Modeling the September 2017 SEP and LDGRF Events

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Abstract

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The large flares of 2017 September 4 to 10 were significant microwave events with revealing multi-wavelength images of the flare environment. The event on September 6 was a large long-duration, gradual rise-and-fall, gamma-ray (LDGRF) event, as was the even larger September 10 event. The finale of the sequence on September 10 also produced a Ground Level Enhancement (GLE). We interpret and model the behavior of the energetic flare protons of September 6 and 10 events in the context of stochastic acceleration in a large coronal structure to produce the high-energy long-duration gamma-ray emission, using constraints from microwave imaging spectroscopy from the Expanded Owens Valley Solar Array.

Objectives

History

The phenomenon of Long Duration Gamma-Ray Flares is a peculiar one, because the emission is singularly energetic, delayed and prolonged with respect to all other emissions emanating from the flare. Because of the delay and energies of the gamma rays, it has been postulated from the first occurrences that the same particles that produce ground level enhancements also produce the radiation from the Sun. However, the modeling of the robust and reliable repeatability of particle transport from great distances once accelerated in the IP shock is strained. Magnetic connections to the shock front are changing and transient, diffusion through the downstream region to the solar surface from distances as long as a fraction of an AU would seem to be unreliable, given the magnetic re-structuring taking place behind the CME. And one must produce a profile, remarkably diffusive in nature, no bumps, no wiggles—a pure exponential.

Alternatively, we can investigate a diffusion solution to the particle transport and acceleration as it can take place in large coronal loops, distinct from the receding CME and shock. Modeling by Ryan and Lee (1991) shows that the trapping volumes must be large and filled with MHD turbulence to accelerate the ions via second-order Fermi acceleration and transport them diffusively to the solar photosphere where they radiate for long periods. Estimates indicate that the level of turbulence need not be large, provided the volume is large. Lacking is a visualization of such an active loop that could be the home and the accelerating agent for the protons. Because little else is required of the trapping loop, other than embedded turbulence, it may not readily radiate, which would reveal its location, size and orientation, much less the contained energetic particles.

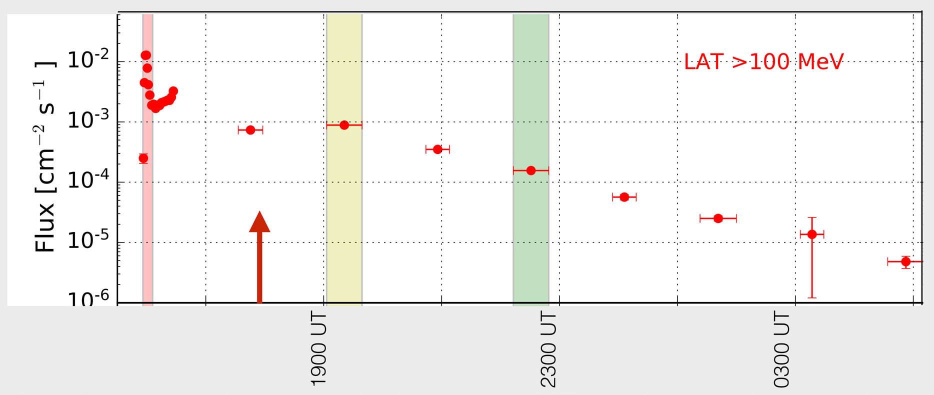
The unique microwave observations of the 2017 September flares reveal these loops, allowing us to model the acceleration and transport. The events were *bona fide* LDGRFs with accompanying energetic ions detected in space. With the length and orientation of the loop structure measured in the imaging data via emission by the attendant electrons and positrons, we can set constraints on the necessary embedded (and largely invisible) turbulence.

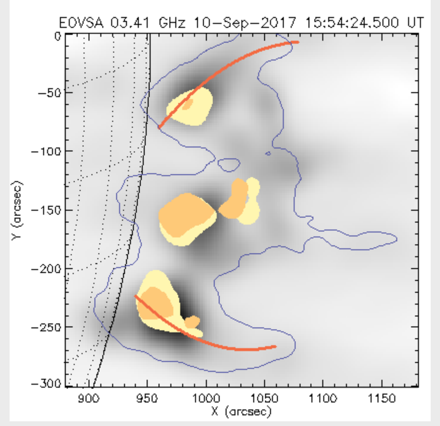
We search for a self-consistent, data-supported diffusion model of the LDGRF process without invoking a distant receding shock.

