GALACTIC COSMIC RAY VARIABILITY IN THE HIGH AND MID LATITUDES DURING SOLAR CYCLES 22 AND 23

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JUNE, 2014

CERTIFICATION

This is to certify that the work embodied in this project is original and has not been submitted in full or part thereof for any degree or professional qualification for this or any other University

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APPROVAL PAGE

UGWUOKE, ANSELM IKECHUKWU a postgraduate student in the department of Physics and Astronomy with registration number **PG/M.Sc/11/59551** has satisfactorily completed the requirement for the course and research work for the degree of Master of Science in Atmospheric physics, University of Nigeria, Nsukka.

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DEDICATION

To

All that died for offences they never committed

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ABSTRACT

Galactic cosmic rays are modulated in the hliosphere primarily due to the global merged interaction regions with intense magnetic field which leads to a decrease in the galactic cosmic rays throughout the heliosphere. Using long term averages of solar wind (SW) component parameters in addition to cosmic ray count rates of two high latitude Neutron monitor stations (Apatity and Thule) and two mid latitude stations (Newark and Tbilisi) with different rigidity cut-offs, we analyzed the effect of these SW components on the counts rates under different interplanetary magnetic field (IMF) disturbance levels. From first order partial correlation, we found that the total interplanetary magnetic field (Total B) was the most dominant modulating parameter especially during quiet conditions and the solar wind dynamic pressure (SWDP) was more effective during disturbed conditions. The influence of the more subtle parameters like solar wind speed (SWS), Z component of IMF (Bz) and solar wind density were masked by these dominant parameters vis IMF (Total B) and SWDP. Also, cosmic ray count rates on these stations studied showed similar annual variation trend, with station of lowest cut-off rigidity having highest amplitude and vice versa, confirming cut-off rigidity as another important modulating factor.

CHAPTER ONE

1.1 COSMIC RAYS

The cosmic rays (CRs) are energetic charged subatomic particles originating from the outer space with lifetime of the order 10^6 years or longer, incident at the top of the terrestrial atmosphere and produce showers of particles on interaction with the atmosphere which penetrate and impact the earthʼs atmosphere and sometimes reach the earthʼs surface. Apart from particles associated with solar flare, cosmic Rays come from outside the solar system. The incoming charged particles are modulated by the solar wind, the expanding magnetized plasma generated by the sun, which decelerate and partially excludes the lower energy cosmic rays from the inner solar system. CRs are mostly pieces of atoms: protons, electrons, and atomic nuclei which have had all of the surrounding electrons stripped during their high-speed (almost the speed of light) passage through the space.

The need to study cosmic rays and their interaction with earth is driven by the understanding that CRs are the major source of ion production in the lower atmosphere (troposphere and stratosphere), therefore, the electrical properties of the atmosphere such as atmospheric electric current, lightening production and thunder cloud formation e.t.c., can be affected by cosmic rays (Ermakov and Komozokov, 1992). It also damages micro-electronics and life outside the protection of the atmosphere and Geomagnetic field. CRs have sufficient energy to alter the state of element in electronic integrated circuit, causing transient errors to occur, such as corrupted data in electronic memory devices or incorrect performance of central processing unit (CPU). It ionizes the nitrogen and oxygen molecules in the atmosphere which leads to a number of chemical reaction; and is responsible for the continuous production of a number of unstable isotopes in the atmosphere of the earth, such as carbon 14 (^{14}C).

$$n + {}^{14}N \rightarrow P + {}^{14}C \qquad 1$$

Cosmic Rays are one of the most important barriers standing against interplanetary travel and pose threat to electronics placed aboard outgoing probe. Magnetic shielding for spacecraft have to be considered in order to minimize damages to electronics and human by cosmic rays (Nancy, 2005).

1.2 Types of Cosmic Rays

Types of cosmic rays are classified according to two categories; one, depending on their sources, they are of three types, galactic cosmic rays (GCRs), solar cosmic rays (SCRs), and anomalous cosmic rays(ACR). Two, depending on interaction with space, they are of two types, primary and secondary cosmic rays. Cosmic rays originate as primary cosmic rays, which are those originally produced in various astrophysical processes. Primary cosmic rays are composed primarily of 98% nuclei and 2% electrons. Of the nuclei, 87% are protons, 12% helium nuclei, and 1% heavier nuclei (Andreas, 2008). Heavier nuclei examples, carbon, oxygen, iron and other nuclei synthesized in stars are primary cosmic rays.

Secondary cosmic rays are caused by decay of primary cosmic rays as they impact on atmospheric materials; they include neutron, pion, and muon. Nuclei such as lithium, beryllium and boron (which are not abundant end-product of stellar nucleosynthesis) are secondaries. Antiprotons and positrons are also in large part secondary cosmic Rays. One primary ñrayò can cause 50 secondary ñraysò, a cascading effect that eventually gets down the ground. The shower of secondaries can spread over a large area. We are constantly being bombarded by these particles.

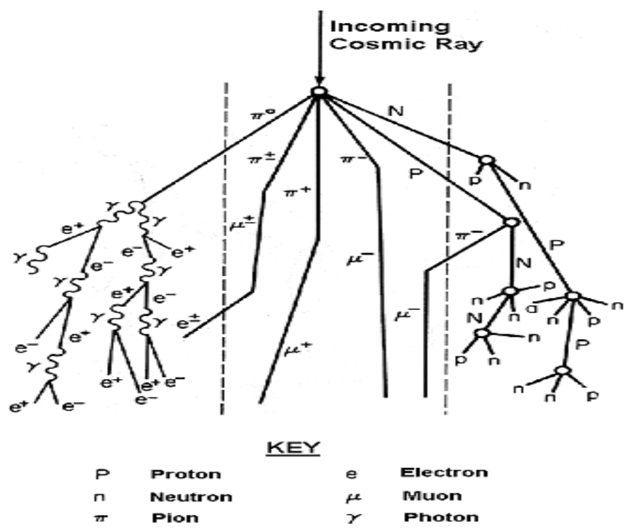

FIG., 1.1: Schematic diagram of primary CR interaction with atmosphere materials producing secondary cosmic rays.

Secondary Cosmic Rays as a shower particles composed of electrons, gamma ray, pion and muon. We know that atoms are made up of protons, neutrons and electrons. Muons are in the same family of electrons. These are the secondary cosmic ray particles we usually detect on the ground to know that a primary cosmic ray has reached the earthôs surface. Secondary particles can travel faster than the speed of light in air (they are still slower than the speed of light in vacuum), thus causing Cherenkov radiation (cerenkov light is emitted when the velocity of charged particle is greater than the speed of light in a medium with a given refractive index n:

$$V > \frac{c}{n} \qquad 1.1$$

A typical Cerenkov cone, produced in an attitude between 7 and 20km, has radius of about 150m. The number of the cerenkov protons for a primary with an energy of ITeV amount to about 10^6. The dectetor of these photons is made by photomultipliers; disadvantage of this technique is that the observation can only be made during moonless nights. The traveling cosmic rays disrupt the surrounding molecules in our air and cause the electrons from the atoms in air to change their energy state. As the electrons restore back to equilibrium, they emit photons which increase the intensity of the radiation, thereby producing Cherekov radiation.

About 150 muons are striking every square meter of the earth every second. We are bombarded with these particles every day. Not all shower particles reach the ground (sea level) the atmosphere blocks some. Muons are produced when pions decay. Pions are in the same family of particle (hadrons) as protons and neutrons because they are made up of quarks. Muons have negative electric charges and are in the same family of particles (leptons) as electrons.

There are more cosmic rays of certain element than there should be. However the actual abundance among cosmic rays differ immensely, especially for lithium, Beryllium, and Boron which are far more common. This increased abundance may be due to the collision by cosmic rays into carbon, Nitrogen, or oxygen, breaking them apart and creating new lithium, Beryllium and Boron.

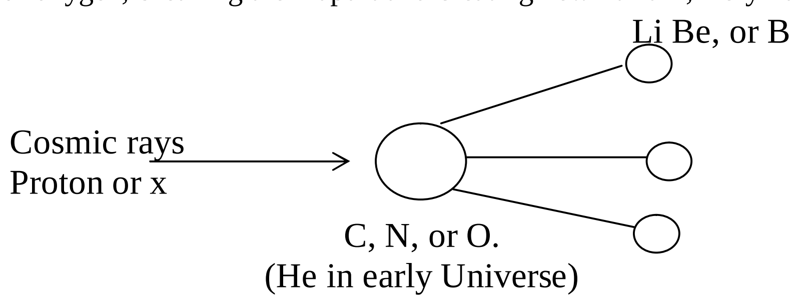

Fig., 1.2: Shows abundance of Li, Be, or B due to collision by cosmic rays into C, N, or O

The constituents of cosmic rays can be summarized thus.

1. Primary cosmic rays:
   ≈ 2% electrons
   ≈ 98% nuclei

These 98% nucleonic nuclei is made up of
   ≈ 87% protons
   ≈ 12% Helium nuclei
   ≈ 1% heavier nuclei (Andreas, 2008)

2. Secondary cosmic rays
   - Leptons: all
     Mostly electrons, positions, (anti) muons, electron, and muon (anti) neutrinos.
   - Hadrons: all
     Mostly neurons, nuclei, pions, anti protons.

1.2.1 Galactic Cosmic Rays (GCRs)

Galactic cosmic rays are cosmic rays that come from outside the solar system but generally from within the galaxy (Milky Way). They have probably been accelerated within the past million years and have travelled many times across the galaxy, trapped by the galactic magnetic field (GMF); they have been accelerated to nearly the speed of light, most probably by supernovae explosions. The magnetic field of the earth, the sun and the galaxy itself bend the paths of the galactic cosmic rays. Some of the isotopes have half-lives that are comparable to the time interval since their formation and isotopic ratio can therefore have some information about the amount of time that has passed since they were formed. In a few cases, there are isotopes that are unstable with respect to electron capture, but because they are fully stripped, they have not decayed in flight. Most galactic cosmic rays have energies that are low to penetrate the earthồs atmosphere, and the radius of their trajectories due to earthồs magnetic field tends to channel them to the poles when they strike the atmosphere. These can create large showers of secondary particles that are detected on earthồs surface. Cosmic rays that are detected in the neutron monitors are galactic cosmic rays, because they have a very high energy that will enable them traverse galactic, interplanetary and earthồs magnetic field as they travel through space before being detected in the earth surface. Owing to this propagation process, we expect a spatial dependence of G C R intensity. In addition, because of the high variability of the solar wind and the embedded magnetic field we also expected temporal variations. The observable quantities therefore are time sequences of fixed positions in space and spatial gradients in GCR intensity between observers at different positions. In addition, an easy access of GCR over the poles of the sun was expected. In the plane of the ecliptic, the magnetic field line is tightly wound to an Archimedian spiral while it is much less wound up above the pole. Thus it was expected that in the inner heliosphere, GCR intensities are higher over the poles than in the plane of the ecliptic illustrated in figure 1.3.

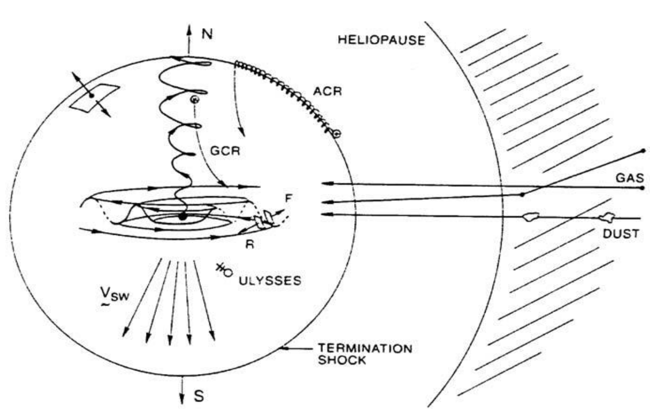

Fig**., 1.3** Travel paths for particles in the heliosphere. Thus an easy access of GCRs was expected at high heliographic latitudes [Lee, 1995].

Origin of GCRs are probably from shock acceleration at super-nova remnants. A supernova is a star of several times the mass of our sun that has run out of the nuclear fuel of light elements, especially hydrogen, needed to keep it shinning. Its nuclear burning gradually converts the light elements into heavier ones through a process known as supernovae nucleosynthesis. Light element in big bang followed by the formation of the first star and by the production of heavier element in subsequent nuclear burning phase in the interior. The heat it produces keeps it from collapsing under its own immense weight. When the star can no longer produce nuclear heat, it suddenly collapses to a small volume, releasing enormous amount of gravitational energy. Much of that energy is spent in a grand explosion blowing the stars outer layers out to space and thereby creating a huge expanding shock front. It is this shock front which is believed to accelerate the cosmic rays particle to nearly the speed of light.

The chemical composition and the presence of heavier elements like Fe, C, Ni , Li, Be, B etc in the CR detected in the ground based neutron monitors gives clear evidence that CR at the Earthôs surface are of galactic origin. ^{58}Fe which is very abundant in cosmic ray source material, the other well known anomaly in the cosmic ray Isotopic composition is ^{22} Ne; the ^{22}Ne/^{20}Ne ratio which is greater in the cosmic ray source than in the solar wind. Both ^{22}Ne and ^{58}Fe are product of He burning in supernovae nucleosynthesis process.

1.2.2 Solar Cosmic Rays (SCRs)

Sun is also a source of cosmic ray shown from the acceleration of energetic protons, ions and electrons in close association with solar flare and coronal mass ejection. These are provided by direct observation of the energetic particles in interplanetary space or at the Earth surface. Also, by the dictation of various neutral radiations produced in interaction of the accelerated particle with the solar atmosphere and the solar magnetic field. These solar energetic particles which originate mainly from solar flare, coronal mass ejection and shock in the interplanetary medium occurs sporadically. They may have energies up to several GeV, observed in the heliosphere usually for several hours mainly during solar maximum activities.

1.2.3 Anomalous Cosmic Rays (ACRs)

The anomalous cosmic rays were originally interstellar neutral atoms that got singly ionized relatively close to the sun. They are transported as so called PICK-UPS ions to the outer heliosphere where they get accelerated up to ~100MeV through various processes. Their compositions consist of hydrogen, helium, nitrogen, oxygen, neon and argon. Immediately upon ionization, the interstellar particles are picked up by the solar wind and acquire energies of about 1KeV/nucleon to become ACRs.

The principal acceleration mechanism to accomplish these remarkable features has been considered to be diffusive shock acceleration.

1:3 VARIABILITIES OF GALACTIC COSMIC RAYS

Life on earth is protected against galactic cosmic rays by three space ñfrontiersò, the first one (1) the dynamic heliosphere with the solar wind and the accompanying turbulent Heliospheric magnetic field (HMF) (2) the earthôs magnetic field, with its dynamic character. This means that significant changes in the geomagnetic cut-off rigidity for galactic cosmic rays occur, sufficiently large over the past 400 years so that the change in galactic ray FLUX impacting the earth may approximate the relative change in FLUX over a solar cycle (Shea and Smart, 2004). The magnetosphere withstand the space weather change that the sun produces, and also reverses its magnetic polarity on a very long-term (the last one was 780,000 year ago, so that the next reversal is considered long overdue). (3) The atmosphere with all its complex physics and chemistry. The galactic cosmic ray intensity decreases exponentially with increasing atmospheric pressure.

