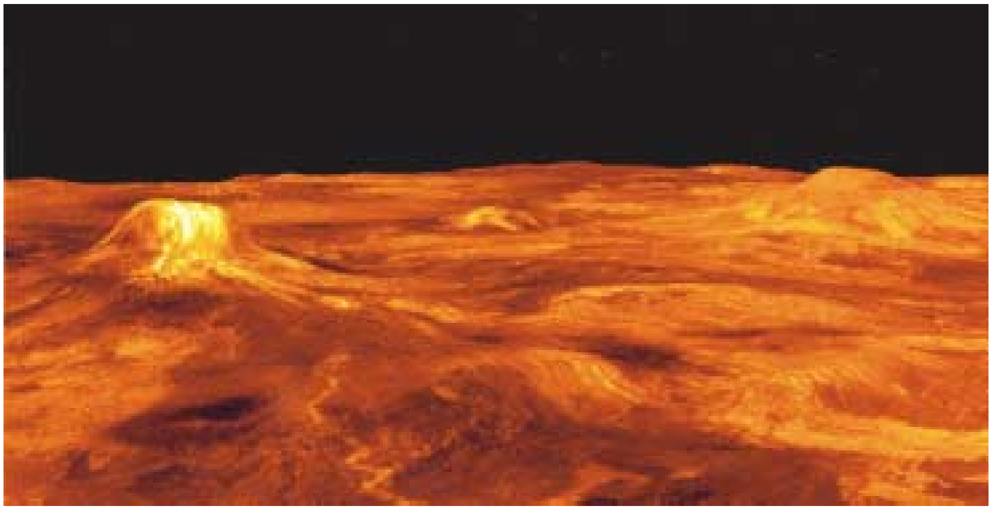

Figure 10 A three-dimensional perspective view of the surface of Venus, showing the western Eistla region with the volcanic peaks of Gula Mons (left, 3 km high) and Sif Mons (right, 2 km high). The image was obtained by use of synthetic aperture radar (SAR) data combined with radar altimetry, both from the US-American Magellan mission. The hues are based on colour images recorded by the Soviet Venera 13 and 14 probes.

extensive water flows at some undetermined earlier epoch were discovered. These observations and findings in meteorites of Martian origin greatly increased interest in the question of whether life, or at least extinct life, could be found on Mars.

THE OUTER SOLAR SYSTEM

Pictures and other data transmitted from probes that have visited the outer planets and their environs, and also observations with space telescopes, have revealed a fantastic variety of surfaces, atmospheric phenomena, ring systems, and Io's plasma torus. Shepherd moons, which constrain thin rings of shards circling planets, were found as well. The larger moons, in particular, showed traces of geologically recent changes on their surfaces and even current activity. The most dramatic example is the ongoing activity of Io, the innermost of Jupiter's Galilean moons (Figure 11). This activity not only shapes the surface of this satellite, it also gives rise to the famous sulphur-rich Io torus, which in turn is a major source of ions for the huge magnetosphere of Jupiter. Given Io's size, which is similar to that of the Earth's Moon, internal energy sources could not possibly drive the strong sulphur volcanism that exists in the present epoch. The answer to the puzzle is the tidal force exerted by Jupiter, which has over 300 times the mass of the Earth.

Europa, though farther from Jupiter than Io, still appears to be affected by this tidal force. Evidence of mobile 'ice rafts' on the surface of Europa indicates fluid flow. Tidal stress may exceed the tensile strength of the ice, lead to cracks in the ice and expose the liquid underneath, which then freezes upon exposure. Changes in the orientation of this satellite's magnetic axis with time are, in fact, consistent with a conductive liquid-water layer less than 100 km below the surface. Europa's icy shell is therefore thought to cover a salt-rich ocean, in which life might exist.

Saturn's largest satellite, Titan, also evoked considerable interest (Figure 12). The temperature structure of its atmosphere and the abundance of nitrogen and hydrocarbons are reminiscent of the early Earth. Titan, however, has not evolved because of the low temperature and the lack of liquid water at 10 AU from the Sun.

THE ORIGIN OF THE SOLAR SYSTEM, METEORITES AND COMETS

The question of the origin of the Solar System remained largely a domain of physicists well into the twentieth century. It was concluded that the process starts with the gravitational collapse of a cloud of gas and dust, and is followed by the formation of a disk from which the Sun and planets evolved. When chemical arguments were introduced, meteorite research became important in studying the origin and evolution of the Solar System. From isotope abundance measurements in terrestrial and meteorite samples, it was found that the age of the Earth and of the Solar System was 4.5 billion years.

In 1986, at the time of the return of Comet Halley, a fleet of spacecraft was despatched to encounter this celestial body and its environment. The Giotto spacecraft, in particular, went deep into the coma, obtaining the first detailed picture of a

Figure 11 Left: the giant planet Jupiter with two of its Galilean moons, Io (reddish) and Europa (white). While these and other moons of Jupiter have nearly the same size as our Moon, they are tiny in comparison with their parent planet. Right: close-ups of Io and Europa, both of which exhibit geological activity that stems from powerful tidal forces exerted by massive Jupiter.

