A Rutherford Appleton Laboratory Monograph

The Cosmos from Space

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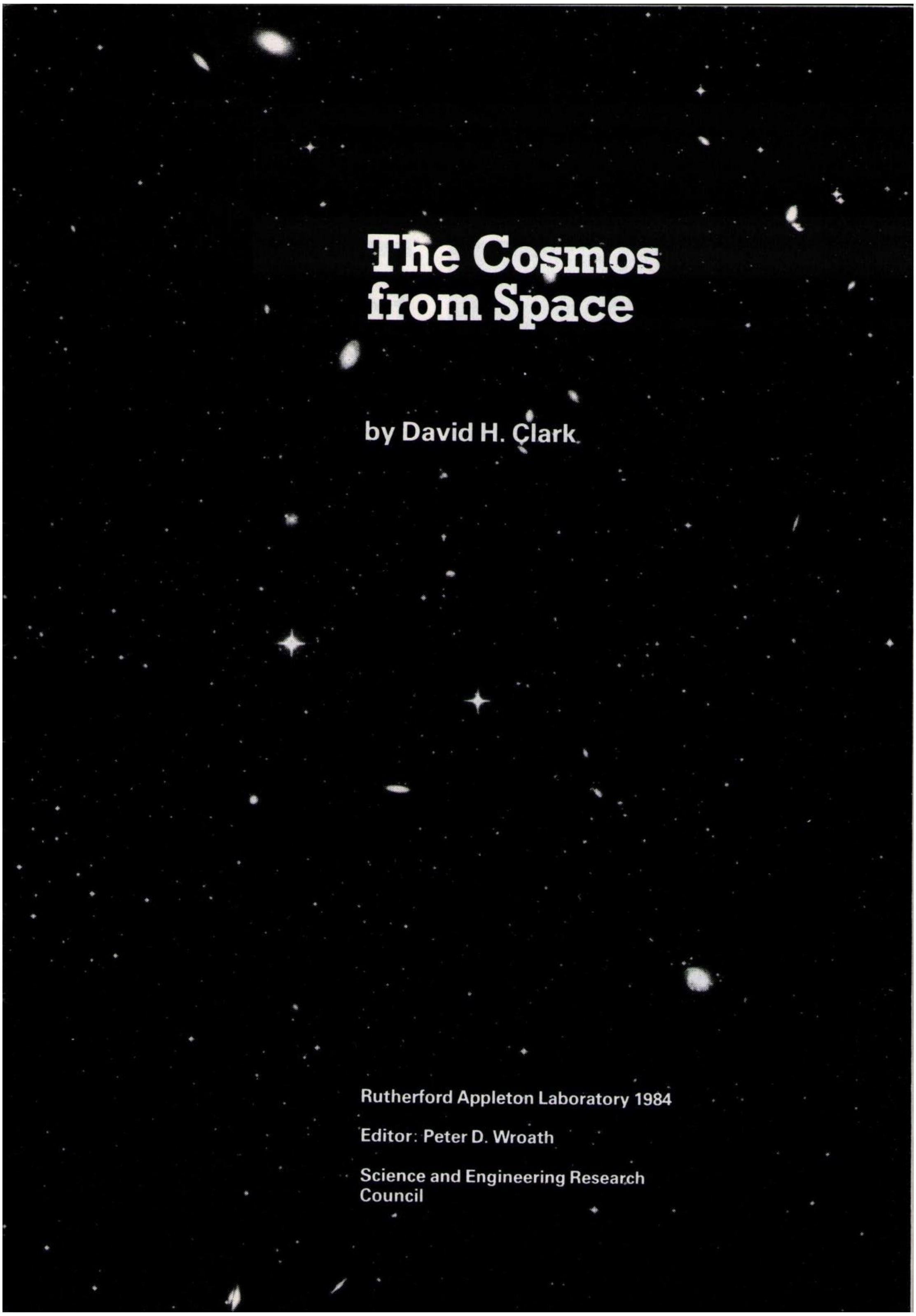


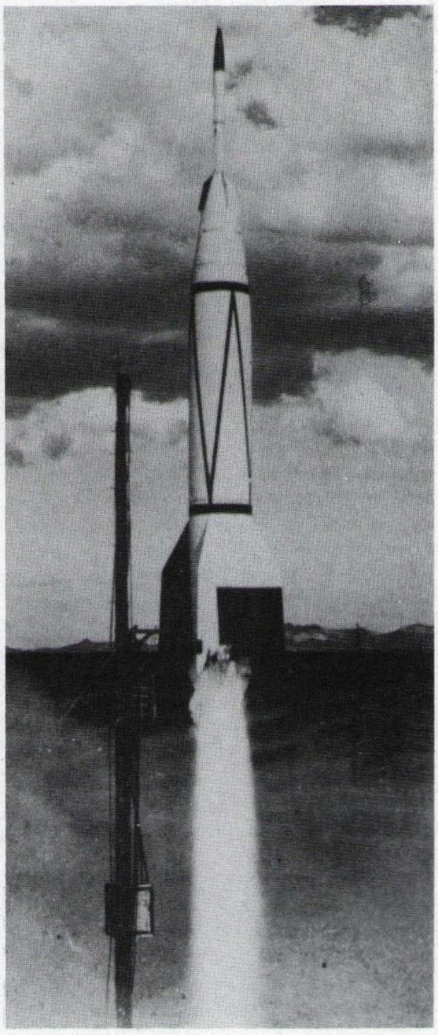
The Cosmos from Space

by David H. Clark

Rutherford Appleton Laboratory 1984

Editor: Peter D. Wroath

Science and Engineering Research Council



A wartime German V-2 rocket blasts off from White Sands (April 25th 1949) lifting the first man-made object (a WAC Corporal rocket) to reach above the Earth's atmosphere.

The Cosmos from Space

Introduction

In June 1945, the US Army evacuated 300 freight car loads of captured German rocket parts from an underground factory near Nordhausen (East Germany), just days before the region was due to pass to Russian control. These relics of German war technology were shipped to El Paso, Texas; at the nearby White Sands military test range, the first atomic bomb, Trinity, had been exploded just a few weeks earlier. Along with the captured technology came German rocket scientists, led by Dr Werner Von Braun, who set to work to help develop the first American missiles.

The early rockets tested from the White Sands range in 1946 were refurbished V-2s, the second of the German "vengeance" weapons *Vergeltungswaffe.* Now the "swords of war" were being beaten into the "ploughshares of peace", as scientists were given the opportunity to fly scientific instruments high into the atmosphere. The military, eager to develop the rocket technology, was nevertheless willing for the unarmed test rockets to be used for scientific research. The vacant half-cubic-metre V-2 warhead compartments were quite adequate to house pioneering instruments for direct measurements of the upper atmosphere and for observations of hitherto hidden phenomena.