The most important variability time scale related to solar activity is the 11-year cycle. This quasi-periodicity is convincingly reflected in the records of sunspots since the early 1600s and other solar activity indices and also in the galactic cosmic rays intensity observed at ground and sea level especially since the 1950ôs when neuron monitors (NM) as cosmic ray detectors were widely deployed as part of the International Geophysical year (IGY 1957).

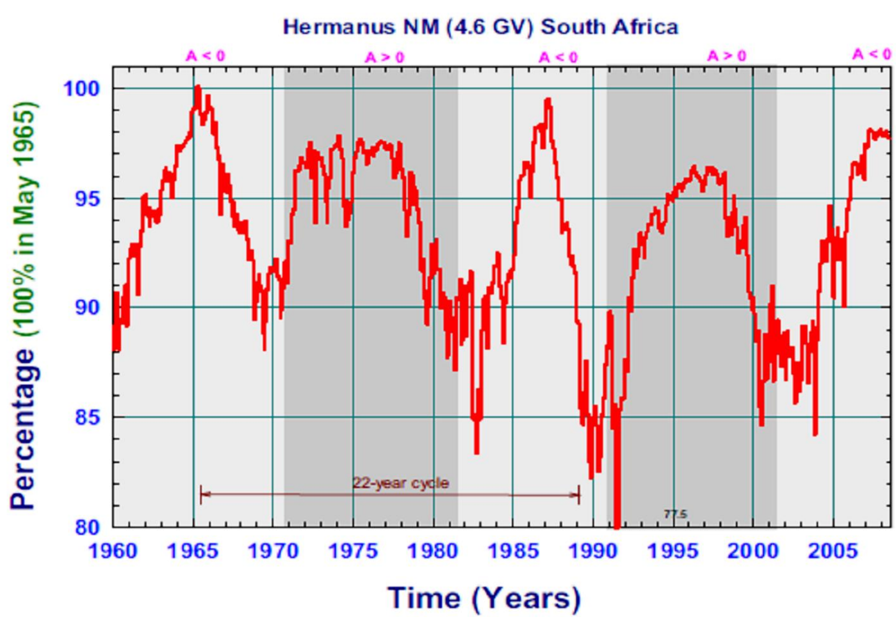

Fig., 1.4: The Hermanus CR Monitor station, illustrating the 11-year and 22-year cycles (Potgieter, 2013).

Another important cycle in figure 1.4 is the 22-year cycle shown, directly related to the reversal of the solar magnetic field during each period of extreme solar activity. There are several additional short periodicities evident in neutron monitor (NM) and other galactic cosmic ray data eg the 25-27 day variation caused by the rotational sun, and the daily variation caused by the earthôs rotation. These variations seldom have magnitude of more than 1% with respect to the previous quiet time. The well-studied corotating. Effect is caused mainly by interaction regions created when a faster solar wind overtakes a previously released slow solar wind. They usually merges as they propagate outwards to form various types of interaction regions, the largest ones are known as global merged interaction regions (GMIRs). They are related to what happened to the solar magnetic field at an earlier stage and are linked to coronal mass ejections, that are always prominent with increased solar activity but dissipate during solar minimum.

Much of the short-term variability can be explained by changes in solar activity, while longer-term variations appear to correlate with changes in the earthôs magnetic dipole. It is widely known fact that of the heliosphere asymmetry has a complex character. Not only distribution and structure of magnetic poles and inhomogeneities are complex but also sunspot numbers spatial distribution character is complicated. We believe that the sunspot numbers, in the epoch maxima of solar activity, toward the apex are more. In other words the sun activity has asymmetrical character and develops in the apex direction. It should be one of the causes of the heliosphere asymmetry that should be mapped on distribution of density and gradients and also on annual variations of Galactic Cosmic Rays (GCRs). The influence of heliospheric geometry on cosmic ray intensity were studied by several authors Fichtner and Sreenivasan, (1996), Fichtner and Sreenivasan, (1999), and Hasbrock and Potgiester, (1997).

Another variability of galactic cosmic rays is noticed when energy density of solar clouds is high enough to distort the motion of the galactic cosmic rays and causes the Forbush decrease. On the other words, the flux of galactic cosmic rays in region of disturbed solar wind caused by geomagnetic storms shows a significant decrease, this phenomenon is called Forbush decrease.

1.4 COSMIC RAY MODULATION

Galactic Cosmic Rays (GCRs) that enter the heliosphere are affected by the interplanetary magnetic field (IMF) and solar wind. This result in the modulation of their total flux and differential energy spectrum as measured in the vicinity of the earth. The modulation varies with the varying solar activity and is often described in terms of the so-called force field model (Gleeson and Axford, 1968; Caballero Lopez and moral, 2004; and Mc Cracken et al., 2004). The only explicit parameter of this model is the modulation potential ϕ whose value is given in units of MV (in literature it is also called ñForce field parameterò) the ϕ corresponds to the average energy loss of cosmic ray inside the heliosphere.

In the region between ≈ 10AU and ≈ 43AU there was a close relation between the changes in the cosmic ray intensity decreases at a rate proportional to interplanetary magnetic field (B). When B is less than the average the cosmic ray intensity increases at a constant rate. Step like decrease in the cosmic ray intensity which propagate into the outer heliosphere at the solar wind speed where observed by Mc Donald et al., (1981).

Apart from the dynamic heliospheric processes that produce the anomalous cosmic ray, the modulation of the galactic cosmic ray intensities by the solar wind has a major effect on the observed intensities at earthộs Orbit. Figure 1.5 shows the intensity of high-energy cosmic rays measured in the Climax neutron monitor station (cut-off energy 2.99 Gev) over several solar cycles. The alternating appearance of more sharply pointed ñVersus ñFlalterò solar minima peaks is due to particle drifts whose effects alternate as the solar magnetic field undergoes a 22 year cycle. (kota and Jokipii, 1983)

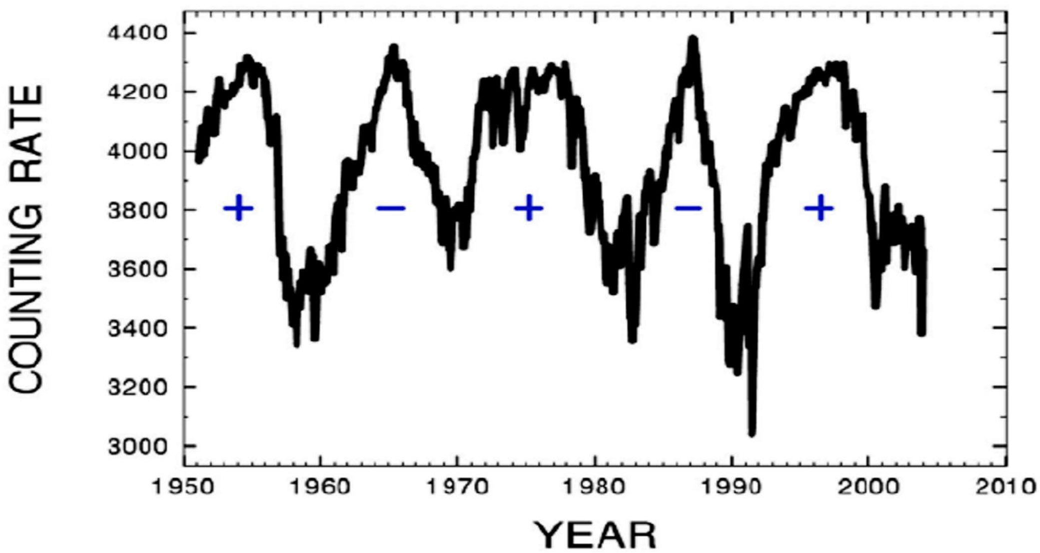

Fig., 1.5: High-energy cosmic rays measured in Climax neutron monitor station over almost five solar cycles

More complete model of the heliosphere are now being used to help interpret there observation Example, it is now evident that a significant fraction of GCR modulation takes place in the Heliosheath well beyond the present location of the voyager spacecraft (consider figure 1.5). For the GCR, the primary effect of modulation is adiabatic energy loss that prevents low energy particles from reaching I AU (Fisk et al., 1998). As a result, little is known of the spectrum of low energy (<300 Mev /nuc) cosmic rays outside the heliosphere.

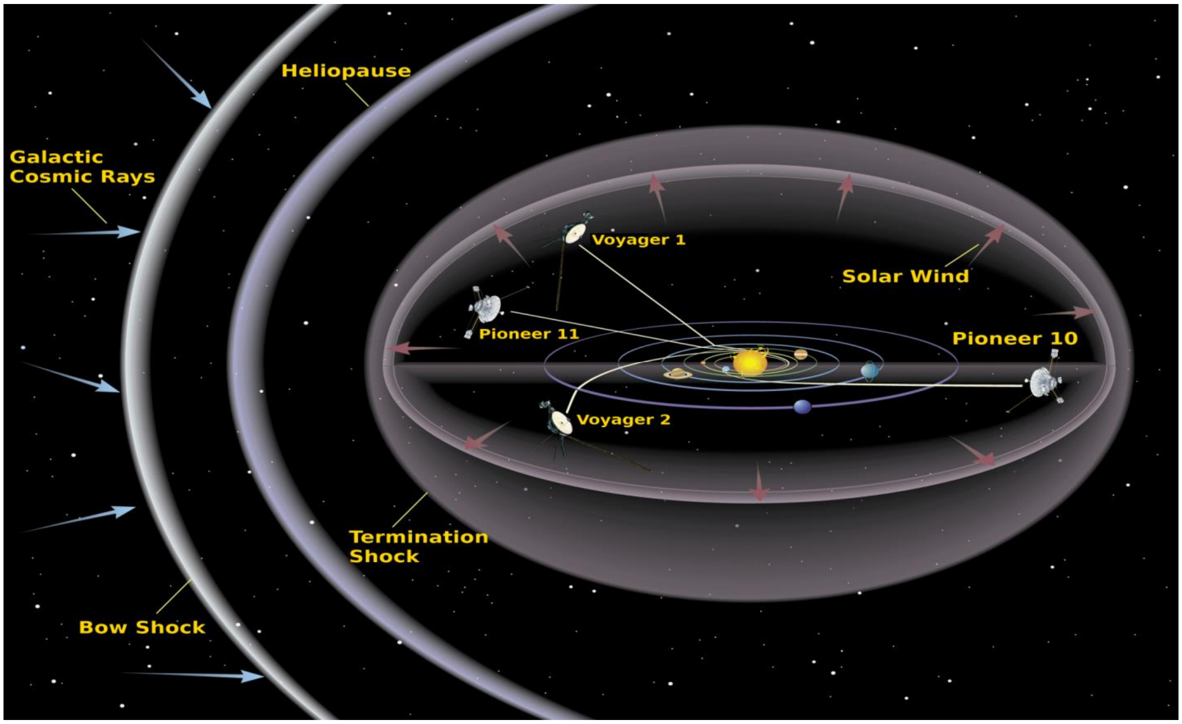

Fig.,1.6 Schematic diagram of the Heliosphere
(image: http://www.nasa.gov/centers/ames/images/content/72408main_ACD97-0036-1.jpg).

1.4.2 GEOMAGNETIC FIELD MODULATION

The geomagnetic field equally offers its own shielding in terms of the cut-off rigidity, this geomagnetic cut off rigidities are a quantitative measure of the shielding provided by the earthôs magnetic field. More precisely, geomagnetic cutoff rigidities predict the energetic charged particle transmission through the magnetosphere to a specific location as a function of direction. The generally accepted manner for determining cutoff rigidities is by the method of tracing particle trajectories in model magnetospheres. Since the earth magnetic field is basically dipolar, Störmer (1995) came with equation that described cut off rigidity:

$$R_c = 1.9M\left(\frac{R_o}{R}\right)^2 Cos\,\lambda_G (GV) \qquad 1.2$$

where R_C = Rigidity cut off, M= Geomagnetic field dipole moment, R_o = Earth mean radius
R = distance from the given location to the dipole centre, and λ_G = Geomagnetic latitude.

It is expected that changes in the dipole moment will modulate the flux of galactic cosmic rays and this expectation is global.

1.4.3 Solar Modulation

When cosmic rays enter our solar system, they must overcome the outward flowing solar wind. This wind imbedded with the solar magnetic field scatters and slows the incoming cosmic rays, reducing their energy and preventing cosmic rays with lowest energy from reaching the Earth. This effect is known as solar modulation. The sun has an 11 year activity cycle which is reflected in the ability of the solar wind to modulate cosmic rays. As a result, the cosmic ray intensity on earthôs surface is anti-correlated with the level of solar activity. When solar activity is high and there are lots of sunspots, the cosmic ray intensity at earth is low and vice-versa. This so-called solar modulation of galactic cosmic rays is due to the propagation of the energetic particles in the dynamical environment of the Heliosphere. The magnetic field in the heliosphere is highly variable during periods of high activity, i.e. when the number of sunspots, flares and mass ejections, is high. The turbulent interplanetary magnetic field deviate the cosmic rays much more efficiently than in periods of low activity, when the magnetic field is more regular. The strong magnetic field fluctuations do not only reduce the number of cosmic rays reaching the inner heliosphere and earth, but they also change their energy spectrum (because particles of lower energy are more strongly affected than very energetic ones) and their direction of propagation (anisotropy).

Coming together of slow and fast solar wind give rise to merged interaction region (MIR) that also causes CR variation. First, the GMIR consists of clusters of strong fields, rather than a single broad region of strong field, second, the step-like decrease in the cosmic ray intensity are not smooth decrease, but they contain some relatively large and abrupt decrease, each of which is related to a localized peak in B. third, prior to the step decrease, B was relatively low and the cosmic ray intensity was increasing. Fourth, following the step-decrease, the cosmic ray intensity was relatively constant and the magnetic field strength was near average. This type of behaviour (decrease cosmic ray intensity when B is relatively strong; increasing CR intensity when B is relatively weak, and constant Cosmic Ray intensity when B is near average has been observed by V2 and V1 for many years beginning at approximately 11 AU in 1981 (Burlaga et al., 1985).