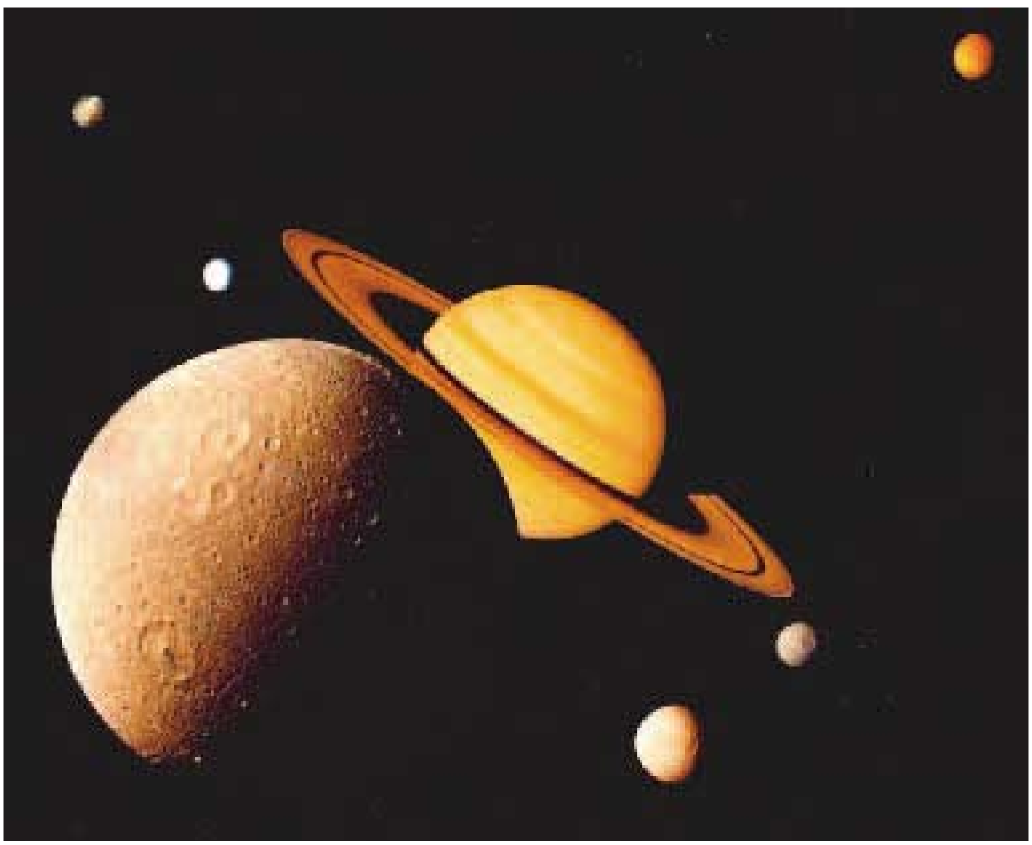

Figure 12 A collage of Saturn and its moons: Dione (foreground) and (from left to right) Thea, Enceladus, Tethys, Mimas and Titan.

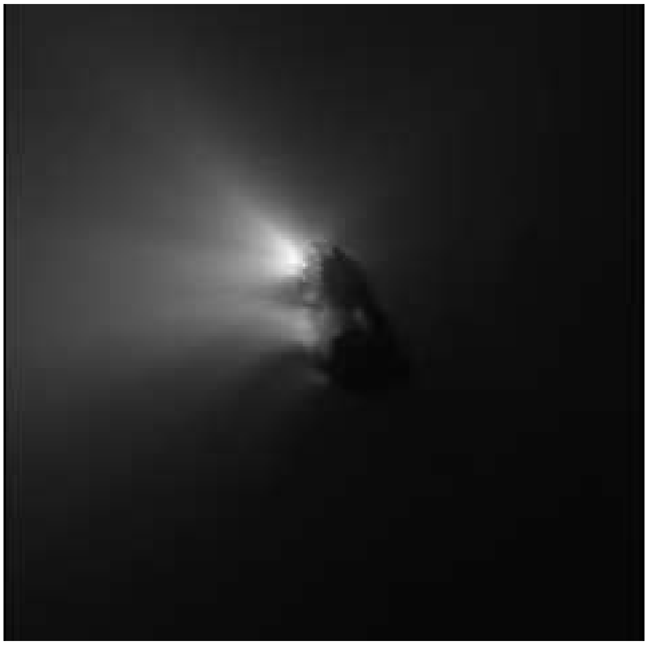

Figure 13 The nucleus of Comet Halley imaged by the Halley Multicolor Camera on board Giotto.

cometary nucleus and determining the composition of the gas and dust grains in the coma (Figure 13). This confirmed and considerably refined the so-called dirty snowball hypothesis, and also showed that comets have indeed preserved a wealth of virtually unchanged interstellar material, much like the material from which the Solar System was formed.

THE SUN

The Earth, its climate and the life it supports are all subjected to and governed by solar radiation and its subtle variations. The astronomer, on the other hand, looks upon the Sun as a Rosetta Stone. Being the dominant object in the sky, it is easily accessible to observations and has become a proving ground for advanced observing techniques. Indeed the first space experiments that went beyond investigating the terrestrial atmosphere and ionosphere were devoted to recording solar ultraviolet spectra.

Among the early astronomical satellites were the series of Orbiting Solar Observatories, followed in 1973 by the pioneering Apollo Telescope Mount on Skylab. From this first, albeit short-lived, space station the outer solar atmosphere and the extension of the outer corona into the heliosphere could be investigated by a multiwavelength complement of imaging, spectroscopic and coronagraphic telescopes having focal lengths that enabled observations down to arc-second resolution. (At a time when photoelectric imaging detectors were not readily available, the presence of astronauts onboard Skylab made it possible to use photographic film and return it to Earth for developing.)

With access to a halo orbit around the L_1 Lagrangian point on the Earth–Sun line, it became possible to combine remote-sensing observations with *in-situ* solar-wind measurements. The Solar and Heliospheric Observatory, placed in such an orbit, went a step further. It also enabled space observations by the method of helioseismology, and thus provided a detailed look into the solar interior as well (Figure 14). A complete picture of the structure and dynamics of the solar interior, the processes that maintain the high temperatures in the corona and the processes of solar-wind acceleration is thus emerging from this observatory.

The riddle of whether the ‘missing’ solar neutrino flux at Earth should be explained by some exotic behaviour of the energy-generating solar core or by adapting the theory of elementary particles is now resolved, since the solar core does not have any unexpected properties. It is currently thought that the electron neutrinos generated in the core change their flavour while passing through the Sun and on their way from the Sun to the Earth. Consequently, since the first large neutrino detectors on Earth were only capable of detecting electron neutrinos, the solar neutrino flux appeared lower since some of them had become μ- or τ-neutrinos.

Measurements by the Solar and Heliospheric Observatory also confirmed that the solar ‘constant’ varies with the solar cycle. The solar irradiance was found to increase by about 0.1% between solar minimum and maximum.

Moreover, we now know that the Sun’s magnetic field supplies the energy that heats the corona. Waves which had previously been thought to contribute to the heating of the corona were identified as the accelerating agent – through the ion-cyclotron mechanism – for the fast solar wind (Figure 15) that emerges from coronal holes (i.e. from open magnetic field configurations).

Coronal mass ejections, a phenomenon discovered by Skylab, can now be followed far into interplanetary space,

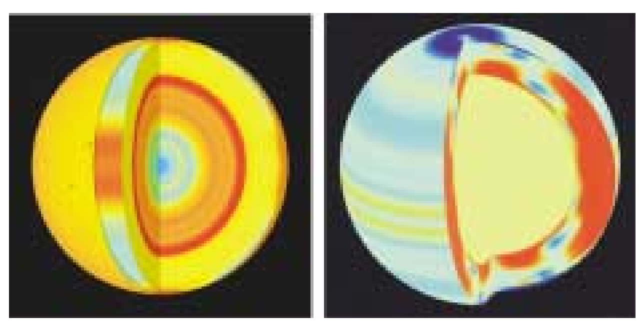

Figure 14 Temperature and rotation in the solar interior. The images show the deviations of these properties, as derived from SOHO measurements, from current models.

