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DIPESH SATPATI*, ARGHYA BISWAS**,ANKITA MUKHERJEE AND SANKHADEEP AGARWAL***

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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 extraterres- trial 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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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

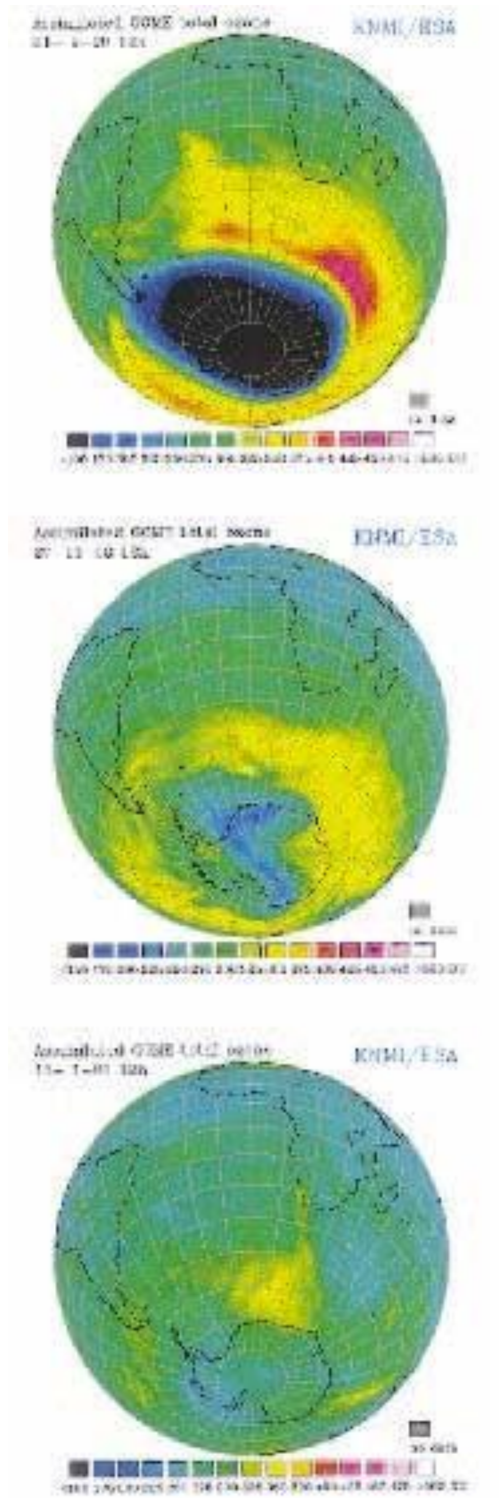

Figure 2 Assimilated total ozone maps showing the evolution of the Antarctic ozone hole between September 2000 and January 2001.

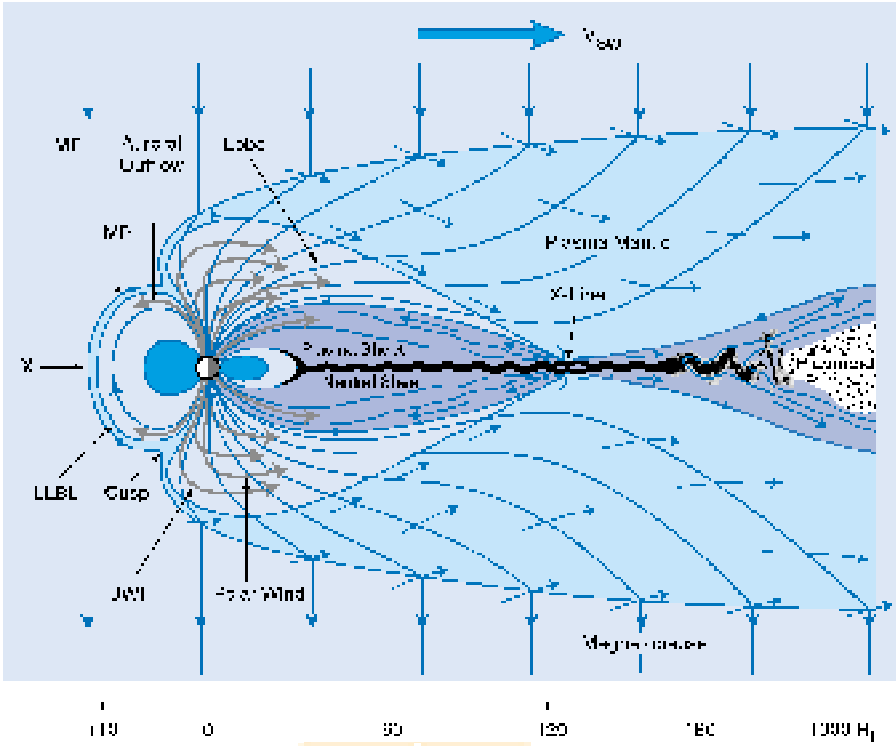

Figure 3 The terrestrial magnetosphere, which results from the interaction of the solar wind with the magnetic field of the Earth, was completely unknown before the advent of the space age. This schematic drawing gives an impression of the complexity of the interaction.

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.

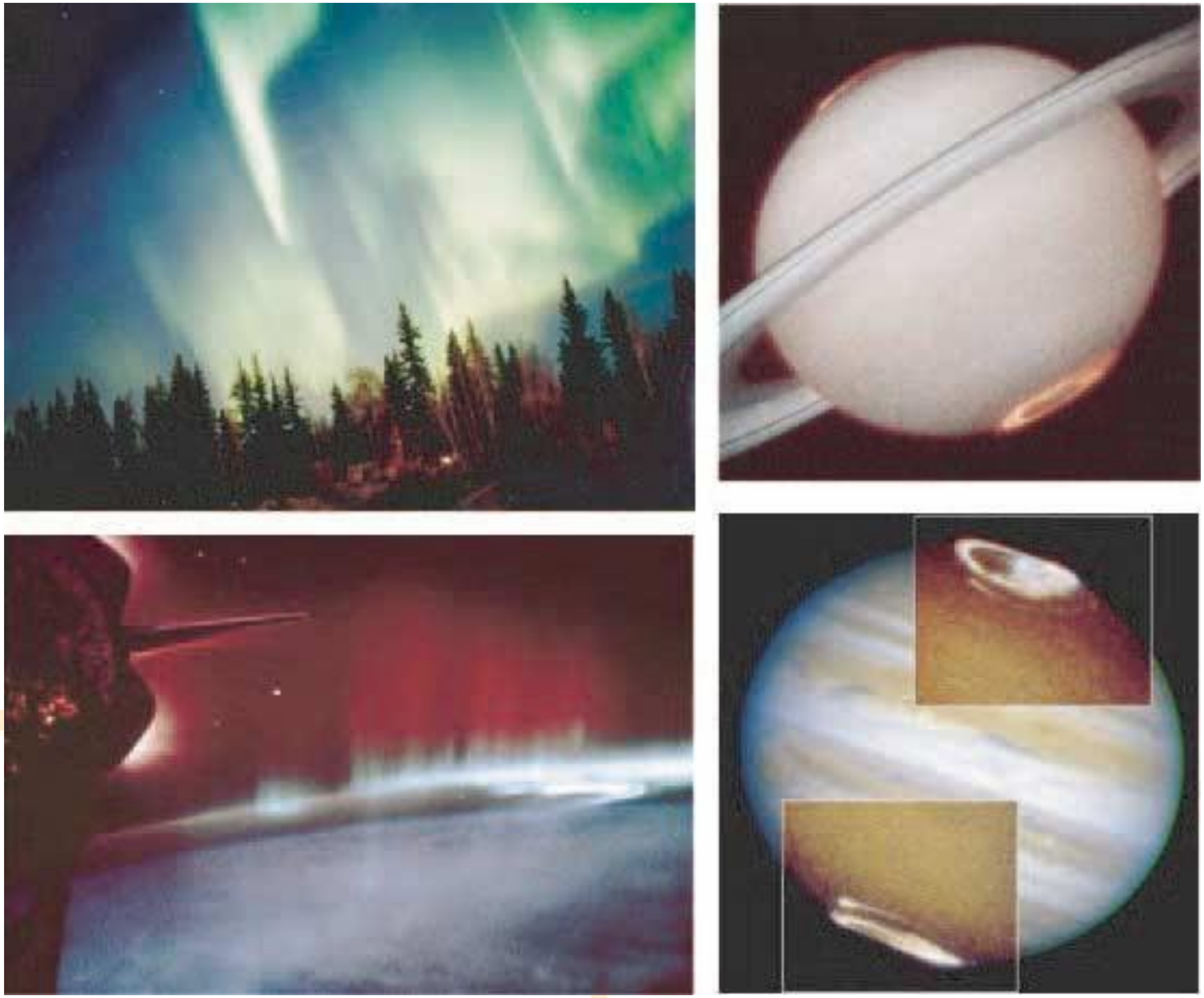

Figure 4 The aurora borealis as seen from the ground and from the Space Shuttle (note the silhouetted tail fin and engine shrouds), and pictures of aurorae on Jupiter and Saturn, as observed by the Hubble Space Telescope.

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 geo-chemical 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

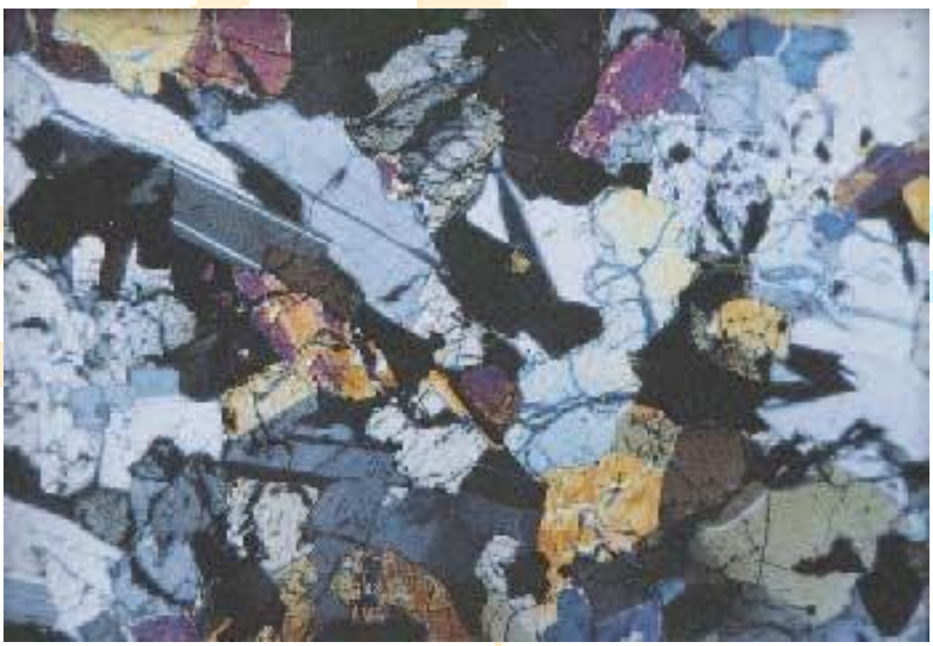

Figure 6 A thin section of basaltic rock collected by Neil A. Armstrong and Edwin E. Aldrin in the Lunar Mare Tranquillitatis. The Moon is virtually free of hydrogen, carbon, nitrogen and other volatile elements; accordingly, the minerals in this sample of lunar rock do not contain these elements.

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

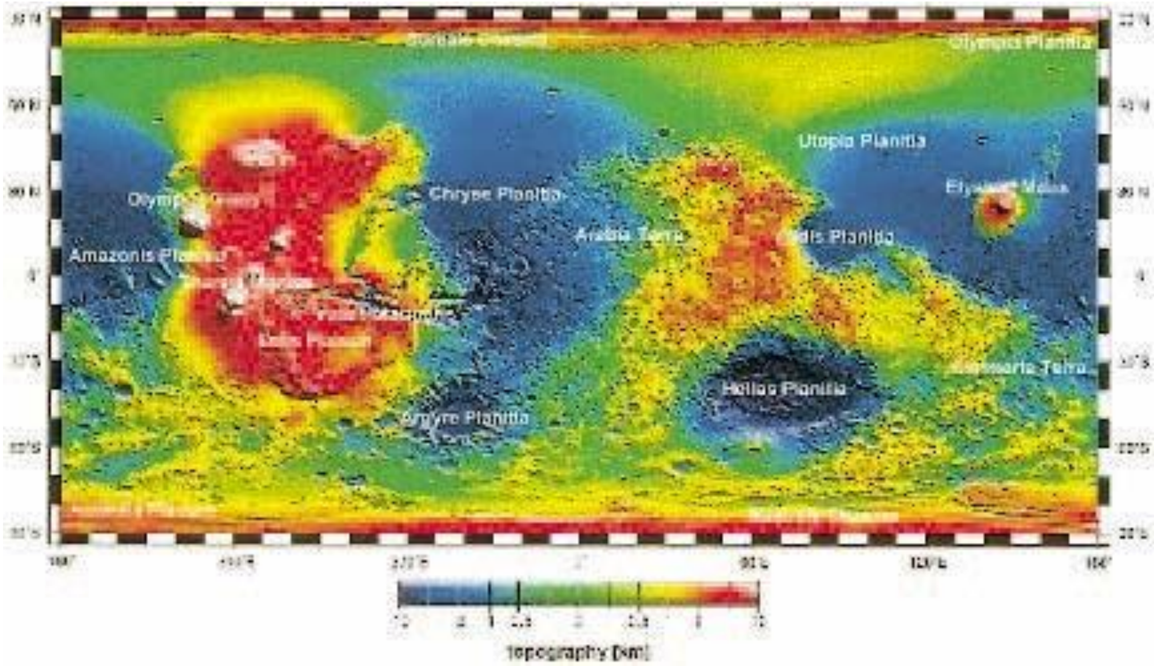

Figure 8 Topographic map of Mars. Low levels are shown in blue, as a reminder that in the past there was probably extensive flooding on Mars.

