Cosmic Ray Transient Variations Observed from the Earth

M. L. Duldig
Australian Antarctic Division,
c/o Physics Department, University of Tasmania,
GPO Box 252C, Hobart, Tas. 7001

Abstract: Cosmic ray transient variations are signatures of the underlying solar processes which affect the heliomagnetic structure. They can be found in the data from surface systems, such as neutron monitors and muon telescopes, and from shallow underground muon telescopes. Although sometimes observable at all latitudes, the global distribution of the effects is important in determining the structures and causes. Three transient variation types are known, namely Forbush decreases, ground level enhancements, and quasi-periodic fluctuations. The latter category includes some variations which are, perhaps, too long-lived to be considered truly transient. In this review, the detection techniques and background of cosmic ray research are followed by a summary of some observations in each transient category. The heliomagnetic structures and dynamics inferred from such transients are discussed together with the possible impact such events can have on human activity.

1. Introduction
Cosmic rays are ionised nuclei of very high energy, typically $10^8$-$10^{20}$ eV, which arrive at the Earth almost isotropically. Their elemental abundances are similar to the observed galactic abundances, with approximately 90% being protons. In general, cosmic rays are of non-solar origin and the acceleration mechanism responsible for the high particle energies is not well understood, particularly at the highest energies. The spectrum can be adequately described by a power law with an exponent of $-2.6$ over the energy range $10^9$-$10^{11}$ eV where transient variations are observed.

Before considering cosmic ray transient variations it is necessary to understand the detection techniques and corrections to the data which must be included in any analysis of cosmic ray phenomena.

2. Cosmic Ray Detection

(2a) Secondary Particle Production
The atmosphere is an integral part of any cosmic ray detector. Figure 1 is a schematic representation of the energy-dependent processes that occur when an incident cosmic ray particle (primary cosmic ray) interacts with atmospheric nuclei to produce secondary products. It is these secondaries that are detected by ground-based and underground detectors. Primary cosmic rays with energies less than about $10^9$ eV (1 GeV) will not produce secondaries capable of reaching sea level, due to ionisation losses and eventual absorption in the atmosphere. For particles up to about 50 GeV the initial atmospheric interaction can produce energetic nucleons which in turn generate a small cascade of collisions, eventually resulting in multiple neutrons (and a few protons) at sea level. Due to the relativistic nature of these processes the scattering remains within a few degrees of the incident direction of the primary cosmic ray at the top of the atmosphere.

At higher energies, above about 1000 GeV the initial interaction can produce a charged pi-meson (pion) which rapidly decays into a mu-meson (muon) of the same charge. Note that there is an overlapping energy range where either a nucleon cascade or charged pion production is possible. The muons are highly penetrating and can be detected at depths in excess of 1 km underground.

At the highest energies, above about 1000 GeV, the initial interaction can produce a charged muon which decays into a gamma-ray pair. The gamma rays undergo pair production, the positron annihilating with an atmospheric electron to produce another gamma-ray pair. The process continues through
the atmosphere, generating an electron shower (and Cerenkov light) of roughly cigar-shaped profile which may reach the Earth's surface. The only transient events observed in this energy range are associated with compact galactic objects. Ultra-high-energy (UHE) gamma rays from these point sources interact in the atmosphere with a very similar cascade to those produced by high-energy cosmic rays. UHE gamma-ray sources are not discussed further but Protheroe (1994) and Clay and Dawson (1983) are recommended reviews of the topic.

Figure 2—Schematic diagram of the NM64 or IQSY neutron monitor construction.

(2b) Neutron Monitor

The neutron monitor shown in Figure 2 detects neutrons through a neutron capture nuclear reaction:

\[ ^{10}\text{B} + n \rightarrow ^{7}\text{Li} + \alpha. \]

The lead moderator and polyethylene 'reflector' are designed to thermalise the secondary neutrons through scattering and multiplication in nuclear collisions with lead nuclei. The resulting thermalised neutrons then enter the BF3 proportional counters at the energy of maximum cross section for the nuclear reaction. Following the reaction the ionised lithium atoms and the alpha particles in the proportional counter produce countable pulses. The design of various neutron monitors has been extensively described by Hatton (1971).

The scattering in the lead moderator and the subsequent nuclear reaction do not maintain any directional relationship to the incoming neutron path, so that the instrument cannot be considered a telescope. However, the neutron monitor does have a restricted opening aperture. Neutrons produced in the upper atmosphere by the nucleonic cascade will only have sufficient energy to reach the lower atmosphere from zenith angles up to about 30\(^\circ\). The geomagnetic field further restricts the incident particle directions which can access the neutron monitor to an energy-dependent window, called the asymptotic cone of acceptance or viewing cone.

