Gateways to the galaxy: New findings in cosmic rays from Spacelab-3 experiment 'Anuradha'

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The Anuradha cosmic-ray experiment, flown on board Space Shuttle Spacelab-3, remains one of the most successful Indian space science experiments conducted so far. This experiment provided the first direct and unambiguous results on the ionization states of the newly discovered anomalous cosmic rays that conclusively established the interstellar neutral atoms as their source. New and unexpected results on the properties and composition of low-energy cosmic ray heavy nuclei were also obtained. The scientific and technical activities that made this experiment a reality—from the planning stage to its operation during the Spacelab-3 mission, and the details of the post-flight data analysis and synthesis that provided the new results are described. Some new possibilities have emerged for future space experiments in this area.

Cosmic rays: A sample of galactic matter

LIKE many branches of science cosmic rays had a humble beginning. In the early part of this century, soon after the discovery of radioactivity, scientists were puzzled to note the leakage of electric charge from well-insulated bodies. To explore this problem, the German scientist H. Hess had flown well-insulated electroscopes in balloons in 1912, in one of which he himself was a passenger, and discovered that a penetrating radiation is impinging on the earth from extra-terrestrial sources. It was named cosmic rays by the American scientist R. A. Millikan, as the Sun could be ruled out as a source of this radiation. The energies of cosmic-ray particles are really astounding—it covers the vast span of about 10^6 eV to as high as 10^{20} eV. With instruments flown in high-altitude balloons it was discovered that cosmic-ray particles are composed of atomic nuclei of various elements such as hydrogen, helium, carbon, nitrogen, oxygen, etc. up to iron. In fact elements up to uranium are also present in cosmic rays with small intensities. The cosmic rays thus provide us with an unique sample of matter from interstellar space and opened to us a new window to the universe—to explore high-energy processes in the galaxy and beyond. On anticipating the fascinating discoveries in the field of cosmic rays, the eminent scientists, J. J. Thomson and J. P. Thomson remarked in 1928: 'It would be one of the romances of science if these obscure and prosaic minute leakages of electricity from well-insulated bodies would be the means by which the most fundamental problems in the evolution of the cosmos came to be investigated.' In the past decades many studies were made in spacecrafts to unravel the mysteries of the origin and acceleration of cosmic rays to high energies. In spite of spectacular progress, many of these problems still remain obscure and elusive. At present supernovae, their remnants, and pulsars are considered as likely sources of galactic cosmic rays; some of the radio-galaxies, quasars and active galactic nuclei could be possible sources of extragalactic cosmic rays. These studies have captured the fascination of numerous scientists in the world as high energy cosmic gateways to the galaxy and to the universe[1].

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The discovery of anomalous cosmic rays

In the early 1970s, a new component of cosmic rays was discovered by analysing the data recorded in cosmic-ray detectors in Pioneer 10 and 11 spacecrafts that were on their way to Jupiter and in the interplanetary space probe IMP-8 orbiting the earth[2-4]. This component of low-energy cosmic rays of extra solar origin has some surprisingly new properties. In galactic cosmic rays, we normally have about 90% proton and ~ 9% of He, while C, N, O and heavier nuclei constitute ~ 1%. In contrast, in the new component of low-energy cosmic rays, protons were not detected, abundances of helium, oxygen, nitrogen and neon were enhanced, while other elements such as carbon, magnesium, silicon and iron had very low abundance or almost absent. As for example, in the new component the abundance ratio of O/C is ≥5 in contrast to O/C ~ 1 in galactic cosmic rays (GCR). Because of its unusual composition and energy spectra, this new component of low-energy cosmic rays was called the Anomalous Cosmic Rays or ACR in short.

The ACR oxygen ions are the most well studied for their intensity and spectral characteristics in the energy range 4–50 MeV/n. The intensity of ACR oxygen and nitrogen ions decreases from ~5 to ~50 MeV/n, where it merges with galactic cosmic rays (see Figure 1). The ACR helium ions have intensities higher than the GCR component in the 10–100 MeV/n energy range. Another striking feature of the ACR that was revealed, as the two spacecrafts, Pioneer 10 and 11, travelled further away from the Sun, was that the intensity of the ACR oxygen ions increased continuously and near the orbit of Jupiter it was ~40 times higher than that near the earth. These data established that the Sun cannot be the source of the anomalous cosmic rays and they must originate from sources or processes located beyond the orbit of Jupiter. So what could be the origin of this new type of cosmic rays? Several new ideas were proposed in the seventies to explain the presence of the ACR component. Before discussing these, we shall have a quick look at the results obtained from another experiment conducted in 1973–74 using the Skylab spacecraft.

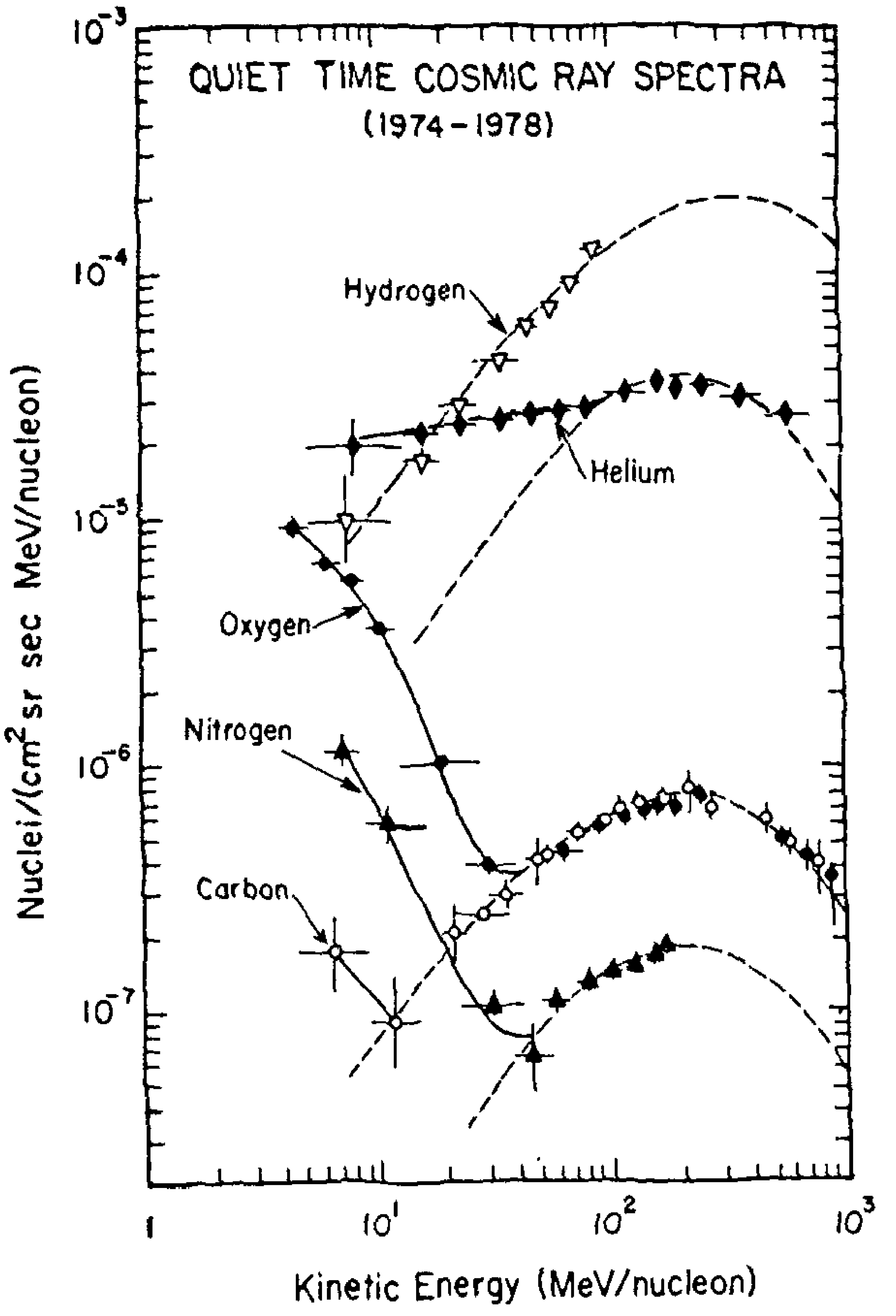

Figure 1. Energy spectra of H, He, C, N and O during solar quiet time of 1974–78. The solid lines indicate the ACR component, the dashed lines represent GCR component.

In the Skylab mission of NASA, a stack of passive *solid state nuclear track detector (Lexan polycarbonate)* was exposed on the outside of the Spacecraft for 74 days, between November 1973 and February 1974, a period that was entirely free from solar particle activity. Scientists from the Tata Institute of Fundamental Research (TIFR), Bombay, and the Physical Research Laboratory (PRL), Ahmedabad, have jointly analysed the data recorded in the detector stack and observed some strikingly new aspects of low-energy particles present within the earth's magnetosphere[5,6]. Firstly, ACR, O, N and C were observed for the first time inside the magnetosphere, with the same composition as in the interplanetary space. Secondly, it was concluded that these ACR particles must be in partially or singly ionized state; otherwise they will not be allowed by the earth's magnetic field to reach the Skylab orbit. Thirdly, the measured intensity of ACR oxygen was ~25 times higher than that expected on the basis of the measured interplanetary flux, from which it was concluded that ACR oxygen ions are trapped in the earth's magnetic field[6,7]. These findings made in 1975–80 have now been confirmed with instruments flown in different spacecrafts.