Until 1946, almost all we knew about the Universe had been learnt from the optical light radiated by the stars and galaxies (giant star conglomerates) and visible to the human eye, albeit usually aided by a telescope. But other forms of radiation exist — gamma and X-rays, ultraviolet and infrared radiation, micro and radio waves. These are collectively known as *electromagnetic waves.* The experiments that revealed light to be a form of wave date from the seventeenth and eighteenth centuries. Different types of radiation were subsequently discovered, before it was realised that they were all similar in nature. The properties of common examples of waves are well known. A travelling wave is characterised by the distance between adjacent crests (the wavelength), the amplitude of the wave, and by the number of crests passing a stationary observer per second (the frequency). The wavelength of a particular light wave determines its colour. Electromagnetic waves are identical in nature, travel with the same speed, and differ only in wavelength (and frequency).

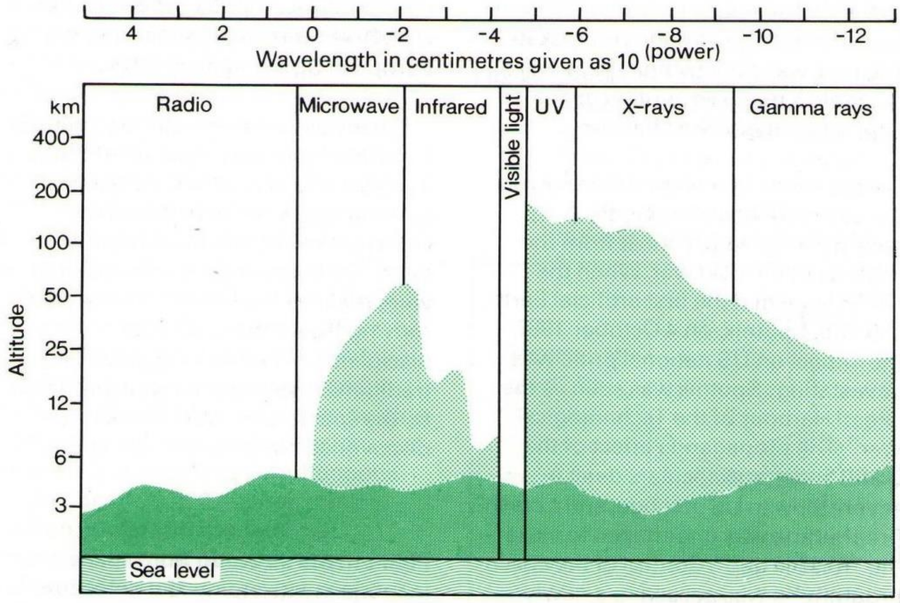


Fig. 1. The transparency of the Earth's atmosphere to electromagnetic radiation from space.

Technology has provided the means to extend the human senses to detect the invisible electromagnetic radiations. However, gamma and X-rays, ultraviolet and infrared radiation cannot penetrate the Earth's atmosphere to be observed by Earth-bound telescopes. Only optical and radio astronomy (and some infrared astronomy) can be carried out from the ground (see Fig. 1). Thus even if it had been expected (which it had not!) that various cosmic objects and phenomena could generate all forms of electromagnetic radiation, the means just did not exist prior to 1946 to get instruments above the atmosphere to detect them. All of this was to change as the first scientific instruments were launched to high altitudes on rockets. The new war-time technologies were to herald a major revolution in our understanding of the heavens.

If the spoils of real war had allowed the advent of space research, it received its greatest boost from the hysteria of the cold war. When the USSR launched the first artificial Earth satellite, Sputnik, on 4 October 1957, the impact on US national pride was devastating: Sputnik was seen as the "Pearl Harbour of the Technological War". The propaganda effect of the USSR space spectaculars dealt a severe blow to US prestige, and a crash programme was undertaken to close the "missile gap". Control of the space programme was passed to a newly created civilian space agency — NASA. Each new shiver in the cold war, or failure in foreign policy, seemed to be matched by a renewed injection of funds into the space programme as the US strove to "regain the high ground"; by 1961, when John F. Kennedy announced the US goal of placing a man on the Moon, federal support of space had rocketed to billions of dollars annually. The space race was not limited to the superpowers, however. The "space club" rapidly gained new members; Britain, France, Germany, Italy, The Netherlands, India, Japan and China. The Europeans combined their space science resources into the European Space Research Organisation (ESRO) and their rocketry aspirations into the European Launcher Development Organisation (ELDO) — later amalgamated as the European Space Agency (ESA).

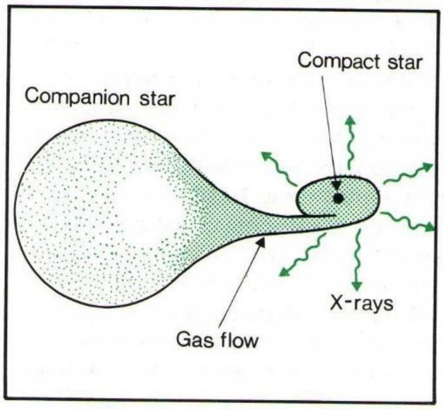
Clearly astronomers stood to benefit from the enormous injection of funds into space, and satellites carrying gamma-ray, X-ray and ultraviolet detectors were soon launched into orbit. The pioneers of space research were mainly engineers, or researchers moving from other scientific disciplines — before long, however, traditional astronomers were attracted by the spectacular and unexpected discoveries being made from space.

Phenomena detected from space

In modern astronomy, the detection and analysis of all types of radiation are important. All electromagnetic radiations are produced by celestial objects in varying degrees, with each telling something different about the nature of the cosmos. Certain cosmic phenomena can be observed only in those radiations detected from space. For example, observations in X-rays reveal extremely hot gas at temperatures of millions of degrees. Ultraviolet radiation comes from gas at less extreme temperatures (hundreds of thousands of degrees). Infrared radiation comes from comparatively cool regions (hundreds of degrees). Even for visible light, there are enormous advantages to be gained by placing instruments in space. The atmosphere distorts any point stellar image (the star "twinkles"). Above the atmosphere, much clearer images are obtained and much fainter (and more distant) objects can be seen.

The stars show new phenomena when studied from space. The very rarified external atmospheres, or *coronae,* of stars have been found to glow in the ultraviolet and X-rays. Stars which have reached the end of their natural evolution sometimes blow themselves apart in events called *supernovae.* The energy released in these spectacular acts of stellar suicide is almost beyond comprehension — at least equivalent to the simultaneous explosion of 10,000 million, million, million, million 10 megatonne hydrogen bombs. The debris from the holocaust is blasted into space and may glow in X-rays and ultraviolet radiation for tens of thousands of years. The burnt-out core of the original star implodes to a state of high density — a so-called *neutron star,* which may be observed as a radio pulsar or an X-ray star. In extreme cases, implosion can create a *black hole* — the ultimate state of compaction of matter. If a neutron star or black hole is in orbit about a normal companion star, material from the companion may swirl onto the neutron star, like water flowing down a plug hole. In the process it is heated to the extreme temperatures required to produce X-rays. The vast majority of bright X-ray stars in the sky are such objects (see Fig. 2).

