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Cosmic Rays and Earth's Atmospheric Processes: A review

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Abstract

The modulation of cosmic ray flux incident on the Earth's upper atmosphere by solar activity results in changing the global electrical properties of the atmosphere, which is in turn believed to affect weather and climate. In this review paper an attempt has been made to summarize the present understanding of Earth's atmospheric processes that are affected by Cosmic rays.

Introduction

The idea that the cosmic rays could affect the weather received due importance when a positive correlation was reported between the monthly galactic cosmic rays and the satellite-retrieved low cloud amount from 1983 to 1994 (Marsh and Svensmark, 2000). Close correlation has also been reported between cosmogenic isotopes and paleo-climate records such as monsoon activity (Neff *et al.,* 2001) and ocean temperature (Bond *et al,* 2001). Cosmic rays help the formation of dense clouds in the lower atmosphere while having a small negative effect on cloud cover in the upper atmosphere. The low clouds retain more surface energy, keeping the surrounding air hot, while the high clouds reflect more sunlight into space keeping the upper atmosphere cooler (Yu, 2002). The solar magnetic field is the major parameter needed to reconstruct the secular variation of the cosmic rays flux impinging on the terrestrial atmosphere; this is because a stronger solar magnetic field more efficiently shields the earth from cosmic rays. Further, it is believed that the cosmic rays affect the total cloud cover of the earth and thus provide a driver for the terrestrial climate, although the physical mechanism underlying the link is still poorly understood (Svensmark and Friis-Christensen, 1997; Siingh et *al.,* 2005, 2007).

A conventional mechanism involves ion induced formation of aerosol particles followed by new particle growth to a size of cloud condensation nuclei (Carslaw *et. al.,* 2002; Arnold, 2006) and thereby influence the climate both in direct and indirect ways. Therefore, any variation in the cosmic ray flux can be expected to affect the distribution of lightning around the world and also the climate.

Modelling work (Yu and Turco, 2001) suggested that the small ions can produce a source of atmospheric cloud condensation nuclei, which indicates a potential effect on clouds and ultimately climate (Carslaw *et al,* 2002). In this area many studies have been carried out which suggest that variations in cosmic rays on the scales of days and years influences global cloudiness (Svensmark and Friss-Christensen, 1997), cloud cover (Todd and Knievton, 2001), mid-latitude cyclones (Tinsley and Deen, 1991) and high level cloud (Pudovkin and Veretenenko, 1995).

In India, the cosmic ray research has recently grown as one of the largest activities covering all aspects of the radiation. In 1937, Prof. Homi Bhabha has published a paper entitled "On the penetrating component of cosmic radiation" published in 'Proceeding of Royal Society". In this he concluded that a breakdown of the higher energies, as proposed by some theorists, would not explain the experimental results on the latitude effect of cosmic rays and the shape of the transition curve of large cosmic rays bursts. During the period, a new particle called 'meson' was discovered. Prof. Homi Bhabha predicted that the 'meson' would be unstable and would probably decay into an electron and neutrino. After that, the Indian Institute of Science at Bangalore constructed a 12" diameter cloud chamber that was used by Prof. M.S. Sinha to study the scattering characteristics of 'meson'.

Time distribution of cosmic rays has been tested and investigated by using different Geiger counter (Vikram Sarabhai, 1942). He has found that the arriving of cosmic rays follow a law of complete time randomness and their behaviour is similar to that shown by radiation from radioactive sources. Prof. Vikram Sarabhai also discussed the possibility of detecting deviation from time randomness in the case of cosmic rays. Prof. Piara Singh Gill and his students studied time variations of cosmic rays and extensive air showers at high latitude station Gulmarg by using the Geiger Muller counters.

Ahluwalia (1962) studied the semidiurnal variation of the cosmic rays intensity for geomagnetically disturbed days based on the data at the equatorial stations of Ahmedabad (India) and Huancayo (Peru) during 1957 and 1958. He showed that the low average amplitude of the semidiurnal variation observed on geomagnetically disturbed days, compared with geomagnetically quiet days, is primarily due to the large variability of the time of maximum of the semidiurnal variation on disturbed days. He also suggested that any theory which seeks to explain the origin of daily solar variation of cosmic rays must take account of semidiurnal as well as diurnal variations.