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

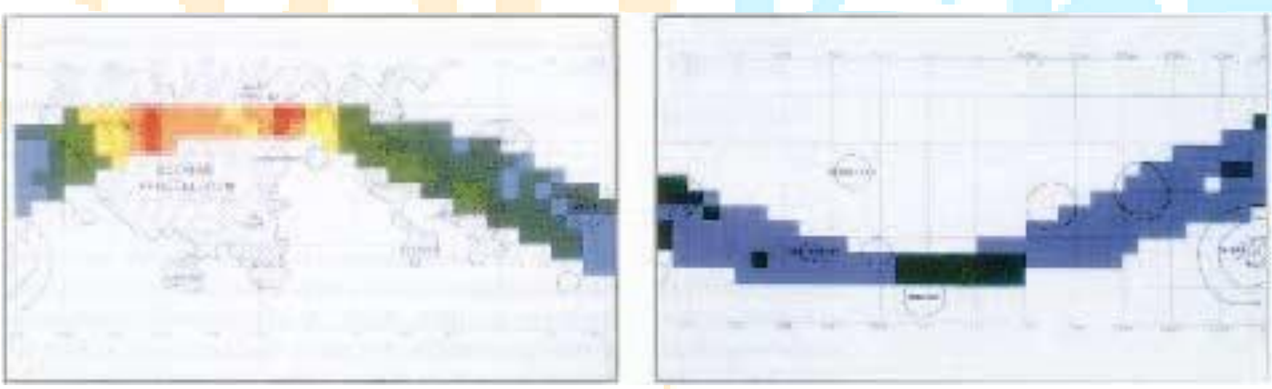

Figure 9 A compositional map of the Lunar surface as determined by the Apollo 15 gamma-ray spectrometer. High concentrations of radioactive elements (red and yellow regions) are found in the maria and other regions on the nearside.

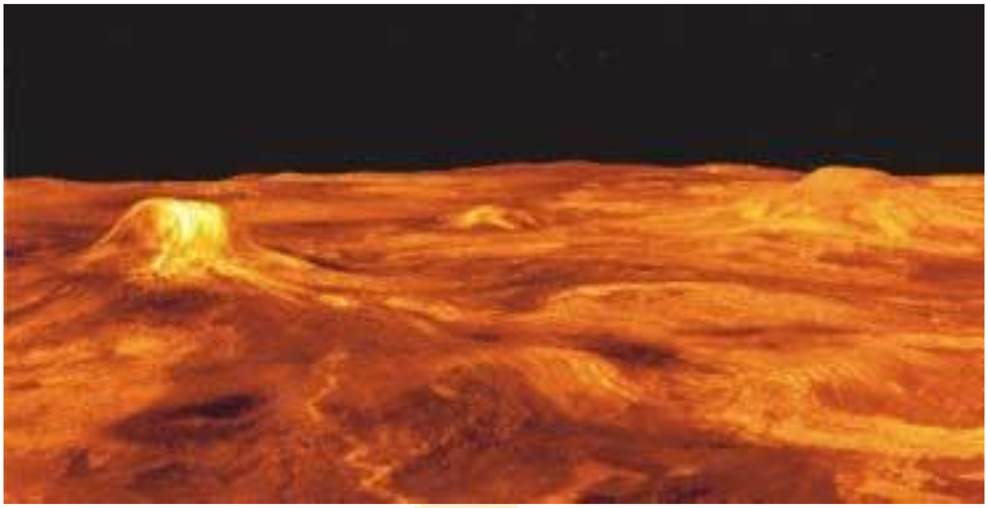

Figure 10 A three-dimensional perspective view of the surface of Venus, showing the western Eistla region with the volcanic peaks of Gula Mons (left, 3 km high) and Sif Mons (right, 2 km high). The image was obtained by use of synthetic aperture radar (SAR) data combined with radar altimetry, both from 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.

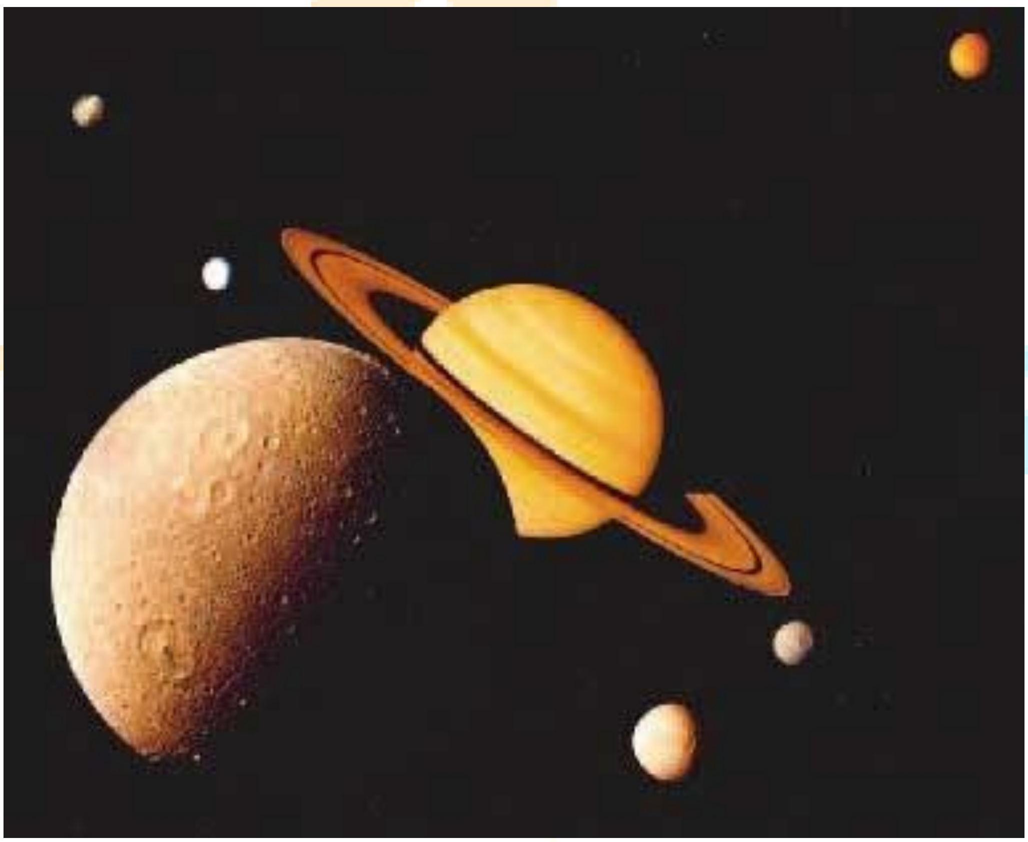

Figure 12 A collage of Saturn and its moons: Dione (foreground) and (from left to right) Thea, Enceladus, Tethys, Mimas and Titan.

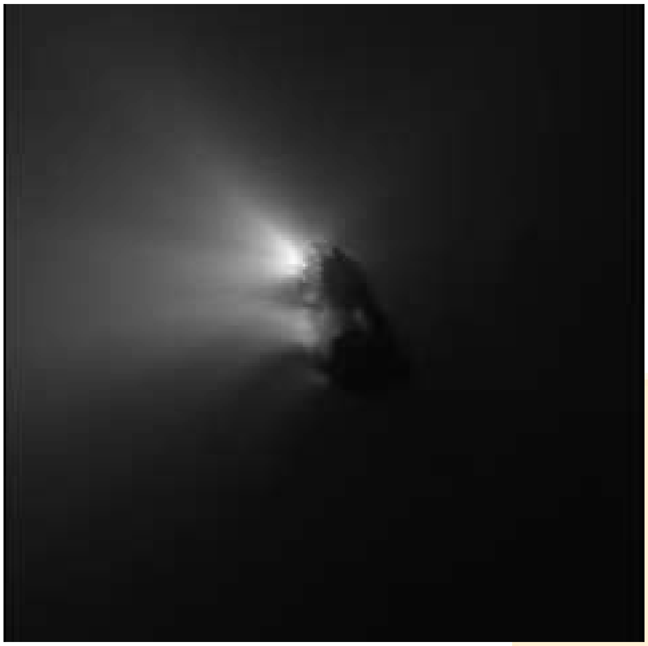

Figure 13 The nucleus of Comet Halley imaged by the Halley Multicolor Camera on board Giotto.

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 ν-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,

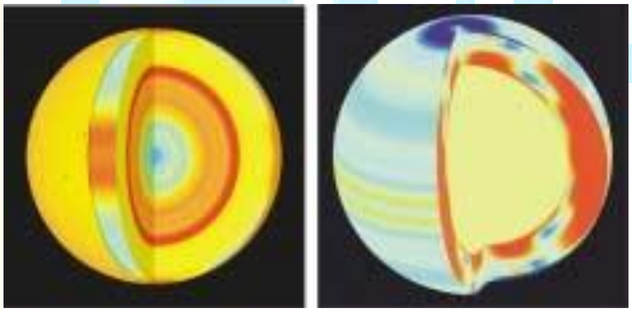

Figure 14 Temperature and rotation in the solar interior. The images show the deviations of these properties, as derived from SOHO measurements, from current models.

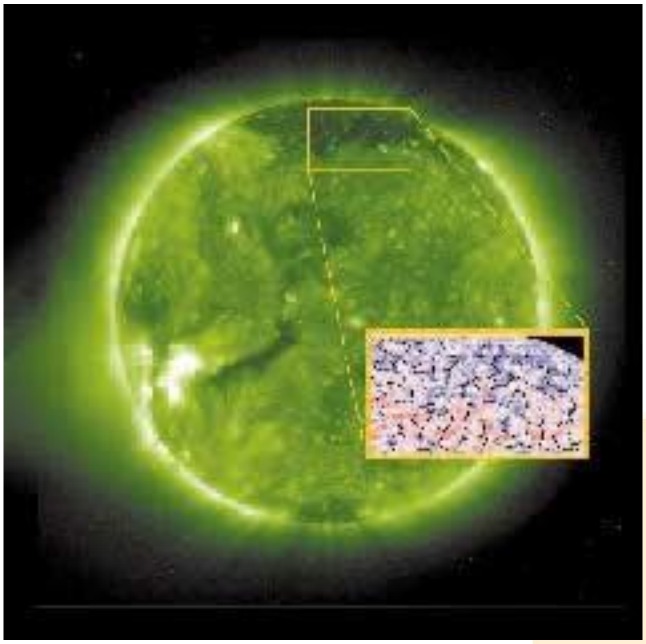

Figure 15 Dopplergram showing the (blueshifted) source regions of the fast solar wind, namely the boundaries and boundary intersections of magnetic network cells in a coronal hole.

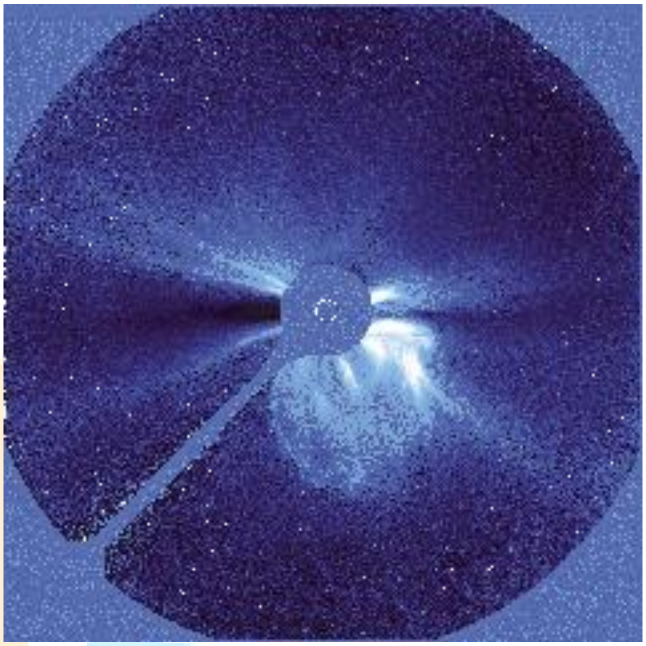

Figure 16 A coronal mass ejection propagating into the heliosphere. Stars are visible in this coronagraph image whose field of view is thirty solar diameters wide.

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.

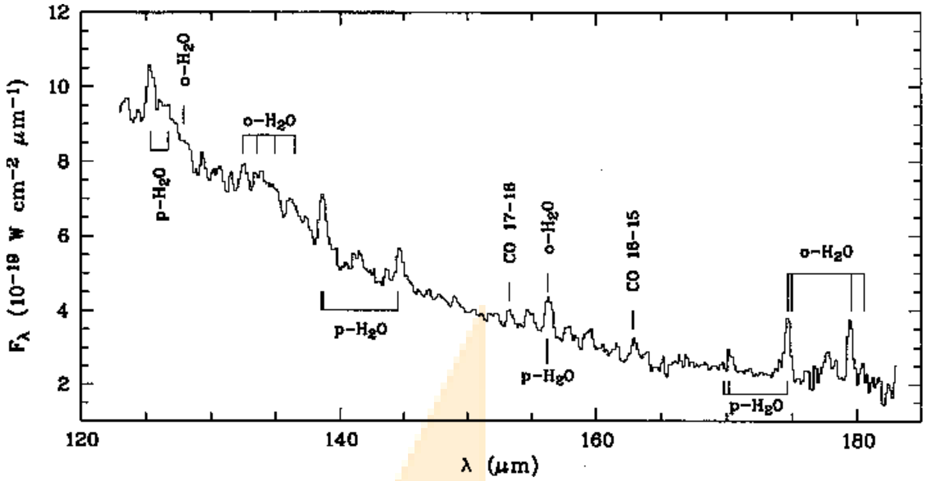

Figure 17 Water acts as a coolant in the stellar winds of AGB stars.