Fig. 2. An X-ray star system: As gas flows under the action of gravity, from a normal star in a binary system to a compact companion, it is heated to the extreme temperature necessary to produce X-rays.



The space between the stars is not merely a void, but is occupied by gas and dust. Within the interstellar matter astronomers find evidence for the birth of stars. Cold dark cocoons of gas and dust shrink under the action of gravity, heating as they shrink to eventually "switch-on" as newly radiating stars. These regions are opaque to optical light, but can be penetrated and seen in infrared radiation. Between the cool regions lies tenuous hot material which is detected as a faint background glow of X-radiation.

Complex chemical compounds have been identified in the interstellar material. These include some of the same organic molecules that on Earth play a role in living organisms. Space observations in the ultraviolet and infrared, as well as ground-based observations of extremely short wavelength radio emissions, may eventually link the complex chemical reactions of interstellar space to the processes which led to the evolution of life on Earth.

Stars are found to be grouped together in massive conglomerates called *galaxies.* The Earth's parent star, our *Sun,* lies in the Milky Way galaxy containing some 100,000 million stars. The nearest star beyond the Sun is at a distance of 40 million, million kilometres. The remote stars in our galaxy are 20 thousand times more distant. The observable Universe contains of the order of 10,000 million galaxies. Galaxies are detected from space in a variety of radiations. Many are found to be sites of violent upheaval.

The region of sky around the constellation Orion as observed by the Infra-Red Astronomical Satellite (IRAS), where astronomers find evidence for the birth of new stars.

In many ways, the questions being asked in present-day astronomical research are just those which have puzzled men and women since antiquity — for example, how far away are the stars? (i.e. establishing the cosmic distance scale); what is the distribution of matter in the Universe, how did the Universe begin, and what will be its ultimate fate? (i.e. cosmology); how are stars born, how do they evolve, and how do they die? (i.e. stellar evolution); how are the elements created? (i.e. nucleogenesis), etc. Current ideas on these various questions have advanced dramatically this century, with an accelerating increase in our level of understanding in the past few decades as data have become available from space. It is unlikely that an artist would wish to attempt to create a masterpiece with only black and white pigments on his pallet — astronomers were similarly constrained in the past in modelling the Universe with access from the ground only to visible and radio cosmic emissions.

Many of the discoveries from space were totally unexpected. The first cosmic X-ray source was discovered in 1962 by a rocket experiment designed for a completely different purpose. There were many other surprises in store in X-ray astronomy; star systems involving "black holes", galactic jet systems, X-ray stars that flashed on and off like lights on a Christmas tree. . . . No less surprising were some of the accidental discoveries of gamma ray astronomy. The Vela spacecraft were placed in orbit by the US to detect bursts of gamma rays generated in nuclear explosions and so monitor the atmospheric nuclear test-ban treaty. In 1973 scientists from Los Alamos announced the detection by several of the spacecraft of short bursts of gamma rays from beyond the solar system. The mistrust between the superpowers had led to a major astronomical discovery. Such new discoveries from space have depended on remarkable advances in technology — not only in rocketry and spacecraft, but also on the instrumentation to detect the various cosmic radiations. From the advent of the optical telescope in AD 1609 to the construction of the 200-inch Mount Palomar telescope in 1952, almost 3½ centuries of scientific advancement were required to achieve a 10 million-fold increase in sensitivity — a similar advance in the sensitivity of X-ray astronomy instruments was achieved in a mere 2½ decades.

The "pre-space-era" picture of a sedate universe revealed in its visible light, and undergoing little change on the human time-scale, has been replaced over the four decades since the first rocket experiments by a new view of a cosmos undergoing violent upheaval and change; a universe not merely populated by normal stars and galaxies, but by a whole host of bizarre objects and phenomena. Who but the most imaginative science fiction writer could have envisaged, a mere four decades ago, a star so dense that a pebble dropped on to its surface would release more energy than a hundred exploding hydrogen bombs — or a star squirting giant jets of material into space at speeds approaching that of light — or galactic "triffids" with insatiable appetites consuming stars and interstellar gas, belching part of their stellar diet back into space — or "star quakes" releasing more energy in a matter of seconds than does our Sun in a hundred thousand years — or "cannibal" galaxies consuming unsuspecting passing "missionaries". . . . A new vocabulary has evolved for the discoveries of modern astronomy — "pulsars", "quasars", "scintars" and "bursters"; "black holes", "red giants", "white dwarfs" and "blue stragglers". . . .

The tools and techniques of space astronomy

To detect electromagnetic radiations from the cosmos one needs a "telescope", possibly a device to separate the radiation into its component "colours", and some means of recording the information. For a terrestrial optical telescope (see Fig. 3) reflecting optics would normally be used. This configuration is also suitable for space telescopes used for infrared, optical, and ultraviolet observations. The infrared regime has very special problems, since infrared is "heat" radiation; while the heat radiated by a celestial object is enormous the amount reaching Earth over the vast distances of space is extremely small. At room temperature an infrared telescope itself produces approximately 10 million times more heat radiation than could be detected from the brightest infrared source in space. This problem is overcome by

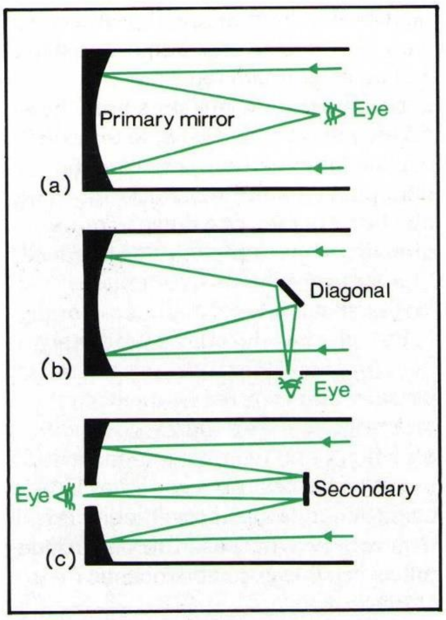


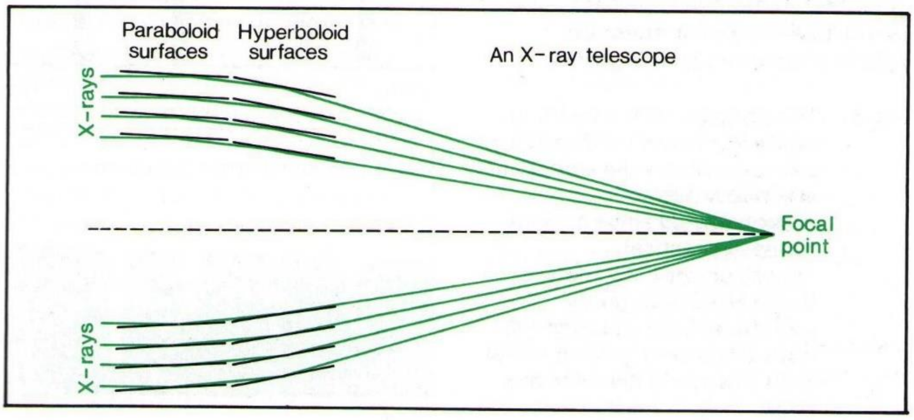
Fig. 3. Shown here are three reflecting telescopes, utilising different focal points: (a) prime focus; (b) Newtonian focus; (c) Cassegrain focus.

cooling the telescope to extremely low temperatures, within a few degrees of absolute zero. So cooled, a small infrared telescope could detect the heat radiated from a cricket ball over a distance equivalent to that of London to New York. Even at optical and ultraviolet wavelengths, the hostile space environment and severe conditions of a rocket launch require the use of forefront engineering techniques for telescope construction: for example, the use of light-weight rigid structures, novel reflective coatings, precision pointing and tracking capability, remote interchange and control of instruments, reliable monitoring of instrument status and performance, etc. The requirements of space astronomy have extended engineering practices to new frontiers, and remain a challenge to technical innovation.