Cosmic Rays and Electrical System of the Earth Atmosphere

The variables of electrical system of the Earth's atmosphere are highly dependent on a wide range of atmospheric processes, ranging from scales of a few meters on the edges of clouds up to global scale (Harrison and Carslaw, 2003). A possible connection between electrical environment and climate of the Earth atmosphere including the modulation of electrical conductivity and cloud nucleation rates by cosmic radiation have been discussed by Carslaw *et al* (2002) and Singh *et at.* (2004). CTR Wilson in early days has discussed the importance of cosmic rays in the electrical properties of the atmosphere and cloud formation. Variation in ionization was suggested as an explanation for changes in weather and climate (Ney, 1959; Bering 1995).

The profiles of the ion production rate for cosmic rays for various geomagnetic latitudes during the solar cycle minimum using the data from Nehar (1967) is presented in Fig. 1. The ionization rate increases with geomagnetic latitude, and both the height of the peak and the slope of the ionization rate after the peak also increase. Near the ground there is about 20% variation between the equatorial region and the higher latitudes. The additional charge pairs produced by cosmic rays enhance conductivity of the lower atmosphere and hence enhance the thunderstorm charging current by facilitating enhanced charge transfer. Ionospheric potential is also enhanced in the process.

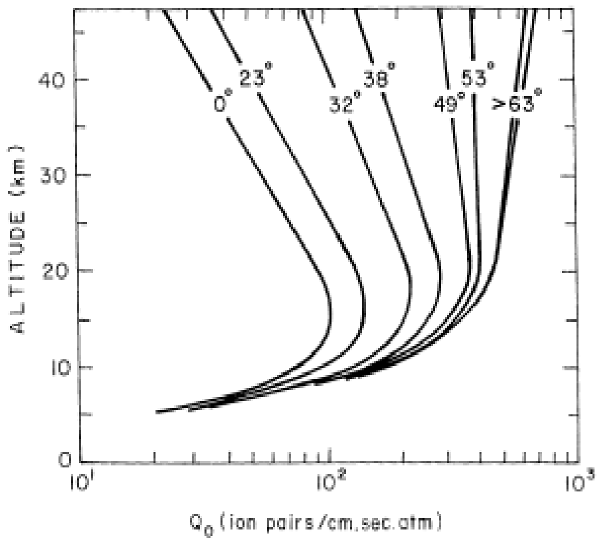

Fig.1: Vertical profiles of the cosmic ray ion production rate at various geomagnetic latitudes during solar minima (Neher, 1967)

Ion produced by cosmic rays in lower atmosphere had shown the largest modulation through a solar cycle leading to similar modulation in aerosols and water vapor condensation (Rogers and Yu, 1989). The aerosol particles may initiate the nucleation process in a slightly super-saturated water vapor. When the aerosol is dissolved in a tiny haze particle, the vapor pressure of the drop is lowered, increasing the probability of drop growth. The size of the aerosol is dependent on the statistical distribution of charges on the aerosols (Hoppel *et al.,* 1986; Gringel *et al.,* 1986).

Serrano *et al.* (2006) using the electric field data recorded at the Portela meteorological station (Lisbon) have shown a negative correlation with cosmic radiation flux and also analysis of the seasonal behavior of this correlation indicated that it is strong in wintertime and mild in summertime, while it follows the annual mean in autumn and in spring. They have given a probable explanation by considering that cosmic rays, instead of acting directly through air ionization may have indirectly acted by enhancing droplet and cloud formation by ion capture and formation of a negative layer in the lower atmosphere, which would reduce the electric field. This is similar to the reduced field hypothesis (GCR-CN-CCN-cloud hypothesis) proposed by Yu (2002).

Bazilevskaya (2000) reviewed the cosmic rays variability and emphasized that the difference between GCR and solar cosmic rays could be used to investigate possible atmospheric responses. He also discussed how ions could affect ice nucleation, atmospheric chemical reactions, droplet nucleation and global atmospheric electric circuit. Harrison (2000) had evaluated the effect of image charge on aerosol collection by droplets. The microphysics of the aerosols on cloud boundaries as a link between high-energy particles and the global circuit was summarized by Tinsley (2000) and Siingh *et al.* (2005).

Cosmic rays ionize the atmospheric gas constituents and hence modify the atmosphere's columnar resistance and ionospheric potential (Markson, 1981). The effect of cosmic rays on ionospheric potential was originally identified from solar modulation of low energy cosmic rays in the form of eleven-year cycle. The correlation between galactic cosmic rays and cloud cover for an 11-year solar cycle basis (Carslaw *et al.*, 2002) has enhanced the interest in the study of relationships between solar variations and weather changes. The cosmic ray flux penetrating down to the earth's lower atmosphere during active period of the Sun decreases due to its interaction with solar wind. The steady increase in solar activity during the twentieth century has led to a secular decline in cosmic rays (Carslaw *et al.,* 2002) and the expected global circuit response has been identified in surface measurements of potential gradient in the United Kingdom (Marcz and Harrison, 2003), although aerosol changes have also been suggested to be responsible agent (Williams, 2005). Harrison and Ingram (2005) have also reported a decrease in the air-earth current at Kew and in the potential gradient in mountain air in the 1970s.

