Galactic cosmic rays in the heliosphere

Article

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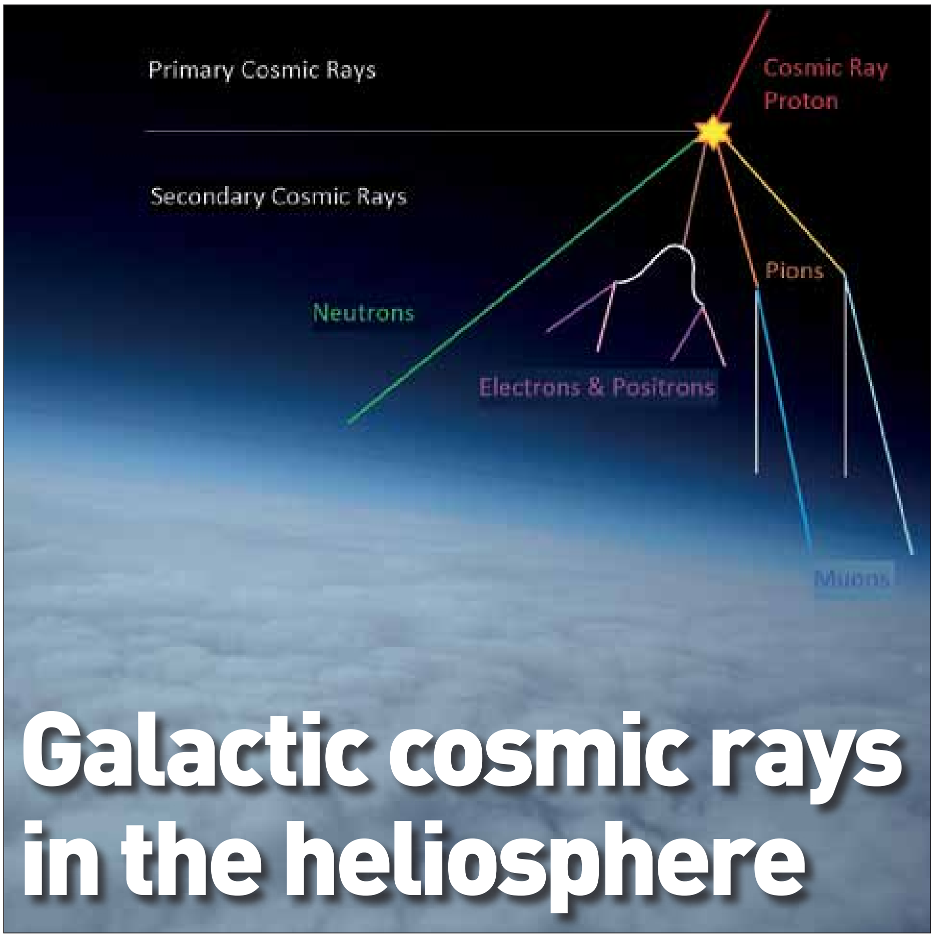


1: A cosmic-ray cascade in the atmosphere. A primary cosmic-ray proton collides with a molecule within the atmosphere and creates a series of decay products, collectively known as secondary cosmic rays. (Photo: NASA)

Simon R Thomas, Mathew J Owens and Mike Lockwood discuss how neutron monitor counts can help map space weather. This won the 2014 Rishbeth Prize for the best student talk at the Hot Spring MIST Meeting in Bath, April 2014.

Galactic cosmic rays (GCRs) are very-high-energy, charged particles with sources outside our solar system, such as supernovae. Because their energy is large enough for them to penetrate the magnetosphere and interact with the Earth's atmosphere, they can be detected at neutron monitor stations across the globe. The rate of neutron counts at these stations varies with changes in the solar wind and heliospheric magnetic field (HMF) on a range of different timescales. Over hours to days, transient structures in the solar wind can temporarily shield Earth from GCRs, resulting in sudden decreases in neutron monitor counts at Earth, known as "Forbush decreases". In the longer term, large-scale changes and cycles in the HMF modulate neutron monitor counts, so that traces of cosmic rays in terrestrial reservoirs can help reconstruct solar variability over millennia. In this article we summarize our work on GCR variations on both long and short timescales.