At X-ray wavelengths, a normal reflecting telescope configuration will not work; the X-rays will traverse the mirror material without being reflected. However, X-rays can be reflected at "grazing incidence", i.e. at very shallow angles of incidence. By using in conjunction parabolic and hyperbolic mirrors of extreme surface precision, X-rays can be focused on to a suitable detector. Indeed, several mirrors can be nested concentrically to increase the total X-ray collecting power (see Fig. 4). Such X-ray telescopes are now used in the study of cosmic X-ray emissions. For high-energy X-rays and gamma rays, even grazing-incidence devices will not work, and novel methods of collimation and "focusing" must be used.

The electromagnetic radiation gathered by a telescope (be it of normal incidence or grazing incidence kind) can be analysed using a "spectrometer" to split the radiation into its component wavelengths. The fact that a beam of white light passing through a prism produces the colours of a rainbow has been demonstrated since ancient times. The prism bends

Fig. 4. X-rays can be focused by causing them to reflect from specially shaped surfaces at grazing angles of incidence. In one type of X-ray telescope the rays are reflected first from a paraboloidal surface and then from a hyperboloidal one.



the different components of white light (red being bent least, violet most) into a merging row of colours called a "spectrum" (see Fig. 5a). A practical spectrometer normally uses a grating rather than a prism to disperse the light. Since white light produces a continuous range of colours, it is said to have a "continuous spectrum" (Fig. 5b). By contrast, the spectrum of some particular light source may show just selected features of different colours against a dark background. Such a spectrum is called an "emission-line spectrum" (Fig. 5c), each spectral line being an image of the slit-shaped instrument aperture in a single colour. An emission-line spectrum is a unique characteristic of the radiating material — a fingerprint or signature that allows its unambiguous identification. If a beam of white light, displaying a continuous spectrum, shines on a low-density gas that does not itself radiate, certain colours of the incident light are absorbed so that the emergent light shows dark lines in its spectrum against a continuous background.

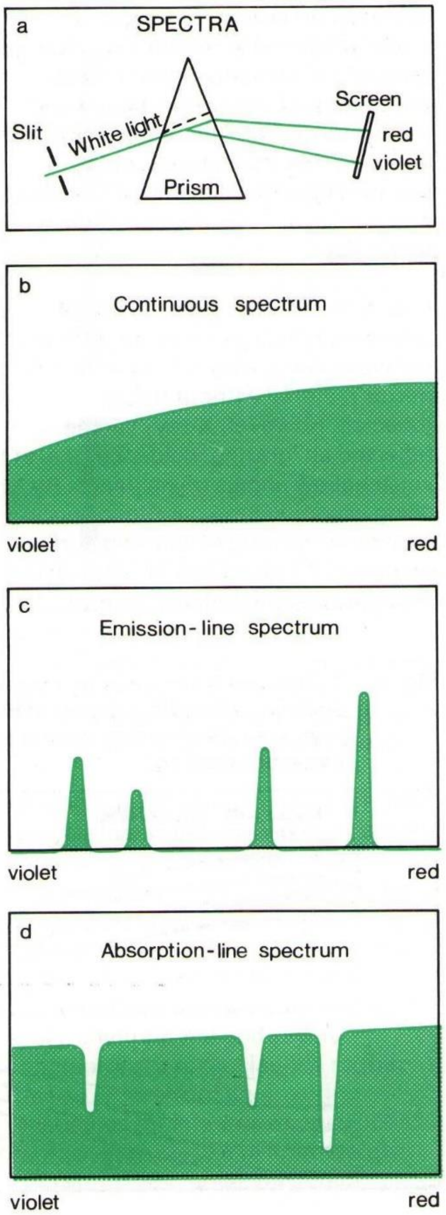


Fig. 5. The principle that a beam of white light passing through a prism produces the colours of a rainbow has been demonstrated since ancient times. A practical "spectrometer" to analyse these electromagnetic radiations from the cosmos normally uses a grating rather than a prism to disperse the light.

Such a spectrum is referred to as an "absorption-line spectrum" (Fig. 5d). The colours of light absorbed are the same as those that would be emitted by the gas if it were made to radiate, so that an absorption-line spectrum of a gas reveals the same information as would its emission-line spectrum. Since the spectrum of a particular light source provides important information on the composition, density, temperature, and velocity of the light source, "spectroscopy", the study of spectra of different sources of electromagnetic radiation, has proved to be an extremely powerful technique in astronomical observation from space. Often, however, just the intensity, or overall "brightness" of a source of cosmic radiation is required — this is measured with an accurately calibrated detector known as a "photometer".

Techniques for the detection and recording of the focused radiation vary with wavelength. In the optical and ultraviolet, photographic emulsions could be used (as with ground-based telescopes) if there was some way for films to be returned to Earth. Remotely-operated satellite equipment requires the use of various forms of electronic detectors. Some use devices which enhance faint light levels by converting incoming light to cascades of accelerated electrons which then produce intensified images on a phosphor — the phosphor can then be scanned by a television camera whose output is processed, stored as digital data and eventually transmitted to ground (see Fig. 6). Various forms of so-called "solid-state" detectors are also now being used. At X-ray and gamma-ray energies, proportional counters constitute a common type of detector. These work on the principle that when an incoming X-ray interacts with gas in the instrument, it creates a

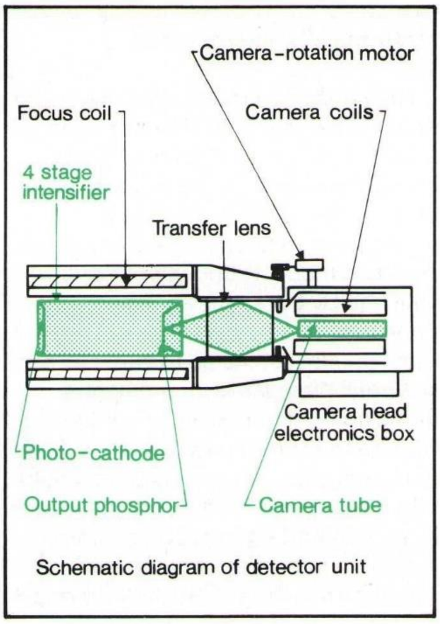


Fig. 6. Remote-operated astronomical satellites use a variety of electronic detectors. Some convert incoming low light levels from the cosmos to cascades of accelerated electrons which strike a phosphor screen scanned by a television camera.

cascade of electrons which is amplified electronically and recorded.