Particles entering the geomagnetic field near the equator will be deflected back into space unless their energies are greater than about 15 GeV. At mid-latitudes particles require less energy to penetrate the field, whilst at the magnetic poles, where the particles can travel along the field lines, there is no such minimum energy for access, although the particles still require about 1 GeV to penetrate the atmosphere to sea level. This minimum energy for access for a given observatory location is called the geomagnetic cutoff, and energy discrimination of cosmic ray events is achieved by employing data from locations having a range of cutoff values. Thus by siting neutron monitors at a range of magnetic latitudes it is possible to obtain spectral information about low-energy cosmic ray phenomena. As the viewing cones also vary with longitude it is important to site neutron monitors over a range of latitudes and longitudes if adequate coverage of free space directions and of energy is to be achieved. It was this requirement that led to the establishment of the worldwide neutron monitor network which has operated since the International Geophysical Year, 1957.

(2c) Muon Telescopes

Muon telescope systems comprise two or more trays of charged particle detectors arranged to record coincident events. The detectors were traditionally Geiger–Müller tubes but over the last three decades plastic scintillator and proportional counter systems have become the preferred choices due to their long-term stability and low maintenance requirements. The multiple tray configuration and coincidence electronics allow directional information to be recorded, but opening apertures are generally large due to the low flux of particles and the need for good counting statistics. Response to local radioactivity is reduced by placing absorbing material between the trays.

Surface telescopes at mid to high latitudes with high background rates often employed triple coincidence systems to reduce the number of accidental triggerings from independent particles which cause an apparently genuine coincident event. A two resolving-time technique was developed (Jacklyn and Duldig 1987) that allowed two-tray telescopes of lower initial cost and subsequent reduced maintenance to be effectively employed without significant accidental triggering contamination. The reduced maintenance of such telescopes is particularly advantageous because the systems are often located at unstaffed, remote sites.

Energy discrimination with muon telescopes is achieved in two ways. By viewing at high zenith angles, the amount of absorbing atmosphere may be increased and lower-energy particles will no longer penetrate to the telescopes. Siting the telescopes below ground allows the overburden to be used as the additional absorbing material, again removing the lower-energy particles.

As a result of the directional information possible with muon telescope systems, global coverage can be achieved from a smaller number of carefully chosen...
observatory sites than is possible with the worldwide neutron monitor network. Global coverage is still necessary to interpret both transient variations and long-term anisotropies. Some examples of observatory design considerations can be found in Mori et al. (1991), Duldig (1990) and Duldig et al. (1985a).

(2d) Energy or Rigidity?

So far we have discussed the detection of cosmic ray particles in terms of their energy. Although this is useful for comparison with other branches of astronomy or radiation physics, energy is not the most appropriate reference unit for studies of charged particle propagation in a magnetic field.

The total energy of a relativistic particle is given by

$$E = m_0 c^2 \gamma,$$

where $\gamma = 1/(1 - v^2/c^2)^{1/2}$ is the usual relativistic correction factor. The particle momentum is similarly $p = m_0 v \gamma$ and as $v \to c$, $E \to pc$. The rigidity or normalised momentum per unit charge of a particle represents its tendency not to deviate from its path in a magnetic field (hence the name being related to a tendency not to bend) and is defined as

$$P = pc/q,$$

where $q$ is the charge of the particle. In a magnetic field $B$ the particle gyroradius $r$ is given by

$$Br = p/q$$

and the relationship can be rewritten as

$$r = P/45B,$$

where $r$ is in units of AU, $B$ in nT and $P$ in GV. Furthermore, as is clear from Table 1, for protons the energy in GeV and rigidity in GV have almost the same numerical values above $\sim 2$ GeV.

