Solar Longitude Distribution of High-energy Proton Flares: Fluences and Spectra

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Abstract

The distribution of the longitudes of solar flares associated with the high-energy proton events called ground level events (GLEs) can be approximated by a Gaussian with a peak at ~W60, with a full range from ~E90 to ~W150. The longitudes of flares associated with the top third (24 of 72) of GLEs in terms of their >430 MeV fluences \((F_{430})\) are primarily distributed over E20–W100 with a skew toward disk center. This 120° span in longitude is comparable to the latitudinal spans of powerful coronal mass ejections (CMEs) from limb flares. Only 5 of 24 strong GLEs are located within the W40–80 zone of good magnetic connection to Earth. GLEs with hard spectra, i.e., a spectral index \(S_{30/200} = \log(F_{30}/F_{200}) < 1.5\), also tend to avoid W40–80 source regions. Three-fourths of such events (16 of 21) arise in flares outside this range. The above tendencies favor a CME-driven shock source over a flare-resident acceleration process for high-energy solar protons. GLE spectra show a trend, with broad scatter, from hard spectra for events originating in eruptive flares beyond the west limb to soft spectra for GLEs with sources near central meridian. This behavior can be explained in terms of: (1) dominant near-Sun quasi-perpendicular shock acceleration of protons for far western (>W100) GLEs; (2) quasi-parallel shock acceleration for well-connected (W40–80) GLEs, and (3) proton acceleration/trapping at CME-driven bow shocks from central meridian (E20–W20) that strike the Earth.

Unified Astronomy Thesaurus concepts: Solar energetic particles (1491); Solar flares (1496); Solar coronal mass ejections (310); Solar coronal mass ejection shocks (1997)

1. Introduction

The high-energy proton events monitored by the worldwide network of ground-based neutron monitors (NMs; Simpson et al. 1953; Bieber & Evienson 1995; Mavromichalaki et al. 2011) are termed ground level events (GLEs). The effective energy threshold for GLEs is 1 GV in rigidity (430 MeV in energy; Mishev et al. 2013). GLEs were first detected in 1942 by ionization chambers (Lange & Forbush 1942; Forbush 1946). To date, 72 GLEs have been observed.4

Until recently, the principal measure of GLE strength was the largest percentage increase above background observed at any sea-level station (e.g., McCracken et al. 2012; Poluianov et al. 2017). This intensity measure is not ideal because it depends on event timing relative to the location of a changing network of monitors. Because of the lack of a well-defined parameter for GLE strength, distributions of the solar longitudes of GLE-associated flares typically include all GLEs, regardless of size, resulting in a broad Gaussian centered at ~W60 (e.g., Figure 1 in Smart & Shea 1996), near the nominal ~W55 footprint (based on the Sun’s rotation rate and the average speed of the solar wind) of the magnetic field-line connecting to Earth. Data now exist to examine the solar longitude distribution of GLEs in greater detail. Tykka & Dietrich (2009) undertook a systematic evaluation of NM and space-based data to construct spectra for all GLEs that were sufficiently large. This work was recently updated and more thoroughly documented by Raukunen et al. (2018) to provide a homogeneous database of GLEs, permitting the determination of proton fluences at all energies.

In this study we use this database to examine where the strongest (and weakest) GLEs in terms of >430 MeV fluence \((F_{430})\) originate on the Sun. We also examine the variation of GLE spectra, as characterized by \(\log(F_{30}/F_{200})\), with source longitude. Our analysis is presented in Section 2 and results are discussed in Section 3.