How does a space mission come into being? The first step is for an individual scientist, or group of scientists, to identify a need for a particular type of observation and put forward a proposal as to how such observations could be made. Proposals are often solicited by the space agencies, but may arise on an *ad hoc* basis. They are then usually subjected to some form of scientific peer assessment, before undergoing detailed technical scrutiny. Such is the complexity of most space missions that this process alone might take a year or more. If the scientific case is an outstanding one, and technical feasibility is proven, a competitive selection has then to be made amongst projects competing for the scarce resources of the various space agencies.

There are five clearly-identifiable components of any space project — these are the spacecraft, the launch vehicle, the scientific instruments, the ground-control centre, and the facilities for scientific analysis. The spacecraft would usually be designed and constructed by industry; several different models might be needed to perform particular tasks in the development of the final spacecraft to be launched into orbit. The spacecraft would normally include a guidance system to point the scientific instruments to a desired direction (there are usually strict limitations on this — for example, sensitive instruments could not be exposed to the Sun, Moon or Earth's limb), a power system to provide electrical power to the spacecraft and instruments, a data handling system for processing scientific data from the different instruments and monitoring both their performance and that of the spacecraft, and a communication system for receiving control signals from the ground and returning scientific data. The scientific instruments (for example, telescopes, spectrographs, photometers, etc.) might be constructed by industry, but are often built in universities or scientific establishments. Before being launched into orbit, the various instruments and spacecraft systems must be rigorously tested to ensure that they will survive the harsh space environment (see Fig. 7). Not all countries that build spacecraft have an independent launcher capability; thus, for example, the UK construct spacecraft for scientific, commercial and military purposes but rely on NASA and ESA for launch opportunities. After the launch, a ground station (or stations) has responsibilty for planning the operations of the spacecraft, sending it control signals, receiving back scientific data, checking the "health" of the spacecraft, pre-analysing scientific data and distributing it to interested scientists. Many space astronomy satellites are now operated very much like a ground-based observatory; astronomers visit the ground-station

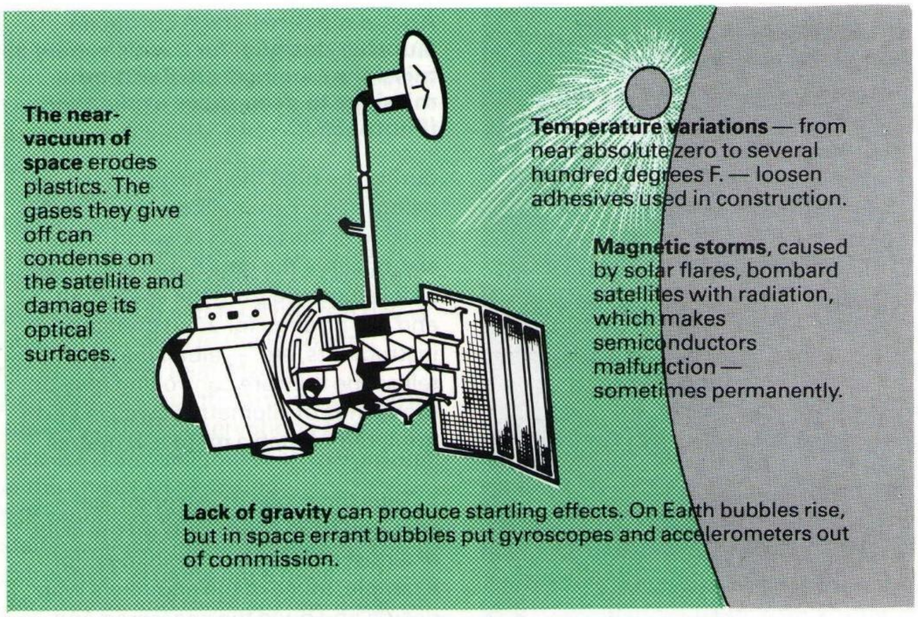
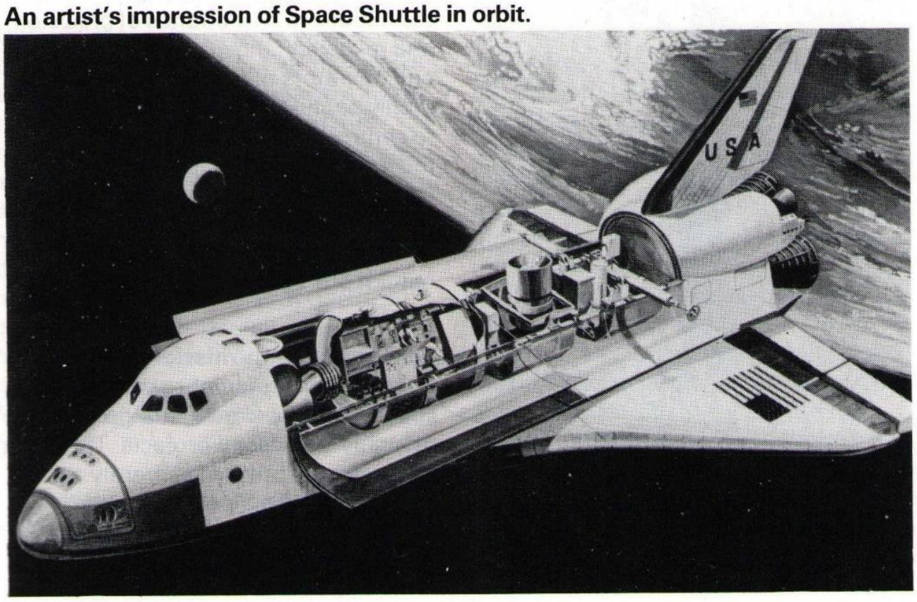
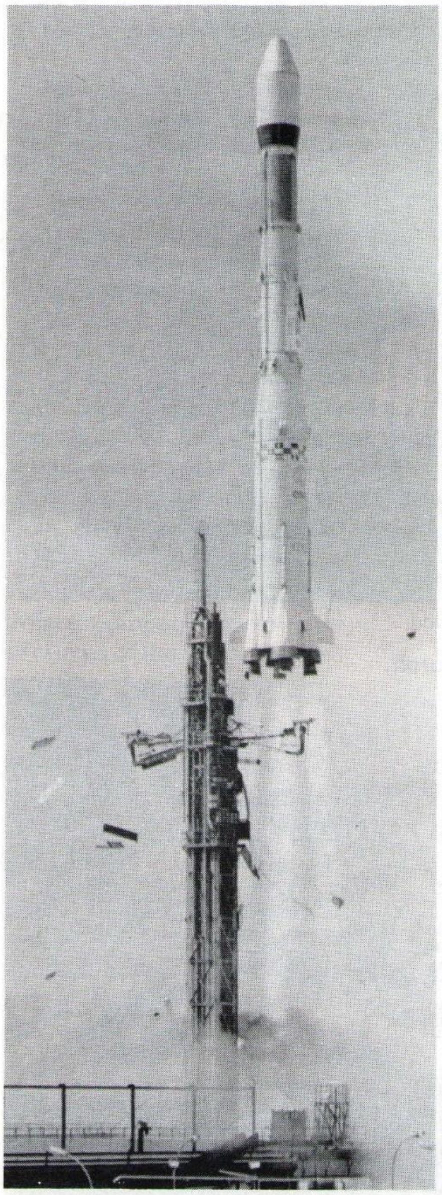


Fig. 7. The hazardous environment of space.