Where do anomalous cosmic rays come from?: Theoretical ideas

As the new data on the properties of the anomalous component of cosmic rays started accumulating, cosmic-ray theorists proposed a host of ideas to explain its origin. These ideas can be divided into two classes. The first category considers local galactic or solar system sources as responsible for generating the ACR component and predicts multiple charge states of ACR particles. McDonald *et al.*[2,8] suggested that the ACR particles originate in some unusual sources located in nearby interstellar space. Hoyle and Clayton[9] suggested that stars reaching white dwarf stage in stellar evolution may be responsible for the origin of ACR. Durgaprasad[10] proposed novae as possible sources, while Biswas *et al.*[11] suggested O-type stars emitting strong stellar wind as the ACR sources. A rather unusual model was proposed by Fowler *et al.*[12], who suggested that materials and gases brought in by comets are accelerated within the solar system to produce the ACR particles. All these theories would predict multiple charge states for the ACR particles, e.g. O^{1+}, O^{2+}, ... O^{8+}, etc. for ACR oxygen.

The other category of model, that considers local interstellar neutral atoms as the source of ACR, was proposed by Fisk *et al.*[13]. How do these neutral atoms evolve to become energetic anomalous cosmic-ray particles? A somewhat involved mechanism was proposed by the authors which constitute of four stages (Figure 2). In the first stage, interstellar neutral atoms enter the solar system as the Sun and the heliosphere (i.e. the volume in which solar plasma and magnetic field are confined) moves at a speed of 20 km/sec through the interstellar medium (ISM). The ionized particles in the ISM, on the other hand, are deflected at the heliospheric boundary by the solar magnetic field. This process therefore leads to the enhancement of those elements that exist predominantly in the neutral state of the ISM, i.e. helium, oxygen, nitrogen, and neon, and depletion of the elements that are mostly in ionized states, e.g. H, C, etc. In the second stage, when the interstellar neutral atoms approach the inner solar system, they are stripped off of their outermost electron by the strong solar UV radiation and they become *singly ionized* (i.e. He^{1+}, O^{1+}, N^{1+}, Ne^{1+}). This happens at different distances from the Sun, depending on the ionization potential of the element[14]. Once ionized, these particles are linked up with solar wind plasma and move outward with the speed of the solar wind, till they reach the boundary region of the heliosphere. The particles at this stage have an average energy typical of solar wind particles, i.e. 1 keV/n. In the third stage, these particles travel back and forth around the heliospheric shock front, which is the seat of random motion or turbulent magnetic field, and are accelerated from 1 keV/n to several hundred MeV/n. In the final stage, a fraction of the accelerated ACR ions diffuse back into the solar system where they suffer a decrease in their intensity and energy as they now move against the solar wind plasma in a situation similar to the case of transport of the more energetic galactic cosmic-ray particles. Thus we have singly ionized anomalous cosmic rays of ~ 1–100 MeV/n in the inner solar system. This model therefore predicts that ACR particles must be only in single ionized state, in contrast to the models of the first category which allows all ionization state of ACR. Thus, it was realized then that measurement of the ionization states of the anomalous cosmic-ray particles is crucial to pinpoint their source and origin. As this information was not available from experiments on board Pioneer 10/11 and IMP 8 spacecrafts there was a need for designing new experiments that could provide direct information on the ionization states of individual ACR particles. This brings us to the genesis of the Anuradha experiment.

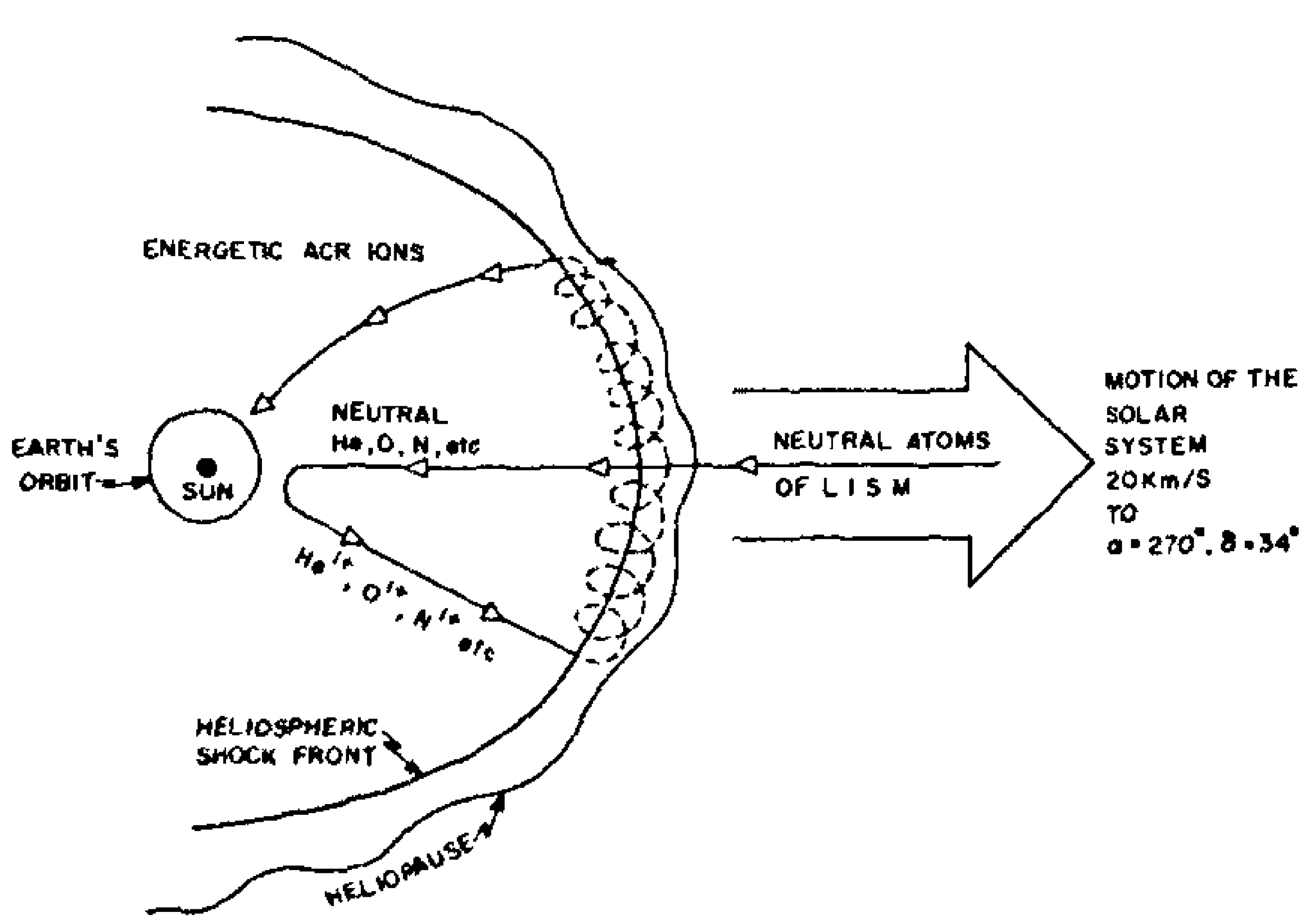

Figure 2. A schematic of the model proposed by Fisk *et al.*[13] to explain the origin of anomalous cosmic rays from interstellar neutral atoms

Spacelab era begins: The 'Anuradha' cosmic-ray experiment

In 1977, the National Aeronautics and Space Administration (NASA) of USA invited proposals for new generation of scientific investigations from some of the major space research centres to be conducted in the Spacelab-1 mission aboard the Space Shuttle. The TIFR and PRL group of scientists, who were involved in the earlier Skylab experiment, jointly responded to the invitation and submitted a proposal entitled 'Studies of ionization states of solar and low energy galactic cosmic ray heavy nuclei', through the Indian Space Research Organization (ISRO). This proposal was selected by NASA for the Spacelab-1 mission, and this experiment, afterwards called 'Anuradha', was one of the two experiments from Asia, among about thirty US and European science experiments selected for this mission.

Scientific objective and instrument characteristics

The scientific objective of the Anuradha experiment was primarily to determine the ionization states of the newly discovered low-energy anomalous cosmic rays and also of solar energetic particles in case of solar energetic particle events occurring during the mission duration. The novel feature of this experiment was to use the earth's magnetic field as a giant spectrometer which filters out cosmic-ray particles according to their rigidity, i.e. momentum divided by effective charge (pc/Z^*). The instrument was designed in a manner that the arrival direction and time (and hence arrival location) of each of the cosmic-ray particle detected in the experiment could be determined. This information coupled with a model for the geomagnetic field allow us to trace back the probable complex trajectories of the incoming particles in the earth's magnetosphere and we can obtain the minimum value of rigidity the particle must have to reach the Spacelab orbit at the point of its detection (see Figure 3). The other kinds of data obtained in the experiment are those recorded in the passive solid state nuclear track detectors which yielded the mass, nuclear charge, kinetic energy and momentum of each individual particles. Combining these results for each particle with its minimum permissible rigidity (R_{min}) obtained from the trajectory tracing calculation, the upper limit of ionic charge ($Z^* \leq pc/R_{min}$) of individual low energy anomalous and galactic cosmic-ray particles could be determined.

