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Temporal Evolution of a Gradual SEP Event and the Possible Role of Coronal Particle Acceleration

Karl-Ludwig Klein, Gérard Trottet

Observatoire de Paris, DASOP & CNRS UMR 8645, F-92195 Meudon

Edward L. Chupp, Philip P. Dunphy

University of New Hampshire, Physics Department and Space Science Center, Durham, NH 03824

Erich Rieger

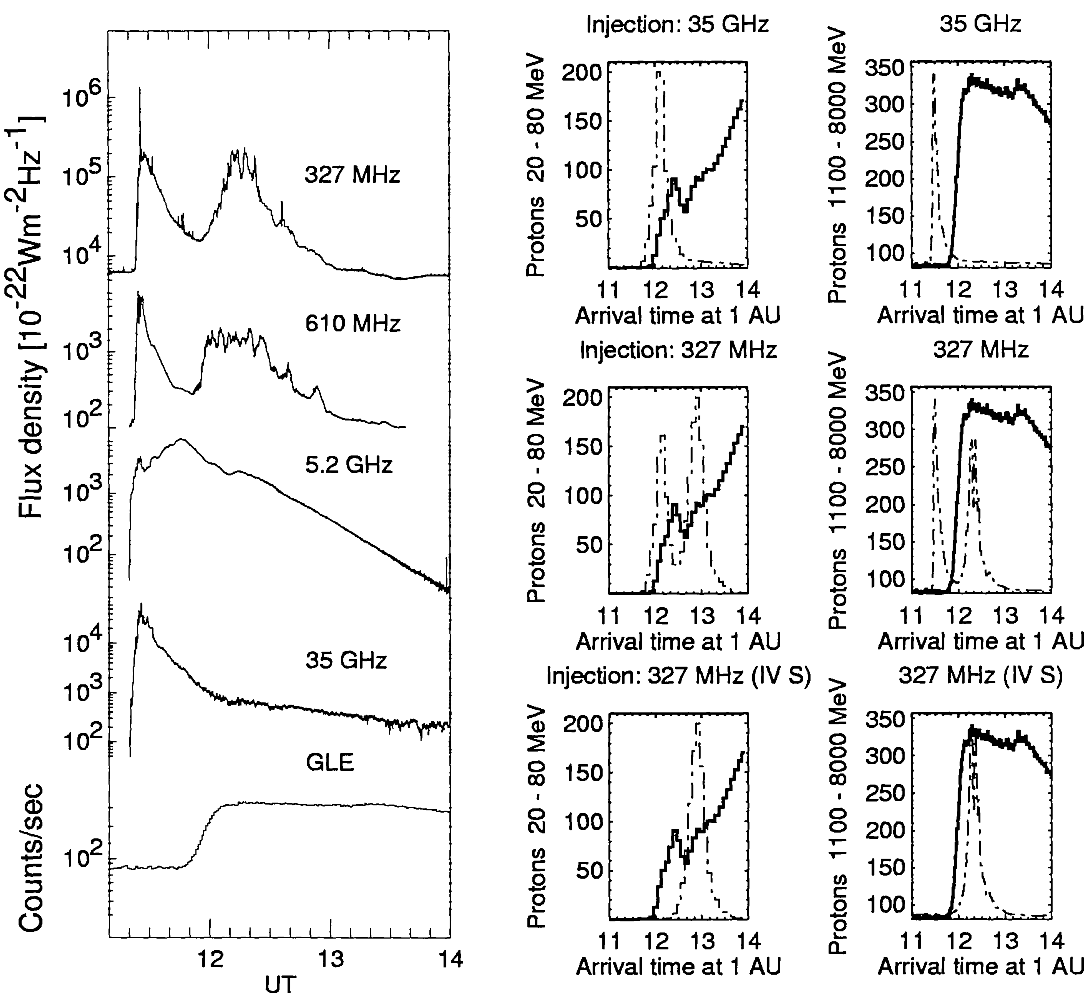
Max-Planck-Institut für Extraterrestrische Physik, D-85740 Garching

Abstract. The largest ("gradual") energetic particle events, where protons up to relativistic energies are detected in interplanetary space, are widely believed to result from acceleration at the bow shock of a coronal mass ejection (CME). Contrary to this view, a comparison of the time histories of coronal electron acceleration and interplanetary energetic protons ($E > 20$ MeV) during the large 1989 September 29 event suggests that coronal acceleration behind the bow shock of the CME leaves its fingerprints in the particle time profile at 1 AU. Acceleration sites suggested by the radio emission include a more dilute plasma than the acceleration source of particles producing the most intense microwave - and presumably also hard X-ray and gamma-ray emission. This is consistent with the low charge states of, e.g., Fe reported for such large events.

