Defence Science Journal, Vol 42, No 4, October 1992, pp 245-251

Anomalous Cosmic Rays and their Ionization States

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ABSTRACT

Ionization states of 16 individual anomalous cosmic ray events have been determined in the *Anuradha* cosmic ray experiment conducted onboard Spacelab-3. The geomagnetic field was used as a rigidity filter for the energetic charged particles, and the upper limit on their ionization states is obtained by using the relation $Z \leq M.p.c/R_c$. Out of 16 events, 11 are found to be singly ionized and the other five events are consistent with their being in singly ionized states. The singly ionized nature of the anomalous cosmic ray particles suggests neutrals in the local interstellar space as their source.

1. INTRODUCTION

The Indian cosmic ray experiment *Anuradha* conducted onboard space shuttle Spacelab-3 during 29 April-6 May 1985, was primarily aimed at determining the ionization states of low energy cosmic rays and anomalous cosmic rays (ACR) in particular. The cutoff rigidity, *Rc*, for each cosmic ray particle is determined in this experiment from the knowledge of its arrival location and direction in the Spacelab orbit, and is used in conjunction with the measured momentum of the particle to obtain upper limit on its ionization state. The results from the first phase of the data analysis yielded 10 ACR events, most of which are in singly ionized state. The results from the analysis of additional data from this experiment are reported here, which further consolidate earlier findings of the authors.

2. EXPERIMENTAL METHOD

The *Anuradha* instrument was especially designed to get information on the arrival locations and directions of individual low energy charged particles incident on the instrument detector. The detector module consisted of two circular co-axial stacks of solid-state nuclear track detectors. The top stack, a single CR-39 sheet of 0.33 mm thickness was kept fixed during the experiment and the bottom stack consisting of 149 sheets of CR-39 and lexan polycarbonate (nominal thickness 0.25 mm each) was made to rotate in a stepwise manner with an angular speed of 40″ of arc in every 10 s. The rotation of the bottom stack was activated by a stepper-motor-gear-box assembly. A shaft encoder was used to monitor the rotation of the stack. The total exposure duration of the detector in space was 144 hr, out of which the bottom stack rotation was active for the last 64 hr. Thin films of aluminium and thermal tape that allow *CNO* particles with energy 10 MeV/n to reach the detector were used as top shielding. The detectors, after their space exposure, were chemically processed, in a 6.25N *NaOH* solution for 6 hr at 70 °C to reveal tracks formed by charged particles.

The arrival time for the energetic charged particles that were incdent during the rotation of the bottom stack and could produce nuclear tracks in both the top and the bottom detector stacks, could be determined from the angular displacement between the track segments produced by them in the two stacks when the bottom stack rotation was stopped (Fig. 1). The corresponding arrival location could be easily obtained