Data and Modeling

For this study we primarily use data from the Large Area Telescope (LAT) on the Fermi mission and the microwave data from the Expanded Owens Valley Solar Array (EOVSA). The flare of 2017 September 10 was well observed by both instruments.

The 2017 September 10 event was an unusually powerful LDGRF, emitting >100 MeV γ rays for several hours. It was a somewhat less impressive GLE and SEP event at Earth (Bruno *et al.* 2018). Being on the west limb with coronal loop structures oriented with a significant N-S orientation, the event was seen in profile by EVOSA, allowing examination of the dimensions of the affected volumes in the corona. Shown below are the γ-ray photometry >100 MeV and the corresponding intensity image at 3.4 GHz.



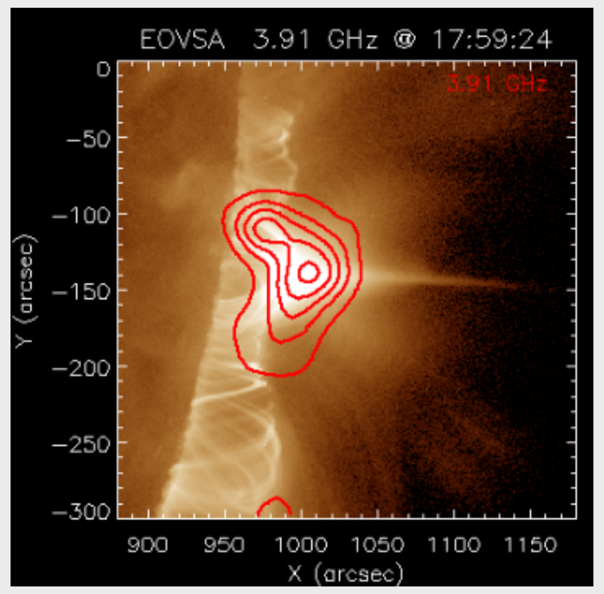


We focus on the period after 1900 UT on September 10 that exhibits a smooth photometric exponential decay (±10%) with a time constant of ~6500 s, while the deduced spectral index for the next 8 hours softens from a value of 3.7 to 6 (Omodei et al. 2018). This time period was chosen because not only did the γ-ray event enter its exponential decay, but it is well after any disturbance produced by reconnections in and around the smaller internal loop and after any CME would have exited the magnetic volumes considered here, allowing the system to relax. There is more complicated activity leading up to the slow decay, including an impulsive phase and an intermediate recovery and fall (hidden by Earth occultation) that gives way to the >9.5-hour gradual feature we examine here. The onset of the gradual phase appears to have started some time, of order two hours, before 1900 UT as shown on the right in the AIA and EVOSA image at 1800 UT.

The microwave/AIA image above covers the time from 1600 to 2430 UT, i.e., the impulsive phase and well into the gradual phase. It defines the relevant structures and their dimensions. In particular, the separation of the most northern and southern lobes is of order 175″ or 0.2 $R_\odot$ in the plane normal to the observer. We take them to be the feet of a larger loop-like structure. Given that the top of the loop is out of the frame, we estimate that the loop reaches a height of 0.4 with a **circular length of 1.4 $R_\odot$**, perhaps longer if it has not fully relaxed into a potential field.

Modeling

The model in its simplest incomplete form is a 1-d leaky box, if one only considers the long-term decay, neglecting the early time dependent aspect of the problem, i.e., the initial acceleration and transport of the particles to the footpoints, where they radiate. This diffusion that governs the physical transport of the particles also is responsible for the acceleration of the protons via the second-order Fermi process, the time scale of which is inversely proportional to the spatial diffusion time. If we further assume that the spectral shape is stationary (which it is not, i.e., acceleration is not keeping up with the losses) then this decay in a linear box of length ℓ is governed only by the measured time constant $\tau = \ell^2/\pi^2\kappa$, where κ is the inferred spatial diffusion coefficient. κ should be considered an upper limit because of the measured diminishing acceleration. Furthermore, this model relies on diffusive transport where $\lambda \ll \ell$. Also, implicit here is that the acceleration rate with respect to the loss rate has stabilized and that the spectral shape of the ions above the γ-ray production threshold (~300 MeV) is steady. We also treat the energetic protons as test particles. Thus, if one knows both ℓ and τ, one can deduce κ the diffusion coefficient. In this case the gradual phase time constant is approximately 6500 s. From this, quasi-linear theory can be used to estimate some plasma properties within the trap, such as $\delta B/B$, and from that the spectrum-integrated wave-energy density (e.g., Lee, 1983).