1. Introduction

Energetic particles interacting in the solar atmosphere, where they emit gamma-ray, hard X-ray and radio emission, and those detected at 1 AU were long believed to stem from a common acceleration process in the solar corona, during a flare. Long standing problems such as the duration of the enhanced particle fluxes at 1 AU and the conditions of escape from the coronal acceleration region led to the idea that the largest, "gradual" particle events, where protons up to relativistic energies are observed, are actually accelerated at the bow shocks of fast coronal mass ejections (CMEs; e.g. Kahler 1994; Reames 1999). A consequence of this interpretation is that interacting particles and particles detected *in situ* should evolve independently.

In this contribution we analyse the time history of coronal electron acceleration during the large gradual event of 1989 September 29 and show evidence for co-evolution of the high-energy proton intensity time profiles ($E > 20$ MeV)



a. b.

Figure 1. **a.** Time profiles of radio flux densities and of the Hobart neutron monitor response (GLE) during the 1989 September 29 event. Radio data from Berne (35 and 5.2 GHz, court. A. Magun), Trieste (610 MHz, court. P. Zlobec) and the Nançay Radio Heliograph (327 MHz). **b.** Comparison of observed time profiles of protons at 1 AU (fat lines) with protons from coronal injections that stream freely along an interplanetary field line of length 1.3 AU (dashed lines). The left column refers to protons in the energy range 20-80 MeV (data: IMP-8, court. R. McGuire), the right one to relativistic protons (Hobart neutron monitor). The three rows refer to three different time profiles of the assumed proton injection function, represented by the radio emission at the frequency noted at the top of each panel.

at 1 AU with the coronal electron acceleration. A detailed analysis of this and the 1989 October 19 event is published elsewhere (Klein et al. 1999).

2. 1989 September 29: Radio and Optical Observations

Time profiles of radio emission and of the neutron monitor response are plotted in Figure 1.a. Radio emission at different frequencies traces different populations of non thermal electrons in different regions of the corona. Millimetric and centimetric emission is due to gyrosynchrotron radiation of mildly relativistic electrons in the low corona. Decimetric-to-metric emission results from collective plasma emission of suprathermal electrons in the middle corona ($\gtrsim$0.1 $R_\odot$ above the photosphere). The time profiles in Figure 1 exhibit a systematic trend of variation from high to low frequencies. At millimetre waves (35 GHz) the event lasts a few tens of minutes. It displays a rapid rise, several peaks, and a subsequent monotonous decay after ~1140 UT. A similar behaviour is observed during the first minutes of the event at all frequencies. We refer to this period as the main phase of the event in the following. At decimetre and metre waves (frequency $\leq$610 MHz) the main phase is followed by a new rise after ~ 1150 UT ("stationary type IV" continuum). It starts with a progressive delay of some minutes at lower frequencies, as is frequently observed, probably due to plasma emission from expanding magnetic structures where the ambient density, and hence the emission frequency, gradually decreases (e.g. Pick 1986). Centimetric waves (e.g. 5.2 GHz) display the main phase, the late enhancement and a peak in between that has no counterpart at millimetre waves and only a weak response at 610 MHz. The low frequency cutoff suggests that this peak is due to electrons injected into extended closed loops, while the high-frequency cutoff can be explained if the footpoints of the loop are hidden from view.

The radio emission is associated with a flare (GOES class X9.8) and CME. In the Hα images (Figure 2, left column) post flare loops become visible above the south-western limb well after the onset of the radio emission. The flare occurs in AR 5698 about 10° behind the limb. Three images of a fast coronal mass ejection (1800 km s^{-1}; Burkepile & St.Cyr 1993; Kahler 1994) were taken by the SMM coronagraph. The evolution of the radio sources in the two rightmost columns of Figure 2 can be summarized in three steps as indicated by the three rows in the Figure: prior to and at the onset of the event (top row) the decimetric - metric emission is concentrated above the occulted active region. The same is true for the stationary type IV continuum (bottom row). During the main phase of emission from millimetric to metric waves (middle row) the decimetric-metric radio sources fill the whole cone of the white light CME as indicated by the dashed radial lines. The radio sources are located behind the front of the CME, within the range of the occulting disk of the coronograph. The configuration is similar to the radio event associated with the CME and GLE on 1997 November 6 (Maia et al. 1999).