### Table 1. Proton properties at high energies in a 5 nT field typical near the Earth

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Rigidity (GV)</th>
<th>Speed</th>
<th>Gyroradius (AU) (5 nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.35</td>
<td>0.35c</td>
<td>0.004</td>
</tr>
<tr>
<td>2</td>
<td>1.77</td>
<td>0.88c</td>
<td>0.009</td>
</tr>
<tr>
<td>3</td>
<td>2.85</td>
<td>0.95c</td>
<td>0.013</td>
</tr>
<tr>
<td>5</td>
<td>4.91</td>
<td>0.98c</td>
<td>0.022</td>
</tr>
<tr>
<td>10</td>
<td>9.96</td>
<td>0.996c</td>
<td>0.044</td>
</tr>
<tr>
<td>100</td>
<td>99.996</td>
<td>0.99996c</td>
<td>0.444</td>
</tr>
</tbody>
</table>

The gyroradius of a particle is a fundamental characteristic length in the study of cosmic ray modulation and thus the use of rigidity as the prime unit is preferred. Note that a field strength of 5 nT has been assumed in calculating the gyroradius in Table 1. This is the average value of the heliomagnetic field near the Earth.

(2e) Geomagnetic Effects

The geomagnetic field significantly distorts the viewing aperture of a cosmic ray detector. Figure 3 shows the viewing direction in geocentric coordinates of vertically incident secondaries of several neutron monitors.

**Figure 3**—Rigidity-dependent viewing directions of various neutron monitors for vertically incident secondaries. The dotted curves are for undisturbed geomagnetic conditions ($Kp = 0$), whilst the solid curves are for the disturbed geomagnetic conditions ($Kp = 5$) applicable at the time of the 22 October 1989 ground level enhancement.
monitor detectors for an undisturbed (Kp = 0) and a moderately disturbed (Kp = 5) geomagnetic field. Because the geomagnetic field is compressed on the sunward side and has a long tail on the night side, the cones of view are also dependent on the time of day and the date within the year. Incorporation of these corrections into cosmic ray trajectory calculations has only recently been developed (Duldig et al. 1993; Cramp et al. 1993a, 1993b; Bieber et al. 1992; Flückiger and Kobel 1990; Kobel 1989) and are used by only three research groups at present. For muon telescope systems, where the response to particles of rigidity below 10 GV is small, the effect of the time of day and geomagnetic disturbance may be ignored in the cones of view but the underlying geomagnetic field must still be considered for rigidities below about 100 GV. This is most significant for telescopes which view across the magnetic field, like the Mawson south-pointing telescope. Figure 4 shows the rigidity-dependent viewing of this telescope.

(2f) Atmospheric Effects

An increase in atmospheric pressure at sea level indicates a greater mass of air over a site. This in turn means that secondary particles lose more energy in penetrating the increased absorbing material and fewer particles have sufficient energy to reach the detector. It is therefore necessary to correct the recorded count rates for variations in pressure. For muon telescopes second-order corrections may be required. The mean production of pions is at ~125 mb but the height above sea level of this pressure level varies, particularly seasonally. The muon decay product will therefore have a varying transit time through the atmosphere depending on the height of pion production. The positive muons have a significant probability of decaying into positrons before reaching sea level. An increase in the flight time (height of production) will therefore result in more positive muon decays and a lower particle rate at sea level. The temperature at the pion production level is inversely proportional to the air density and also varies seasonally. At higher densities the pion is more likely to be absorbed before decaying into a muon, so that lower temperatures result in fewer muons being produced.

Radiosonde balloon measurements may be employed to determine the day-to-day values of these parameters and correct the count rate for variations. See Baker (1993), Baker et al. (1993) and Lyons (1981) for further discussion of these corrections. These atmospheric structures vary relatively slowly and so correction for the height and temperature effects are only required for longer-timescale studies such as annual anisotropies. The only transient variations where these corrections can be important are the quasi-periodic variations related to the solar rotation, which may last several months.

(2g) Heliomagnetic Effects

The solar magnetic field is ‘frozen’ into the solar plasma and carried outward by the solar wind. Because the Sun also rotates, the field at equatorial latitudes forms a spiral structure. In addition, a neutral sheet results from this flow maintaining a separation between the northern and southern...
regimes. The angle of the solar field dipole to the rotation axis produces a wavy structure in the neutral sheet, as shown in Figure 5 (Flückiger 1991). An added complication in these structures is the 11-year solar sunspot cycle, which produces a relatively flat neutral sheet at solar minimum, but neutral sheet waves extending up to 70° heliolatitude at solar maximum. Furthermore, the solar field polarity reverses at each solar maximum, giving rise to a 22-year periodicity in the heliomagnetic field.

The combined effect of these field structures on galactic cosmic rays can be seen in Figure 6, where the neutron monitor response at Mawson is plotted against time together with the smoothed monthly sunspot numbers. The anti-correlation with solar activity is due to the solar wind and field acting as a more efficient barrier to galactic cosmic ray transport into the inner solar system at times of high solar activity. Recurrent differences between successive solar cycles are also apparent and have been interpreted as arising from the field reversals. Recent evidence from the current cycle and a reconsideration of the scaling of early records suggests that the assumption of alternating peaked and flat-topped cosmic ray intensity profiles for each solar cycle may not be valid, raising questions about the field reversal interpretation (R. Pyle 1993, personal communication).

