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Recurrent cosmic ray modulations at solar minimum and solar maximum

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Abstract. Cosmic ray modulations associated with corotating high-speed streams from coronal holes, though most prominent around and preceding solar minimum, are present throughout the solar cycle. We illustrate examples from the current solar maximum which arise in near-equatorial coronal holes and show that the relationship between streams and the associated cosmic ray modulations is similar to that previously found for streams at solar minimum.

1 Introduction

Modulations of the galactic cosmic ray (CR) intensity which recur at the solar rotation period and are associated with corotating high-speed streams from coronal holes, are prominent features of the declining and minimum phases of the solar cycle (e.g., Richardson et al., 1996 and references therein). The cosmic rays presumably respond to deviations from the average solar wind properties associated with these streams. For example, changes in the solar wind speed will cause variations in convection and adiabatic deceleration. The diffusion tensor varies with field turbulence levels, and changes in the magnetic field strength may cause variations in particle drifts and the diffusion tensor. In a previous study, we used data from the anti-coincidence guards of the GSFC instruments on IMPs 7/8 and University of Kiel instruments on Helios 1/2, to examine the relationship between recurrent modulations and corotating streams at ≤ 1 AU near the ecliptic (Richardson et al., 1996). We found that, though there were event-to-event variations, these depressions most frequently onset at the leading edges of corotating high-speed streams (63% of events). The CR intensity tended to be anti-correlated with the solar wind speed within individual streams, suggesting that enhanced convection of cosmic rays from the inner heliosphere in streams contributes to the depression. In may cases, immediately preceding the depression, the CR intensity reached a local maximum within the corotating interaction region (CIR) formed ahead of the stream. We have also pointed out a 22-year dependence in the size of recurrent modulations observed by neutron monitors and spacecraft observations during the last 5 solar minima, with larger modulations when $\boldsymbol{A}$ (the solar global field direction) > 0 (Richardson et al., 1999).

Although most prominent at solar minimum, corotating streams and their associated particle effects are present throughout the solar cycle. Examples near the maximum of solar cycle 21 were discussed by Richardson et al. (1993). In this paper, we illustrate further examples near the maximum of the current solar cycle (23). We briefly summarize the relationship of streams and recurrent depressions around solar maximum and solar minimum and consider whether there is any change in this relationship. Again we will use data from the anti-coincidence guard of the IMP 8 GME instrument, which measures the isotropic CR intensity above ∼60 MeV and is dominated by ∼1 GV particles when solar particle intensities are low. The lower energy response is advantageous since modulations are weaker at higher energies. Also, there are no diurnal variations as there are in observations from a single neutron monitor. To provide an independent estimate of the near-Earth cosmic ray intensity, we also illustrate observations from the Thule neutron monitor (76.5N, 68.7W) (courtesy of J. Bieber) which, because of its high latitude, has a low geomagnetic energy cut-off and is minimally affected by diurnal variations.

2 Observations

From considering recent near-Earth solar wind observations from the ACE spacecraft and energetic particle data from IMP 8, we found that extended sequences of corotating streams were present in 1999-2000 near the maximum of solar cycle 23 (see also Berdichevsky et al., 2000). We examined 30 of these streams in which the particle observations were not compromised by the presence of solar events. All but