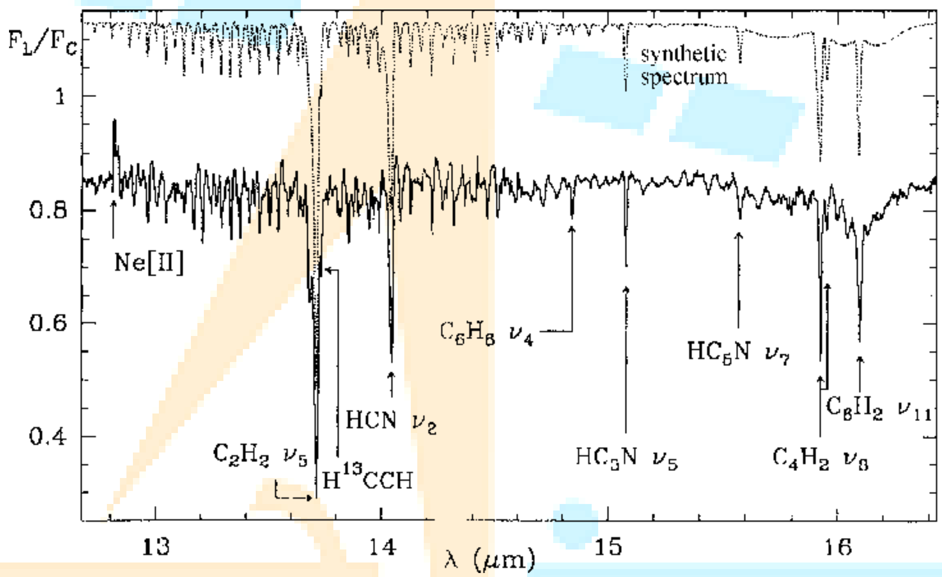

Figure 18 Carbon-rich protoplanetary nebulae as organic chemistry factories in space.

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).

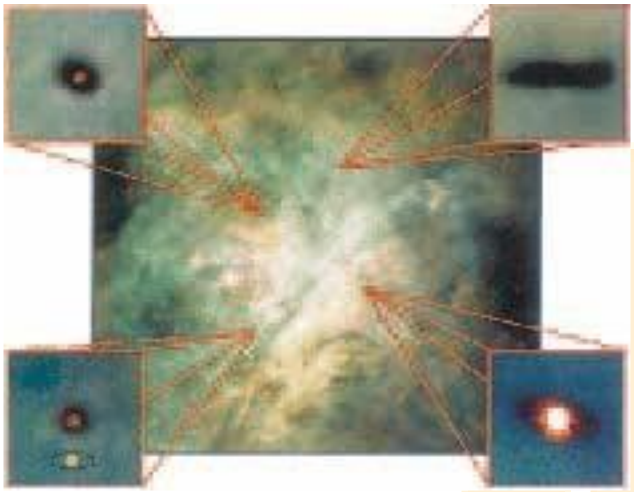

Figure 19 Hubble Space Telescope picture showing disks of planetary material orbiting around young stars in the Orion Nebula. The size of the solar system is indicated by the lower image in the lower left corner.

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

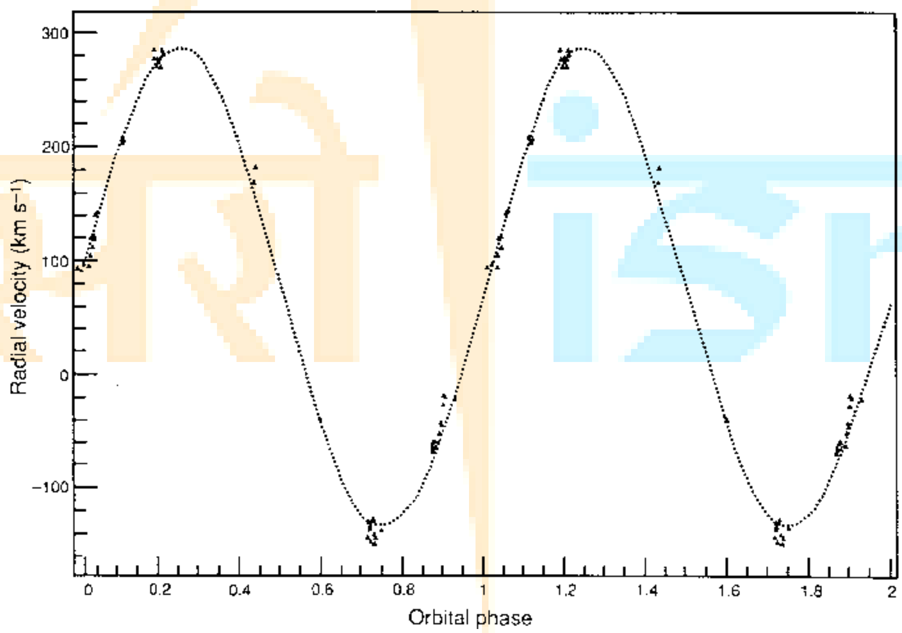

Figure 20 Radial velocity curve of the black hole system V404 Cygni.

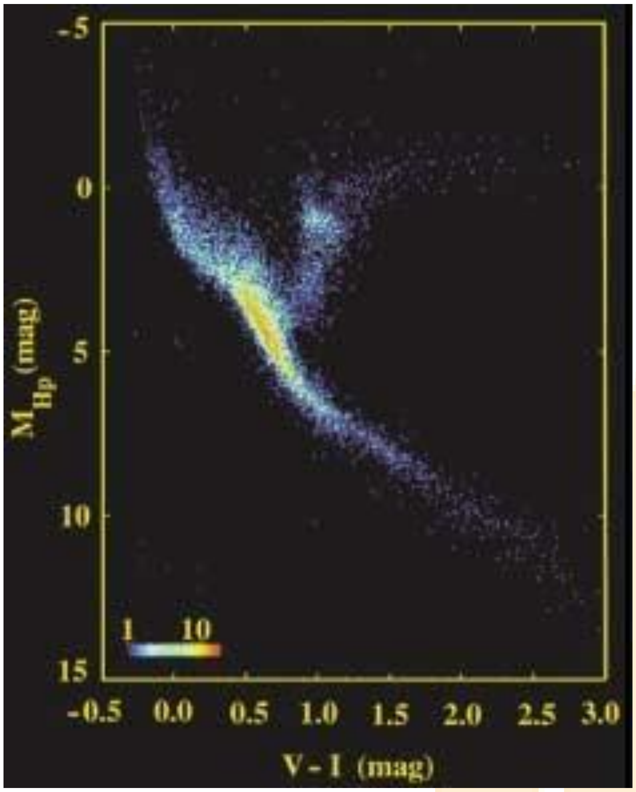

Figure 21 Hertzsprung–Russell diagram, reflecting stellar evolution, for the 16631 single stars from the Hipparcos Catalogue whose distances and colour magnitudes are known to within 10% and 0.025 mag, respectively. The colour indicates the number of stars in each pixel of the diagram.

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,

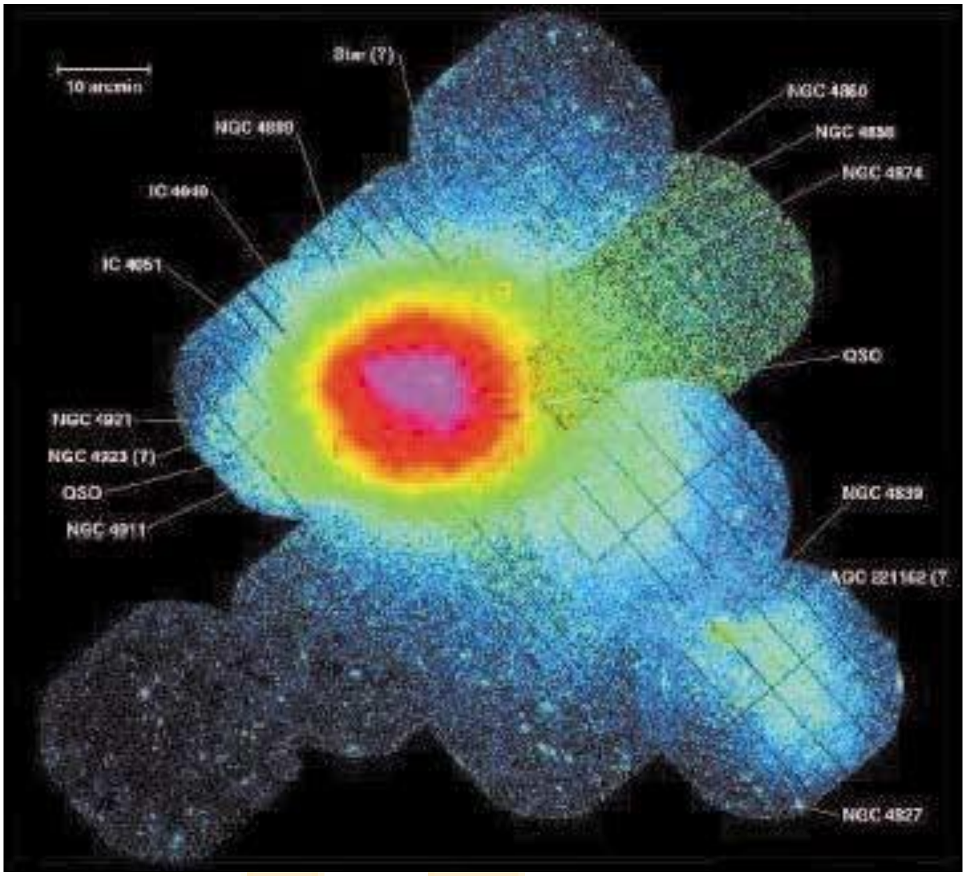

Figure 22 XMM-Newton image of the hot X-ray emitting gas in the Coma Cluster of galaxies.

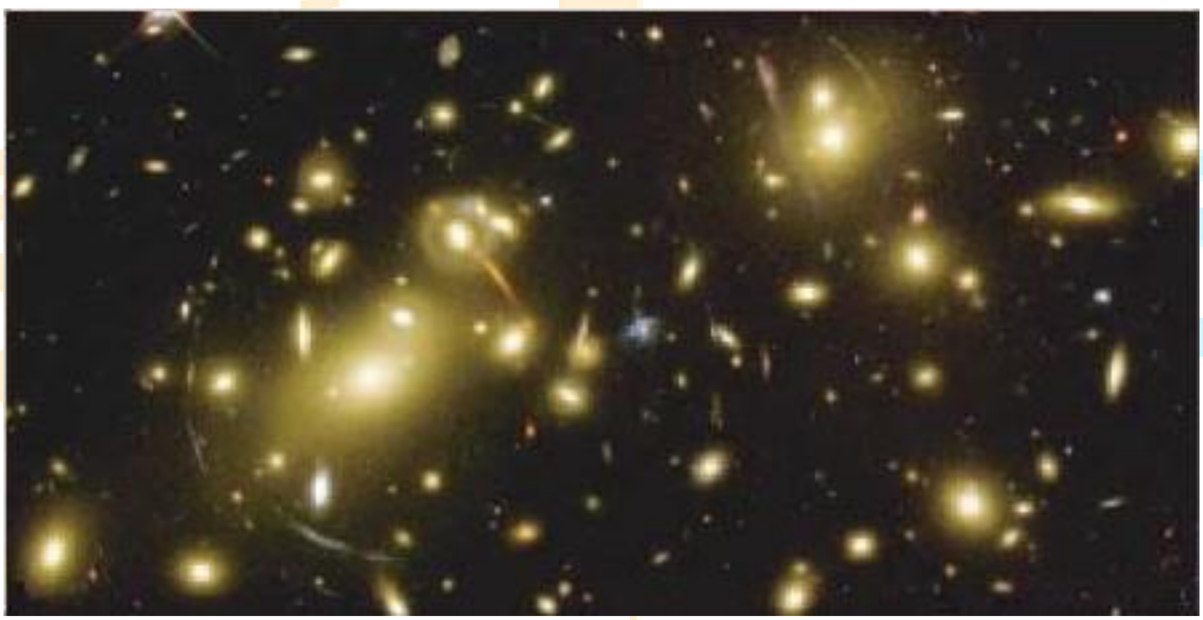

Figure 23 Although gravitational lenses have been discovered from the ground, the sharper pictures obtained from space permit a refined interpretation of the information provided by the deflected light.

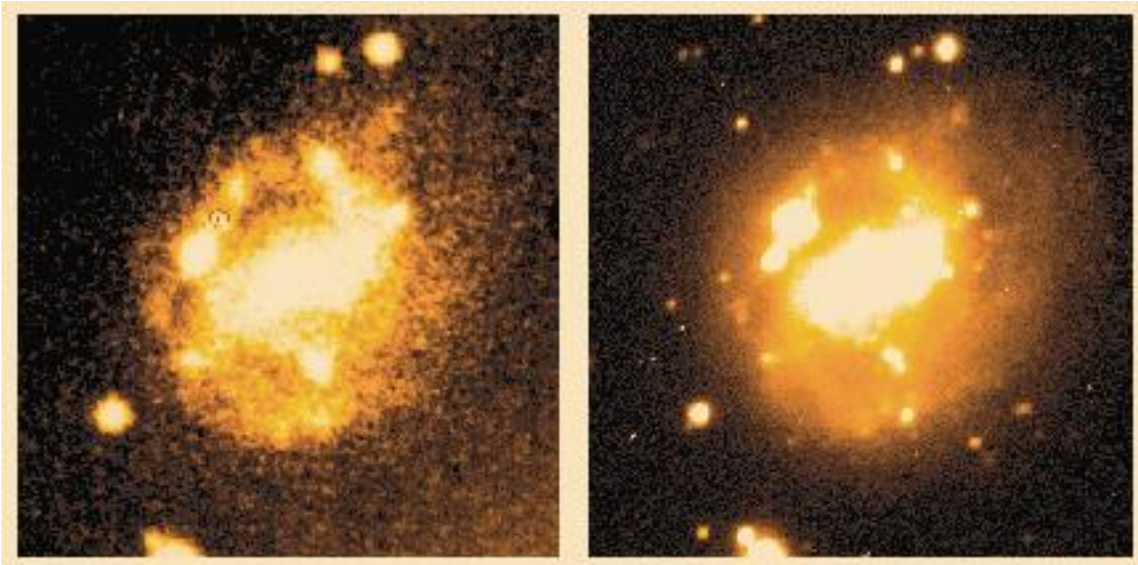

Figure 24 Hypernova 1998bw.