The cosmic rays may also affect the climate / weather involving cloud processes such as condensation of nucleus abundances (Wilcox *et al.*, 1974), thunderstorms electrification and thermodynamics (Markson and Muir, 1980), ice formation in cyclones (Tinsley, 1996), *etc.* Svensmark and Friis-Christiansen (1997) have analyzed data and showed a correlation between cosmic rays and the earth's cloud cover over a cycle. Turco *et al.,* (1998) and Marsh and Sevensmark (2000) suggested that galactic cosmic rays could generate aerosol particles that can act as cloud condensation nuclei and affect, particularly over ocean, the formation and thickness of cloud. They also found a strong association between low clouds, at around 3 km altitude, and cosmic rays flux. Thus, it is likely that the cosmic ray influences the GEC as well as climate/weather. This early suggestion of Ney (1959) still remains to be explored in depth. In fact the observation of a correlation between cosmic ray intensity and cloudiness provides an opportunity to investigate ion-aerosol-cloud interaction, because variation in ion production rate due to cosmic rays may impact aerosol distribution and cloud formation. Rainfall is an important controlling factor of average cloudiness of a region via cloud lifetime. Even ice-particles growth induces rainfall because liquid clouds are highly supersaturated with respect to ice. Both these aspects can be studied in detail through ion-aerosol-cloud interactions in which ion production is governed by galactic cosmic rays.

Cosmic rays provide the sole source of ions away from terrestrial sources of radioisotopes such as radon, and cosmic ray variations directly influence the global atmospheric electric circuit on cloud formation (Tinsley, 2000). Variations in atmospheric electric fields maintained within the clouds due to the solar activity are proposed as a means of modifying the rate of droplet formation, which would in turn affect the latent heat release rates and transfer properties. Global circulation affects the temperature and thunderstorm activity as part of this process and thus causes change in the local thermodynamics. The global circuit links the upper atmosphere to the surface changes in the electrical potential of the ionosphere, which are communicated directly by the air-earth current flowing through cloud layers to the surface (Gray *et al.,* 2005; Singh *et al.*, 2007 and references there in). The physical consequence of this coupling for climate is not clear till now. Electrically induced aerosol microphysics on the boundaries of clouds may be important, such as coagulation and scavenging. This involves complex processes, which are not yet fully developed as compared to the particle nucleation process. Gray *et al.,* (2005) summarized the range of processes that can result from the solar modulation of cosmic rays and link global atmospheric electrical circuit with global climate. It is clearly seen that the cosmic rays and shower clouds control atmospheric electrical system which affect cloud microphysics leading to change in ice cloud and stratiform cloud and hence change in climate. The atmospheric electrical system also affects radiative transfer mechanism of the atmosphere leading to global temperature changes which control thunderstorm activity, and hence electrical system of the atmosphere, thus forming a closed system. The global temperature variation also affects cloud microphysics, ice cloud and stratiform cloud formation.

Cosmic Rays and the Earth's Climate

The ionization variation influences the optical transparency of the atmosphere by changing the aerosol formation and also by influencing the transition between different phases of water (Ney, 1959; Tinsley, 1996). Cloud reflects more energy than they stop and lead to a cooling in the range 17-35 Wm^{-1} (Ramanathan *et al.,* 1989). A close correlation has been observed between cloud coverage and cosmic ray activity (Svensmark and Friis–Christiansen, 1997). The cloud coverage may control atmospheric heating profile because cloud could reflect incoming short wave radiation leading to cooling, where as it may reflect the outgoing long wave radiation and produces heating.

Yu (2002) pointed out that the global warming in 20^{th} century coincides with decreased cosmic ray intensity. Since cosmic ray intensity reaching the earth depends on solar winds, which is controlled by solar conditions. This suggests that the sun has also some role to play in global warming. Under suitable conditions, cosmic ray-induced cloud changes may warm the earth's surface and cool the lower troposphere and thus provide an explanation of the earth's varying temperature trends. The light ions produced during cosmic ray ionization also act as a source of cloud condensation nuclei (Arnoldo, 2006) leading to the fact that cosmic rays induces cloud formation.

