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On the Origin of Gamma-Ray Emission From the Behind-the-Limb Flare on 29 September 1989

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ABSTRACT

Solar gamma-ray-line (GRL) emission was observed by the Gamma Ray Spectrometer on SMM in association with a flare behind the west limb on 29 September 1989. We present observations that support a CME-driven coronal shock as a plausible source of the energetic protons that produced the GRL emission on the visible disk.

1. INTRODUCTION

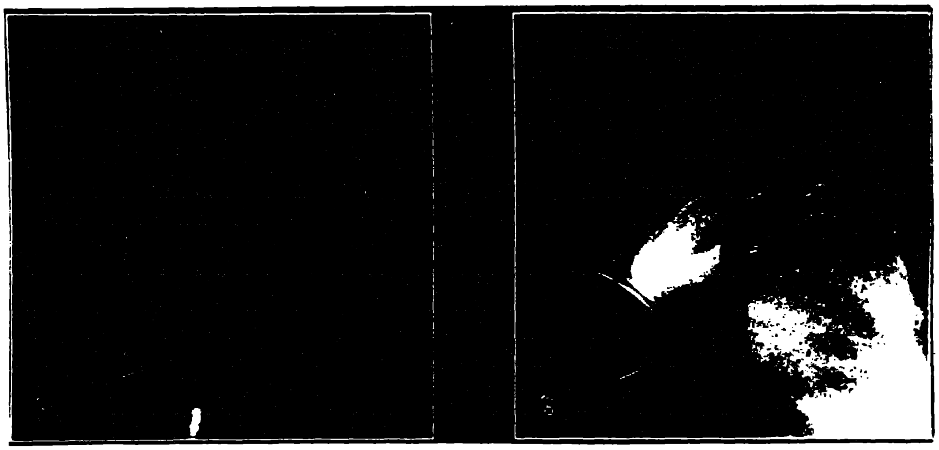
As reported by Vestrand and Forrest (1993), a large flare located behind the southwest limb of the sun on 29 September 1989 was associated with detectable gamma-ray-line (GRL) emission. SMM Gamma Ray Spectrometer observations of this event began when the satellite emerged from an SAA pass at 1133 UT, coincident with the maximum of the X9.8 soft X-ray burst but presumably after the peak of the impulsive phase GRL emission. The flare start time in soft X-rays was 1047 UT and metric type III emission, an impulsive phase phenomenon, was observed from 1124.3-1128 UT. GRL emission was observed from 1133 UT until 1150 UT when SMM entered orbital night. The first Hα emission that can be confidently associated with the GRL event (Vestrand and Forrest, 1993, cf., Swinson and Shea, 1990) was a 1B flare (S24 W90) observed at 1141 UT from region 5698, then estimated from the positions of flares during disk passage to have been located at (~S25 W98±5). This uncertainty in longitude corresponds to a range of occultation heights of ~1-20 x 10^3 km.

The GRL flare was remarkable for the observed high (~0.2) ratio of the 2.2 MeV to 4-7 MeV emission. As Vestrand and Forrest (1993) point out, because of the large attenuation of the 2.2 MeV neutron capture line near the limb, this ratio implies that a significant fraction of the GRL emission originated at longitudes on the visible disk as far as 25° from the flare centroid. Thus this flare provides the first evidence of a spatially extended component of GRL emission from solar flares.

Vestrand and Forrest (1993) suggest that the spatially extended component is powered either by particles that diffuse from flare loops or by particles precipitating from a coronal shock. We favor the latter suggestion. The 29 September 1989 flare was associated with the largest ground level event (GLE) observed since 1956, with particles observed at energies > 20 GeV (Swinson and Shea, 1990). The fact that these solar energetic particles (SEPs) were rapidly injected onto interplanetary field lines rooted in the corona far from the flare site indicates a similar transport problem for SEPs as for the GRL-producing protons in this event, if the flare region were the source of both. For SEPs, such rapid "transport" from the flare region is generally attributed (Lin and Hudson, 1976) to widespread acceleration on open field lines by a coronal/interplanetary shock. Cliver (1982) presented observations supporting a coronal shock as the fast propagation mechanism for the behind-the-limb (~W120) GLE-flare on 1 September 1971 and Debrunner et al. (1988) made similar arguments for the GLE-flare (~W130) on 16 February 1984. Following the work of Kahler et al. (1984) such shocks are thought to be driven by fast coronal mass ejections (CMEs). In this paper, we present observations of a broad and high-speed CME that was associated with the SEP/GRL flare and calculate the fraction of > 30 MeV protons that would have had to precipitate from the shock in order to produce the observed GRL emission.

