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IONS (ANURADHA): IONIZATION STATES OF LOW ENERGY COSMIC RAYS

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ABSTRACT

IONS (ANURADHA) (1), the experimental payload designed specifically to determine the ionization states, flux, composition, energy spectra and arrival directions of low energy (10 to 100 MeV/amu) anomalous cosmic ray ions of helium to iron in near-Earth space, had a highly successful flight and operation in Spacelab-3 mission. The experiment combines the accuracy of a highly sensitive CR-39 nuclear track detector with active components included in the payload to achieve the experimental objectives. Post-flight analysis of detector calibration pieces placed within the payload indicated no measurable changes in detector response due to its exposure in spacelab environment. Nuclear tracks produced by α-particles, oxygen group and Fe ions in low energy anomalous cosmic rays have been identified. It is calculated that the main detector has recorded high quality events of about 10,000 α-particles and similar number of oxygen group and heavier ions of low energy cosmic rays.

DISCUSSION

The low energy (5 to 100 MeV/amu) anomalous component of cosmic rays discovered in the early seventies has been studied in great detail over the last decade. Comprehensive information on composition, energy spectra, radial gradient and time variation of the anomalous cosmic rays (ACR) in the interplanetary medium have been obtained using instruments on board the IMP, Pioneer and Voyager spacecrafts [2,3]. The near-Earth component of the ACR was first identified in a Skylab experiment [4]; this has, however, not been studied in detail. The spacelab mission offered a unique opportunity for such a study and the Indian experiment "IONS" (or Anuradha) on board Spacelab-3 was primarily intended for this purpose.

Several suggestions have so far been made about the origin of the anomalous cosmic rays [5]. The major distinguishing features of these models are the predicted charge states of ACR and its radial gradient and time variation. Further, the models of Fisk et al. [5] and Fowler et al. [5] suggest production of the anomalous component within the solar system, whereas Biswas et al. [5] suggested a stellar origin for these low energy particles. Extensive studies of the interplanetary ACR component [3,6] have yielded valuable information on their radial gradient and time variation for the period 1973-1984 which indicate an extra solar system origin for these particles. However, no direct measurement of ionization states of ACR is presently available. The primary objective of the IONS experiment was to obtain this crucial information for the near-Earth component of ACR. Additional information on composition and intensity of this component will also be obtained from this experiment. In this report we present the salient features of the IONS payload, the experimental approach, flight operations and performance of the instrument and also preliminary results on anomalous particle fluences based on analysis of auxiliary detector elements placed inside the payload. The processing and analysis of the main detector stacks are currently in progress.

Instrument and Experimental Approach

The IONS payload flown in Spacelab-3 is shown in Figure 1. It is 48 cm in diameter, has a height of 53 cm, and weighs 45 kg. The payload houses two detector modules, the main detector module (bottom stack) being about 40 cm in diameter and 4.5 cm thick. It is composed of 174 sheets, mostly of CR-39, All Diglycol Carbonate (DOP), nuclear track detectors along with a few sheets of Lexan Polycarbonate each of thickness of 250 μm. On the top of this stack, separated by a gap of 500 μm is a single sheet of CR-39 of thickness 250 μm which is held rigidly to the instrument frame by a stainless steel ring structure. During experiment operation the main stack is rotated using a high resolution stepper motor and a gear assembly in discrete steps of 40 sec of arc once every 10 sec., so as to make one complete revolution in 90 hrs. The movement of the stack is monitored by a 15 bit absolute shaft encoder coupled to it. A thin 75 μm aluminum alloy dome acts as the top enclosure of the sealed payload which is maintained at a pressure of 0.1 atmosphere during its space exposure. The payload was mounted directly on a cold plate fixed to a specially prepared experimental support structure to maintain the instrument temperature at a nominal value of 25°-40°C. The IONS instrument is mounted on spacelab with its Z-axis tilted by 25 deg so as to reduce the Earth shadow on the viewing cone during the flight. The gravity gradient stabilized attitude of the shuttle provided very favourable celestial viewing of IONS with a viewing cone of about 110 deg. Inside the payload a temperature sensor was placed close to the detector module to monitor its temperature during the duration of the exposure. Small samples of test CR-39 detector elements, irradiated to energetic heavy ion beams from accelerators, are also included in the payload for monitoring any possible changes in the detector response due to its exposure in pressure and temperature conditions within the payload. The entire operation of the IONS instrument was controlled by onboard computer and the relevant data regarding instrument functions (e.g. BMT, stack movement, temperature, etc.) are telemetered down link once every second for record and monitoring by experimenters. The instrument operation could be initiated and interrupted, if required, by crew interface or via ground command.