As the fluxes of the ACR particles are rather small, a large area detector of about 1200 cm^2 was used in this experiment. We used the newly discovered passive solid state nuclear track detectors with high sensitivity, called CR-39, and the detector films were assembled in the form of a circular stack composed of 150 sheets, each of thickness 250 μm and diameter about 40 cm.

A novel feature of the Anuradha experiment was its capability to determine the arrival time information of each cosmic-ray particles with an accuracy of ± 10 sec. This information and the record left by each particle in the detector, coupled with the information on the orientation and orbital parameters of the shuttle (which is available at all times) provide the arrival location (latitude, longitude and altitude) and direction of the particle as it entered the detector stack. To obtain the arrival time information, the detector module was divided into two stacks: a thin 'top' stack that was kept fixed and a thick rotatable 'bottom' stack that was coupled to a 15 bit absolute shaft encoder connected to a stepper-motor-gear assembly. The rotation of the bottom stack could be activated in steps of 40 sec of arc once in 10 sec so that it made a full rotation in 90 h. This part of the instrument was the most critical one, as very high mechanical precision in the fabrication and assembly is needed to achieve the high accuracy in the extremely small stepwise angular movement of a heavy load. The time information of an event in this detection arrangement can be obtained when an event is recorded both in the fixed 'top' and the rotating 'bottom' stacks of detectors. This is provided by the angular displacement between the two matched track segments produced by an individual event in the two detector stacks and the time history of stack rotation given by the shaft encoder output. Thus the information on the arrival time, location and direction of individual cosmic-ray particles is used for the trajectory computations and to obtain the value of R_{min} and finally its ionization states.

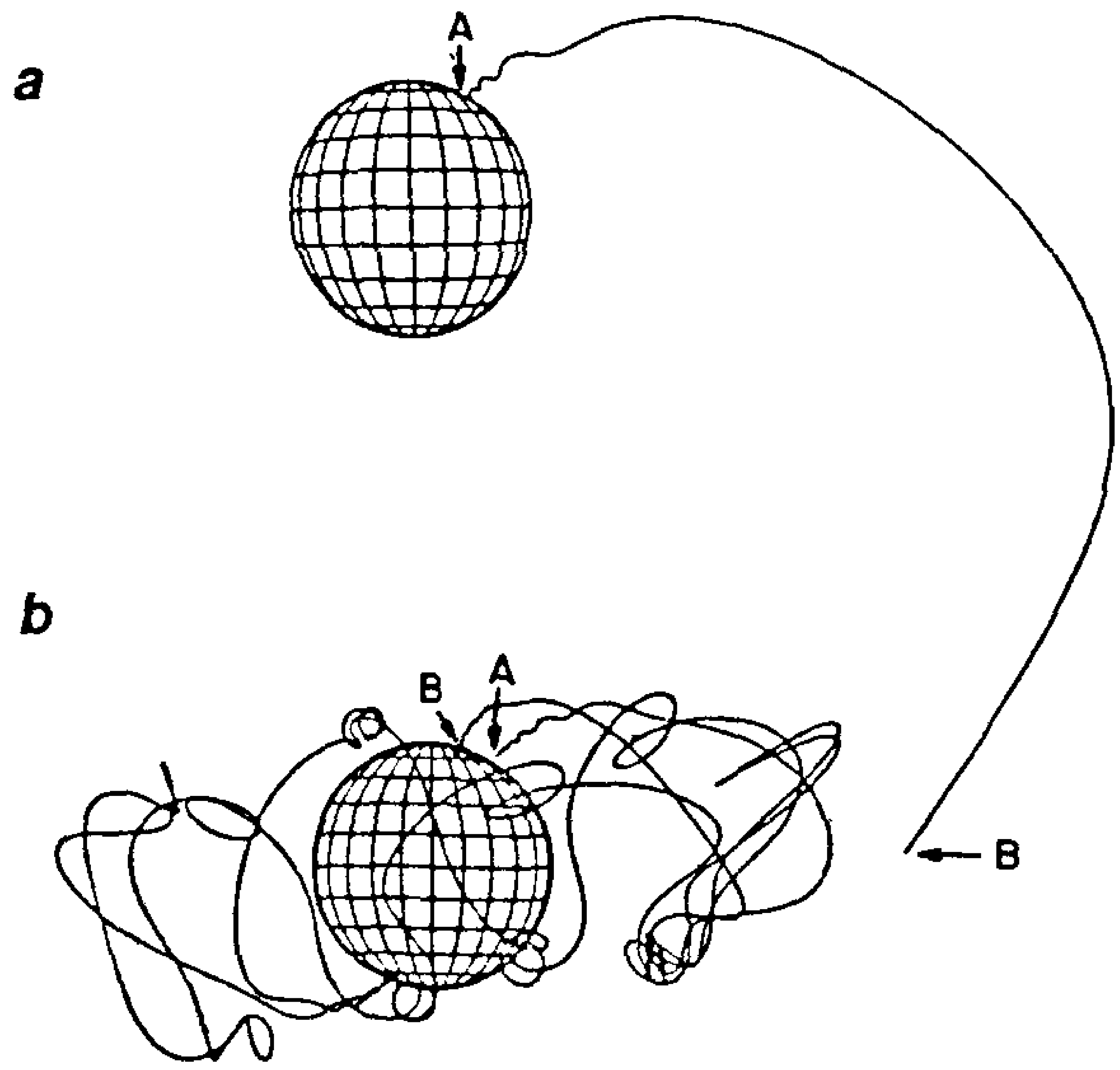

Figure 3. Complex trajectory of a cosmic-ray particle back-traced from its arrival point on Spacelab-3 orbit, for two values of rigidities: (*a*) shows an allowed trajectory that connects to the interplanetary space while (*b*) depicts the case when the assumed rigidity was too low for the particle to have an allowed trajectory.

One may ask the question why one needs the above complex procedures. The reason is that it is not possible to determine the ionization states of cosmic-ray particles by measurements confined in any detector system, active electronic or passive track detectors. This is so because when a cosmic-ray particle traverses a very small thickness of matter (~ a few μg/cm^2) in the upper most layer of a detector or its shielding, it is stripped off most of its orbital electrons and attain an equilibrium charge state and the information on the original ionization state is lost. Hence the momentum-filtering effect of the geomagnetic field is to be utilized, to obtain this information.

Anuradha takes shape

The detailed studies of experiment designs and requirements made in 1978–79 led NASA to work out a new schedule in 1980 for the Spacelab missions. It was arranged that Anuradha and another US experiment would be accommodated in Spacelab-3 mission in 1984–85, instead of in Spacelab-1. This rescheduling was most welcome as the orientation of Spacelab-3 was such that it provided continuous viewing of the deep space which was not the case of Spacelab-1.

A memorandum of understanding was signed by ISRO on behalf of the Govt of India and NASA in June 1980, according to which the Indian side had the responsibilities of the design, fabrication, assembling and testing of the instrument to meet the NASA specifications. NASA undertook its integration, flight operations, ground operations and related matters. The instrument and the data were to be returned to the Indian team for post-flight analysis.

The years 1980–82 were periods of intense activities on the design, procurement of materials and components, fabrication of mechanical, electrical and electronic systems and their integration, followed by various testings according to the NASA specifications. These were successfully accomplished by the engineering and scientific team members of TIFR–PRL–ISRO supported by BARC and several other centres. Six subgroups carried out specific works related to different subsystems. For example, the Detector Module Group of TIFR and the Laser Group of BARC had set up a special arrangement of CO_2 laser and He–Ne laser to cut ~ 500 CR-39 detector sheets—which are glass-like and brittle—into annular shapes of required dimensions. About 150 sheets of these were assembled in stainless steel housing and three such units were constructed.

The top enclosure—a curved sheet of Al alloy of thickness ~ 100 μm—was a critical element of the instrument as it must be thin enough to allow low energy (~ 8 MeV/n oxygen nuclei) to enter the detector and at the same time thick enough to provide an air-tight enclosure. Two pairs of venting valves maintained the inside pressure of the instrument at 0.1 atm during the flight and at 1 atm at all other times. The electrical and electronic systems and necessary softwares were fabricated and tested by the PRL group. This subsystem provided the required pulses to the high resolution stepper motor, which rotated the bottom stack by an increment of 40 sec of arc once in 10 sec (or by any other predetermined rate) and has the capability to correct for any overshoot or undershoot in the step movements. The rotational motion was read out by the 15 bit absolute encoder which was displayed and was monitored along with house keeping data such as the inside temperature of the instrument. Details of the instrument design and operation are given elsewhere[15] and a summary of the main characteristics is given in Table 1. A sectional view of the Anuradha instrument is shown in Figure 4.

Various tests of the instrument were carried out according to the NASA requirements at different Indian centres. The random and sinusoidal vibration tests, the thermovacuum and electromagnetic tests were carried out at the ISRO Satellite Centre, Bangalore. The acceleration tests were performed at the ISRO Shriharikota Centre and acoustic tests were done at IIT, Madras.