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.

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).

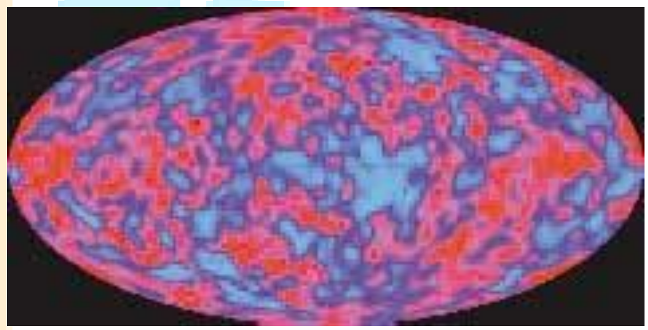

Figure 25 The microwave temperature structure of the sky.

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.

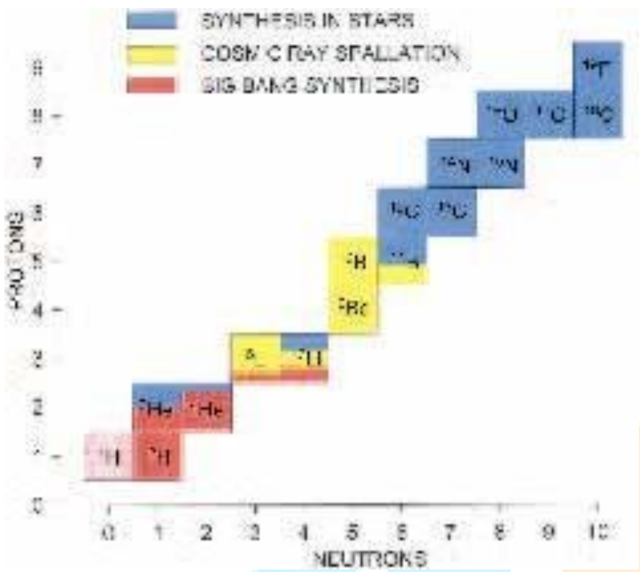

Figure 26 The three principal production sites of nuclei. Carbon and all heavier elements are produced in stars. The big bang yields only the lightest species. For species with mixed origin, such as ^{3}He and ^{7}Li, the relative proportions change with time and location in our Galaxy – and elsewhere.

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, ▲, 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 ▲ a finite value. After Edwin Hubble had discovered the expansion of the Universe in 1928, ▲ 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 ▲ 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.

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MY SLV THESIS CUM RESEARCH PAPER:- SLV LANDER SP MACHINES AND ENGINES PSLV23 DEVICE AND DEVICE EXPLANATION.THESIS SUBMITTED WITH PROFESSOR DR.P.V VENKITAKRISHNAN “FOS SYSTEM” AND “SCRAMJET ENGINE DEVICE” HAS BEEN ACCEPTED IN “SLV ENGINE SATELITE DEVICE”{PSLV-ISRO SLV23}.

The research paper is split into five major Programmes of ISRO namely Launch Vehicle, fos system,lander device, Space Science Programme and scramjet engine device. This paper has been compiled and worked outin a precise manner by RESPOND Team, CBPO, ISRO HQs in consultation with the different Centres of ISRO to enable Faculty/Researchers.

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DIPESH SATPATI*, ARGHYA BISWAS**,ANKITA MUKHERJEE AND SANKHADEEP AGARWAL***
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From the ionosphere to high energy astronomy - a personal experience

In the first half of the 20th century, recognition of the existence of an electrified layer of the upper atmosphere that provided a mode for radio communication over great distances on the Earth grew with little sense of the role of invisible solar radiation in creating the electrical mirror. Solar radiation was thought to be black-body in spectral shape characterized by a temperature of 6000 K with a maximum in the yellow-green, trailing off rapidly in the infrared and ultraviolet. None of this spectrum could produce significant ionization of the major constituents of the atmosphere.

X-rays were discovered by Wilhelm Röntgen shortly before the turn of the century and Guglielmo Marconi, a few years later, demonstrated trans-Atlantic radio communication via a high altitude, natural electrical mirror. Several ingenious physicists and electrical engineers pursued the problems of radio reflection but had few clues to the nature of the solar radiation that keyed the phenomena of ionospheric production and variability. The true nature of solar ionizing radiation remained a baffling puzzle until after WW II when the availability of rockets to carry detectors directly into the ionosphere finally made the studies definitively diagnostic. Captured German V-2 (Vengeance) rockets while being studied by propulsion engineers were also turned from "weapons into plowshares", when they were adapted to ionospheric studies.

To preface the story of the modern era it is interesting to sketch the early ideas of radio propagation science. The perceptions of solar-terrestrial connections had developed slowly over most of the 19th century. Lord Kelvin, one of the most influential physicists of his time, was adamant in rejecting any notion (Kelvin 1892) "that terrestrial magnetic storms are due to the magnetic action of the Sun; or to any dynamic action within the Sun, or in connection with hurricanes in his atmosphere, or anywhere near the Sun outside." Furthermore he held strongly "that the connection between magnetic storms and sunspots is unreal and the seeming agreement between the periods has been mere coincidence." Kelvin's enormous prestige discouraged any dispute and set back solar-terrestrial research for decades.

Toward the end of the 19th century Colonel Sabine of the British army monitored a network of magnetic observatories throughout the empire and noted that by "a most curious coincidence" the magnitude and frequency of magnetic disturbances was synchronized with the appearance and disappearance of sunspots. The direction of the compass needle swung in regular fashion over the diurnal cycle, but at times the movements became more intense and rapid in the auroral zone, giving rise to the name "magnetic storms". It was commonly believed that interplanetary space was a vacuum and that auroras were excited by direct streams of particles from Sun to Earth unimpeded by any interplanetary medium. By timing the appearances of auroras and magnetic storms relative to the visible outbursts of flares on the Sun, the travel speed was calculated to be about 800 km per sec, slower than light, but consistent with concepts of particle streams.

Friedrich Gauss, the great German mathematician-physicist-astronomer, as early as 1839, related fluctuations in the compass needle to the passage of electric currents at high altitudes. In 1882, the Scotsman, Balfour Stewart, defined these currents as a great dynamo of tidal movements of ionized air above 100 km that were driven by solar heating. The vertical movement was only 2 or 3 km, but it was sufficient to generate a great horizontal current sheet of electricity. Observations near the geomagnetic equator indicated circulating systems of electric currents of opposite symmetries in the northern and southern hemispheres. At

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the equator the currents joined to form a strong flow from west to east at 1100 local time, that Sidney Chapman, in the early 20th century, named the Equatorial Electrojet.

The young Guglielmo Marconi at age 21, in 1895, built a demonstration wireless telegraph on his father's estate near Bologna, Italy. On December 12, 1901 he transmitted a simple Morse code signal from England to Newfoundland, a distance of 2900 km to the astonishment of most scientists who could not fathom how the waves, that were thought to travel in straight lines, could curve over the 160 km high bulge of the surface of the earth. In 1902, Arthur E. Kennelly proposed that the radio waves were ducted around the earth by an electrically conducting layer. Almost simultaneously, Oliver Heaviside reached the same conclusion and the layer came to be called the Heaviside layer. With the above background, the stage was now set for a more focused scientific attack on the nature of a reflecting layer, now called the ionosphere, that eventually came to be associated with solar X-rays. In England, ionospheric research was lead by Edward Appleton and his student Miles Barnett [1925]; in the United States studies were conducted by E.O. Hulburt and A. Hoyt Taylor at the Naval Research Laboratory [1926] and by Gregory Breit and Merle A. Tuve at the Carnegie Institution [1926]. Successful experiments and interpretations were achieved almost simultaneously in England and the United States, both groups working from the ground. When German V-2 rockets were captured by the Americans, they moved ionospheric research into space and outraced the ground-based competition.

Appleton set out to determine the height of reflection of a continuous wave with the cooperation of the British Broadcasting Co. whom he persuaded to provide him with a continuously varying signal from London at the end of the broadcast day so that he could detect the interference pattern of ground and sky waves at Oxford. He observed the elapsed time between emission and reception of the same frequency, as the broadcast frequency was oscillated back and forth. Starting with low frequencies, Appleton probed only the lower portion of the reflecting layer; working later with higher frequencies, he distinguished layered regions of reflection, that he labeled D, E, and F. For these experiments, Appleton later received the Nobel Prize.

Much of the early research by NRL scientists was characterized by an admirable simplicity and economy of means. Hulburt and Taylor cooped the partnership of radio amateurs around the world who used vacuum tubes with power outputs of less than 50 watts and very short radio waves, less than 200 meters, to communicate around the world. Transmissions skipped over a "zone of silence" encircling the transmitter to a distance of 30 to 50 km and at the same time were received out to distances of hundreds of kilometers. Hulburt and Taylor showed that the waves were reflected only when the angle of incidence exceeded a critical value. At smaller angles the waves penetrated the reflecting region and escaped into space. At night, skip distances were greater than during the day and greater in winter than in summer in temperate latitudes. From these simple observations Hulburt calculated the height of reflection and the electron density (about 500,000 electrons and ions per cm^3 at a reflection height of about 150 km). By 1926, Hulburt and Taylor were able to publish a remarkably accurate account of the diurnal variation of ionospheric electron density. The work was almost coincident with Appleton's and Barnett's 1924–25 studies.

In the early years of ionospheric research, theorists speculated about particle radiation as a possible source of ionization of the upper atmosphere. Confronted with an apparent 6000 K solar spectrum it was not possible to model interactions of electromagnetic radiation with atmospheric constituents that would lead to the required ionization. Within the space of a decade after the end of WW II, however, the solar spectrum was revealed from its X-ray limit throughout the ultraviolet with instruments carried on rockets to ionospheric height. Ionizing radiation was observed in X-rays and ultraviolet from the solar corona and chromosphere, where temperatures range from hundreds of thousands to millions of degrees K, and every spectral interval was matched with its absorption at a particular height range.

Throughout this early epoch, some theorists still favored solar particles as the source of ionizing radiation. Confronted with the apparent 6000 K temperature of the solar disk (Figure 1) it wasn't possible to model atmospheric interactions with solar radiation that would lead to the required ionization. At the higher chromospheric and coronal temperatures shorter-wavelength extreme ultraviolet and X-rays would be produced but the particle concentrations

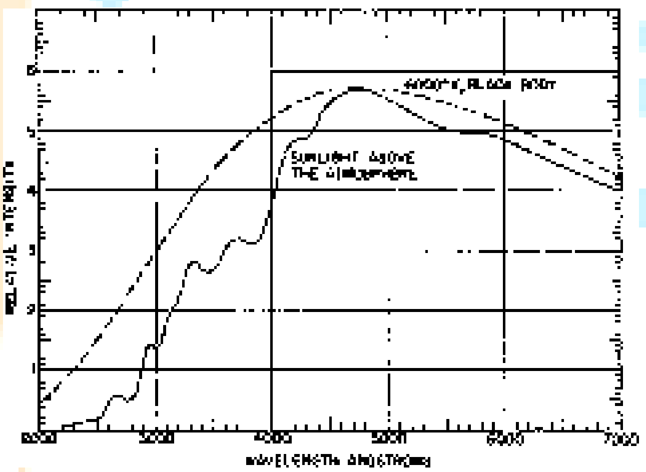

Figure 1 Solar spectral energy distribution from 2000 A to 7000 A compared with 6000 K black body sunlight above the atmosphere.

in the solar atmosphere were estimated to be too thin (emission measure too low) to provide high enough intensities to generate an E or F region. Appleton's early measurements of vertical reflections between midnight and sunrise showed that substantial concentrations of electrons or ions persisted throughout the night, contrary to the prevailing idea that charges would disappear rapidly by attachment once the source of ionization was removed. Radio scientists were thus led to believe that an important portion of the ionization might be produced by corpuscles arriving equally by both day and night. Because a charged particle stream could not readily penetrate the earth's magnetic field, serious thought was given to neutral particle streams.

In 1928, Hulburt proposed that ultraviolet radiation shortward of 1230 Å might be the source of the ionosphere. By 1930 he was intrigued by a possible connection between solar ultraviolet and sunspots and their link to magnetic storms and radio fadeout. In 1935, J.H. Dellinger at the U.S. National Bureau of Standards (NBS), summarized observations of a series of sudden ionospheric disturbances over a period of six months and stressed the importance of understanding the connection with solar activity. He proposed a joint effort of the NBS and the solar observatory on Mt. Wilson. During the same time frame, Robert H. Goddard was developing his rocket to carry instruments to high altitudes for atmospheric research. Correspondence between Hulburt and John Fleming reveals that Hulburt contemplated solar rocket astronomy to understand the basic physics of solar control of the ionization. He noted the theoretical match between atmospheric absorption of solar soft X-rays and the altitude of ionization and suggested that a good test would be to fly photographic film covered with thin aluminum foil or black paper in one of Goddard's rockets to detect X-rays.

Those early glimmerings of high altitude research with rockets were interrupted by the war but the new technologies of the war were soon transferred to peaceful research. In 1942, Ernst Krause in the radio division at NRL undertook to develop a program of guided missiles, specifically a new version of the German V-1 buzz bomb known as the JB-2 and the Lark, a rocket-propelled, guided ship-to-air missile. At the end of the war, Krause pursuaded NRL to commit to a substantial effort in rocket development for high altitude research which led to the resurrection of V-2 rockets late in the 1940s (see Figure 2). The first generation of successful studies of solar X-rays and extreme ultraviolet radiation began in 1949 when my NRL group flew a set of Geiger counters sensitive to a narrow band of X-rays centered at about 8 A, hydrogen Lyman-alpha (1216 A), and the Schumann region, 1425 to 1600 A. As the rocket climbed to an altitude of 150 km, the detectors pointing normal to the spin axis swept the sky repeatedly. X-rays were detected above 80 km with increasing intensity to about 120 km (Figure 3). It appeared that a thermal corona at one to two million deg C made a good fit with the ionization requirement of the E-region.