An artist's impression of Space Shuttle in orbit.





Ariane is a three-stage European launcher designer for a wide variety of missions ranging from Earth-orbit missions to deep space exploration (Photo: ESA).

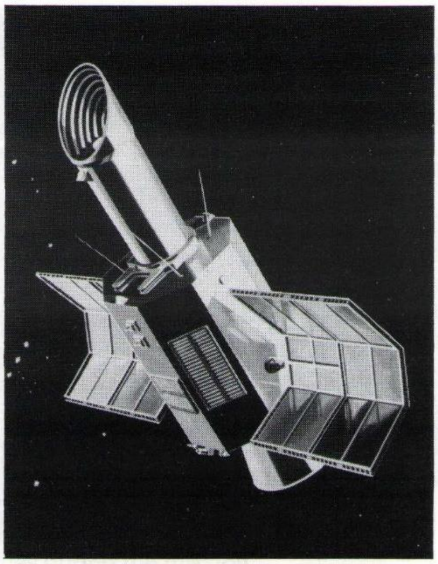
during the time their observations are being made, can check the spacecraft is looking at the correct position in the sky, observe the data being displayed as it is received from the spacecraft, and can arrange for adjustments to instruments, etc. — albeit that the telescope they are controlling may be thousands of kilometres away in Earth orbit, rather than a mere few metres.

Thus the scope of astronomical research from space calls on the skills of a host of research disciplines: for example, those of the engineers who design and build the spacecraft and instruments, extending engineering techniques to new bounds of precision and reliability; those of the designers and operators of ground-stations and highly sophisticated computers used to control the spacecraft and process the information they acquire; and those of the astronomers, physicists, and mathematicians who interpret the astronomical data in terms of known natural processes.

Space astronomy missions

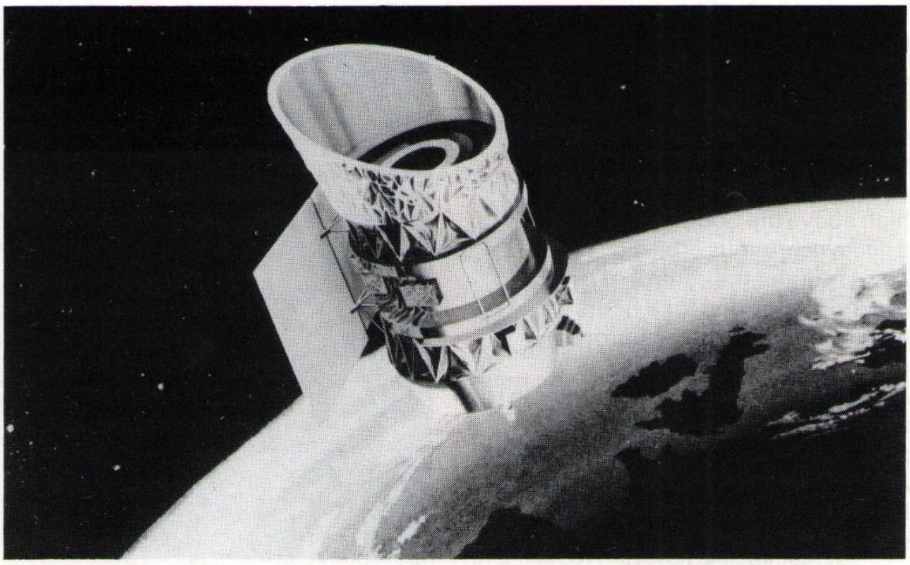
It is difficult to highlight just a few space missions from the large number of highly-successful projects. The following are presented merely as examples of the type of astronomy experiments undertaken in space.

The International Ultraviolet Explorer (IUE) satellite, launched in January 1978, is a collaborative project between NASA, the European Space Agency, and the UK SERC. IUE is operated like a ground-based observatory. The satellite is located high above the South Atlantic Ocean in a geosynchronous orbit. For 16 hours a day it is under the control of a NASA ground station and for 8 hours a day is under the control of the European ground station near Madrid. Astronomers visit the ground station to supervise their observations and process data transmitted to the ground at the end of an exposure.
IUE produces spectra of stars and stellar systems in the ultraviolet. The astrophysical gains have been impressive, and there are few areas of astronomical research which have not been influenced significantly by IUE. Ultraviolet spectra of stars have enabled the composition, temperature and density of their outer atmospheres to be studied. Observations of the debris from ancient supernovae have suggested how the matter surrounding the site of a supernova explosion is heated, and contributed to studies of the composition of this interstellar medium. The steady flow of gas from certain hot stars is revealed, as are haloes of hot gas surrounding certain galaxies. Indeed, our own Galaxy is found to be imbedded in a halo of hot gas.



The International Ultra-Violet Explorer (IUE) is an astronomical observatory carrying a 45 cm telescope and operating in the ultra-violet region.

The Infra-Red Astronomical Satellite (IRAS) was a collaborative project involving NASA, The Netherlands, and the UK SERC. The prime objective of the project was to carry out the first complete survey of the infrared sky. In addition, some time was made available for astronomers to carry out detailed investigations of particular infrared objects of special scientific interest. On IRAS a cryostat contained a cooled telescope, with an array of infrared detectors mounted in its focal plane. The spacecraft was launched in January 1983, and operated for 300 days, before the liquid helium cooling the system was entirely depleted. Astronomical sources of infrared radiation are generally cool objects



An artist's impression of the Infra-Red Astronomical Satellite (IRAS), carrying out its main task collecting data to make a catalogue of infra-red sources in space.

with temperatures less than a few hundred degrees, and range from planets and cool stars to galaxies. But valuable information can also be obtained in the infrared of much hotter sources where the radiated energy is degraded by obscuring dust clouds. Some of the highlights from IRAS included:-

(i) The discovery of over 200,000 cosmic infrared objects.

(ii) The discovery of five new comets, including the closest to approach the Earth for 200 years.

(iii) The discovery of an asteroid which will pass closer to the Sun than any other known asteroid, and is the progenitor of the Geminid meteor shower.