Gradual Phase Behavior

Shown above is the AIA (171 Å) with the EVOSA 3.9 GHz image at 1800 UT near the peak of the gradual phase.

At this time the remaining microwave and HXR activity is confined to the smaller central loop and is thermal in nature (20 MK) as is the x-ray emission (Omodei et al. 2018). No measurable non-thermal emission is detectable in the field of view of the observing instruments, other than the 100-MeV γ-ray emission, which is just starting its 6500-s decay. This is behavior similar to that reported by Grechev et al. (2018) for the over-the-limb LDGRF of 2014 September 1 and earlier non-imaging observations (Chupp and Ryan, 2009).

The error circle of the 100 MeV emission from LAT is large late in the event, but may only reflect the poorer statistics late, rather than true extended emission.

To obtain a 6500-s precipitation of particles to the footpoint, a loop of length 1.4 $R_\odot$ requires a diffusion coefficient of 1.4×10^{17} cm^2-s^{-1}, corresponding to a **mean free scattering path length of ~200 km**, consistent with the diffusion approximation.

We normalize the wave power spectrum to the intensity at the resonant wave number in a 1-G field, and we extend the $k^{-5/3}$ Kolmogorov form to a k value representative of the loop cross section diameter, where it is flat to the origin.

This in turn implies a **wave field energy of 0.7 ergs-cm^{-3}**. This value exceeds the ambient B field energy at 1 G (0.04 ergs-cm^{-3}), what we might expect at 0.4 $R_\odot$. However, no such problem exists farther down the legs of the loop, where B is much greater. For example, when B~10 G, only 18% of the ambient B energy need be in the form of waves. The situation improves rapidly with increasing B in a dipolar field.

Are we accelerating particles? An acceleration time scale τ_a $(9\kappa/V_A^2)$ (Schlickeiser 1986) can be computed. For the acceleration time scale to equal the diffusion time scale, **one needs an Alfvén speed >140 km–s^{-1}, a modest requirement**. Greater speeds shorten τ_a.

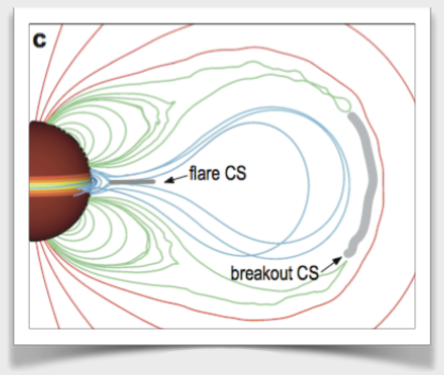
Discussion

This simple analysis reveals several things:

1. With unprecedented microwave imaging, we have been able to put some realistic numbers on coronal traps that can produce protons of sufficient energy to power an LDGRF.
2. Accompanying images and data from SDO, RHESSI and LAT allows us to quantitatively examine the energetic particle environment.
3. We see that diffusion in a static loop can successfully both impede the transport of particles, while accelerating them to the requisite energy.

However, this new information highlights shortcomings of the model.

1. Grechev et al. (2018) concluded that a shock passage seeds the large loop, in which the diffusion process occurs. This event is similar, in that, the reconnection site associated with the central HXR, AIA and μ-wave image gives rise to a breakout process (Karpen, this meeting), producing a shock that likely accelerates particles to modest energy at low altitudes. However, after three hours, the region behind the blob will likely re-configure into a more dipole like structure. This would leave behind a large loop with seed particles, with those particles being unrelated to those in the impulsive phase, reminiscent of Hudson's lasso picture (Hudson 2018).



2. The model is too simple and for large loops must incorporate the inhomogeneity of magnetic field.
3. In regions where B is too small to support the necessary wave field, the containment of the wave energy must be included, perhaps like that discussed by Hollweg (1984) where waves in loops are reflected off gradients and discontinuities in the "index of refraction."
4. Investigate self generated waves produced by the low-energy protons that resonate with higher energy protons, producing a non-Kolmogorov spectrum, similar to that computed by Lee (1982).
5. Include a momentum-dependent diffusion coefficient that will describe a varying power law spectral index.

Conclusions

Conceptually and qualitatively, a coronal trap, with spatial and momentum diffusion governing the precipitation of high-energy particles, can re-produce LDGRF behavior witnessed since 1982 (Chupp et al. 1983). The diffusive behavior produces a "perfect" exponential decay, difficult to achieve by other processes. By inserting realistic numbers obtained from new measurements of an actual environment, the direction of future modeling efforts is clearer, with a goal of minimizing handwaving arguments.

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