Interplanetary Type II Radio Bursts from Wind/WAVES and Sustained Gamma-Ray Emission from Fermi/LAT: Evidence for Shock Source

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Abstract

We present quantitative evidence that interplanetary type II radio bursts and sustained gamma-ray emission (SGRE) events from the Sun are closely related. Out of about 30 SGRE events reported in Share et al. we consider 13 events that had a duration exceeding ∼5 hr to exclude any flare-impulsive phase gamma-rays. The SGRE duration also has a linear relation with the ending frequency of the bursts. The synchronism between the ending times of SGRE and the type II emission strongly supports the idea that the same shock accelerates electrons to produce type II bursts and protons (>300 MeV) that propagate from the shock to the solar surface to produce SGRE via pion decay. The acceleration of high-energy particles is confirmed by the associated solar energetic particle (SEP) events detected at Earth and/or at the Solar Terrestrial Relations Observatory spacecraft. Furthermore, the presence of >300 MeV protons is corroborated by the fact that the underlying coronal mass ejections (CMEs) had properties identical to those associated with ground-level enhancement events: they had speeds of >2000 km s⁻¹ and all were full-halo CMEs. Many SEP events did not have detectable flux at Earth in the >300 MeV energy channels, presumably because of poor magnetic connectivity.

Key words: Sun: coronal mass ejections (CMEs) – Sun: particle emission – Sun: radio radiation – Sun: X-rays, gamma rays

Supporting material: figure set

1. Introduction

Gamma-ray emission extending for hours beyond the flare-impulsive phase (Akimov et al. 1991; Kanbach et al. 1993) is thought to be pion-decay photons from >300 MeV proton interactions. Possible sources of these protons are long-term storage of protons on coronal field lines (Kanbach et al. 1993), and sunward diffusion of protons from coronal/interplanetary shocks (Akimov et al. 1991). The association of gamma-ray line emission (GRL) with type II radio bursts and fast coronal mass ejections (CMEs) has been contemplated for quite some time (Bai & Dennis 1985; Ramaty et al. 1987; Cliver et al. 1989). GRL emission observed on the visible disk from the 1989 September 29 backside eruption warranted a shock source (Cliver et al. 1993). The Large Area Telescope (LAT; Ajello et al. 2014) on board the Fermi satellite has shown that the extended-duration gamma-ray events are very common (Ackermann et al. 2014, 2017; Share et al. 2017; Klein et al. 2018; Omodei et al. 2018). Such sustained gamma-ray emission (SGRE) lasting for several hours after the flare-impulsive phase certainly require a CME-driven shock, and this became clear when LAT observed gamma-ray emission from backside eruptions (Pesci-Rollins et al. 2015; Ackermann et al. 2017; Plotnikov et al. 2017; Jin et al. 2018).

Type II radio bursts are caused by nonthermal electrons accelerated at coronal/interplanetary (IP) shocks (Gopalswamy et al. 2001a; Vršnak et al. 2001; Reiner et al. 2007). Bursts with emission components in the metric (m) to kilometric (km) wavelengths are due to CMEs with the highest energy (Gopalswamy et al. 2005), and the CME properties are similar to those associated with large solar energetic particle (SEP) events (Gopalswamy 2006). The SEP association rate of IP type II bursts originating from the western hemisphere of the Sun is 100% when the CME speed is >1800 km s⁻¹ (Gopalswamy et al. 2008). Unlike SEP events, type II bursts are not affected by magnetic connectivity, so they can be readily observed from anywhere on the Sun and even from eruptions that are tens of degrees behind the limb. The starting frequency of type II bursts indicates the shock-formation distance from the Sun that can range from ∼1.2 solar radii (Rs) to >100 Rs (Gopalswamy et al. 2010a, 2013b, 2015, 2017; Mäkelä et al. 2015). Occasionally, the shock-formation heights can even be closer to the Sun (e.g., Pohjolainen et al. 2008). The ending frequency of type II bursts indicates the distance traveled by the shock before becoming weak and radio-quiet, and hence has implications for the duration of SGREs.

In this Letter, we consider SGREs exceeding ∼5 hr to be definitive that there are no impulsive-flare emission. We compare the SGRE duration with the duration and ending frequencies of the associated IP type II bursts to show a quantitative relationship that points to the common shock source. We also investigate the properties of the underlying CMEs that further confirm the acceleration of high-energy particles required for SGREs.

