EXTRAORDINARY SOLAR MODULATION EFFECTS ON GALACTIC COSMIC RAYS OBSERVED BY V1 NEAR THE HELIOPAUSE

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ABSTRACT

We discuss here two extraordinary increases of cosmic ray intensity that were observed by Voyager1 in the last 1.1 AU before it crossed the heliopause in August, 2012, at 121.7AU. These two increases are roughly similar in amplitude and result in a total increase of $\sim 1$GV cosmic ray nuclei of over 50% and of 0.01GV electrons of a factor $\sim 2$. During the 1st increase the changes in the magnetic, B field are small. After the 1st increase, the B field changes become large and during the 2nd increase the B field variations and the cosmic ray changes are correlated to within $\pm$ one day. The intensity variations of H and He nuclei and electrons during these time intervals are measured from 0.1 to over 1 GV. The total increase of GCR in the two increases resemble those to be expected from a simple force field "like" solar modulation with a modulation potential $\sim 80$ MV. This is nearly 1/3 of the total modulation potential $\sim 250$ MV that is required to produce the modulation of these particles observed at the Earth at the 2009 sunspot minimum and adds a new aspect to the heliospheric modulation.

1. INTRODUCTION

When V1 crossed the heliopause on or about August 25, 2012 (day 238), there were extraordinary changes in the magnetic field and the energetic particle intensities (Burlaga et al., 2013; Stone et al., 2013; Webber and McDonald, 2013). On that day, the particle intensities and field strength and direction began a change to values that have remained relatively unchanged now for over 20 months. Prior to this "final" event there were several unusual features in the energetic particle intensities that occurred. For energetic particles, we mean GCR nuclei and electrons as well as the most energetic anomalous cosmic rays (ACR). The first of these intensity-time features occurred about May 7th (day 128) when both the
GCR nuclei and electrons increased by \( \sim 15\% \) and 20\% respectively. After reaching these higher levels near the end of May (day 150), these intensities remained nearly constant for \( \sim 58 \) days (\( \sim 2 \) solar rotation periods). Meanwhile the ACR intensities did the opposite, decreasing by \( \sim 20\% \) to a lower level where they also remained nearly constant for the 58 day time period.

On about July 28\textsuperscript{th} (day 210), the GCR nuclei and electron intensities increased suddenly for the second time. This increase was more rapid and eventually larger (20\% and 40\% respectively) than the 1\textsuperscript{st} increase. However, the increase occurred in several stages, the final one starting on August 25\textsuperscript{th} (day 238). At this time, GCR nuclei increased to their final values which were \( \sim 32\% \) higher than they were before May 7\textsuperscript{th} for \( >70 \) MeV/nuclei and \( \sim 96\% \) higher for 7-100 MeV electrons. The "trapped" nuclei, termination shock particles (TSP) and anomalous cosmic rays (ACR), disappeared suddenly (Krimigis et al., 2013), so that within just a few weeks the intensity of 2 MeV protons was less than 0.1\% of their intensity before May 7\textsuperscript{th}.

The magnetic field changes, both in amplitude and direction, are a crucial backdrop for the energetic particle changes. In this paper, we will discuss the GCR and magnetic field temporal changes during the time period from day 128 to day 238 when V1 moved outward \( \sim 1.1 \) AU. We will then present the rigidity dependence of the observed changes for the species H, He and electrons to help define the modulation mechanisms responsible for the intensity changes.

2. THE INTENSITY-TIME CHANGES AND A DISCUSSION OF THEIR IMPLICATIONS

The data presented here from V1 clearly shows two periods of increase for both GCR nuclei and electrons. This is illustrated in Figure 1 which shows the integral rate of \( >70 \) MeV nuclei and 5-60 MeV electrons. The total increase for each component from before May 7\textsuperscript{th} to after August 25\textsuperscript{th} (32\% for \( >70 \) MeV H and 96\% for 5-60 MeV electrons) are made equal in the plot using different scales on the left hand and right hand axes. This is to show the relative magnitude of the increase on May 8\textsuperscript{th} to that in the second change between July 28\textsuperscript{th} and August 25\textsuperscript{th} for the two species. The intensity changes for the two species are not identical in relative magnitude or in their relationship to the magnetic field.

The format in Figure 2 is similar to Figure 1 and shows the electrons 3-10 Mev (left hand scale and the relative magnetic energy density \( \sim B^2 \) (right hand scale).

