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Ionization states of cosmic rays: *Anuradha* (IONS) experiment in Spacelab-3

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Abstract. The measurements of the ionization states, composition, energy spectra and spatial distribution of heavy ions of helium to iron of energies 10–100 MeV/amu in the anomalous cosmic rays are of major importance in understanding their origin which is unknown at present. *Anuradha* (IONS) cosmic ray experiment in Spacelab-3 was designed to determine the above properties in near earth space and this had a highly successful flight and operations aboard the shuttle Challenger at an orbital altitude of 352 km during 29 April to 6 May 1985. The instrument employs solid state nuclear track detectors (CR-39) of high sensitivity and large collecting area of about 800 cm^2 and determines the arrival time information of particles with active elements. Experimental methods, flight operations and preliminary results are briefly described. Initial results indicate that relatively high fluxes of low energy cosmic ray α-particles, oxygen group and heavier ions were obtained. The flight period corresponded to that of quiet Sun and the level of solar activity was close to solar minimum. It is estimated that about 10,000 events of low energy cosmic ray alpha particles with time annotation are recorded in the detector together with similar number of events of oxygen and heavier ions of low energy cosmic rays.

Keywords. Cosmic rays; anomalous component; ionization states of cosmic rays; Spacelab-3 flight.

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1. Introduction

In 1973–74 a detector module was flown in Skylab space craft for 74 days at an altitude of 430 km at an orbital inclination of 55° with very small amount of shielding material and this showed for the first time a new kind of low energy cosmic ray heavy ion population in near earth space (Biswas *et al* 1975a). The detailed studies of these heavy ions of atomic number $Z = 6$–18 of energy $E = 8$–30 MeV/amu revealed the abundances of oxygen, nitrogen and neon relative to carbon enhanced by a factor of about 5, 4 and 2 respectively as compared to high energy cosmic rays (Biswas and Durgaprasad 1980), and these were the same as those of anomalous cosmic rays (ACR) measured in interplanetary space (Hovestadt *et al* 1973; McDonald *et al* 1974 and

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The authors felicitate Prof. D S Kothari on his eightieth birthday and dedicate this paper to him on this occasion.

Garcia-Munoz *et al* 1973), and hence it is concluded that a large part of the heavy ions measured in near earth space in the Skylab are anomalous cosmic rays. A striking feature of these anomalous heavy ions observed in the Skylab was that these must be in partly ionized state because otherwise the earth's magnetic field would not allow these ions to reach the Skylab detector (Biswas and Durgaprasad 1980); however it was not possible to determine from Skylab data the precise ionization states and their relative proportions. Hence these and other observations raised several intriguing questions such as: What are the ionization state of anomalous cosmic ray heavy ions? Are these composed of singly-ionized particles or particles with different states of ionization? What are their spatial distributions in near earth space? and so on. In order to investigate these new properties of heavy ions in anomalous cosmic rays in near earth space, an experiment was designed for flight in Spacelab mission of NASA. This experiment, the proposal of which was initiated in 1976, was flown in orbit in 1985. The intervening period was devoted to evolve in India the instrument design and fabrication, assembly, environmental testings of several models and their functional operations prior to the integration of flight instrument in Spacelab-3 in USA. The successful flight of this experiment provided us for the first time high quality data of heavy ions in near earth space with arrival time and arrival direction information of each of these ions recorded in a detector of large collecting power.

So far there have been very few experiments in near earth space with a high degree of precision on heavy ions of cosmic rays. Bobrovskaya *et al* (1983) measured in 'Salyut-6' fluxes of C, N, O ions of 10–25 MeV/amu during 111 hr exposure from 16 to 21 May 1981, and observed steeply falling spectra, similar to other studies. In the experiment on the isotopic composition of heavy nuclei of 100–700 MeV/amu in a detector exposed in Spacelab-1 from 28 Nov. to 8 Dec. 1983, the Kiel group (Beaujean *et al* 1984; Oschlies *et al* 1985) obtained 113 events of low energy oxygen group nuclei of 10–20 MeV/amu of anomalous cosmic rays and a preliminary flux of 4×10^{-8} particles/(cm^{2}sr sec MeV/amu).

During the last several years, the studies of anomalous cosmic rays (ACR) in interplanetary space using instruments on board IMP, Pioneer and Voyager spacecrafts have yielded interesting information, in addition to composition and energy spectra, on the radial gradient and time variation of ACR (Klecker *et al* 1977; Cummings *et al* 1985; Mewaldt and Stone 1985; Mason *et al* 1985; Webber *et al* 1985 and McKibben *et al* 1985). These results have confirmed that anomalous cosmic rays are of nonsolar origin and are incident on the solar system from outside, i.e. $R > 30$ a.u. The unusual composition and time variation of ACR indicate that the source of these is distinctly different from that of high energy (> 100 MeV/amu) cosmic rays. However, the origin of the ACR is unknown at present.

Several models have been suggested on the origin of ACR (Fisk *et al* 1974; Fowler *et al* 1979; Biswas *et al* 1981a, 1985; Pesses *et al* 1981). Fisk *et al* suggested that interstellar neutral atoms after entering the heliosphere become singly ionized by solar UV and are subsequently accelerated in the heliospheric boundary. Biswas *et al* proposed the hypothesis that ACR originates in the stellar winds of O-type stars in a region of a few Kpc around the solar system and these 10–100 keV/amu heavy ions of $He^{+1,+2}$, O^{+1}, O^{+2}, O^{+3}, etc in the hot stellar winds are further accelerated to 5–100 MeV/amu at the shock fronts of supernova remnants and then enter the solar system via interstellar magnetic field connected to the solar magnetic field. The distinctive features of these models are that ISM-heliospheric theory of Fisk *et al* predicts only singly-ionized states of ACR ions such as O^{+1} whereas the model of Biswas *et al* predicts ions of different ionization states such as O^{+1}, O^{+2}, O^{+3}, etc. The comparisons of features of these models are discussed elsewhere (Biswas and Durgaprasad 1980; Vahia and Biswas 1983). Pesses *et al* (1981) postulated the model with the source located over the solar pole and acceleration at the heliospheric boundary shock front. Potgieter *et al* (1985) examined this model including drifts and concluded that the observed radial gradient and some other features are inconsistent with the above model.