2. Data

Share et al. (2017) reported 30 SGRE events, of which 14 had durations exceeding ∼5 hr. We dropped the 2014 September 1 backside event because the duration is uncertain. We identified the associated CME, flare, and type II burst for
the remaining 13 events. The CMEs were observed by the Large Angle and Spectrometric Coronograph (LASCO; Brueckner et al. 1995) on board the Solar and Heliospheric Observatory (SOHO) and the Sun Earth Connection Coronal and Heliospheric Investigation (Howard et al. 2008) on board the Solar Terrestrial Relations Observatory (STEREO). Type II bursts were recorded by the Radio and Plasma Wave Experiment (WAVES; Bougeret et al. 1995) on board the Wind spacecraft. We refine the type II end times from the list https://cdaw.gsfc.nasa.gov/CME_list/radio WAVES type2.html. The sky-plane \((V_{sky})\) and \((V_{con2})\) deprojected speeds CMEs are from the CDAW catalog: (https://cdaw.gsfc.nasa.gov/CME_list). The peak value of the three-dimensional (3D) speeds \((V_{ph})\) are obtained using the graduated cylindrical shell fit (Thernisien 2011) as reported in previous publications (Gopalswamy et al. 2014, 2016, 2018a, 2018b).

Figure 1 shows the 2017 September 6 fast \((\sim 1570 \text{ km s}^{-1})\) halo CME from S08W33 associated with an X9.3 flare, a shock and a type II radio burst. The type II burst ended around 08:00 UT with a possible extension until \(\sim 10\) UT, giving a mean duration \((t_2)\) of 20.92 \(\pm\) 1.0 hr. The SGRE start time is taken as the soft X-ray peak time \((12:02\) UT\) to avoid the impulsive phase; the end time is defined as the mid-time \((06:28\) UT\) between the last data point above the gamma-ray background \((05:39\) UT\) and the next data point \((07:16\) UT\). Thus, the SGRE duration \((t_{SGRE})\) is \((18.43 \pm 0.8)\) hr. We used the gamma-ray background level available online (https://hesperia.gsfc.nasa.gov/fermi_solar/). The uncertainties are half the orbit period in most cases, but longer if the Sun was not visible to Fermi during an orbit. Figure 1 demonstrates that SGRE ends when the type II burst ends.