2. Analysis

2.1. Data

Table 1 gives the dates, solar flare coordinates, proton fluences \((F_{30}, F_{200}, \text{and } F_{430})\), and the spectral index \(S_{30/200} (= \log(F_{30}/F_{200}))\) determined from the spectral parameters given in Raukunen et al. (2018) for 59 of the 72 GLEs. The Raukunen et al. analysis did not consider the first four GLEs (all observed before the neutron monitor era), the most recent GLE on 2017 September 10, and eight other GLEs for which the proton fluences were considered too small to make reliable spectral fits. In our fluence analysis, we divided GLEs into the top third (24 GLEs), middle third, and bottom third in terms of their >430 MeV fluence. We assigned GLE Nos. 1–4 to the top third. Because of their less sensitive mode of observation, the first four GLEs are considered to be among the largest observed (Duggal 1979; Smart & Shea 1991; Shea & Smart 2019). We took the eight events not analyzed by Raukunen et al. (2018) to be among the smallest third. Quoting from their paper, “...eight GLEs had too small fluences for the [spectral fits] to be reliable.” Based on comparison with other GLEs on the Oulu website, we assigned GLE No. 72 (Mishev et al. 2018) to the middle third of events. For six of the GLEs (No. 42: 1989...
| No. | Year | Month | Day | $F_{50}$ (cm$^{-2}$) | $F_{200}$ (cm$^{-2}$) | $F_{430}$ (cm$^{-2}$) | $S_{50/200}$ | Location |
|-----|------|-------|-----|---------------------|----------------------|---------------------|-------------|----------|
| 1   | 1942 | Feb   | 28  | N/A                 | 1.42E+09             | 2.12E+08            | 3.03E+07    | 1.07      | N07E04   |
| 2   | 1942 | Mar   | 07  | N/A                 | 4.84E+06             | 5.31E+05            | 1.50E+05    | 0.96      | N07W90   |
| 3   | 1946 | Jul   | 25  | N/A                 | 3.59E+07             | 1.48E+06            | 1.38E+05    | 1.39      | N1W884   |
| 4   | 1949 | Nov   | 19  | N/A                 | 3.17E+09             | 6.40E+07            | 6.99E+06    | 1.70      | N27W40   |
| 5   | 1956 | Sep   | 03  | N/A                 | 1.72E+07             | 3.03E+07            | 3.47E+06    | 1.75      | N25W35   |
| 6   | 1969 | Apr   | 29  | N/A                 | 7.24E+07             | 2.34E+05            | 5.99E+04    | 1.59      | S08W46   |
| 7   | 1969 | Oct   | 25  | N/A                 | 8.32E+07             | 4.36E+06            | 7.14E+05    | 1.29      | N22W154  |
| 8   | 1970 | Sep   | 19  | N/A                 | 1.53E+08             | 1.73E+06            | 1.18E+05    | 1.94      | N21W87   |
| 9   | 1971 | Apr   | 29  | N/A                 | 7.71E+06             | 2.32E+05            | 3.36E+04    | 1.52      | N13W33   |
| 10  | 1971 | Sep   | 19  | N/A                 | 4.76E+07             | 6.75E+05            | 6.01E+04    | 1.85      | N08W57   |
| 11  | 1972 | Oct   | 25  | N/A                 | 2.53E+07             | 1.38E+06            | 2.30E+05    | 1.26      | N10W120  |
| 12  | 1972 | Nov   | 22  | N/A                 | 6.41E+07             | 2.01E+06            | 2.91E+05    | 1.50      | N24W40   |
| 13  | 1973 | May   | 07  | N/A                 | 1.57E+07             | 4.61E+05            | 8.56E+04    | 1.53      | N23W72   |