3. Cosmic Ray Transients

Ground-based cosmic ray transients can be divided into three broad categories:

1. Forbush decreases—where the cosmic ray flux reduces by ~3–20% over timescales of hours or a few days and recovery takes days to weeks;
2. ground level enhancements—where the cosmic ray flux increases by ~3–4500% over timescales of minutes to an hour or two and recovery is from a few hours to a day; and
3. enhanced quasi-periodic variations—where the peak-to-peak flux variation is typically no greater than a few per cent and lasts for several to 10 or 15 cycles, with periods related to the solar or the Earth’s rotation.

Each of these classes of event is attributed to different causes which are discussed below.

(3a) Forbush Decreases

Forbush decreases may be divided into two types, rapid- and slow-onset. Very little work has been carried out in the study of slow Forbush decreases. By contrast the rapid-onset, sometimes known as classical, Forbush decrease has been extensively studied (see e.g. the review by Rao 1972). Lockwood (1971) wrote an excellent review on Forbush decreases but this has now become somewhat dated. Venkatesan and Badruddin (1990) reviewed cosmic ray intensity variations in the three-dimensional heliosphere, including a more up-to-date discussion of Forbush decreases. Figure 7 shows one of the largest such events as seen by a range of neutron monitors of increasing cutoff and one underground muon telescope.

The spectral response characteristics are evident simply from looking at these data. At Mawson the minimum particle rigidity observable is determined by the atmospheric absorption and is about 1 GV. At Mt Wellington the geomagnetic cutoff is 1.9 GV whilst at Brisbane it is 7.2 GV and at Darwin it is 14.2 GV. The minimum rigidity of particles capable of producing a statistically significant observation in the Mawson underground north telescope is ~15–20 GV, depending on the spectrum of the event. Clearly, there were few particles above ~25–30 GV that were modulated during this decrease. The solar flare that led to the decrease was located at E36° on the solar disk.

Figure 8 shows three further Forbush decreases observed by the Mawson neutron monitor and
exhibiting some of the common features seen during such events. The top trace shows a two-step decrease which also indicates quite large diurnal variations before the event and during the recovery phase. Significant anisotropy of particle distribution is also in evidence, as demonstrated by the rapid initial recovery followed by at least one significant rise and fall. The ‘parent’ flare for this disturbance was located at E33° on the solar disk. The middle trace shows a single step decrease with a slight pre-decrease enhancement, not in phase with the diurnal variation before the event. Note that the phase of the diurnal peaks has shifted after the event. The ‘parent’ solar disturbance is unknown for this event. The lower trace shows an event embedded within a cosmic ray storm. Complex

Figure 7—Large Forbush decrease of 13–14 July 1982 as recorded by the Australian neutron monitor network and the Mawson underground north-pointing muon telescope. The effective vertical cutoff rigidities for the neutron monitors are from top to bottom 0.2, 1.9, 7.2 and 14.2 GV respectively. The effective minimum rigidity of the Mawson muon telescope is 15–20 GV due to rock and atmospheric absorption.
Figure 8—Mawson neutron monitor observations of three Forbush decreases showing some of the typical features found, as discussed in the text.
anisotropics existed three to four days before and a distinct semi-diurnal variation can be seen for up to three days immediately prior to the decrease. This semi-diurnal variation most likely indicates a bi-directional flow of cosmic rays. Again a significant diurnal variation is seen in the recovery phase but the 'parent' flare location is unusual being at W43° on the solar disk.

Figure 9 summarises the features of a rapid-onset Forbush decrease. It is worth noting that there is sometimes a tendency for a recurrence of the decrease, though with slower onset, after a solar rotation of 27 days.

Models to explain Forbush decreases have been many and varied. Alfvén (1954) proposed magnetised plasma clouds with frozen-in fields, whilst Morrison (1956) proposed turbulent magnetic clouds as the region responsible for scattering cosmic rays. In the late 1950s Cocconi et al. (1958) proposed a magnetic
tongue model, whilst Piddington (1958) suggested that a magnetic bubble of plasma was responsible. Parker (1961) was the first to recognise the importance of a magnetic shock wave and shock front passage past the Earth as an important aspect of Forbush decreases, although he did not require a plasma cloud. Barnden (1973) presented an excellent paper at the 13th International Cosmic Ray Conference where he was able to explain the observed anisotropy of many decreases with a plasma-driven shock and associated magnetic field. Unfortunately this work has never been fully written up in a journal article but his figures are reproduced here as Figures 10 and 11. Hundhausen (1987) has more recently presented a description of the magnetic field and plasma structures for coronal mass ejections, as seen in Figure 12.