The experimental approach for obtaining ionization states of ACR involves several major steps. The atomic number, energy and arrival direction of each energetic particle incident on the detector modules are determined from an analysis of the track records left by the ions in the two CR-39 detector stacks. The revelation of latent tracks for optical viewing in these detectors is achieved by etching the detector sheets in a 6.25 N NaOH solution at 70°C for suitable durations of several hours. Track parameters like length, diameter, and residual range are measured and used in conjunction with energetic accelerator ion calibration data, for the same CR-39 detector samples to determine atomic number and energy of the tracks forming ions using standard procedures [7]. The arrival time information will be obtained from the angular displacement of each track in the bottom detector stack compared to its location on the top CR-39 sheet. This information will be coupled with space shuttle's trajectory data. Thus, the arrival direction of each ion in space is determined. The threshold magnetic rigidities (i.e., momentum/charge) of ions are then derived from the computation of charged particle trajectories in geomagnetic field for the known latitude, longitude, altitude, and arrival directions. By combining the data of magnetic rigidities with momentum of ions measured in the main detector, the ionization states of the heavy ions are determined.

Flight Performance

The Spacelab-3 with IONS on board was successfully launched on day 119 at 16:02:18 GMT from Kennedy Space Center, Florida. Several factors contributed to make the Spacelab-3 mission ideally suited for the study of low energy cosmic rays. First, the flight period was characterized by very low level of solar activity free from any flare events. This is illustrated in Figure 2, where we show two specific parameters characterizing the solar activity during the flight period and also their levels during solar minimum and maximum. Second, the instrument operation period was also free from any significant geomagnetic activity. Further, recent studies of anomalous cosmic rays in interplanetary space [3] have indicated that during the last solar magnetic field reversal in 1980-81 the intensity of ACR was at its minimum value, and the ACR flux for 10 MeV/N oxygen ions showed a steady rise from its 1981 value by a factor of about 10 during early 1985.

The IONS instrument was activated on the third day into the mission via ground command. Following the activation, a snag was noticed as the payload was not responding to some of the commands sent by the onboard computer. The cause was finally traced to a faulty cable connecting the computer to the remote acquisition unit through which commands were fed to the instrument. The fault was rectified by the crew following procedures drawn up by NASA ground support personnel, and IONS started operation from day 123, 12:44:08 GMT. The performance of the instrument was excellent during the entire period of operation of 64 hours, which was 71 percent of the planned operation duration. The thermal control system also worked perfectly and the temperature within the instrument was maintained in the range of 22°-40°C during the entire period of operation. We show in Figures 3(a) a sample of encoder readings showing the actual and commanded positions of the rotating bottom detector stack versus GMT. Each encoder step corresponds to about 40 sec of arc once every 10 sec. An offset of 10 divisions in commanded position is introduced for the sake of clarity. Figure 3(b) shows the instrument temperature for the same time slice, monitored by the temperature sensor kept inside the payload close to the detector module. Following the successful completion of the mission, the IONS payload was examined and all sub-systems including the two detector modules were found to be in perfect condition, with no sign of any physical stress or strain suffered during its space exposure.

Detector Response and Preliminary Results

The CR-39 (DOP) (Allyl Diglycol Carbonate) plastic used in the present experiment is an extremely sensitive nuclear track detector, and was specially manufactured by Pershore Co. (UK) adopting a long curing cycle and doping treatment with 1 percent dioctyl phthalate. Prior to the flight, sample pieces of this CR-39 (DOP) plastics were exposed to accelerator beams of low energy, upto 10 MeV/N α-particles, ^{12}C, ^{16}O, $^{20,22}Ne$, ^{28}Si, ^{52}Cr, ^{58}Ni and high energy, 1.88 GeV/N ^{56}Fe and 200 MeV/N ^{238}U ions to determine its nuclear track recording characteristics. The results obtained from measurement of track parameters in these calibration samples are shown in Figure 4, where we plot the ratio of track etch rate to bulk etch rate, V_t/V_b, as a function of energy loss, dE/dx, for different ions. It can be seen that in the low energy loss region the etch rate ratio is a linear function of energy loss, whereas at higher energy loss region it can be approximated as a power function of energy loss. A least square fit to the data yielded the following response function for the detector over the energy loss region of interest.

$$V_t/V_b = 1 + 5.67 \times 10^{-4} (dE/dx) + 1.22 \times 10^{-10} (dE/Dx)^{2.7} \quad (1)$$

The results of the calibration studies also showed that the CR-39 (DOP) detector used in this experiment efficiently records tracks of all energetic particles with $Z/\beta \geqslant 8$, where Z is the nuclear charge and βc is the velocity of the ions and it should be possible to achieve a charge resolution of 0.2 charge unit. Sample pieces of CR-39 exposed to alpha particles, neon, iron, and uranium beams were also kept inside the IONS payload to monitor any change in its response function due to the ambient pressure (0.1 atm) and temperature (25-40°C) within the payload. Post flight analysis of these calibration pieces indicates that response characteristics of these CR-39 detectors remained the same during its exposure in spacelab environment. This can be clearly visualized from Figure 4 where we have plotted the track etch ratio for neon and uranium ion tracks obtained from measurements made in calibration detector pieces flown in the payload. Hence the response curve [equation (1)] is adequate for identifying atomic number of the track forming nuclei in the IONS detector stack.