Direct measurements of ionization states of the anomalous cosmic ray heavy ions such as helium, oxygen, nitrogen, neon, etc and their other properties are of crucial significance in identifying the origin of ACR. The IONS (*Anuradha*) experiment in Spacelab-3 provided an unique opportunity for such a study. The objective of this paper, which is first of the series, is to present briefly the scientific aspects of the experiment including some preliminary results. Subsequent papers will deal with technical aspects and different types of scientific results as soon as they are available.

In §2 we discuss scientific objectives and significance; the instrument and experimental methods are briefly outlined in §3. The space flight and instrument operations are given in §4, followed by post-flight operations and initial results in §5.

2. Scientific objectives and their significance

In addition to the main objective of the experiment, namely, the ionization states of heavy ions of the anomalous cosmic rays as discussed in §1, there are a number of other studies of ACR, galactic cosmic rays (GCR), heavy ions in near earth space and of solar cosmic ray heavy ions (in case of solar flares) which can be conducted with this instrument. These are summarized in table 1 and their significance is briefly discussed in what follows.

In case of ACR ions we would investigate whether in addition to the known abundance enhancements of ions such as N, O, Ne, there is abundance depletion of some elements such as Mg, Si, etc as indicated in the Skylab experiment. Observations of these will be of much interest in understanding the source or origin of ACR ions.

Table 1. Scientific objectives of IONS experiment in Spacelab-3.

I. Anomalous cosmic rays (ACR): 10–100 MeV/amu

— Enhanced abundances of elements and their energy spectra, e.g. He, N, O, Ne.
— Depletion of abundances, if any, e.g. Mg, Si, etc.
— Spatial distribution of ACR ions, e.g. He, O, etc.
— Ionization states of ACR ions such as He, N, O, Ne, etc.
— Isotopic composition of ACR nuclei, e.g. $^{22}Ne/^{20}Ne$ ratios.

II. Heavy ions in near earth space: $E = 10–50$ MeV/amu

— Search for trapped or quasi-trapped heavy ions in near earth space.
— Spatial distribution of these heavy ions.

III. Galactic cosmic rays (GCR): $E > 100$ MeV/amu

— Sub-Fe, i.e. (Cr to Mn) to Fe abundance ratios in 100–500 MeV/N energy range.
— Isotopic composition of Fe nuclei.

Spatial distribution of ACR heavy ions of helium and oxygen are of special interest to understand the propagation of these ions in the magnetosphere. The cut-off rigidities at high latitudes will be determined taking into account the external current system in the geomagnetic field and these are expected to provide good estimates of the ionization states of cosmic ray heavy ions. The other interesting observations of the isotopic composition of some of the heavy elements of ACR, such as ^{20}Ne/^{22}Ne ratios can be studied and these can give additional clues to their origin.

The present experiment in the near earth space may be used to search for trapped heavy ions of C, N, O nuclei and the presence of these, if any, would have to be understood in terms of their origin.

In addition, GCR heavy ions are recorded in the detector with high efficiency and we plan to study some of the important problems of GCR, such as the abundance ratios of (Ca to Mn)/Fe ions in the energy range 50–500 MeV/amu. This ratio yields good determination of the pathlength traversed by cosmic rays in interplanetary space and the Skylab measurements indicated much larger ratios at 50–150 MeV/amu than those at 200–1000 MeV/amu (Biswas *et al* 1975; Durgaprasad *et al* 1985). Since these have important implications in the theory of origin of galactic cosmic rays as pointed out by Ramadurai *et al* (1984), it is important to measure these values with higher accuracy in the IONS experiment.

The IONS experiment can also be used to measure the isotopic composition of iron group nuclei in GCR in 100–300 MeV/amu energy interval and it is well known that more accurate measurements of ^{58}Fe/^{56}Fe in GCR will provide important clues on the nucleosynthesis in GCR (see e.g. Biswas *et al* 1981b).

In the event of a solar flare the same instrument can be used to measure the ionization states of solar cosmic ray heavy ions which are of major interest in understanding the acceleration process of ions in solar flare.

Thus we wish to point out that the design of IONS (*Anuradha*) instrument provides special opportunities to study in addition to the main science objective, a number of other scientific problems which are of major importance in cosmic rays and space physics.

3. Instrument and experimental method

The photograph of the *Anuradha* (IONS) instrument is shown in figure 1 and its sectional view in figure 2. The top enclosure of the instrument consists of a thin shell of aluminium alloy which is only 0·075 mm thick and is covered by 0·012 mm thermal tape of Kapton so that it is thin enough to allow low energy cosmic-ray ions to reach the detector and at the same time provide completely sealed enclosure of the detector and the electronic system. The thin shell is supported by a five-element rib structure on the outside. The cosmic ray detectors located below the shell consists of cylindrical modules of two stacks of SSNTDs. The top 'stack' is a circular single sheet of CR-39 of diameter 40 cm and thickness 0·337 mm which is mounted on a stainless steel ring and is fixed to the main housing. The bottom stack is about 39 cm in diameter and 4·5 cm thick, and is composed of 175 sheets, mainly of CR-39 and a few Lexan polycarbonate films, each of nominal thickness of 0·25 mm and of outer and inner diameter of 40 and 20 cm respectively. The bottom detector stack which is placed at a separation of only 0·5 mm from the top fixed stack is mounted on a vertical shaft coupled to a 15-bit