| 14  | 1973 | Sep   | 23  | N/A                 | 4.78E+08             | 2.56E+06            | 2.23E+05    | 2.27      | N35W50   |
| 15  | 1979 | Aug   | 21  | N/A                 | 3.95E+08             | 2.88E+07            | 2.79E+06    | 1.31      | N17W40   |
| 16  | 1981 | Apr   | 10  | N/A                 | 9.96E+09             | 2.63E+07            | 3.82E+06    | 1.87      | N07W36   |
| 17  | 1981 | May   | 10  | N/A                 | 2.93E+07             | 2.74E+05            | 2.86E+04    | 2.03      | N03W75   |
| 18  | 1982 | Nov   | 26  | N/A                 | 2.05E+08             | 1.38E+06            | 1.49E+05    | 2.17      | S18E31   |
| 19  | 1982 | Dec   | 07  | N/A                 | 6.97E+07             | 1.28E+06            | 1.93E+05    | 1.74      | S19W86   |
| 20  | 1984 | Feb   | 16  | N/A                 | 1.73E+07             | 6.88E+05            | 7.76E+04    | 1.40      | ~W130   |
| 21  | 1989 | Jul   | 25  | N/A                 | 7.50E+06             | 4.74E+05            | 5.43E+04    | 1.20      | N26W85   |
| 22  | 1989 | Aug   | 16  | N/A                 | 3.07E+08             | 5.16E+06            | 4.15E+05    | 1.17      | S15W85   |
| 23  | 1989 | Sep   | 29  | N/A                 | 3.21E+07             | 3.73E+05            | 1.38E+05    | 0.93      | ~W100   |
| 24  | 1989 | Sep   | 29  | N/A                 | 1.38E+09             | 3.07E+07            | 4.18E+06    | 1.65      | N25E37   |
| 25  | 1989 | Sep   | 29  | N/A                 | 1.38E+09             | 3.10E+07            | 4.32E+06    | 1.65      | N20E37   |
| 26  | 1989 | Sep   | 29  | N/A                 | 3.10E+07             | 2.34E+06            | 2.89E+05    | 1.31      | N36W76   |
| 27  | 1990 | May   | 21  | N/A                 | 2.03E+07             | 1.60E+06            | 2.03E+05    | 1.10      | ~W100   |
| 28  | 1990 | May   | 28  | N/A                 | 2.62E+07             | 1.02E+06            | 1.16E+05    | 1.41      | ~W120   |
| 29  | 1991 | Jun   | 11  | N/A                 | 3.43E+07             | 3.94E+06            | 4.21E+05    | 1.94      | N23W15   |
| 30  | 1991 | Jun   | 15  | N/A                 | 2.07E+08             | 4.28E+06            | 3.81E+05    | 1.68      | N36W70   |
| 31  | 1992 | Jun   | 25  | N/A                 | 3.77E+07             | 5.38E+05            | 5.07E+04    | 1.85      | N10W68   |
| 32  | 1992 | Nov   | 02  | N/A                 | 3.07E+08             | 2.77E+06            | 1.37E+05    | 2.05      | ~W100   |
| 33  | 1992 | Nov   | 06  | N/A                 | 1.55E+08             | 3.63E+06            | 3.49E+05    | 1.68      | S18W63   |
| 34  | 1998 | May   | 02  | N/A                 | 1.73E+07             | 5.95E+05            | 5.60E+04    | 1.46      | S15W15   |
| 35  | 1998 | May   | 06  | N/A                 | 7.82E+06             | 1.57E+05            | 1.19E+04    | 1.70      | S15W64   |
| 36  | 1998 | Aug   | 24  | N/A                 | 1.05E+07             | 3.00E+05            | 4.88E+04    | 1.54      | N35E09   |
| 37  | 1998 | Aug   | 24  | N/A                 | 2.47E+07             | 8.64E+04            | 6.04E+03    | 2.46      | N23W80   |