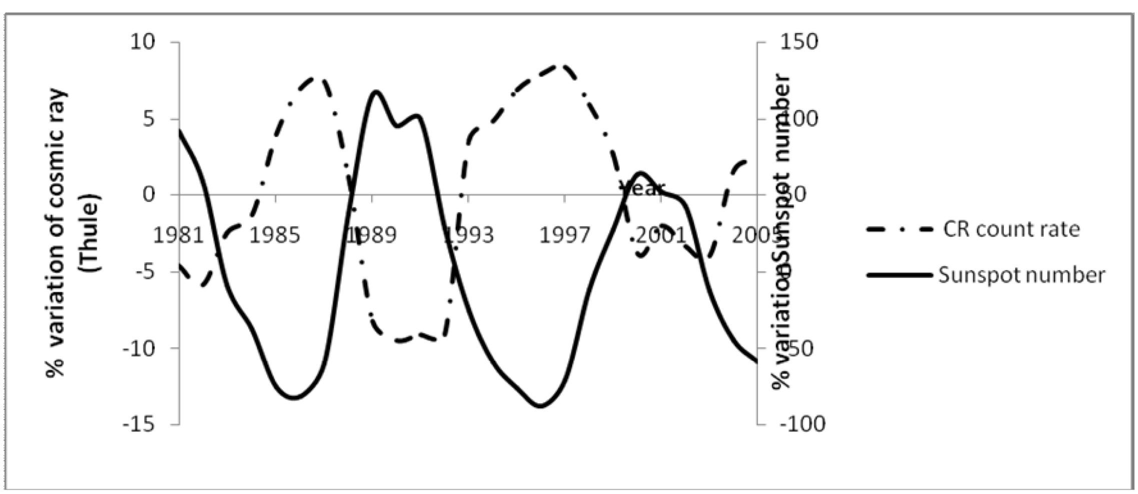

Fig., 1.7 Illustration of Inverse-relation of solar wind parameters and cosmic ray count rate

1:5 CURRENT MISSION TO UNDERSTAND COSMIC RAY SOURCES AND TRANSPORT.

Pinpointing a direct source of cosmic rays is impossible (except for perhaps, the highest energy cosmic- rays) individual cosmic rays move along random path. In the turbulent magnetic fields, they are observed to come from all direction in the night sky (at any point they are isotropic). Indirect methods indicate that most cosmic rays < 10^{15} eV are from shock wave driven by super nova explosions. Despite wide agreement that supernovae remnants (SNRs) are the sources of galactic cosmic rays, unequivocal evidence for the acceleration of protons in these objects is still lacking. When accelerated protons encounter interstellar material, they produce neutral pions, which in turn decay into gamma rays. This offers a compelling way to detect the acceleration sites of protons. The identification of pion ï decay gamma rays has been difficult because high-energy electrons also produce gamma rays via bremsstrahlung and inverse Compton scattering. Ackermann et al., (2013) using Fermi Large Area Telescope gave direct evidence that cosmic ray proton are accelerated from supernova remnants. Sun is also a source of cosmic rays, evidenced from the acceleration of energetic protons, ions and electrons in close association with solar flares and coronal mass ejections.

Comparing the proportion of various heavy isotopic in cosmic ray source material and solar system material implies that cosmic rays source material must originate from a stellar mixture very similar to that which contributed to the interstellar matter from which the solar system condensed (Wiedenbeck, 2003). In addition, since the cosmic ray lifetime in the Galaxy is $\approx$ 15 million years as a result of various loss processes, cosmic rays must be recent sample of galactic material, and it appears that there has been relatively little evolution in the composition of interstellar matter over the 4.6 billion years since the solar system formed.

Some years ago, Casse and Paul, (1982) proposed that a significant fraction of heavy cosmic ray originate in Wolf-Rayet (W-R) stars-massive (>$25M_o$) star with intense stellar wind of several thousand Km/s. As a result of mass loss, the hydrogen envelopes of the stars have been stripped off and the wind of owe class of these stars are comprised of helium burning product emerging from their surfaces.

1.5.1 Equations (S) For Cosmic Ray Transport

The major tool, for understanding cosmic ray is the Parker transport equation (Parker, 1965). It is an excellent and applicable approximation nearly all the time. The transport equation for pitch-angle-averaged distribution function ä(*r, p, t)* as a function of position r, particle momentum p, and time t; may be written as a combination of the four effects (Jokipii and Kota, 2007) stated below;

1. Diffusion, caused by the scattering of the cosmic rays by the irregularities in the magnetic field. The associated diffusion K_{ij} is significantly large along the magnetic field than normal to it.

2. Convection, outward flow from the sun at the solar wind velocity V_w

3. Guiding-centre drift V_d, given in terms of the average magnetic field B_o, the particle charge q defined by Fisk and Schwadron , (1995) as

$V_d = (pcw/3q) \nabla \times (B_0/|B_0|^2)$ 1.3

Where w = speed of particles, C = speed of light, B_0 = average magnetic field

4. Energy change caused by expansion/compression of the background fluid $\nabla.U$

When Q is Local sources, like particles accelerated at the termination shock or interplanetary shocks

These effects are combined in Parkerȍs transport equation.

The Parkers transport equation is

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[K_{ij}^{(s)} \frac{\partial f}{\partial x_j}\right] .... \Big\} \ diffusion$$

$$-U.\nabla f \quad \Big\} \text{Convection by plasma}$$

$$-V_d.\nabla f \quad \Big\} \text{Gradient \& Curvature drift.}$$

$$+\frac{1}{3}.\nabla.U\left[\frac{\partial f}{\partial_{\ln p}}\right] \quad \Big\} \text{ Energy change}$$

$$+Q \quad \Big\} \text{ source.} \qquad 1.4$$

where, $K_{ij}^{(s)}$ = is the symmetric part of the diffusion tensor, B_o = average magnetic field and U is the cosmic ray number density per unit interval of kinetic energy.

Where the drift velocity due to the large scale curvature and gradient of the average magnetic field is

$$V_d = \frac{P_{cw}}{3q} \nabla \times \left[\frac{B}{B^2}\right], |V_d| = O\left(\frac{r_c}{\angle} w\right) \qquad 1.5$$

It is difficult to overstate the importance of the equation. It is the basis of 95% or more analysis of energetic particles and cosmic ray-sun, hemisphere, galaxy, intergalactic etc.

The parkers transport equation is generally applicable for cases in which the anisotropy is small. The associated anisotropy is obtained from the diffusive streaming flux

$$S_i = -k_{ij} \frac{\partial f}{\partial xi} + \left(\cup_i / 3\right) p \frac{\partial f}{\partial p} \qquad 1.6$$

or bulk velocity s_i / w, which gives the anisotropy

$$\delta_i = 3S_i / w \qquad 1.7$$

Where w is the particle speed one can generally estimate the anisotropy as

$$\frac{\delta \frac{1}{4} \lambda}{L} \quad 1.8$$

where λ is the mean free patch and L is the macroscopic scale.

1.8 SOLAR ACTIVITY AND THE CYCLES 22 AND 23

The occurrence of various solar activity features shows non-uniformity over the solar disk. It has also been noticed that more activity features occurs in one part of the solar hemisphere than the other at the same time. When there features are examined with respect to equator of the sun, they are referred to as the North-South (N-S) asymmetry. They N-S asymmetry of several solar activity features viz relative sunspot number (SN) (this is calculated by first counting the number of sunspot groups and then the number of individual sunspot). Sunspot groupȏs arears (SA), flare, HX flare indices (Q) solar active prominences (SAP), coronal mass ejections (CME), radio bursts, solar gamma ray bursts, coronal holes, faculae, green corona, corona ionization temperatures and magnetic fluxes.

This North-South asymmetry or polar regions are occupied by unipolar regions of opposite polarity, further the sign of polarity changes every 11 years. This particular distribution is partly responsible for the apparent dipole like field of configuration inferred from structure of the solar corona. For this reason, sun was thought to have a centered dipole field. In the mid and low-latitude belts there are both unipolar regions and much stronger bipolar regions. In general a well-developed bipolar region can be identified by two darks spots namely the sunspots. Sunspots are also magnetic regions on the sun with magnetic field strengths thousands of times stronger than the earth magnetic field. How suns magnetic field reconnects with the geomagnetic field determines how solar activity affects the earth.

Sunspots usually come in groups with two set of spots. One set will have positive or north magnetic field while the other set will have negative or south magnetic field. The field is strongest in the darker part of the sunspots (the umbra), weaker and more horizontal in the lighter part of the sunspots (penumbra). Faculae are bright areas around the sunspot, and are usually most easily seen near the limb or edge, of the solar disk. They are also magnetic areas, but the magnetic field is concentrated in much smaller bundles than in sunspot. While the sunspots try to make the sun look darker, the faculae make it look brighter. During a sunspot cycle, the faculae actually win out over the sunspot and make the sun appear slightly brighter at sunspot maximum than at sunspot minimum. Recent measurements from satellites reveal that during a sunspot maximum, more radiation may actually leave the photosphere. The reason for this lies in the fact that the bright areas around the sunspots (known as faculae) radiate more energy as sunspot activity increase. Sunspots do not appear at random over the surface of the sun but are concentrated in two latitude band (N-S) on either side of the equator. These bands first form at mid-latitudes, widen, and then move toward the equator as each cycle progresses. During transitions between cycles, typically the old cycle spots continue even as new cycle spots appear at higher latitude with reverse polarity. Eventually new spots overwhelm the old spots which gradually end; consider the butterfly diagram in figure 1.8

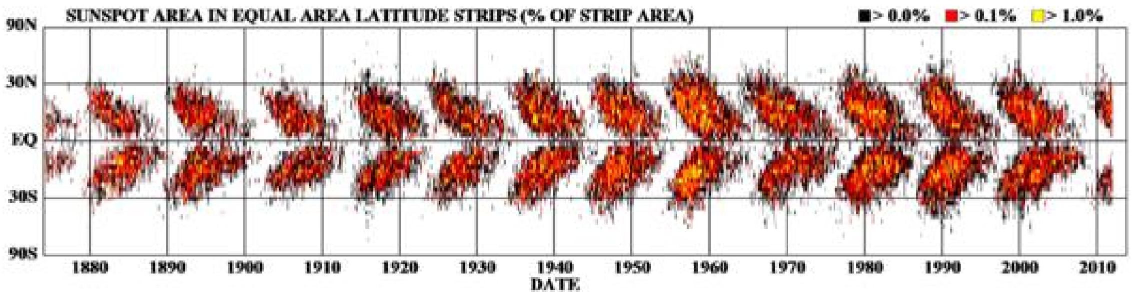

Fig., 1.8: The sunspot butterfly diagram by the solar group at NASA Marshall Space Flight Center.

It is observed that solar cycle 23 is magnetically week when compared to solar cycle 22 also, when compare the amplitude of solar cycle 22 and 23 using different solar activity features in all activity indices the amplitude of solar cycle 23 are distinctively weaker than the solar cycle 22. During the time of decreased amplitude of solar activity we would accept longer-period cycles as in cycle 23 (Hathaway et al., 2002). This is enough evidence to support that solar cycle 23 is magnetically weaker; the activity in rising phase of solar cycle 22 is higher than the solar cycle 23, which means that the activity in solar cycle 22 is higher than solar cycle 23.

1.8 PURPOSE OF STUDY

This study is aimed at investigating the role of solar wind parameters on galactic cosmic ray variation during solar cycles 22 and 23 at different interplanetary conditions (quietest conditions, all conditions, all-quietest conditions, and disturbed conditions).

We shall attempt to statistically determine solar wind parameters that plays dominant role in the modulation of galactic cosmic ray flux measured from cosmic ray neutron monitor stations in high and mid latitude during different interplanetary magnetic conditions.

CHAPTER TWO

LITERATURE REVIEW

2.1 RECENT REVIEW LITERATURE ON DAY – TO – DAY VARIABILITY

Relationships of cosmic ray intensity with solar activity have been studied by a number of authors (Gupta et al., 2006; Kane, 2006; Mishra and Agrawal, 2007; Shrivastava and Agrawal, 1993; Dwivedi et al., 2010). Owing to the rotation of the sun, interplanetary magnetic field has a form of Parkerõs spiral. A three dimensional form of the Parker spiral that result from the influence of the sunõs rotating magnetic field on the plasma in the interplanetary medium. Intensity of cosmic ray in solar system results from two processes; one, convective outflow of galactic cosmic rays due to scattering on solar wind discontinuities and, two, diffusion of cosmic rays into solar system. Daily variations understood to result from a combination of inward diffusion along the spiral interplanetary magnetic field and outward convection by the solar wind. If we decompose cosmic ray flux into radial and tangential components, radial flux of galactic cosmic rays will be compensated by the solar wind convective outflow while the tangential component, due to earthõs rotation, cause variation with maximum at 18.00 hour local time.

Solar diurnal variation of cosmic ray intensity shows a large day to day variability (Ananth et al., 1974). This variability is a reflection of the continually changing condition in the interplanetary space (Fluckiger, 1991). The average diurnal anisotropy of cosmic radiation is being explained in terms of azimuthal corotation (Venkatesan and Badruddin: 1990). The systematic and significant deviations of amplitude as well as phase for diurnal/semi diurnal anisotropies from the average values are known to occur in association with strong geomagnetic activity (Kumar et al: 2001). The distinguishing features of these systematic deviations are the unusually low or high amplitude and usually, though not always, a shift in the phase towards earlier hour (Hashim and Thambyahpillai: 1969)

The average characteristics of cosmic ray during anisotropy are adequately explained by the co-rotational concept (Parker 1964) and (Axford 1965). This concept supports mean diurnal amplitude in space by 0.4% along the 18:00 hour direction using the world wide neutron monitor data. Though, the day-to-day deviation both in amplitude and phase and the abnormally large amplitudes or abnormally low amplitudes of consecutive days cannot be explained in co-rotational terms.

Many scientists (Rao et al 1972), (Kane: 1974), (Kane 1975) and (Owens and kash: 1976) used a new concept for the interpretation of the diurnal variation. (Jokipii: 1991) first suggested the extension of this new concept from the solar cosmic event to the observed diurnal variation and the theoretical formulation was provided (Forman and Glesson: 1975). On the basis of this mechanism the diurnal variation can be explained in terms of radial convection together with diffusion, which is mainly along the magnetic field line. The co-rotational concept is a special case of the convective ï diffusive model with which we can explain the characteristics of the diurnal variation even on a day-to-day basis. The phase shift of the diurnal anisotropy to earlier hour is well understood in terms of the convective ï diffusive mechanism (kane: 1974). Owen and Kash (1976) have noted that the non-field aligned diffusion on the days of normal diurnal amplitude is influenced by magnetic passages. Kane (1975) showed that, on a day-to-day basis, the diffusion vector deviates from the interplanetary magnetic field (I M F) direction in the ecliptic plane by more than 30^o on about 35% of the quiet days.

Comparing the diffusion vector with magnetic field vector (Ananth et al 1974) pointed out that this concept holds well on more than 80% of days. Of the rest of 20% of days, the diurnal anisotropy characteristics seem to indicate the presence of a significant component of a transverse diffusion current in addition to normal convection and diffusion flow. Such days are found to be present in the form of trains of consecutive days, and to be associated with abrupt change in the interplanetary field direction. The value of the ratio of perpendicular diffusion coefficients K_1 to the parallel diffusion coefficient K_{II}, that is K_I/K_{II} which is normally Ò0.05 for field ï aligned days, and ~ 1.0 on non-field ï aligned days. It has been shown by Axford (1965) that on many days the interplanetary field seems to stick to the garden ï hose direction and on some other days the reverse situation is observed. Owen and Kashi (1976) selecting only these days in which there are no complications from changing magnetic sectors and eliminating days with a poorly determined anisotropy or mean magnetic field direction, showed that the diffusion is field- aligned, on essentially all well-determined days (Rao et at 1972). Mavromichalaki (1980) has shown that the diffusion vector is field ï aligned during days exhibiting enhanced diurnal variation. The diffusion current on an average basis is being driven by large cosmic ray gradients in the ecliptic plane.

