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Rogue SEP events: Observational aspects

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Abstract. About once in a solar cycle, a SEP event occurs whose fluence dominates that for the entire cycle. We refer to such events as 'rogue' events, in analogy to rogue ocean waves having unusually large amplitudes. Well-known examples of rogue SEP events at Earth occurred on 14 July 1959, 4 August 1972, 19 October 1989, and 14 July 2000. Rogue events also have been observed in the inner heliosphere (with Helios 1 on 4 November 1980 at 0.5 AU) and with Ulysses in March 1991 at 2.5 AU. In this paper we review the solar (multiple CMEs) and interplanetary circumstances (converging shocks) that give rise to these rare but, if observed at Earth, geophysically important events.

1 Introduction

Solar energetic particles (SEPs) represent an important aspect of solar-terrestrial physics or space weather as it is currently called. Energetic particles disrupt high-frequency communictions in the Earth's polar regions, introduce clutter on spaceborne sensors, and pose a radiation threat to shuttle and space station astronauts. SEPs can also modify the atmospheric chemistry in the polar regions, resulting in the reduction of ozone. For this terrestrial effect, particle events with high fluences (not necessarily fluxes) at tens and hundreds of MeV are required. In the ozone depletion record, the events of August 1972 (e.g. Heath et al., 1977), 19 October 1989 (e.g. Jackman et al., 2000), and 14 July 2000 (Jackman et al., 2001) stand out.

While the consequences of some of these events for atmospheric chemistry are compared in Quack et al. (2001), in this paper we will focus on the solar and interplanetary conditions that gave rise to these unusual particle events and will identify leading criteria for their identification, such as long-lasting high intensities between two converging shocks. Since the converging shock appear to be the leading criterion, we've called these particle events rogue events, in analogy to rogue ocean waves during which, due to the superposition of two wave fields, wave heights of more than 30 m can be acquired.

2 Observations

Since we are interested in consequences of energetic particles on the terrestrial environment, we started with a list of large events. Shea and Smart (1995a) have ordered major solar proton events according to large peak fluxes and large peak fluences and found that the latter events generally are associated with a sequence of activity as an active region crosses central meridian while the former more often seem to be relatively isolated events in the western hemisphere, that is with good magnetic connection between flare and observer. In Shea and Smart's (1995a) list the largest fluences were observed (in decreasing order) in October 1989, July 1959, August 1972, and March 1991. The November 1960 event exceeded these fluences, however, since observations are sparse during that event it will not be considered here. The basic properties of these (and some other events) are summarized below.

2.1 August 1972 and July 1959 Rogue Events

Ground level events in August 1972 and July 1959 that were associated with high fluence intervals or rogue events have been analyzed by Pomerantz and Duggal (1974) who suggested that these GLEs arose as "a consequence of the acceleration of ambient lower energy protons to relativistic energies by reflection between two shocks moving with respect to each other in the interplanetary medium." Their main observations leading to this conclusion can be summarized as follows.

The intense August 1972 solar-geophysical activity originated in McMath active region 11976 which produced major eruptions from 2-11 August. Pomerantz and Duggal associated flares at ∼1900 UT (1B, N14E26) and ∼2400 UT (2B, N14E26) on 2 August with a pair of closely spaced SCs on

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4 August at 0119 UT and 0220 UT, just a few hours before the arrival of particles from a subsequent large flare at Earth. This latter 3B flare at 0620 UT on 4 August was followed within ∼15 hr by an SC at 2054 UT. d'Uston et al. (1977) obtained a wind speed of 550 km/s before this SC from HEOS 2 and Prognoz 2 measurements (cf., Zastenker et al., 1978). With the passage of the shock, the solar wind speed increased to values ~ 2000 km/s (Cliver et al., 1990, and references therein).

The accompanying energetic particle event showed a rather unique signature: IMP SEP data for this period (Pomerantz and Duggal, 1974) show a remarkable pulse of particles, particularly prominent at E > 60 MeV that is roughly bounded by the times of the 3B flare and the SC at 2054 UT. Pomerantz and Duggal (1974) obtained a GLE onset time of ≈ 1200 UT, more than 6 hours after the optical maximum of the associated flare (and 2 hours after its termination!). The GLE was characterized by an unusually steep spectrum. The particle fluence > 10 MeV during this event (which included the contribution from a major SEP event on Agust 7) was about $1.1 \cdot 10^{10}\ \mathrm{cm}^{-2}$ (Shea and Smart, 1995a), which is exactly half of the integrated solar proton fluence during the entire cycle 20 of $2.2 \cdot 10^{10}\ cm^{-2}$ (Shea and Smart, 1995b).