Four units of the Anuradha instrument were constructed—the engineering model for design testing, prototype model for all tests qualifications, the flight instrument for actual flight and the flight standby for contingency. After NASA's acceptance of test records, the flight instrument and the flight standby—installed

Table 1. Summary of Anuradha instrument features and flight characteristics

Weight	: 50 kg
Volume	: 48 cm diameter; 56 cm height
Detector	: Composite CR-39 detector modules coupled to a high resolution stepper motor and a 15-bit absolute optical shaft encoder for arrival time and direction measurements of cosmic ray ions
Spacelab flight	: Space shuttle Challenger launch – 29 April 1985, 1602 h GMT, and landing 6 May 1985, 1611 h GMT
Orbit	: Altitude : 352 km Inclination : 57° to the equator Attitude : Gravity gradient stabilization
Ions exposure	: Instrument activation, 123-12-44 GMT and deactivation, 126-05-00 GMT
Power allocation	: 10 W average for 90 h
Thermal control	: Cold plate in pallet and a multilayer insulation
Command and data management	: 5 discrete on-off command channels 16 discrete data acquisition channels 1 analogue data channel
Experiment control	: By stored program in on-board computer of SL-3 through I/O unit and interfacing with remote acquisition unit (RAU)
Data acquisition	: CDMS telemetry of 372 bits every 1 s via TDRS and other satellites to ground station for stack movement and other house keeping data. Other data are recorded in track detectors and are processed post-flight.

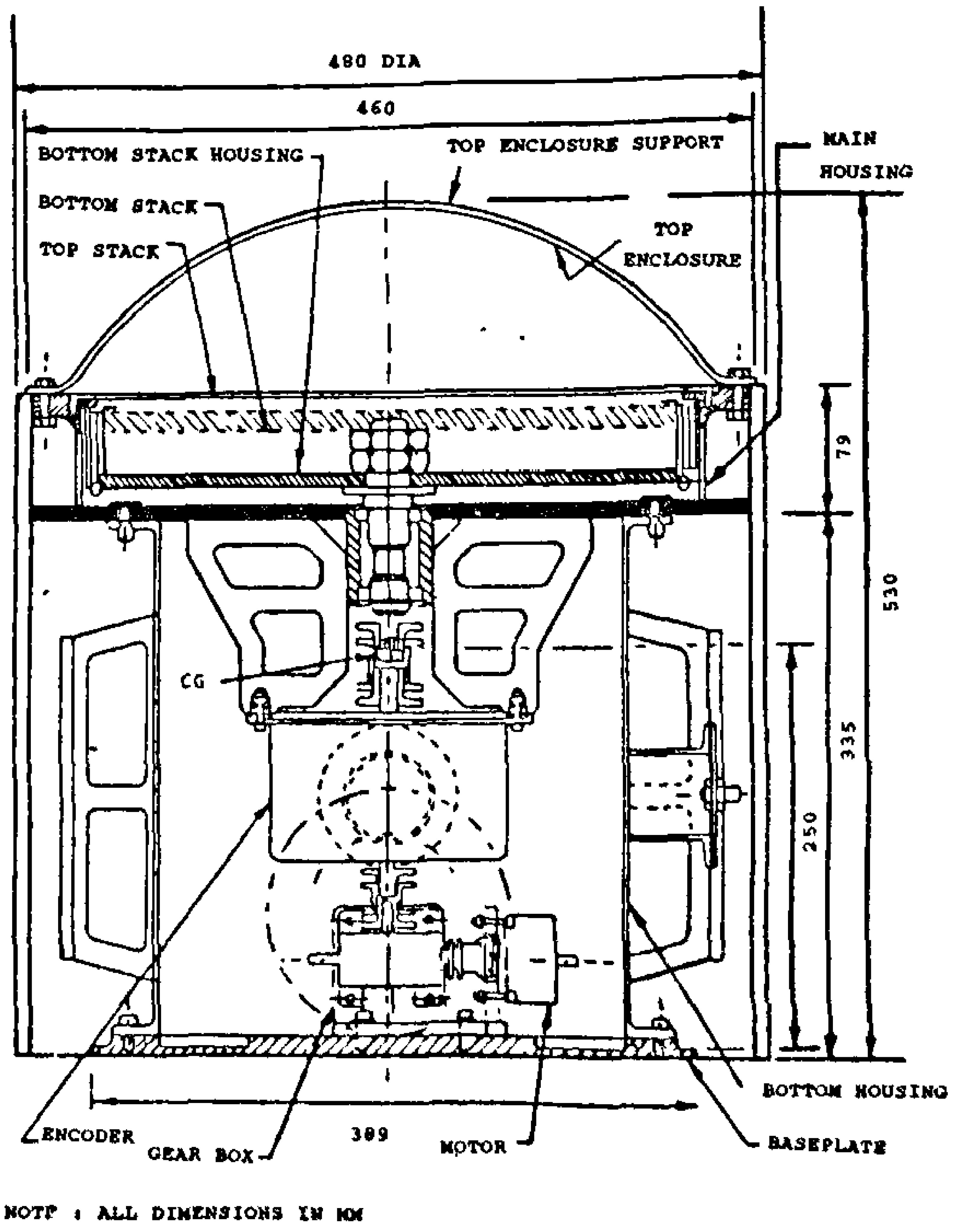

Figure 4. A sectional view of the 'Anuradha' cosmic-ray instrument

specially designed containers and other accessories—were airlifted from India to NASA Kennedy Space Center, Florida, USA in December 1983. During 1984, NASA and Indian engineers installed Anuradha in the Spacelab-3 on the instrument-support structure and integrated it with Spacelab-3 electrical, electronic software and thermal control systems. In addition to passive thermal control with multilayer insulation, Anuradha was provided with active thermal control through a cold plate with circulating freon, on which the instrument was mounted. After the completion of various tests of the integrated payload, Spacelab-3 aboard Space Shuttle Challenger was ready for spaceflight in December 1984.

Space shuttle in orbit: Anuradha collects cosmic data

On mid-day of 29 April 1985, the space shuttle Challenger with Spacelab-3 on board was launched successfully into a circular orbit at a height of 350 km at an orbital inclination of 50° to the equator. The thirteen experiments flown in Spacelab-3 were in the areas of material science, life science, fluid mechanics, atmospheric science and astrophysics; countrywise, ten of these belonged to USA, two to France and one to India. A special feature of the SL-3 mission was the role of crew members, seven in number, five of whom were specially trained for the science experiments. A vax computer provided on-board support for control and operation of the experiments. These and other facilities in the mission enabled the scientists to undertake several new types of experiments for the first time. The Anuradha experiment could be activated and controlled either by SL-3 computer by a crew member or by ground commands from the control centre at Houston, Johnson Space Centre (JSC). Data were transmitted from Spacelab-3 by relay satellites to JSC Houston and Goodard Space Flight Center, Maryland.

When the Anuradha experiment was activated on the third day of the mission according to schedule it was found that some command channels were not responding while some others were operating. After studying the instrument response the Indian team informed the mission manager that the instrument characteristics are alright and the problem must be somewhere else, which should be identified and rectified. After a series of tests conducted by the NASA ground engineers and SL-3 crew, the problem was identified in the faulty NASA cable connecting SL-3 computer to the Anuradha experiment. As there was no spare cable, this problem was ingeniously solved by NASA engineers by replacing the faulty cable by a cable of another experiment, which just completed its operation. These and associated activities were carried out during a 24 h period and the instrument was switched on again on 3 May 1985. It was an exciting and dramatic moment for all present at the control centre to see that all channels of Anuradha were responding beautifully and the instrument operated perfectly for the next three days. It was switched off at the experiment closing time of the mission on 5 May 1985. A few photographs of the Anuradha and SL-3 mission are shown in Figure 5.

A schematic diagram of the experiment operation in orbit and of the flow of signals between Anuradha instrument in Spacelab-3 and the ground control centre is shown in Figure 6. The instrument operation takes place in the following manner. Once every 10 sec command signal generated by the experiment computer rotates the 'bottom' detector stack by one step of 40 arcsec and the encoder output is read out. The encoder reading, together with GMT, instrument temperature and other relevant information are transmitted from the SL-3 by high-rate multiplexer to payload operation and control centre once in 2 sec. The stepwise rotation is repeated once in every 10 sec, until a maximum of 32,736 rotational steps are made during about four-day period. In actual operation, Anuradha experiment had undergone rotational steps for about 64 h, i.e. for ~70% of the maximum value. The telemetered data of the instrument and of the Spacecraft position and orientation, were both recorded every 2 sec in the data tapes at the control centre and these tapes containing about 400 million data bits were provided to us by NASA for postflight analysis.

Postflight activities, data acquisition and synthesis

The postflight operations included the calibration of CR-39 stacks with three types of accelerator beams. Firstly, 50 MeV alpha particle beams from the Variable Energy Cyclotron (VEC), Calcutta were used to provide visible markings of the starting position of rotation on both the stacks. Secondly, 1 GeV/n ^{179}Au beams from the Bevalac, University of California at Berkeley, were used in vertically incident manner at six positions of the bottom stack to facilitate realignment of the CR-39 sheets after disassembly and processing. Thirdly, 140 MeV/n ^{56}Fe beams incident at 45° were used in six positions in the bottom stack to provide known events for charge calibration of the CR-39 detector.