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Table 1: Parameters of GLEs, 1942–2017
September 29; No. 43: 1989 October 19; No. 58: 1998 August 24; No. 59: 2000 July 14; No. 62: 2001 November 4; No. 65: 2003 October 28, Raukunen et al. obtained spectra for both the initial prompt (P) component of a GLE and a delayed energetic storm particle (ESP; Rao et al. 1967; Lario & Decker 2002) component. In these cases we give the P and ESP components in Table 1, as well as the combined (P + ESP) fluences that we used to obtain the log \( F_{300} / F_{200} \) spectral index. The largest bottom third (middle third) \( F_{430} \) event was 2001 December 26 with \( 8.63 \times 10^4 \text{ cm}^{-2} \) (1991 June 15 with \( 3.81 \times 10^5 \text{ cm}^{-2} \),

Table 1

| No. | Year | Month | Day | \( F_{300} \) (\text{cm}^{-2}) | \( F_{200} \) (\text{cm}^{-2}) | \( F_{430} \) (\text{cm}^{-2}) | \( S_{300/200} \) | Location |
|-----|------|-------|-----|-----------------|-----------------|-----------------|-----------------|---------|
| 58  | 1998 | Aug   | 24  | 3.52E+07        | 3.86E+05        | 5.48E+04        | 1.96            | N22W07  |
| 59  | 2000 | Jul   | 14  | 8.72E+08        | 1.95E+07        | 9.76E+05        | 1.65            | S20W84  |
| 59  | 2000 | Jul   | 14  | 2.15E+09        | 1.44E+07        | 7.42E+05        | 2.17            | N07W19  |
| 60  | 2001 | Apr   | 15  | 3.02E+09        | 3.39E+07        | 1.72E+06        | 1.95            | N08W54  |
| 61  | 2001 | Apr   | 18  | 4.31E+07        | 1.25E+06        | 1.45E+05        | 1.54            | N08W54  |
| 62  | 2001 | Nov   | 04  | 2.33E+08        | 2.43E+06        | 1.33E+05        | 1.98            | S16W07  |
| 62  | 2001 | Nov   | 04  | 2.19E+09        | 9.11E+06        | 2.14E+05        | 2.38            | S16W07  |
| 63  | 2001 | Dec   | 26  | 7.65E+07        | 1.34E+06        | 8.63E+04        | 1.76            | S02W81  |
| 64  | 2002 | Aug   | 24  | 5.11E+07        | 8.13E+05        | 6.11E+04        | 1.80            | S16W07  |
| 65  | 2003 | Oct   | 28  | 5.79E+08        | 6.24E+06        | 3.72E+05        | 1.97            | S16W07  |
| 65  | 2003 | Oct   | 28  | 1.54E+09        | 8.87E+05        | 3.34E+05        | 2.24            | S16W07  |
| 65  | 2003 | Oct   | 28  | 2.12E+09        | 1.51E+07        | 7.06E+05        | 2.15            | S15W02  |
| 66  | 2003 | Dec   | 29  | 4.41E+08        | 8.17E+05        | 6.10E+05        | 1.73            | S14W56  |
| 68  | 2005 | Jan   | 17  | 1.61E+08        | 1.42E+06        | 1.03E+05        | 2.06            | S14W56  |
| 69  | 2005 | Jan   | 20  | 3.35E+08        | 2.10E+06        | 7.74E+04        | 2.23            | N13W23  |
| 70  | 2006 | Oct   | 28  | 1.55E+08        | 5.35E+06        | 5.16E+05        | 1.45            | S08W23  |
| 71  | 2012 | May   | 17  | 2.42E+07        | 9.86E+05        | 1.10E+05        | 1.39            | N11W76  |
| 72  | 2017 | Sep   | 10  | N/A             |                 |                 |                 | S09W92  |

Note.

* Data sources: Cliver et al. (1982), Cliver (2006), Gopalswamy et al. (2012, 2013, 2018).

Figure 1. Histograms of the solar longitudes of (a) the strongest third of GLEs in terms of \( F_{430} \) from 1942 to 2012 and (b) the weakest third of GLEs during this interval. The chronological number of individual GLEs in each bin is indicated, with those for which a delayed ESP component was observed given in red.

2.2. Analysis

Figures 1(a), (b) contain histograms of \( F_{430} \) for the GLEs with the 24 highest and 24 lowest rank order fluences, respectively. The highest-fluence events show a broad distribution from E20 to W100 that is skewed toward disk center, similar to the distribution Smart et al. (2006) obtained for >30 MeV protons. The GLE numbers are given in the histograms, with the two-component (P + ESP) events in red. It is likely that GLE Nos. 1 and 3 were also in this category.
Removal of the ESP component for the six events for which we have data would change the classification for GLE No. 42, dropping it out of the top third. This event was unusual in that while the other five events were all located within 20° of disk center, the 1989 September GLE is associated with an eruptive flare located at W100.