Figure 2 A V-2 rocket just prior to launch at the White Sands Proving Ground in New Mexico. About 45 feet tall and 5 feet in diameter it was fueled by 10 tons of alcohol and liquid oxygen. The rocket is shown connected by an umbilical cable to the firing line. To service the rocket and its payload a portable ladder was brought up. Only later was a gantry provided from which each level of the rocket could be reached comfortably. A successful flight could reach 170 km and last for 450 sec. (NRL.)

The Lyman alpha detector and the extreme ultraviolet detector showed how those radiations shaped the bottom of the ionosphere and the upper part of the reflecting E-region. Lyman alpha, originating in the hot solar chromosphere at 10,000 K and higher, contains most of the energy in the extreme ultraviolet and is absorbed between 75 and 90 km but does not interact with any of the major constituents, oxygen or nitrogen, atomic or molecular. Only later on did M. Nicolet, the brilliant Belgian atmospheric scientist point out that it could ionize nitric oxide, a trace constituent present at only 10^8 molecules per cm^{-3}. with almost 100% efficiency and thus have control of D-region. Radiation in the Schumann region produced no ionization but played a very important role in shaping the high ionosphere by dissociating molecular oxygen. By the process of dissociative

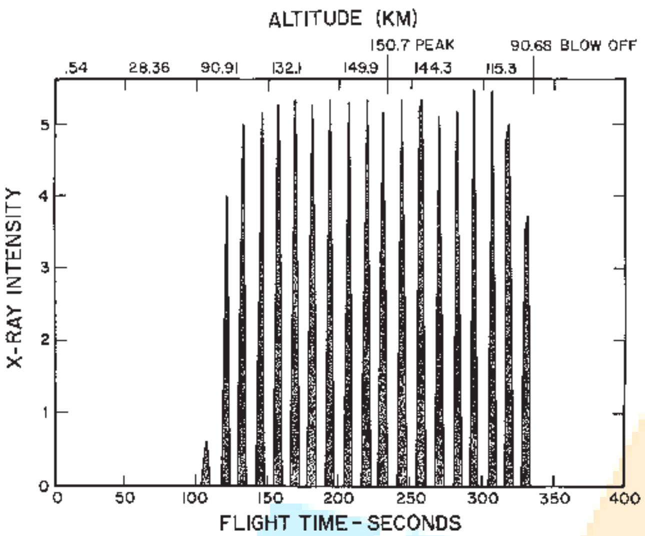

Figure 3 The first measurement of the penetration of solar X-rays into the upper atmosphere made by a V-2 rocket in 1949. The 8 A X-ray signal was modulated by the spin of the rocket as the Sun came into view once each roll period. X-rays were first detected at about 90 kilometers and reached peak intensity at about 130 km. (U.S. Naval Research Laboratory.)

recombination, molecular oxygen controls the rate of neutralization of F-region electron density much more effectively than atomic oxygen.

The 1949 measurement of harder X-rays (1–8 Å) led to several years of broad band photometry of solar X-rays that extended the range of the spectrum, primarily with the aid of simple filters of beryllium, aluminum, titanium, mylar, formvar, etc. serving as the window materials of the photon counters. It seems in retrospect that the NRL group was almost alone in that decade of pioneering studies of the Sun. The X-ray spectral distribution from 1 Å to 44 Å resembled thermal emission from a thin corona at a temperature of a few million degrees. Successive measurements at intervals of months to years showed flux variations of as much as a factor of 7 for X-rays (8–20 Å) over the sunspot cycle. Such variability was consistent with ionospheric electron density variations in the E-region, supporting a direct connection between solar X-rays and E-region. But the observed variability over a solar cycle made it clear that the concept of X-ray emission from a spherically symmetrical solar corona was very inadequate. Instead it seemed that the corona was structured in condensations, formed over sunspots, that produced enhanced X-ray emission. To resolve the question of spatial origin would require an X-ray scan of the solar disk or an X-ray photograph. Both methods were successfully applied at the end of the decade. The X-ray photograph was obtained with primitive pinhole photography (Figure 6); the scan required a very special combination of a total solar eclipse and an array of rockets launched from the deck of a ship.

SOLAR FLARES

Of all the forms of solar activity, flares are the most spectacular. A solar flare creates a strong impact on the terrestrial environment, producing prompt shortwave radio blackout that may last for two to three hours. The after-effects may persist for one or two days in the form of great auroral displays, and ionospheric and magnetic storms that seriously degrade shortwave radio communications.

The new arsenal of rockets that became available late in the 1950s made it possible to plan a program of solar flare studies. Although the supply of V-2 rockets was exhausted by 1952 it was replaced by smaller Aerobees and two staged rockets that mated the Deacon with a Nike booster or a Skyhook balloon. The latter combinations were particularly attractive for studies that required a form of instant rocketry. Launch from shipboard at sea offered range safety. By sailing downwind the ship could achieve nearly zero relative wind conditions for inflation and release of the balloon with its suspended rocket. The well deck aboard the U.S.S. Colonial measured 392 feet by 41 feet which we could use to store three trailer-truckloads of helium while the broad helicopter deck above served admirably for the balloon operations. The lumbering ship could make a speed of 15 knots which was slower than the expected drift of the balloon at altitude. To assure radio contact with the balloon payload we were assigned a destroyer, the U.S.S. Perkins that could track the balloon with a speed of 28 knots. Finally a crew of 650 sailors was tasked to man the ship for the naval chase.

Each day as inflation began, the polyethylene balloon, most of it draped in tight folds resembling the stem of an onion, rose 100 feet above the deck, crowned by a 20 foot bulge filled with 5000 cubic feet of helium that would expand further to thirty times that volume at altitude. The 12-feet long Deacon rocket dangled at the end of a 100-foot nylon line (Figure 4). At 80,000 feet, when a flare was observed in visible light, a radio command would fire the rocket and send it upward, piercing the balloon and rushing ahead another 50 or 60 miles through the ionosphere.

An NRL proposal for a naval expedition as part of the International Geophysical Year (IGY) to launch ten Rockoons for solar flare studies with the support of the USS Colonial, an LSD with a large helicopter deck, was approved by the Office of Naval Research. Our ship was a sea-going drydock. The operational plan was to release a Rockoon each morning on ten successive days and allow it to float at 80,000 feet until the onset of a solar flare was detected, when it would be fired. One flare was successfully observed

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Early ultraviolet spectroscopy from space

The period starting around 1950 and extending into the twenty-first century will probably ultimately be remembered as the golden age of discovery in observational astronomy. This is because of the simultaneous occurrence of three technological advances: the ability to observe the entire electromagnetic spectrum, by combining observations from the ground and from above the absorbing effects of the Earth's atmosphere; the creation of efficient and high-precision detectors of electromagnetic radiation; and the development of computers for processing and manipulating large electronic data sets. The field of ultraviolet (UV) astronomical spectroscopy at wavelengths shorter than 3100 Å has benefited from all three of these technological revolutions and has required access to space for its very existence.

In this chapter I follow the development of the field of UV astronomical spectroscopy from space over the period from approximately 1945 to 1980, with the emphasis on spectroscopy of objects located beyond the Solar System. The discussions concentrate on scientific developments in the wavelength range from ~900 to ~3100 Å. The lower limit of ~900 Å represents the wavelength where bound–free opacity of neutral hydrogen in the interstellar gas becomes large, and the upper limit of 3100 Å is where observations begin to become possible from telescopes situated on the ground. The wavelength regions of 100–900 Å, 900–1200 Å, and 1200–3100 Å are usually referred to as the extreme ultraviolet (EUV), far-UV, and UV regions of the spectrum, respectively. I shall not review the beginnings of EUV spectroscopy from above the atmosphere since those beginnings were delayed by a decade compared with activities in the far-UV and UV bands; for a review of the beginnings of EUV astronomy see Bowyer (1991). This delay resulted mostly from the fear that the interstellar H I opacity in most directions would be so large that only the stars closest to the Sun would be observable. However, the highly irregular distribution of H I in the local interstellar medium and the existence of the local hot bubble of ionized hydrogen rendered these fears invalid. EUV astronomy achieved its first photometric detection of a stellar source during the Apollo–Soyuz mission (Lampton *et al*. 1976) and the first low-resolution EUV stellar spectra were obtained several years later (Holberg *et al*. 1980) as part of the Voyager 1 mission.

In preparing this historical overview of developments in the field of UV astronomy from space, I benefited substantially from reference to various papers summarizing the state of UV astronomy over the past 40 years. These include the reviews by Friedman (1959), Wilson and Boksenberg (1969), Wilson (1970), Bless and Code (1972), Code and Savage (1972), Spitzer and Jenkins (1973), Boggess and Wilson (1987), and Brosch (1999).

THE OBSCURING ATMOSPHERE

The attenuation produced by the Earth's atmosphere in the UV as a function of wavelength in angstroms is shown in Figure 1. The solid curve gives the altitude in kilometers at which radiation normal to the atmosphere is reduced in intensity by a factor of 1/*e*. The various molecules and atoms mostly responsible for the atmospheric absorption are indicated on the curve. The atmospheric absorption that rapidly sets in near 3100 Å is produced by ozone (O_3) while

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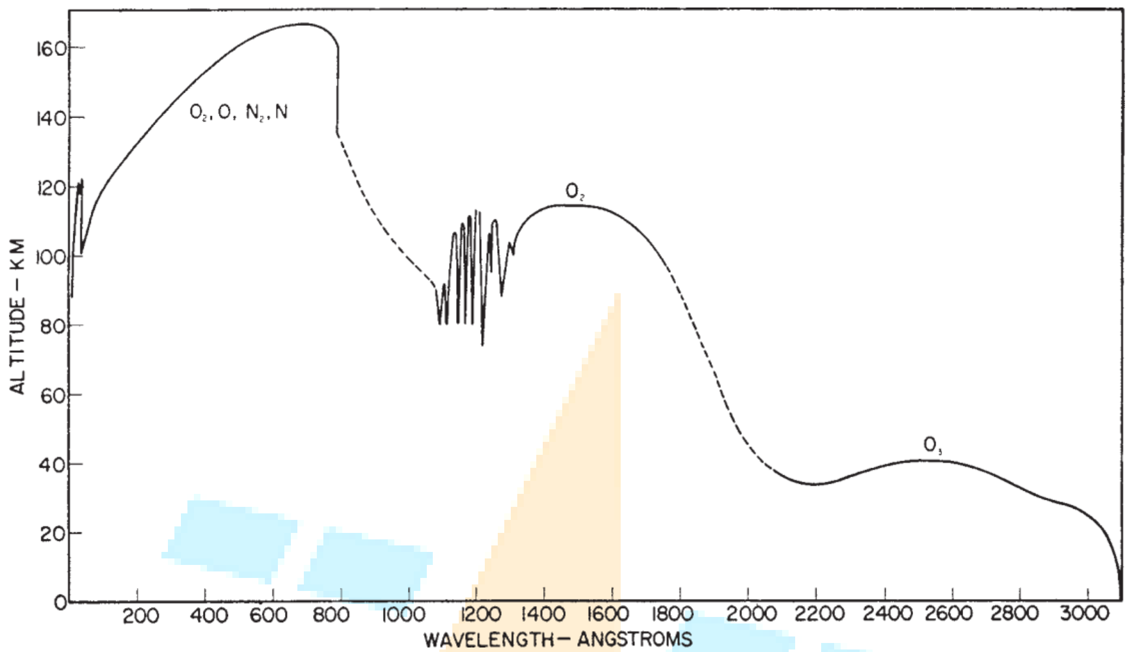

Figure 1 This figure from Friedman (1959) shows the altitude in kilometers at which the fraction of radiation at wavelengths shorter than the visible incident on the Earth's atmosphere is reduced by a factor of 1/*e*. Strong atmospheric absorption due to O_3 sets in at about 3100 Å. While in the mid-UV it is possible to carry out observations from high-flying balloons, satellite altitudes are required to observe celestial sources for the UV wavelengths below ~2000 Å. (By permission of the *Journal of Geophysical Research*.)

absorption at shorter wavelengths is mostly from O_2, O, N_2, and N. In the wavelength range ~2000–3000 Å it is possible to carry out UV observations from balloons carried to altitudes of 30–40 km (see later section on Near-UV Spectroscopy from Balloons). However, rocket or satellite altitudes are required to observe at UV wavelengths shorter than ~2000 Å. Even at rocket or satellite altitudes exceeding 300 km, the trace atomic constituents in the atmosphere can interfere with astronomical observations. In particular, the hydrogen geocorona extends many Earth radii from the surface of the Earth, and the H I scatters sunlight in the Lyman series lines producing very strong emission, particularly in the Lyman a, þ, and µ lines at 1215.67, 1025.72, and 972.54 Å. Similarly, Earth airglow emission can be strong in various O I transitions. Even at the altitudes of the major modern observatories such as the Hubble Space Telescope, there is enough residual O I in the atmosphere for terrestrial O I absorption lines to be apparent in high-resolution spectra of hot stellar continuum sources.

THE SCIENTIFIC IMPORTANCE OF ACCESS TO SPACE

More than 75 years ago, Oberth (1923) pointed out that an astronomical observatory orbiting above the Earth's atmosphere would have several major advantages over an observatory on the Earth's surface. He noted that at optical wavelengths the orbiting observatory would not suffer the blurring effects of the Earth's atmosphere. Therefore the orbiting observatory could produce images limited only by the quality of the telescope optics and its pointing system. He also pointed out that the orbiting telescope would be capable of observing celestial objects over the entire electromagnetic spectrum, including spectral regions that are not accessible to the ground-based observer. No professional astronomers took these ideas seriously when they were first discussed, and over the subsequent 20 years the only other published speculations about observatories in space that I am aware of appear in the science fiction literature (Richardson 1940). However, everything changed after World War II, in part as a result of the development and capture of the V2 rocket technology and the start of the Cold War between the United States and the Soviet Union.