Energetic cosmic ray nuclei incident on solid state track detectors such as CR-39 cause radiation damage along their path by breaking the chemical bonds of the constituent molecules. This leads to the formation of nascent damage trails of diameter ~100 Å which are preserved as latent tracks. When CR-39 detector sheets are treated with strong alkaline solution (e.g. 6.25 N NaOH at 70°C for 6 h) preferential etching takes place along the latent damage trails, which are revealed as conical etched tracks visible in an optical microscope.

Figure 5*a*. The Anuradha instrument

The length of the etched cones, which is a measure of the ionization loss rate, and the residual range can yield the nuclear charge and kinetic energy of the incident particle[16,17]. Etched cones of a cosmic ray Fe nucleus traversing several CR-39 sheets are shown in Figure 7. In Anuradha experiment we initially scanned an annular area of width 2 cm in the two uppermost CR-39 sheets using a specially constructed semi-automatic microscope whose stage could be rotated in angular steps of 40 arcsec and in radial direction, *R*. The selected tracks of cosmic-ray particles, located in *R*, θ coordinate system, were followed through successive plates in the stack till the end of their range. A detailed analysis of track parameters was made which yields the atomic number, kinetic energy and other particulars of the incident cosmic-ray particles. Thus cosmic-ray ions of nitrogen to nickel of 8 to 150 MeV/n were identified.

The procedure of determining the arrival time and direction of the particles involves more complex procedures as briefly described earlier. By matching track segments in the top (fixed) stack and in the bottom (rotating) stack using algorithm that uses four or more track parameters, angular displacement between the track segments is obtained. This information when combined

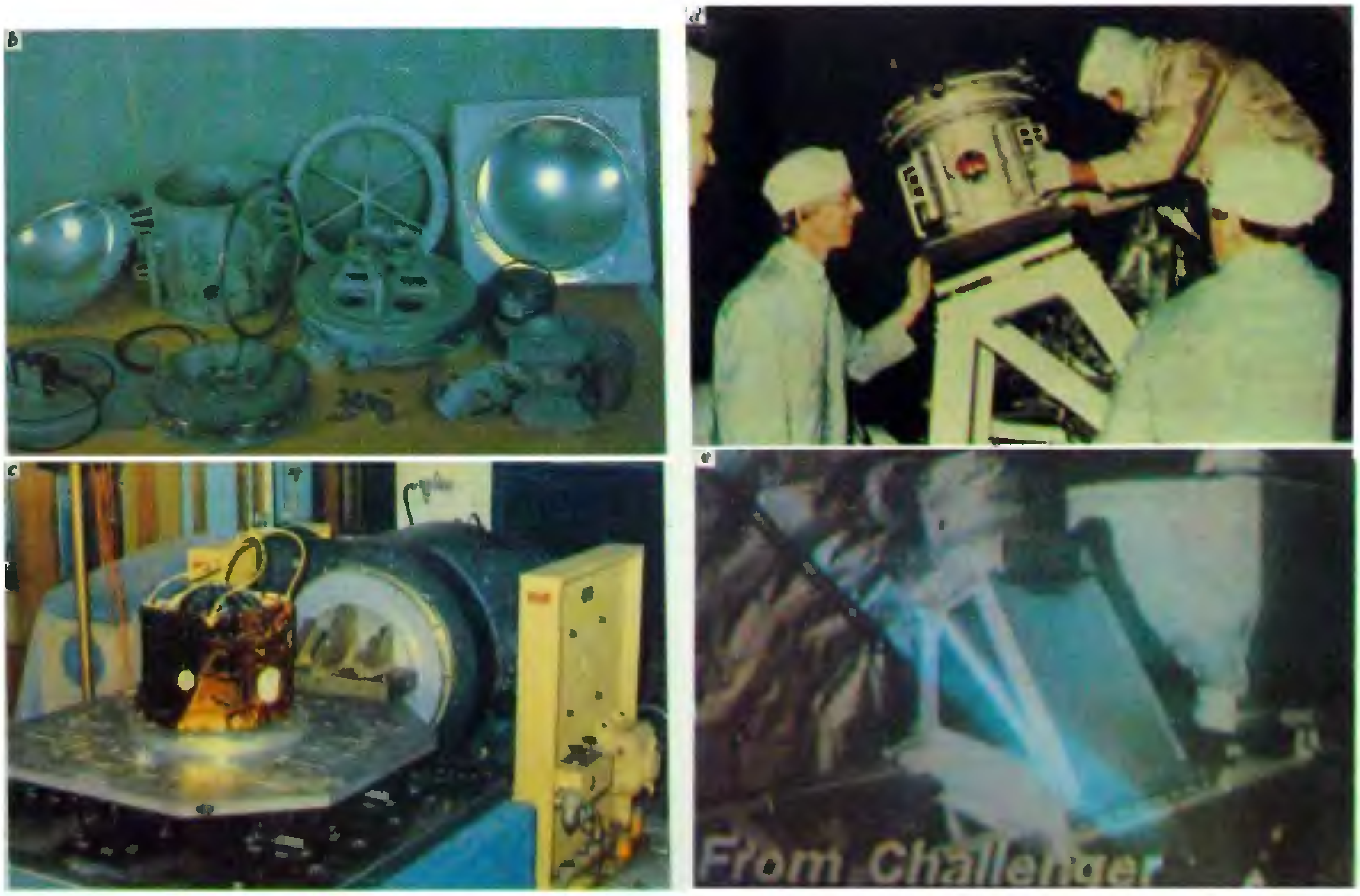

Figure 5*b–e*. *b*, The Anuradha instrument individual components; *c*, The Anuradha instrument on the vibration testing platform. *d*, The Integration of Anuradha to Spacelab-3 platform. *e*, Anuradha in space (on board space shuttle Challenger)

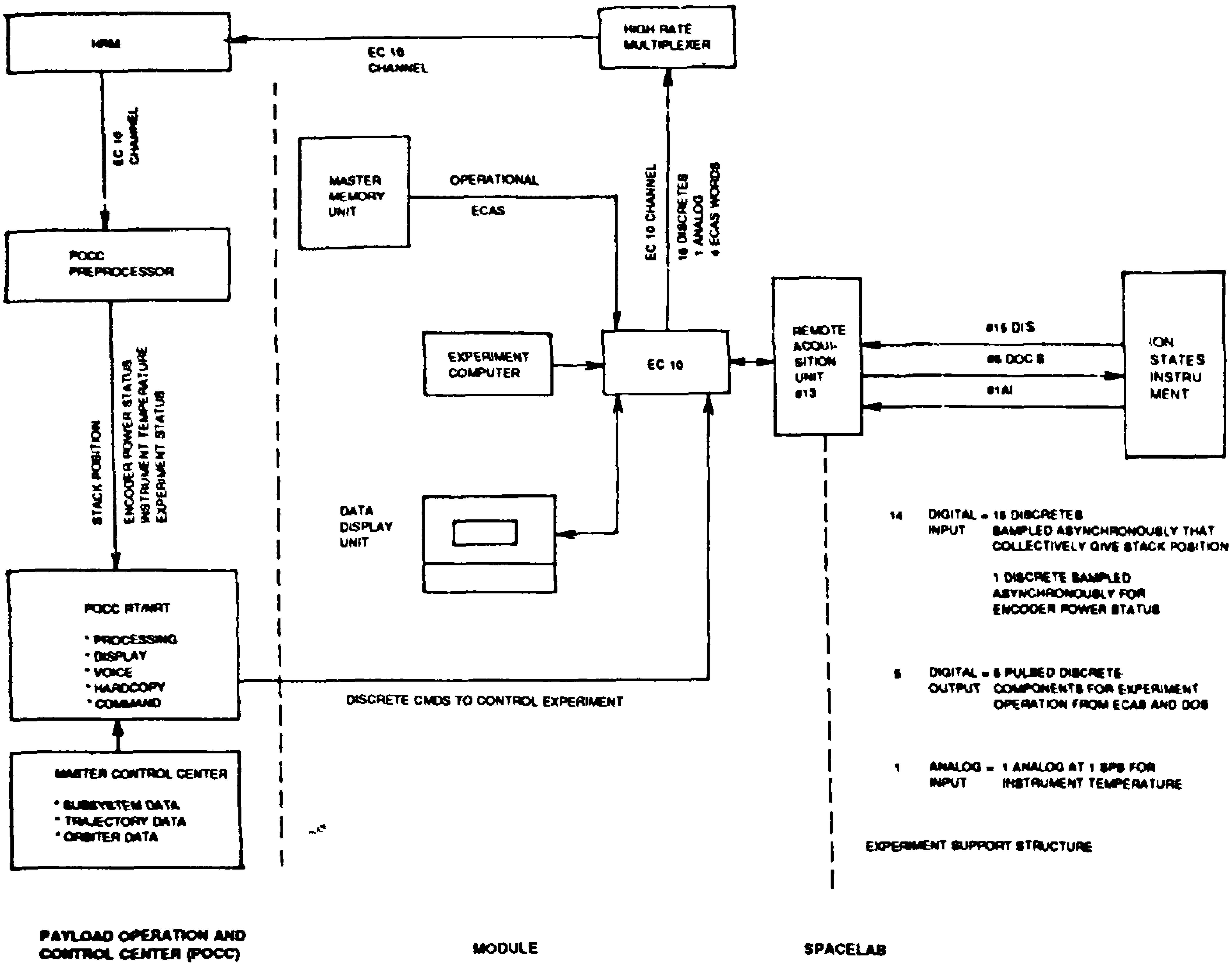

Figure 6. Block diagram showing the experiment operation and flow of signals between the SpaceTab module, the instrument and the ground control centre.

with the telemetered data on encoder position vs GMT and orbital parameters of SL-3 yielded the arrival time and direction of the cosmic-ray particle.