Received 6 September 1992
** Code 661, NASA-GSFC, Greenbelt, MD 20771, USA

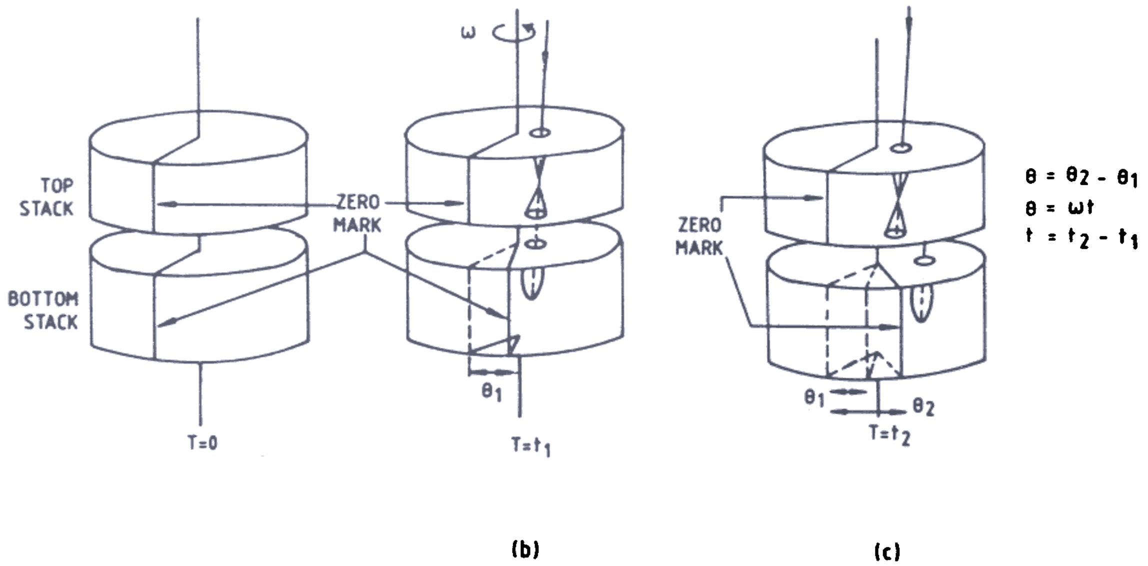

Figure 1. A schematic diagram for the procedure used in determining the arrival time of a track forming energetic charged particles incident on the *Anuradha* detector module, (a) the '0' lines on the top and the bottom stacks were coincident before the start of the bottom stack rotation (at $T = 0$); (b) at $T = t_1$, when the particle is impinged on the detector, the bottom stack has rotated by an angle $\theta 1$, (c) at $T = t_2$, the bottom stack rotation was stopped and the angular difference between the '0' lines in the two detector stacks was θ_2. The angular difference θ ($= \theta_2 - \theta_1$), obtained by matching the track segments produced by the same energetic particle in the two detector stacks, gives the time of arrival of the particle prior to the stopping of the bottom stack rotation.

as the position and orientation of the spacecraft was known at all times and was monitored at an interval of 2 s during the mission. The cutoff rigidity for a particular arrival location and direction is calculated by the trajectory tracing method[2] using the International Geomagnetic Reference Field (IGRF) for the 1985 epoch[3]. The calibration of the plastic CR-39 nuclear track detector was done by using 140 MeV/n ^{56}Fe beams from Berkeley Bevelac. Additional calibration points were obtained from cosmic ray iron ion tracks found in the detector stacks. Standard procedures were used to determine the atomic number (Z), mass (M) and energy (E) of the particles from the measured track parameters[4,5]. The upper limits on the ionization states (Z^*) of the particles are determined by using the relation $Z^* \leq M.p.c/R_c$, where M is the mass of the particles, p is its momentum per nucleon, c is the speed of light and R_c is the calculated cutoff rigidity for its arrival location and direction in the Spacelab orbit. The details of the instrument, calibration and experimental procedures used for track matching as well as method used for trajectory tracing computations are described elsewhere[1,6,7]

3. RESULTS

The results from the initial phase of scanning of 200 cm^2 detector area were reported earlier[1] Ten ACR events (two nitrogen, five oxygen and three neon) were detected and the upper limits of ionization states determined are (1^+, 3^+ (nitrogen), 1^+, 1^+, 1^+, 1^+, 2^+ (oxygen) and 1^+, 1^+, 1^+ (neon) . Now data from additional 200 cm^2 detector area have been analysed and the results from the combined scanned area of 400 cm^2 are presented here. The anomalous cosmic rays are identified as those events in the energy range 15-30 MeV/n that are geomagnetically forbidden if they are fully ionized. A total of 16 events consisting of two nitrogen, ten oxygen and four neon ions are identified as ACRs using this criterion and their arrival locations and directions and hence ionization states could be determined. The experimental data for these 16 events are given in Table 1. The encoder position refers to the difference between the encoder readings of the matched pair of track segments produced by the same event as measured during the actual scanning. This provides the information on the arrival time and hence the arrival location of the particle, which are also given in

Table 1. The dip and the azimuth angles refer to the direction of entry of the particle in the detector frame of reference, which are then converted into arrival directions in geocentric and local coordinate system using appropriate coordinate transformations[1]. Table 2 shows the arrival time of the particles, their energies, momenta and the cutoff rigidities (R_c), calculated by the trajectory tracing method. Combining the data on the particle momenta and calculated cutoff rigidities, the results on the upper limits on the ionization states of each particle are shown in the last column of Table 2. The upper limits on the ionization states shown in this table and Fig. 2 suggest that a majority of the ACR events are singly ionized and the rest of the events are also consistent with their being in singly ionized states.

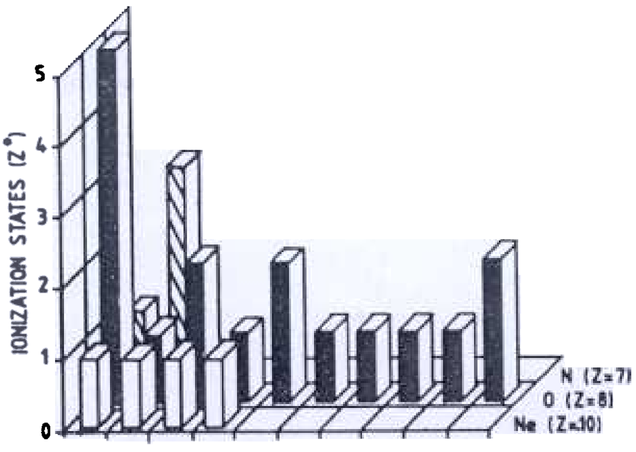

Figure 2. **The distribution of the ionization states for 16 anomalous cosmic ray events detected in the *Anuradha* experiment.**