For zero time marking of the fixed top detector and the moving bottom detector module, the detector assembly was exposed to a narrow collimated beam of 50 MeV alpha particles in the Variable Energy Cyclotron, Calcutta. We first completed the analysis of a set of small area auxiliary detectors of CR-39 flown in the IONS detector module in order to obtain initial information on the types of low energy cosmic ray particles and their fluxes. These CR-39 samples were etched in 6.25 N NaOH at 70°C for 6 hrs. Figure 5 shows photomicrographs of some samples of tracks produced by low energy cosmic ray alpha particles, oxygen group (Z = 6-10) and Fe nuclei recorded during the flight. The sharp definition of the tracks is clearly evident in these photomicrographs. Based on the measured number of tracks of different ions the fluxes of low energy cosmic ray alpha particles, oxygen group and iron nuclei were determined. The time-average differential flux of alpha particles at 8 MeV/N is obtained as $(1.3 \pm 0.23) \times 10^{-5}$ particles cm^{-2} sr^{-1} sec^{-1} $(MeV/N)^{-1}$. Assuming that the energy spectrum of alpha particles is flat in the region 8-50 MeV/N as in interplanetary space. We expect to obtain about 10,000 times annotated alpha particles in 8-40 MeV/N energy interval in the main detector. The time-average differential flux of oxygen group particles at 17 MeV/N is obtained as $(1.7 \pm 0.5) \times 10^{-6}$ particles cm^{-2} sr^{-1} sec^{-1} $(MeV/N)^{-1}$. This value is in the range expected from the interplanetary flux measured in early 1985 in Voyager-2, which is about 1×10^{-6} p/(cm^2.sr.sec.MeV/N) at 15 MeV/N, considering the radial gradient of ACR and the transmission factor in the geomagnetic field. At 26 MeV/N, the time average oxygen group flux is obtained as $(5.8 \pm 2.0) \times 10^{-8}$ p/(cm^2.sr.sec.MeV/N). This shows the steady recovery of ACR since solar maximum in 1980-81, and by April-May 1985 it has increased by a large factor and has reached a level, being only 5-10 times lower from maximum flux of 1974 level. The expected number of anomalous cosmic rays of the oxygen group in the IONS detector in the energy interval of 15-30 MeV/N with arrival time information is estimated to be about 8000 events. The expected number of other components of anomalous cosmic rays can be estimated from the above number of events. In addition to anomalous cosmic rays we expect to obtain more than 10,000 galactic cosmic ray nuclei of oxygen and heavier nuclei in the IONS detector. Several important types of measurements such as isotopic composition of iron group nuclei can be carried out with high degree of reliability. The top CR-39 sheet and several upper sheets of the bottom stack of the main detector of the IONS have been processed and the measurements and analysis of tracks in these are currently in progress. The results obtained from these data will provide us the information on the ionization states and also on the composition, intensity and energy spectra of low energy anomalous cosmic rays in near-Earth space which will provide new clues to the origin of this enigmatic component of energetic particles in our solar system.

REFERENCES AND NOTES

1. "ANURADHA" is the sanskrit name of the star δ-Scorpii or a part of the constallation Scorpius. As cosmic rays originate from some type of stars in some phase of their evolution, the stellar name is given to the experiment.

2. Hovestadt, D., Vollmer, O., Gloeckler, G., and Fan, C. Y.: Phys. Rev. Lett., Vol. 31, 1973, p. 65. Garcia-Munoz, M., Mason, G. M., and Simpson, J. A.: Ap. J. (Letters), Vol. 182, 1973, p. L81; Apl. J., Vol. 202, 1975, p. 265. McDonald, F. B., Teegarden, B. J., Trainor, J. H., and Webber, W. R.: Ap. J., Vol. 187, 1974, p. L105. Klecker, B., Hovestadt, D., Gloeckler, G., and Fan, C. Y.: Ap. J., Vol. 212, 1977, p. 290, and references therein.