Complete details of these procedures are given by Singh[18] and Dutta[19]. A total of about 100 cosmic-ray particles of carbon to nickel in the energy range ~ 12 to 150 MeV/n were identified and all the relevant data obtained in each case. For the trajectory tracing calculations we have followed the approach of Shea and Smart[20] and used a polynomial expansion of 10th order and the parameters suggested by the International Geomagnetic Reference Field (IGRF) for the epoch 1985 for an accurate representation of the geomagnetic field. The effects of external current system etc. were also considered in the final analysis of the data.

Anuradha results: New findings in anomalous and galactic cosmic rays

The scientific results from the Anuradha experiment had several new features and we shall briefly discuss these and their implications.

Firstly, the Anuradha experiment established the detailed method of using the earth's magnetic field as a giant momentum analyser for the accurate determination of minimum rigidities of individual cosmic-ray particles utilizing the arrival time and direction information[21,22].

Secondly, the mean ionization state of a sample of ACR oxygen ions was determined as O^{+1} for the first time using the orbit averaged flux method[23,24]. In this method data for the interplanetary ACR flux obtained by spacecrafts are used to calculate the expected flux of ACR oxygen inside the magnetosphere for different assumed ionization states. These values were then compared with the measured orbit averaged fluxes in Anuradha to determine the charge state of ACR oxygen as 1^+ (Figure 8). Recent studies by a Russian–US group of scientists, who used this method and analysed data from COSMOS and IMP-8 satellites, have confirmed this result[25].

Thirdly, the ionization states of 75 individual low-energy GCR and ACR particles were successfully measured for the first time[21,26]. Sixteen of these events were identified as ACR particles of N, O and Ne, whose upper limit of ionization states show that they are singly ionized or consistent with it[21,26] (Figure 9). The distributions in geographic latitude and longitudes of these ACR particles were found to be uniform (Figure 10) as expected and so also their arrival times.

Fourthly, a new unexpected result was obtained while measuring the ionization states of low-energy heavy ions. It was found that galactic cosmic-ray ions of sub-iron (Sc to Cr) and iron (Fe–Ne) group of 30–150 MeV/n are composed of about 20% particles which are partially ionized, e.g. Ti^{6+}, Cr^{5+}, Fe^{10+}, etc.[22,26]. This is contrary to the normal assumption that all GCR particles are fully ionized.

Lastly, another significant observation is that the abundance ratio of sub-iron to iron group of particles in low-energy GCR (30-130 MeV/n) within the magnetosphere is about a factor of two higher than the interplanetary value[27]. This, we believe is due to the presence of partially ionized ions in GCR at these energies.

Implications of the new findings, gateways to the galaxy and future perspective

The results from the Anuradha experiment established that ACR particles originate from interstellar neutral atoms and these are in singly ionized state as proposed by Fisk *et al.*[13]. However, details of the acceleration mechanism are yet to be fully understood[28]. It is gratifying to note that recent satellite experiments of German–US collaboration[29] and Caltech–NASA groups[30] have adopted the basic method of the Anuradha experiment and have confirmed our results on the ionization states of ACR particles.

The ACR particles bring to us a new sample of interstellar matter undergoing ionization and acceleration. One can attempt to deconvolute the processes to estimate the abundances of neutral atoms in ISM as discussed elsewhere[28]. Also, one can determine the isotopic composition of neutral atoms in ISM from ACR particles, as these remain unaffected by the intervening processes. A recent satellite experiment has also identified the presence of a third radiation belt composed of trapped ACR particles in near earth space[30]. This confirmed our observations made in the Skylab experiment in 1973–74 (see review by Biswas[31]). Now we can have easy access to a large flux of interstellar particles in the near-earth space.

Energetic particles of galactic cosmic rays (GCR) have travelled a significant amount of matter (~ 10 g cm^{-2}) in interstellar medium before reaching us. Hence these are mostly bare nuclei, stripped of their orbital electrons. The known values of electron capture and

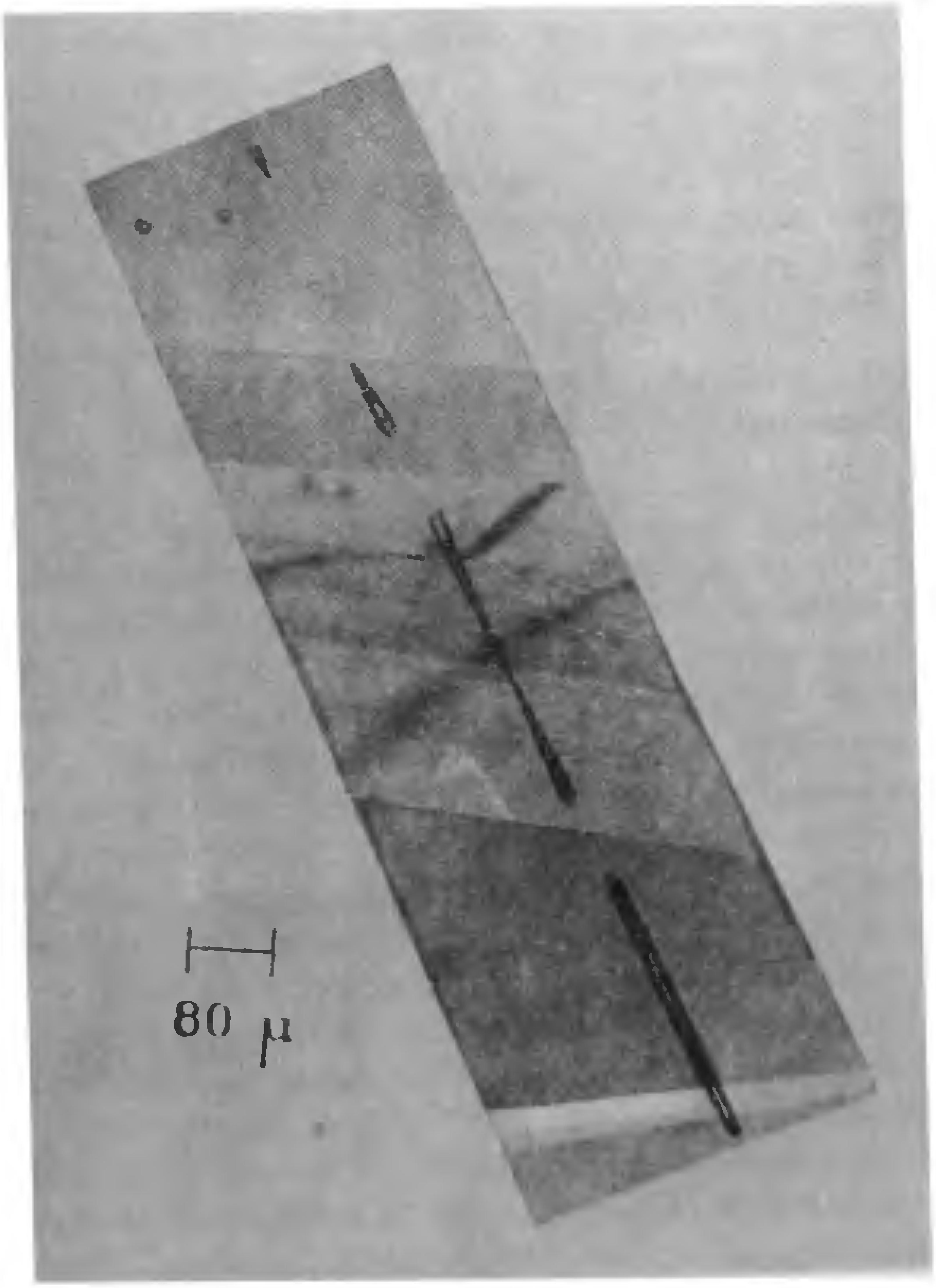

Figure 7. Nuclear track produced by a Fe ion in several sheet of CR-39 detector used in the Anuradha experiment.