GCRs typically have energies in the range 100 MeV to 10 GeV and are generated at a few extreme environments outside the heliosphere. They consist mainly of protons, light nuclei and electrons and they enter Earth's atmosphere almost isotropically. GCRs are an important component of "space weather": they can cause radiation hazards for human activity outside the protective shield of our atmosphere, they have been known to damage technology on satellites and cause upsets in aircraft electronics. In addition, and as we will discuss below, indirect records of GCRs in terrestrial reservoirs such as ice cores, tree trunks and lake sediments, can be used to deduce long-term records of solar variability; in the shorter term, GCRs have been found to influence a number of meteorological processes (e.g. Harrison and Ambaum 2010).

Neutron monitors

When a GCR particle enters the atmosphere and collides with an air molecule, it produces a "shower" or "cascade" of secondary particles, shown in schematic view in figure 1. Two of the products for a cosmic-ray cascade are neutrons and muons, which are detected across the globe by ground-based neutron monitors or muon telescopes. Thus neutron monitor counts are a proxy for the flux of GCRs entering the top of the atmosphere. Neutron monitor count rates are available from many locations at different longitudes and latitudes, giving a broad range of viewing directions and particle rigidities (the rigidity of a charged particle is defined as the ratio of momentum/charge and is a measure of how well a particle can penetrate the magnetic field). At high latitudes there are a broader range of particle rigidities because here the Earth's magnetic field is open to the HMF and, as lower energy GCRs follow magnetic field lines more readily, the poles are the only regions at which these particles can reach the atmosphere and be detected at the surface. High-energy GCRs, however, are less bound to the magnetic field lines and so can access all latitudes.

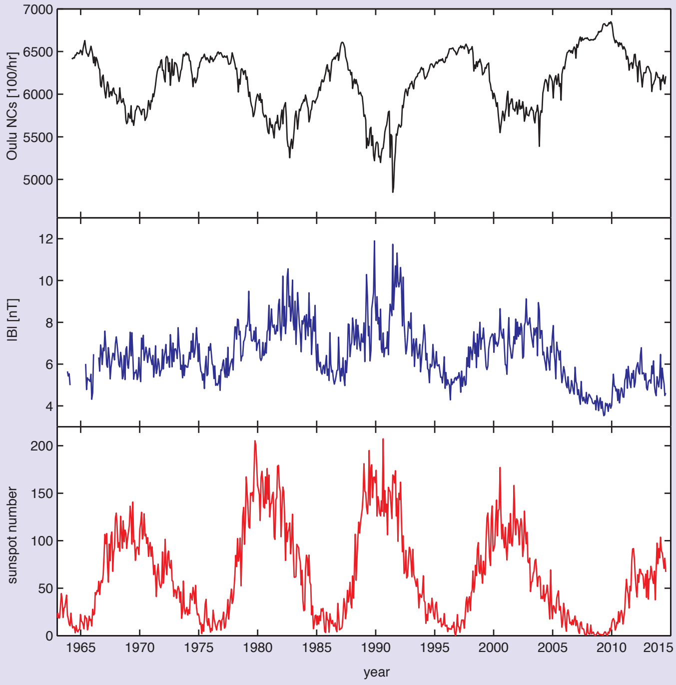
Both the solar wind and HMF vary in a number of long-term activity cycles (from decades to millennia), but also on the short term (hours) primarily because of large eruptions of plasma and magnetic field from the Sun known as coronal mass ejections (CMEs), or large magnetic barriers between fast and slow solar wind which rotate with the Sun, known as corotating interaction regions (CIRs). Here we first discuss GCR variations with attention to the 22-year cycle in neutron monitor counts and then move on to recent work on short-term GCR modulations associated with remote CMEs.

Long-term cosmic-ray variations

The study of GCRs is important for the study of long-term solar variability. Traces of radioactive isotopes such as beryllium-10 or carbon-14, created by interactions between atmospheric particles and cosmic rays, can be found in ice sheets and tree trunks respectively, and give a record of the number of cosmic rays entering the atmosphere over timescales of millennia (Beer *et al.* 2006). Because the flux of GCRs in the atmosphere is inversely correlated with solar activity, these long-term records of beryllium-10 can provide very good estimations of solar activity over millennia.