3. Cummings, A. C., Stone, E. C., and Webber, W. R.: Proc. 19th Int. Cosmic Ray Conf., Vol. 5, 1985, p. 163. Mewaldt, R. E. and Stone, E. C.: Ibid, Vol. 5, 1985, p. 167. Mason, G. A., Klecker, B., Galvin, A. B., Hovestadt, D., and Ipavich, F. M.: Ibid, Vol. 5, 1985, p. 168. Webber, W. R., Cummings, A. C., and Stone, E. C.: Ibid, Vol. 5, 1985, p. 172. McKibben, R. B., Pyle, K. R., and Simpson, J. A.: Ibid, Vol. 5, 1985, p. 198.

4. Biswas, S., Durgaprasad, N., Nevatia, J., Venkatavaradan, V. S., Goswami, J. N., Jayanthi, U. B., Lal, D., and Mattoo, S. K.: Astrophys. Sp. Sci., Vol. 35, 1975, p. 337.

5. Biswas, S. and Durgaprasad, N.: Sp. Sci. Rev., Vol. 25, 1980, p. 285. Biswas, S., Durgaprasad, N., and Trivedi, S.: Proc. Ind. Acad. Sci., Vol. 90, 1981, p. 337. Fisk, L. A., Kozlovosky, B., and Ramaty, R.: Ap. J. (Letters), Vol. 190, 1974, p. L35. Fowler, P. H., Redfern, R. M., and Swordy, S. P.: Nature, Vol. 279, 1979, p. 622.

6, McKibben, R. B., Pyle, K. R., and Simpson, J. A.: Ap. J., Vol. 227, 1979, p. L147. Hovestadt, D., Klecker, B., Gloeckler, G., Ipavich, F. M., Fan, C. Y., and Fisk, L. A.: Proc. 16th Int. Cosmic Ray Conf., Kyoto, Vol. 3, 1979, p. 255.

7. Fleischer, R. L., Price, P. B., and Walker, R. M.: Nuclear Tracks in Solids: Principles and Applications. Univ. of California Press, 1975. Henke, R. P., and Benton, E. V.: Nuclear Inst. and Methods, Vol. 97, 1971, p. 483.

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Figure 1. IONS payload flown in Space Shuttle Spacelab-3. In actual flight the payload was wrapped on its side by a thermal blanket for maintaining appropriate thermal environment and was placed on the open cargo bay on a specially mounted experiment support structure. The pressure inside the payload was maintained at 0.1 atm. during the flight with the help of pressure senitive venting valves fixed on the wall of the payload.