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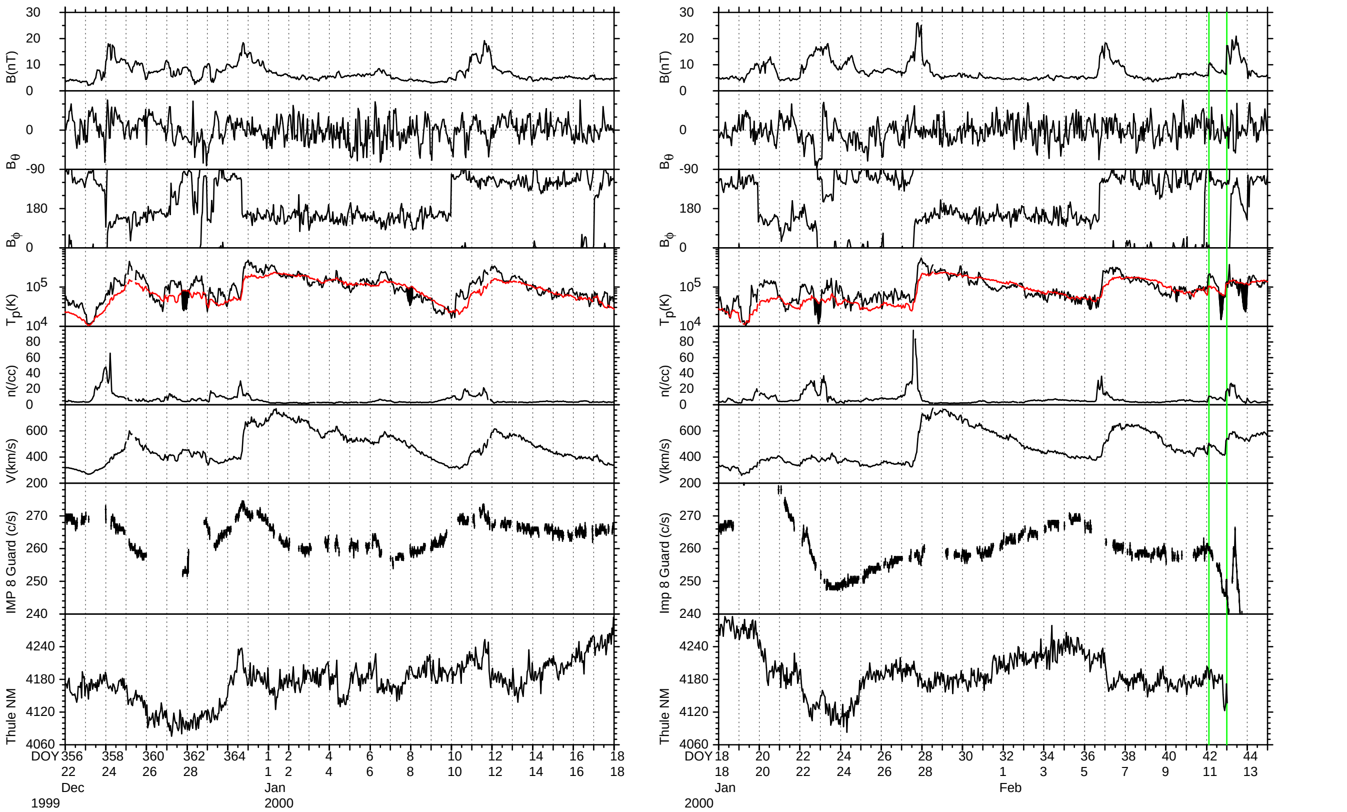

Fig. 1. Corotating high-speed streams and associated cosmic ray modulations during two successive solar rotations near the maximum of solar cycle 23. The magnetic field and plasma data are from the ACE spacecraft. The cosmic ray intensities are measured by anti-coincidence guard of the IMP 8 GME experiment, which responds to > 60 MeV particles, and by the Thule neutron monitor. The three streams in the left-hand panel are accompanied by cosmic ray depressions. On the second rotation, the first stream has declined, though the depression is still evident, and the depression in the second stream is weaker.

two of these streams were associated with significant CR depressions. Comparing their solar connection longitudes with coronal hole maps inferred from Kitt Peak He I 1083 nm observations (ftp://argo.tuc.noao.edu/kpvt/synoptic/choles/), we conclude that all these streams were associated with isolated near-equatorial coronal holes. Figure 1 shows examples of near-Earth solar wind magnetic field, plasma and particle observations during two successive 27-day solar rotation intervals in December 1999 – February 2000. The top three panels show the magnetic field intensity and polar and azimuthal angles at ACE. The next three panels show the plasma proton temperature (T_p), density and bulk speed. In the T_p panel, the red line indicates the temperature expected for "normally-expanding" solar wind (T_{ex}), which is calculated from the observed solar wind speed using the well-established correlation between the solar wind speed and T_p (Lopez, 1987). We find that comparison of T_{exp} and T_p provides a useful indication of the presence of possible interplanetary coronal mass ejections (ICMEs; Richardson and Cane, 1995). In corotating streams, T_{ex} tends to track T_p, whereas possible ICMEs have $T_p << T_{ex}$ (shaded in black in Figure 1). The next panel shows 30-minute averages of the IMP 8 guard counting rate (counts/s). The bottom panel shows the cosmic ray intensity measured at Thule. Note that the solar wind transit time from ACE to Earth/IMP 8 is $\sim 30 - 60$ minutes.

In the left-hand panel of Figure 1, the solar wind is dominated by three corotating high-speed streams, commencing on December 24, December 30, and January 10. The enhanced magnetic fields and plasma densities at the leading edge of each stream indicate the CIR created when the high-speed stream interacts with the slower, denser solar wind ahead of it (Belcher and Davis, 1971; see also Schwenn (1990) and Volume 89 of Space Science Reviews (1999) for additional information on CIRs). Within the CIR, the "stream interface" separating slow and fast stream plasma can often be identified as a relatively abrupt decrease in plasma density accompanied by increases in T_p and solar wind speed. The clearest interface here may be identified at the leading edge of the stream commencing on December 30. Figure 2 shows 5-minute averaged ACE solar wind data for a two day interval around passage of this CIR. The most prominent interface-like feature is the discontinuity at ~ 18 UT on December 30, though as is often the case, the transition from slow to fast solar wind includes other discontinuities (including a crossing of the heliospheric current sheet at ~ 16 UT) which might also mark the actual interface. Solar wind composition variations (e.g.. Wimmer-Schweingruber et al.,