Such records have been useful to identify secular trends in the Sun's magnetic field. The space age has been primarily associated with a period of enhanced magnetic activity, often referred to as a grand solar maximum. On decadal time-scales, the relation between GCR flux and solar activity means that neutron monitor counts have 11-year variations associated with the 11-year solar cycle. This can be seen in figure 2 where the neutron monitor count rates (here from Oulu, Finland), shown in the top panel, vary inversely to the near-Earth magnetic field strength (second panel), and the sunspot number (bottom panel), both of which display the famous 11-year cycle.

Sunspot number is a reasonable proxy for solar



2: Time series to show how neutron monitor count rates vary with solar activity from 1965 to present. (Top): Neutron monitor counts from Oulu, Finland. (Middle): Near-Earth magnetic field strength from OMNI2 data set. (Bottom): International sunspot number. All data are averaged over 27-day solar rotation periods.

activity, because sunspots are associated with more complex magnetic fields and are typically the sites for CME release, whereas the near-Earth magnetic field strength is a more direct measure and contributes to the modulation of GCRs reaching Earth. However, looking at the neutron monitor data series in figure 2 we see the 22-year cycle (the "Hale Cycle") clearly, with consecutive cycles adopting either a "spiked" or "domed" appearance. This structure arises in part from different cosmic-ray particle drift patterns through the heliosphere to Earth between consecutive cycles (Jokipii *et al.* 1977). The particle drifts differ because, at solar maximum, the solar magnetic poles reverse, reversing the polarity of the magnetic fields throughout the heliosphere. The result is that GCRs arriving at Earth predominantly come from over the solar poles when there is negative magnetic polarity in the Sun's northern hemisphere, and approximately along the ecliptic plane when the northern magnetic polarity is positive. However, in addition to this effect, we have found that there is also a contribution from 22-year variations in the HMF, purely during the declining phase of the solar cycle (Thomas *et al.* 2014a).

As fluctuations and enhancements in the HMF are well documented to modulate the number of GCRs it is apparent that the "spiked" cycles have that shape because of an enhanced magnetic field strength near Earth that persists two to three times longer for negative northern solar polarity cycles compared to positive cycles. However, these 22-year variations in the heliospheric magnetic field seem to appear only during grand solar maximum conditions. When using geomagnetic reconstructions of the heliospheric magnetic field (Lockwood and Owens 2011), the differences noted between consecutive solar cycles in the HMF strength during solar cycles from 1960 to the present do not exist for cycles prior to 1960. Thus space-age observations of the Sun and heliosphere may not be representative of other activity conditions.

Short-term cosmic-ray variations

Short-term GCR variations can arise from magnetic structures within the heliosphere such as coronal mass ejections or corotating interaction regions. Forbush (1937) first noted observations of a swift reduction in the number of GCRs detected at the surface when fluctuations in the Earth's magnetic field were also recorded. It has since been found that this arises from magnetic structures in the heliosphere that both impact the magnetosphere and modulate the number of GCRs. A "typical" Forbush decrease is shown in figure 3. The top three panels show neutron monitor counts from McMurdo, Newark and Oulu. The lower panels display the HMF magnitude ($|\mathbf{B}|$), the radial solar wind speed ($|V_x|$) and finally the solar-wind plasma density (n_p). Each type of heliospheric data shows enhancements associated with a CME passing over the spacecraft; the neutron monitor data shows a sudden decrease of a few percent in magnitude.

The precise definition of a Forbush decrease is not set in stone, but here we define it as a drop in neutron count rate of greater than 1% with a sudden onset of a minimum being reached within a day, before a longer recovery period of a number of days to weeks. Forbush decreases do not only occur when a CME or CIR passes over Earth. Indeed some have been observed when there is very little or no structures in the near-Earth HMF (Cane *et al.* 1993, Thomas *et al.* 2014c). Figure 4 shows an example of such a Forbush Decrease. The neutron monitor counts are shown in the top three panels, as in figure 3. However, in panels 4–6 we now display $|\mathbf{B}|$ from STEREO-B, L1 (from the OMNI2 dataset), and STEREO-A respectively, with $|V_x|$ from STEREO-A in the bottom panel. The STEREO spacecraft were launched in 2006 and have since been drifting around the Sun in approximately Earth's orbit, STEREO-A ahead of Earth and STEREO-B behind. These provide further vantage points to observe magnetic structures that are not directed towards Earth.