We extend the SGRE connection to type II burst, CME, SEP event, and flare demonstrated in Figure 1 to all 13 SGRE events. Table 1 lists details on SGRE (columns 1–3), CME (columns 4–7), soft X-ray flare (columns 8–11), SEP event (columns 12–13), and type II burst (columns 14–21). A suffix “H” to \(V_{sky}\) indicates that the CME is a halo CME. The \(>10\) MeV proton intensity (column 10) in large SEP events is from https://cdaw.gsfc.nasa.gov/CME_list/sepe/; in minor events (intensity \(<10\) pfu), we determined the peak flux from GOES data. The numbers in parentheses denote the \(>10\) MeV flux from STEREO—Behind (STB). Column 11 notes whether or not a detectable signal in a \(>300\) MeV GOES energy channel exists \((N = No, Y = Yes)\). The onset times of metric type II bursts (column 12) are either from the online Solar Geophysical Data or from our own examination of the dynamic spectra from radio observatories. The onset times of decameter-hectometric (DH) type II bursts (column 13) are from the CDAW Data Center (https://cdaw.gsfc.nasa.gov/CME_list radio WAVES type2.html). The end times (column 14) are obtained by examining the Wind/WAVES type II bursts as the time when the bursts either ended or weakened significantly. Column 15 (end2) denotes the upper limit of the ending time. The upper \((f_2)\) and lower \((f_1)\) edges of the type II band at \(f_1\) and the ending frequency \([f_2 = (f_1 + f_2) / 2]\) are listed in columns 16, 17, and 18, respectively. The SGRE durations (column 3), DH type II burst durations (column 18), and \(f_2\) (column 21) are the main parameters used in this study. In two events, the ending times/frequencies are not reliable because of an intense low-frequency background in one case (2012 March 9) and a faint, fragmented emission in the other (2013 May 14). These events occurred in clusters with preceding CMEs and elevated SEP background. We consider only type II bursts in the IP medium (DH wavelengths and beyond) because metric type II bursts indicate shock formation, but it takes \(\sim 10\) minutes to accelerate high-energy particles after the shock has formed (Reames 2009; Gopalswamy et al. 2012).
| SGRE (Columns 1–3) | CME (Columns 4–7) | Flare (Columns 8–11) | Large SEP (Columns 12–13) | Type II Radio Burst (Columns 14–21) |
|-------------------|-------------------|---------------------|---------------------------|----------------------------------|
| Start UT | End UT | Dur. hr | UT | V_{sw} km s^{-1} | V_{cme} km s^{-1} | V_{pk} km s^{-1} | Location | Class | Start UT | Peak UT | >10 MeV^a | >300 MeV^a | Metric | DH Start UT | DH End UT | DH EndZ UT | Dur. hr | f_s | f_l | f_c |
| 2013 May 13 17:00 | 00:46 | 8.68 ± 0.95 | 16:07 | 1850H | 1852 | 2889 | N11E85 | X2.8 | 15:48 | 16:05 | 1 (400 HB) | N | 15.57 | 17:55 | 05/13 | 16:15 | 00:40 | 05/13 | 14:01 | 0.15 |
| 2013 May 14 01:20 | 07:10 | 5.98 ± 0.82 | 01:25 | 2625H | 2645 | 2963 | N08E77 | X3.2 | 00:00 | 01:11 | 1 (608 HB) | N | 01.07 | 05/05 | 14/01 | 01:16 | 14/08 | 06:40 | 05/05 | 14/08 | 06:31 |
| 2013 May 15 02:00 | 05:24 | 3.60 ± 0.82 | 01:48 | 1366H | 1408 | 2294 | N12E64 | X1.2 | 01:25 | 01:48 | 42 | N | 01.37 | 05/05 | 14/01 | 01:16 | 14/08 | 06:40 | 05/05 | 14/08 | 06:31 |
| 2014 Feb 6 00:50 | 09:17 | 8.46 ± 1.59 | 01:25 | 2147H | 2153 | 2777 | S12E82 | X4.9 | 00:39 | 00:49 | 24 (400) | Y | 00.56 | 02/25 | 00:56 | 02/25 | 12:00 | 02/25 | 12:00 | 02/25 | 12:00 |
| 2015 Jun 21 02:20 | 16:40 | 14.06 ± 1.61 | 02:36 | 1366H | 1740 | 2119 | N12E16 | M2.6 | 02:06 | 02:36 | 1066 | N | 02.24 | 06/21 | 22:00 | 06/21 | 07:00 | 06/21 | 07:00 | 06/21 | 07:00 |
| 2017 Sep 6 12:35 | 06:28 | 18.43 ± 0.80 | 12:24 | 1571H | 1884 | 2000 | S08W33 | X9.3 | 11:53 | 12:02 | 844 HiB | Y | 12.02 | 09/12 | 22:00 | 09/12 | 07:00 | 09/12 | 07:00 | 09/12 | 07:00 |
| 2017 Sep 10 15:56 | 07:17 | 15.18 ± 0.81 | 16:00 | 3163H | 3165 | 4191 | S09W92 | X8.3 | 15:35 | 16:06 | 1490 | Y | 15.53 | 09/10 | 11:00 | 09/10 | 06:50 | 09/10 | 06:50 | 09/10 | 06:50 |

Notes:

^a^ Times given by Share et al. (2017), not used in computing the SGRE duration; the 2013 May 15 event had a duration $\geq$5 hr in Share et al. (2017), but the duration turned out to be 3.6 hr based on our criterion.

^b^ Time corresponds to the next day.

^c^ Interacting event.

^d^ The eruption was followed by an X1.3 flare and a fast CME (1825 km s^{-1}), but slower than the preceding one.

^e^ Peak time of the soft X-ray flare taken as the start time of SGRE for computing the SGRE duration.

^f^ The numbers in parentheses are $>10$ MeV flux from STB data by extrapolating the spectrum to 150 MeV; HiB = high background, so the estimated intensity is approximate.

^g^ N = No; Y = Yes; the question mark indicates that the signal is extremely weak.

^h^ Shock arrival time at Earth.

^i^ Type II duration is uncertain because of intense background below 500 kHz.

^j^ Type II burst is fragmented and weak.

^k^ Fragmented emission observed until the Wind shock arrival at 22/18:01 UT.