Changes have also been observed in the diurnal amplitude and phase during the high speed solar wind streams (ASSWS) coming from coronal holes (lucci et al: 1981, Munakata et al.1987) The diurnal variation might be influenced by the polarity of the magnetic field (Parker. 1991), so that the largest diurnal variation is observed during the day when the daily average magnetic field is directed outward from the sun.

2.2 REVIEW LITERATURE ON COSMIC RAY VARIABILITY.

Solar modulation of cosmic ray intensity has been extensively investigated in the past by using the data of ground based detectors in association with various solar, interplanetary and geomagnetic parameters (Schrivastava et al., 1993, and Heber et.al., 2006). It is well known fact that there is an inverse correlation between cosmic ray intensity and solar wind activity. Potgieter (2009) studied the relation between the dynamics of the heliosphere, its geometry, solar activity and cosmic ray variation, and the effects of the solar wind termination shock and the heliosheath on cosmic ray variability, also related to important recent observation in the heliosheath by the two voyager space craft. He observed that life on earth is protected against cosmic rays by three space ñfrontiersò,

(1) The dynamic heliosphere with the solar wind and the accompanying turbulent heliospheric magnetic field (HMF).

(2) The earthôs magnetic field, with its dynamic character

(3) The atmosphere with all its complex physics and chemistry. The cosmic ray intensity decreases exponentially with increasing atmospheric pressure. Cosmic ray variability contributes to the understanding of the importance of the complex field of space weather.

Only recently has the dynamics of the heliosphere been studied and appreciated, in particular its role in cosmic variability and ultimately its role in space climate (Scherer et al., 2006). Gupta et al., (2005) have it that correlation between cosmic ray intensity and various solar activities parameters are highly correlated with each other and modulate cosmic ray in the similar manner. An attempt was made to find out the most suitable index of the solar activity in order to reproduce to a certain degree the modulation of cosmic ray intensity (Nagashima and Morishifa, 1980).

Perko and Burlaga (1992) were of the opinion that GMIRs (global merged interaction regions) are shell-like region with intense magnetic fields extending around the sun and to high latitudes. They are associated with the interaction of transient and corotating MIRs (merged interaction regions) and produce step-like intensity decrease in GCRs throughout the heliosphere which in turn produces most of the modulation. Burlaga et al., (1985) on the close correlation between increasing magnetic Field strength and decreasing GCR intensity, suggested the relationship called cosmic ray-magnetic field relation (CR-B relation), this change in GCRs intensity J and magnetic field strength B relates to the Parkerôs magnetic field strength B_p

$$\frac{dJ}{dt} = -D\left(\frac{B}{B_p} - 1\right) \quad \text{For } B \geq B_p \qquad 2.1$$

$$\text{And } \frac{dJ}{dt} = R \quad \text{for } B < B_p \qquad 2.2$$

where D and R are constants and are equal to 0.0030 and 0.00125 respectively.

CR-B relation is a quantitative description; it does not make any assumption about the underlying processes. On analysis (Agrawal, el. al., 2011) showed that the enhancement in the cosmic ray diurnal anisotropy result from the corresponding enhancement in the magnitude of the solar wind speed and the interplanetary magnetic field strength B. This reflects that both the solar wind speed (SWS) and interplanetary magnetic field (IMF) contribute significantly in cosmic ray modulation.

Sigh et al., (2006) observed that Bz of IMF generally give rise to large Ap change, though it is not effective in producing CR intensity decrease. The southward, B_Z component of IMF does not usually contribute to the solar modulation of cosmic rays since the long-term average of this component near the Earth is proportional to zero (Sabbah, 1996).

The role of the solar wind speed (SWS) in cosmic ray modulation by Chirkov, (1985), seems necessary to account its influence, because the solar wind velocity determines two components of the comic ray modulation mechanism; the convection and adiabatic energy changes. Solar wind speed and IMF play an important role in controlling the electrodynamics of the heliosphere. The globally weaker solar wind is directly related to the lower average strength of the Sun's open field which leads to lower supply of mass and energy. Jokipii, et al., (1977) pointed out that in a standard parker field, the drift speed can be several times the solar wind speed. These drift effect; by far can exceed convection with the solar wind making drift an important effect in transport equation. The contributions of more than one solar, interplanetary or geophysical parameter to the cosmic ray modulation process have been reported (Mavromichalaki, and Petropoulous, 1984).

Dynamic pressure carries most of the energy of the solar wind in form of bulk flow energy. Thus, this quantity is an excellent measure of the average energy being introduced in the corona, which ultimately accelerates the solar wind. Leer and Holzer, (1980) showed that addition of momentum in the subsonic region increases the mass flux while keeping the solar wind speed roughly constant. So it is expected that the contribution of these parameters to GCR modulation will vary in response to the level of anisotropy in the heliopsheric energy density. The solar windȏs dynamic pressure is particularly interesting according to McComas et al., (2008) because it inflates the heliosphere, and balances the external pressure from the surrounding local interstellar medium. The recent crossings of the termination shock by the two Voyager space craft have been a major accomplishment that has renewed the interest in cosmic ray modulation and the physics of the heliosheath. The termination shock crossing by Voyager 1 at a heliocentric distance of 94 AU on 16 December 2004 (Stone et al., 2005) occurred during a significant inward motion of the shock. This was likely caused by the substantial drop in the pressure in early 2004 (McComas et al., 2006). While the pressure initially rebounded to ~2.6 nPa (at 1 AU) around the end of 2004, this was a temporary increase and the pressure has continued to drop off since. The overall decrease in dynamic pressure to ~2 nPa has surely made the heliosphere smaller than it was a decade ago, and is likely at least a contributing factor in Voyager 2 crossing the termination shock at just 84 AU in September 2007 (Richardson et al., 2008). More importantly, such low dynamic pressure also reduces the distance to the heliopause, meaning that if it stays low, Voyager 1 will reach this critical boundary earlier than previously anticipated.

Florinski and Zank (2005) on the study of galactic cosmic ray response to heliospheric environment changes and implications for cosmogenic isotope records and how it relates to cosmic ray viability, had it that changes in the local interstellar environment of the sun due to its encounter with an important source of long term cosmic-ray variability as measured in comogenic isotope records. Long-lived radioactive isotopes, such as ^{10}be, are produced in air showers caused by the passage of highly energetic cosmic ray, ions (mostly protons) through the earthôs atmosphere. The production rate (p) is

$$P = \int_{-0}^{-\infty} S(T)\frac{dJ}{dT}\,dT \qquad 2.3$$

Where S (T) is the specified yield of the product isotope from the primary particle with kinetic energy (T) (Webber and Higbie, 2003) and $\frac{dJ}{dT}$ is the primary proton spectrum at IAU.

Langer and Potigieter (2005) in the study of the heliospheric modulation of cosmic ray protons during increased solar activity, and effect on the position of the solar wind termination shock and the heliopause, found that what is of primary importance is the location of the heliopause. It can also conclude from their result that significant asymmetric modulation is to be expected between the up-wind and down-wind directions of the heliosphere but this may become measurable only when Voyager spacecraft move beyond the termination shock into the heliosheath. At the time of their research, the Voyager space craft is at the vicinity of the termination shock (McDonald et al, 2003). An active or inflated heliosphere is expected to filter a larger fraction of the GCR reaching the Earth. The interplanetary magnetic field is compressed on approach to the heliopause, producing a ñmagnetic wallò structure that tends to inhibit particle access to the heliosphere (Florinski et al., 2003).

The sunspot number, which is the most common tracer of solar activity, is not only manifestation for solar induced effect in the interplanetary medium including the cosmic ray variations, the flare related parameters are also indicator of this modulation (Mishra and Mishra, 2007; Mavromichalaki, et al., 2003).

Smart and Shea, (2005) pointed out that a charged particle reaches a specific location on the Earthôs surface or in an orbit, depends on the direction in which the particle is travelling (trajectory) and the magnetic latitude of that point. Few studies have considered modulations of cosmic rays during solar activity and using certain arrangements of geomagnetic activity level example, Tiwari et al., (2005), but not much work has been done to understand the association of the solar wind parameters during different levels of interplanetary disturbance. Since a wide range of processes lead to the modulation of GCR flux on the surface of the Earth, search for dominant factors of solar wind parameters under different interplanetary conditions is needed.

2.3 FACTORS AFFECTING COSMIC RAY PRODUCTION AND/OR TRANSPORT

The intensity of galactic cosmic rays recorded by the neutron monitors (NM) shows periodic and abrupt changes. An abrupt change of the galactic cosmic rays intensity such as the Forbush Decrease can be used to estimate the moving, direction of interplanetary magnetic cloud relative to the Earth (Oh and Y1, 2009). (Oh, et al, 2010) in the study of modulation cycles of galactic cosmic ray diurnal anisotropic variation, has it that diurnal variation is a nearly sinusoidal variation of galactic cosmic rays intensity with amplitude of 1 ï 2%. The diurnal variation is mainly due to local anisotropy of galactic cosmic ray flux due to the convection by the solar wind and to the diffusion along the interplanetary magnetic field (IMF). It is also caused by the asymmetry of the earthôs magnetosphere leading to a daily variation of the local geomagnetic cutoff and by the day-night difference in the atmospheric structure.

The phase and amplitude of the diurnal variation (direction of the galactic cosmic ray anisotropy) are modulated by various factors such as drift motions, local latitudinal gradient in GCR intensity, varying level of diffusion; changing solar wind conditions etc. These factors lead to the anisotropy in the GCR intensity in the heliosphere, and they vary with the solar activity. An idea of the phase of diurnal anisotropy of GCR begins from studies of (Forbush 1969, 1981) and (Agrawal and Bercovitch 1983) that, the intensity of high-energy particles is controlled by the diffusion effect due to magnitude of IMF (interplanetary Magnetic field). On the other hand, the intensity of low-energy particles is modulated by the drift effect due to the polarity of IMF. Thus, the phase of the diurnal anisotropy consists of two components, such as one and two sunspot cycles. Both high and low GCR particles contribute to the component of 22-years cycle in the phase variation, while the contribution to the 11 ï year component is higher for the higher energy GCR.

Potgeiter and Ferreira (2001) have developed models that have been used to study 11 ï year and 22 ï year variability of GCR. Ferreira and Potgeiter (2003) showed that the tilt angle of the perturbed current sheet in the heliosphere could be successfully used as a proxy for solar activity in the cosmic ray modulation model with particle drift in addition. Also, (Nachkebia and Tal, 2001) compared the heliospheric current sheet tilt from 1971 ï 1992 with cosmic ray intensity recorded in Deep ï River Neutron Monitor (DRNM), solar wind speeds and sunspot numbers. He observed differences in the sensitivity of cosmic ray intensity to change in the neutral sheet angles before and after the reversal of interplanetary magnetic field polarity.

Potgieter (2009),and (Scherer et al 2006) that studied the cosmic Ray in the Dynamic Heliosphere, have it that the galactic cosmic Ray flux is not only varying due to the solar activity ï induced changes of the solar wind and heliosphere magnetic field (HMF) but also in the response to the changing state of the interstellar medium surrounding the heliosphere. Change in the interstellar environment would have a dramatic effect on the heliosphere. The region expands in low density environment and contracts when the ambient density is high. This implies that the properties of the heliospheric interface as a medium for galactic cosmic ray (GCR) propagation vary with time. A thicker heliosheath is expected to filter a larger fraction of the galactic radiation reaching the earth. In addition, more charge exchange will occur in the solar wind when the neutral hydrogen density inside the cloud is high, resulting in higher pick-up ion production rate and, consequently, more turbulent conditions in the solar wind which would accordingly increase the amount of modulation (Florinski and Zank: 2005). The sunspot number, which is the most common tracer of solar activity, is not the only manifestation for solar induced effects in the interplanetary medium including the cosmic ray variations. The flare related parameters are also indicator of this modulation (Mishra and Mishra, 2005, Mavromichalaki et al, 2005). The numerical solution of the time-dependent cosmic ray transport equation (Parker, 1965)

$$\frac{df}{dt} = (V + \{V_D\}).\nabla f + \nabla.(Ks.\nabla f) + \frac{1}{3}(\nabla.V)\frac{df}{d\ln p} + Qsource$$

Where f (r,p,t) is the onmidirectional cosmic ray distribution function, p is the particle momentum, r is position, and t is time , with v the solar wind velocity. Terms on the right hand side represent convection, gradient and curvature drifts, diffusion, adiabatic energy changes and a source function respectively. The tensor Ks consist of a parallel diffusion coefficients (K_{II}) and perpendicular diffusion coefficients (K_I). The average guiding centre drift velocity for a near isotopic cosmic ray distribution is given by $\{V_D\}$ = ∇ x (kTeB) with eB = B/B_m where B_m is the magnitude of the modified background Heliospheric Magnetic Field (HMF). The Qsource may represent any local source, such as Jovian electrons (e.g. Ferreira, 2002).

The transport equation is generally solved numerically using boundary conditions. For qualitative studies of interstellar-terrestrial reaction, it is necessary to have a model of three-dimensional heliosphere, which is immersed in a dynamic local interstellar medium. There are at least two reasons why such model should be three dimensional. First, a comprehensive and self-consistent treatment of the cosmic ray transport must take into account for the 3-D structure of the turbulent heliosphere plasma and second, the heliosphere can be in a disturbed state for which no axisymmetric description can be justified. The present state of the art of the modeling of a dynamic heliosphere with a self-consistent treatment of the transport of cosmic ray is reviewed (Fichtner, 2005, Sherer et al, 2006) according to them, the major challenges is the development of three dimensional hybrid model

2.4 SOLAR CYCLE 22 AND 23

The sun undergoes various quasi-periodic changes, the principal one referred to as the solar cycle has an 11-year quasi period. Only the 11 and closely related 22 year cycle are clear in the observations. In this 11 year period, most obvious are gradual increase and more rapid decrease of the number of sunspots over a period ranging from 9 to 12 years, called the solar cycle. Differential rotation of the sunộs convection zone consolidates magnetic flux tubes, increases their magnetic field strength and makes them buoyant. As they rise through the solar atmosphere, they partially block the convective flow of energy, cooling their region of the photosphere causes sunspots. The magnetic field of the sun reverses during each solar cycle, so, the magnetic poles return to the same state after two reversals.

Solar activities features when examined with respect to the equator of the sun, they are referred to as the North-South (N-S) asymmetry. The North-south asymmetry of several solar activity features have been investigated by (Li et al: 2009). Bell (1962) has found long term North-south asymmetry in the solar activity data for solar cycle 8-18.