Pomerantz and Duggal reported similar circumstances for the 17 July 1959 GLE. They linked a 3+ flare beginning at 0319 UT on 14 July with an SC on 15 July at 0803 UT. The GLE-associated flare began on 16 July at 2116 UT with maximum at 2128 UT; the associated SC occurred at 1638 UT on 17 July. As was the case for the August 1972 event, the GLE onset in this event was significantly delayed. GLE onset was at 0130 UT on the 17th, one hour after the end of the optical flare. As was the case for the 4 August 1972 event, the GLE spectrum was exceptionally soft.

For the August 1972 event, the mean transit speed of the disturbance responsible for the second SC on 2 August was ∼1600 km/s vs. 2850 km/s for the shock following the GLE-associated flare. For the July 1959 event, the mean velocity of the first shock was ~ 1450 km/s vs. 2150 km/s for the second. Thus in both cases, there is evidence for converging shocks, the sine qua non for a rogue event. In addition, as Pomerantz and Duggal (1974) point out, the initial flare/CME in each case provides a population of lower energy seed particles.

As terrestrial effect of the August 1972 eruptions aside from the geomagnetic storm, a reduction of ozone in high latitudes by about 20% at the 4 mbar level has been reported (Heath et al., 1977) which lasted for more than a month. Ozone depletion has not been observed in mid-latitude or at the equator where energetic particles do not precipitate.

2.2 19 October 1989

The October 1989 event is the largest well-recorded particle event so far. It is part of a series of energetic flares and particle events in September/October 1989, which included 4 ground level events. Although at neutron monitor energies the 29 September 1989 event stands out, the October 19 event is remarkable for its extremely high fluence, at tens to several hundred MeV, topping even that of the August 1972 event (Shea and Smart, 1995a; Kohno, 1991).

The particle event originated in a flare at E9. Cliver et al. (1990) reported a possible shock at ~ 1700 UT on the 20th of October, near the maximum in the SEP intensity time profile. A confirmed SC occurred at ~ 0900 UT. It seems likely that the earlier shock originated in a long-duration solar X-ray event on October 18 beginning near 0 UT from the same active region that produced the major flare on the 19th. Presumably the second (possible) shock arose in the flare at E9.

In the series of events in September/October the difference between high fluence and high flux events in terms of flare location is particularly well pronounced: as the active region rotates to the western limb, it continues to produce large flares and energetic particle events. These latter lead to higher maximum fluxes, in particular at high energies, however, since they are only associated with one shock they do not contribute significantly to the total fluence.

2.3 14 July 2000

The Bastille day event on 14 July 2000 had the highest fluence recorded since the October 1989 event (Jackman et al., 2001). It was associated with a X5 flare starting at 1024 UT in NOAA region 9077 at N17 E01 and was accompanied by a full halo CME observed by the LASCO coronograph. The transient speed of the shock is of order 1500 km/s. Particle intensities start immediately after the flare, during the rising phase (the maximum at energies of more than about 100 MeV/nucl) a shock and a CME from a different event pass by. Intensities stay constant or continue to rise at energies below about 100 MeV while the start to decrease at higher energies except for a hump at the time of shock passage (cf. Quack et al., 2001).

The flare caused a strong ground level event; the arrival of the shock at Earth was associated with strong geomagnetic acitivity. During the particle event, ozone mixing rations above the 0.5 hPa level dropped by more than 30% in the polar cap region (Jackman et al., 2001).

2.4 14 November 1980 on Helios 1

This SEP event, although observed at 0.5 AU, exhibits the typical properties of a rogue event, cf. Kallenrode (1993). The flare occurred behind the west limb and was accompanied by a fast CME (Sheeley et al., 1985), the resulting interplanetary shock had a transient speed of more than 1600 km/s. Because Helios was located above the west limb, the geometry corresponds to a central meridian flare. The particle event starts immediately after the parent flare, about an hour after event onset an interplanetary shock and a magnetic cloud from an earlier flare pass by. The intensity reaches a plateau in some MeV/nucl; in higher energies it continues to rise towards the shock associated with this flare. With the passage of the shock the intensity drops. Thus the time profile is similar to that in the August 1972 event. Particle acceleration could be observed up to some hundred MeV/nucl. A ground level event was not recorded; however, this might be a result of rather poor magnetic connection between Earth and flare site (although with a similar magnetic connection the ground level events late in October 1989 have been observed at Earth). The initial particle spectrum is unusual steep but hardens through the course of the event.