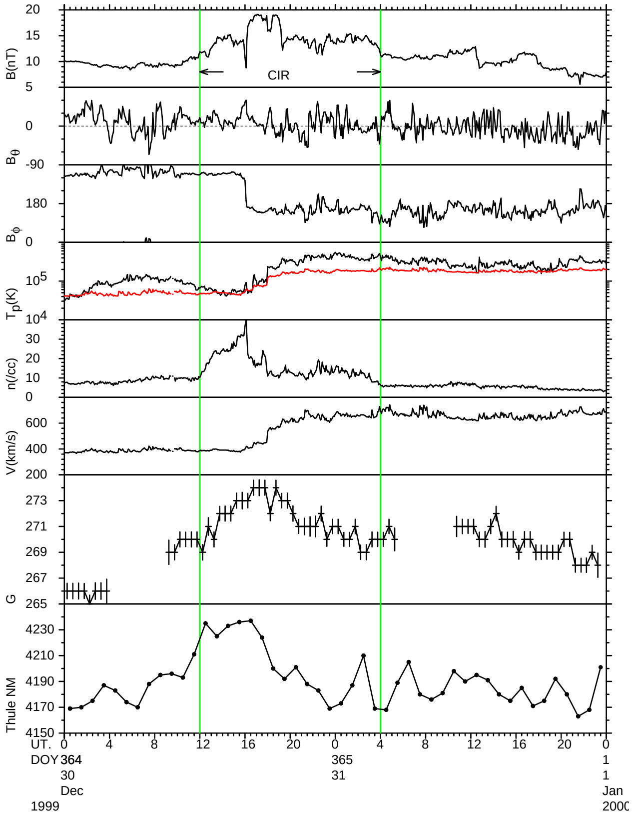

Fig. 2. The onset of a recurrent modulation event on December 30, 1999, showing the local CR maximum inside the CIR.

1997) can provide additional verification of the interface location in such events. Returning to the left-hand panel of Figure 1, three extended cosmic ray depressions were observed within the three high-speed streams by the IMP 8 guard and Thule NM. Their features are similar to those observed at solar minimum (Richardson et al., 1996). For example, the depressions amount to a few percent in the IMP 8 guard, and each has the typical gradual decline and recovery, with the particle intensity tending to be anti-correlated with the solar wind speed.

The right-hand panel of Figure 1 shows the recurrence of the second and third streams in the left-hand panel, commencing on January 27 and February 5, 2000. The high plasma densities in the CIR on January 27 ($\sim$90 cm^{-3}) are particularly notable. Both streams are accompanied by cosmic ray depressions, though the depression commencing on January 28 is weaker than that on the previous rotation, possibly because the CR intensity has not fully recovered in the preceding slow solar wind. The first stream in the left-hand panel is much weaker (in terms of its speed) when it returns a rotation later. The negative-to-positive magnetic sector boundary and associated magnetic field enhancement evident on January 19-20, may indicate the recurrence of the CIR on December 24. Features related to solar events may also be present such as the enhancement in the guard counting rate (above the range shown in the figure) on January 19-20 and a possible ICME on January 22. Nonetheless, there is clear evidence of an extended cosmic ray depression similar to that seen on the previous rotation. Towards the end of the interval in the right-hand panel, variations of the guard rate associated with shocks (green vertical lines) and ICMEs are evident which, as would be expected, have no counterparts on the previous rotation.