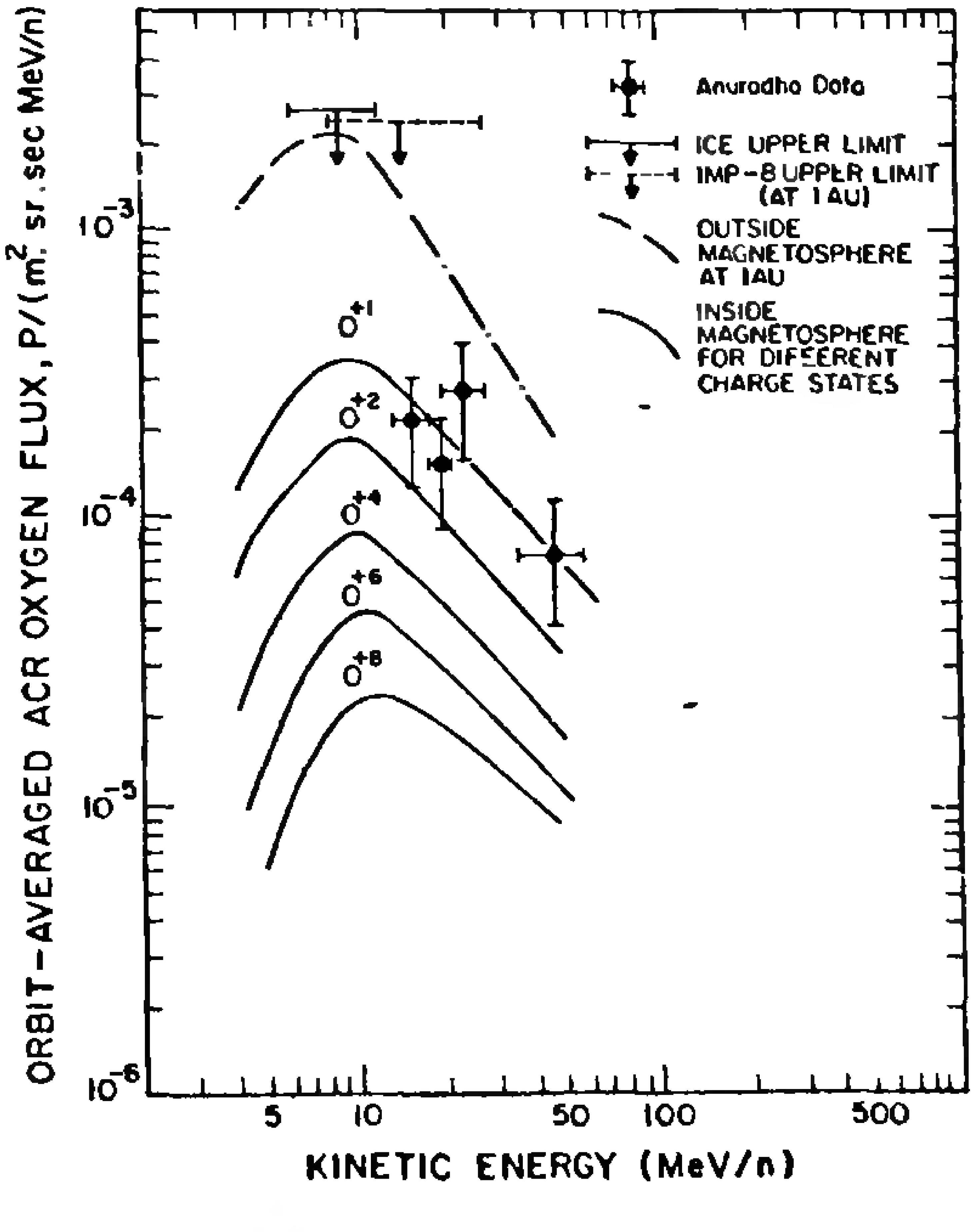

Figure 8. Measured fluxes of ACR oxygen in Anuradha experiment and the expected values, based on interplanetary fluxes from ICE, IMP and Voyager data for different charge states. The Anuradha data suggest ACR oxygen to be singly ionized

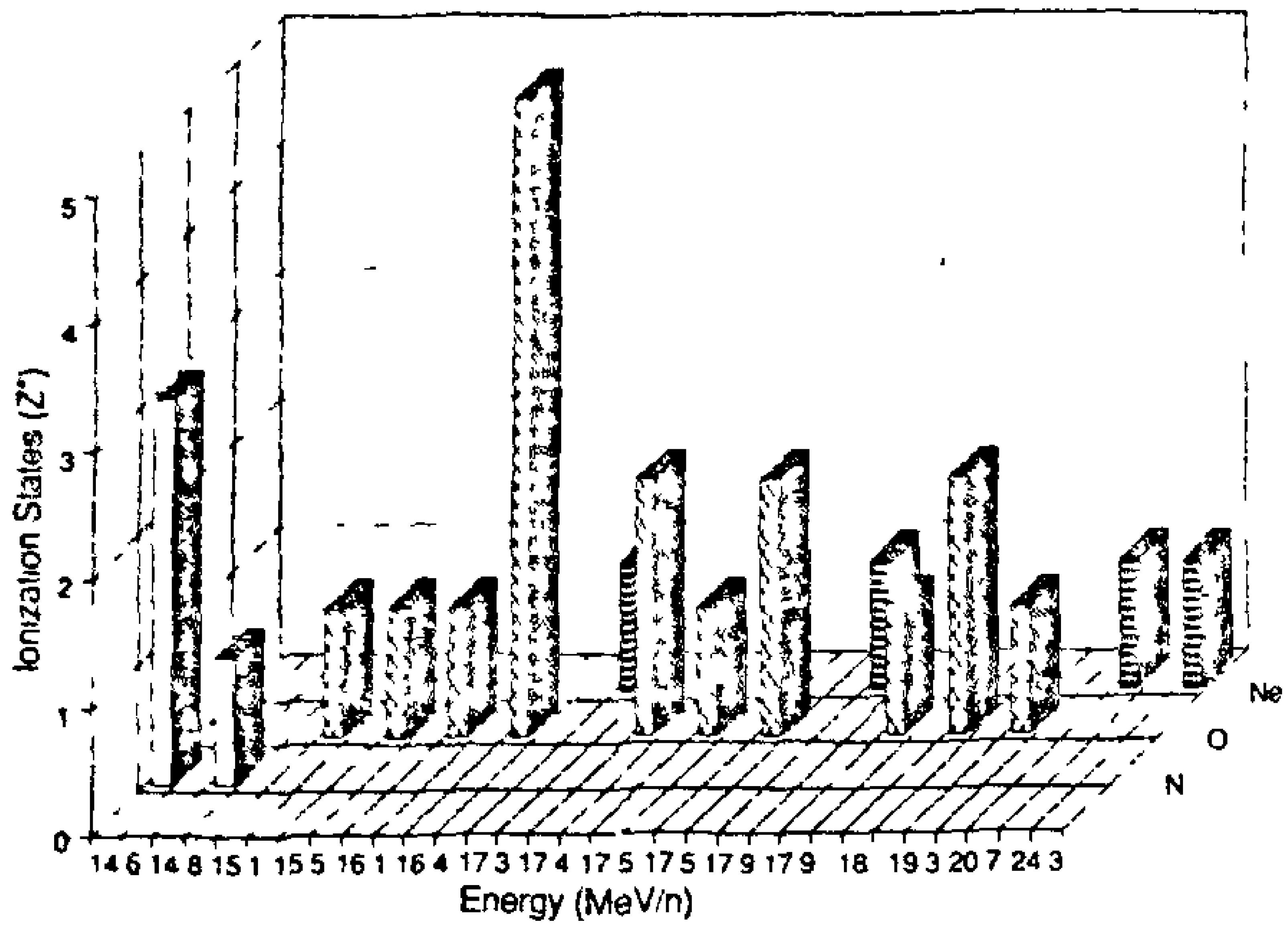

Figure 9. The measured upper limits of ionization states of ACR particles of N, O and Ne as a function of kinetic energy.