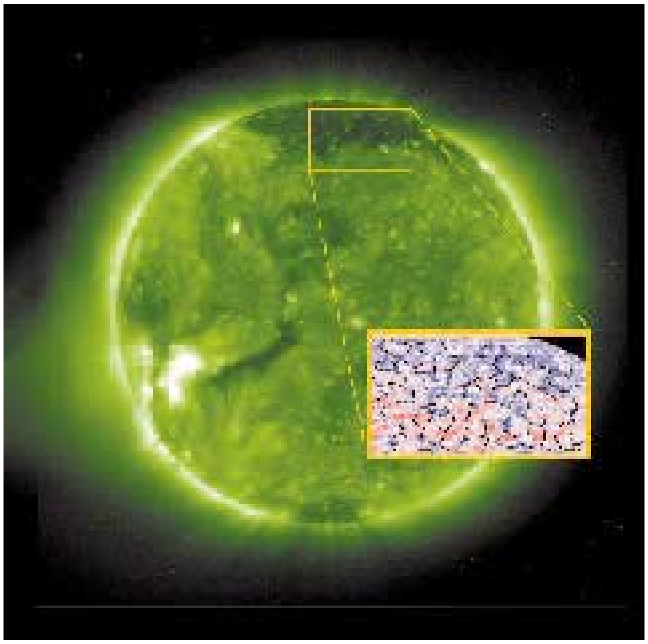

Figure 15 Dopplergram showing the (blueshifted) source regions of the fast solar wind, namely the boundaries and boundary intersections of magnetic network cells in a coronal hole.

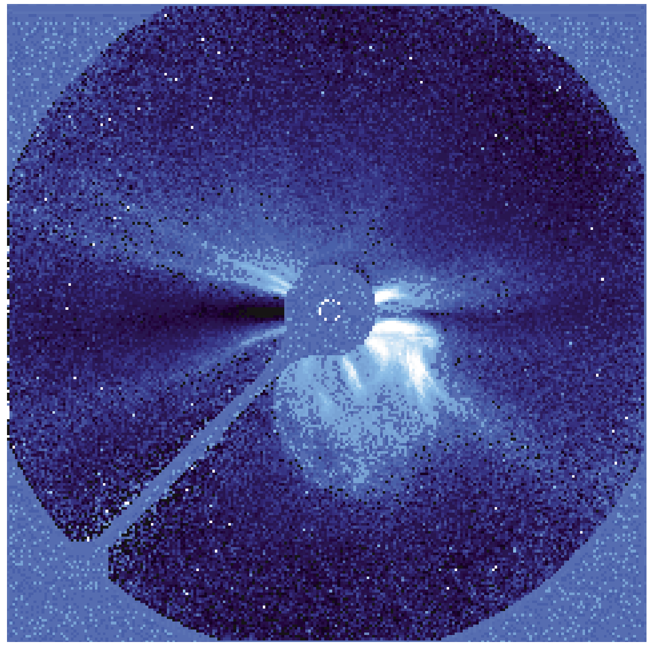

Figure 16 A coronal mass ejection propagating into the heliosphere. Stars are visible in this coronagraph image whose field of view is thirty solar diameters wide.

and also as they propagate towards the Earth (Figure 16). This provides a useful means of predicting disturbances in the Earth's environment – a range of phenomena which have been collectively termed 'space weather'. Given the increasing dependence of our civilization on communication, navigation and Earth-observing satellites – all vulnerable to major disturbances in the space environment – space weather forecasting is becoming another important service whose roots lie in space science.

THE MILKY WAY

The impact of the space age on the evolution of, and progress in astronomical research has been huge, since the full breadth of the electromagnetic spectrum and primary cosmic-ray particle population became available as information carriers for cosmic diagnostics. Space observatories exploring the infrared, ultraviolet, X-ray and gamma-ray wavebands have revealed a dynamic and violent Universe harbouring a zoo of exotic objects. Inevitably, we have to limit ourselves here to selecting a few scientific highlights from space-borne astronomy and obviously they reflect a subjective choice.

Although ground-based radio astronomy has unveiled a variety of molecular species, a major asset among the scientific harvest of space-borne spectroscopy in the infrared and far-infrared regions has been the molecular signature of water in circumstellar and interstellar environments. Water possesses a very large number of strong rotational transitions in the far infrared, which suggest that it can act as a major or even dominant coolant in shocks and circumstellar outflows. In particular, the Infrared Space Observatory unveiled a host of water-emitting cosmic sites. Among them are the asymptotic giant branch (AGB) stars, confirming that water molecules are the dominant coolants of the stellar winds emanating from these stars (Figure 17).

Moreover, the Infrared Space Observatory revealed, for the first time in a circumstellar medium, polyacetylenic chains, including C_4H_2 and C_6H_2, and benzene (C_6H_6). From these observations it appears that carbon-rich protoplanetary nebulae are capable of producing prebiotic matter in space (Figure 18).

While our picture of stellar evolution has been established with the aid of ground-based observations, progress in the study of star formation has come to depend increasingly on observations from space. Diagnosing the process of star formation requires penetration into the interiors of protostellar clouds, provided by measurements at infrared and microwave frequencies. Observations from space have played a crucial role in improving our understanding of star formation, notably in the form of spectroscopic measurements from the Infrared Space Observatory, and astrometric measurements and imaging from Hipparcos and the Hubble Space Telescope, respectively.

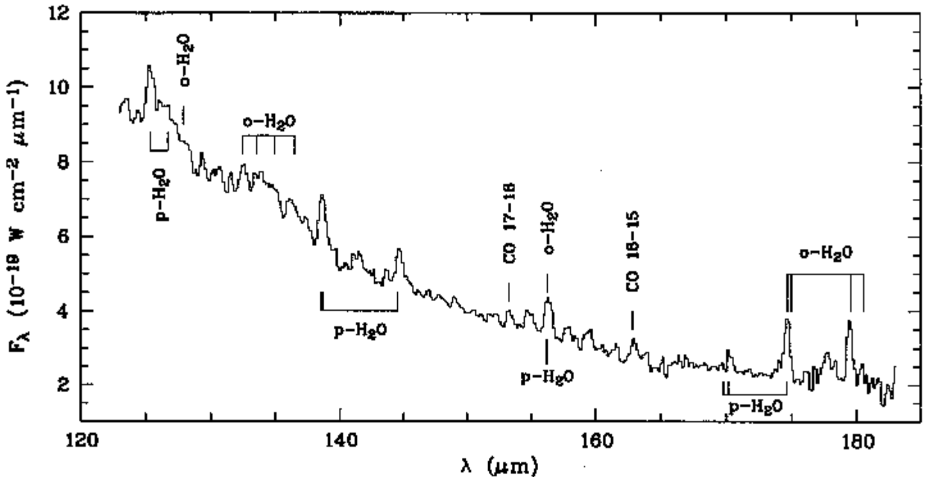

Figure 17 Water acts as a coolant in the stellar winds of AGB stars.