Although we observe only projected positions, the plasma origin of the radio emissions implies that the sources are located behind the front of the CME and its presumed bow shock, and are not projected sites of sources in front of the CME. We conclude that the radio emitting electrons are accelerated behind the front of the CME, in the course of restructuring of the large scale coronal

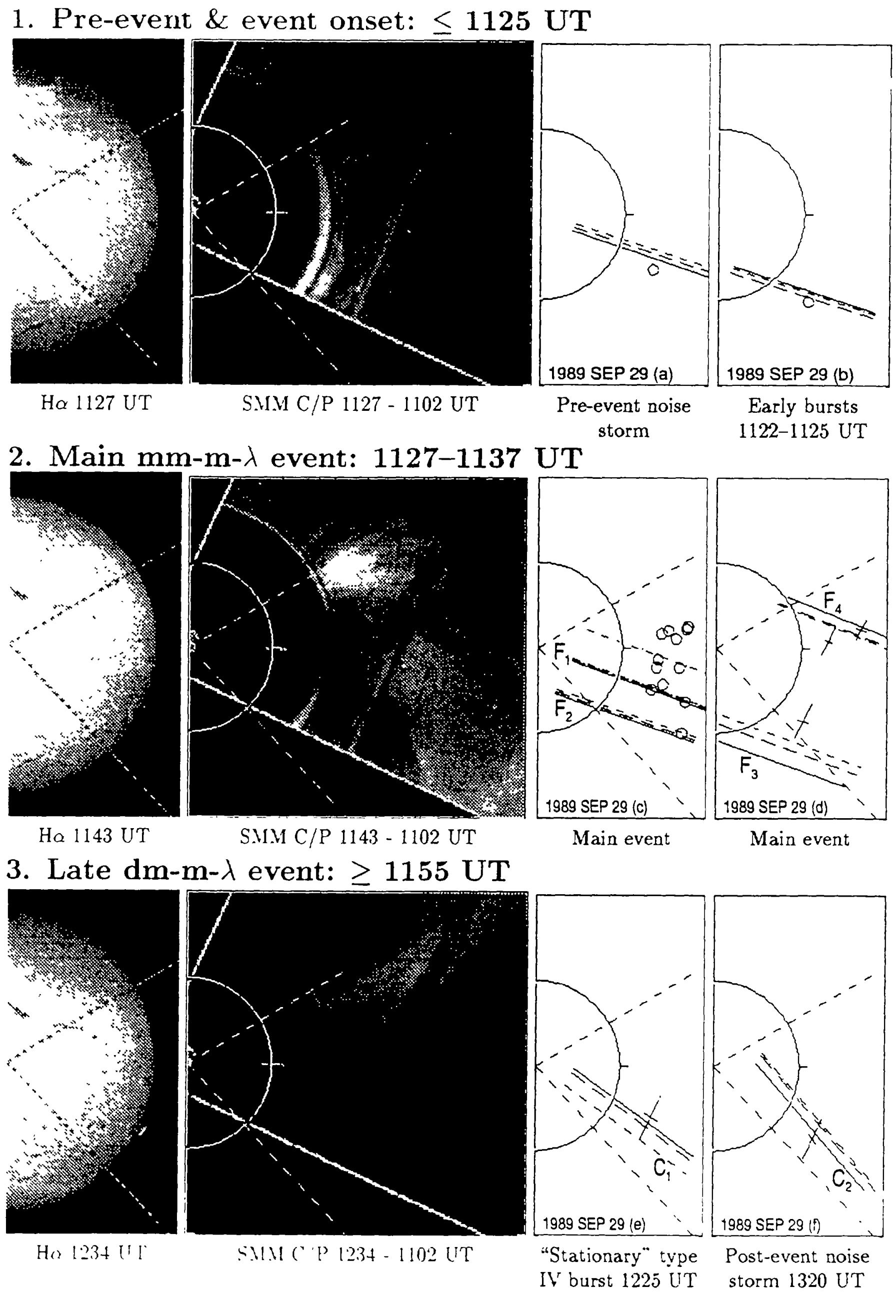


Figure 2. Evolution of the source configuration during the 1989 September 29 event: Hα (Meudon Heliograph, court. Z. Mouradian; left column), SMM Coronograph/Polarimeter (court. J. Burkepile, second col. from left) and radio source positions (Nançay Radio Heliograph; small circles give the centroids, crosses centroids and half widths of radio sources at 164 MHz; line segments designate the one-dimensional location of sources at higher frequencies, measured with the north-south branch of the NRH).

magnetic field, from where they get access to a broad cone of flux tubes connected with interplanetary space. The acceleration sites are probably different during the main phase and the stationary type IV continuum. If the late acceleration occurs in the vicinity of the decimetric-to-metric radio source, the typical plasma density is of the order of 10^9 cm^{-3}, under the hypothesis that radio emission is generated near the local electron plasma frequency or its harmonic.