The first truly serious discussions of the potential scientific importance of placing satellite observatories instrumented for UV spectroscopy above the absorbing atmosphere are found in an internal report entitled "Advantages of an Extra-Terrestrial Observatory," written for the Rand Corporation in 1946 by Lyman Spitzer reprinted in Spitzer (1997). Spitzer's report discusses the science that could be pursued with several types of orbiting observatories of different sizes. In addition to observatories designed to observe the Sun in the UV, he discussed the scientific potential of a modest 0.25 m (10-inch) reflecting telescope designed to obtain UV spectra of stellar sources, and the potential value of a large reflecting telescope operating at optical wavelengths.

The scientific programs Spitzer proposed for this instrument included:

- studies of the composition of planetary atmospheres
- measures of the structure of stellar atmospheres, including the possibility of detecting expanding atmospheres in the strong absorption lines of C, N, and O
- measures of the color temperatures of hot stars
- measures of stellar bolometric magnitudes
- the analysis of eclipsing binary UV light curves to obtain information about stellar masses and atmospheric properties
- using the improved understanding of stellar atmospheric conditions from the UV studies to improve on stellar distance determinations
- measures of the composition of the interstellar gas
- measures of the properties of interstellar absorbing grains
- measures of the UV spectra of supernovae in order to better understand the explosion processes.

For each of these topics Spitzer discussed how observatories above the atmosphere could be used to make major advances in the given science area. For example, in the case of measuring the composition of the interstellar gas, Spitzer pointed out that in interstellar space most atoms and molecules were expected to be found in their ground (lowest-energy) state. Therefore measures of the composition of the gas through absorption line spectroscopy would require an observatory operating at UV wavelengths since most absorption lines out of the ground state of abundant atoms fall in the UV. Slightly more than 25 years after creating this vision for the future of UV astronomy in space, Spitzer pioneered UV studies of the interstellar medium by using the high-resolution UV spectrograph aboard the Copernicus satellite (see the section on the Orbiting Astronomical Observatories).

Shortly after the launch of Sputnik in 1957 and the organization of NASA in 1958, several papers appeared discussing the science that could be pursued with UV spectrometers operating above the Earth's atmosphere, including those of Spitzer and Zabriskie (1959) and Code (1960). I find the Spitzer and Zabriskie paper, entitled "Interstellar research with a spectroscopic satellite," particularly interesting because my professional field of interest is the interstellar medium. I remember referring to that paper in 1965 when taking Professor Spitzer's course on "Physical Processes in the Interstellar Medium." During the course I recall a particularly interesting class assignment. Professor Spitzer asked his students, "What observations would you obtain with a 1 meter satellite observatory equipped with a high-resolution spectrometer operating from 912 to 2000 Å in order to obtain information about the physical properties of the gas between the stars?" In answering the question I was intrigued by the possibility of using a satellite observatory to study aspects of the interstellar gas (the hot phase) that were difficult or impossible to study from the ground. I didn't realize at the time that this assignment was one I would continue to work on for most of my professional career.

TECHNOLOGICAL CHALLENGES

The technological challenges faced by the pioneers of UV spectroscopic space astronomy were considerable. They included gaining reliable access to space, developing small light weight UV spectroscopic optical systems, developing rocket and satellite pointing and control systems, and developing efficient UV sensitive detectors. The most difficult challenge was to design and build complex robotic systems that would actually operate in the space environment.

The progression through these various technological challenges did not always proceed smoothly. As a beginning graduate student in 1964, I witnessed the activities around Princeton University involving the pioneering projects in UV spectroscopy through the efforts of Donald Morton and Lyman Spitzer and in optical diffraction limited imagery through the Stratoscope II balloon-borne telescope program involving Robert Danielson and Martin Schwarzschild. I vividly remember discussions in the halls about rockets blowing up on the launch pad, pointing and control systems that failed to operate, rocket parachute systems that deployed too early, and balloon flights where the 3600 kg Stratoscope II telescope system failed to unlatch from the vertical pointing position, or where the sealed door on the pre-cooled 0.9 m diffraction-limited primary mirror failed to open at altitude. Reflecting on all these problems and wondering how long it might take to complete an experimental thesis in space astronomy, I made an arrangement with Robert Danielson and Martin Schwarzschild to pursue a theoretical PhD thesis and to briefly join the Stratoscope II team following my graduation to continue to explore my experimental interests. The lesson I learned during this period was that the most difficult technical challenge faced by the early pioneers in space astronomy was to achieve a high level of reliability for remotely controlled robotic systems operating in the space environment. Even today, it appears that this is a difficult goal to meet on a regular basis.

SOUNDING ROCKET SPECTROMETERS

UV space astronomy began as an experimental field at about the same time as Spitzer was considering its future.

Using captured German V2 rockets which could carry a 1000 kg of equipment to 150 km altitudes, scientists working at the Naval Research Laboratory (NRL) led by Richard Tousey obtained the first UV spectrum of the Sun to wavelengths as short as 2200 Å (Baum *et al*. 1946). The first UV stellar photometry followed about ten years later when NRL scientists observed 59 hot stars in a 130 Å wide UV band centered on 1115 Å (Bryam *et al*. 1957). These early UV stellar observations involved scans of the sky with simple photometer systems from unstabilized sounding rockets.

The flight of a scanning objective grating spectrometer on an unstabilized Aerobee rocket produced the first low-resolution UV stellar spectrophotometry over the 1600–4100 Å region at 50 Å resolution (Stecher and Milligan 1962). In this observation the dispersion direction of the spectrograph was normal to the rocket roll axis. The roll of the rocket produced the spectral scan at the slit with a photomultiplier recording the spectrum. However, to capture enough photons during the short intervals for which the stars were in the field of view, the slit needed to be wide and the resulting resolution of 50 Å was insufficient to resolve discrete stellar absorption or emission lines.

The first moderate-resolution spectroscopic observations of stars required the development of three-axis stabilization systems for pointing rocket-borne instruments at stars for long enough periods of time to record the spectra. The pointing control system developed by the Space General Corporation was a three-axis stabilized gas reaction system that could be used to orient the entire sounding rocket during its free fall. This system could point the payload within 3° of a desired direction and was stabilized to a limit cycle jitter of ±15 arc minutes. In their pioneering experiment, Morton and Spitzer (1966) employed an additional fine stabilization system as part of their instrument package which improved the pointing in the spectrograph dispersion direction to approximately ±16 arc seconds. Their instrument (Figure 2) consisted of two 1200 lines/mm objective plane gratings followed by *f*/2 Schmidt cameras with 100-mm focal lengths and 10° fields. One Schmidt corrector was made of calcium fluoride and transmitted to 1250 Å; the other corrector was quartz and transmitted to 1700 Å. The resulting UV spectra had a dispersion of about 65 Å/mm and were recorded on UV sensitive Kodak Pathe SC5 film. This small pair of UV spectrometers produced spectra with a resolution of approximately 1 Å when the fine stabilization platform achieved its design pointing stability in the dispersion direction.

The pioneering attempts to obtain UV spectroscopic observations of stars did not achieve instant success. During these learning stages there were often problems associated with making the attitude-control pointing systems work properly. For example, quoting from the abstract

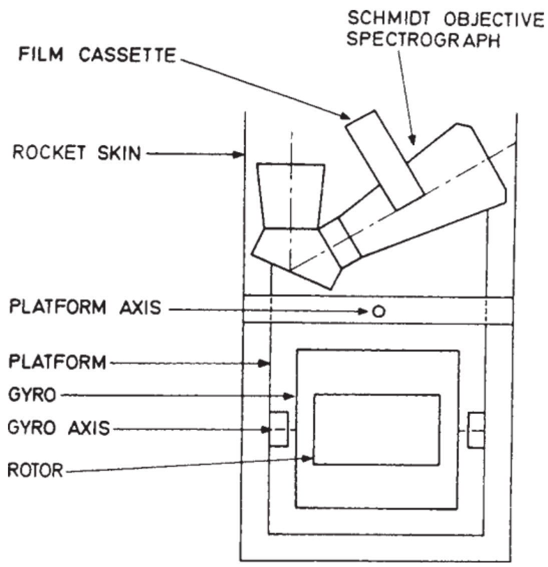

Figure 2 A schematic diagram of the simple UV spectrometer and fine stabilization system flown on an Aerobee rocket by Morton and Spitzer (1966). The fine stabilization in the spectrometer's dispersion direction allowed the instrument to obtain UV spectra of *G* and *6* Sco from 1260 to 1720 Å at a resolution of 1 Å. (By permission of Donald Morton and the *Astrophysical Journal*.)

of the paper by Morton and Spitzer (1966) reporting the observations of first line spectra of stars in the UV,

> On the first two flights the attitude control system failed to stabilize the rocket. On the third flight both coarse and fine systems worked properly, but the parachute failed on re-entry so that the impact damaged the payload beyond repair and admitted light into the film cassettes. Most of the films were totally fogged, but underdeveloping one from the calcium fluoride camera showed wide spectra of the early B-type stars 6 and G Sco with a resolution of 1 Å.

I can recall the gloomy mood after this third flight among the returning Princeton scientists and engineers when they discussed their totally blackened images. However, that mood quickly changed to one of joy when the last piece of film was underdeveloped, and revealed clear spectra of G and 6 Sco extending from ~1260 to 1720 Å.

One year after the success of obtaining the first moderate-resolution UV spectra of stars in Scorpius, Morton (1967) obtained high-quality spectra of six stars in Orion at 3 Å resolution from 1150 to 1630 Å. Those data provided the first evidence for high-speed mass loss from hot stars in the form of P Cygni profiles of the Si IV and C IV stellar absorption lines (Figure 3). This result must have pleased Lyman Spitzer since in his 1946 Rand Corporation study he remarks that, "In addition the nature of unusual stellar

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The early days of infrared space astronomy

INTRODUCTION

Infrared observations can provide a number of unique perspectives on the Universe. This article concerns itself with the men and women who pioneered infrared space astronomy, traces the different techniques they employed, describes the trials and tribulations they had to overcome, and lists some of the gains they achieved. In the process it also examines the social institutions, both academic and military, that were most influential in determining the evolution of the field.

While many infrared and submillimeter observations required going into space, a large number of others were carried out from the ground. The earliest successes of infrared astronomy were largely the work of ground-based astronomers. Going into space required major technological breakthroughs that took time to materialize. A rich texture of sometimes friendly, occasionally aggressive, competition among ground-based, balloon, airborne, rocket, and satellite observers emerged, that persists to this day.

As an active participant in the field, the author makes no claims to objectivity. Nor is he able, in a chapter of twenty or thirty thousand words, to give proper credit to all who made significant contributions. The story told here is overwhelmingly based on personal experiences in the USA. Many of the struggles faced in the USA, however, were duplicated in Europe, Japan, and the Soviet Union. An excellent review written more than 20 years ago by J.E. Beckman and A.F.M. Moorwood (1979) may provide the reader with a complementary European perspective, and D.A. Allen's even earlier book adds an Australian's viewpoint (Allen 1975). The author hopes that contributions such as these may eventually be synthesized to produce a dispassionate, comprehensive, truly international, and perhaps more broadly incisive account.

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The cold universe

Much of the Universe is cold. The wavelength, , at which stars, galaxies, and interstellar or intergalactic gases radiate is inversely proportional to their temperature, T (Figure 1). The peak emission tends to occur at =3700/T micrometers, where T is measured in kelvin (K). One micrometer is a millionth of a meter, traditionally called a micron and abbreviated to μm (or simply μ in the early literature of the field). Observations at infrared wavelengths from 1 to 1000 μm are thus uniquely sensitive to astronomical sources in the temperature range from ∼3000 K to 3 K. These include the coolest stars, planets, and interplanetary dust, circumstellar and interstellar matter, and, at the longest wavelengths and coldest temperatures, the earliest known radiation emitted by the entire Universe.

A dusty universe

Interstellar dust – microscopic particles composed of ices, minerals, and common organic and inorganic materials – is abundant throughout the Universe. These particles obstruct a clear view of the cosmos at optical wavelengths. Fortunately, a cloud of dust that may be totally opaque in the visible or ultraviolet can be virtually transparent in the infrared. Thus,

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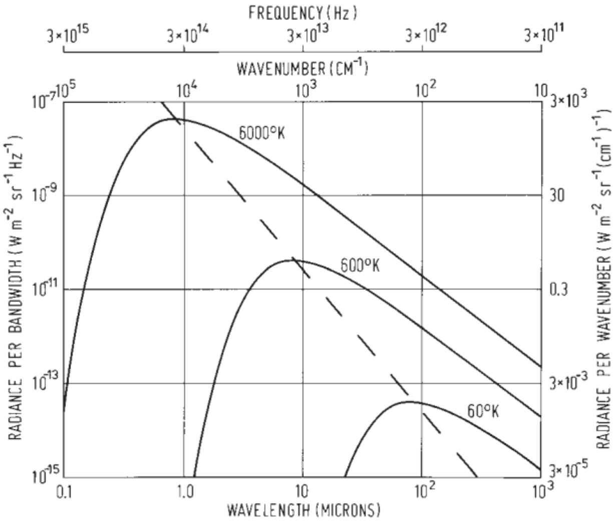

Figure 1 Blackbody radiation spectrum as a function of temperature. As the temperature *T* decreases by a factor of 10, the wavelength of peak emission increases by the same factor and the total power emitted over the entire wavelength range decreases by a factor of 10^4.

infrared wavelengths can probe regions deep in the core of a dusty galaxy that are inaccessible at shorter wavelengths.

Dust grains are heated by short-wavelength, mainly visible and ultraviolet radiation. They absorb this energy, and re-radiate it at infrared wavelengths. Because of this efficient conversion, the majority of the radiant energy emitted by dense, dusty regions, such as star-forming clouds and occasionally entire galaxies, lies at infrared wavelengths.