^l^ WAVES data gap on 9/10, but STEREO WAVES data show type II emission in the gap.
SGRE events are all very fast with an average sky-plane speed of 1912 ± 646 km s\(^{-1}\), slightly above the average speed (~1500 km s\(^{-1}\)) of SEP-associated CMEs (see e.g., Gopalswamy et al. 2004). The deprojected speeds average to 2094 ± 621 km s\(^{-1}\), while the peak speeds average to 2504 ± 682 km s\(^{-1}\). In addition, all 13 CMEs (100%) were halo CMEs (those that appear to surround the occulting disk of the coronagraph in sky-plane projection; Howard et al. 1982). For a given coronagraph, halo CMEs are indicative of an energetic population (Gopalswamy et al. 2010b). The speeds and halo fractions of SGRE CMEs are properties shared by ground-level enhancement fractions of SGRE CMEs are properties shared by ground-level population a given coronagraph, halo CMEs are indicative of an energetic (Gamma Ray Experiment Telescope Regression method, which considers errors in both X and Y variables. The shaded area represents 95% confidence interval of the fit. The 1991 June 11 Energetic Gamma Ray Experiment Telescope (EGRET) event (not included in the fit) is denoted by the blue symbols, which are consistent with the linear relationship.

3. Analysis and Results

3.1. Properties of the Associated CMEs

Table 1 shows that the CMEs associated with the 13 SGRE events are all very fast with an average sky-plane speed of 1912 ± 646 km s\(^{-1}\), slightly above the average speed (~1500 km s\(^{-1}\)) of SEP-associated CMEs (see e.g., Gopalswamy et al. 2004). The deprojected speeds average to 2094 ± 621 km s\(^{-1}\), while the peak speeds average to 2504 ± 682 km s\(^{-1}\). In addition, all 13 CMEs (100%) were halo CMEs (those that appear to surround the occulting disk of the coronagraph in sky-plane projection; Howard et al. 1982). For a given coronagraph, halo CMEs are indicative of an energetic population (Gopalswamy et al. 2010b). The speeds and halo fractions of SGRE CMEs are properties shared by ground-level enhancement (GLE) events, in which particles are accelerated to GeV energies. The average speed of GLE CMEs is >2000 km s\(^{-1}\) and all but two of the 18 GLEs (88%) in solar cycles 23 and 24 are halos (Gopalswamy et al. 2016). Another property shared by SGRE and GLE events is that the associated DH type II bursts extend to kilometric wavelengths (see Table 1). The extreme CME properties in SGRE events are thus indicative of copious levels of >300 MeV protons needed for SGRE. Not all SGRE events have GLEs because the latter need to have magnetic connectivity to Earth to be detected.

3.2. Association with Type II Radio Bursts

The type II burst durations (\(t_{II}\)) range from 3.80 to 27.93 hr (average: 13.34 ± 7.99 hr), very similar to the SGRE durations (average: 12.07 ± 5.80 hr). The ending frequencies (\(f_{II}\)) range from 63 to 380 kHz (average: 200.7 ± 92.5 kHz). For comparison, the typical local plasma frequency at the Wind spacecraft (Sun–Earth L1 point) is ~30 kHz. The average ending frequency corresponds to a plasma density of ~500 cm\(^{-3}\). Such a density prevails at a heliocentric distance of tens of Rs. For example, ending frequency (~190 kHz) in the 2015 June 21 event corresponds to a heliocentric distance of ~90 Rs (Gopalswamy et al. 2018a).

The scatter plots of SGRE duration with \(f_{II}\) and \(t_{II}\) in Figure 2 show linear relationships (\(f_{II}\) and \(t_{II}\) are related, so the correlations are complementary). The \(f_{II} - t_{SGRE}\) best-fit line has a negative slope because the plasma density and hence the emission frequency is lower at larger heliocentric distances. The regression lines were obtained using the Orthogonal Distance Regression method (see, e.g., Oliveira & Aguiar 2013) suitable when both X and Y variables have errors. Figure 2 shows that all of the data points are within the 95% confidence interval of the best-fit line, except for one data point (2012 March 9); as noted before, this event had intense low-frequency background so the type II duration and ending frequencies were not determined accurately. Thus, in longer-duration SGRE events, the shock remains stronger over a larger distance from the Sun. Figure 2 supports the idea that DH type II duration (and hence the duration over which the shock efficiently accelerates particles) is a good indicator of SGRE. Physically speaking, the same shock accelerates protons responsible for SGRE and electrons responsible for the type II bursts. A reverse study is underway to check the gamma-ray association of all DH type II bursts observed after the launch of Fermi.