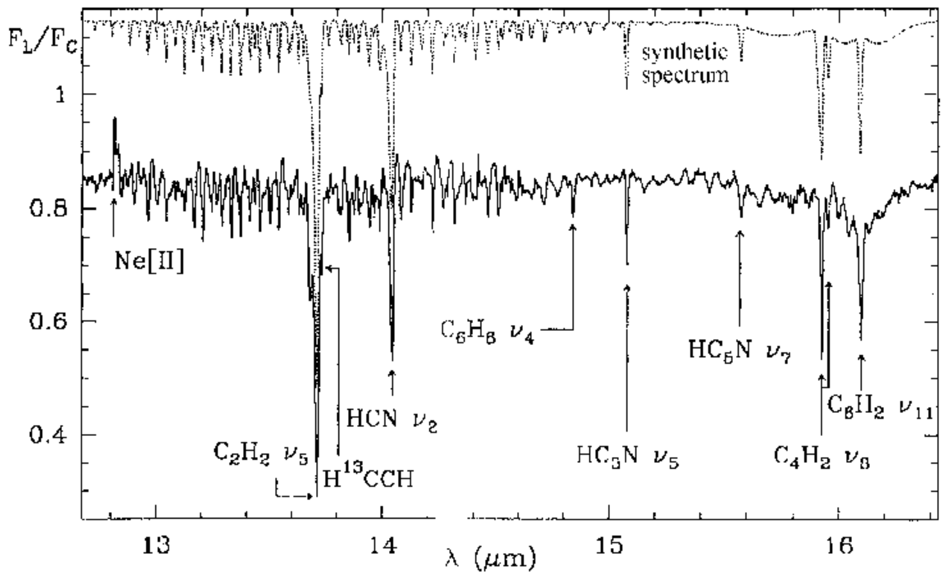

Figure 18 Carbon-rich protoplanetary nebulae as organic chemistry factories in space.

Observationally, it has now been confirmed that practically all low-mass stars like our Sun are born via the formation of a disk, which arises from the angular momentum conservation of the gravitationally collapsing protostellar cloud. The final dimensions of these disks are comparable to the size of our Solar System, and they have a mass approximately ten times the mass of our 'heaviest' planet, Jupiter, which implies the presence of sufficient material to form a planetary system.

Disks of planetary material orbiting newborn stars are called protoplanetary disks. The Hubble Space Telescope has recently obtained high-resolution images of such disks around young stars in the Orion Nebula, where they show up as dark silhouettes in images obtained in visible light (Figure 19). Ground-based observations of exoplanets indicate a great diversity of morphology in planetary systems: Jupiter-like planets are also found much closer to the central star than in our Solar System and they are, most likely, formed first. Earth-like planets are believed to form later, through the aggregation of a large number of planetesimals a few kilometres in size.

Observations from space have not only helped to identify the early stages in the life of a star, but have also revealed the most extreme remnants of stars, namely stellar-mass black holes. The strongest evidence for the existence of such black holes comes from observations of compact X-ray binary sources in which the orbital velocity of the normal companion star can be measured from the Doppler shift of its characteristic spectral lines at optical frequencies.

Using Kepler's laws, a quantity called the mass function, $f(M)$, of the system can be determined from measurements of the orbital period of the compact binary and the semi-amplitude of the radial velocity. This mass function is the observational lower limit of the presumed black hole mass. Fundamental physical arguments show that, among very compact objects, only a black hole can have a mass in excess of 3 solar masses ($M_{\odot}$), so if mass function values above $3M_{\odot}$ are found, the compact source has to be a black hole. So far about ten black hole systems (i.e. objects with $f(M)$ greater than $3M_{\odot}$) have been found in our Galaxy. The largest mass function was found for the recurrent nova V404 Cygni, a low-mass X-ray binary with a 6.5-day periodicity, for which $f(M) = 6.26$ (Figure 20).

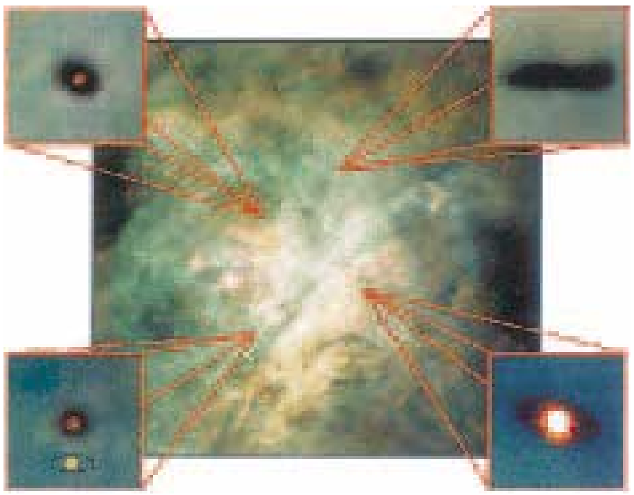

Figure 19 Hubble Space Telescope picture showing disks of planetary material orbiting around young stars in the Orion Nebula. The size of the solar system is indicated by the lower image in the lower left corner.

A remarkable achievement of space-borne astronomy concerns astrometry, the oldest, most classical subdiscipline of astronomy: measuring precise positions, parallaxes and proper motions of stars to study the Galaxy's structure and kinematics. The Hipparcos satellite has boosted this field by providing positions of nearly 120 000 stars to milli-arc-second accuracy, and established accurate distances for tens of thousands of stars. In fact, Hipparcos pushed the effective range for parallax measurements from 30 pc out to 300 pc. Accurate distances yield accurate luminosities for all kinds of stars, and consequently theories of stellar evolution can be tested much more rigorously (Figure 21). The kinematic data provided by Hipparcos through the measurement of proper motions coupled with accurate distances allows an in-depth assessment of the dynamic evolution of the Milky Way system. Among other things, these dynamical studies will display the interplay between gravity and pressure and the role of instabilities in our Galaxy.