2. OBSERVATIONS

Images of the CME associated with the 29 September 1989 flare obtained at 1127 UT and 1143 UT by the coronagraph/polarimeter on SMM are given in Figure 1 (J. Burkepile, private communication, 1993). The CME was centered at S08 and the latitudinal span was 77°. If we assume that the longitudinal extent of the CME is comparable to the latitudinal extent, then it is reasonable to suppose, given the flare location ~10° beyond the limb, that the CME encompassed a substantial area of erupting field lines on the visible hemisphere. Since the flanks of shock waves can extend beyond the driving piston (Sime and Hundhausen, 1987), it is plausible that the coronal/interplanetary shock in this event extended to the nominal field lines (~W60°) that connect to Earth. (There is a gap in IMP-8 solar wind data from ~0200 UT on 27 September to ~1200 UT on 1 October; the wind speed on either side of the gap is ~350 km s^{-1}.)



11:27 UT

11:43 UT

Fig.1 Images of the CME associated with the 29 September 1989 GRL/SEP flare. These are difference images obtained by subtracting a base image at 10:12 UT. The dotted line indicates the limb of the sun; the arrow points north.

The height-time plot of the motion of the leading edge of the CME (Figure 2) indicates, assuming no acceleration, a limb-time (1 R_O) of ~1121 UT. The Alfven speed at the ~2 R_O radial distance at which the CME was first observed is ~500 km s^{-1}, well below the radial speed of 1828 km s^{-1} determined for the CME (Burkepile and St. Cyr, 1993), and consistent with the formation of a coronal/interplanetary shock. The durations of metric type III (impulsive phase) and type II (coronal shock) bursts reported by Weissenau Observatory and the inferred injection profile of the first arriving ~20 GeV protons at 1 AU (M.A. Shea, private communication, 1993) are also indicated. The timings of these phenomena are consistent with a CME driven shock as the source of the SEP event. The injection profile of 21 GeV protons in Figure 2 is based on the assumption that there was no scattering in the interplanetary medium. Any scattering would lengthen the effective travel distance to the Earth and would thus move the onset of the injection profile earlier, toward the time of the first detection of GRL emission following the SAA.

It is of interest to calculate the fraction of SEPs with energies > 30 MeV that would be required to precipitate from the shock in order to produce the front-side

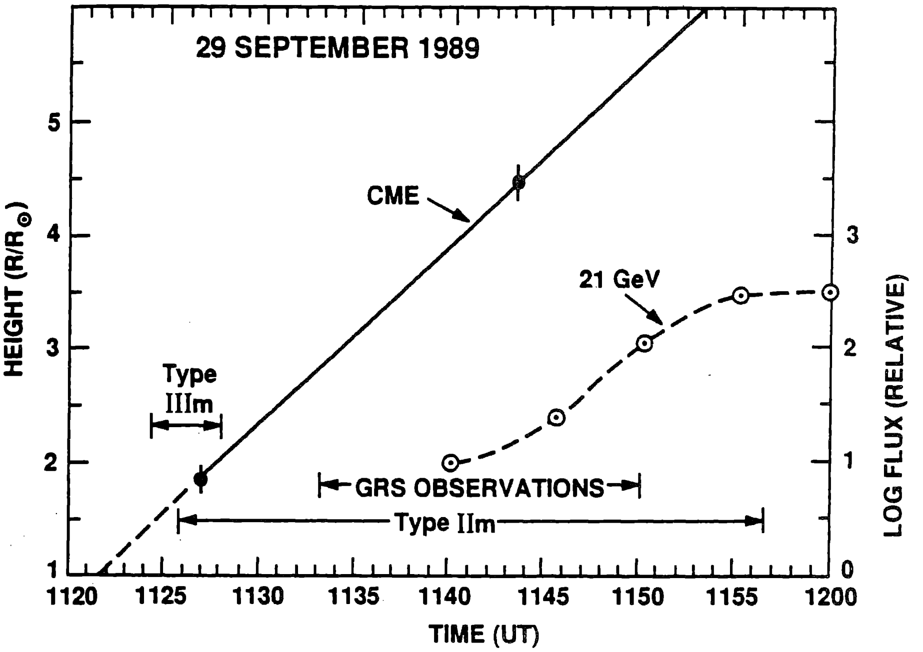


Fig. 2 Height-time plot of the leading edge of the CME associated with the 29 September 1989 GRL/SEP flare. Timings of metric radio bursts, the GRS observing window, and the injection profile of 21 GeV protons are indicated.