Since the transparency of dust clouds increases at longer wavelengths, red light is transmitted more readily than blue. Stars lying behind a tenuous dust cloud thus appear reddened. This reddening can be a useful measure of the amount of dust in the cloud.

The early universe

In the expanding Universe, the more distant an object the greater the velocity with which it recedes from us. This cosmic expansion shifts starlight from distant galaxies into the infrared region; the more distant the source, the farther is its radiation shifted into the infrared. The expansion is characterized by a redshift parameter, z, where $1+z$ gives the ratio of "wavelength reaching the observer" divided by "wavelength actually emitted in the distant source": $1+z = {}_{\text{received}}/_{\text{emitted}}$. The most distant quasars and galaxies observed to date have redshifts $z > 5$, so that radiation from the center of the visual band is shifted to beyond 3 μm. Because $1+z$ also represents the factor by which the Universe has expanded since the radiation was emitted, objects at $z = 5$ are seen as they were at an epoch when the Universe was only one-sixth of its present size.

The chemical universe

The infrared band contains the spectral signatures of a variety of atoms, molecules, ions, and solids, at least some of which are found in any astrophysical environment. Infrared spectroscopy allows us to recognize large varieties of substances, ranging from cool ices in the interstellar medium to highly excited ions in active galactic nuclei. By determining the strengths of different spectral features, we obtain important, often unique insights into the chemical and physical conditions in these systems.

INFRARED ASTRONOMICAL CONSTRAINTS

The human eye ceases to respond to radiation beyond the red part of the spectrum. This limit falls at a wavelength of ~0.72 μm. The *infrared spectral domain* begins approximately at a wavelength of 0.7–1 μm, and stretches out to ~1000 μm (=1 mm). The wavelength range between ~200 μm and 1 mm is often called the *submillimeter domain*.

While the atmosphere tends to be opaque to much of the infrared spectral band, observations can be carried out from high mountain tops in a number of *atmospheric windows*. The lowest panel of Figure 2 shows the approximate widths and depths of the atmospheric windows at an observatory like Mauna Kea, Hawaii, sited at an altitude of 4.2 km.

As seen from the upper panels, atmospheric absorption decreases and transmission increases considerably with increasing altitude, and becomes quite high throughout much of the infrared domain at aircraft and balloon altitudes, respectively, at ~14 and ~28 km.

For the astronomer, good atmospheric transmission is not enough. Low atmospheric emission is also essential. The atmosphere radiates powerfully throughout much of the infrared, and this emission is often orders of magnitude greater than the radiation from astronomical sources. The intensity of atmospheric emission also tends to fluctuate with time. In the near-infrared, at 1 ™ ™ 4 μm, emission by OH radicals is highly variable. In the far-infrared, at around 100 μm, variable atmospheric water vapor content produces varying emissivity. Such fluctuations cause the flux, or *signal*, from an astronomical source to be marred by superposed *noise* due to randomly varying atmospheric emission.

Poor atmospheric transmission, and strong atmospheric emission are the prime reasons for undertaking infrared astronomical observations from space. However, in the early 1960s when serious efforts to conduct such observations were beginning, many of these factors were poorly understood. This led to parallel developments in infrared astronomy. Most astronomers worked with ground-based equipment taken to high mountain tops, while a few

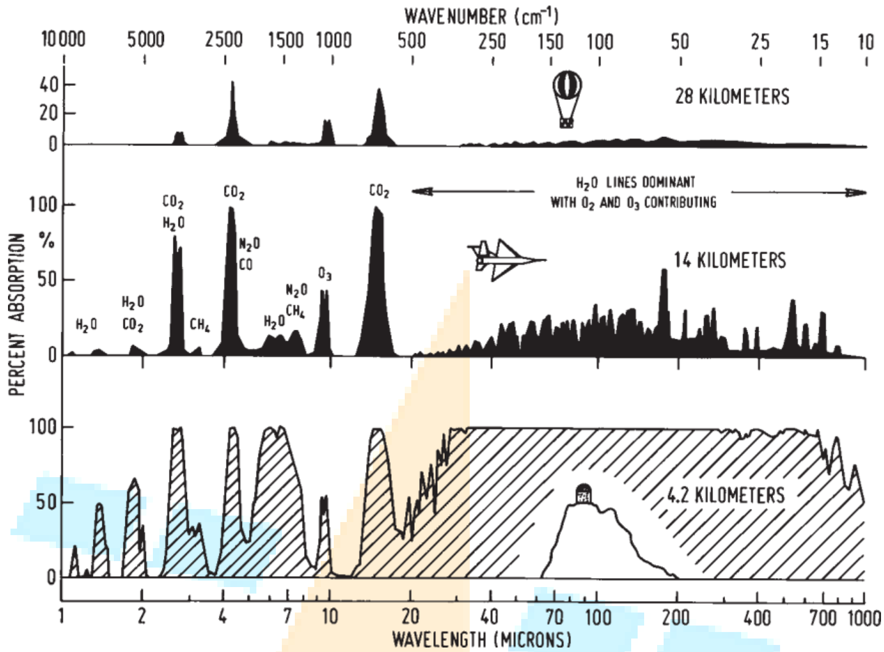

Figure 2 Atmospheric absorption in the infrared at altitudes of balloons, aircraft, and a mountain-top site like Mauna Kea (after Traub and Stier 1976).

attempted to build the instrumentation required to carry out observations from above the atmosphere.

Since rocket payloads were relatively expensive, US ground-based observers feared that the National Aeronautics and Space Administration (NASA) or National Science Foundation (NSF) support for rocket work would drain away funding from their own efforts. Uncertainties about the precise limitations of ground-based techniques often led to acrimonious disputes between ground-based observers and those who wanted to launch sensitive infrared astronomical telescopes above the atmosphere on rockets. Time and again, the more traditional astronomers bluntly recommended that rocket-borne efforts be slashed or pared back to an absolute minimum. Pioneering infrared rocket astronomy was not a happy venture!

To understand the backdrop against which the first successful observations were obtained, one needs to understand not only the technical difficulties that had to be overcome, but also the considerable early successes of ground-based observers who also had to surmount significant instrumental limitations but were able to make headway more quickly in more modest efforts.

EARLY GROUND-BASED EFFORTS

While the earliest attempts to conduct observations of astronomical sources beyond the red part of the spectrum date back to those of Sir William Herschel (1738–1822), who noted the thermal emission of the Sun beyond the visible spectral range, rapid progress did not occur until the 1960s. Two factors limited serious advances: a lack of sufficiently sensitive detectors and a lack of motivation.

In 1838 William Herschel's son John determined the total power emitted by the Sun. His results, obtained by measuring the rise in temperature of water in a blackened vessel on which was focused sunlight, were remarkably accurate given the simplicity of his apparatus. He found that the Sun radiated with enormous power. This posed a problem. Julius Robert Mayer's principle of conservation of energy, enunciated in 1845, led to the realization that the source of this energy had to be huge or the Sun very young, otherwise the Sun's energy would long ago have been depleted. Though many sought to resolve this puzzle, a satisfactory explanation did not emerge until the twentieth century and the development of theories of relativity and nuclear physics.

Thirty years after John Herschel's monumental finding, William Huggins used a thermopile connected to a galvanometer in the far more difficult attempt to measure the heat emitted by stars (Huggins 1869). (A thermocouple is a device consisting of strips of dissimilar metals that generate a voltage when one end of the device is heated.) These measurements were not particularly convincing, but Huggins's contemporary E.J. Stone developed the technique further (Stone 1870). He used two thermopiles back to back, alternating the positioning of a star first on one thermopile and then on the other, in a mode that we would today call "push–pull chopping" (Figure 3). He also calibrated his system against a radiating cube kept at the temperature of boiling water. With these steps he obtained more credible results.

Struggles to perfect increasingly sensitive instrumentation persisted. In the early decades of the twentieth century, pioneering work on better radiometers enabled W.W. Coblentz at the US National Bureau of Standards to report radiometric measurements of 110 stars, and a series of collaborations between Edison Pettit and S.B. Nicholson provided greater insights into planetary and lunar phenomena (Coblentz 1914, Pettit and Nicholson 1922).

The history of infrared detector development, however, was largely guided not by astronomers, but by military needs, such as "night vision" enabling warm objects to be discerned in the dark. World War II brought about the development of lead sulfide (PbS) cells that were far more sensitive than thermopiles. In the post-war era, Peter Felgett in Britain was one of the first to use these devices to measure the fluxes from bright stars (Felgett 1951). Later, the Cold War further accelerated military development of infrared sensors. One particularly successful detector, indium antimonide (InSb), came into use at wavelengths out to 5 μm. At longer wavelengths, the military was developing copper-doped germanium (Ge:Cu) and gallium-doped germanium (Ge:Ga) photoconductors. All these devices worked at their best only over a limited bandwidth, roughly $A / \sim\frac{1}{3}$. To obtain continuous coverage over a broader bandwidth a succession of different detector materials had to be employed, each cryogenically cooled to its own optimum operating temperature.

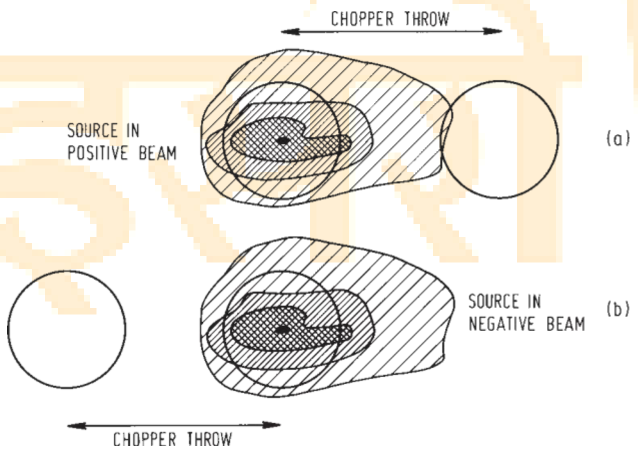

Figure 3 "Push-pull chopping" of a source by switching the field of view of the telescope between an astronomical source and its surroundings on two opposite sides. By subtracting the emission from the surroundings, a first attempt is made to correct for atmospheric emission above the telescope.

If an astronomer could secure a particularly sensitive and stable detector, it was possible to undertake novel infrared measurements. One observer who took good advantage of these detectors was Harold L. Johnson who, with various co-workers, pioneered the Ultraviolet–Blue–Visual–Red–Infrared (UBVRI) photometric system still in wide use. The *I* band lies at 0.9 μm. Johnson also made observations in the *K* band at 2.2 μm and at longer wavelengths. He set out to obtain accurate photometric data on several thousand bright stars and soon realized the importance of reddening and extinction by interstellar dust (Johnson 1965). The general attitude of his time, however, remained that infrared astronomy would continue to be merely an adjunct to optical work. Stars, after all, were known to be visible objects; and the Universe appeared to be largely an aggregate of stars.

Given the still-formidable technical difficulties, most astronomers found little motivation for embarking on a career in infrared astronomy.

This attitude changed with the work of Gerry Neugebauer and Robert W. Leighton at Caltech, who decided to conduct an unbiased survey of the sky at 2.2 μm, where the atmosphere is transparent and PbS is sensitive. Since the amount of observing time that would be required was great, and no telescope was available for the purpose, Leighton and Neugebauer constructed their own. Much of their inexpensive instrumentation was w

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Space-borne observations of the life cycle of interstellar gas and dust

The gas and dust in the interstellar medium (ISM) form an essential part of the evolution of galaxies, the formation of stars and planetary systems, and the synthesis of organic molecules that may lead to the emergence of life elsewhere in the Universe. Over their lifetimes, stars return much of their mass to the ISM through winds and supernova explosions, leading to a slow enrichment in heavy elements and dust that form the building blocks from which future generations of stars and planets are made. Stars also inject energy into the ISM via ultraviolet photons, shocks, and wind-blown stellar bubbles. Cosmic rays, x-rays, and ionizing photons influence the ionization state of the gas, whereas shielding by gas and dust leads to the cold, neutral phases of the ISM where molecules can flourish. As a result, the composition and structure of the ISM is governed by a complex interplay of microscopic and macroscopic processes. Understanding this life cycle of gas and dust in the ISM is a key problem in astrophysics, for understanding not only our own Galaxy but also the much more rapid cycling between the ISM and stars in the earliest star-forming galaxies in the Universe (Figure 1).

Research on the ISM started early in the twentieth century with the ground-based detection of interstellar Na and Ca^+ optical absorption lines (Hartmann 1904, Heger 1919) and the appearance of many dark regions on photographic surveys of the Milky Way (e.g., Barnard 1919). Definite evidence for the presence of interstellar dust came from observations by Trumpler (1930), whereas the first interstellar molecules, CH, CH^+, and CN, were identified between 1937 and 1941 (Swings and Rosenfeld 1937, McKellar 1940, Douglas and Herzberg 1941). Around the same time were detected the diffuse interstellar bands (DIBs; Heger 1922, Merrill 1934), whose identification is still uncertain after more than 75 years. Initially, inspired by the identification of simple diatomic species in the ISM, these bands were attributed to molecular absorbers. However, once interstellar dust was established as an important interstellar component, an origin for the DIBs in absorption by dust grains was taken for granted. Nowadays the pendulum has swung back – and for good reason – to molecules as the prime candidates for the carriers of these absorption features (Snow 1995). The foundation of the theoretical study of the ISM and the physical conditions that may prevail there was put forward by Arthur Eddington (1926) in his famous Bakerian Lecture. It was also he who exclaimed that "atoms are physics but molecules are chemistry" with the scarcely hidden message that astronomers should stay away from molecules. Nowadays, despite Eddington's warning, molecular astrophysics is a thriving field driven to a large extent by the wealth of molecular data that has become available over the last three decades, much of it harvested from space.