As mentioned in the opening paragraph of this chapter, the discovery of cosmic rays may be regarded as the first result of space research. Although this discovery took place in 1912, the fact that the primary radiation consists of charged particles coming from the depths of space became generally accepted around the middle of the century. Cosmic rays observed at the surface of the Earth are mostly secondary

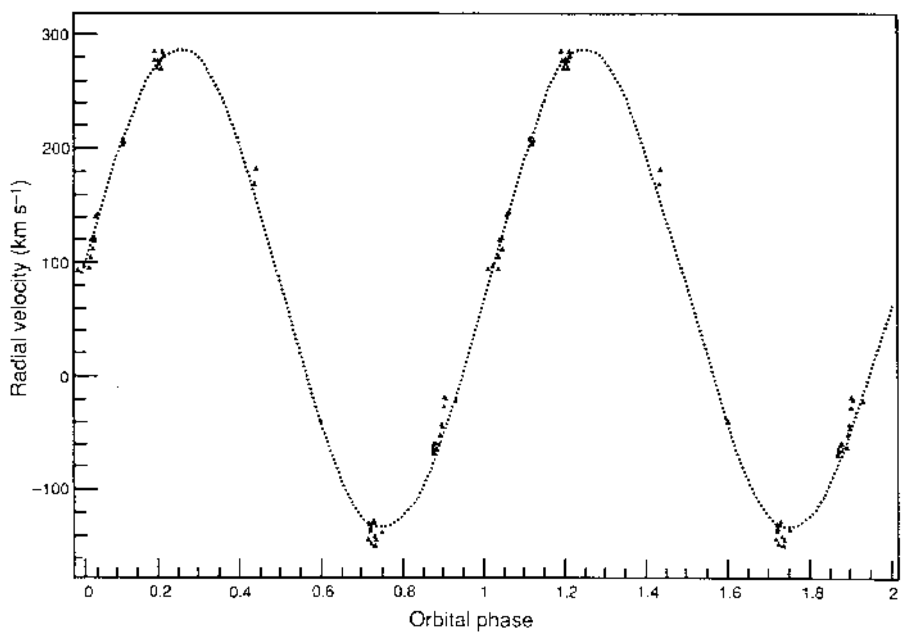

Figure 20 Radial velocity curve of the black hole system V404 Cygni.

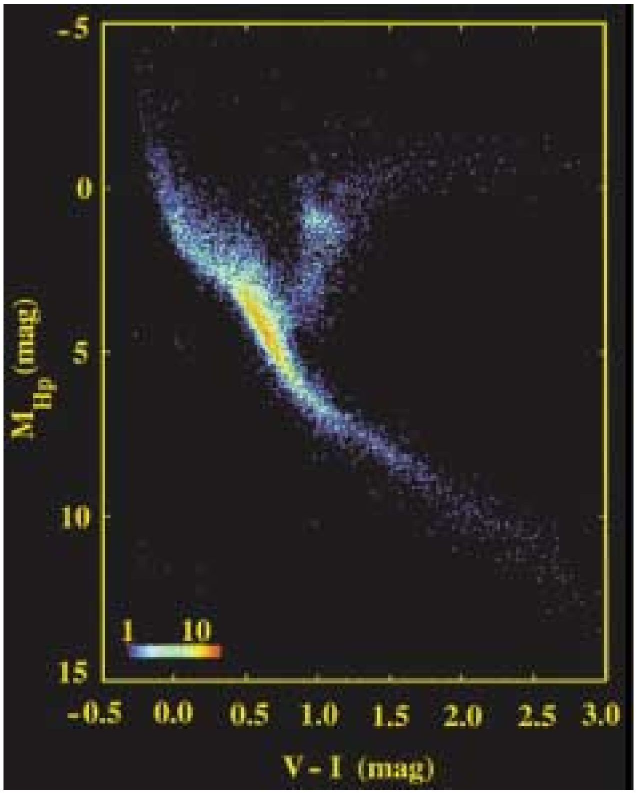

Figure 21 Hertzsprung–Russell diagram, reflecting stellar evolution, for the 16631 single stars from the Hipparcos Catalogue whose distances and colour magnitudes are known to within 10% and 0.025 mag, respectively. The colour indicates the number of stars in each pixel of the diagram.

particles. Therefore measurements had to be made from space to detect the primary radiation. (In the 1930s and 1940s, cosmic rays were the main source of particles for the emerging field of elementary particle physics. Positrons, muons, pions, kaons and hyperons were discovered as secondary particles produced in the atmosphere by cosmic rays, and their lifetimes and modes of decay were determined.)

Three principal sources of cosmic rays were identified namely (i) high-energy particles originating in the Galaxy, (ii) solar particles accelerated by shocks created by solar flares, coronal mass ejections and the co-rotating interaction regions, and (iii) the so-called anomalous component of cosmic rays. The latter are accelerated pick-up ions produced from the neutral interstellar gas flowing through the heliosphere. Towards the end of the twentieth century, cosmic-ray research, in conjunction with gamma-ray and X-ray astronomy, became more and more important for localizing and studying violent processes in the Galaxy. Supernova remnants were identified as the main source of galactic cosmic rays. However, it is not yet clear to what extent extragalactic sources contribute to cosmic rays of the highest energies.

The modulation of cosmic rays by the reversal of the solar magnetic field in the course of its 22-year cycle has proved to be an important tool for investigating heliospheric processes and dimensions. It has been suggested that the modulation of cosmic rays may also influence – via ionization and nucleation in the troposphere – the formation of low-lying clouds, and may therefore represent a coupling mechanism between solar activity and terrestrial climate variations.

THE GRAVITATING UNIVERSE AND COSMOLOGY

The notion that most of the mass of the Universe is in a form we cannot see is among the most striking discoveries of contemporary science. As early as the 1930s, Fritz Zwicky pointed out that the visible mass we can observe is not sufficient to explain the motions of galaxies in clusters. The nature of this invisible mass, known as dark matter, is under intense discussion and investigation. Despite its invisibility, it can be detected through the effects of its gravitational field, which allows us to probe its distribution in and around galaxies and in galaxy clusters.

Giant clusters of galaxies form in gravitational potential wells dominated by dark matter that extends well beyond the observed galaxy population. However, the dark matter content and distribution can be probed by observing the hot X-ray emitting intracluster gas that is gravitationally bound by the total cluster mass. Space-borne observations by X-ray telescopes play a pivotal role in furthering this research (Figure 22).

An alternative method of probing the large-scale distribution and concentrations of gravitating matter in the Universe is provided by gravitational lenses (Figure 23). Extragalactic gravitational lensing provides us with an 'optical bench' whose length is comparable to the radius of the observable Universe. And here a dissimilarity with traditional astronomical observations emerges most significantly: this method probes all mass – not only 'the visible 10% of the iceberg' (i.e. the luminous content of the Universe).

Confirmation that the enigmatic gamma-ray bursts are objects in the remote Universe, rather than transient sources lying in the close galactic vicinity, came from observations made from space. The location of such events in distant galaxies, through the optical identification of the X-ray afterglows detected by the BeppoSAX X-ray satellite, showed that gamma-ray bursts are the most powerful sources of explosive energy released in the Universe since its very creation in the hot big bang.

