Abstract

The interplanetary space in the vicinity of the earth have many components of energetic charged particles. The Solar Wind (SW) particles with energies ≤1 KeV/n, emitted continuously from the Sun, dominate at low energies. In the energy interval of ~1 - 100 MeV/n, the Solar Energetic Particles (SEP), emitted sporadically from the Sun during solar flares, are most abundant. Above 100 MeV/n and up to energies of TeV/n and more we have Galactic Cosmic Rays (GCR) coming from outside the solar system. In the energy range of 1-30 MeV/n, a new component of energetic particles was discovered in nearby interplanetary space during solar quiet period in the early seventies. The most characteristic feature of this component is the overabundance of He, N, O and Ne relative to C compared to their abundances in SEP and GCR. While the GCR energy spectrum in this low energy range show a positive power law index in energy, the spectra of this new component has a negative power law index. Because of these peculiar features and unknown source and origin, this new component was termed Anomalous Cosmic Rays (ACR).

The ionization states of the energetic particles of solar and extra-solar origin provide clues to the plasma conditions (e.g. temperature, density etc.) prevailing at their source regions and at their acceleration sites and also of the processes occurring during their interstellar and interplanetary propagation. The ionization states of low energy SW and SEP particles are well studied earlier, using electrostatic charge analyzers, which revealed the presence of partially ionized particles in both SW and SEP. In the case of GCR, available data on the electron capture and stripping cross sections, and the large amount of matter traversal during their interstellar propagation, predict their equilibrium charge states to be fully ionized for energies >10 MeV/n. Although the ionization states of high energy (>1 GeV/n) GCR particles were inferred to be fully ionized from the measured dependence of their flux on the geomagnetic latitude, no attempt has been made so far to determine the ionization states of low energy (≤100 MeV/n) GCR particles. Such a determination is important as there could be differences in the
propagation histories of low and high energy galactic cosmic rays. The ionization state of the ACR component, which is one of the key parameters in all the models proposed for its source and origin, have also not been measured directly until recently. Indirect inferences for a partial ionization state of ACR particles have been drawn from several experiments. One such experiment was conducted in 1973 using the Skylab platform (λ = ±50°, altitude = 435 km), which provided the first indirect hint that the ACR particles are in partially ionized states. This inference was based on the observation of high fluences of low energy CNO group particles that are geomagnetically forbidden at the Skylab orbit. The similarity in the composition of these particles with that of the ACR component led to the suggestion that they are indeed a part of ACR, and, these particles could be observed inside the magnetosphere only because of their partial ionization states and hence higher effective rigidities.

The direct determination of the ionization states of ACR particles as well as that of low energy GCR particles have been accomplished recently by us based on the data obtained from the Indian cosmic ray experiment 'Anuradha' flown on board Space Shuttle Spacelab-3 during April-May, 1985. This experiment takes advantage of the presence of the low energy ACR and GCR particles inside the earth's magnetosphere and use the geomagnetic field as a rigidity filter to determine their ionization states. The present thesis mainly deals with the results obtained from this experiment, and their implication towards understanding the source and origin of the ACR as well as the characteristics of the low energy GCR particles in the near-earth-space. Since the approach of using the geomagnetic field as a rigidity filter to determine the ionization states of low energy charged particles has not been utilized before, we have also made a special effort to check the validity of the geomagnetic transmission factor calculated using the International Geomagnetic Reference Field model and trajectory-tracing method.

The main topics on which results and discussion are presented in this thesis are:
1) GCR oxygen ion flux in the energy interval (50-250 MeV/n) inside the magnetosphere and a check on the validity of the calculated geomagnetic transmission factor.

2) Ionization states of anomalous cosmic rays (ACR) and the implications of the results concerning the source and origin of the ACR.

3) New results on the ionization states of low energy (<125 MeV/n) particles (6 <Z <28) of GCR origin and their implications.

The basic structure of the thesis is as follows:

The general features of the energetic particles in the near-earth-space viz. the SW, SEP, magnetospheric, ACR and GCR along with the present knowledge about their ionization states are discussed in the first chapter.

In the second chapter we discuss the method followed in the present work to determine the ionization state(s) of low energy particles and the Nuclear Track technique used to determine the atomic number, mass and energy of the charged particles based on the records left by them in the plastic (CR-39) detectors used in the Anuradha experiment. A brief description of the instrument is also given in this chapter.

Calibration of the detector, data acquisition procedures, error estimation etc. are outlined briefly in the third chapter.

In the fourth chapter we present the results on the calculated values of the orbit-averaged geomagnetic cutoff rigidity obtained by trajectory-tracing method and the deduced transmission factors at the Spacelab-3 orbit as a function of the rigidity of the charged particles. Results obtained on the orbit-averaged flux of the low energy (50-250 MeV/n) GCR oxygen at the Spacelab-3 orbit are presented along with a discussion on the validity of the calculated geomagnetic transmission factors. Finally, the method used to
calculate the threshold rigidity of individual ions is also discussed in this chapter.

In the fifth chapter we present new result on the observation of low energy (20-125 MeV/n) partially ionized iron group ions and discuss why we consider GCR as their most plausible source. We then present a plausible model for the origin of these partially ionized heavier ions assuming them to be of GCR origin. The results on the ionization state of ACR particles alongwith their implications are also presented in this chapter.