A slightly different view was presented by Cane et al. (1988), in which the ejected plasma is more flattened. Their conclusions are for coronal mass ejections with a plasma-driven shock and are derived in part from multi-spacecraft measurements of individual events. Figure 13 is an adaptation

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**Figure 14**—Schematic view of the location of the ‘parent’ solar flares which produced GLEs, referred to the Sun–Earth coordinate system at the time of the events.

**Figure 15**—Typical heliomagnetic field geometry showing the ‘Garden Hose’ field line that connects the Sun and Earth.

**Figure 16**—Responses of some neutron monitors to the 29 September 1989 GLE.
of their diagram. This structure seems to be the best model deduced to date to explain Forbush decreases. The most compressed field, and hence the greatest barrier to galactic cosmic rays, is found to the west of and in front of the ejecta. There may be closed field lines within the ejecta, or the field lines may thread through the ejecta and back toward the Sun. It is not known if these field lines and others behind the ejecta connect to the Sun.

The strong tendency of Forbush decreases to be associated with eastern and central meridian flares is clearly expected from all the later models, as are the complex anisotropies during the decreases, but the Cane et al. (1988) model gives a better understanding of the second step observed in some decreases which result from the ejecta passage past the Earth. Their model also accounts for other features including the multi-spacecraft plasma and field observations from 0.5–1 AU.

The slow-onset decreases do not appear to be as well described by such a model. Some events do fit this scenario but an alternative explanation may be the compressed field resulting from a fast solar wind stream, as described by Burlaga (1983) in his review at the 18th International Cosmic Ray Conference. This model also explains nicely the 27-day recurrence tendency.

The explanation for 27-day recurrence of the rapid-onset decreases is still a relative mystery. After such a long time the original shock is far out in the solar system and cannot, of itself, be responsible for the subsequent decreases. It is not yet clear how the region behind the ejected plasma and the shock behaves in the longer term, and it may be that remnant structures capable of modulating galactic cosmic rays of up to 10 GV rigidities are present for a few solar rotations. It may also be possible that fast solar wind streams may form behind some shocks.

Figure 17—Derived spectra of the 29 September 1989 GLE using the new least-squares modelling technique and data from 42 neutron monitors in the worldwide network.

Figure 18—Derived particle pitch angle distributions for the 29 September 1989 GLE. The zero pitch angle corresponds to the 'source' directions given in Table 2.
(3b) Ground Level Enhancements

Ground level enhancements (GLEs) are rare events in which a sudden rise in the cosmic ray flux is followed by an approximately exponential decay back to pre-increase levels. There is a weak tendency for these events to occur around times of solar maximum but they can be observed at any time in the solar cycle. Fifty-two events have been observed since reliable observations began in the 1940s, but 13 of these were observed within a two-year period centred on the last solar maximum. In a recent paper Nagashima et al. (1991) pointed out that no GLEs have been observed during the peak of the solar activity cycle while the magnetic field is undergoing a reversal. For an excellent summary of GLE observations up to the end of the previous solar cycle see Shea and Smart (1990), and a more recent summary appears in Shea and Smart (1993).

Figure 14 shows the ‘parent’ flare location for all recorded GLEs. There is a strong tendency for ‘parent’ flares to be located between W30° and W90° on the solar disk.

The acceleration of protons to cosmic ray energies during solar flares is not well understood and no suitable model has been developed to explain the observed characteristics of the radio, optical, X-ray and particle observations. The propagation of the solar protons to Earth is clearer. Figure 15 shows the typical geometry of the field line connecting the Sun and the Earth, the so-called ‘Garden Hose’ field line. This geometry is highly variable depending on solar activity, wind speed and the previous passage of shocks and coronal mass ejections. It does, however, explain the greater likelihood of a GLE being observed when the ‘parent’ flare is located in the west. For these flares the accelerated solar protons have immediate access to the ‘Garden Hose’ field lines. Distortions of the heliomagnetic field in interplanetary space closer to the Sun than 1 AU may explain the field connection to Earth of ‘parent’ flare events near the meridian or beyond the west limb, but the explanation for significantly eastward ‘parent’ flares generating a GLE is not at all apparent.