The amount of explosive energy release is currently best explained by the so-called fireball model. This postulates a cataclysmic event in which the gamma-ray emission arises from internal shocks generated in a relativistically expanding,

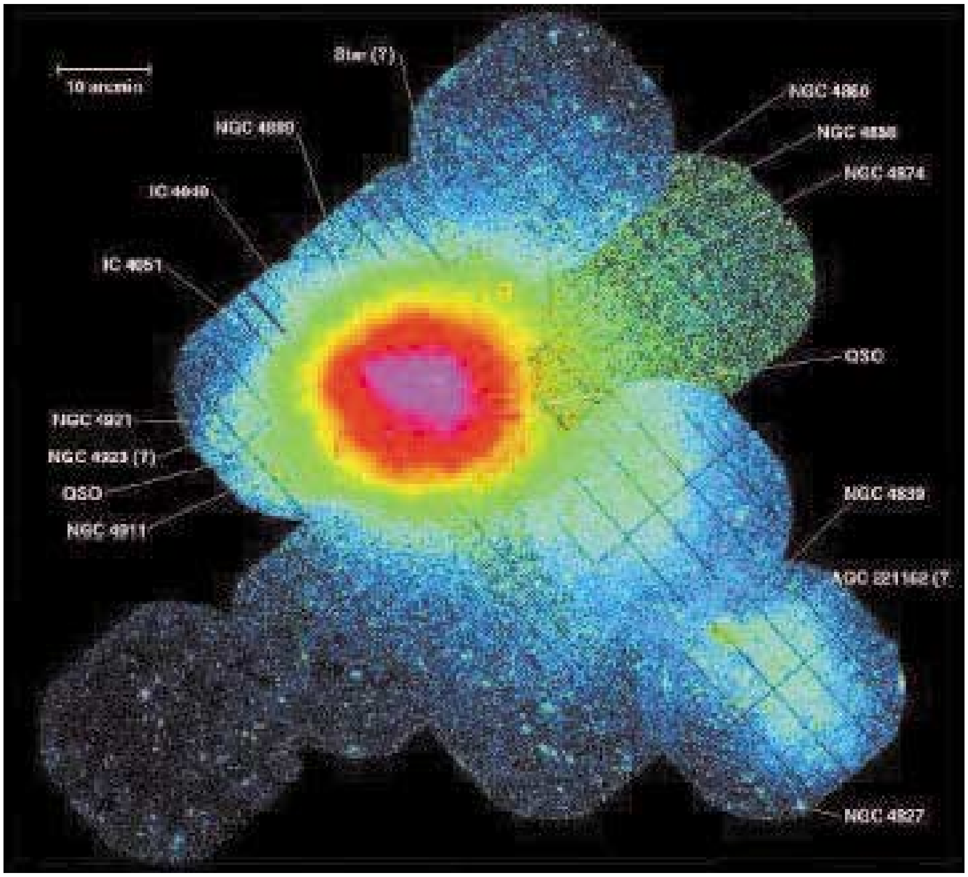

Figure 22 XMM-Newton image of the hot X-ray emitting gas in the Coma Cluster of galaxies.

Figure 23 Although gravitational lenses have been discovered from the ground, the sharper pictures obtained from space permit a refined interpretation of the information provided by the deflected light.

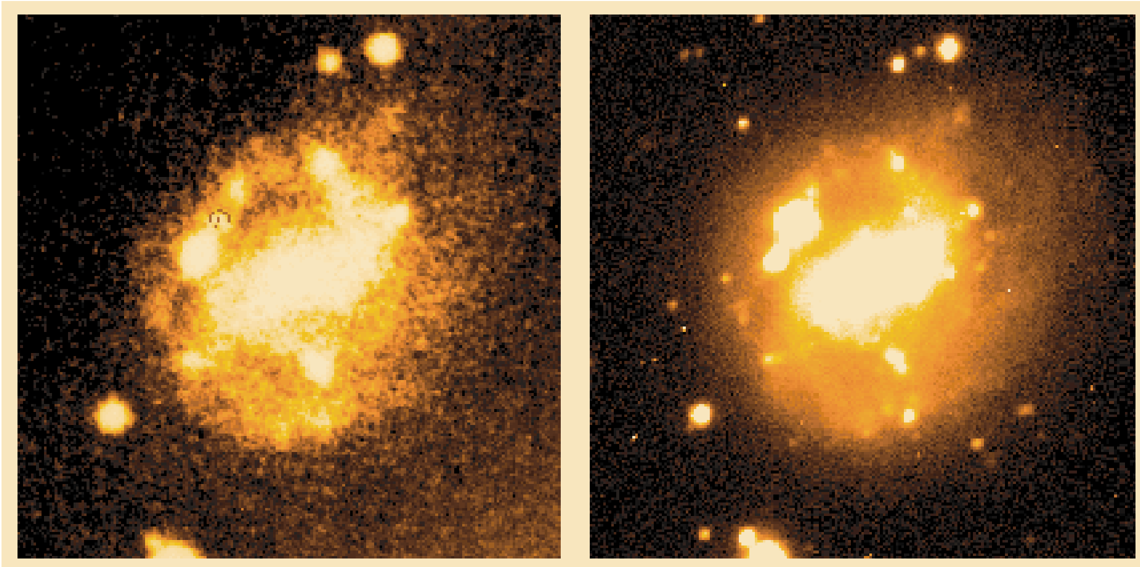

Figure 24 Hypernova 1998bw.

optically thick plasma cloud travelling at more than 99.99% of the velocity of light. Gamma-ray burst sources would thus seem to produce the most extreme form of cosmic acceleration. Some gamma-ray bursts appear to be associated with a peculiar type of highly luminous supernova, a so-called hypernova, implying the explosive death of a very massive star in which a black hole is formed in the gravitationally collapsing core (Figure 24).

The earliest picture of the Universe so far has been obtained by observing in the microwave region. The cosmic microwave background radiation (i.e. the isotropic high-frequency radio emission) was discovered in 1964 by Arno Penzias and Robert Wilson, who used a ground-based antenna. It turned out that the early Universe was very smooth. The radiation in question was last scattered from the universal primordial plasma when the Universe had an age of roughly 300 000 years.

The Cosmic Background Explorer satellite mapped the temperature distribution of the microwave background over the entire sky with an angular resolution of several degrees and revealed tiny spatial fluctuations of the microwave radiation field (Figure 25). This implied the existence of slight density perturbations, the first solid observational evidence confirming the simplest hypothesis for the origin of large-scale structure, namely that it grew out of tiny primordial density perturbations.

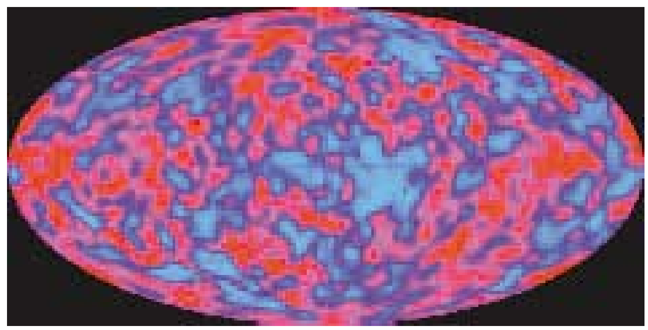

Figure 25 The microwave temperature structure of the sky.