2.5 March 1991 on Ulysses

The 22 March 1991 event was observed at both Earth and Ulysses at 2.5 AU. This is not surprising because the field line from Ulysses to the site of the parent flare almost passes through Earth. Although the event is not a ground level event, its fluence is recorded as only slightly smaller than that in the August 1972 event (Shea and Smart, 1995a). In addition, the parent 3B/X9.4 flare starting at 2243 UT at S26 E28 was strong enough to generate a significant neutron event at Earth (Pyle and Simpson, 1991). Particles were detected at the Earth shortly after the large 3B flare. Subsequently, an overlapping sequence of six flares gave a composite long duration event of peak magnitude M6.8 during which additional particles might have been accelerated. A major magnetospheric perturbation occurred on 24 March around 0342 UT, which corresponds to a travel time of 30 hours if the large 3B flare is assumed to be the parent flare for this event. The measurements at Earth are difficult to interpret because the relation between flares, particles, and shocks is difficult to establish. The observations are summarized in Smart et al. (1995).

The Ulysses observations are of particular interest because (a) the temporal evolution is complex but can be interpreted more easily, and (b) it shows essentially the same features of a rogue event as discussed above but at a much larger radial distance: the particle event starts shortly after the flare, there is a shock with CME in the rise phase of the particle event, and intensities stay high or even rise towards the shock associated with the parent flare (Sanderson et al., 1992; Wibberenz et al., 1992). Thus although at Earth the fluence in this event is large enough to probably account for about 1/3 of the total particle fluence during solar cycle 22, the particular features of a rogue event seem to be masked and become obvious only at the larger distance of Ulysses.

3 Conclusions

From these observations we can define criteria for the identification of a rogue event as well as for the circumstances leading to a rogue.

3.1 Criteria for a rogue events

From the observational viewpoint, the essential features of a rogue event can be summarized as follows: (1) converging interplanetary shocks, (2) unusual high proton intensities with an increase in intensity towards the following shock, (3) a strong parent flare with efficient particle acceleration associated with the following shock, (4) high and long-lasting intensity increases up to energies of some hundreds of MeV (but not necessarily a ground level event!), and (5) as terrestrial effect a strong polar cap absorption (PCA) accompanied by ozone loss.

3.2 Comparison to ground level events

Although most of the events discussed above are ground level events, a ground level event is not a necessary condition for the creation of a rogue event, as can be seen in the example of the March 1991 event. However, since the flare and/or the shock must be very efficient accelerators to create a rogue event, there is a rather high likelihood of a rogue being associated with a GLE. This can be interpreted as some kind of big flare syndrome (Kahler, 1982). On the other hand, a ground level event also is not a sufficient condition for a rogue event because many of the largest ground level events are relatively small in terms of fluence (cf. Shea and Smart, 1995a, or Fig. 11 in Shea and Smart, 1995b). This is obvious because the rogue event requires some kind of barrier to prevent particles from escaping the inner heliosphere while ground level events do not necessarily come as a sequence of events.

3.3 Comparison to multiple shocks/CMEs periods

Converging interplanetary shocks have been identified as the core property of rogue events. Thus in our interpretation converging shocks are a necessary requirement for the generation of rogue events, as had been suggested in Pomerantz and Duggal (1974) and Levy et al. (1977). However, converging shocks are not a sufficient condition for a rogue event: some pairs of converging shocks do not have any effect on particle intensities while others cause only minor local modifications in particle profiles which can be smaller than the ones caused by individual single shocks (Kallenrode, 1993). Levy at al. (1977) had offered the following interpretation for similar observations: in addition to the convergence of shocks, one needs (a) a pre-accelerated particle population and (b) a high reflectivity (or low transmissivity) of the shocks for energetic particles.

3.4 Physical mechanisms leading to a rogue event

From our analysis of the additional events, from the refined observations allowing the detection of magnetic clouds, and from the fact that a magnetic cloud can act as an efficient barrier for particle propagation, we would like to modify the suggestion by Levy et al. (1977) as follows: Physically, the most important features of a rogue event seem to be (a) a barrier (most likely the magnetic cloud) upstream of the particle event and shock, and (b) a continuous (strong) injection of particles from the shock belonging to the particle event. This scenario has been adopted in the simulation studies in Kallenrode and Cliver (2001).

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