For the 3-10 MeV electrons, the total increase is 69\%, which is less than the increase of
Fig. 1.— Five day GCR running average of > 70 MeV (mostly nuclei, left scale), red line and 5-60 MeV (mostly electrons, right scale), blue line. The two increases starting day 128 and day 208 are the solar modulation events discussed in the text.
Fig. 2.— Similar to figure 1 except the 3-10 MeV (mostly electrons) GCR are shown in red, along with the relative energy density ($B^2$) and direction of the magnetic field.
96% for the 5-60 MeV electrons. For the B field, also shown in Figure 2, the changes in amplitude are over a factor 4 during this time period from values \( \sim 1 \mu G \) to \( \sim 4.5 \mu G \) (the final field value) in just a few days from day 208-210. There are two changes in B field direction (days 163-172) from a positive to a negative polarity and a much more sudden and final change, on days 208-209, from negative to positive polarity.

The 1\(^{st}\) step in the cosmic ray intensity changes at day 128 does not occur in association with any major B field amplitude change. After this intensity change and later during the period of constant GCR intensity, the B amplitude decreases and then increases by a factor of 3 between days 162-172, during a 10 day period when the field direction is also changing from 270\(^{\circ}\) to 90\(^{\circ}\). During this 10 day period the field inclination increases from \( \sim 0^{\circ} \) to \( \sim 90^{\circ} \) (Burlaga et al., 2013). The locally measured GCR intensities were remarkably insensitive to these extraordinary B field changes.

The next field polarity change occurred on day 209 and is the final, decisive polarity change from 90\(^{\circ}\) to \( \sim 270^{\circ} \). One day later the B field amplitude changes by a factor 3 in one day to its final value of 4.5\(\mu G\). The B field changes that occur between days 210 and 238 are matched within \( \pm \) day by the corresponding increases in GCR and decreases in TSP and ACR as seen in Figure 2 and also in Krimigis et al., (2013) and Burlaga et al., (2013). Also, as seen in Figure 2, the lower rigidity electrons are more responsive to these changes in field amplitude that pass V1 between day 210 and day 238.

So overall we have the observation by V1 that the 1\(^{st}\) GCR increase starting on day 128 was not coincident with corresponding large B field amplitude or direction changes. A following period of nearly constant GCR intensity, however, was coincident with large amplitude and direction changes of the B field, as well as unusual field elevation angle changes.

The 2\(^{nd}\) GCR increase starting on day 208 and the following intensity changes culminating with the final increase on day 238, were all simultaneous with \( \pm \) one day with the very large B field magnitude changes, but there were no field direction changes during this time. The lower rigidity electrons were more responsive to these B field changes than the GCR nuclei whose rigidity is \( \sim 50 \) times that of the electrons. In this second increase of GCR, the TSP and ACR intensity changes were opposite to the GCR to within \( \pm 1 \) day as these components disappeared.

### 3. INTENSITY AND SPECTRAL CHANGES OF GCR H, He NUCLEI AND ELECTRONS BETWEEN DAY 128 AND DAY 238 OF 2012

In the Stone et al., (2013) article in Figures 2, 3 and 4 the intensities and spectra of H and He nuclei and electrons are shown for the time periods before May 8\(^{th}\) and after August
25th. This includes the period of the two GCR increases. Below an energy of \(\sim 80\) MeV/nuc.,
the time period before May 8\textsuperscript{th} is contaminated by background ACR intensities for H and
He nuclei and therefore these energies cannot be used in the comparison.
The intensity changes of these particles with different mass to charge ratio, A/Z, have historically been very useful for understanding the origin of solar modulation effects. For example, Gleeson and Axford (1968) have compared the H and He intensity changes in their derivation of the force field approximation to the solar modulation. They find that if the changes in intensity, \(M = \beta \ln(j_1(P)/j_2(P))\), are plotted as a function of rigidity, there is a splitting of the modulation for each species according to their charge to mass ratio A/Z. This splitting arises from the fact that the modulation itself, expressed in MeV, is defined by a modulation function, \(\Psi = Z e \int \frac{(V/3)dr}{K(r)}\) where \(K(r)\) equals the scaler diffusion coefficient which has dependence \(K(r) \propto \beta Pf(r)\) and V is the radial wind speed. Gleeson and Axford (1968), however, also introduced another quantity called the modulation potential, \(\phi = \int \frac{(V/3)dr}{K(r)}\) expressed in MV. This modulation potential is the same for H, He and electrons at the same rigidity. The modulation function, M, that is commonly used, is defined by \(\Psi\). M describes the amount of modulation between two different times (or places) and is different at the same rigidity for particles of different A/Z. Hence the use of the term charge splitting when this quantity is used. The section by Ken McCracken pp 50-58 in the book Cosmological Radio Nuclei (2012) discusses the two quantities, modulation function and modulation potential. The modulation function is useful for comparing intensity changes of different species.