3.3. SEP Association

All SGRE events were associated with SEP events, but three of the eastern events were minor (>10 MeV intensity at Earth <10 pfu, see Table 1) presumably because of poor connectivity. These and other eastern-hemisphere events were intense >10 MeV SEP events at STB. Share et al. (2017) were able to compare the durations of >100 MeV protons with the SGRE durations in only 10 events. Of these, only two events had SGRE durations >3.5 hr, so we cannot do any statistics. However, we can show that it is highly likely that the required high-energy protons were present in our events. Intense eastern-hemispheric SEP events generally have a soft spectrum because only the shock flanks are connected to Earth (e.g., Gopalswamy et al. 2016). This is the reason that GLE CMEs generally originate from the western hemisphere of the Sun, where the longitudinal connectivity is better. Western CMEs with very high initial speeds produce hard SEP events (Gopalswamy et al. 2016), so it is highly likely that >300 MeV protons were present in these events. The 2014 February 25 CME had speeds exceeding 2000 km s\(^{-1}\) (see Table 1). The
initial speed from STB images obtained by the Extreme Ultraviolet Imager (EUVI) and the inner coronagraph COR1 was $\sim$2300 km s$^{-1}$. We do not expect a GLE, however, because of the poor connectivity (source at S12E82). The $>$10 MeV intensity was only $\sim$24 pfu at Earth, but $\sim$400 pfu at the well-connected STB. To compute the $>$100 MeV proton intensity, we extrapolated the SEP spectra obtained from STB particle data, assuming that no particles were present beyond 1 GeV. The resulting $>$100 MeV intensity is compared with that from GOES in Figure 3: the GOES intensity increased gradually to reach a peak level of $\sim$1 pfu, whereas the STB intensity rose promptly and reached $>$10 pfu. The $>$100 MeV intensity remained high when the type II emission and SGRE were above the background, as illustrated in Figure 3.

Winter et al. (2018) highlighted the 2011 March 7 SGRE event as a counter example to the shock-source idea because there were no $>$300 MeV protons above the background. We think the lack of $>$300 MeV signal at Earth is probably due to poor latitudinal connectivity. For an SEP event to be a GLE, the ecliptic distance of the shock nose should be $\sim$13° (Gopalswamy et al. 2013a, 2014, 2018b; Gopalswamy & Mäkelä 2014). This happens when the highest-energy particles are accelerated at the shock nose. In the 2011 March 7 event, the CME nose was at position angle (PA) $= 313°$, which is $\sim$43° away from the equator, consistent with a northern (N31W53) source and an unfavorable solar B0 angle ($-7°.25$). The nose area, where $>$300 MeV particles are accelerated, is expected to be larger than that for GeV particles, but should not reach as far as 43°. Thus, despite the good longitudinal connectivity (W53), the poor latitudinal connectivity seems to be a plausible explanation for not observing $>$300 MeV particles at Earth, but they can flow from the shock nose toward the solar surface to produce the observed SGRE. In the 2012 January 23 event, $>$300 MeV particles were barely detected at Earth. The CME nose was at PA = 326° consistent with the source location,

Figure 3. (a) Type II burst and SGRE during the 2014 February 25 CME showing synchronous ending. (b) $>$100 MeV proton intensity from GOES (black) and STB (blue) compared with the 1–8 Å GOES soft X-ray (arbitrary units) and SGRE (red) light curves. The SGRE duration is marked by the double arrow. STB was located at E160 and hence well connected to the solar source at S12E82.

Figure 4. Ulysses/URAP type II burst during the 1991 June 11 SGRE. The two black lines roughly mark the edges of the type II burst. The intense type III burst is typical of energetic CMEs. There are also short-duration type III bursts superposed on the type II emission. The long vertical feature after 8:00 UT marks a data gap. Data from ftp://ftp.cosmos.esa.int/ULYSSES/URAP/data/.
N28W21. The 110–900 MeV GOES channel did have a weak signal indicating a wider nose. The CME interacted with a preceding CME that is similar to seven other events (see Table 1). It is possible that the preceding CME causes a localized constriction of the magnetic field lines leading to mirroring of particles toward the Sun—a scenario often invoked in GLE events (Bieber et al. 2002). Most of the events occurred when there was elevated background from preceding eruptions suggesting the availability of seed particles. These aspects need further investigation.