With the detection of the 21 cm H I line by Ewen and Purcell (1951), the study of the ISM turned to ground-based radio observations, and data thus gathered still provide a wealth of information on the distribution and kinematics of the neutral, atomic ISM in our Galaxy and other galaxies (e.g., Hartmann and Burton 1997). The detection of the first molecules at radio wavelengths (Weinreb *et al*. 1963, Cheung *et al*. 1968) paved the way for the development of millimeter and submillimeter wave astronomy. The ubiquitous CO molecule was detected by Wilson *et al*. (1970), and a surprisingly large number of other molecules have since been found in dense molecular clouds (see van Dishoeck and Hogerheijde (1999) for a recent overview).

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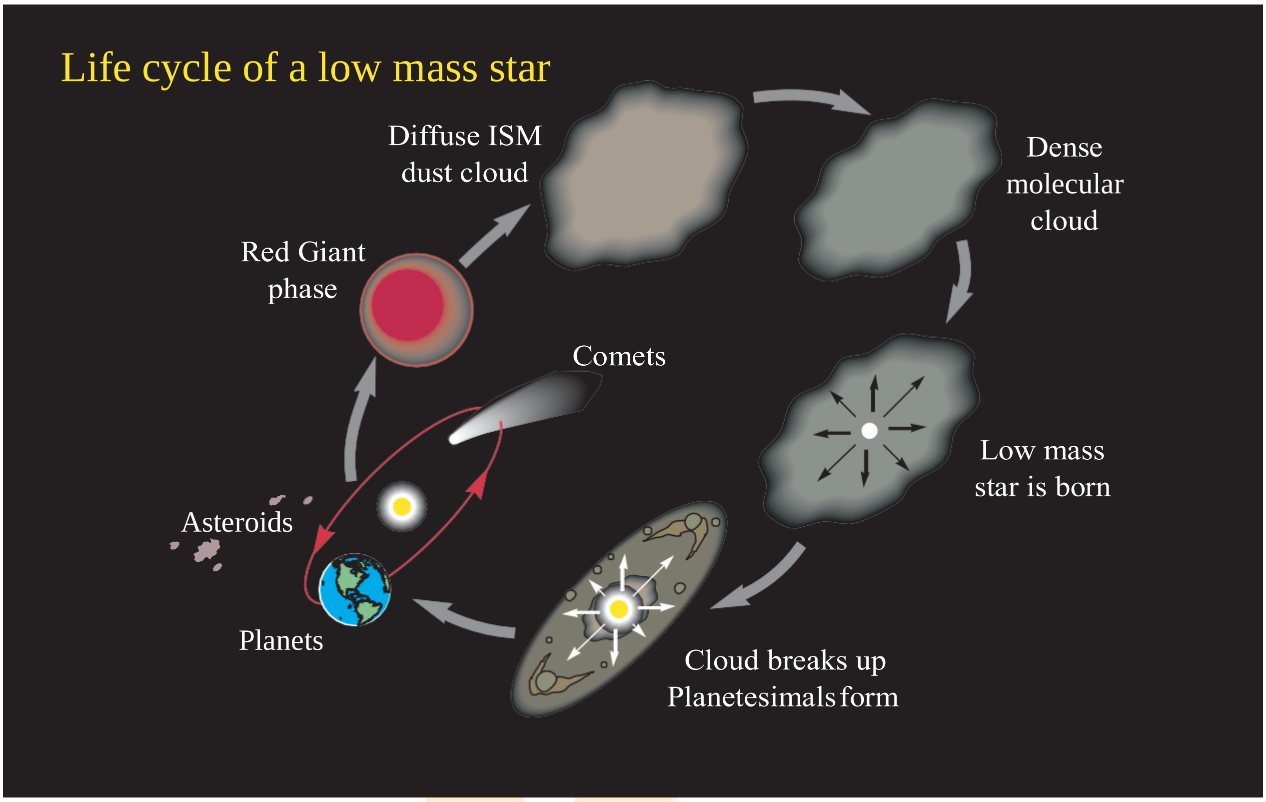

Figure 1 Schematic diagram of the lifecycle of dust and gas from the diffuse ISM, through star formation, to the late stages of stellar evolution. (Pendleton and Cruikshank 1994.)

Space-based ultraviolet observations of the neutral ISM started with small spectrometers flown on rockets, which led to the important detection of H_2 by Carruthers (1970). The later Copernicus satellite (Spitzer and Jenkins 1975) provided extensive new information on H_2 and other interstellar lines, mostly of atoms in various ionization stages. Together with the ground-based H I data, they stimulated the development of the two- and three-phase model of the ISM in which the gas is heated by the action of the photoelectric effect on grains and by large-scale supernova explosions, and is cooled by line radiation from atoms (Field *et al*. 1969, McKee and Ostriker 1977).

Because the typical temperatures of the cold, neutral ISM range from ~10 to a few hundred K, most of the thermal emission occurs at mid- and far-infrared wavelengths, a part of the spectrum which is largely inaccessible from the ground. It is therefore not surprising that much of our progress over the last 30 years or so has come from space-based observations in the infrared. To our knowledge, the earliest discussion of the importance of the infrared for the study of the ISM goes back to an exchange between Spitzer, Kahn, and Drake at the 3rd Symposium on Cosmical Gas Dynamics (Burges and Thomas 1958). Of course, the first detection of infrared radiation – from the Sun – was by William Herschel in 1800, while his son John Herschel was the first to measure the total power emitted by the Sun, in 1838, and Edward Stone that of stars, in 1869–70 (Harwit 1999). In the late 1870s Thomas Edison observed Arcturus and the solar corona in the infrared from a chicken coop in order to win a bet (Eddy 1972). However, despite these early successes the field of infrared astronomy lay dormant until the late 1960s to early 1970s, when progress in infrared instrumentation truly opened the infrared window of the spectrum.

The 1958 discussion mentioned above went on to consider the observational difficulties of detecting a low-intensity astronomical signal against a 300 K telluric background and emphasized the advantage of balloon or satellite observations. This was elaborated upon in an early discussion of infrared radiation from interstellar grains by Stein (1967), who concluded that it was hopeless even to consider observing it through the mid-infrared telluric windows. Fortunately he was not much impressed with his own pessimistic prediction, and, together with (among others) Fred Gillett, he went on to pioneer the field of mid-infrared spectroscopy of interstellar dust using a circular variable filter-wheel. By the early 1970s it was fully appreciated that the best way to determine the composition of interstellar

Table 1 Selected infrared space missions and instruments relevant to ISM research

Mission	Instrument	Acronym	Wavelength range (μm)	Resolving power	Operational period
IRAS	Photometers		12, 25, 60, 100	3–5	1983
	Low Resolution Spectrometer	LRS	7.7–22.6	20–60	
COBE	Far-InfraRed Absolute Spectrophotometer	FIRAS	100–10 000	100–500	1989–1993
IRTS	Far Infrared Line Mapper	FILM	63, 158	400	1995
ISO	Short Wavelength Spectrometer	SWS	2.5–45	2000, 20 000	1995–1998
	Long Wavelength Spectrometer	LWS	43–197	200, 10 000	
	Camera	CAM	2.5–17	3–20	
	Camera+Circular Variable Filter	CAM-CVF	2.3–16.5	35–50	
	Photometer	PHT	3.3–200	3	
	Photometer-Spectrometer	PHT-S	2.5–5, 6–12	90	
SWAS	Heterodyne Instrument		545, 610	5×10^5	1999–

dust was through infrared spectroscopy (Gaustad 1971). That was an impressive foresight and insight, as well as a change of direction in a short time. It should be remembered that by the late 1960s and early 1970s, rocket-borne ultraviolet studies had revealed the ubiquitous presence of 2200 Å bump in the interstellar extinction curve (Stecher 1965, Bless and Savage 1972), which had been successfully modeled in terms of small graphite grains (Gilra 1972).

Yet, as has become abundantly clear since then, advances in our knowledge of the physics and composition of the dust and gas have followed advances in infrared detector and heterodyne submillimeter receiver technology, and the development of airborne and space-based platforms through pioneers such as Martin Harwit, Gerard Kuiper, Frank J. Low, Charles H. Townes, and many others (e.g., Harwit *et al*. 1966, Kleinmann and Low 1967). The Lear Jet and the Kuiper Airborne Observatory (KAO) in the USA, and the US–Netherlands–UK Infrared Astronomical Satellite (IRAS), have been pivotal in developing the field, which has culminated with ESA's recent Infrared Space Observatory (ISO) (Table 1). Other important missions include NASA's Cosmic Background Explorer (COBE), balloons, rockets, the Japanese Infrared Telescope in Space (IRTS), the US Air Force project Midcourse Space Experiment (MSX), and NASA's Submillimeter Wave Astronomical Satellite (SWAS). In this respect, the future looks very promising, with the Space Infra Red Telescope Facility (SIRTF), the ASTRO-F mission, the Herschel Space Observatory (formerly known as FIRST), and the Next Generation Space Telescope (NGST) all on the horizon.

This chapter presents an overview of the air- and space-borne observations that over the last 30 years have played a crucial role in our understanding of the cold and dense neutral ISM and the formation of stars. The various phases of the ISM considered here are summarized in Figure 2, and are discussed in order from the diffuse medium to old stars. The richness of the infrared wavelength region is illustrated in Figure 3, which shows the complete ISO Short Wavelength Spectrometer (SWS) spectrum of Orion centered at the IRc2 source (van Dishoeck *et al*. 1998). Its proximity and extraordinary brightness have made this source the prime target for most of the pioneering observations at infrared wavelengths (e.g., Genzel and Stutzki 1989). Much of the complexity is the result of the disruption of the star-forming environment by powerful outflows from the massive young star, and its intense ultraviolet radiation dissociating and ionizing the gas on the cloud surfaces. Orion is the nearest and best studied region of massive star formation in the Galaxy, and therefore also serves as a template for more distant star-forming regions in other galaxies. The strong continuum is due to thermal emission from warm dust (50–300 K) and peaks around 70 μm. A wealth of superposed lines of atoms, ions, and molecules is seen, which can be used to constrain the physical parameters (see Figure 8 of Genzel 1992) and assess the relative importance of different processes, in particular shocks *v*. ultraviolet radiation.

Space limitations preclude a comprehensive review of the field, and only topics in which space-based observations have played a crucial role are covered. For example, ground-based submillimeter observations of molecular clouds are not mentioned, but the composition of ices in such clouds, as deduced from mid-infrared spectroscopy is. Ultraviolet observations of the atomic component of the ISM and space-based data on ionized H II regions and continuum observations of young stars are discussed elsewhere in this volume. Each section starts with a brief historical review and an introduction of the basic physics, and goes on to

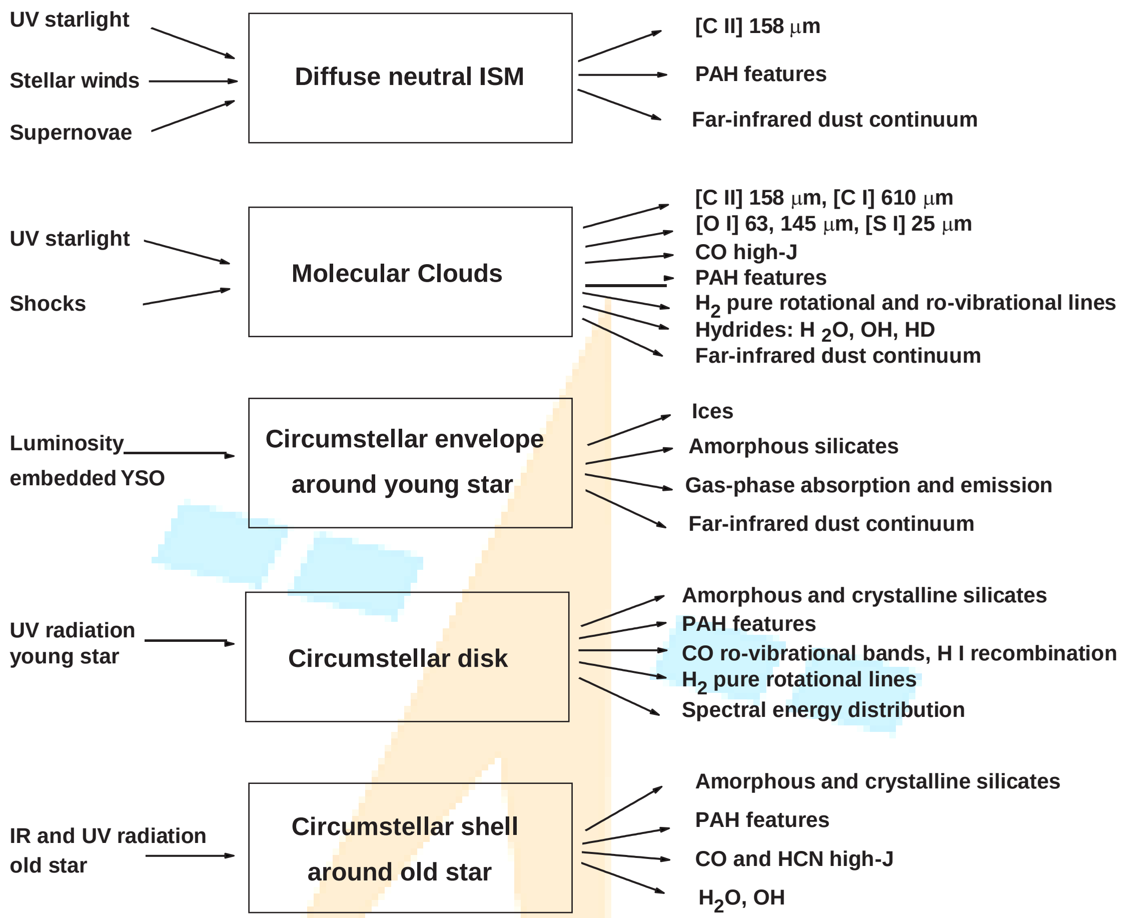

Figure 2 Schematic diagram of the energy input to the various phases of the ISM discussed here, and the resulting diagnostic lines at mid- and far-infrared wavelengths. Most of these features can only be observed from air- and space-borne platforms. *PAH* stands for polycyclic aromatic hydrocarbons or large carbonaceous molecules in general; YSO for young stellar objects.

List of best research & project papers

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