The histogram in Figure 1(b) shows a broad distribution centered at ~W60 for the solar locations of the third of GLEs from 1942 to 2017 with the lowest $F_{430}$ values. Figure 2 shows that the broad peak in the distribution for all GLEs in the overarching histogram is primarily due to the concentration of small GLEs in the W20–100 range.

Figure 3 is a plot of the proton spectral index log ($F_{30}/F_{200}$) versus solar longitude (Kovaltsov et al. 2014; Asvestari et al. 2017) for the 59 GLEs from 1956 to 2012 analyzed by Raukunen et al. (2018). These GLEs span a total longitude range of ~240°, from E88 to W154. The events are color-coded by their $F_{430}$ fluence ranking as follows: top third (magenta), middle third (black), and bottom third (green). The dashed horizontal line bounds hard spectrum events with log ($F_{30}/F_{200}$) values <1.5, and the two dashed vertical gray lines mark the zone of favorable magnetic connection from W40 to 80. The solid line is an ordinary least-squares fit (solid line) is shown. The two GLEs at W120 with $S_{30/200}$ ~ 1.25 are slightly offset in longitude for visibility in the plot.

Figure 4 shows a broad distribution centered at ~W60 for the solar locations of the third of GLEs from 1942 to 2017 with the lowest $F_{430}$ values. Figure 2 shows that the broad peak in the distribution for all GLEs in the overarching histogram is primarily due to the concentration of small GLEs in the W20–100 range.

Figure 3 is a plot of the proton spectral index log ($F_{30}/F_{200}$) versus longitude for 59 GLEs from 1956 to 2012 analyzed by Raukunen et al. (2018). The events are color-coded according to the rank order of their >430 MeV fluence: top third (magenta), middle third (black), and bottom third (green). The gray horizontal dashed line is drawn at a spectral index of 1.5, and the vertical dashed lines mark the ~W40–80 region of good magnetic connection to Earth. An ordinary least-squares fit (solid line) is shown. The two GLEs at W120 with $S_{30/200}$ ~ 1.25 are slightly offset in longitude for visibility in the plot.

Figure 3. Plot of the proton spectral index log ($F_{30}/F_{200}$) vs. longitude for 59 GLEs from 1956 to 2012 analyzed by Raukunen et al. (2018). The events are color-coded according to the rank order of their >430 MeV fluence: top third (magenta), middle third (black), and bottom third (green). The gray horizontal dashed line is drawn at a spectral index of 1.5, and the vertical dashed lines mark the ~W40–80 region of good magnetic connection to Earth. An ordinary least-squares fit (solid line) is shown. The two GLEs at W120 with $S_{30/200}$ ~ 1.25 are slightly offset in longitude for visibility in the plot.

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Figure 2. Histogram of the source longitudes of all GLEs. Black shading indicates the top two-thirds of GLEs in terms of $F_{430}$, with the gray shading denoting the bottom third of GLEs in this parameter.

Figure 3. Plot of the proton spectral index log ($F_{30}/F_{200}$) vs. longitude for 59 GLEs from 1956 to 2012 analyzed by Raukunen et al. (2018). The events are color-coded according to the rank order of their >430 MeV fluence: top third (magenta), middle third (black), and bottom third (green). The gray horizontal dashed line is drawn at a spectral index of 1.5, and the vertical dashed lines mark the ~W40–80 region of good magnetic connection to Earth. An ordinary least-squares fit (solid line) is shown. The two GLEs at W120 with $S_{30/200}$ ~ 1.25 are slightly offset in longitude for visibility in the plot.
### Table 2
Parameters of GLEs Associated with (a) Central Meridian (E20–W20) Eruptive Flares and (b) GLEs Associated with Far West (>W100) Eruptions