Solar cycle 22 was 22nd solar cycle since 1755, when recording of solar sunspot activity began. This solar cycle lasted 9.7 years, beginning in September 1986 and ended in May 1996, Solar cycle 23 lasted 12.6 years, beginning in May 1996 and ending in January 2008 (Kane: 2002). Chapman, Dobias and Arias (2011) present an analysis of facular/network and sunspot areas covering most of cycle 22 and all of 23. On the variation of the area of the facular/network compared to the area of sunspots over the past two solar cycles. The average ratio of facular to spot area for cycle 22 is 45 and for cycle 23 the ratio is 42. The values are substantially higher than those from earlier studies. The increase is due to a combination of higher spatial resolution and the removal of a correction factor in millionths.

The amplitude of an even-numbered cycle of the number of large group is smaller than that of its immediate following odd-numbered cycle. This is consistent with the well known Gnerysher and Ohl rule (1948) of G-O rule of solar cycles, generally described by using the Zurich sunspot number (Wolf Number) R_z. During cycle 12-21 the G-O rule hold for the variation in the number of small group, but it was violated by cycle 22 and 23 as in the case of R_z. The variation in the small group is largely responsible for the anomalous behaviour of R_z in cycle 22 and 23.

The properties of solar cycle are generally described by the Zurich or wolf number or international sunspot number $R_z = K (10g + f)$, where k is a correction factor for the observer, g is the number of identified sunspot groups and f is the number of individual sunspot (Javaraiah, 2011). The solar cycle 23 is magnetically weak compared to solar cycle 22, and solar cycle 23 has a lower intense activity than the previous cycle 22.

Friis Christensen and Lassen (1991) has it that solar cycle length correlate inversely with the magnitude and directly with temperature. It is not surprising that solar cycle length has been shown to correlate very well with temperature. As the sun undergoes cyclic changes that appear to correlate with temperature, the current cycle 23 appears to be the longest in at least a century and may project to quieter subsequent cycles and cooling temperature ahead.

The annual variation of sunspot number shows a remarkable feature in sunós history during the period from 1645 ï 1715 when the sunspot numbers become very low. This is called a maunder minimum. Another minimum in sunspot activity is observed between 1800 and 1825 called Dalton minimum. During Maunder minimum, the absence of strong magnetic field region on the surface of the sun affects the solar wind flow and hence modifies the characteristics features of cosmic ray incident on earthós atmosphere.

CHAPTER THREE

SOURCES OF DATA

Data used in this study include solar activity parameter (sunspot numbers), Interlpanetary magnetic field parameters for 25 years covering solar cycle 22 and 23. And cosmic ray count rate for four stations (Apatity, Newark, Tbilisi and Thule) with varying Cut-off rigidity (0-6.73GV).

TABLE 3.1: Locations and cut-off rigidities for stations under study

Station	Country	Latitude	Longitude	Cut-off rigidity	Altitude
Apatity	Russia	67.6^{o}N	33.4^{o}E	0.65GV	177m
Newark	Delaware	39.7^{o}N	75.8^{o}W	2.4GV	50m
Tbilisi	Georgia	41.43^{o}N	44.49^{o}E	6.73GV	510m
Thule	Greenland	76.5^{o}N	68.7^{o}W	0GV	44m

3.1 COSMIC RAY DATA

The hourly pressure-corrected data for cosmic ray neutron monitor count rate on the four stations Apatity, Newark, Tbilisi and Thule from high and mid latitude are from. http://crO.izmiran.ru/Apty/main/htm,http://crO.izmiran.ru/tbls/main.htm and http://crO.Izmiran.ru/thule/main/htm respectively. The Thule and Newark station data is courtesy of Prof. John W. Bieber of Bartol Research institute, University of Delaware, Newark, U.S.A. comprises of hourly data. Apatity station data is courtesy of Prof. Eduard Vashenyuk of Polar Geophysical institute, Kola science center, Russian Academy of Sciences and Tbilisi is courtesy of Dr. Demuri Bochikashvili of Institute Geophisiky (IG) Giorgian Academy of Sciences, Tbilisi, Giorgia. These data were presented as hourly values of CR count corrected for atmospheric effect.

3.2 DATA ON SOLAR WIND PARAMETERS

Hourly data on solar wind parameters are from www.dartmouth.edu/~rdenton/magpar provided by Richard Deuton and zhengui Qin. And, hourly Data on total IMF are from http://www.Ominiweb.gcfc.nasa.gov. Other Data used are daily sunspot number obtained from sidc.Oma.be/sunspot-data/dailySSN.Php The international quietest and disturbed days from http://www.ga.gov.au/oracle/geomag/iqd_form.jsp.

CHAPTER FOUR

METHODS OF DATA ANALYSIS

4.1 CALCULATION OF YEARLY AVERAGE

Twenty-four hours (daily) averages were calculated from the data, and the yearly averages (365/366 day) were calculated from the daily average. Sixty days of both international Quietest Days (QD) and Disturbed Days (DD) were selected from daily average values calculated. Yearly average values for Quietest, All, All ï quietest, and Disturbed conditions shown in appendix i, ii, iii, and iv respectively, were finally calculated from the calculated daily average values. Yearly averages for sunspots number (SSN) were calculated in similar method.

$$x = \frac{\sum_{f=1}^{24} h_f}{24} \qquad 4.1$$

where x =daily average value, f = each hour of the day, and h_f =the value of CR for each hour of the day.

$$C_q = \frac{\sum_{i=1}^{12} \sum_{j=1}^{5} x}{60} \qquad 4.2$$

where C_q = yearly mean for quietest days, j = each quietest day of the month, and i= each month of the year.

$$C_d = \frac{\sum_{i=1}^{12} \sum_{l=1}^{5} x}{60} \qquad 4.3$$

where C_d = yearly mean for disturbed days, and l = each disturbed day of the month

$$C_a = \frac{\sum_{i=1}^{12} \sum_{m=1}^{\alpha} x}{\beta} \qquad 4.4$$

where C_a = yearly mean for all days, m = each day of the month, Ŭ=number of days in a month, and ɓ = number of days in a year.

$$C_{aq} = C_a - C_q = \frac{\sum_{i=1}^{12} \sum_{p=1}^{\theta} x}{\pi} \qquad 4.5$$

where C_{aq} = yearly mean for all days- quietest days, p = each day without quietest days of the month, d= number of days without quietest days in a month, and ´ = number of days without quietest days in a year.

4.2 CALCULATION OF PERCENTAGE VARIATION OF YEARLY AVERAGE DATA.

In this project, the percentage variability was applied this gives us the percentage rate of change of cosmic ray count rate in a station, this will also explain the rate of modulation of cosmic ray. The number of count rate alone might be misleading because it depends on the number of Neutron Monitor in a station. Appendices v-viii are the percentage variation of all the parameters used in this work.

$$\% \text{ variation} = \frac{\text{Yearly Mean Value} - 25 \text{ Year Mean Value}}{25 \text{ Year Mean Value}} \times 100 \qquad 4.6$$

4.3 METHOD OF ANALYSIS FOR YEARLY AVERAGE DATA

In the analysis of data for this project, linear regression analysis was performed on year to year basis to understanding the effect of percentage variation of different solar wind parameters on percentage variation of GCR flux on each of the stations at different interplanetary magnetic field disturbances. Figures 4.1-4.4 are examples of IMF (Total B) and cosmic ray count rates on Apatity station at different level of disturbances, and figure 4.5 is example of solar wind dynamic pressure (SWDP) and cosmic ray count rates on Apatity station during disturbed conditions. Pearsonǿs correlation was used. Thus, Pearsonǿs correlation coefficients r_{xy} is given by

$$r_{xy} \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2\sum_{i=1}^{n}(y_i-\bar{y})^2}} \qquad 4.7$$

Where: x and y are the yearly average values of solar wind parameters and cosmic ray count rate respectively, and $\bar{x}$ and $\bar{y}$ are the mean of x and y respectively.

The correl ( ) function in excel also calculate r_{xy}

Partial correlation was also used in this project. The first ï order partial correlation was used which measure the linear relationship between two variables after removing the effect of or controlling for a single (third) variable.

First-order partial correlation is given by

$$r_{xy.z} = \frac{r_{xy}-(r_{xz})(r_{yz})}{\sqrt{(1-r_{xz}^2)}} \qquad 4.8$$

Where $r_{xy.z}$ = the (first-order) partial correlation of x and y controlling Z.

r_{xy}, r_{xz}, and r_{yz} are bivariate (zero-order) correlation of x and y, x and z, and y and z respectively. Excel software was finally used in calculating these correlations, and partial correlations.

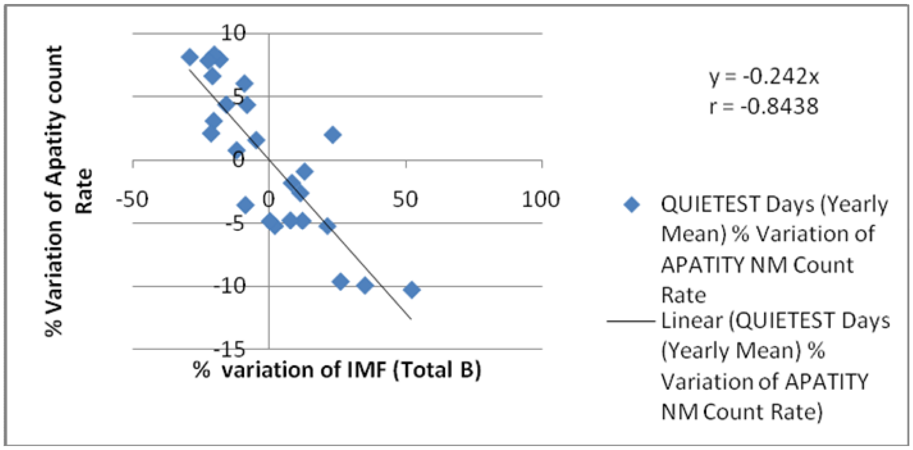

Fig., 4.1: % Variation of APATITY NM Count Rate and IMF (Total B) for Quietest conditions (QCs).

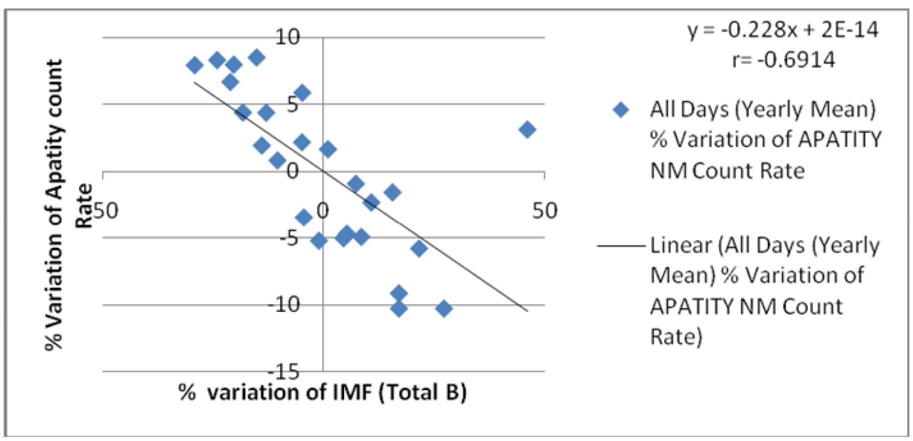

Fig., 4. 2: % Variation of APATITY NM Count Rate and IMF (Total B) for All conditions.

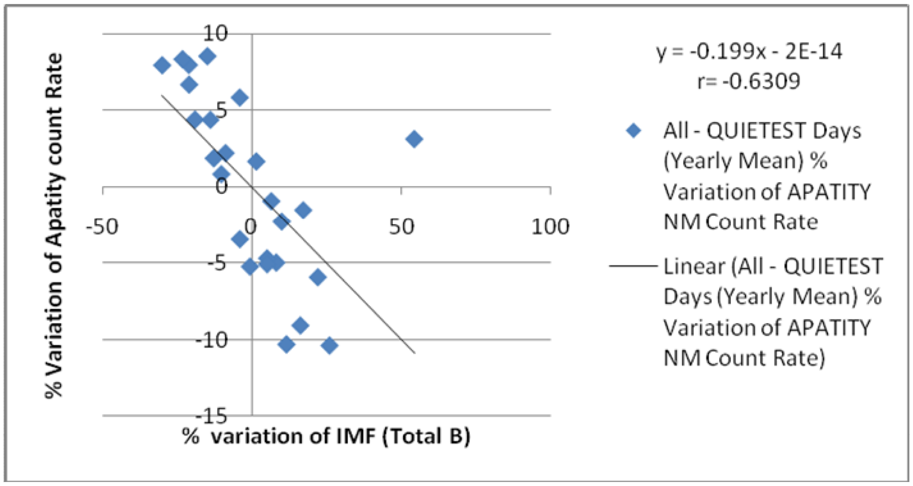

Fig., 4.3: % Variation of APATITY NM Count Rate and IMF (Total B) for All-QCs.

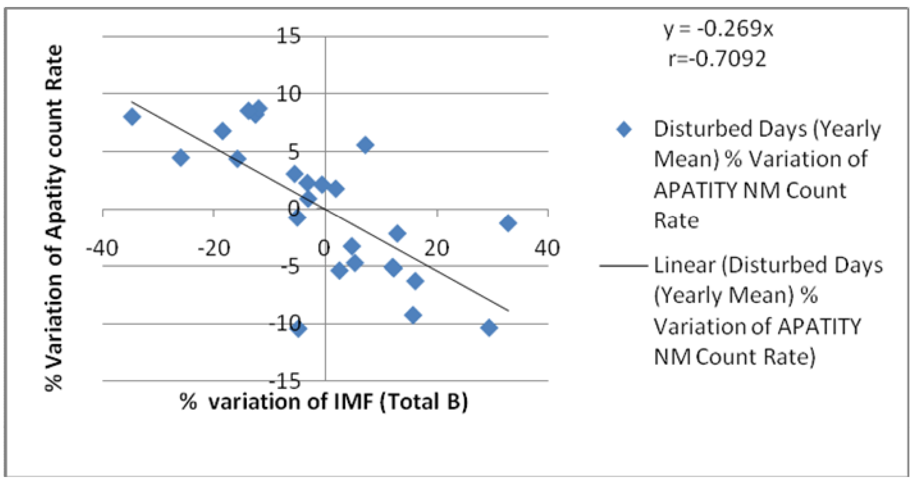

Fig., 4.4: % Variation of APATITY NM Count Rate and IMF (Total B) for disturbed conditions.

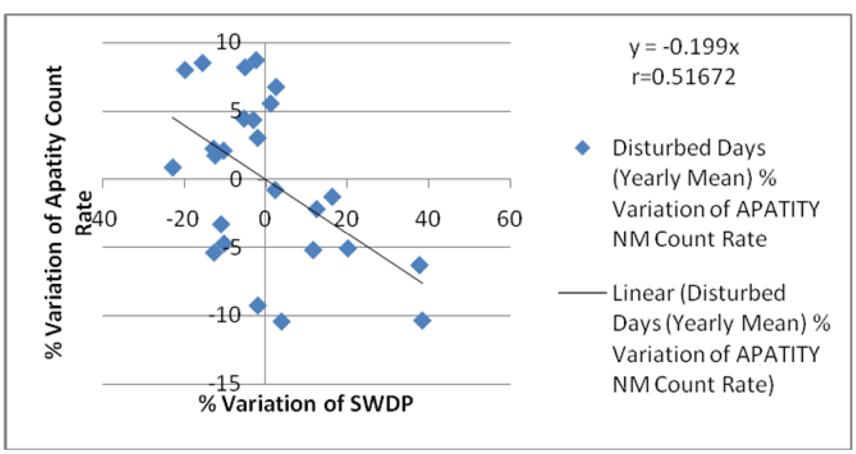

Fig., 4.5: % Variation of APATITY NM Count Rate and SWDP for disturbed conditions.