Based on the premise that aerosols ionized by cosmic rays are more effective as ice nuclei and cause freezing of super cooled water in cloud, Brian Tinsley (1996, 2000) has developed a more detailed mechanism for the link between cosmic rays and cloudiness. It is not easy to estimate the net change in radiative forcing from a solar modulation of the cloud cover. The main problem is that it is not known which part of the cloud volume is effective in heat energy transport / reflection. However, net effect of clouds on planet is either to cool or to warm depending upon the thickness, density and altitude location of the cloud above the earth's surface, atmosphere, and therefore, one could imagine that an increase in cosmic rays flux could lead to a complex phenomena involving heat transfer and under some situation may lead to warming.

Cloud variation:

The cosmic rays and low attitude cloud (<3 km altitude) observed by global satellite are well correlated around the cosmic rays minimum of 1990 (Svensmark and Friis-Christensen, 1997; Marsh and Svensmark, 2000). The limitations of the data analysis and acquisitions have been the subject of considerable discussions (Kernthaler *et al.*, 1999). Kuang *et al.,* (1998) repeated Svensmark and Friis-Christensen's analysis of International Satellite Cloud Climatology Project (ISCCP) data and showed high correlations with an El Nino-Southern Oscillation (ENSO) index difficult to distinguish from the GCR flux. The pattern of change of cloudiness over the period, particularly in the Pacific Ocean, corresponds to what would be expected for the atmospheric circulation changes characteristic of E1 Nino (Farrar, 2000). Kernthaler *et al.* (1999) have also studied the ISCCP data set, using both geostationary and polar orbiter data and suggested that the correlation with cosmic rays flux is reduced if high latitude data are included. Jorgensen and Hansen (2000) also noted that a mechanism whereby cosmic rays resulted in greater cloud cover would be most likely to affect high cloud as ionization is greatest at these altitudes. Kristjansson and Kristiansen (2000) have analyzed additional data set of the ISCCP D2 satellite recorded during 1989 to 1993, and found little statistical evidence of a relationship between GCRs and cloud cover with the possible exception of low marine clouds in mid latitudes. They also could not find correlation between outgoing long-wave radiation and cloud cover as represented in ERBE data and GCRs. Harrison and Stephenson (2006) analyzed data recorded at different meteorological sites in UK and GCR data and confirmed the existence of cosmic ray effects on clouds on long time scales with less variability than the considerable variability of daily cloudiness. Yu (2002) has explained differential cosmic rays effects on low and high clouds in terms of ion-induced particle production and its recombination rates which are proportional to their concentrations.

The ion life time is greater at lower altitude where the cosmic ray produced ionization rate is smaller. In the lower atmosphere aerosol particle density is larger and hence cloud condensation nuclei would be formed easily. A negative correlation between cosmic rays and global temperature has been reported by Shaviv and Veizer (2003) for cosmic ray changes generated by the solar system and passing through the spiral arms of the galaxy. An attempt was made to explain it using a mechanism similar to ion-induced CCN formation (Marsh and Svensmark, 2000), in which the CCN lead to more cloudiness, reduced insolation and lower temperatures. Thus, the evidence for a cosmic rays impact on cloudiness could not be accepted with certainty. If there is a systematic variation in low cloud properties caused by solar variability, it could have important implications for the valuation of Earth climate. It is essential to exactly pin-point the control of solar variability on cloud cover under different conditions and then to obtain the role of cosmic rays on the cloud cover and control of global temperature.

Carslaw *et al.* (2002) proposed two mechanisms linking cosmic ray produced ions to clouds named as clear air mechanism and near-cloud mechanism. In the clear air mechanism, ions produce ultra fine particles (Harrison, 2002), which is based on the examination of aircraft exhaust (Yu *et al.,* 1998). Extending the same work, Yu and Turco (2000) showed that charged molecular clusters can grow significantly faster than neutral clusters through the process of condensational growth and coagulation from molecular cluster scale to micron size, large enough to become stable particles. Charge may also act to stabilize small clusters, reducing evaporative loss. The primary particle in the above process is ultra-fine aerosol whose density is controlled by a competition between new particle formation and scavenging by the large pre-existing background aerosol. Based on the above physical process, Yu (2002) argued that increases in cosmic ray would lead to differential particle production with increases in the lower troposphere but decreases in the upper troposphere because of the altitude dependence of the sensitivity of particle production to the ionization rate. Using this fact one can explain the observed different correlations between cosmic ray variations and low, middle and high cloud anomalies. This hypothesis can be extended also to explain the observed global surface and troposphere temperature trends. The above physical processes could explain the measurements reported by many authors (Aplin and Harrison, 2001; Harrison and Aplin, 2001; Laasko *et al.,* 2004; Wilhelm *et al.,* 2004).