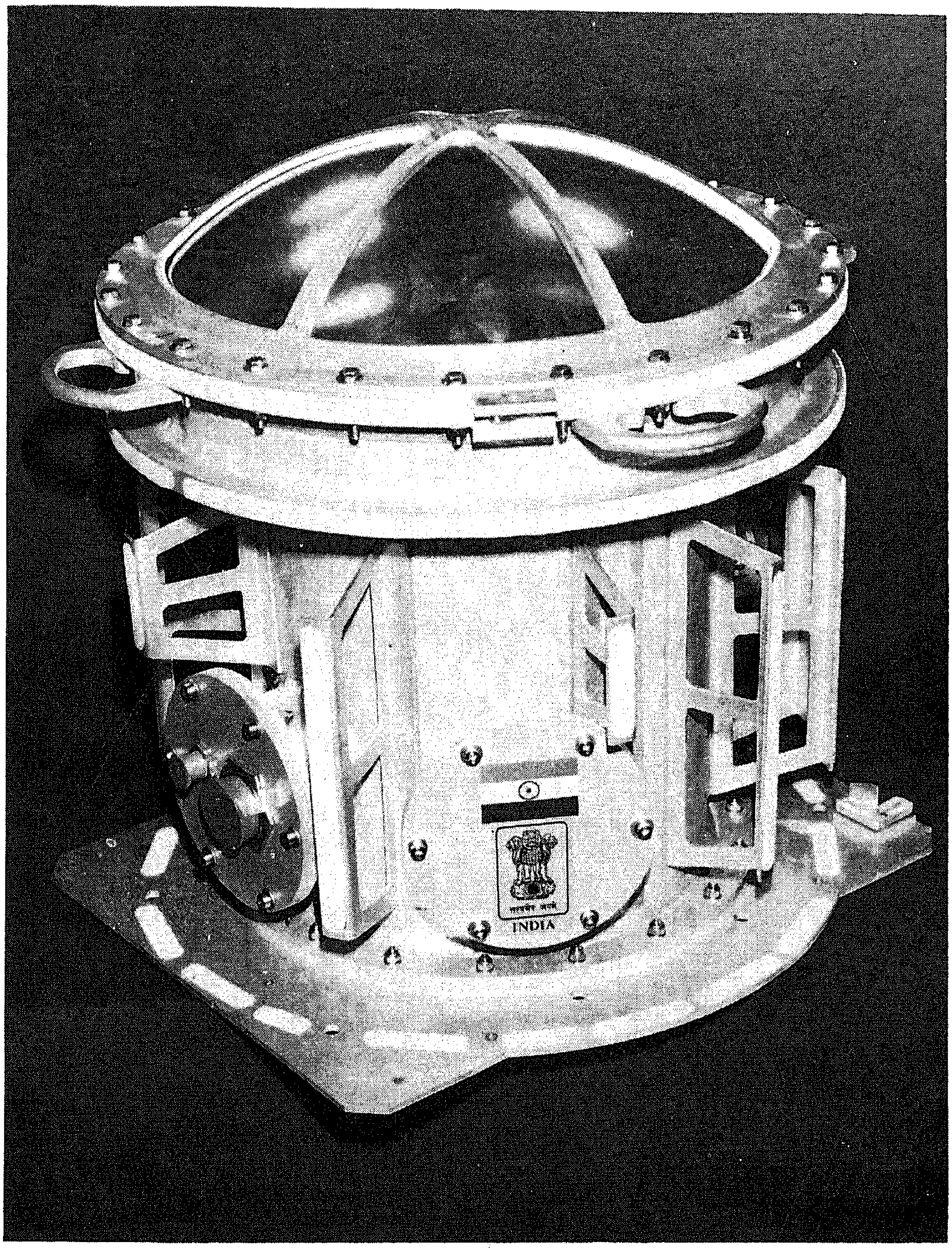

Figure 1. The *Anuradha* cosmic ray instrument that orbited the earth 116 times at 352 km altitude in Spacelab-3 aboard the shuttle Challenger is shown without the thermal blanket that covered the cylindrical side and the base plate. The quartz alignment cube (see text) is seen in the right on the base plate.

absolute shaft encoder and a gear box and a high resolution stepper motor. By suitable pulsing system for the stepper motor, the bottom stack is rotated with respect to fixed upper stack, in small steps of 40 sec of arc once in 10 sec so that it completes one revolution of 360° in 90 hr after executing 32,768 steps as measured by the shaft encoder whose 15-bit output is telemetered to ground through spacelab interfaces. There are two separate power supplies for the motor drive and the encoder electronics. The temperature is measured by a temperature sensor placed closed to the detector module and its digital output is telemetered to the ground. The instrument is kept at a pressure