Table 4.1 shows the correlation coefficient r of the parameters used on 4 grouped days (All days, All ï Quiet days, Quietest days and Disturbed days), and partial correlation, removing effect of particular parameter are shown in tables 4.2 and 4.3. Figure 4.6 shows amplitude variation for percentage variation of CR count rates and SSN for all stations during quietest conditions.

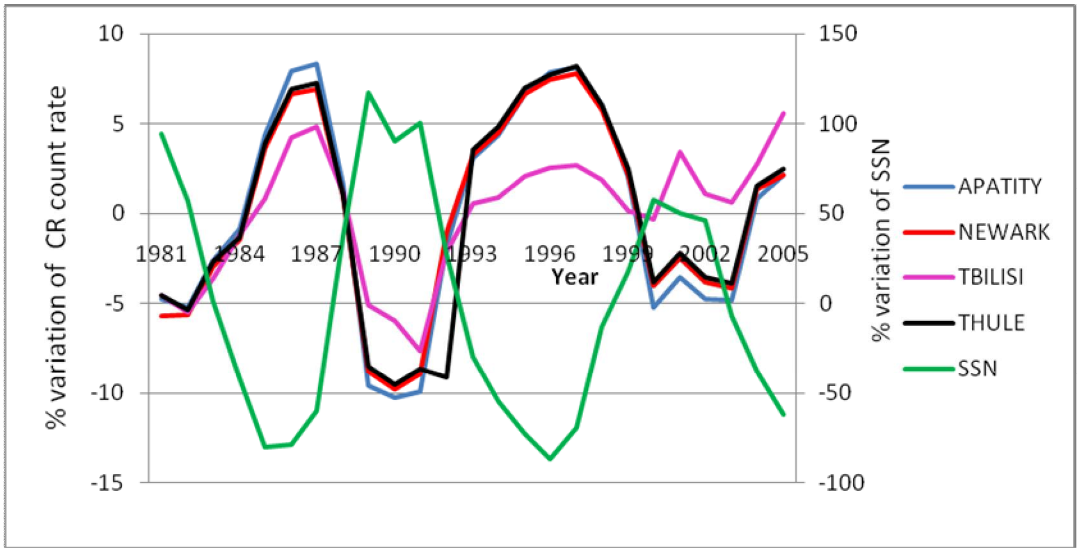

Fig., 4.6: Amplitude Variations for CR count rates and SSN for all station during quietest conditions.

Table 4.1: Correlating solar wind parameters and count rates

60 QDs (Correlating with Count Rate)	Apatity	Newark	Tbilisi	Thule
SWDP	-0.03375	-0.08165	-0.40971	-0.18620
SWDEN	0.38346	0.33951	-0.11116	0.20969
IMF (Bz component)	-0.36245	-0.34683	-0.19238	-0.31029
IMF (Total B)	-0.84387	-0.85991	-0.86567	-0.89436
SSN	-0.89065	-0.89129	-0.75934	-0.88722
SWS	-0.35413	-0.36916	-0.28369	-0.35085
ALL DAYS (Correlating with Count Rate)	**Apatity**	**Newark**	**Tbilisi**	**Thule**
SWDP	-0.23747	-0.28645	-0.59231	-0.35244
SWDEN	0.28303	0.23676	-0.19706	0.13409
IMF (Bz component)	-0.19479	-0.23799	-0.26621	-0.29555
IMF (Total B)	-0.69156	-0.69840	-0.71186	-0.71087
SSN	-0.88047	-0.87926	-0.75957	-0.85593
SWS	-0.29459	-0.29832	-0.16266	-0.25362
ALL - 60 QDs (Correlating with Count Rate)	**Apatity**	**Newark**	**Tbilisi**	**Thule**
SWDP	-0.27934	-0.32759	-0.62453	-0.39339
SWDEN	0.25284	0.20704	-0.21602	0.09450
IMF (Bz component)	0.09510	0.14391	0.20621	0.21051
IMF (Total B)	-0.63106	-0.63589	-0.64630	-0.65660
SSN	-0.87792	-0.87596	-0.75878	-0.85546
SWS	-0.27510	-0.27632	-0.13879	-0.22305
60 DDS (Correlating with Count Rate)	**Apatity**	**Newark**	**Tbilisi**	**Thule**
SWDP	-0.51738	-0.54425	-0.75535	-0.57756
SWDEN	0.11841	0.08364	-0.27416	-0.04614
IMF (Bz component)	-0.15971	-0.12448	-0.00911	-0.03895
IMF (Total B)	-0.70958	-0.70963	-0.62683	-0.79354
SSN	-0.87858	-0.87715	-0.76406	-0.85167
SWS	-0.16920	-0.15581	-0.01962	-0.06803

Where SWDP= solar wind dynamic pressure
SWDEN = Solar wind density
IMF = Interplanetary Magnetic field
SSN = Sunspots number
SWS = Solar wind speed
C/R = Count Rate

Table 4.2: Partial Correlation, removing effect of IMF (Bz) and Total B

PARTIAL CORRELATION (IMF Bz REMOVED)					**PARTIAL CORRELATION(IMF Total B REMOVED)**				
60 QDs	**Apatity**	**Newark**	**Tbilisi**	**Thule**	**60 QDs**	**Apatity**	**Newark**	**Tbilisi**	**Thule**
SWDP	-0.22964	-0.27688	-0.55983	-0.37679	SWDP	0.26966	0.19418	-0.46948	-0.001
SWDen	0.27477	0.22160	-0.19589	0.08699	SWDen	0.44740	0.39496	-0.52669	0.12303
IMF(Total B)	-0.81956	-0.83949	-0.87185	-0.88273	IMF(Bz)	-0.09670	-0.05610	0.27983	0.05488
SSN	-0.87647	-0.88081	-0.77460	-0.88514	SWS	-0.14250	-0.16990	0.01199	-0.1231
SWS	-0.51019	-0.51877	-0.35885	-0.48048	SSN	-0.65470	-0.64650	-0.19030	-0.6145
ALL DAYS	**Apatity**	**Newark**	**Tbilisi**	**Thule**	**ALL DAYS**	**Apatity**	**Newark**	**Tbilisi**	**Thule**
SWDP	-0.15432	-0.18568	-0.55991	-0.23017	SWDP	0.18404	0.11191	-0.38053	0.01535
SWDen	0.39339	0.34662	-0.10159	0.26015	SWDen	0.50782	0.45846	-0.16475	0.3122
IMF(Total B)	-0.67712	-0.67621	-0.68621	-0.68091	IMF(Bz)	0.03875	-0.02140	-0.05773	-0.1021
SSN	-0.87542	-0.87273	-0.74547	-0.84864	SWS	-0.2123	-0.21760	-0.02009	-0.1526
SWS	-0.26447	-0.26143	-0.11316	-0.20496	SSN	-0.7768	-0.77300	-0.53975	-0.7256
ALL - 60 QDs	**Apatity**	**Newark**	**Tbilisi**	**Thule**	**ALL- 60 QDs**	**Apatity**	**Newark**	**Tbilisi**	**Thule**
SWDP	-0.28121	-0.30629	-0.64472	-0.34232	SWDP	0.08000	0.01076	-0.43831	-0.07460
SWDen	0.33457	0.28175	-0.12751	0.19591	SWDen	0.47389	0.41998	-0.13979	0.27722
IMF(Total B)	-0.63287	-0.62710	-0.62643	-0.63670	IMF(Bz)	-0.11330	-0.04970	0.03081	0.03308
SSN	-0.87682	-0.87537	-0.75899	-0.85863	SWS	-0.21130	-0.21290	-0.02955	-0.14100
SWS	-0.26300	-0.25628	-0.10373	-0.19076	SSN	-0.80090	-0.79690	-0.60070	-0.75960
60 DDS	**Apatity**	**Newark**	**Tbilisi**	**Thule**	**60 DDs**	**Apatity**	**Newark**	**Tbilisi**	**Thule**
SWDP	-0.52620	-0.55015	-0.75556	-0.57854	SWDP	-0.11200	-0.16180	-0.58996	-0.14280
SWDen	0.08769	0.05794	-0.28710	-0.05448	SWDen	0.47735	0.40938	-0.12565	0.29899
IMF(Total B)	-0.70373	-0.70486	-0.63104	-0.79584	IMF(Bz)	-0.09630	-0.04590	0.09387	0.10673
SSN	-0.87607	-0.87833	-0.78213	-0.86578	SWS	-0.30260	-0.28360	-0.07478	-0.19230
SWS	-0.14890	-0.13986	-0.01847	-0.06297	SSN	-0.74220	-0.73910	-0.56937	-0.63360

Table 4.3: Partial Correlation, removing effect of SWS and SWDP

PARTIAL CORRELATION (SWS REMOVED)					**PARTIAL CORRELATION (SWDP REMOVED)**				
60 QDs	Apatity	Newark	Tbilisi	Thule	60 QDs	Apatity	Newark	Tbilisi	Thule
SWDP	0.14497	0.09641	-0.33095	-0.03815	IMF (Total B)	-0.85601	-0.86463	-0.87476	-0.89033
SWDen	0.34611	0.31046	-0.17157	0.15832	SWDen	0.60831	0.42667	0.21213	0.36184
IMF(Bz)	-0.51511	-0.50560	-0.29595	-0.45535	IMF(Bz)	-0.41981	-0.42695	-0.45326	-0.44354
IMF (Total B)	-0.82312	-0.84090	-0.85292	-0.88048	SWS	-0.37791	-0.37224	-0.12658	-0.30484
SSN	-0.92689	-0.93220	-0.77210	-0.92226	SSN	-0.89630	-0.90309	-0.86896	-0.92003
ALL DAYS	Apatity	Newark	Tbilisi	Thule	ALL DAYS	Apatity	Newark	Tbilisi	Thule
SWDP	-0.16795	-0.22050	-0.57725	-0.30240	IMF (Total B)	-0.68250	-0.67005	-0.59178	-0.65978
SWDen	0.20073	0.14238	-0.26274	0.04701	SWDen	0.67485	0.47621	0.29117	0.41861
IMF(Bz)	-0.14214	-0.18780	-0.24050	-0.25609	IMF(Bz)	-0.06876	-0.08803	0.13207	-0.11450
IMF (Total B)	-0.67411	-0.68140	-0.70252	-0.69544	SWS	-0.24394	-0.23625	0.00696	-0.17120
SSN	-0.94014	-0.94020	-0.78031	-0.90100	SSN	-0.88030	-0.88378	-0.84534	-0.86931
ALL - 60 QDs	Apatity	Newark	Tbilisi	Thule	ALL -60 QDs	Apatity	Newark	Tbilisi	Thule
SWDP	-0.22699	-0.27860	-0.61507	-0.35819	IMF (Total B)	-0.59286	-0.57691	-0.47828	-0.57507
SWDen	0.16398	0.10506	-0.27964	0.00733	SWDen	0.66662	0.47546	0.29783	0.40823
IMF(Bz)	0.04543	0.09693	0.18498	0.17572	IMF(Bz)	-0.10087	-0.07679	-0.28767	-0.04281
IMF (Total B)	-0.61484	-0.61990	-0.63780	-0.64283	SWS	-0.22160	-0.21354	0.02013	-0.14145
SSN	-0.93724	-0.93560	-0.77889	-0.89724	SSN	-0.87505	-0.87732	-0.83518	-0.86509
60 DDs	Apatity	Newark	Tbilisi	Thule	60 DDs	Apatity	Newark	Tbilisi	Thule
SWDP	-0.52197	-0.54830	-0.75527	-0.57778	IMF (Total B)	-0.57491	-0.55955	-0.27994	-0.67504
SWDen	0.03037	-0.00250	-0.29641	-0.08400	SWDen	0.58278	0.56618	0.28370	0.41704
IMF(Bz)	-0.13794	-0.10360	-0.00625	-0.02918	IMF(Bz)	-0.19429	-0.15782	-0.02849	-0.05670
IMF (Total B)	-0.73190	-0.72950	-0.62935	-0.80109	SWS	-0.18697	-0.17420	-0.00941	-0.07074
SSN	-0.91555	-0.91060	-0.77092	-0.86621	SSN	-0.83200	-0.82617	-0.64667	-0.78586

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 RESULT

Table 4.1 shows the correlation of different solar activity parameters : Solar Wind Dynamic Pressure(SWDP), Solar Wind Density (SWDen), Interplanetary Magnetic Field (Bz Component), IMF(Total B) Solar Wind Speed (SWS), and Sunspot Number (SSN) with count rate of Apatiti, Newark, Tbilisi, and Thule stations studied, in the 4 grouped yearly conditions(quietest, all, all ï quietest, and disturbed conditions). Tables 4.3-4.4 are partial correlation, removing Bz and Total B, SWS and SWDP respectively in these stations at the four grouped yearly condition. Figures 4.1-4.4 show the linear regression of IMF (Total B) and Apatity CR count rates in the four grouped conditions. Figure 4.5 shows the linear regression of SWDP and Apatity CR count rates for disturbed condition. Figure 4.6 plots amplitude variation of percentage variation of CR count rate and SSN on all stations for quietest condition only.

Solar wind dynamic pressure (SWDP) has a strong inverse correlation with count rate. This correlation is strongest during disturbed conditions ($r > 0.51$). At Tbilisi with highest Cut off rigidity (C.O.R.), among the stations studied, the correlation is strongest ($r > 0.75$). This may suggest that SWDP reduces the C.O.R. of stations. The strength of correlation of SWDP and count rate decreases with decreasing solar activity therefore, weakest during quietest condition ($r < 0.187$). Suggesting that SWDP affects the heliosphere which is in agreement with McComas et al., (2008), that SWDP inflates the heliosphere and the effect varies with the level of interplanetary magnetic disturbances, strongest during disturbed conditions and decreases with decreasing solar activities. A more active and inflated heliosphere is expected to filter a larger fraction of GCR reaching the earth and vice versa. These suggest that SWDP play major roles in cosmic ray modulation during disturbed condition. Removing effect of Bz, and SWS have no significant effect on the correlation. Removing the effect of Total B on the correlation of SWDP and count rate reduces the strength of correlation, their differences increases with decreasing C.O.R.