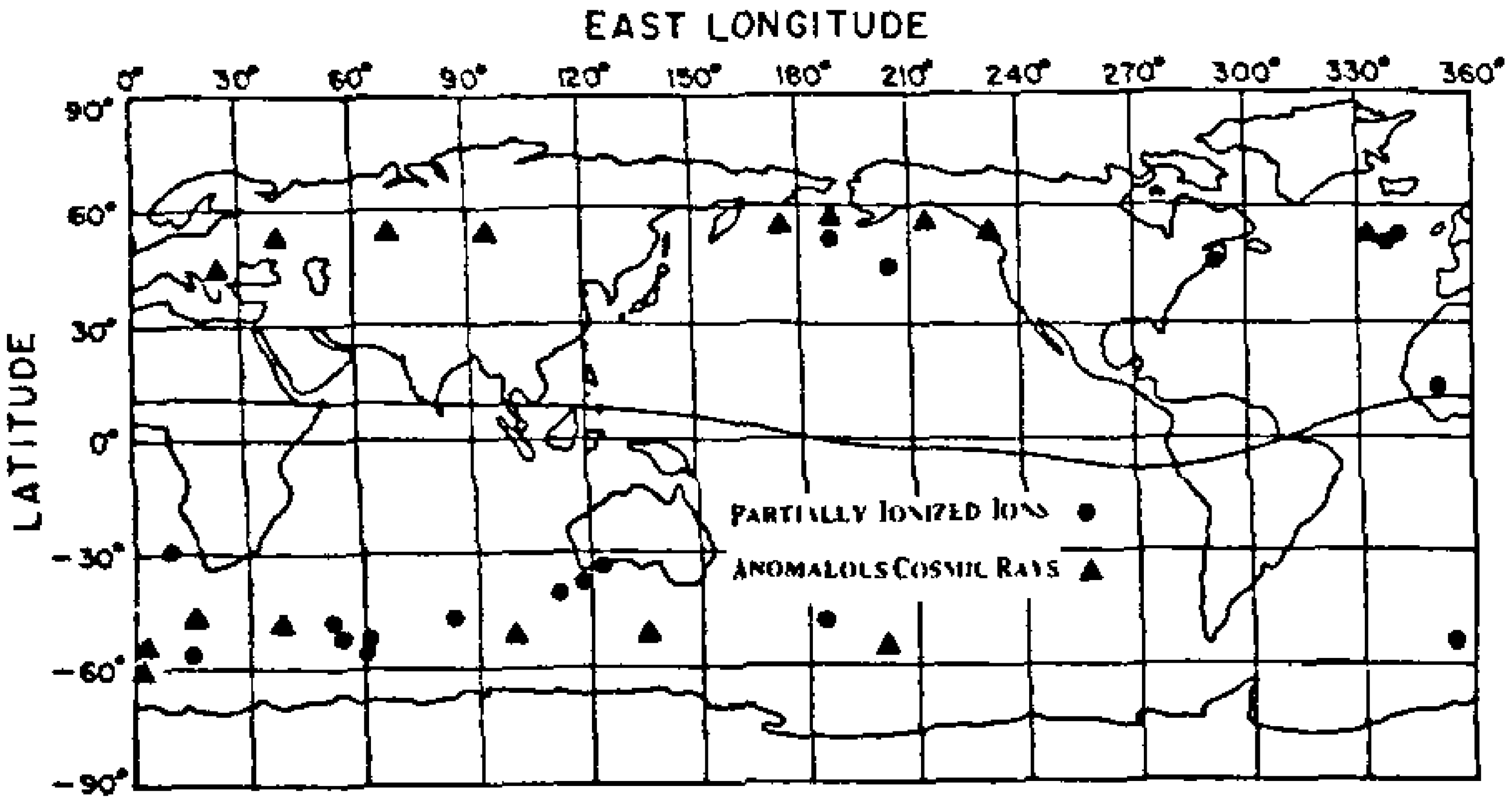

Figure 10. The geographical distributions in the latitudes and longitudes of the arrival locations of the ACR and partially ionized GCR particles.

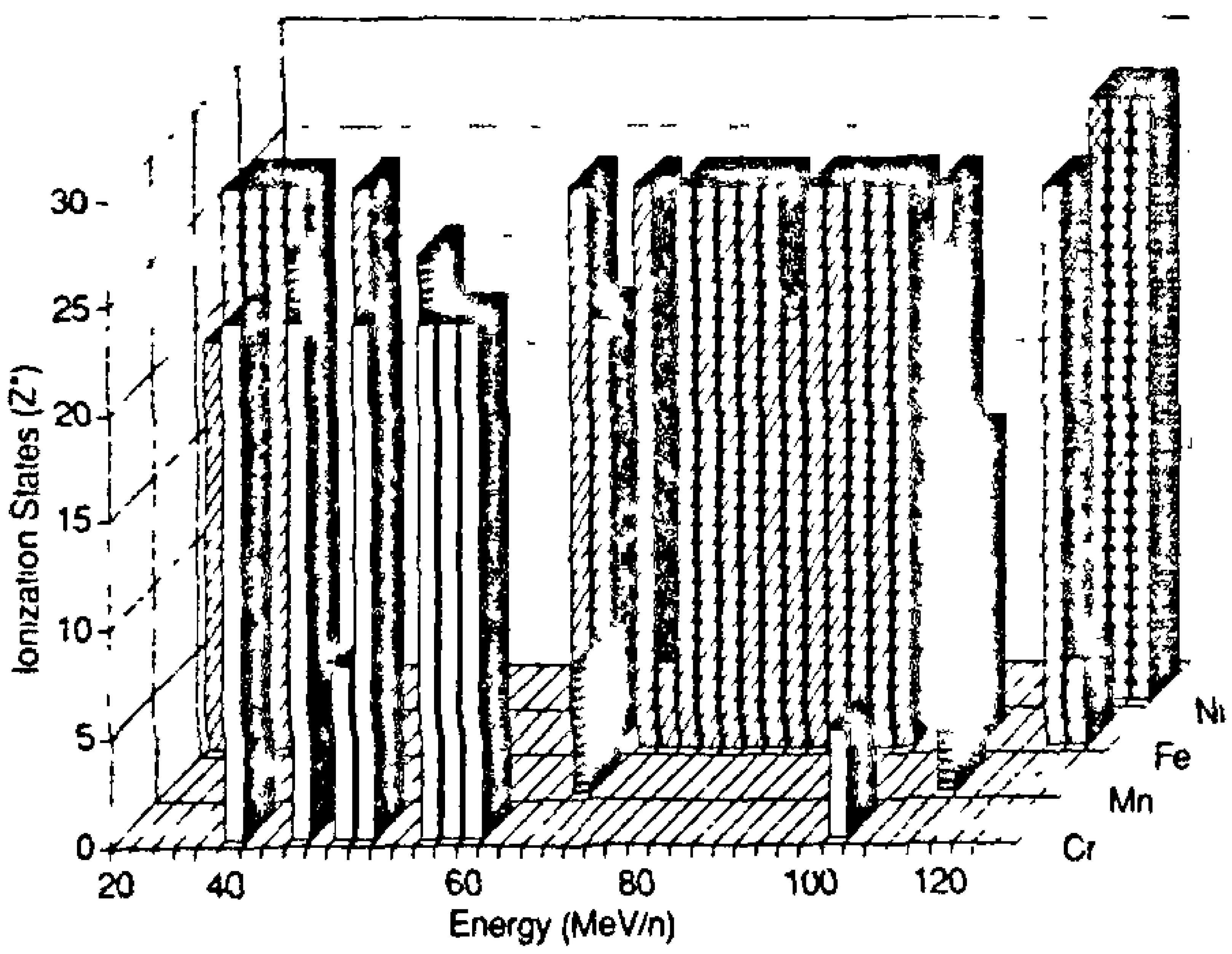

Figure 11. The measured upper limits of ionization states of low energy GCR heavy ions (Cr-Ne) detected in the Anuradha experiment. Note the presence of partially ionized particles

stripping cross-sections measured in the laboratory show that iron group nuclei in GCR can capture orbital electrons only at very low energies (1–5 MeV/n) and above 10 MeV/n, electron stripping dominates. Therefore, the important question arises, how do we get GCR iron and sub-iron ions of ~ 100 MeV/n in partially ionized states observed in Anuradha? Logical conclusion appears to be that these particles captured electrons at low energies and are subsequently accelerated to > 100 MeV/n in ISM and have traversed very small amount of matter before reaching the solar system. Thus, our observation provides evidence for reacceleration or distributed acceleration of GCR in ISM. Probable sites for reacceleration are shock fronts of supernova remnants in ISM. Confirmation of the above will have important new implications on acceleration of galactic cosmic rays. Several attempts are currently on to study this enigmatic component of cosmic rays (e.g. see ref. 32).

Future space experiments may explore these new pathways to interstellar medium using low energy anomalous and galactic cosmic rays as tracers. Measurements of ACR oxygen flux beyond the orbit of Uranus during the period of minimum solar activity in 1997–98 will give definitive results on the intensities of these particles at the boundary region of the heliosphere and hence their energy density in the local ISM. In galactic cosmic rays, the new phenomena of partially ionized low energy iron and sub-iron group of particles need further studies. Such experiments should hopefully allow us to build new gateways to explore processes taking place in local interstellar medium as well as further away within our galaxy.

Summary

Studies of energetic cosmic-ray particles, that are an unique sample of matter from the interstellar space, continue to provide us with new insights of the high energy nuclear and astrophysical processes taking place within our galaxy and beyond. A significant recent contribution in this context has been the findings of the extremely successful Indian cosmic-ray experiment 'Anuradha' flown on board space shuttle Spacelab-3. This experiment was planned and executed jointly by scientists from the Tata Institute of Fundamental Research, Bombay and Physical Research Laboratory, Ahmedabad, under the aegis of the Indian Space Research Organization (ISRO), and with active help and collaboration from various ISRO centres and the Bhabha Atomic Research Centre, Bombay. The main scientific objective of the experiment was to determine the ionization states of the newly discovered anomalous cosmic rays to identify their source and origin. A very special experimental payload, that combines a passive nuclear particle detector and an active electro-mechanical system, was designed and constructed to achieve this objective. Some of the important results obtained in this experiment are: (i) a clear demonstration that the geomagnetic field can be used as a giant momentum analyser for determining the rigidity (momentum/charge) of individual low energy cosmic-ray particles impinging on the earth, (ii) the first direct determination of the ionization states of individual anomalous cosmic-ray particles, which showed them to be singly ionized and confirmed the interstellar neutral atoms as their source, and (iii) detection of low energy partially ionized iron group particles in galactic cosmic rays, a completely unexpected result with important significance. The basic principle used in the Anuradha experiment has been adopted in a couple of recent satellite experiments that have confirmed the results on the ionization states of the anomalous cosmic rays obtained in the Anuradha experiment. Further studies of the enigmatic partially ionized iron group particles are also being pursued in these experiments. The findings of the Anuradha experiment point towards the exciting possibility of understanding the elemental and isotopic composition of the local interstellar matter by sampling the anomalous cosmic rays in the interplanetary or the near-earth space.

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