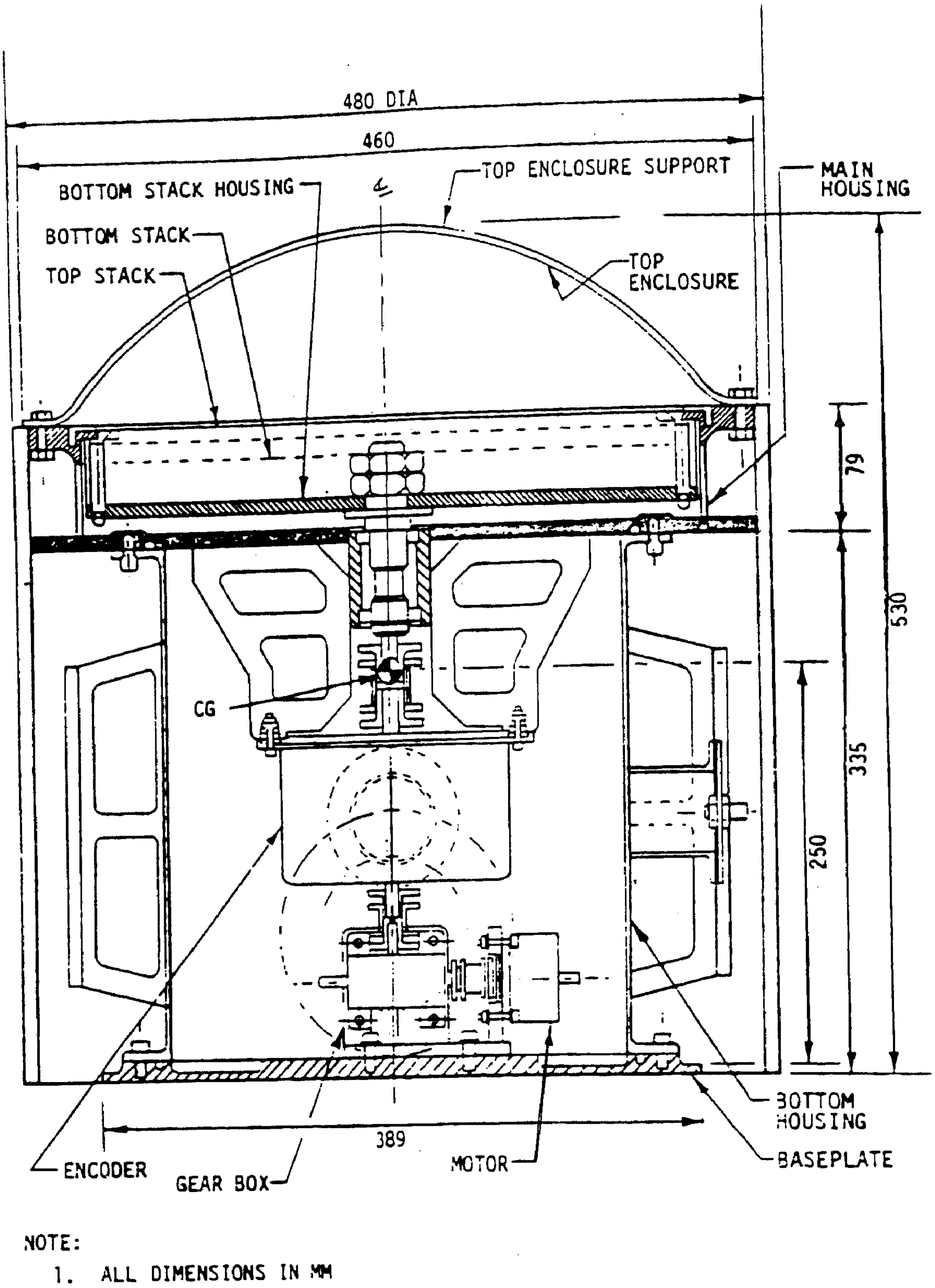

Figure 2. A sectional view of the instrument. The thermal sensor (not shown) was located close to the bottom stack. The electronics boxes (not shown) were located on the base plate and above the shaft encoder.

of 0·1 atmosphere during the flight by means of two pairs of venting valves. One pair allows air to escape from the instrument enclosure during the venting of cargo bay during the ascent phase of space shuttle till the pressure inside drops to 0·1 atm and is then sealed. Another pair of venting valves opens during the re-entry of Spacelab when outside pressure drops to 0·1 atm so that it allows air to enter the instrument and at the end of the mission the instrument lands with air at one atmospheric pressure.

For cosmic-ray particle detection we selected the new semiglass-semi plastics, allyl diglycol carbonate (ADC) ($C_{12}H_{18}O_7$) which is a polymer of the monomer, commercially known as CR-39 (manufactured by Pershore, UK) as these were found to be the most sensitive and efficient solid state detector for cosmic ray heavy ions (Durgaprasad *et al* 1981). The advantages of the IONS detector system are: large collecting area of about 800 cm^2, low or zero background and ability to withstand space environment with very little shielding material. To these we have added the ability to measure within ± 5 sec the arrival time of cosmic ray particles by small stepwise rotation of 40 arcsec at every 10 sec of the bottom stack with respect to fixed top stack as noted earlier. Thus the detector system combines the major advantages of passive and active detectors.

The thermal control of the instrument is provided by passive multilayer thermal blanket on the cylindrical side of the instrument and on the base plate, and by active system of heat control by cold freon circulating through the cold plate on which the instrument base plate is mounted.

A summary of the basic features of the instrument and flight characteristics is given in table 2.

The experimental method to determine the ionization states of low energy cosmic rays employs two novel approaches. Firstly the distribution in time of cosmic ray ions incident on the detector is converted into distribution in spatial bins in the detector by means of bottom stack executing small and precise rotational steps (of 40 arcsec every 10 sec as mentioned earlier). By using appropriate algorithms of cosmic-ray track parameters the spatial distribution is reconverted into arrival time distributions. An energetic cosmic-ray heavy ion entering through the top stack and stopping in the bottom stack leaves a radiation damage trail along its path in CR-39 due to breaking up of the chemical bonds in the polymer and this is revealed by suitable chemical treatment in the laboratory. The mass, nuclear charge, kinetic energy of the ion can then be

Table 2. 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 hr GMT, and landing 6 May 1611 hr GMT.
Orbit	Altitude: 352 km Inclination: 57° to the equator Attitude: Gravity-gradient stabilization.
'IONS' exposure	Instrument activation, 123-12-44 GMT and deactivation, 130-05-00 GMT
Power allocation	10 Watts average for 90 hr.
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 analog 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 second 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.

determined from measurements on the geometry of the tracks and the range traversed in the stack after suitable calibration with energetic heavy ions from accelerators. By matching the segments of the same track in the top and bottom stacks by suitable algorithm, the displacements between the track segments are determined. The telemetered data of shaft encoder readings vs GMT are then used to determine the arrival time (T) of the particle. Next the arrival direction of the particle, measured in the detector, is combined with the telemetered data of the altitude (H), latitude (λ), longitude (θ) and the orientation vectors of the Spacelab at the arrival time (T) of the particle to determine the H, λ, θ, azimuth and elevation of the arrival point and direction of the cosmic ray heavy ion in space. The above measurements are carried out individually for each of the incident cosmic rays ion identified in the detector.

The next step involves the determination of the threshold magnetic rigidity of the cosmic ray ion incident from the given direction at the required latitude, longitude and the altitude. This is determined from the trajectory computation of the cosmic ray particle in the geomagnetic field using multipole expansion of the field and including other relevant parameters as applicable for particles incident at high latitudes $\lambda \simeq 40$–$57°$. From the threshold rigidity, R, and the total momentum of the heavy ion as determined from the measurements in the bottom stack, the ionic charge is determined as $Z^* = APc/R$, where A is the atomic mass, P is the momentum per nucleon, and c is the velocity of light.

It may be noted that the above complex stages of measurements and calculations are needed to determine the ionic charge, because in any type of detector, cosmic ray heavy ions are stripped of their orbital electrons while passing through a few micrograms of matter in the shielding or in the uppermost layers of the detector, and thus no information of the ionic charge of the particle can be obtained from the measurements confined to the detector only. In this investigation, we have adopted the method by which the earth's magnetic field is used as a momentum analyzer for each of the heavy ions and we combine this information with other properties measured in the detector to determine the ionization state, as given above.

Figure 3 shows the different stages of information processing involved in the determination of ionization states.

4. Space flight and instrument operations

The *Anuradha* (IONS) instrument was the only Indian experiment in Spacelab-3 which orbited a multi-disciplinary payload of 15 investigations in five scientific fields. A brief summary of Spacelab-3 experiments is reported by Fichtl *et al* (1986) and of the present experiment by Biswas *et al* (1986).