Considering in more detail the relationship between the cosmic ray depressions and the stream structures in Figure 1, the depressions generally commence in the vicinity of the high-speed stream leading edge and extend through to the stream trailing edge, with some tendency for the CR intensity to be anti-correlated with the solar wind speed (note in particular the latter half of the middle stream in the left-hand panel). One point we particularly note is that the modulations do not appear to be consistent with the assumption that they result from enhanced particle scattering in CIRs. Model results (e.g., Figure 3 of McKibben et al. (1999)) making this assumption show modulations near the ecliptic commencing at the start of the CIR-associated magnetic field enhancement, reaching maximum depression at the trailing edge of the CIR, and then recovering. These results are calculated for 3 AU. At 1 AU, field lines in the slow solar wind ahead of the CIR, and in the high-speed stream following the trailing edge of the CIR, will thread into the CIR in the outer heliosphere. In this case (e.g., Morfill et al., 1980), modulation caused by the CIR should be experienced over a region extending from before passage of the CIR through into the high-speed stream. Maximum particle depression will occur on field lines within the CIR at 1 AU because these field lines remain embedded inside the CIR at and beyond 1 AU. The observations in Figure 1 show a quite different pattern. In particular, CR intensities are not strongly depressed within the CIRs. In fact, on the contrary, both the IMP 8 and Thule observations indicate that CR intensities often *maximize* on field lines inside the CIR at 1 AU (e.g., on December 30, 1999, January 11, 2000, and possibly on December 24, 1999). The onset of the modulation on December 30 is shown in detail in Figure 2. Even after allowing for the $\sim$1 hr solar wind transit time from ACE to IMP 8/Earth, it is very clear that the CR intensity reaches maximum *inside* the CIR (which extends from $\sim$12 UT, December 30 to $\sim$04 UT, December 31) at the time of maximum magnetic field intensity and in the vicinity of the stream leading edge and interface, before declining. Similar behaviour was noted at solar minimum by Richardson et al. (1996). Also, maximum depression tends to occur within the high-speed stream well after the CIR, as is evident in Figure 1. In Figure 1, we also note that the strong ($\sim$25 nT) field enhancement on January 27 had little impact on the CR intensity. Hence, we conclude that models assuming that corotating CR depressions are simply the result of enhanced scattering in the strong fields inside CIRs do not include some of the detailed physics of these events. In fact, the observations are more consistent with the results of Morfill et al. (1979) which predicted a CR peak at the stream interface at 1 AU arising because the "most probable" turbulence direction vector is more closely aligned with the magnetic field in this region which more than counteracts the effect of increased scattering on radial diffusion.

Table 1. Characteristics of CR modulations associated with corotating streams

	Solar Max. (1999-2000)	Solar Min.
Depression size	$3.7 \pm 2.6\%$	$3.0 \pm 1.7\%$
Time of onset wrt:		
Interface	-5.9 ± 16.1 hr	-4.8 ± 7.3 hr
Vsw increase	-1.2 ± 14 hr	-1.3 ± 6.9 hr
B increase	1.8 ± 15 hr	3.9 ± 7.2 hr
B maximum	-6.3 ± 13.2 hr	-5.4 ± 7.4 hr
Turbulence increase	-0.2 ± 16.7 hr	0.7 ± 6.1 hr

The characteristics of the 30 streams examined in 1999-2000 are summarized in Table 1 and compared with those for around 300 streams, predominantly from solar minimum, studied by Richardson et al. (1996). The average depression in the IMP 8 guard ($3.7 \pm 2.6\%$) and the times of CR onset relative to various solar wind structures (negative = time of onset is before structure is observed) are comparable to those for the streams studied by Richardson et al. (1996). Nonetheless, there is considerable scatter in the times, indicating that the modulation onset is not simply ordered by a single type of structure. For the 1999-2000 events where plasma and particle data are sufficiently complete and the relevant solar wind structure can be identified reasonably clearly, we estimate that the onset occurs in the slow solar wind well ahead of the CIR in $\sim$17% of events, at the leading edge of the CIR in $\sim$13% of events, at the interface/stream leading edge in $\sim$43% events, and in the high-speed stream in $\sim$9% of events. In $\sim$9% of events, minimum depression occurs within the CIR, while there are no CR depressions in $\sim$9% of these streams. Thus, the modulations are more likely to commence at the interface/stream leading edge than at other locations. Corotating streams were also present around the maximum of cycle 22, but they are more difficult to study in detail because of the several day data gaps in the solar wind parameters whenever IMP 8 (the only spacecraft making such observations) was located in the magnetosphere. The few examples with good solar wind coverage show similar relationships with solar wind structures to those discussed above.

3 Summary

Corotating streams and their associated cosmic ray depressions are conspicuous features of the current solar maximum, and were present around the maxima of previous solar cycles; they are not simply features of low solar activity conditions. The sources of these streams were isolated near-equatorial coronal holes. There is little difference in the sizes of recurrent CR depressions at solar minimum and maximum and in their relationship with solar wind structures. This suggests that the ability of corotating streams to modulate the CR intensity is not strongly influenced by the global change in the solar wind structure from solar minimum to maximum, or by the accompanying change in the predominant stream source from polar to equatorial coronal holes. This is perhaps a little surprising based on our previous conclusion that the sizes of recurrent CR modulations at solar minimum are dependent to some degree on the polarity of the solar magnetic field, indicating that the large-scale heliospheric structure is a controlling factor. On the other hand, the similar behaviour throughout the solar cycle suggests that local solar wind conditions, such as convection with the solar wind and scattering play a role. Again, we emphasize however that the observations are not consistent with the simple idea that increased particle scattering associated with enhanced magnetic fields in CIRs is the major process generating corotating CR depressions.

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