The near-cloud mechanism involves changes in electric field adjacent to a horizontal layer of cloud/aerosol, which may arise from the vertical conduction current flowing in the global electric circuit. This change in electric field causes the upper part of a thin stratiform cloud to become more positively charged than the clear air above it because of decrease in conductivity due to removal of ions in the layer. In fact the vertical electric field increases in the low conductivity region to maintain a constant conduction current. Tinsley and Heelis (1993) suggested that the electric field could enhance the effectiveness of aerosol as ice-forming nuclei. Tripathi and Harrison (2001, 2002) have confirmed it and shown that this electro-scavenging effect increases as the aerosol radius decrease below one micron. This effect is independent of sign of the aerosol charge, because electrical image force dominated at the near by distances from the droplet (Tinsley *et al.,* 2000). The observed peak in precipitation at cosmic ray maxima is the only argument to support cosmic rays related-scavenging (Kniveton and Todd, 2001); where as the physical mechanism should involve irradiance changes, which has not yet been studied. Gray *et al.* (2005) have asserted that the electrical effects are very much smaller in stratiform clouds than in thunder storms and the local electric fields and charge densities are modulated by cosmic rays and global circuit changes. Further, in the near-cloud mechanism, the aerosol charging is coupled with global electric circuit changes and hence the aerosol-cloud microphysics at long distances away from the source disturbance could be affected. This point has not been explored systematically. Through GEC short term solar changes may be communicated to cloud formation processes and hence to the climate variability. Further study in this direction is required.

Temperature influence:

Recent developments showed that global warming may result in enhanced convective activity of thunderstorm and in turn increased thunderstorm production on a global scale (Markson and Price, 1999). During the last century the temperature on the Earth's surface increased by ~ 0.6^{o} C (Hansen *et al.,* 1999), where as its effect on lightning is not very well known. Even the causes which could explain these phenomena have not been found till now. Stozhkov (2002) had suggested two mechanisms for heating namely solar influence on the weather and climate, and the influence of human activities on atmospheric processes (such as green house effect). The physical mechanism of the green house gases has been understood where as the mechanism of solar influence on weather and climate requires further investigation.

Lean *et al.* (1995) have calculated the correlation between Northern hemisphere surface temperature and solar irradiance (reconstructed from solar indices) from 1610 to 1994 and showed the coefficient to be 0.86 in the pre-industrial period from 1610 to 1800. Extending this correlation, they have suggested that solar forcing may have contributed about half of the observed 0.6C^{o} surface warming since 1860 and one third of the warming since 1970. The remaining change in global temperature during the pre-industrial period may be due to cosmic rays forcing. It is possible to compute the variation in cosmic ray flux and the temperature change based on simple assumptions. From numerical modeling and satellite observations it is found that a 1% change in the total composition of the Earth's cloud cover corresponds to 0.5 W/m^{2} change in net radiative forcing (Rossow and Cairns, 1995). Global cloudiness changed approximately 3.0%, which can estimate to 1.5 W/m^{2} from the year 1987-1990 (Marsh and Svensmark, 2000). In the same period cosmic rays, as measured from ion chamber, has changed by ~ 3.5% (Marsh and Svensmark, 2000). He also calculated the approximate radiative forcing by taking in to account the running mean 11-years average increase of cosmic rays from 1975-1989 in between 0.6-1.2%, which comes out to be 0.3-0.5 W/m^{2} change in cloud forcing. The direct influence of changes in solar irradiance is estimated to be only 0.1^{o}C (Lean *et al.,* 1995). The cloud forcing however, gives for the above sensitivity, 0.2-0.5^{o}C. In this calculation it is assumed that the whole cloud volume is affected by solar activity. From the above discussion it appears that an increase in cloud cover results in lower temperatures.

Maunder Minimum:

The annual variation of sunspot (darker cooler regions of the Sun's surface associated with high magnetic flux) number shows a remarkable feature in Sun's history during the period from 1645 to 1715, when the sun spot numbers almost became zero. This is called as Maunder Minimum (MM). Another minimum in sun spot activity is observed between 1800 and 1825 called Dalton Minimum as is evident from Fig. 2 which summarized the 400 years of regular sunspot number observations.

The presence of Maunder minimum and Dalton minimum shows that the sun was less active. The variation in activity suggests that the sun may have been more active some time before than we have seen in the last 400 years. In future also Sun's activity may considerably change (increase or decrease). These upheavals in solar behavior may have been accompanied by significant long-term changes in radiative output. During Maunder minima, the absence of strong magnetic field region on the surface of the Sun affects the solar wind flow and hence modifies the characteristic features of cosmic rays incident on the Earth's atmosphere. The long term changes in solar radiative output and cosmic ray features may result in to long term climate changes on the Earth's surface.