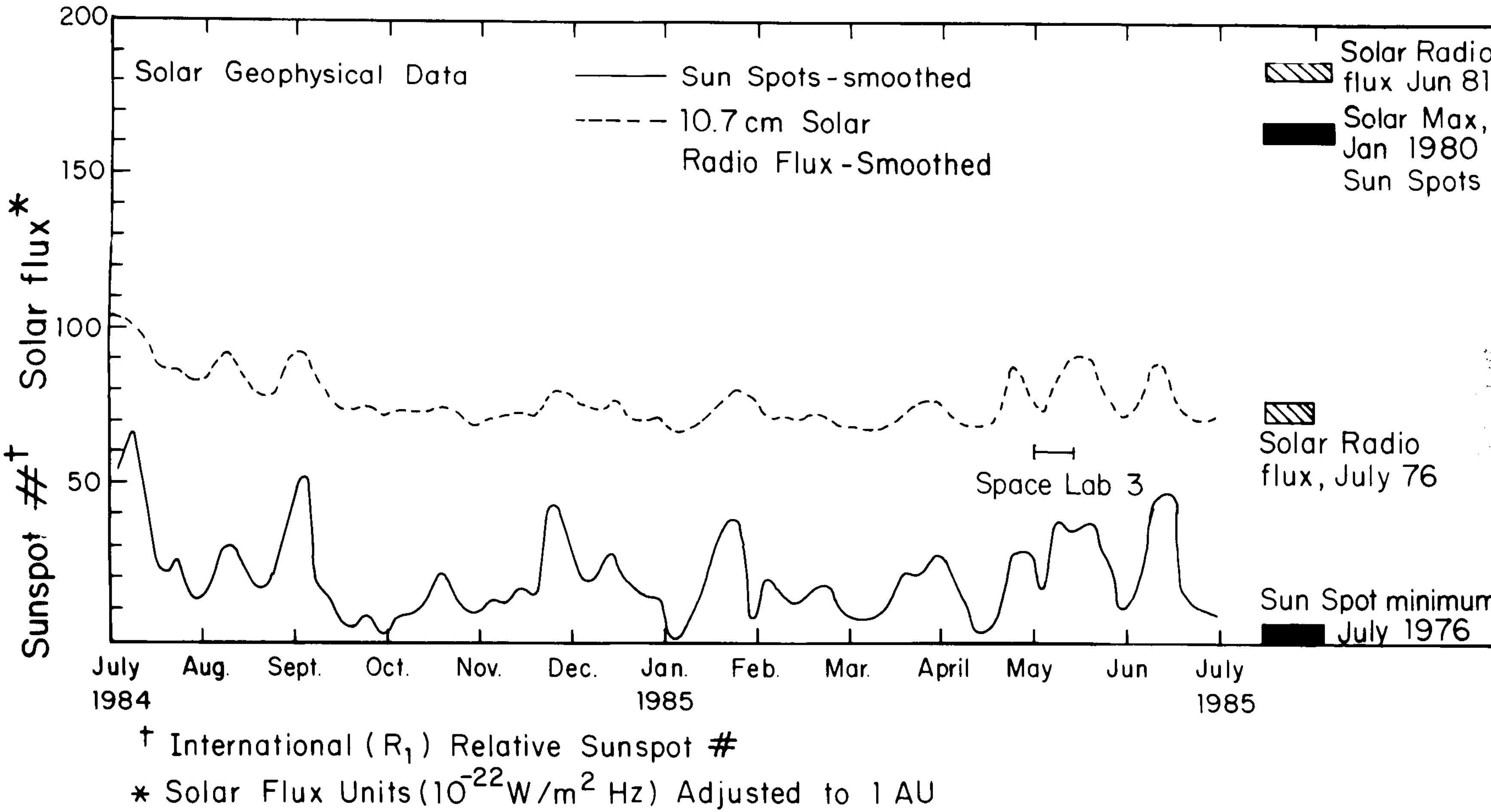

Figure 2. The level of solar activity during and close to the Spacelab-3 flight period is shown in terms of the two indices of solar activity: the sunspot number and 10.7 cm solar radio flux. The level of solar activity during the last solar minimum (1976) and maximum (1981) are also shown. The low level of solar activity during Spacelab-3 flight duration is clearly seen. The data are from solar geophysical data No. 491, Part I, July 1985 (Publ. American Geophysical Union).