(iv) The discovery of two rings of dust on either side of the asteroid belt; almost certainly the result of major asteroid-asteroid collisions within the past million years.

(v) The discovery of a remarkable dust shell, possibly a protoplanetary system, around the bright nearby star Vega.

(vi) The discovery of "infrared cirrus"; emission from dust spread through interstellar space with a wispy distribution.

(vii) The discovery of "starburst" galaxies emitting 50 times as much far infrared radiation as visible radiation.

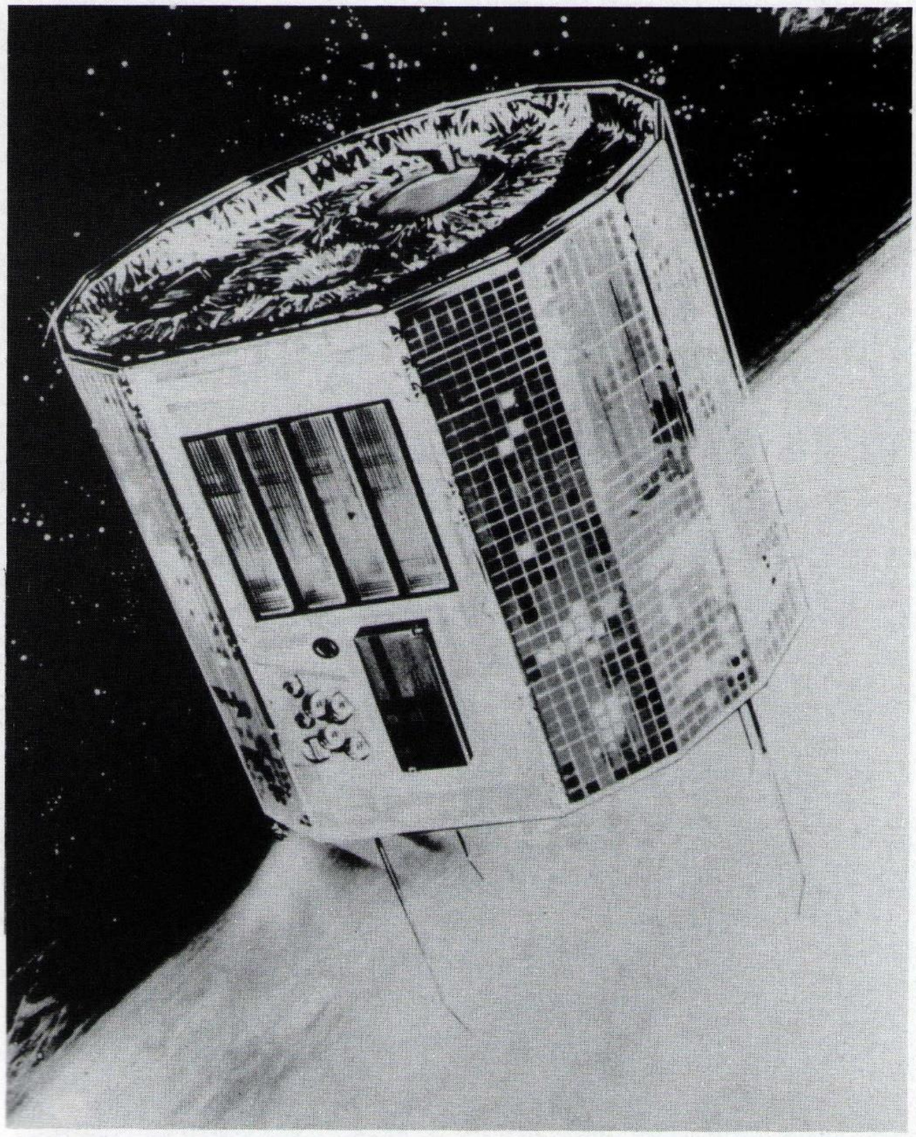
The Infra-Red Astronomical Satellite (IRAS) Control Centre at RAL Chilton. The antenna (inset) received scientific and engineering data transmitted from the satellite and sent control messages during the mission.

The first survey of the X-ray sky was completed by a NASA satellite called UHURU, launched in December 1970. X-rays have now been detected from a host of celestial objects, both within our Galaxy (such as neutron stars, the debris from stellar explosions, and X-ray binary stars) and beyond (haloes around normal galaxies, clusters of galaxies, active galaxies, etc.). X-ray astronomy has revealed a range of cosmic phenomena that had not previously been considered possible. In October 1974 the Ariel V satellite, a UK SERC project, was launched dedicated to X-ray astronomy. The scientific returns from Ariel V during its five years in orbit exceeded even the most optimistic predictions — it was a mission highlighted by the number of unexpected discoveries. For example, a distinct new class of transient X-ray source, which flared brilliantly, was discovered. A particular new X-ray source identified by Ariel V (SS433) has proven to be one of the most unusual astronomical objects ever studied — a star system spraying out material at a quarter the speed of light in two finely collimated "jets". Many Ariel V sources were identified with active galaxies — enigmatic objects called Seyfert galaxies, and quasars. Some of these also displayed jet phenomena, on a vast scale. The X-rays were found to be concentrated to the centres of these systems, requiring central sources of energy hitherto uncontemplated. It is speculated that such energetic galaxies might be powered by massive black holes at their cores, consuming stars and interstellar material.