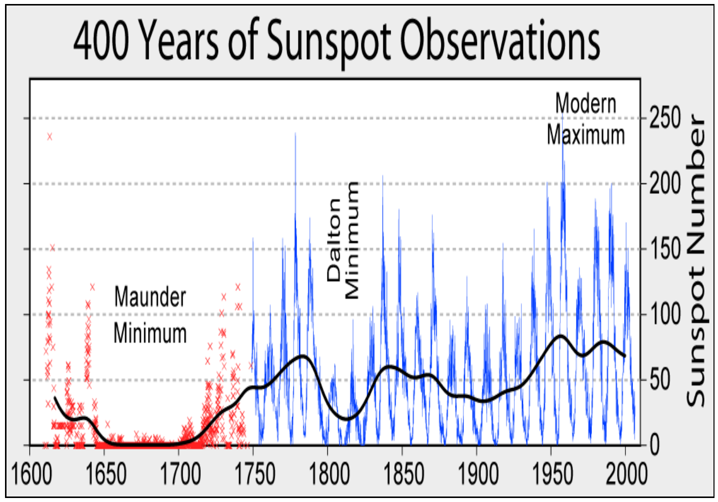

Fig. 2: Summarizes the 400 years of regular sunspot number observations. The source of the figure is (http://en.wikipedia.org/wiki/Maunder_minimum)

The cause of these variations are not well understood, but because sunspots and associated faculae affect the brightness of the sun, solar luminosity is lower during the period of low sunspot activity. During Maunder minima period, a striking similarity between ^{10}Be curve and the temperature curve has been pointed out (Marsh and Svensmark, 2000). There seem to be a cyclic behaviour in both the magnetic and temperature data. In fact the decade 1690-1700 is the coldest during the last 1000 years, at the same time ^{10}Be concentration has the largest peak. A good agreement between temperature and ^{10}Be concentration suggests that cosmic rays are important in sum / climate link. It is general perception that the low activity during the MM and earlier periods may be among the principal cause of the Little Ice Age (Lean *et al.,* 1995 and references there in). Extending the same hypothesis, some scientists have proposed that the modern maximum may be partly responsible for global warming especially the reported temperature increase between 1900 and 1950 (Eddy, 1976). The above discussion shows that the sun may play significant changes in the climate in the time to come and even the destruction of civilization may be possible.

Fig. 3 (http://en.wikipedia.org/wiki/Maunder_minimum) shows two different proxies of solar activity during the last several hundred years. The lower curve in the figure shows sunspot number (Rg) as reconstructed from historical observations by Hoyt and Schatten (1998) and the upper curve shows the Beryllium -10 concentration (10^4 atoms/(gram ice-core) which is a cosmogenic isotope created in the atmosphere by galactic cosmic rays as measured from Dye-3 Greenland (Beer *et al.,* 1998). Both of the curve match well except some microscopic changes.

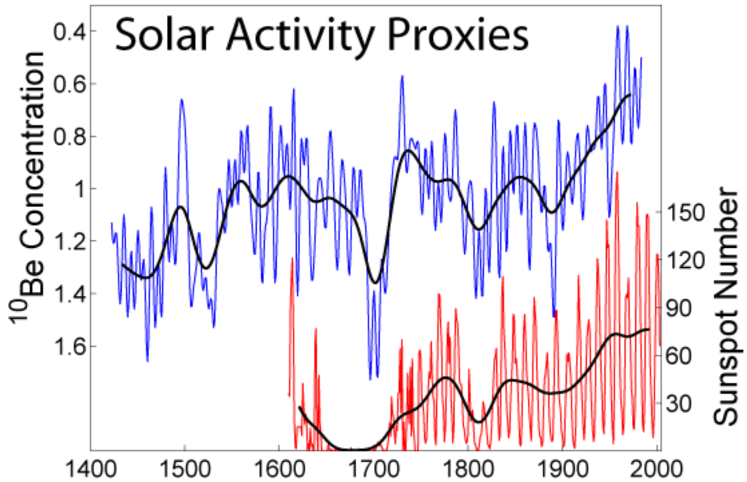

Fig. 3: The lower panel of the figure shown sunspot Number (Rg) as reconstructed from historical observations (Hoyt and Schatten,1998) and upper panel of the figure shown the Beryllium-10 concentration (10^4 atmos/(gram ice-core) (Beer *et al.,* 1994). Both of the proxy is related to solar magnetic activity. The source of the figure is (http://en.wikipedia.org/wiki/Maunder_minimum).