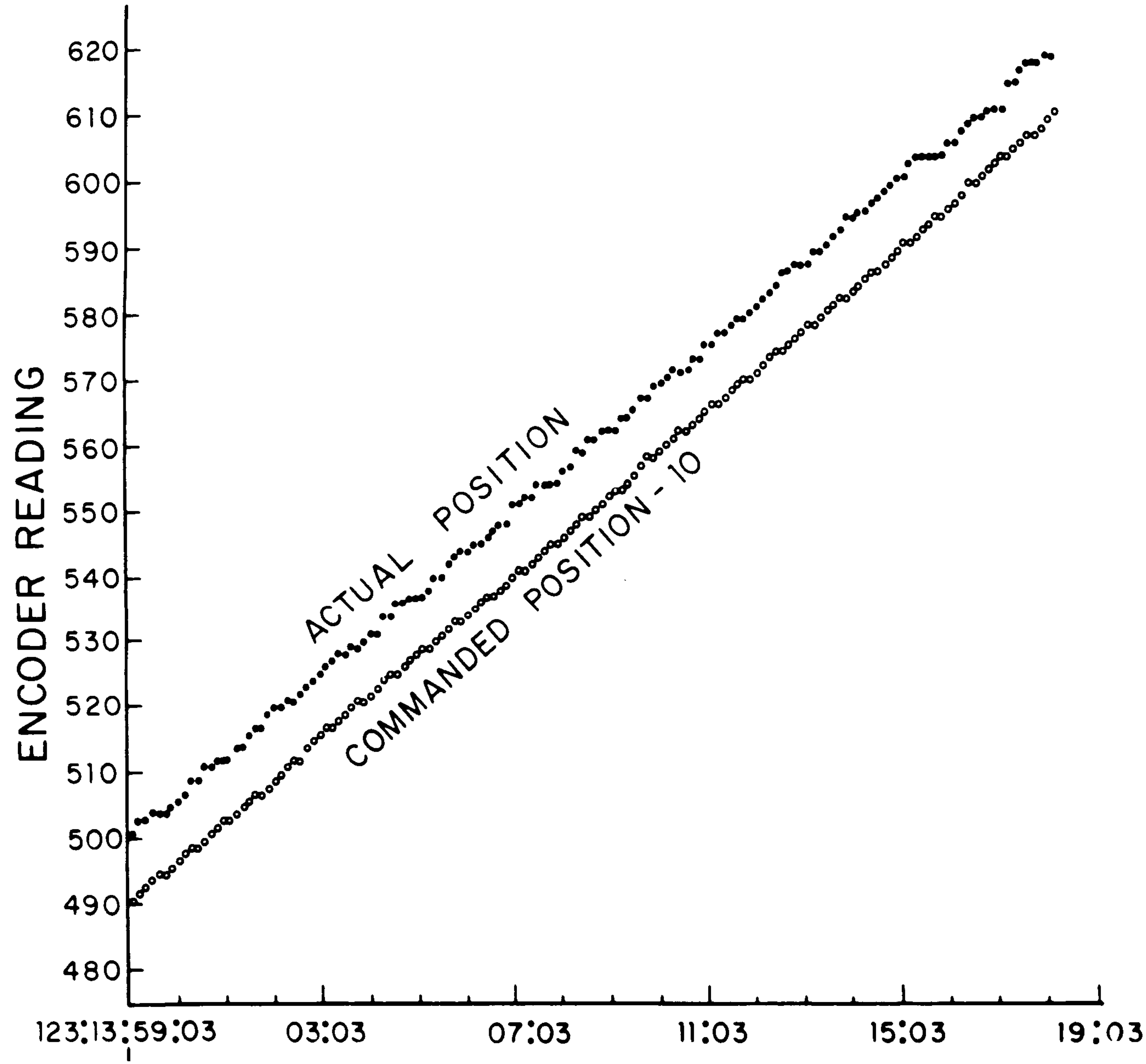

Figure 3(a). Sample data of encoder readings indicating positions of the rotating bottom detector stack following about an hour of instrument activation. Both commanded and actual encoder readings are shown as a function of GMT (day-hr-min-sec). An offset of 10 steps has been introduced in the commanded position for the sake of clarity. Each step-rotation is equivalent to 40 arc sec and takes place every 10 secs.