GRL emission. Observations of the 29 September 1989 SEP event by GOES (H. Sauer, private communication, 1993) and by the JHU/APL detectors on IMP-8 (S. Krimigis and T. Armstrong, private communication, 1993) give a peak flux of ~1200 protons cm^{-2} s^{-1} sr^{-1} and a spectrum ~ E^{-2} at ~30 MeV. If we assume that the particles flow out over π sr and that the injection profile is ~ 10^3 s, we obtain,

$$N_{esc}(> 30\ \mathrm{MeV}) \sim 8 \times 10^{32}\ \mathrm{pr} \qquad (1)$$

We can estimate the number of ions that precipitated into the solar atmosphere from the observed nuclear gamma-ray emission. By jointly fitting a nuclear model (viz. 27 April 1981 nuclear spectrum) and power-law bremsstrahlung spectra to the GRS measurements, we find a livetime corrected 4-7 MeV nuclear fluence of ~25 photons/cm^2. The spatially extended nature of this event precludes the use of the standard diagnostic provided by the 2.2 MeV to 4-7 MeV fluence ratio to derive the 10-300 MeV ion spectral shape. However, if we use the spectral slope provided by the SEP measurements and the gamma-ray yield functions given in Ramaty et al. (1993), we find for the number of precipitating ions,

$$N_{precip}(>30\ \mathrm{MeV}) \sim 3 \times 10^{32}\ \text{(composition 1), or}$$
$$\sim 2 \times 10^{31}\ \text{(composition 2)} \qquad (2)$$

The large range for this estimate reflects the sensitivity of the nuclear yield to the compositions of the precipitating ions and target material. The estimate is bracketed by the values for the photospheric composition (composition 1) and the 27 April 1981 composition (composition 2). For shock-accelerated ions that precipitate well away from the flare site, it is probably more appropriate to use the photospheric composition than that based on the 27 April 1981 flare.

There are other uncertainties in the above estimates for the numbers of the GRL-producing ions and the SEPs. The N_{precip} values calculated for both compositions are underestimates because the time interval over which GRL emission is observed is artificially limited by the SAA and also because any precipitation-induced GRL emission on the invisible disk cannot be observed. Because of scattering and less than optimal connection, N_{esc} should probably be viewed as a lower limit for the number of escaping protons with E > 30 MeV. With these caveats, if we assume that all of the protons in this event were accelerated at a coronal shock, then a precipitation rate, $R = (N_{precip}/(N_{precip} + N_{esc})) \times 100\%$, in the range from ~3-30% is required to produce the observed GRL emission.

3. DISCUSSION

We suggest that the front-side GRL emission observed from the 29 September 1989 behind-the-limb flare was caused by protons accelerated at a CME-driven coronal shock. This scenario, depicted in Figure 3, is appealing because of its simplicity: particles accelerated on open field lines can either escape to be observed as SEPs or precipitate to give rise to GRL emission. For both types of emissions, fast "transport" is accomplished by widespread shock acceleration. Spatially, the CME/shock ensemble should be broad enough, based on the CME latitudinal extent, to encompass the front-side regions from which the 2.2 MeV emission must originate. Temporally, the onset of GRL emission is marginally consistent with the presence of high-energy SEPs in the corona. A simple calculation indicates that ~3-30% of the protons accelerated at a coronal shock would need to precipitate to the sun to produce the observed 4-7 MeV emission. A detailed modeling effort is required to determine whether a shock can precipitate up to $\lesssim$ 30% of its E > 30 MeV protons and still efficiently accelerate protons to energies > 20 GeV.

A similar "precipitating-shock" model has been proposed by Ramaty et al. (1987) to account for the pion-rich phase of gamma-ray emission observed in the 3 June 1982 solar flare. It is an open question whether the spatially extended GRL emission in the 29 September 1989 flare is the same as the de-delayed high-energy components observed in intense disk flares such as 3 June 1982.

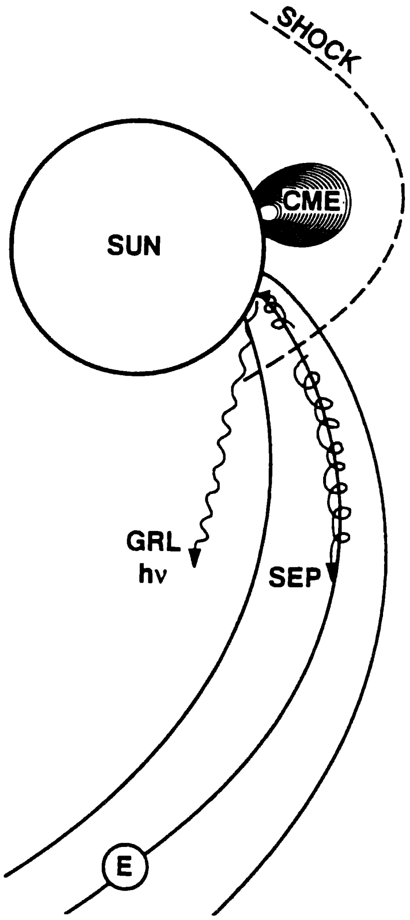


Fig. 3 Proposed scenario for shock acceleration of GRL-producing protons from a behind-the-limb flare on 29 Sep 1989.

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