Cosmic Rays and Aerosol

The nature and size of aerosol particles are height dependent and also have a significant effect on the earth atmosphere heat balance. The observation of spectra in the region of low cloud formation indicates that participating aerosols are produced locally. In the troposphere ionization, is the main contributor to the gas particle formation of ultra-fine particles (<20nm) aerosol, and the subsequent growth into the matured aerosol distributions which act as CCN (Yu and Turco, 2000). Ionization density height profile of the atmosphere and the major ion species produced is shown in Fig. 4 (Viggiano and Arnold, 1995, Marsh and Svensmark, 2000). It is clearly seen from this figure that the complexity of ions increases with decreasing altitude and ions produced within the troposphere by cosmic rays are potentially important for aerosol production in the atmosphere (Marsh and Svensmark, 2000). However, it is not simple and straight forward to show that the variability in atmospheric ionization due to the GCR flux could have a significant effect on either aerosol production or droplet growth. Simulation models have revealed that nucleation through ion-ion recombination is capable of maintaining a background aerosol distribution with realistic concentrations in the troposphere (Turco *et al.,* 1998). In the absence of other potential sources, we may expect that a systematic change in cosmic ray ionization could lead to a change in aerosol population acting as CCN and thus influence cloud formation process which may be different at different altitudes. For example, in the upper troposphere the short lived organic precursor gases may be less important because they may be destroyed during transport from the surface to the upper troposphere. Further, the atmospheric trace gas ammonia, which promotes sulphuric acid nucleation in continental ground level air may not be abundantly available in the upper atmosphere due to its large solubility in liquid water and hence wet removal.

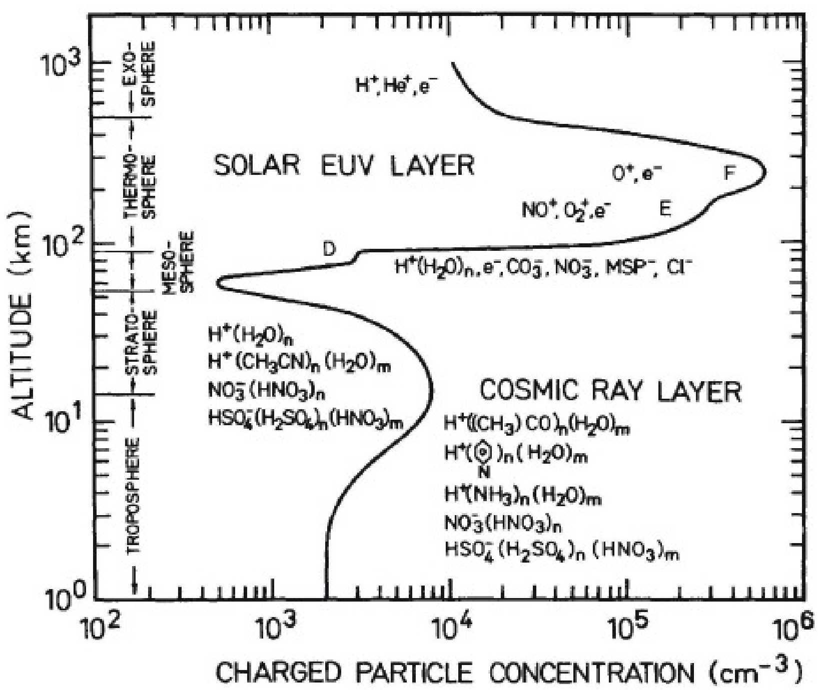

Fig.4. Ionization density height profile of the Earth atmosphere and the major ion species at various altitudes (Viggiano and Arnold, 1995)

Cosmic rays and ozone

The solar energetic particle events including GCR affect the atmospheric ozone. During these events a shower of high energy charged particles penetrate the terrestrial atmosphere and perturb the stability of its chemistry. Specially, the balance of nitrogen (NOx) and hydrogen (HOx) components are changed and the O_3 destruction begins via catalytic process (Jackman *et al.,* 1995). The high energy charged particle's effect can be synthesized as follows:

i- ozone response to solar proton event is generally observed at high latitudes where the shielding action of the geomagnetic field is reduced

ii- solar cosmic rays (SCRs) with energies greater than 10 MeV affect the stratosphere chemistry

iii- ozone depletion starts within few hours of the arrival of charged particles

iv- solar particle induced effects in the atmosphere could last days or weeks, but no relevant long-lived effects were claimed. However, by the downward transport of chemical components, NOx is primarily found in the troposphere as HNO_3, which dissolves in water vapor is finally removed with snow (Kudela *et al.,* 2000 with references therein).