Solar wind density (SWDen) has weak and direct correlation with count rate ($0.046 < r < 0.384$) in all conditions. The correlation is strongest during quietest conditions ($r < 0.384$) and weakest during disturbed conditions ($r < 0.274$). This weak and direct correlation suggests that SWDen do not play any major role in the modulation of cosmic rays. Removing the effect of Bz, and SWS has no significant on the correlation. Also, removing the effect of SWDP increases the strength of correlation of SWDen and CR count rate. Removing the effect of Total B increases the strength on correlation of SWDen and cosmic ray count rate, the difference in strength of correlation decreases with increasing C.O.R.

Interplanetary magnetic field (Z Component), Bz generally has weak correlation with cosmic ray count rate. There was no pattern with respect to the disturbance level. Suggesting that Bz do not play a significant role in CR modulation. This corroborates with the findings of Sabbah (1996) that Bz does not usually contribute to the solar modulation of cosmic ray since the long-term average of this component near Earth is proportional to zero. Its major role is in magnetic reconnection that converts magnetic energy to kinetic energy, thermal energy, and particle acceleration, thereby transferring energy, mass, and momentum from solar wind to magnetosphere (Stern, 1996). Removing the effect of IMF (Total B) significantly reduces the strength of correlation of Bz and cosmic ray count rate, the difference in the strength of correlation decreases with increasing interplanetary magnetic disturbances. Removing the effect of SWDP on the correlation between Bz and count rate slightly increases the strength of the correlations.

Interplanetary magnetic field (Total B) has good inverse correlation with count rate. The strength of correlation is strongest during quietest condition (r > 0.84) and weakest during disturbed conditions (r < 0.63), therefore, the strength of correlation decreases with increasing solar activities, and increases with increasing C.O.R. Removing effect of IMF (Bz), and SWS have no significant effects on correlation of IMF (Total B) and count rates. Removing effect of SWDP significantly reduces the strength of correlation of IMF (Total B) and CR count rate. This reduction in the strength of correlation is highest during disturbed conditions and decreases sharply with decreasing solar activities. Total B play a major role in modulation of cosmic rays in all conditions, this is in agreement with Burlaga et al., (2005) and their CR ï B relation.

Solar wind speed (SWS) has poor inverse correlation with count rate. It is poorest during disturbed conditions (r < 0.17) and increases with decreasing solar activity, (0.28 < r < 0.37) during quietest conditions. Removing the effect of Bz, and SWDP have no significant effect on SWS and count rate. Removing the effect of IMF (Total B) significantly reduces the strength of correlation of SWS and count rate. This reduction in the strength of correlation is highest during quietest conditions and decreases sharply with increasing level of disturbances.

Sunspot number (SSN) generally has very good inverse correlation with count rate (r > 0.75). Like Total B, it has the strongest correlation with count rate during quietest condition, and decreases with increasing solar activity. Removing the effect of Bz, and SWS have no significant effect on these correlations, removing the effect of SWDP significantly reduces the strength of correlation during disturbed conditions only. Removing the effect of Total B significantly reduces the correlation of SSN and count rate with slight decrease in the rate of reduction during disturbed conditions. These support that Total B and SWDP have major roles in modulation of cosmic rays.

From Figure 4.6-4.9, the annual means of the Galactic cosmic ray flux showed similar annual variation trend with Thule and Apatity having the highest amplitude because of their low cut off rigidity. Tbilisi has the least amplitude because of the high cut off rigidity of the station. This also, suggests that cut off rigidities play important role in modulating galactic cosmic rays.

CHAPTER SIX
CONCLUSION

From the result obtained, the following conclusions may be drawn: Solar activity parameters generally showed inverse relation with cosmic ray count rates. SWDP and IMF (Total B) have major contributions in cosmic ray modulation. SWDP is a strong factor for the modulation of cosmic ray during disturbed conditions. The extent of modulation is depending on level of disturbance. IMF (Total B) is another strong factor for the modulation of cosmic rays; it is Strongest during quietest conditions and decreases with increasing solar activities. Cut-off rigidity is another important modulating factor, the extent of modulation decreases with increasing cut-off rigidity.

SWS, IMF (Bz Component), and SWDen have poor and spasmodic correlation with cosmic ray count rate and are not major contributing factors in cosmic ray modulation.

Appendix i

	YEARLY AVERAGE FOR QUIETEST CONDITIONS									
YEARS	**SWDP nP**	**SWDen part/cm^3**	**IMF Bz nT**	**IMF Total B nT**	**SSN**	**SWSpeed KM/s**	**ApatiTY C/R**	**Newark C/R**	**TibilisI C/R**	**Thule C/R**
1981	1.720	6.593	1.140	6.243	139.550	369.171	6444.737	3116.32	8110.37	2700.4
1982	2.588	8.880	0.483	6.752	112.533	397.913	6416.473	3118.39	8026.26	2678.8
1983	2.710	7.103	0.486	6.200	72.617	436.338	6593.666	3206.61	8187.01	2746.3
1984	2.929	7.792	0.468	6.286	41.800	463.406	6708.553	3255.63	8390.63	2787.1
1985	2.857	9.084	0.505	4.686	14.283	409.977	7066.486	3423.60	8566.89	2877.7
1986	2.784	9.373	0.542	4.553	14.967	407.424	7308.012	3523.25	8852.50	2955.3
1987	2.509	9.096	0.481	4.441	28.600	380.777	7333.187	3533.48	8909.06	2970.1
1988	2.040	7.544	0.449	5.297	98.733	403.056	6876.307	3336.46	8592.71	2844.8
1989	2.377	7.262	0.756	7.021	155.917	394.439	6117.280	3014.20	8062.29	2645.5
1990	2.286	6.855	0.535	8.476	136.417	404.293	6073.278	2981.31	7988.80	2620.3
1991	3.009	8.737	0.915	7.519	144.100	406.717	6097.039	3010.06	7845.54	2606.2
1992	2.666	8.368	0.548	6.026	91.250	406.465	6647.308	3268.27	8310.90	2753.1
1993	2.583	8.381	0.242	4.432	50.467	387.235	6978.549	3412.41	8543.61	2865.5
1994	2.540	7.781	0.433	5.110	32.500	423.347	7064.948	3453.67	8567.41	2888.5
1995	1.933	9.463	0.869	4.405	19.283	343.041	7218.776	3523.72	8669.95	2923.4
1996	2.049	8.422	0.482	4.322	9.300	390.405	7301.004	3551.12	8711.65	2944.9
1997	1.803	9.226	0.348	3.943	21.867	331.123	7320.121	3561.85	8725.04	2950.3
1998	1.505	6.156	0.623	5.058	62.500	365.418	7178.901	3494.28	8655.93	2913.3
1999	1.476	5.165	1.200	6.860	84.450	377.433	6904.941	3376.56	8509.59	2850.6
2000	1.530	4.567	0.790	5.677	112.867	424.452	6416.509	3172.15	8465.46	2749.5
2001	1.328	5.348	0.783	5.078	107.483	373.887	6529.477	3222.66	8784.90	2810.1
2002	1.620	5.051	1.167	5.997	104.750	380.191	6447.011	3177.92	8585.96	2770.0
2003	1.691	4.313	0.525	5.578	66.733	443.635	6443.279	3167.53	8546.96	2761.0
2004	1.458	4.224	0.578	4.897	44.267	414.139	6821.932	3349.12	8732.23	2857.4
2005	1.559	5.042	0.661	4.377	27.267	379.101	6912.636	3375.69	8968.95	2896.3

Appendix ii

	YEARLY AVERAGE FOR ALL CONDITIONS									
YEAR	**SWDP nP**	**SWDen part/cm^3**	**IMF Bz nT**	**IMF Total B nT**	**SSN (Rz)**	**SWSpeed KM/s**	**Apatiti C/R**	**Newark C/R**	**Tbilisi C/R**	**Thule C/R**
1981	2.513	7.069	-0.017	7.877	140.460	424.476	6422.199	3121.32	8089.88	3136.53
1982	3.483	8.686	-0.066	8.827	115.940	458.698	6363.769	3095.21	7987.62	3095.21
1983	3.256	7.882	0.201	8.042	66.792	471.884	6598.143	3207.99	8197.86	3207.61
1984	3.336	7.967	0.169	7.788	45.614	487.027	6692.641	3246.09	8382.87	3245.52
1985	3.082	8.499	0.263	5.933	17.986	467.432	7051.731	3418.86	8560.64	3418.83
1986	2.974	8.559	0.339	5.782	13.359	457.302	7292.942	3517.28	8827.32	3517.28
1987	2.862	9.050	0.270	6.158	29.419	426.926	7329.001	3533.36	8910.90	3533.36
1988	2.530	7.769	0.187	7.330	100.406	428.068	6866.554	3327.77	8569.14	3328.42
1989	2.995	7.425	0.359	8.495	157.597	457.314	6137.529	3019.00	8046.03	3019.00
1990	2.774	7.125	0.087	8.495	142.567	440.600	6060.902	2976.11	7981.44	2976.11
1991	3.798	8.942	0.205	9.235	145.701	464.922	6060.861	2989.04	7801.15	2989.04
1992	3.396	9.587	0.262	8.390	94.011	430.882	6649.192	3260.45	8277.31	2989.04
1993	3.123	8.724	0.097	10.605	54.564	452.009	6965.822	3406.20	8537.29	3406.20
1994	2.961	6.893	0.054	6.316	29.899	513.467	7050.799	3446.41	8564.75	3446.41
1995	2.616	8.777	-0.203	5.725	17.460	428.895	7205.716	3514.35	8657.30	3514.35
1996	2.456	8.025	-0.111	5.141	8.636	422.416	7290.460	3546.99	8701.73	3547.10
1997	2.241	8.720	-0.240	5.509	21.501	379.988	7315.871	3561.79	8723.98	3563.83
1998	2.242	7.259	-0.163	6.908	64.304	410.429	7151.494	3484.33	8635.11	3484.33
1999	2.045	5.937	0.065	6.903	93.307	438.383	6901.985	3375.69	8501.32	3375.69
2000	2.294	5.827	-0.080	7.181	119.515	448.056	6403.108	3162.84	8431.59	3162.95
2001	2.103	5.971	-0.032	6.933	111.000	425.529	6522.367	3221.09	8776.37	3221.09
2002	2.198	5.971	0.157	7.641	104.049	439.448	6438.267	3178.40	8579.65	3178.21
2003	2.312	4.424	-0.091	7.585	63.707	543.979	6415.886	3156.44	8511.97	3156.44
2004	1.947	4.881	-0.166	6.501	40.359	451.862	6810.306	3340.80	8711.32	3340.69
2005	2.177	5.757	-0.083	6.244	29.830	470.761	6885.481	3365.29	8935.54	3365.29

Appendix iii

	YEARLY AVERAGE FOR ALL MINUS QUIETEST DAYS									
Years	**SWDP nP**	**SWDen Part/cm^3**	**IMF Bz nT**	**IMF Total B nT**	**SSN**	**SWSpeed Km/s**	**Apatity C/R**	**Newark C/R**	**Tibilisi C/R**	**Thule C/R**
1981	2.669	7.163	-0.245	8.198	140.24	435.355	6417.765	3122.11	8085.85	3135.07
1982	3.659	8.648	-0.174	9.254	116.61	470.656	6353.401	3091.14	7980.02	3090.66
1983	3.364	8.035	0.145	8.338	65.646	478.876	6599.024	3207.97	8200.00	3207.81
1984	3.416	8.002	0.107	8.071	46.364	491.673	6689.511	3244.00	8381.34	3244.27
1985	3.126	8.384	0.220	6.136	18.705	478.794	7048.514	3417.83	8559.44	3418.02
1986	3.011	8.399	0.299	5.979	13.043	466.954	7290.004	3515.85	8822.33	3516.07
1987	2.931	9.042	0.229	6.449	29.58	436.005	7328.178	3533.64	8911.26	3533.33
1988	2.627	7.813	0.1297	7.693	100.73	432.988	6864.635	3326.59	8564.51	3317.64
1989	3.116	7.457	0.2808	8.810	157.93	469.682	6141.512	3020.54	8042.83	3019.94
1990	2.870	7.179	-0.001	8.458	143.78	447.742	6058.468	2974.80	7980.00	2975.08
1991	3.953	8.982	0.066	9.550	146.02	476.373	6053.744	2984.56	7792.41	2984.91
1992	3.540	9.827	0.202	8.884	94.554	435.686	6649.563	3258.55	8270.7	2988.14
1993	3.229	8.791	0.068	11.700	55.37	464.751	6963.318	3404.73	8536.04	3404.98
1994	3.044	6.718	-0.020	6.527	29.387	531.196	7048.016	3444.88	8564.23	3444.98
1995	2.751	8.643	-0.414	5.987	17.102	445.784	7203.146	3512.59	8654.81	3512.51
1996	2.536	7.947	-0.224	5.302	8.505	428.714	7288.386	3546.23	8699.78	3546.64
1997	2.327	8.621	-0.355	5.817	21.430	389.600	7315.035	3561.78	8723.77	3563.74
1998	2.386	7.476	-0.318	7.271	64.659	419.283	7146.103	3482.41	8631.01	3482.37
1999	2.145	6.077	-0.163	6.911	95.403	449.607	6901.403	3375.73	8499.7	3375.51
2000	2.470	6.103	-0.295	7.533	120.930	454.211	6400.206	3160.77	8424.43	3161.36
2001	2.252	6.104	-0.183	7.273	111.550	435.078	6520.792	3220.56	8776.53	3220.61
2002	2.312	6.152	-0.042	7.965	103.910	451.105	6436.547	3178.41	8578.41	3177.41
2003	2.431	4.425	-0.218	7.967	63.121	563.751	6410.411	3154.01	8504.94	3154.24
2004	2.046	5.029	-0.313	6.804	39.833	458.944	6808.884	3339.38	8708.09	3340.05
2005	2.296	5.893	-0.230	6.610	30.246	488.418	6878.743	3362.16	8928.31	3362.51