Figure 3 is a plot of the expected variation of \(\beta \ln(j_2/j_1)\) with P for H and He where the solar modulation potential is taken to be 80 MV. Note the charge splitting of the amount of solar modulation which results in a 2 times greater modulation for H than He at rigidities \(\leq 1\) GV. The data points are for the observed modulation of H and He from before May 8\textsuperscript{th} to after August 25\textsuperscript{th}. They are roughly consistent with an overall modulation \(\sim 80\) MV, but with no obvious charge splitting. The observed modulation function for electrons at lower rigidities is independent of P and is \(\sim 2\) times that for H and He nuclei at \(\sim 0.5\) GV.

4. GENERAL COMMENTS

It is not the intent of this paper to develop a theoretical model for an explanation of these modulation effects observed by V1 by the CRS instrument. We believe that the GCR intensity changes are so unusual and unprecedented in the history of cosmic ray studies that they are not easily accommodated within the Parker (1963) heliospheric modulation picture.
Fig. 3.— The modulation function $M = \beta \ln(j_1/j_2)$ calculated for a modulation potential=80 MeV (solid lines) and the observed modulation obtained by comparing the H (black), He (red) and electron (blue) spectral intensities measured at V1 before day 128 and after day 238 of 2012. The details are discussed in the paper.
as developed by many others, e.g. Gleeson and Axford, 1968; Fisk and Axford, 1969. But there are certain features of the modulation that may indicate the characteristics of the B field, plasma flows, etc., that affect the entrance of the Local Interstellar Spectrum (LIS) cosmic rays into the heliosphere.

We recognise that the 1st step in this modulation process is related to the 1st event that started about May 8th (DOY 128). This event contributed about 40% of the total increase for both GCR nuclei at higher rigidities and electrons at lower rigidities. The changes in the B field were small during the 10-20 day time period of the 1st increase as noted earlier. During the following ∼ 58 day time period up to about day 200 the intensity of the GCR remained relatively constant to within a few percent. However the B field recorded some of the largest changes yet seen at V1 along with a polarity from 270° → 90° and along with unprecedented changes in the elevation angle near the end of this constant GCR intensity period.

The lack of significant time correlation between the GCR intensity changes and the B field changes during the entire time period from DOY 128-208 suggests that the GCR changes during the first increase could be related to much larger scale features that may not be evident in the local field being measured at V1 at that time.

The lack of correlation between B and the GCR intensities in the 1st event is definitely not present in the 2nd event which started on July 28th (day 208). In this event, from July 28th to August 25th, the GCR and B field changes were correlated to within ± ∼ 1 day or less. This correlation continues through all 5 intensity increases and decreases, all of them exceptional, until the final increase on August 28th (day 238). In each of the increases the B field magnitude and direction at the times of the B field maxima was essentially the same as that observed after August 28th. The GCR electrons and nuclei, however, did not reach intensities that were observed after August 28th. For electrons from 5-60 MeV the peak increases were ∼ 80% of the post August 28th intensity. For nuclei, the increases reached levels ∼ 50–60% of the post August 28th intensity. So there is a distinct rigidity dependence of the GCR distribution within these structures that pass V1. Note that the speed of V1 is ∼ 0.01 AU/day. So the ± day correlation between B and GCR could have a scale ∼ 0.01 AU!