To model such events a standard technique has been developed (Humble et al. 1991; Shea and Smart 1982). This technique determines the particle flux, distribution and propagation direction on an instantaneous basis and has not yet been sufficiently developed to produce a dynamic solution. Furthermore, the modelling is restricted to energy-independent and cylindrically symmetric pitch angle distributions. Until recently, best-fit parameters were determined on a trial and error basis. We have developed a least-squares technique using the standard model.

The responses of numerous neutron monitors worldwide are modelled to determine a best-fit spectrum and spatial distribution of the particles arriving from the Sun. The model for the neutron monitor response is of the form

\[ I = \sum_{P_c}^\infty J_\alpha(\alpha, P) S(P) G(\alpha) \delta P, \]

where \( I \) is the recorded percentage increase at the time, \( P \) the particle momentum (in GV), \( P_c \) the cutoff for that neutron monitor, \( \alpha \) the pitch angle of the particles, \( J_\alpha \) the interplanetary differential flux, \( S \) the specific yield function of the neutron monitor and \( G \) the pitch angle distribution of the arriving particles.

The specific yield function includes two components, the neutron monitor yield function (Debrunner et al. 1982), which gives the response to particles arriving at the top of the atmosphere above the detector, and the cones of view described earlier. Note that in some cases it has not been possible to derive fit parameters without including a correction to the viewing cones for disturbed geomagnetic conditions. Analyses where this effect has been ignored should thus be considered with caution. We have recently extended the model to include energy dependence in the pitch angle distribution; these results will appear elsewhere.

The largest GLE in the space era was observed on 29 September 1989 by at least 42 neutron monitor stations in the worldwide network and a number of surface muon telescopes such as Mawson and Hobart. In addition, underground muons were observed at the Embudo observatory (Swinson and Shea 1990). Detailed analyses of this event have been previously reported (Duldig et al. 1993; Cramp et al. 1993a) and are not reproduced here. The least-squares technique has allowed a more rigorous coverage of parameter space. Consequently, improved spectra, pitch angle distributions and source directions have been determined. Figures 16, 17 and 18 show the recorded increases at various monitors and the improved spectra and pitch angle distributions derived for this GLE by taking all available neutron monitor observations into account. The significant reverse particle propagation at 13:25–13:30 UT in Figure 18 is particularly interesting, implying scattering centres beyond the Earth’s orbit which cause particles to propagate back toward the Sun along the interplanetary magnetic field. The source of this scattering is unknown. It should also be

Table 2. ‘Source’ direction parameters derived for the 29 September 1989 GLE

<table>
<thead>
<tr>
<th>Time UT</th>
<th>Source latitude</th>
<th>Source longitude</th>
<th>Angle to Sun-Earth line</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:15–20</td>
<td>N30°</td>
<td>237°</td>
<td>W117°</td>
</tr>
<tr>
<td>13:25–30</td>
<td>N24°</td>
<td>222°</td>
<td>W114°</td>
</tr>
<tr>
<td>16:00–05</td>
<td>N17°</td>
<td>190°</td>
<td>W108°</td>
</tr>
</tbody>
</table>
noted that the minimum pitch angle response on these curves represents the isotropic flux increase and the anisotropy of an event should be considered with respect to this minimum. The zero of the pitch angle is assumed to be the interplanetary magnetic field direction at the Earth at the given time and is fixed as such whenever satellite field data are available. Table 2 shows the improved determination of this pitch angle reference or 'source' direction.

Note that the source longitude variation is partly due to the rotation of the Earth but still represents a significant deviation from the nominal 'Garden Hose' field direction of W45° shown in Figure 14. No satellite field data are available for this event but the field direction at Earth was N16°, W6°, three days before the event and had changed to N65°, W100° two days after the event. The 'source' positions derived are thus not inconsistent with the possible field orientation during the GLE.

A second interesting GLE of 22 October 1989 was also reported earlier (Duldig et al. 1993; Cramp et al. 1993b) in which a 'precursor' peak was observed at only a few observatories prior to the GLE. The event has also been re-analysed with the improved least-squares procedure and Figures 19, 20 and 21 show the recorded count rates and derived spectra and pitch angles of this event. The spectrum steepened throughout the event whilst the pitch angle distribution of the 'precursor' was highly anisotropic. The main GLE showed a large isotropic increase with a superposed anisotropic component. Table 3 shows the 'source' direction parameters.