The present instrument after successfully completing ground testings in India for environmental conditions of space flight and for flight operations, was integrated with Spacelab-3 at the NASA Kennedy Space Centre where the instrument was mounted on the experiment support structure of the Spacelab-3, located behind the Spacelab module. The power and command and data management (CDMS) cables of the instrument connect it to the remote acquisition unit (RAU) located inside the module which is a computer system dedicated to the hardware and functional operation of the IONS instrument. The RAU is connected to the Spacelab computer through input-

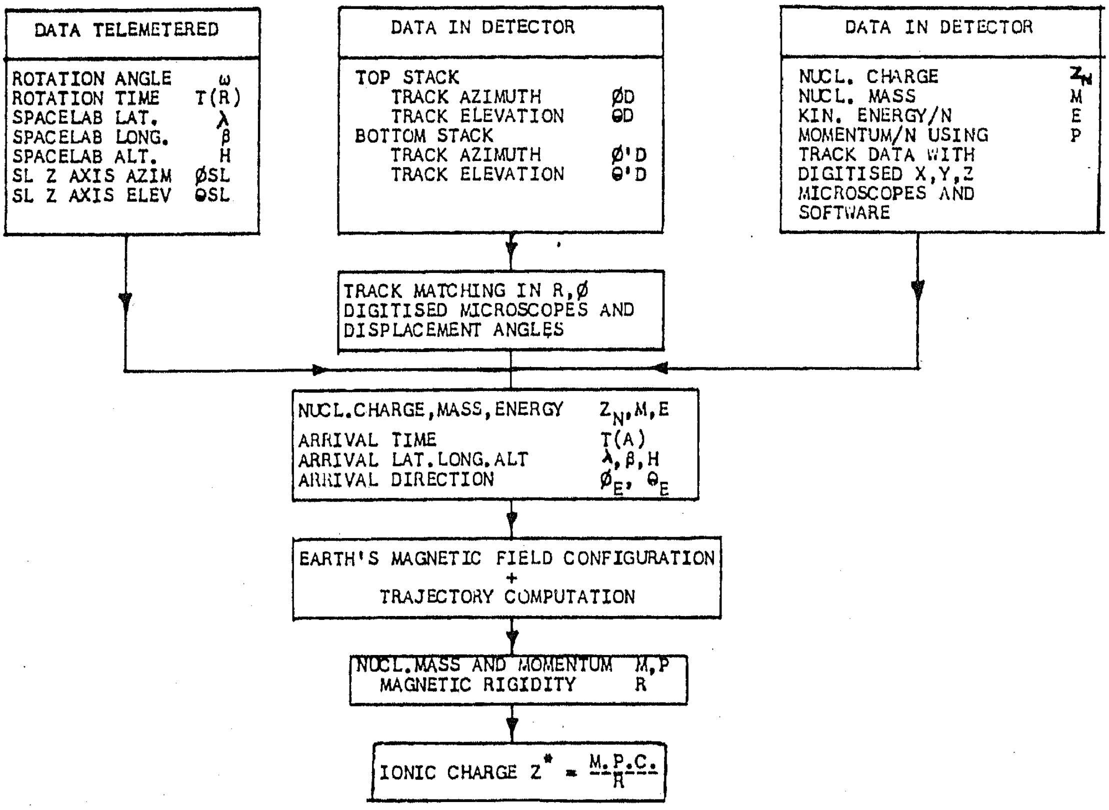

Figure 3. Schematic diagram of the experimental method of data acquisition and processing.

output unit and the instrument is operated and controlled by the software located in the experiment computer coupled to its mass memory unit.

The *Anuradha* instrument was mounted on the experiment support structure (ESS) with its Z-axis inclined at an angle of 25° towards the Spacelab module in the X-Z plane, X axis being along the length of the space shuttle, as shown in figure 4. This angle of inclination was adopted so as to minimize the earth shadow on the viewing cone of the detector for the cosmic ray particles for the gravity gradient stabilization mode of the space shuttle. In this gravity gradient stabilization mode of the spacecraft the X axis or the nose of the space vehicle always kept pointing to the local vertical and its wing, i.e. the Y axis always points towards the velocity vector. This mode is most suitable for cosmic ray instrument for celestial viewing. A high precision quartz cube called alignment cube which was mounted on the base plate of the instrument defines the orthogonal planes of the instrument and this is used for precise measurements of the tilt angle, etc of the instrument as shown in figure 4.

Figure 5 shows the viewing cones of the detector module of the instrument showing the calculated azimuth and elevation regions occulted by the earth and the Spacelab module. Our calculations show that only a small fraction of the total field of view is occulted by the earth and the Spacelab module and 72 % of viewing cones are available for cosmic ray particles. The collecting power ($A\Omega$) is 1800 cm^2 sr.

The instrument was operated with the ground computer system designed and fabricated by IONS team and this simulated the Spacelab computer. After satisfactory performance was noted, the instrument was connected with the electrical and CDMS

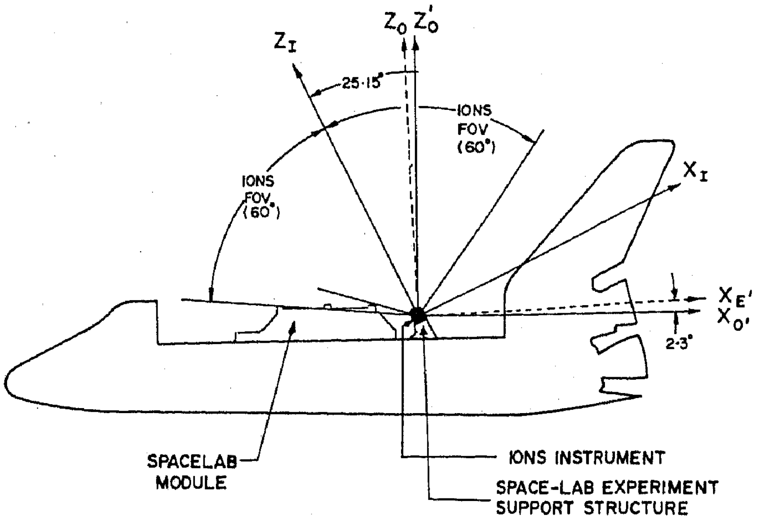

Figure 4. Field of view of *Anuradha* (IONS) in Spacelab-3 experiment support structure. The Z-axis of the instrument was tilted by 25° towards the module to reduce the earth's shadow on the viewing cone of the instrument in the 'gravity gradient' stabilized mode of the spacecraft.

system of the Spacelab and was operated and tested with Spacelab computer and all systems were found to be satisfactory.