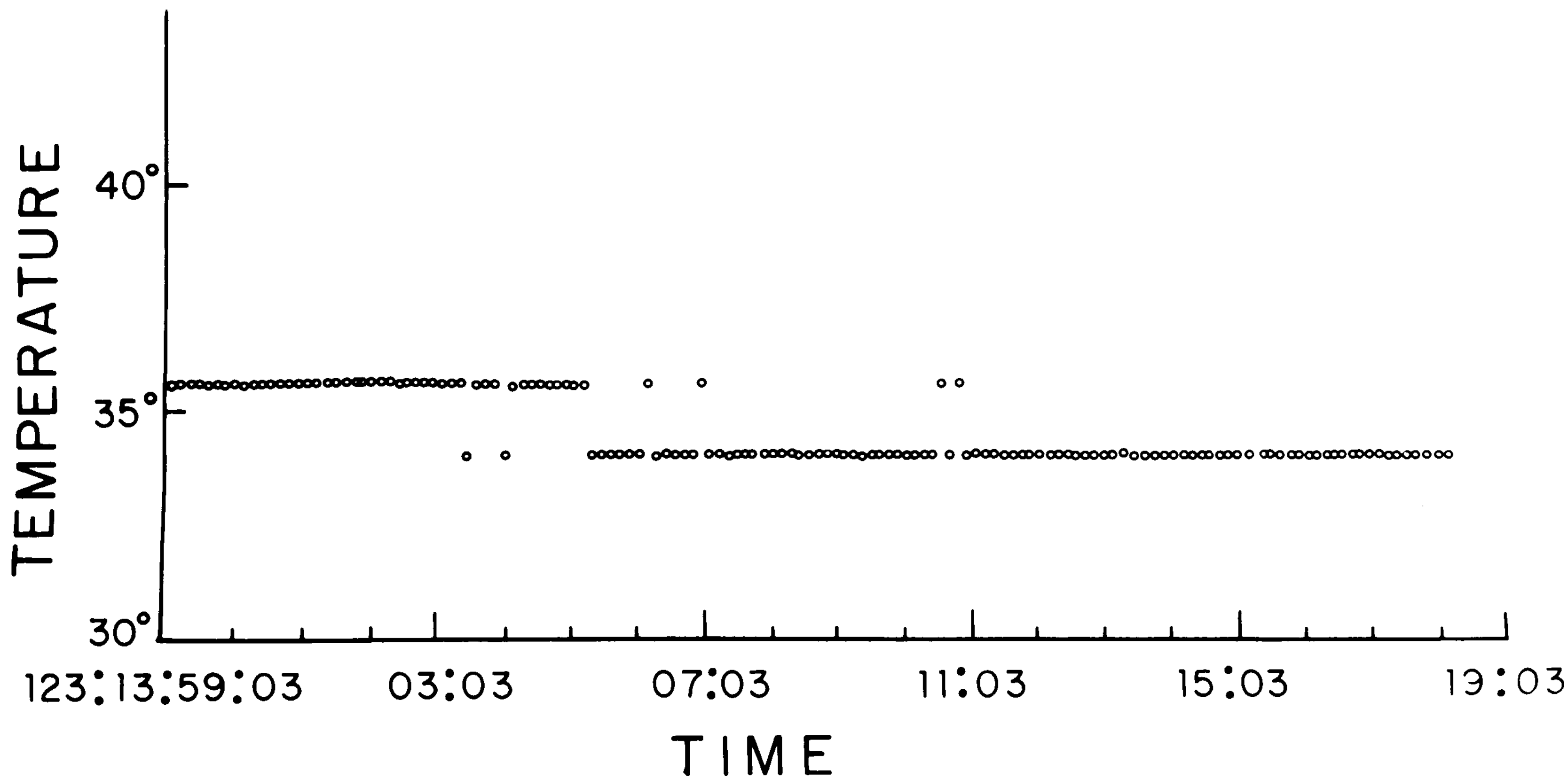

Figure 3(b). Temperature of the instrument, as monitored by a sensor placed close to the bottom detector stack, for the same time-slice as in Figure 3(a).

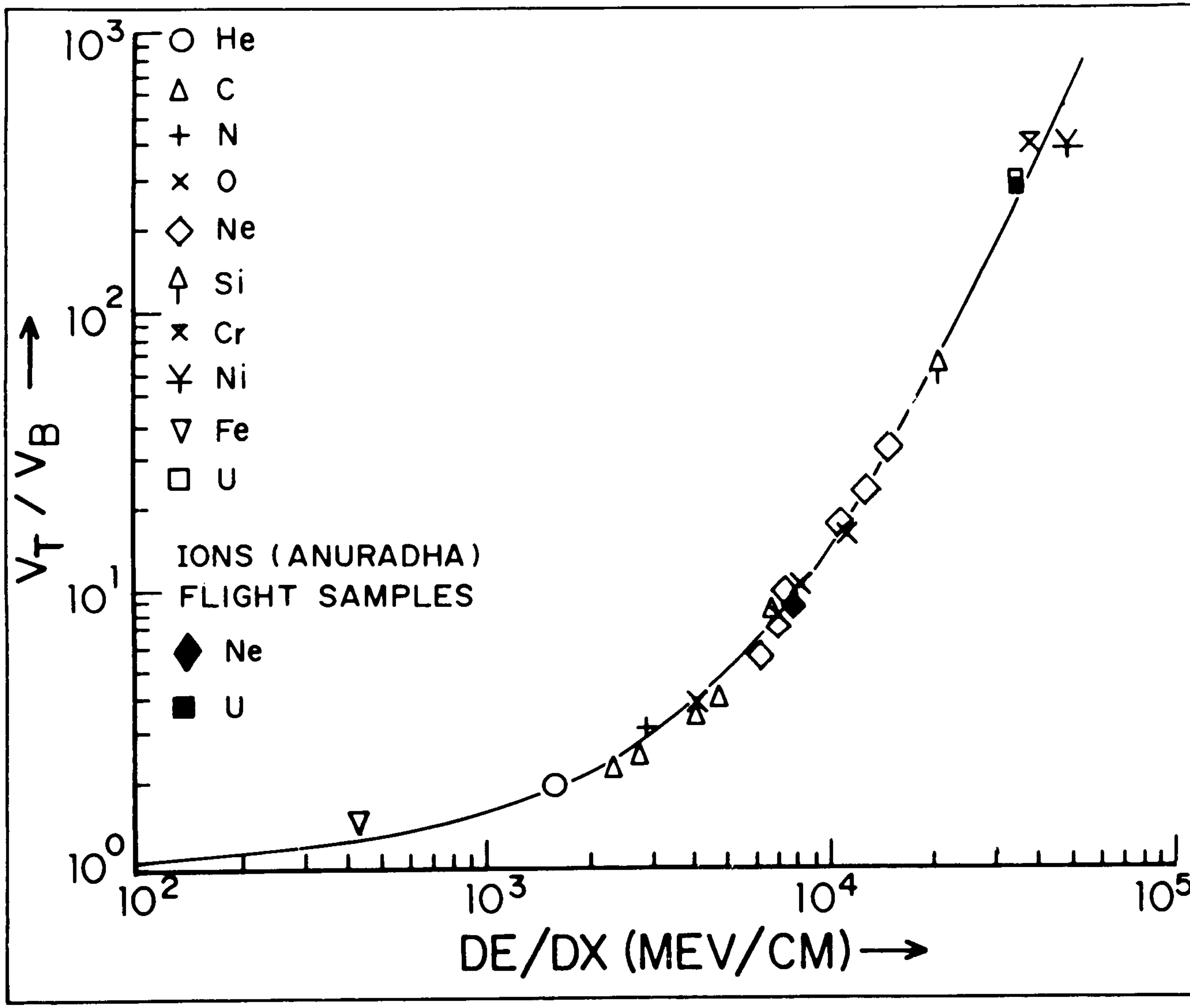

Figure 4. A plot of the ratio of the track etch rate, V_t, to the bulk etch rate, V_b, for the CR-39 plastic detector used in the IONS payload, as a function of energy loss (dE/dx) for various energetic ions. The alpha particle beam was obtained from the VEC, Calcutta (India), the ^{56}Fe and ^{238}U beams from Berkeley (USA) and the other ion beams from Dubna (USSR). Results from studies of neon and uranium ion tracks in the calibration samples were flown on Spacelab-3 (solid symbols) and they clearly indicate that the detector response remained the same during its exposure in space in the Spacelab-3 environment.