The first ideas about the synthesis of chemical elements in the early phase of the expanding Universe were developed in the 1940s. However, the processes and locations that play a significant role in nucleosynthesis were identified only in the 1950s and 1960s. It became clear that the isotopes of hydrogen, helium and lithium were fully or partly produced in the big bang, but that carbon and all the heavier elements are synthesized in the interiors of stars. Spallation by cosmic rays contributes significantly only for some of the extremely rare elements, such as lithium, beryllium and boron (Figure 26).

The theory of stellar nucleosynthesis was almost exclusively based on element and isotope abundances measured on or from the ground, namely in meteorites and in the solar photosphere. But deriving the primordial abundance of the isotopes of hydrogen and helium, the main products of the big bang, required measurements in space as well.

The primordial helium abundance is one of the most important sources of information about the early Universe. Its value derived from observation agrees, with an uncertainty of only a few per cent, with the theoretical prediction. This confirms that the laws of physics derived from laboratory experiments can be applied without change back to the time when the Universe was as young as one second.

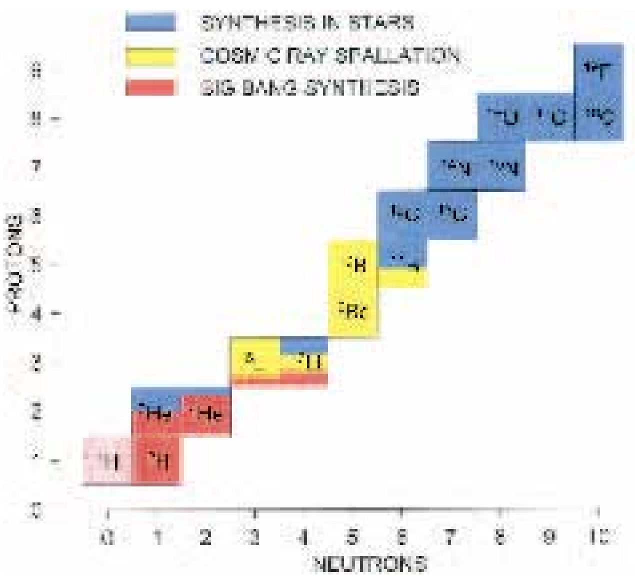

Figure 26 The three principal production sites of nuclei. Carbon and all heavier elements are produced in stars. The big bang yields only the lightest species. For species with mixed origin, such as ^{3}He and ^{7}Li, the relative proportions change with time and location in our Galaxy – and elsewhere.

The average density of the Universe as derived from deuterium and ^{3}He measurements is less than 10% of the critical density, which is the density that would 'close' the Universe and, as mentioned above, it is also less than the matter density that is needed to account for the forces that keep galaxies and clusters of galaxies together. Thus, by the end of the twentieth century it was becoming clear that there exists in the Universe an exotic form of matter that contributes more to the total density than does the visible, baryonic matter. Observations of the subtle inhomogeneities in the cosmic microwave background radiation currently indicate that the exotic matter consists largely of weakly interacting particles that seem to be much more massive than protons.

Perhaps the most striking example of an outcome of the century of space science is the evidence that the cosmological constant, Λ, of Einstein's general theory of relativity is not zero. In 1914, Einstein had to give a non-vanishing value to this integration constant because the observational data available at the time pointed to a static Universe. Consequently, it was necessary to account for the non-collapse of the Universe by giving Λ a finite value. After Edwin Hubble had discovered the expansion of the Universe in 1928, Λ seemed to have lost its meaning. Only towards the end of the twentieth century did space observations of remote supernovae indicate that the Universe had expanded more slowly in an earlier epoch, and therefore that a long-lasting acceleration of the Universe's expansion had taken place, which is described by the cosmological constant Λ or another form of 'dark energy'!

OUTLOOK

Space science has brought us more than new knowledge. Communication and even peaceful collaboration continued between space scientists and engineers living on both sides of the Iron Curtain, even in the darkest times of the Cold War. And space science not only helped to transcend borders between countries and political systems: it also led to intense intellectual exchanges across entrenched confines separating disciplines. As far as everyday life is concerned, we should not forget that reliability considerations and quality control for space hardware – an absolute necessity in view of the unforgiving space environment – has produced a direct payoff in the widespread use of quality assurance in industrial production.

However, the link between basic research and applied science still needs to be strengthened because emphasizing applications without underpinning them by basic research is, in the long run, a dead end. Without science, there is no science to apply.

A case in point is the highly politicized discipline of climate research: understanding the Earth System is required to predict its reaction to changes. Action on the Earth System must not be taken unless it is based on trustworthy predictions. On the other hand, present uncertainties in some of the quantitative predictions must not be used as an excuse for political inaction. The large increase in the quantities of greenhouse gases in the atmosphere caused by human civilization is well documented, and it has undoubtedly begun to affect the climate. Further research is urgently needed, not for recognizing the acute danger – which is obvious – but for predicting the kind of change that will most severely influence life on Earth.

At the beginning of the twenty-first century, the possibilities for science in space are by no means exhausted. Emerging propulsion technology such as solar sailing will expand the range which our spacecraft can explore. And we are just beginning to deploy 'quiet platforms' which provide an essentially acceleration-free environment – often at cryogenic temperatures – and thus enable us to perform tests of the general theory of relativity and, probably within a decade, long-baseline interferometry from free-flying spacecraft. Extending the technique of interferometry into space will widen the diagnostic potential of space science tremendously. With laser interferometry we shall be able to set up giant antennas in space for detecting low-frequency gravitational waves, opening an altogether new window on the Universe and making possible further, more penetrating tests of general relativity.

The technique of “nulling” interferometry, will enable us to observe terrestrial planets that orbit stars other than the Sun, and study the spectra of their atmospheres and thus look for signatures of non-equilibrium that may be caused by life. Interferometry will, of course, also benefit other fields of astronomy. Once available in the X-ray domain, for example, interferometers will allow us to expose the event horizons of black holes and thus probe the limits of the observable Universe in objects that are not at cosmological distances.

Planetary exploration will be a central theme of the space effort in the twenty-first century. How this field develops, and how fast, will depend on available technologies as well as scientific findings. Evolution and breakthroughs in the fields of transportation and robotics will affect the relative roles of human landings and automated exploration, including sample return. And any progress in the search for current or extinct life on other planets or satellites will have an enormous influence on the ways and means of planetary exploration. The search for life in the Universe, and more specifically in the Solar System, is on. And space will play an important role in the new field of astrobiology, which has the potential to lead to a new age of scientific understanding. Astrobiology is also dissolving many boundaries between disciplines because it requires the integration of several disparate fields of science, as for example astronomy, biology, chemistry, Earth sciences and physics.