Appendix iv

	60 DISTURBED DAYS YEARLY AVERAGE									
YEAR	**SWDP nP**	**SWDen part/cm^3**	**IMF Bz nT**	**IMF Total B nT**	**SSN**	**SWSpeed KM/s**	**Apatiti C/R**	**newark C/R**	**Tbilisi C/R**	**Thule C/R**
1981	4.435	9.3142	-1.538	10.820	151.250	484.126	6396.876	3127.98	8072.38	3127.9
1982	5.083	8.8031	-1.639	11.210	129.000	524.835	6314.428	3076.31	7949.02	3076.3
1983	4.152	8.7549	-0.279	10.900	70.266	505.007	6593.113	3204.61	8182.81	3202.3
1984	3.777	7.5180	-0.307	9.168	46.516	516.972	6686.892	3235.36	8379.09	3243.7
1985	3.495	8.3066	-0.260	7.149	15.383	526.163	7038.681	3410.92	8544.66	3410.9
1986	3.504	8.0053	-0.050	8.444	13.783	526.899	7290.897	3517.90	8856.06	3517.9
1987	3.604	10.1607	-0.078	8.498	32.600	460.921	7326.184	3534.65	8912.63	3534.6
1988	3.233	8.2303	-0.140	9.834	98.400	441.402	6856.830	3321.26	8558.10	3324.5
1989	3.619	7.0922	-0.769	11.173	155.800	532.791	6115.365	3004.47	8009.04	3004.4
1990	3.835	8.1152	-0.404	9.185	146.317	484.183	6036.896	2963.89	7964.08	2963.8
1991	5.110	9.7701	-0.395	12.490	145.600	508.187	6041.818	2981.86	7770.16	2981.8
1992	4.293	11.1183	0.047	12.818	91.283	438.379	6653.706	3253.47	8263.91	2981.7
1993	3.618	8.4705	-0.404	9.122	54.133	518.716	6943.652	3396.17	8518.45	3396.1
1994	3.579	6.6799	-0.365	8.130	31.150	583.813	7032.042	3443.22	8562.84	3443.2
1995	3.784	9.0346	-1.193	7.875	13.150	532.758	7194.131	3506.84	8650.47	3506.8
1996	2.960	7.0317	-0.409	6.306	9.550	446.667	7277.881	3543.64	8705.04	3544.3
1997	3.118	9.3980	-1.374	8.325	22.400	436.222	7312.657	3558.87	8721.99	3561.3
1998	3.735	9.3839	-1.778	10.346	65.933	475.706	7112.772	3463.34	8605.87	3463.3
1999	3.218	7.3263	-0.994	9.342	96.166	519.856	6890.870	3369.73	8490.56	3369.7
2000	4.121	7.5682	-0.521	10.84	122.417	490.504	6389.126	3148.53	8413.49	3158.1
2001	3.287	5.9247	-1.594	10.112	115.667	493.669	6518.367	3217.97	8772.37	3217.9
2002	3.313	8.1429	-1.252	10.165	106.150	478.658	6420.635	3161.41	8549.87	3160.2
2003	3.223	5.0374	-1.468	9.898	63.683	627.765	6376.108	3140.14	8481.26	3140.1
2004	2.849	5.8599	-0.903	9.357	40.817	475.604	6798.061	3333.15	8685.18	3337.0
2005	3.308	6.4985	-0.831	9.597	33.733	577.402	6880.764	3362.41	8933.14	3362.4

Appendix v

	% VARIATION OF YEARLY AVERAGE FOR QUIETEST CONDITIONS									
YEAR	**SWDP**	**SWDen**	**IMF Bz**	**IMF Total B**	**SSN (SSN)**	**SWSpeed**	**Apati C/R**	**Newark C/R**	**Tibilisi C/R**	**Thule C/R**
1981	-19.720	-8.34	77.959	12.102	94.41	-6.901	-4.79	-5.710	-4.500	-4.061
1982	20.801	23.46	-24.61	21.231	56.78	0.347	-5.21	-5.648	-5.490	-4.827
1983	26.502	-1.25	-24.11	11.324	1.17	10.04	-2.59	-2.978	-3.600	-2.430
1984	36.752	8.328	-26.98	12.87	-41.77	16.86	-0.89	-1.495	-1.200	-0.978
1985	33.373	26.28	-21.16	-15.86	-80.10	3.39	4.40	3.587	0.877	2.240
1986	29.996	30.31	-15.36	-18.25	-79.15	2.746	7.97	6.602	4.240	4.997
1987	17.139	26.45	-24.88	-20.27	-60.16	-3.974	8.34	6.911	4.906	5.521
1988	-4.774	4.88	-29.97	-4.883	37.55	1.645	1.59	0.951	1.181	1.072
1989	10.953	0.96	18.12	26.064	117.21	-0.529	-9.63	-8.800	-5.060	-6.010
1990	6.730	-4.70	-16.48	52.185	90.05	1.956	-10.30	-9.795	-5.930	-6.906
1991	40.468	21.47	42.80	35.006	100.75	2.568	-9.92	-8.925	-7.620	-7.406
1992	24.467	16.34	-14.37	8.203	27.13	2.504	-1.80	-1.113	-2.140	-2.186
1993	20.611	16.52	-62.14	-20.420	-29.69	-2.345	3.10	3.248	0.603	1.808
1994	18.585	8.17	-32.36	-8.243	-54.72	6.761	4.38	4.497	0.883	2.625
1995	-9.775	31.56	35.73	-20.91	-73.14	-13.49	6.65	6.616	2.090	3.865
1996	-4.357	17.09	-24.80	-22.4	-87.04	-1.546	7.86	7.445	2.581	4.628
1997	-15.840	28.27	-45.60	-29.2	-69.54	-16.5	8.15	7.770	2.739	4.817
1998	-29.710	-14.40	-2.64	-9.175	-12.93	-7.847	6.06	5.726	1.925	3.503
1999	-31.080	-28.20	87.41	23.174	17.651	-4.817	2.01	2.164	0.202	1.276
2000	-28.580	-36.50	23.37	1.9272	57.24	7.040	-5.20	-4.021	-0.320	-2.314
2001	-38.000	-25.70	22.33	-8.816	49.74	-5.712	-3.54	-2.493	3.444	-0.16
2002	-24.360	-29.80	82.22	7.6729	45.932	-4.122	-4.75	-3.847	1.101	-1.585
2003	-21.040	-40.00	-17.96	0.1615	-7.031	11.88	-4.81	-4.161	0.642	-1.906
2004	-31.920	-41.30	-9.81	-12.08	-38.33	4.439	0.78	1.333	2.824	1.518
2005	-27.230	-29.90	3.29	-21.41	-62.01	-4.397	2.13	2.137	5.611	2.902

Appendix vi

	% VARIATION OF YEARLY AVERAGE FOR ALL CONDITIONS									
YEAR	SWDP	SWDen	IMF Bz	IMF Total B	SSN (SSN)	SWSpeed	Apati C/R	Newark C/R	Tibilisi C/R	Thule C/R
1981	-7.208	-4.85	-129.30	8.468	92.10	-5.594	-4.93	-5.380	-4.560	-4.628
1982	28.588	16.92	-212.50	21.548	58.56	2.017	-5.80	-6.180	-5.760	-5.885
1983	20.214	6.10	242.57	10.739	-8.65	4.949	-2.33	-2.760	-3.280	-2.467
1984	23.153	7.24	187.80	7.248	-37.62	8.317	-0.93	-1.600	-1.100	-1.314
1985	13.792	14.40	349.67	-18.300	-75.40	3.959	4.39	3.636	0.999	3.956
1986	9.786	15.21	478.08	-20.370	-81.73	1.706	7.96	6.619	4.145	6.949
1987	5.654	21.82	361.76	-15.200	-59.77	-5.049	8.49	7.106	5.131	7.438
1988	-6.575	4.57	218.67	0.943	37.32	-4.796	1.65	0.874	1.099	1.206
1989	10.557	-0.05	512.82	16.983	115.53	1.709	-9.15	-8.490	-5.070	-8.202
1990	2.414	-4.09	48.51	16.983	94.98	-2.01	-10.30	-9.790	-5.830	-9.506
1991	40.222	20.37	250.70	27.175	99.27	3.401	-10.30	-9.390	-7.960	-9.113
1992	25.387	29.05	347.20	15.538	28.57	-4.170	-1.57	-1.170	-2.340	-9.113
1993	15.297	17.43	64.87	46.042	-25.38	0.529	3.17	3.252	0.723	3.572
1994	9.327	-7.22	-7.46	-13.020	-59.11	14.200	4.37	4.471	1.047	4.794
1995	-3.408	18.15	-446.70	-21.160	-76.12	-4.612	6.67	6.530	2.139	6.860
1996	-9.334	8.022	-288.60	-29.210	-88.19	-6.052	7.92	7.520	2.663	7.856
1997	-17.260	17.38	-508.80	-24.130	-70.59	-15.490	8.30	7.968	2.926	8.365
1998	-17.240	-2.29	-378.50	-4.876	-12.06	-8.719	5.87	5.620	1.877	5.947
1999	-24.490	-20.10	11.19	-4.940	27.61	-2.501	2.17	2.327	0.299	2.644
2000	-15.320	-21.60	-236.00	-1.107	63.45	-0.350	-5.21	-4.130	-0.520	-3.825
2001	-22.350	-19.60	-154.20	-4.529	51.81	-5.360	-3.45	-2.360	3.544	-2.057
2002	-18.830	-19.60	168.01	5.227	42.30	-2.264	-4.69	-3.650	1.223	-3.361
2003	-14.640	-40.50	-255.00	4.458	-12.87	20.980	-5.02	-4.320	0.424	-4.023
2004	-28.100	-34.30	-382.80	-10.480	-44.80	0.496	0.81	1.269	2.776	1.579
2005	-19.620	-22.50	-241.90	-14.020	-59.20	4.700	1.93	2.012	5.422	2.328

Appendix vii

	% VARIATION OF YEARLY AVERAGE FOR ALL MINUS QUIETEST CONDITIONS									
YEAR	**SWDP**	**SWDen**	**IMF Bz**	**IMF Total B**	**SSN (Rz)**	**SWSpeed**	**Apati C/R**	**Newark C/R**	**Tibilisi C/R**	**Thule C/R**
1981	-5.347	-4.19	322.07	8.159	91.10	-5.368	-4.96	-5.320	-4.570	-4.625
1982	29.740	15.67	199.88	22.087	58.90	2.306	-5.91	-6.260	-5.820	-5.977
1983	19.264	7.49	-349.30	10.011	-10.55	4.092	-2.27	-2.720	-3.220	-2.413
1984	21.110	7.03	-285.10	6.486	-36.82	6.874	-0.93	-1.630	-1.080	-1.303
1985	10.828	12.14	-479.90	-19.050	-74.51	4.074	4.38	3.644	1.022	3.982
1986	6.7541	12.34	-615.00	-21.120	-82.23	1.501	7.96	6.617	4.125	6.965
1987	3.929	20.93	-495.00	-14.920	-59.69	-5.226	8.52	7.156	5.175	7.490
1988	-6.852	4.50	-323.70	1.496	37.27	-5.882	1.66	0.878	1.082	0.929
1989	10.488	-0.25	-584.20	16.239	115.20	2.094	-9.05	-8.400	-5.080	-8.128
1990	1.761	-3.98	-98.08	11.585	95.92	-2.675	-10.30	-9.790	-5.820	-9.493
1991	40.173	20.14	-213.70	25.990	98.97	3.548	-10.30	-9.490	-8.030	-9.194
1992	25.513	31.44	-448.20	17.211	28.85	-5.296	-1.53	-1.190	-2.390	-9.095
1993	14.493	17.59	-217.10	54.387	-24.55	1.022	3.12	3.247	0.746	3.586
1994	7.934	-10.10	-64.91	-13.890	-59.96	15.470	4.38	4.465	1.079	4.803
1995	-2.465	15.60	614.06	-21.010	-76.70	-3.101	6.67	6.518	2.148	6.857
1996	-10.090	6.29	286.53	-30.040	-88.41	-6.811	7.93	7.538	2.679	7.895
1997	-17.480	15.30	512.50	-23.250	-70.80	-15.310	8.33	8.010	2.962	8.415
1998	-15.390	-0.00	448.29	-4.065	-11.89	-8.861	5.83	5.603	1.867	5.940
1999	-23.940	-18.70	181.77	-8.815	30.00	-2.270	2.20	2.368	0.317	2.689
2000	-12.430	-18.40	408.05	-0.617	64.78	-1.269	-5.22	-4.150	-0.570	-3.826
2001	-20.150	-18.40	215.76	-4.039	52.01	-5.428	-3.43	-2.340	3.584	-2.023
2002	-18.020	-17.70	-28.06	5.084	41.60	-1.944	-4.68	-3.620	1.246	-3.337
2003	-13.790	-40.80	276.50	5.106	-13.99	22.540	-5.07	-4.360	0.379	-4.042
2004	-27.460	-32.70	439.54	-10.230	-45.72	-0.240	0.83	1.265	2.777	1.610
2005	-18.590	-21.20	297.30	-12.790	-58.78	6.167	1.87	1.956	5.376	2.294

Appendix viii

	% VARIATION OF YEARLY AVERAGE FOR DISTURBED CONDITIONS									
YEAR	**SWDP**	**SWDen**	**IMF Bz**	**IMF Total B**	**SSN (Rz)**	**SWSpeed**	**Apati C/R**	**Newark C/R**	**Tibilisi C/R**	**Thule C/R**
1981	20.187	15.54	103.55	12.192	102.08	-3.998	-5.09	-4.960	-4.610	-4.671
1982	37.754	9.20	116.29	16.243	72.35	4.074	-6.31	-6.530	-6.060	-6.246
1983	12.527	8.60	-63.15	13.021	-6.11	0.143	-2.18	-2.630	-3.300	-2.405
1984	2.355	-6.75	-59.33	-4.943	-37.85	2.515	-0.79	-1.690	-0.980	-1.143
1985	-5.294	3.04	-65.58	-25.870	-79.45	4.338	4.43	3.640	0.976	3.952
1986	-5.053	-0.70	-93.35	-12.440	-81.58	4.484	8.17	6.890	4.656	7.212
1987	-2.346	26.04	-89.72	-11.890	-56.44	-8.600	8.70	7.400	5.324	7.723
1988	-12.390	2.09	-81.52	1.969	31.47	-12.470	1.73	0.916	1.134	1.321
1989	-1.920	-12.00	1.76	15.847	108.16	5.652	-9.27	-8.710	-5.350	-8.435
1990	3.916	0.66	-46.57	-4.757	95.49	-3.987	-10.40	-9.940	-5.890	-9.672
1991	38.481	21.19	-47.78	29.505	94.53	0.773	-10.40	-9.400	-8.180	-9.124
1992	16.347	37.91	-106.20	32.913	21.96	-13.070	-1.28	-1.140	-2.340	-9.129
1993	-1.958	5.07	-46.50	-5.412	-27.67	2.861	3.02	3.192	0.666	3.502
1994	-3.016	-17.10	-51.77	-15.700	-58.38	15.770	4.33	4.621	1.191	4.936
1995	2.556	12.07	57.87	-18.340	-82.43	5.646	6.74	6.554	2.226	6.875
1996	-19.790	-12.80	-45.84	-34.610	-87.24	-11.430	7.98	7.673	2.871	8.018
1997	-15.510	16.57	81.89	-13.680	-70.07	-13.500	8.50	8.135	3.071	8.537
1998	1.213	16.40	135.42	7.284	-11.91	-5.668	5.53	5.233	1.699	5.549
1999	-12.800	-9.12	31.44	-3.137	28.49	3.087	2.24	2.389	0.336	2.697
2000	11.676	-6.12	-31.13	12.399	63.56	-2.733	-5.21	-4.330	-0.570	-3.752
2001	-10.930	-26.50	110.88	4.847	54.54	-2.106	-3.29	-2.220	3.667	-1.928
2002	-10.210	1.01	65.69	5.400	41.83	-5.082	-4.74	-3.940	1.037	-3.687
2003	-12.670	-37.50	94.17	2.635	-14.91	24.490	-5.40	-4.590	0.226	-4.301
2004	-22.780	-27.30	19.44	-2.981	-45.47	-5.688	0.86	1.277	2.636	1.700
2005	-10.340	-19.40	10.04	-0.493	-54.93	14.500	2.09	2.166	5.567	2.473

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