The parameters which can significantly affect our results are the possible uncertainties in the geomagnetic field values used in the trajectory tracing calculations for estimating R_c values and in the deduced arrival time of each particle. Since the exposure duration was free from solar flare activity, the solar geophysical data, particularly the k_p index, suggests no geomagnetic disturbances during the exposure period[8,9], the use of the 1985 IGRF is most appropriate in the present case

Table 1 **Arrival information for all the anomalous cosmic ray events**

				Arrival position			Arrival direction				
							Geomagnetic	Geocentric		Local	
Id	EP	Dip$^+$ (deg)	Azimuth$^+$ (deg)	Longitude (deg)	Latitude (deg)	Altitude (km)	Latitude (deg)	Zenith (deg)	Azimuth (deg)	Zenith (deg)	Azimuth (deg)
N	21390	56.8	122.9	212.4	56.9	365.7	59.7	111.7	235.2	80.8	291.4
N	17696	61.0	215.2	135.1	-48.7	366.6	-54.1	141.2	62.0	45.3	212.3
O	20581	57.0	279.1	97.2	-50.1	364.1	-57.9	144.1	-80.3	75.7	181.5
O	21072	38.3	123.4	2.7	-51.5	367.4	-50.6	156.8	111.8	50.3	151.0
O	19937	57.8	104.2	39.2	-47.0	366.2	-51.0	159.6	-135.8	63.3	181.9
O	7330	59.9	342.9	67.1	57.1	365.7	49.9	128.6	55.0	96.2	260.5
O	11240	40.9	10.0	231.0	52.2	363.2	57.3	142.3	290.7	116	305.9
O	13240	71.1	343.5	1.0	-57.1	367.5	-55.7	127.5	188.7	85.3	263.8
O	21365	63.9	149.2	189.3	56.1	364.6	55.8	115.7	220.1	85.7	297.5
O	1748	72.6	184.2	332.6	51.5	365.2	54.9	84.7	309.2	50.5	239.0
O	22833	50.0	298.7	15.1	-44.4	361.6	-45.3	136	-173.9	89.2	173.7
*O**	17758	49.3	332.4	199.4	-54.7	365.9	-51.8	111.4	17.2	104.0	272.1
Ne	4515	81.2	57.5	175.1	56.9	365.3	54.7	104.6	188.8	72.3	284.0
Ne	14611	57.6	246.8	92.5	52.5	363.2	44.5	96.1	85.3	58.8	261.6
Ne	327	28.2	201.7	40.5	52.2	365.5	47.0	39.8	7.9	20.4	171.9
*Ne**	11500	50.5	232.6	21.9	43.6	364.8	-45.3	120.9	320.6	49.3	186.8

Id : identification; EP : encoder position

+ The systematic errors in dip and azimuth angle measurements are $\pm$ 4.0 deg ($\pm$ 1σ) and $\pm$ 3.0 deg ($\pm$1σ) respectively.

* These events have sharp tip tracks at the stopping sheet and as such their stopping point is not accurately known and there may be some error in the estimate of residual range and hence in identification.

Id	Arrival time (GMT) day	hr	min	s	Energy (Mev/n)	Total momentum (GeV/c)	R_c (*GV*)		Stormer cut-off rigidity (*GV*)	Upper limit ionization state (Z^*)
Ne	125	5	0	55	17.9	3.7	3.10		3.51	
								2.10		
								3.55		
Ne	123	13	30	35	24.3	4.3	2.73		3.13	
								2.15		
								2.80		
Ne	124	20	33	35	20.7	3.9	2.39		2.61	1(1,2)
								.95		

Id : identification

Note : The two additional values of R_c and the ionization states given in the parenthesis are obtained for an uncertainty in arrival time of ± 90 s; a: the errors in energy are mostly within 2 to 6 per cent as estimated from uncertainty in measurement of ranges of particles resulting from uncertainty in the measured dip angles. The errors in momenta are nearly half of that in energies; b: limits on cutoff rigidity are not available because trajectory tracing yielded allowed trajectory for only one extreme value of arrival time; c: missing entry (-) indicates that the calculated ionzation state is less than one; and f: trajectory tracing did not yield allowed trajectory, and Stormer cutoff rigidity has been used to calculate the value of Z^*.

corresponding ionization states for a worst case uncertainty of ±90 s (2σ) in the deduced arrival time of each individual event, and these values are also shown in Table 2. Since only a few events can at best have uncertainty in arrival time close to the worst case limit, this analysis should encompass the possible uncertainties in the R_c values noted above, in addition to the uncertainty in the arrival time for most of the events. It can be seen from the data presented in Table 2 that the deduced values of ionization states for the ACR particles do not get modified significantly even after allowing for this worst case uncertainty limit.