The outlook for a new century is always uncertain. Yet – excepting a major catastrophe that affects the physical world, or a radical change in the mode of thought of humanity – there is now such a momentum in technology development that the outlook for space science is good. It is advisable not to make any specific predictions: indeed, possibilities often seem unimaginable. As pointed out in Chapter 3, on the enabling technology for space transportation, an author writing at the beginning of the twentieth century would probably not have foreseen the atom bomb, worldwide air traffic, the Global Positioning System, the Internet or, indeed, the supreme reign of the computer. In this sense, we might expect new concepts for access to space to provide new impetus to the overall space effort – including space science.

Acknowledgements

The editors deeply appreciate the enthusiastic collaboration of those who have contributed to this reference work: the pioneers of space research and today’s leading space science investigators. We acknowledge the initiative of Peter Binfield at Kluwer, and his safe guiding of the project through the difficulties encountered in the editing phase. We commend Hermine Vloemans’ firm and diplomatic leadership during the production process. It is a special pleasure to thank Clare Bingham, Livia Iebba, Lidy Negenborn and Silvia Wenger for their untiring assistance, and Rudolf Treumann for his comprehensive and wise counsel regarding the material reported in this chapter.

FIGURE CREDITS

Figure 1. Photograph by the crew of Apollo-11.

Figure 2. Royal Netherlands Meteorological Institute (KNMI) and ESA. The data were taken by the Global Ozone Monitoring Experiment (GOME) on ESA’s ERS-2 satellite.

Figure 3. From: Hultqvist, B., Øieroset, M., Paschmann, G. and Treumann, R., (eds.) (1999). *Magnetospheric Plasma Sources and Losses.* In ISSI Space Science Series Vol. 6, Kluwer, Dordrecht, and *Space Science Reviews*, **88**, Figure 7.1, p. 371.

Figure 4. Upper left, Jan Curtis; upper right, STScI; lower left, NASA; lower right, STScI.

Figure 5. Painting by William K. Hartmann.

Figure 6. NASA/Johnson Space Center.

Figure 7. Photograph by the Apollo 15 crew, NASA Photo AS-15 9212430.

Figure 8. Courtesy NASA and the Mars Orbiter Laser Altimeter (MOLA) Team of the Mars Global Surveyor project. From Kallenbach, R. Geiss, J. and Hartmann, W.K. (eds.) (2001). *Chronology and Evolution of Mars.* In ISSI Space Science Series Vol. 12, Kluwer, Dordrecht and *Space Science Reviews*, **96**, Figure 2, pp. 466–467.

Figure 9. NASA.

Figure 10. Data from the Magellan mission, NASA picture ID P-38724 (excerpt); http://www.jpl.nasa.gov/magellan/gif/p38724.gif

Figure 11. Left: Voyager photograph, 13 February 1979. Upper right: Galileo Orbiter Mission (NASA), Catalog No. PIA 025727 (excerpt); inset: http://www.planetaryexploration.net/jupiter/io/index.html. Lower right:http://photojournal.jpl.nasa.gov/cgi-bin/PIAGenCatalogPage.pl?PIA01127.

Figure 12. http://www.jpl.nasa.gov/saturn/gif/saturn_montage.gif

Figure 13. From: Keller, H.U., Curdt, W., Kramm, J.-R. and Thomas N. (1994). In R. Reinhard, N. Longdon and B. Battrick (eds.) *Images of the nucleus of Comet Halley*. ESA SP-1127, ESTEC, Noordwijk, Vol. 1, Figure 61, p. 63.

Figure 14. D. Gough and P. Scherrer, Chapter 44, and http://sohowww.estec.esa.nl/gallery

Figure 15. From: Hassler, D.M., Dammasch, I.E., Lemaire, Ph., Brekke, P., Curdt, W., Mason, H.E., Vial, J.-Cl. and Wilhelm, K. (1999). Solar Wind Outflow and the Chromospheric Magnetic Network. *Science*, **283**, 810–813.

Figure 16. Courtesy of SOHO/LASCO consortium.

Figure 17. From: Barlow, M.J., Nguyen-Q-Rieu, Truong-Bach, Cernicharo, J., González-Alfonso, E., Liu, X.-W., Cox, P., Sylvester, R.J., Clegg, P.E., Griffin, M.J., Swinyard, B.M., Unger, S.J., Baluteau, J.-P., Caux, E., Cohen, M., Cohen, R.J., Emery, R.J., Fischer, J., Furniss, I.,

Glencross, W.M., Greenhouse, M.A., Gry, C., Joubert, M., Lim, T., Lorenzetti, D., Nisini, B., Omont, A., Orfeil, R., Péquignot, D., Saraceno, P., Serra, G., Skinner, C.J., Smith, H.A., Walker, H.J., Armand, C., Burgdorf, M., Ewart, D., Di Giorgio, A., Molinari, S., Price, M., Sidher, S., Texier, D. and Trams, N. (1996). The rich far-infrared water vapour spectrum of W Hya. *Astron. Astrophys.* **315**, L241–L244.

Figure 18. From: Cernicharo, J., Heras, A.M., Tielens, A.G.G.M., Pardo, J.R., Herpin, F., Guélin, M. and Waters, L.B.F.M. (2001). Infrared Space Observatory's Discovery of C_4H_2, C_6H_2, and Benzene in CRL 618. *Astrophysical Journal Letters*, **546**, L123–L126.

Figure 19. http://antwrp.gsfc.nasa.gov/apod/ap961207.html

Figure 20. From: Casares, J., Charles, P.A., Naylor, T. (1992). A 6.5-day periodicity in the recurrent nova V404 Cygni implying the presence of a black hole. *Nature* **355**, 614–617.

Figure 21. http://astro.estec.esa.nl/Hipparcos/TOUR/hrdiagram2.html

Figure 22. http://sci.esa.int/img/e5/26085.jpg

Figure 23. Hubble Space Telescope Image STScl-PRC00-08, http://astro.hi.is/lens/pict_th.html

Figure 24. From: Baron, E. (1998). How big do stellar explosions get? *Nature*, **395**, 635–636.

Figure 25. Cosmic Background Explorer Team.

Figure 26. From: Geiss, J. and von Steiger, R. (1997). Production of light nuclei in the early Universe. In A. Wilson (ed.) *Fundamental Physics in Space*, ESA SP-420, ESTEC, Noordwijk, pp. 99–106, Figure 1.

http://www.springer.com/978-0-7923-7196-0

The Century of Space Science
Bleeker, J.A.; Geiss, J.; Huber, M. (Eds.)
2001, XLIX, 1846 p., Hardcover
ISBN: 978-0-7923-7196-0