In this case, the neutron monitor count rates reduce suddenly by a few percent, but this time there is no significant increase in the near-Earth solar wind parameters. Because the cause of such Forbush decreases is not clear, we have termed these events "phantom Forbush decreases". During such phantom events, we used data from the STEREO spacecraft to see if there were any CMEs that missed Earth but still modulated the GCR flux there. On 30 May 2012, STEREO-A was approximately 120° ahead of Earth in orbit; figure 4 shows data for the days around this date. An exceptionally large CME arrived at STEREO-A between two and three days before the phantom Forbush decrease. Similarly, for two further phantom Forbush decreases seen during 2012, where there was no significant structure in the near-Earth solar wind, there were similarly large CMEs two or three days before each decrease, passing to the west of Earth and crossing STEREO-A. These CMEs, therefore, are remotely modulating the number of GCRs detected at Earth. There are two potential mechanisms for this: the CMEs interact with CIRs in the heliosphere which could form large barriers to GCRs, or the CME interacts with the Earth-connected field lines as it progresses further out into the heliosphere.

GCRs can also be modulated by corotating interaction regions (CIRs). These are regions of compressed solar-wind plasma and magnetic field, created when fast solar wind catches up with slow solar wind ahead of it. CIRs are associated with the heliospheric current sheet (HCS), located between the inward and outward magnetic polarities of the Sun's magnetic field, and extending out through the heliosphere. For HCS crossings associated with a large compression of plasma and magnetic field (i.e. those that are described as a CIR), cosmic-ray flux builds up before the CIR and then decreases over a few hours before a longer recovery period. This is known as the "snow-plough effect" as the compression region pushes away the GCRs in front of it, leaving a depletion behind. However, there are often HCS crossings without a large compression region and these have a different effect on GCR flux. With no or very little compression, one might expect that there would be no change in GCR flux as they cross Earth, but we have found that the change in magnetic polarity across the HCS does have an effect.

Indeed, it appears that there is always a greater flux of GCRs in the away-from-Sun sector of the HMF (i.e. if the magnetic field goes from away-from-Sun to towards field, then you would see a decrease in GCR flux as the HCS crosses Earth, but in towards-to-away cases, we would observe an increase) as noted in Thomas *et al.* (2014b).

Future work

There are several questions that arise from our work that we hope to be able to address in future. First, why is there a 22-year cycle in a number of solar wind parameters? This is likely to arise from the solar dynamo because, in addition to differences between consecutive solar cycles in the HMF strength, we also observe changes in the variations of sunspot number. This suggests that there are more "active longitudes" of sunspots on the Sun during one solar magnetic polarity compared to the other. Secondly, the findings from Cane (1993) and Thomas *et al.* (2014c) of Forbush decreases without a significant CME in near-Earth space are the first indication that we can remote-sense large heliospheric magnetic structures using neutron monitor counts. If we can develop a way of using neutron monitor data to look for CMEs in the heliosphere, this may provide a valuable space-weather prediction tool. Observed changes in the diurnal variations of GCRs could be the best method to find heliospheric structures using the neutron monitor data, as one would expect fewer GCRs when a neutron monitor is viewing in the direction of a large "barrier" to GCR propagation. ●