3.4. The Pre-Fermi SGRE

The 1991 June 11 SGRE was detected by the Energetic Gamma Ray Experiment Telescope (EGRET) on board the Compton Gamma Ray Observatory (Kanbach et al. 1993; Ryan 2000). The eruption was associated with intense H-alpha and GOES (X12) flares and a metric type II burst at 02:05 UT. From the X12 flare peak (02:09 UT) to the last interval of significant gamma-ray flux (11:02–14:02 UT, see Kanbach et al. 1993, their Table 1) we estimate the duration as 10.38 ± 1.5 hr. The duration is slightly larger than that (8.33 hr) in Chupp & Ryan (2009) because of the criterion that we used. Pioneer Venus Orbiter (PVO) detected a 780-km s⁻¹ shock about 27 hr after the eruption (Mihalov & Strangeway 1995). Because PVO was at E45, the shock should have been faster at Earth, ~1100 km s⁻¹. A shock with such high speed at Earth might have had a CME initial speed of ~1700 km s⁻¹, assuming typical interplanetary acceleration (Gopalswamy et al. 2001b).
A DH type II burst was detected by the Unified Radio and Plasma waves experiment (URAP; MacDowall et al. 1996) on board the Ulysses mission (Figure 4). The burst drifts from ∼900 kHz at ∼5 UT to ∼300 KHz at 8:00 UT, possibly extending to ∼9:20 UT. The burst is faint, fragmented, and barely discernible because Ulysses was ∼3.3 au from the Sun. The complex type III burst that typically occurs at the IP type II onset, started at 02:20 UT (Earth onset at 02:01 UT because the signal has to travel an additional 2.3 au to arrive at Ulysses). Thus we obtain the type II duration was ∼8.67 ± 0.67 hr, which is similar to the SGRE duration. The Ulysses type II burst and the EGRET SGRE are consistent with the linear relationships in Figure 2 (also evident from the Wind/WAVES dynamic spectra in Figure 5 with overlaid SGRE light curves). The 1991 June 11 GLE (Smart et al. 1994) confirms the presence of the required >300 MeV particles. Solar Geophysical Data reported significant fluxes in the highest GOES energy channel, 640–850 MeV (Coffey 1991). Thus, the EGRET event is consistent with the Fermi/LAT SGRE events in their relationship with IP type II burst durations.

4. Discussion and Summary

Although the association between SGREs and IP type II bursts have been noted before (Share et al. 2017; Klein et al. 2018), we have established a quantitative relation between them: the SGRE ends roughly when the type II ends. The linear relation between SGRE and IP type II durations at 95% confidence level supports the idea that the protons responsible for SGRE and electrons that produce the type II bursts are accelerated by the same shock. The accelerated protons propagate toward the Sun and precipitate to the chromosphere, where the pions are produced. A preliminary look at the shorter-duration SGRE events confirm the results of this Letter. A detailed analysis of those events will be reported elsewhere. The present observations should provide strong constraints on the propagation of high-energy protons from the outer corona and interplanetary medium toward the Sun. One also needs to investigate issues such as magnetic mirroring and the presence of enhanced seed particles in interacting events. In intense events (2012 January 23 and March 7), there was type II emission after a clear break at the SGRE end. These may indicate the difference in accelerating ∼10 keV electrons (for type II) and >300 MeV protons (for SGRE). Investigation of these events will further clarify the sites of particle acceleration on the shock surface.

The main results of this Letter can be summarized as follows.

1. All SGRE events were associated with interplanetary type II bursts in the decameter to kilometer wavelength domains, indicating strong shocks propagating far into the heliosphere.
2. The CMEs associated with SGRE are among the most energetic, a property shared by GLE events: the average CME speed exceeded 2000 km s⁻¹, all (100%) were halos, and all were associated with type II bursts extending to km wavelengths. The similarity to GLE events is important because, if GeV particles are accelerated, the presence of >300 MeV particles is assured.
3. The durations of IP type II radio bursts and SGRE have a linear relationship, suggesting that the same shock is responsible for accelerating both electrons and protons, the underlying energetic particles in the two electromagnetic emissions.
4. The ending frequency of IP type II bursts has an inverse linear relation with SGRE duration confirming that in longer-duration gamma-ray events the IP shocks remaining strong over larger distances from the Sun (where the local plasma frequency is lower).
5. SEP events were associated with each of the SGRE events, but >300 MeV particles were not detected in most of the events presumably because of poor magnetic connectivity to Earth in longitude and latitude.
6. All SGRE events originating from the eastern hemisphere of the Sun were associated with large SEP events observed by the STEREO spacecraft.
7. The only >5 hr SGRE event from EGRET (1991 June 11) was also associated with a long-lasting Ulysses/URAP type II burst consistent with Fermi/LAT SGRE events.

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