The block diagram of the functional operation is shown in figure 6. The instrument was first switched on by ground command from the payload operation and control centre (POCC), Houston, on 1 May at 1645 GMT. It was noted that while the power was ON and the temperature channels were working, other command channels were not responding. This problem was identified by engineering members of POCC as due to a faulty NASA cable which connected the RAU unit to the main computer. On instruction from POCC, the crew on board replaced the faulty cable by another line and some software reprogramming in the mass memory unit was carried out from the ground. Following these operations the instrument was reactivated on 3 May at 1245 GMT and all channels were found to be functioning very well. The instrument operation was continued in excellent manner throughout the operating period for the rest of the mission. The encoder data, GMT and temperature were recorded every second and the spacecraft positional coordinates and attitude vectors were obtained in data tapes for these times. The thermal control system worked perfectly well and the temperature within the instrument was maintained in a very stable manner close to the normal value. The instrument was operated to the maximum possible time prior to the preparation for the landing and was switched off by ground command on 6 May at 0500 GMT, after 64 hr of continuous operation. Thus 71% of the planned maximum operation was achieved.

The shuttle landed on 6 May 1985 in California and later arrived in KSC, Florida where the *Anuradha* instrument in Spacelab-3 was inspected and found to be in good condition. After decoupling it from the Spacelab and its delivery to laboratory in KSC on 21 May 1985, the top enclosure was opened and the detector module, the mechanical and the electronic systems were found in perfect working condition. The instrument was later shipped to India and it reached TIFR, Bombay, on 17 June 1985. The magnetic data tapes containing flight data were processed by NASA Goddard Space Flight Centre, Maryland, and were received in instalments over about 6 to 8 months till

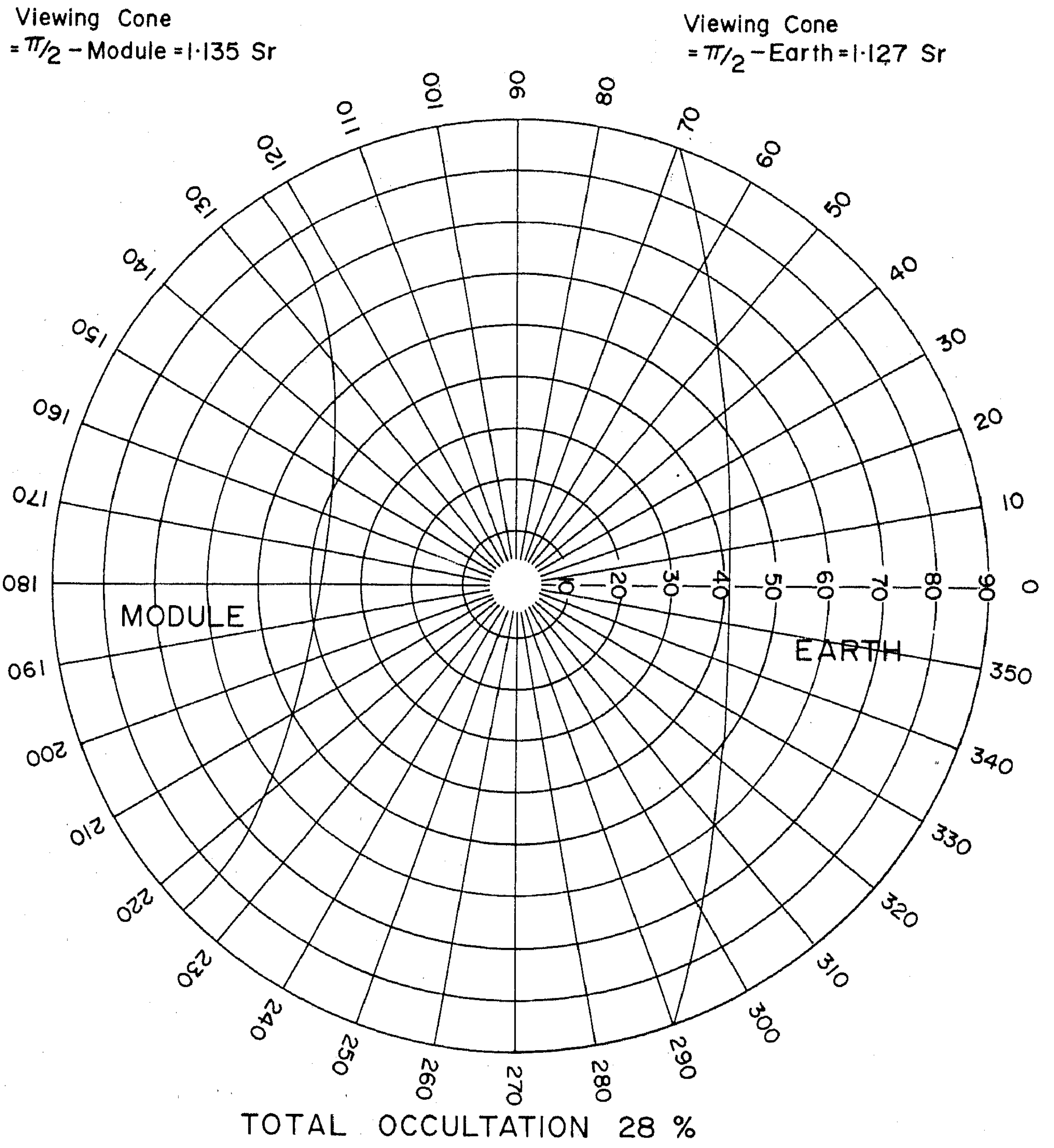

Figure 5. Viewing cone of the instrument and occultation calculations due to the earth and the module. The azimuth and zenith angles of viewing cone occulted by the earth and the module are in the region shown in the figure and these correspond to 28 % of the total field of view. The solid angle of 2·26 sr (out of 3·14 sr) is available for the celestial viewing of the instrument.

February 1986. It is estimated that about 400 million bits of telemetered data were received by us.