Kozin *et al.* (1995) showed that during these events the total ozone content, registered by 29 stations situated in the latitudinal range 35 – 60 ^{0}, decreased practically synchronously with the galactic CR intensity. However, after the depletion, a positive phase of the disturbance occurs with a maximum about 9 – 11 days later. Shumilov *et al.* (1997) have shown an increase of the total ozone up to 10% at high latitudes during Forbush decreases (Fds) while insignificant effect are suggested for middle latitudes. However, Watanabe (1999) reported very small change in the stratosphere and troposphere conditions during Fds and geomagnetic activity at 69° S, 40° E (Sywa). The total ozone response to major geomagnetic storms (Lastovicka and Mich, 1999) were evaluated which was found to be significant, which is probably caused by charges in the atmosphere dynamics. Marcucci *et al.,* (1999) studied the possible relationship between auroral activity and total ozone depletion over Antarctica during the period of the 1979-1987 and 1990 August, and showed a delayed positive correlation between enhanced auroral activity and total ozone depletion over the Austral region. This delay time ranges between 8 to 13 days. These results seem to be in contrast with the ones for Fds and ozone variability. Moreover, high relativistic electron precipitation events, which occur during magnetic storms, leave their imprints in the mesospheric and upper stratospheric ozone content (Callis *et al.,* 1996). These results clearly show the control of cosmic rays over ozone distribution and its chemistry in the terrestrial atmosphere.

Cosmic Rays and Space Weather

Space weather is a new field of science dedicated to the understanding of the Solar Interplanetary-Terrestrial system. According to Lundstert (1998) "Space weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technology system and can endanger human life or health". There are two ways by which the cosmic rays affect our space weather systems: (i) intensity increase caused by the acceleration of particles in solar flares and/ or in the interplanetary space lead to direct changes in materials exposed to the particle radiation both in space and on the surface of the Earth, (ii) CRs detected by the network of neutron monitor (NMs) reveal the anisotropies relevant for space weather research.

Cosmic rays and energetic charged particles in space affect the phenomena occurring in solar atmosphere, heliosphere and geosphere. These particles are relevant for (i) studying changes in the physical state of the magnetosphere and the near Earth inter-planetary medium, (ii) studying effects on space-craft and air-craft electronics, (iii) understanding of the electromagnetic propagation in the Earth environment. In fact high energy particles can deposit enough charge in the electronic components to affect the memory state (SEU: single event upset) or to induce false signals, where as less energetic events affect components by causing permanent damage (Hilgers and Daly, 1998; Johnson and Dyryklev, 1998; Kudela *et al.,* 2000). High energy electrons accumulate charges in poorly conductive material of the space-craft and may lead to dielectric breakdown and material damage. Dorman *et al.* (1993) have discussed the use of CR monitoring in complex studies of phenomena which are considered to be dangerous for the Earth's civilization. Space weather events leave their imprints on the total ozone content of the terrestrial atmosphere, which is also affected by cosmic rays. Thus, space weather events, ozone content and CR are interred linked and a detail study is required to understand the physical processes under laying the coupled system.

Cosmic Rays and Human Health

It is known that any type of radiation is dangerous to human body. But there is always a level below which the amount of radiation received is within the safe zone. However, it is difficult to quantify this level in the case of cosmic rays. Further, the amount of the cosmic radiation received is a function of altitude above the surface of the Earth, geomagnetic latitude and the solar activity cycle. Because of this it is difficult to model accurately the dose level for the human health. As the cosmic ray intensity increases with height, it becomes a cause of concern for those who are frequently flying and also for air craft crew members. The dosage units are μ Sv (Sievert Symbol, 1Sv = 1J/Kg = $1m^{-2}s^{-2}$) per hour and at sea level the dose rate is approximately 0.05 μ Sv per hour where as at commercial aircraft altitudes (~35000 ft), the doze rate between of the order of 4 μ Sv per hour. The accumulated radiation exposure from a flight schedule of 100 hours per month for six months comes out to be 2·4 mSv which is higher than the recommended limit of 2.0m Sv for a pregnant women (Shea and Smart, 2000). In general the recommended limit for human beings is about 20 mSv per year. US Federal Aviation Administration has developed a computer code to quantify the radiation exposure on any specific air route. Using this code one can easily compute the amount of expected radiation dose in a flight.

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