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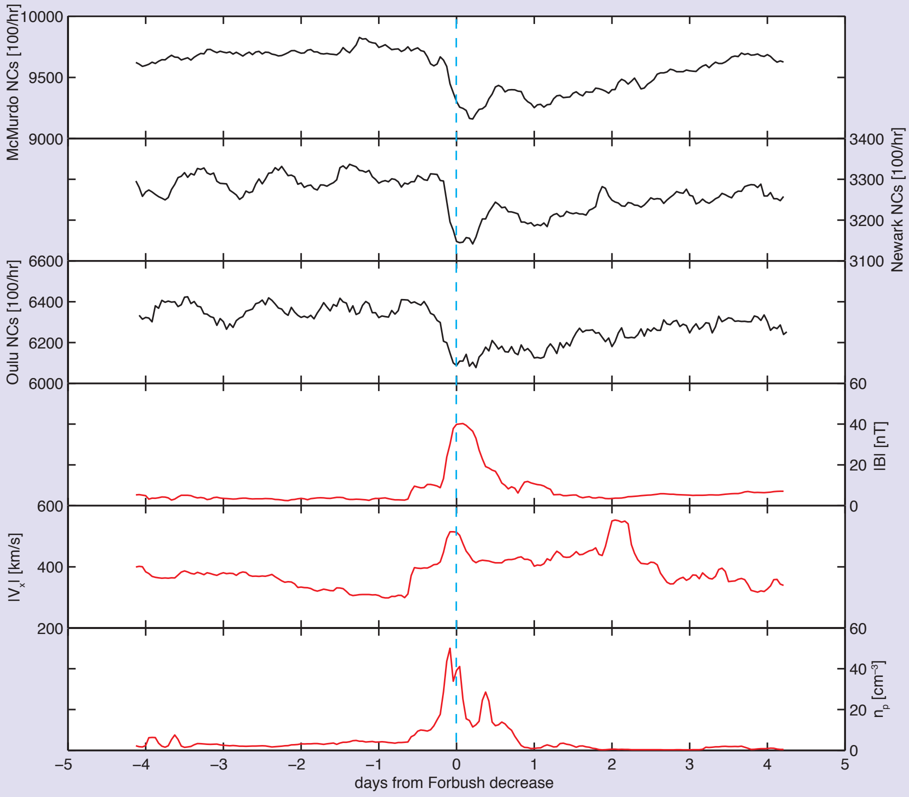
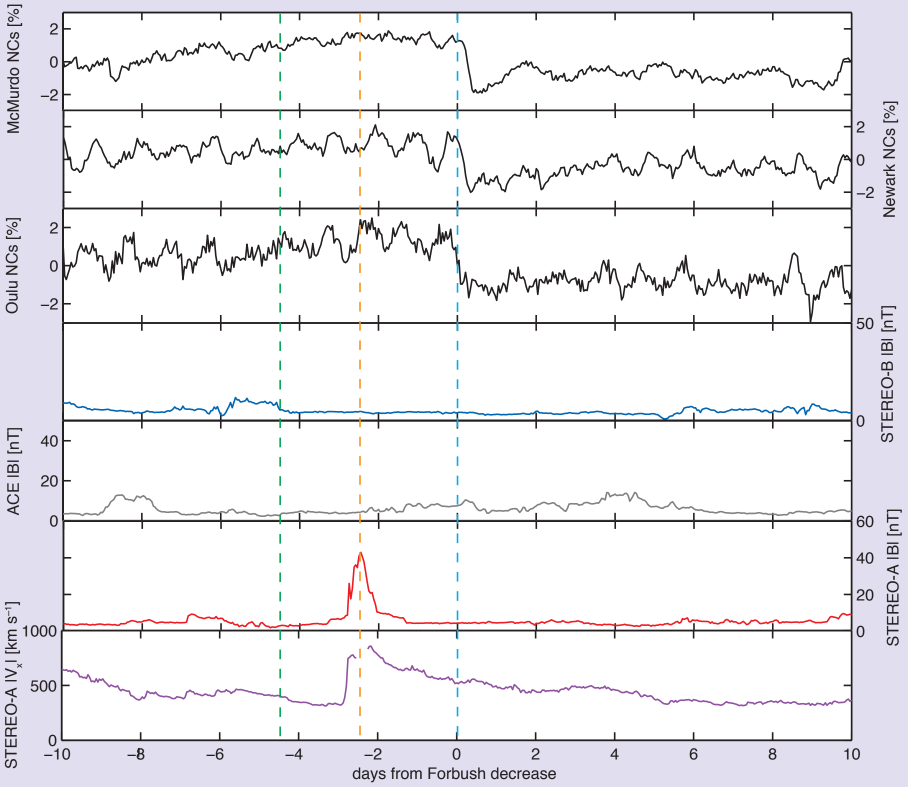


3: A "typical" Forbush decrease event from June 2012. Top three panels show neutron monitor count rates from McMurdo (Antarctica), Newark (USA) and Oulu (Finland). The lower three panels show the near-Earth magnetic field strength, solar-wind speed and plasma density and are plotted from the OMNI2 data set.



4: A "phantom Forbush decrease" on 30 May 2012. Neutron monitor count rates from McMurdo, Newark and Oulu are again shown in the top three panels. The heliospheric magnetic field strength is shown from STEREO-B, L1 and STEREO-A in the next three panels respectively. Finally, the STEREO-A solar wind speed is shown in the bottom panel. The time of the STEREO-A CME leaving the Sun is the green vertical line, its interception with STEREO-A is the orange and the time of the onset of the Forbush decrease is the light blue.