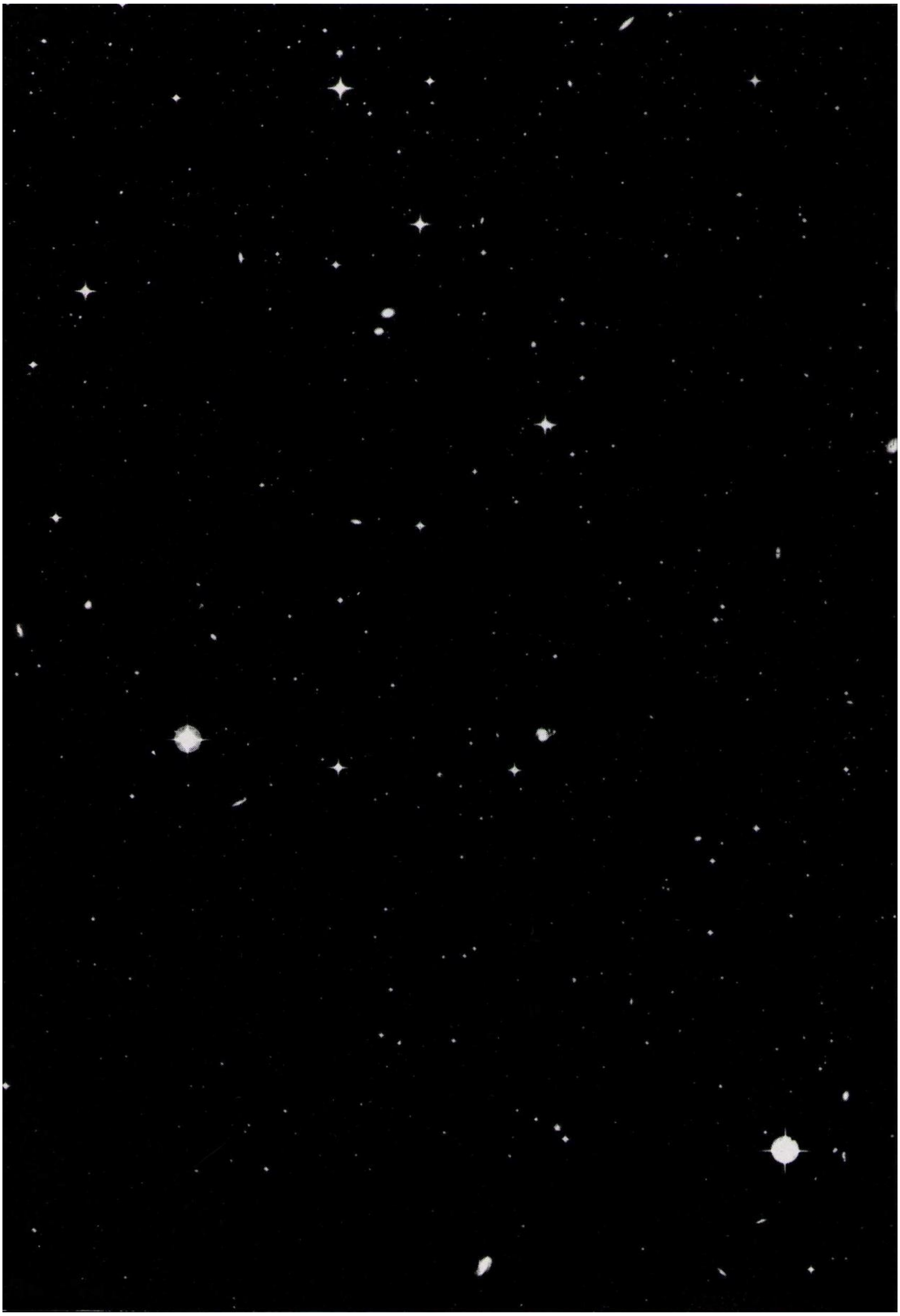
Such have been the spectacular discoveries of the cosmos from space. Space astronomy is still in its infancy— yet the advances in our understanding of the cosmos in the time since the first tentative steps into space, have been unmatched by any other period of scientific endeavour. The next decade will see the launch of NASA's Space Telescope, new X-ray, ultraviolet and infrared observatories, Space Stations which will house many astronomical experiments, radio telescopes in space, and presumably other sophisticated space machines not yet dreamed of.

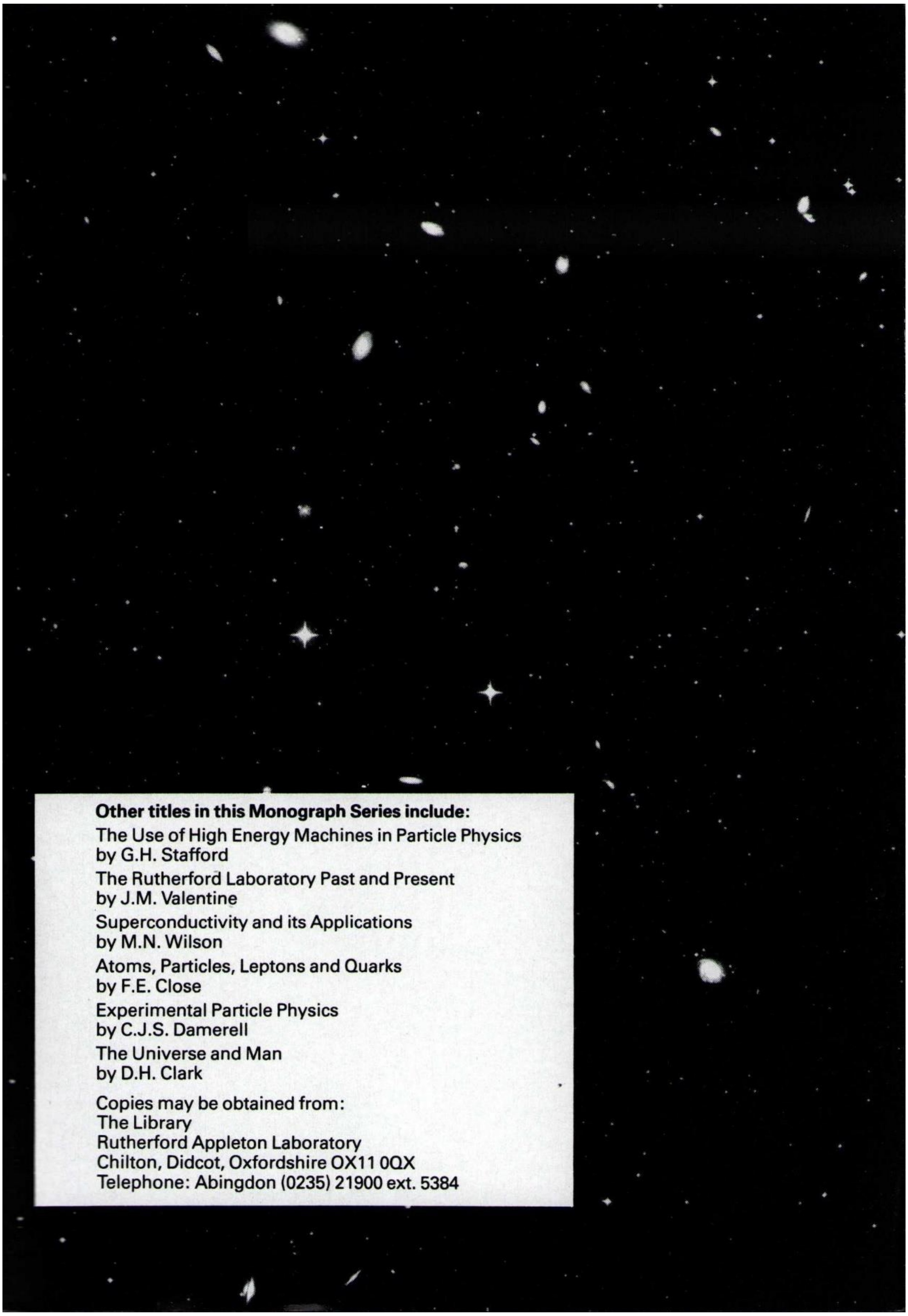
Pre-19th century civilisations left as part of their heritage great cathedrals and newly discovered continents; 20th century humankind will leave as their heritage, giant space stations ("cathedrals in the sky") and newly discovered "cosmic continents". The "New Universe" could never have been revealed without the advent of space astronomy.

Footnote: The ROE photographs are courtesy of the Schmidt Telescope Unit.



The Ariel V satellite in orbit — many important scientific discoveries in the field of X-ray astronomy resulted from its five years of active life.





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