Again no satellite field data are available. The source direction of the 'precursor' is intriguing. The 'precursor' cannot be due to direct solar neutrons (see below) as no stations of high cutoff near the sub-solar point detected an increase at this time. It is possible that channelling of particles along the neutral sheet may be responsible for the extreme anisotropy and unusual 'source direction' and this is being investigated.

Two further features associated with GLEs are worthy of mention. There is now clear evidence for the detection of neutrons accelerated at, or very near to, the Sun and propagating directly to the Earth (e.g. Shea et al. 1991a). These direct solar neutrons are associated with solar flares which also give rise to a subsequent GLE. Various models are being proposed to explain the production of the
high-energy neutrons, but as yet no satisfactory explanation has been found.

Perhaps even more exciting is the work of Shea et al. (1991) where the decay of solar accelerated neutrons near the ‘Garden Hose’ field line is proposed to explain an unusual GLE onset shape. Direct solar neutrons were observed for the event of 19 October 1989 prior to the unusual onset. Figure 22 from Shea et al. (1991b) shows schematically the proposed geometry of the neutron decay process and subsequent GLE particle propagation.

The recent development of techniques to correct for geomagnetic disturbance, together with improvements in modelling capability imply that we should progressively reanalyse the earlier GLEs. Although this will be a computationally intensive undertaking, new insights into the distribution of the propagating particles will lead to a greater understanding of the interaction of the interplanetary magnetic field and cosmic rays and may impose stringent new limits on solar particle acceleration models.

Table 3. ‘Source’ direction parameters derived for the 22 October 1989 ‘precursor’ and GLE

<table>
<thead>
<tr>
<th>Time UT</th>
<th>Source latitude</th>
<th>Source longitude</th>
<th>Angle to Sun-Earth line</th>
</tr>
</thead>
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<td>18:05-10</td>
<td>S48°</td>
<td>265°</td>
<td>0°</td>
</tr>
<tr>
<td>18:30-35</td>
<td>S62°</td>
<td>225°</td>
<td>W34°</td>
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<tr>
<td>18:40-45</td>
<td>S60°</td>
<td>220°</td>
<td>W36°</td>
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<td>19:00-05</td>
<td>S64°</td>
<td>210°</td>
<td>W41°</td>
</tr>
<tr>
<td>19:20-25</td>
<td>S53°</td>
<td>182°</td>
<td>W64°</td>
</tr>
</tbody>
</table>

The recent development of techniques to correct for geomagnetic disturbance, together with improvements in modelling capability imply that we should progressively reanalyse the earlier GLEs. Although this will be a computationally intensive undertaking, new insights into the distribution of the propagating particles will lead to a greater understanding of the interaction of the interplanetary magnetic field and cosmic rays and may impose stringent new limits on solar particle acceleration models.

(3c) Quasi-periodic Variations

Quasi-periodic variations, lasting from a few to ten or so cycles, are indicative of short-term anisotropic structures in the cosmic ray distribution within the...
heliosphere. They have been associated with the rotation of the heliomagnetic field and its large-scale features, such as the neutral sheet, and with plasma features, such as fast solar wind streams.

Periods of enhanced diurnal variations are observed by both neutron monitors and muon telescopes (e.g. Duldig and Humble 1990; Venkatesan and Badruddin 1990; Jacklyn and Humble 1981; Rao 1972). Iucci et al. (1981, 1983) have proposed fast solar wind streams; Murayama (1981) suggested perpendicular cosmic ray gradients; Mori (1975) and Swinson (1981) believed that enhancement of the north–south anisotropy due to changing radial gradients and/or varying field strength were possible causes; and Alania et al. (1981) proposed transverse diffusion of cosmic rays as the likely cause. All of these mechanisms can explain some of the enhanced diurnal variations but none are satisfactory in all cases. Duldig and Humble (1990) tentatively proposed that the neutral sheet may play a significant role during these periods. Unfortunately, insufficient interplanetary magnetic field data have been collected over the last decade or more to make a detailed study possible. It is hoped that this situation may be rectified in the future.