5. Post flight operations and initial results

After receiving the instrument in India, it was operated with the ground computer and was rotated back to the starting position as identified by the encoder reading and also by noting the visual markings under microscope on the top and the bottom stacks. At

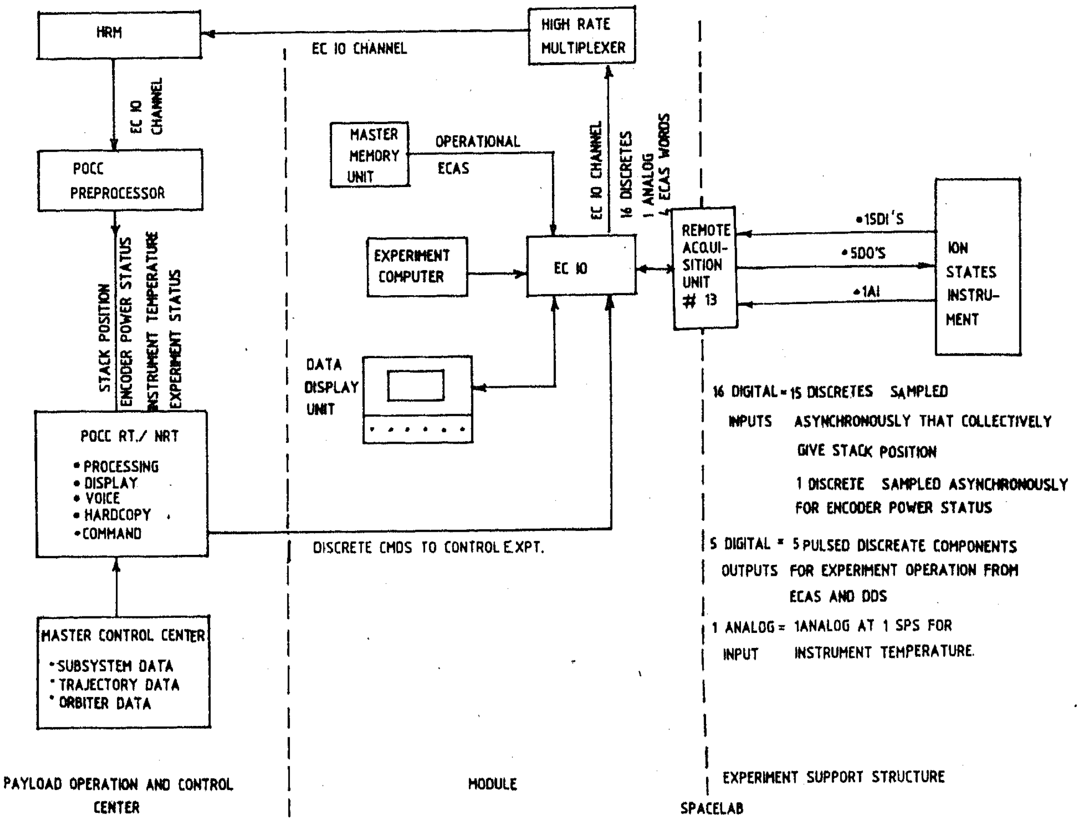

Figure 6. Sketch of the functional operation of the *Anuradha* (IONS) instrument, showing the flow of signals between the payload operation and control centre (POCC), Spacelab module and the IONS instrument on ESS. IONS receives 5 channels of discrete commands from the SL computer and generates 15 channels of discrete output signals and 1 analog output which along with GMT and other software data are telemetered to the ground to POCC.

this position the movable bottom detector module was locked by a specially designed clamp and the entire assembly of the top and bottom detector system was taken to the Variable Energy Cyclotron Centre (VECC) of BARC, Calcutta, for exposures to 50 MeV alpha particle beam. Specially designed collimator system and the intensity monitoring apparatus were used to expose the top and the bottom stacks to narrow and well-defined alpha particle beams of diameter about 0·3 mm at six positions in the direction normal to detector plane. Several test exposures were carried out prior to final ones to ensure the correct intensity of the alpha beam required for the experiment. The objectives of the alpha exposure at VECC are two-fold; firstly these provide permanent and accurate markings on the top and the bottom stacks defining the zero point or the starting position of the rotational motion of the bottom stack with respect to the top detector. The spatial bins on the top and bottom detectors are then assigned from the zero marking position. Secondly, the alpha particles penetrating several sheets of CR-39 in the lower detector provide accurate markings for alignment of the CR-39 sheets after chemical processing. The alpha particle exposures were successfully carried out and the instrument was brought back to Bombay for subsequent operations.

In the central portion on the main detector, a number of small auxillary detectors of CR-39 were placed in four stacks. These detectors numbering about 20 were exposed to beams of alpha particles, oxygen, neon, silicon, iron, uranium, etc from different accelerators and also to other radioactive sources. One set of exposed samples was kept in our laboratory. The details of these calibration exposures are given in a separate paper. During the flight cosmic ray heavy ions, after passing through the top stack, are also recorded on these auxillary detectors. Thus these auxillary detectors serve the twin purpose of inflight calibration of CR-39 detectors as well as for obtaining preliminary flux values during the flight.

5.1 *Initial results*

Figure 7(a) shows a sample of the telemetered data of the encoder reading vs GMT, each point plotted at 10 sec intervals. The commanded position denotes the pulse sequences from computer to the stepper motor translator and one unit of encoder reading corresponds to 39·55 arcsec. It is noted that following command pulses rotational steps of instrument are carried out with precision during the entire period of operation. The computer output gives the encoder reading once in every second.

Figure 7(b) shows a sample of temperature data of the instrument plotted every 10 sec. It is noted that the temperature of the detector was maintained in an excellent manner in the range of 25–40° during the entire mission and it was highly stable over several hours at any given time interval.

The set of auxillary CR-39 detectors exposed to machine beams of heavy ions and flown in the instrument and a similar set kept in the laboratory were processed for 6 hr at 70°C in a solution of 6·25 N NaOH and the track etch rate V_T and bulk etch rates V_G were measured. Some representative data are given in table 3. it is seen that there was no observable change in the response characteristics of the CR-39 detectors flown in space

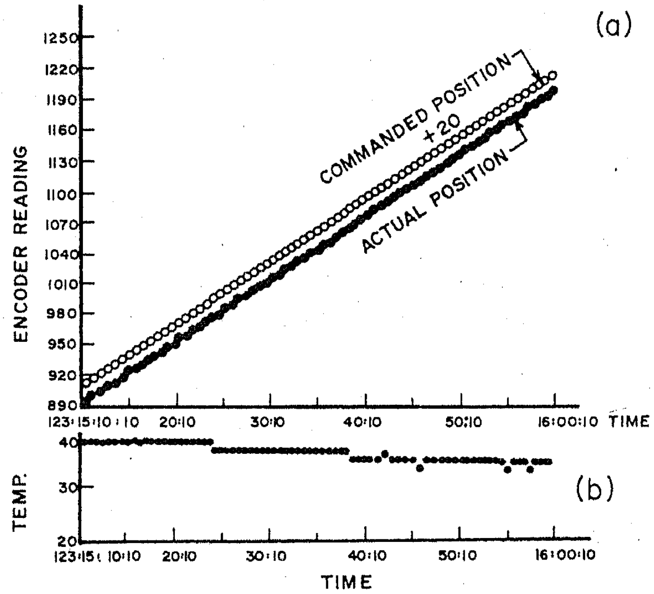

Figure 7. **a.** A sample data of encoder readings vs GMT indicating the positions of the rotating bottom stack. Data are plotted every 10 sec and each unit of encoder reading corresponds to 39·55 arcsec. The commanded positions are shown with an offset for the sake of clarity. **b.** A sample of readings of the temperature of the instrument as recorded by sensor placed close to the detector module, plotted every 10 sec.