A summary of the results alongwith their implications and scope for further work are discussed in the sixth chapter.

The results presented in this thesis are summarized below.

We have measured the orbit-averaged GCR oxygen ion flux in the energy interval 50-250 MeV/n from an analysis of the track records in the detector stacks flown on the Anuradha experiment on board space shuttle Spacelab-3. To obtain the corresponding GCR oxygen flux in the interplanetary space we have calculated the Spacelab-3 orbit-averaged geomagnetic transmission factor by using the 1985 reference geomagnetic field model. The geomagnetic cutoff rigidities are obtained by the trajectory-tracing method. The average rigidities for 5° latitude \times 5° longitude grids are calculated and the time spent by the Spacecraft in each of these grids were considered in calculating the orbit-averaged geomagnetic transmission factor. The interplanetary fluxes derived from the present experiment for three energy bands and the corresponding expected fluxes in units of \( p/(m^2 \cdot sr \cdot sec \cdot MeV/n) \) are: \((1.73 \pm 1.00) \times 10^{-3}\) and \(2.2 \times 10^{-3}\) \((45 \pm 10 \ MeV/n)\), \((3.12 \pm 1.38) \times 10^{-3}\) and \(4.2 \times 10^{-3}\) \((121 \pm 37 \ MeV/n)\) and \((4.96 \pm 3.46) \times 10^{-3}\) and \(5.0 \times 10^{-3}\) \((235 \pm 72 \ MeV/n)\) respectively. These two sets of fluxes compare well within the error limits. We have also calculated the modulation parameter \( \phi \) from the interplanetary oxygen flux derived by us, and compared this value with the \( \phi \) values for proton and helium for the 1985-86 epoch. The normalized modulation parameter \( \Phi = (A \cdot \phi) \) obtained for proton,
helium and oxygen are 650±20, 670±40 and 640±60 MV respectively. The close agreement between the derived and the expected interplanetary oxygen fluxes and in $\Phi$ values for p, He and O give us good confidence in the validity of the calculated orbit-averaged geomagnetic transmission factors and hence on the cutoff rigidity values obtained by the trajectory-tracing method using the 1985 geomagnetic reference field model.

Unambiguous determination of the ionization states of a total of 13 ACR events have been accomplished from the data obtained from the Anuradha experiment in this and earlier work. Out of these, nine events (1 nitrogen, 5 oxygen and 3 neon) have ionization states of 1$^+$. The ionization states of the other four ACR particles are also consistent with their being in 1$^+$ state. These results from the Anuradha experiment thus support the suggestion that the local interstellar neutrals are the source of ACR. In this model the neutral atoms from the nearby interstellar medium enter into the solar system and get singly ionized by solar ultraviolet rays and by charge exchange process with the solar wind. After ionization they propagate away from Sun along with the solar wind and are accelerated to the observed energies perhaps in the heliospheric boundary, before diffusing back into the heliosphere, where we observe them as Anomalous Cosmic Rays.

The experimental and analytical methods used for determining the ionization states of ACR particles were also used to determine the ionization states of low energy ($\leq$125 MeV/n) heavier ions ($6 \leq Z \leq 28$) that were recorded in the Anuradha detector. A total of 26 events out of 46, for which the ionization states could be determined, are found to be in fully ionized state. An additional 4 events are most probably fully ionized, if we consider the extreme limits of experimental uncertainty. The remaining 16 events are definitely in partially ionized states. These include one Titanium (6$^+$), two Vanadium (10$^+$, 16$^+$), two Chromium (5$^+$, 8$^+$), one Manganese (4$^+$), eight Iron (3$^+$, 3$, 10^+$, 11$, 14^+$, 14$^+$, 20$, 20^+$) and two Nickel (8$, 14^+$) ions. We have good confidence in these new results because the use of the same experimental setup and analytical
procedures yielded results that showed that the ACR particles are singly ionized and most of the GCR particles are fully ionized, which are in good agreement with our present knowledge about the ionization states of these components. The results obtained by us therefore suggest that -25- 30% of the low energy (<125 MeV/n) heavy ions are in partially ionized states. We, therefore believe that a new component of partially ionized low energy iron group particles is present in the near-earth-space.

Because of the entirely unexpected nature of the results we have made a detailed analysis for the possible sources of these particles viz. anomalous cosmic rays, solar energetic particles, magnetospheric particles and galactic cosmic rays, and conclude that they are of GCR origin. We also present in the thesis a plausible model for the generation of partially ionized low energy galactic cosmic rays. We postulate the presence of a low energy (1-10 MeV/n) partially ionized GCR component outside the solar system. Such a component could simply represent the low energy steady-state local interstellar GCR spectra or could be produced through trapping of high energy (up to few hundred MeV/n) GCR particles in large molecular clouds in nearby interstellar space, where a fraction of them suffer degradation in energy to -1-10 MeV/n and gets partially ionized through electron capture. Acceleration of this low energy partially ionized GCR component to the observed energies can take place in the heliospheric boundary. Further work will be needed to properly understand the different aspects of this new component.