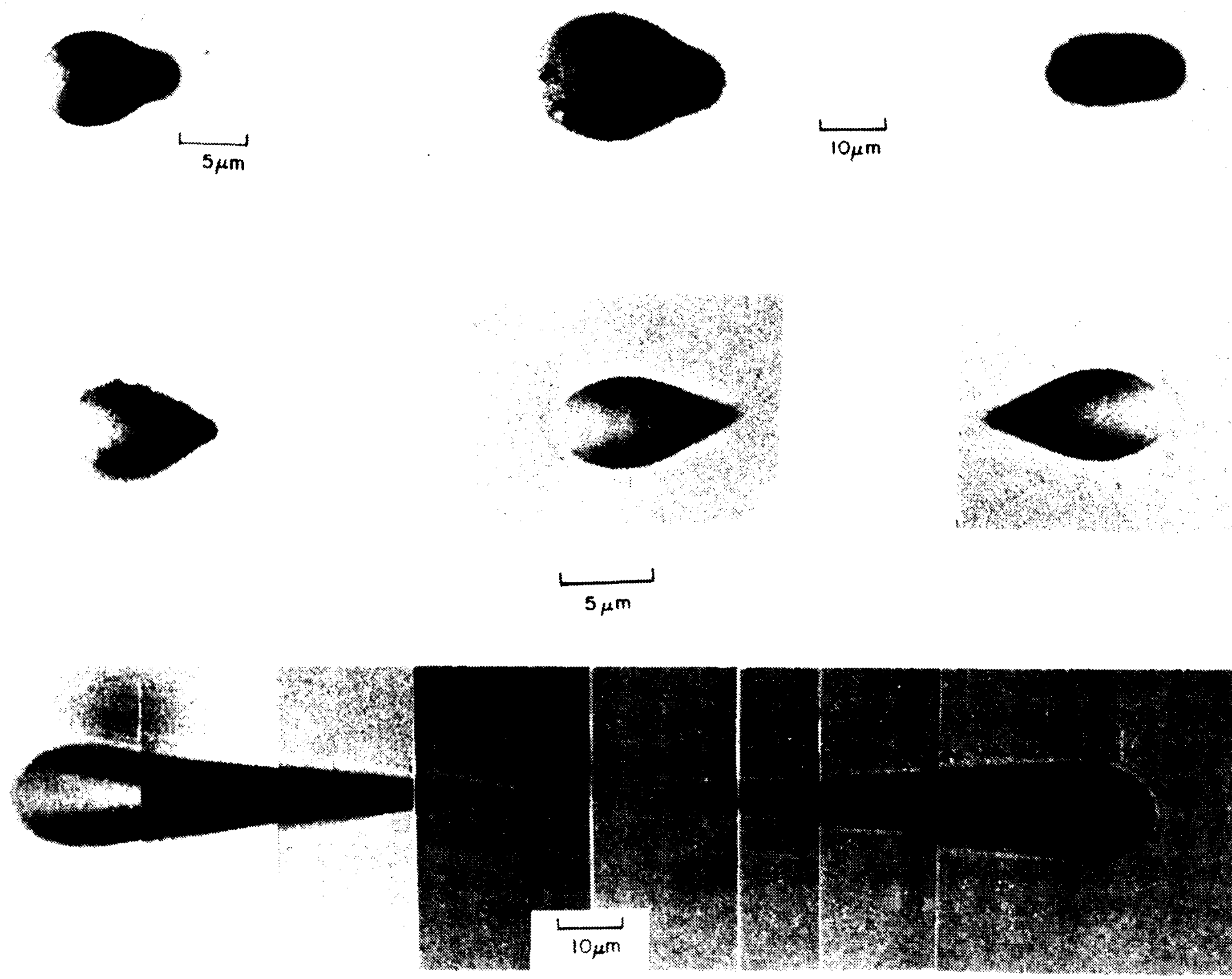

Figure 5. Photomicrographs of low energy cosmic ray tracks due to two stopping alpha particles (top) and a stopping oxygen group particle (from left to right, top row), oxygen group ions (middle), and a Fe ion (bottom) seen in auxiliary detector stack flown in IONS payload.