Table 3. Results on in-flight calibration and initial flux data.

(a) *Inflight calibration of CR-39*

Detector	Beam and energy (MeV/amu)	Energy loss MeV/cm(× 10^3)	V_T/V_G (μm/hr)
Flight CR-39	^{22}Ne 7·5	7·2	11·5 ± 0·8
Lab CR-39	^{22}Ne 7·5	7·2	10·5 ± 0·7

(b) *Initial time average flux values*

Component	Energy (MeV/amu)	Differential flux particles/(cm^2.sr.sec.MeV/amu)
α-particles	8·4	$(1{\cdot}3 \pm 0{\cdot}2) \times 10^{-5}$
Oxygen group ($Z \simeq 6$–8)	17·0	$(1{\cdot}7 \pm 0{\cdot}5) \times 10^{-6}$
-do-	~26·0	$(5{\cdot}8 \pm 2{\cdot}0) \times 10^{-8}$

as compared to those in the laboratory. This is also confirmed from data of other ions. The details of these data are to be published elsewhere.

As low energy cosmic ray fluxes measured in this experiment depend significantly on the solar and geophysical conditions during the flight period, we briefly discuss some of the relevant aspects. The international (R_1) relative sunspot number during the period of exposure was 18 which was very close to the solar minimum value of about 10 predicted for the current solar cycle of 21 on the basis of solar cycles 8–20. The 10·7 cm radio flux was 79 which is close to the lowest level value. There was no solar flare activity of any significant level. There was a small magnetic disturbance on 30 April which subsided on 2 May and the magnetic activity as measured by the K_p index was low during 3–6 May 1985 when the instrument was operated.

Hence the solar geophysical conditions during the operation of the experiment were ideal for the study of low energy cosmic rays which reach a high flux level during the low level of solar activity.

The CR-39 samples of the auxillary stacks were used to obtain preliminary flux values of cosmic ray alpha particles and oxygen group ($Z = 6$–8) are shown in table 3. Alpha particles and heavy ions were located in a scanned area of 7 cm^2 and from track parameters charge groups were identified. Energies were determined from the range of particles stopping in CR-39. The time average differential alpha particle flux of $(1{\cdot}3 \pm 0{\cdot}23) \times 10^{-5}$ particles/(cm.sr.sec.MeV/amu) at 8·5 MeV/amu measured in this experiment in April–May 1985 in near earth space may be compared to the anomalous helium observed in interplanetary space in Pioneer 10 during the solar minimum value of $dJ/dE = 4 \times 10^{-5}\, P/(\text{cm}^2.\text{sr.sec.MeV/amu})$ at $E = 10$ MeV/amu during 1977. This value dropped down to a low level of about $5 \times 10^{-6}\, P/(\text{cm}^2.\text{sr.sec.MeV/amu})$ at 10 MeV/amu during solar maximum in 1981 when it almost disappeared. Assuming that the energy spectrum of alpha particles in 8–50 MeV/amu energy interval is flat as measured in the interplanetary space during solar maximum, we expect to obtain about 10,000 helium ions in 8–40 MeV/amu in IONS detector with time annotation. The time average oxygen group flux of $(1{\cdot}7 \pm 0{\cdot}5) \times 10^{-6}$ $P/(\mathrm{cm}^2.\mathrm{sr.sec.MeV/amu})$ measured in this experiment compares well with the interplanetary fluxes of anomalous oxygen nuclei of about 1×10^{-6} $P/(\mathrm{cm}^2.\mathrm{sr.sec.MeV/amu})$ and 2×10^{-6} $P/(\mathrm{cm}^2.\mathrm{sr.sec.MeV/amu})$ at 15 MeV/amu measured in early 1985 in Voyager 2 and Voyager 1 respectively (Cummings *et al* 1985). Considering the radial gradient of ACR and the transmission in the geomagnetic field, Oschlies *et al* (1985) reported a preliminary flux value of anomalous oxygen nuclei of about 4×10^{-8} $P/(\mathrm{cm}^2.\mathrm{sr.sec.MeV/amu})$ of energy 10–20 MeV/amu measured in near earth space in November–December 1983 at 250 km altitude in Spacelab 1. This value and the present measurements show that in near earth space also the anomalous oxygen flux increased from November–December 1983 by a large factor of about 50 in April–May 1985, showing a trend similar to that in interplanetary space. Thus it is seen that anomalous oxygen flux in April–May 1985 was at a high level being only 5–10 times below the maximum flux of 1977 level. We estimate that in the energy interval of 17–30 MeV/amu the expected number of events of oxygen group ions is about 8000 with time annotation information. From this the expected number of events of other elements of anomalous cosmic rays can be estimated. In addition to low energy cosmic rays we expect to obtain more than 10,000 oxygen and heavier nuclei of galactic cosmic rays of energy > 100 MeV/amu and several important types of investigation can be carried out as mentioned earlier. The top CR-39 sheet and several upper sheets of the bottom stack of the main detector have been processed and high quality cosmic ray events have been seen. The measurements and analysis of these are in progress and these are expected to provide a variety of information including the ionization states of cosmic rays in the near earth space.

6. Conclusions

The Indian cosmic ray experiment *Anuradha* (IONS) designed to measure the ionization states, flux and composition of low energy anomalous cosmic ray ions of helium to iron was fabricated, assembled and tested in India prior to its integration in Spacelab-3 of NASA. It had a highly successful flight and operations in Spacelab-3 aboard the space shuttle Challenger of NASA during 29 April to 6 May 1985. Initial studies indicated that high quality cosmic ray data have been obtained and about 10,000 anomalous cosmic ray α-particles and similar number of heavy ions with arrival time information are recorded.

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