The improved statistics of events in the present work have also allowed the authors to investigate if there is any preferred grouping of the particles with respect to their arrival time and/or location. Such an analysis is important as there could be considerable day-night variations in the values of the threshold rigidity at high geomagnetic latitudes (≥65 °) with lower values of R_c during night times[12-14]. The distribution in the local arrival time for the ACR events, shown in Fig. 3, does not show any preference in arrival time. Further as shown in Table 1, all the ACR particles are distributed over the geomagnetic latitude 45 to 60°. Thus the possibility of uncertainty in the deduced R_c values at high geomagnetic latitude and/or day-night variations in R_c values at these latitudes cannot affect the conclusion regarding ionization states of the ACR particles and thus confirm the results obtained by the authors on the ionization states of ACRs. In summary, there are 11 singly ionized ACR events (one nitrogen, six oxygen and four neon) and additional ACR events with upper limit ionization states of +2 (three oxygen events), +3 (one nitrogen event) and +5 (one oxygen event). All the ACR events detected in this experiment are therefore consistent with their being in singly ionized states.

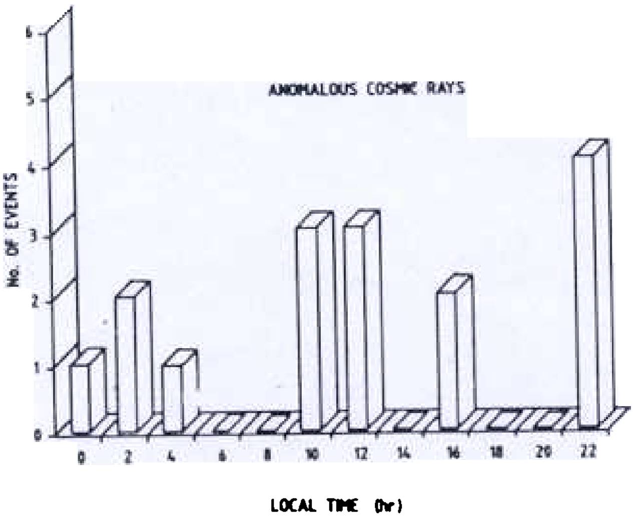

Figure 3. The distribution of the local arrival time for the anomalous cosmic ray events dete_ted in the *Anuradha* experiment.

4. DISCUSSION

The results presented in this work consolidate our earlier findings[1] and clearly establish that the ACR particles are singly ionized. The only other published result on the direct determination of ionization states of ACR is that of Oschiesh, *et al*[15] who have used an approach similar to the one used by the authors in an experiment conducted onboard Spacelab-1 during 1983. Unfortunately, the very low flux level of ACR during that epoch as well as coarse time resolution of ≥ 2 min in their experiment resulted in the observation of only four ACR events in either 1^+ or 2^+ states.

There are, however, additional indirect approaches aimed at inferring the ionization states of ACR. These include the use of phase lag in the recovery of ACR and GCR intensities during declining solar activity periods[16-18], dependence of spectral shape of ACR on their charge state and source spectra[19], and comparison of ACR flux inside and outside the magnetosphere[20]. Most of these analyses suggest ACR particles to be in singly ionized state. Thus, direct determination of ionization states of ACR accomplished in the present study, and results from earlier direct and indirect approaches aimed at determination of the ionization states of ACR, have conclusively established the singly ionized nature of ACRs.

The singly ionized state of ACRs supports the model of Fisk[21], which suggests local interstellar neutrals as the source of the ACR particles. In this model interstellar neutrals enter into the solar system and get singly ionized either through photoionization by solar ultraviolet rays or by charge exchange process with the solar wind. These singly ionized particles then move along with the solar wind out to the heliospheric boundary where they are preferentially energised at the solar wind termination shock following which they diffuse back into the solar system to be observed as ACR. Thus the singly ionized nature of the ACR and the neutrals in the local interstellar space as their source can be considered to be established conclusively. However, the nature of the acceleration process(es) and propagation of ACR within the heliosphere is yet to be understood in all details.

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