3. Coronal Acceleration and Proton Time History at 1 AU

The time histories of the proton intensities at 1 AU during the 1989 September 29 event are plotted by fat lines in Figure 1.b, as observed in the energy ranges 20-80 MeV (left column) and above 1.1 GeV (right column). Both energy ranges display at least two successive rises. Despite the difference in the kinetic energies, the rise of the 20-80 MeV protons lags behind that of the relativistic protons by only a few minutes.

The dashed lines in Figure 1.b represent simple model time profiles. We assume that protons are injected at the Sun with a power law (index 3) and a time profile drawn from the radio time history at a given frequency. We suppose that the protons stream freely along an interplanetary magnetic field line of length 1.3 AU. This model time profile gives an estimate of the start and the minimum duration of the particle event at 1 AU. The three rows of Figure 1.b use injection profiles that emphasize the main phase of the solar event (top row: 35 GHz) or include the delayed coronal acceleration visualized by the decimetric-metric radio emission (middle and bottom row). The late coronal particle acceleration has been isolated in the bottom row, where only the stationary type IV time profile is used as injection function. The contribution of the preceding 327 MHz emission was subtracted using an exponential fit of its decay phase.

Comparison with the free streaming model brings some order into the observed proton time profiles. The predicted arrival time of the first 20-80 MeV protons at 1 AU is broadly consistent with the observed rise (Figure 1.b, left column). It precedes the first observed rise of relativistic protons by several tens of minutes (right column). The observed second rise of the 20-80 MeV count rate has no counterpart in the injection time profile inferred from the millimetric radio emission, but corresponds to the rise of protons expected from injection during the stationary type IV continuum (Figure 1.b, bottom left). The relativistic protons respond only to the late acceleration traced by the stationary type IV emission (Figure 1.b, bottom right). As discussed precedingly, the slow rise of the model time profile reflects the evolution of the ambient density in the radio source, not the particle acceleration. This comparison suggests that the protons at 1 AU result from two injections with different spectra, which are both related with coronal processes behind the CME and its presumed bow shock.

After 13 UT the 20-80 MeV proton profile continues to increase, and the relativistic protons display a new rise, without any coronal counterpart. Neutron monitors (Lovell, Duldig, & Humble 1998) show a marked change of the angular distribution of the protons during this new rise, when large pitch angles, including sunward streaming particles, start to play a major role. Hence the new rise after 13 UT is probably not due to a solar injection.

4. Discussion and Conclusion

The time evolution of the proton intensity during the 1989 September 29 event, which is one of the largest gradual particle events of the last solar maximum, appears to be related with the time history of acceleration of electrons in the corona. Similar features were observed in a few smaller events (Kallenrode & Wibberenz 1991), and were inferred for another large event by Akimov et al. (1996). The co-evolution is hence not a mere coincidence, but reveals a physical relationship. This means that the protons seen at 1 AU are accelerated *behind* the CME and its presumed bow shock. The alternative that both the protons and the interacting electrons are accelerated by the CME shock fails to explain the long duration of the radio emission. The acceleration sites include tenuous coronal plasma, as suggested by the shift of the radio emission to lower frequencies in the late phase of the event. This is consistent with the low charge states detected during gradual events (Ruffolo 1997, and ref. therein). Hence the present analysis is consistent with some peculiarities of gradual SEPs like broad injection cones and low charge states, although it does not suppport the idea of bow shock acceleration. The CME may be essential for the particle enhancements at 1 AU e.g. by the triggering of particle acceleration in a large coronal volume, or by reconfiguring the coronal magnetic field such as to provide accelerated particles rapid access to the interplanetary field lines which guide them to the satellite. Its bow shock may be important in the long lasting acceleration of particles in interplanetary space, but it cannot explain the relationship between the time profiles of protons at 1 AU and electrons interacting in the corona.

The paucity of the radiative diagnostics is a major obstacle to the identification of acceleration sites in tenuous coronal plasmas. Collective radio emission is more sensitive there than the collisional processes yielding gamma rays and hard X-rays. The increased sensitivity and imaging capability of HESSI up to the nuclear line range will hopefully allow us to make further progress.

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