The intensity changes of electrons, H and He nuclei as a function of P for the overall time period from day 128 to day 238 are large and well defined. At least two features of the β ln(jLIS/j2) vs P data for this modulation of the different species, shown in Figure 3, are important: (1) The intensity changes of electrons are nearly independent of rigidity at low rigidities. In addition, if the values of electron modulation function β ln(jLIS/j2) at low rigidities is extrapolated to higher rigidities, it has a value ∼ 2 times the value of the modulation function observed for H and He at about 0.5 GV. (2) The H and He nuclei have observed values of the modulation function that are similar. This lack of splitting in the
modulation of these different charges is not apparent in the normal heliospheric modulation for the Gleeson and Axford (1968), force field approximation (e.g., Lezniak and Webber, 1971). In a simple spherical modulation model (e.g., Gleeson and Axford, 1968) the average magnitude of the modulation function for H and He as a function of rigidity for this final time interval would be equivalent to that for a modulation potential equal to 80 MV, as indicated in figure 3. In fact, in this simple picture, a modulation potential equal to 250 MV, starting with the LIS spectra observed by V1, will reproduce the Carbon and heavier nuclei spectra measured by ACE in 2009-2010 at the Earth (e.g., Lave et al., 2013) as well as the spectrum observed by PAMELA in 2009 (Potgieter et al., 2014). Thus the modulation observed by Voyager 1 in the last 1.1 AU of the heliosheath is an important contributor to the overall solar modulation observed at the Earth, contributing as much as \( \sim 1/3 \) of the modulation potential observed at the Earth at this time of the solar cycle.

5. SUMMARY AND CONCLUSIONS

This paper describes two large and unprecedented modulation events of GCR observed at V1 starting on May 8\textsuperscript{th} and July 28\textsuperscript{th} just prior to the crossing of the heliopause on August 25, 2012 at a distance of 121.7 AU. These events resulted in the increase of GCR electrons from 5-60 MeV by a factor \( \sim 2 \) and H and He nuclei above \( \sim 0.5 \) GeV to increase by factors up to 3 at the lowest rigidities. Although these increases are complex in temporal structure, they can be represented by a modulation potential change \( \sim 80 \) MV which is \( 1/3 \) of the total solar modulation required to reproduce the spectra of the same nuclei observed at Earth at a time of sunspot minimum in 2009 (e.g., Mewaldt et al., 2010). Thus a new and significant feature is added to the description of solar modulation in the heliosphere.

The first modulation event occurred when V1 was 1.1 AU inside the HP. The intensity increases starting on May 8\textsuperscript{th} (day 128) and continuing up to day 150 amounted to about 40\% of the combined increase for both events. During this GCR increase there were only modest changes, both negative and positive, in the B field amplitude with no change in direction. For the next 60 days the GCR and ACR intensities remained almost constant. However, between days 150-160 the B field changed direction from 270\(^\circ\) to 90\(^\circ\) and then decreased by a factor \( \sim 2.0 \), followed in a few days with a sudden increase by a factor \( \sim 3 \) accompanied by an increase in elevation angle from \( \sim 0\(^\circ\) \) to 90\(^\circ\). It almost seems like the B field was 'turning itself inside out' in a period of a few days, perhaps due to the passage of a very large scale quasi-periodic structure, but without any observable effects on GCR or ACR.

The time period of 90\(^\circ\) polarity ended suddenly on July 28\textsuperscript{th} (day 208) when the polarity changed to 270\(^\circ\) followed by an increase in the magnitude of the B field (on day 209), again by a factor \( \sim 3 \) to essentially its final value \( \sim 4.5\mu G \) after day 238. This increase on July 28\textsuperscript{th}
and the subsequent changes in B were coincident within 1 day with corresponding positive and negative intensity changes of GCR. In this period the changes in ACR (Stone et al., 2013) and TSP (Krimigis et al., 2013) were exactly opposite to those of GCR. The details of these changes provide a glimpse into features of the heliopause with structures with a scale which could be $\sim 0.01\text{AU}$. These structures could be moving with speeds much greater than V1.

The second modulation increase was embedded in massive B field fluctuations in contrast to the first modulation increase in which these B field changes were small. In the first increase the B field magnitude and polarity changes actually occurred after the increase and when the GCR changes themselves were small. The 1st and 2nd GCR increases have roughly the same magnitude and same rigidity dependence, however, despite their greatly different correlation with the B field. They could be part of a larger structure $\sim 1\text{AU}$ in extent that characterizes the heliopause region. An over-riding feature of this data is the complexity of the changes of both the B field and the GCR nuclei and electrons on scales which could be as small as $\sim 0.01\text{AU}$. The correlation and lack of correlation of these changes is evident in the second and first modulation events, respectively. A companion work (Quenby and Webber, 2014) attempts to provide a model to explain the events just described, concentrating on estimates of likely plasma speed and diffusion parameters thought to be necessary to account for the V1 GCR observations.

In an astrophysical sense our heliopause, which may be typical of millions of similar cases in the galaxy where there are stellar winds existing on all kinds of scales, is notable for the energy it removes from the local GCR rather than the acceleration of any particular particle population.

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