A second type of quasi-periodic transient was discovered in the cosmic ray records from the Mawson observatory in 1982 (Swinson et al. 1993; Duldig et al. 1985a, 1985b, 1990; Duldig 1987; Jacklyn et al. 1984a, 1984b, 1987). Here intensity variations of isotropic nature and flat spectrum were found to correlate strongly with the neutral sheet structure near the Earth. Periodicities of 27 or 13–5 days were observed, lasting five or so cycles in the latter parts of 1982, 1983 and 1984. These periodicities correlated strongly with the Earth’s position above or below the neutral sheet, implying a differing cosmic ray regime in the northern and southern heliomagnetosphere, at least near the neutral sheet. No mechanism for the relatively abrupt onset and the much slower decline of these waves of varying intensity has been found and the waves have not recurred since the declining phase from solar maximum in the early to mid 1980s. Data following the most recent solar maximum and declining phase have yet to be analysed for these intriguing variations. It is hoped that a recurrence of such periodic episodes will be matched by the availability of high-quality interplanetary field and plasma data on an around-the-clock basis, so that further significant advances in our understanding of cosmic ray interactions in the inner solar system can be achieved.

(3d) Impact on Human Activity

Rapid-onset Forbush decreases are invariably associated with a sudden commencement geomagnetic storm. Such storms can have an enormous impact on human activity, particularly at high magnetic latitudes. The damage to the Canadian power grid, reported worldwide a few years ago, was caused by power surges resulting from such a storm. The economic cost of the resulting large-scale blackout, which lasted many hours, was estimated to be hundreds of millions of dollars. Severe communication disruptions and satellite problems, such as increased rates of single event upsets, have been reported for this and other sudden commencement storms.

Nagashima et al. (1993a, 1993b, 1993c) and Sakakibara et al. (1993) have recently been studying possible precursor indications of Forbush decreases in the cosmic ray records. This work is still in its infancy but may lead to a forecast and warning service of enormous economic benefit. A forecast service would allow precautionary measures to be taken, such as sensitive system shutdowns, to avoid damage induced by sudden commencement geomagnetic storms. This would be similar to the satellite shutdowns employed before crossing the South Atlantic anomaly.

GLEs do not generally pose a hazard to human activity. It is clear, however, that passengers and crew flying high-altitude polar routes may be exposed to significantly higher radiation environments during GLEs. In particular, Concorde flies between London and Washington over the north magnetic pole where the geomagnetic cutoff is zero and at a flight altitude where there is much less protection offered by atmospheric absorption. Concorde carries radiation monitoring equipment to warn pilots of increased radiation during such events and to allow the pilot to fly to lower altitudes for greater protection if necessary. As a precaution, Lufthansa has decided that pregnant crew may not fly high altitude international routes during their 8th to 12th weeks of pregnancy, when the foetus is most susceptible to radiation damage.

The risks in space are much greater, with satellite damage already well documented. The radiation environment of space is harsh and during GLEs could be life-threatening. As humanity moves toward greater usage of space, with possible long-term missions such as that proposed to Mars, the cosmic radiation hazards of space must be reassessed. To this end NATO Advanced Study Institute conferences have been held. The first, in 1987, considered low-Earth-orbit radiation hazards and the second in 1991 considered the deep space environment (Swenberg et al. 1993).

Further study of GLEs, especially with a view to prediction and warning, is needed to minimise the potential radiation risks associated with high-altitude flights and proposed sub-orbital mass transport and for the protection of spacecraft crew.
4. Conclusion
This review has attempted to describe the main transient variations observed by ground-based cosmic ray experiments and to understand how such events are used to probe the heliomagnetic structures and solar acceleration processes. To achieve this it was necessary to first understand the detection process itself and the complexities involved in the atmosphere which is an integral part of the detector.

The data for examples of transient phenomena and, where appropriate, the interpretations have been deliberately parochial to demonstrate to the local astronomical community the breadth and standing of Australian research in this area. The review has been restricted to energies below about 100 GeV where solar processes dominate, and ultra-high-energy gamma-ray sources have only been noted in passing.

It is clear that much has been learnt from the study of transients. It is equally clear that there is much still to be done. The dynamic modelling of GLEs is still many years away but results from energy-dependent pitch angle solutions could prove interesting, and greater generalisation of physically reasonable pitch angle shapes may also lead to new insights.

The importance of the neutral sheet in cosmic ray modulation has become increasingly evident over the last decade. Unfortunately, limited satellite measurement of the interplanetary magnetic field near the Earth is significantly hampering many aspects of research, not only in cosmic ray studies (only IMP-8 is recording, a large fraction of its time being in the geomagnetic tail, and not all of its data are being downloaded). There is a desperate need for additional satellite recording of these important data.

Both Forbush decreases and GLEs will be important as human activity in space increases. Prediction and warning services will thus need to be developed to avoid possible radiation hazards and expensive equipment malfunction.


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