| (a) Date       | Longitude (UT) | Flare Onset (hr) | Transit Time | $F_{30}$ Rank | SI$_{30}$/200 | ESP?   | References |
|---------------|----------------|------------------|--------------|--------------|--------------|--------|------------|
| 1942 Feb 28   | E04            | <11:00           | 20.5         | Top          | N/A          | yes?   | (1)        |
| 1946 Jul 25   | E15            | 15:04            | 27.6         | Top          | N/A          | yes?   | (1)        |
| 1956 Aug 31   | E15            | 12:26            | 38.1         | Bottom       | N/A          | no?    | (2)        |
| 1960 Nov 12   | W04            | 13:15            | 21.2d        | Top          | 1.70         | yes?   | (3)        |
| 1972 Aug 4    | E08            | 6:20             | 14.6         | Top          | 2.74         | yes    | (4)        |
| 1989 Oct 19   | E09            | 12:29            | 28.5         | Top          | 1.67         | yes    | (5)        |
| 1991 Jan 11   | W15            | 2:09             | 32           | Top          | 1.94         | no?    | (6)        |
| 1998 May 2    | W15            | 13:31            | 28.2         | Bottom       | 1.46         | no     | (6)        |
| 1998 Aug 24   | E09            | 21:50            | 33           | Bottom       | 1.96         | yes    | (7)        |
| 2000 Jul 14   | W07            | 10:24            | 27.9         | Top          | 1.95         | yes    | (8)        |
| 2001 Nov 4    | W19            | 16:03            | 33.8         | Middle       | 2.32         | yes    | (7)        |
| 2003 Oct 28   | W08            | 11:06            | 18.9         | Top          | 2.15         | yes    | (8)        |
| 2003 Oct 29   | W02            | 20:41            | 19.7         | Top          | 1.73         | yes    | (9)        |

| (b) Date       | Longitude (UT) | Flare Onset (hr) | Transit Time | $F_{30}$ Rank | SI$_{30}$/200 | ESP?   | References |
|---------------|----------------|------------------|--------------|--------------|--------------|--------|------------|
| 1960 Nov 20   | W113           | 20:17            | 10.3b        | Middle       | 1.37         | Modulation | (1)        |
| 1967 Jan 28   | W154           | 7:54             | ...          | Top          | 1.29         | ...     | (1)        |
| 1969 Mar 30   | W106           | 2:47             | ...          | Middle       | 1.29         | ...     | (1)        |
| 1971 Sep 1    | W120           | 19:34            | 69.2         | Top          | 1.27         | Modulation | (2)        |
| 1977 Sep 24   | W120           | 5:54             | ...          | Middle       | 1.26         | ...     | (2)        |
| 1984 Feb 16   | ~W130          | ~9:00            | ...          | Bottom       | 1.40         | ...     | (1)        |
| 1990 May 28   | ~W120          | 4:33             | 52.5         | Middle       | 1.41         | Modulation | (3)        |
| 2001 Apr 18   | ~W115          | 2:14             | 85.8         | Middle       | 1.54         | no m    | (3)        |

**Notes.**

a Onset times are based on the principal source (first reference listed) for each event and are variously based on Hα, radio, soft X-ray, and CME observations.
b Interval between flare onset time and sudden commencement unless otherwise noted.
c References: (1) Cliver et al. (1990b) and references therein; (2) Mayaud (1973); Švestka & Simon (1975); (3) Gopalswamy et al. (2005) and references therein, Obayashi (1962); (4) Pomerantz & Duggal (1974); Cliver et al. (1990b), Kallenrode & Cliver (2001); (5) Cliver et al. (1990b), Raukunen et al. (2018); (6) flare onset from https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-flares/30MeVprotons/x-rays/goes/xrs/; >30 MeV event time profile from https://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html, SC from Solar-Geophysical Data (SGD); (7) flare onset from NOAA SXR, SGD, Raukunen et al. (2018); (8) Gopalswamy et al. (2005), Raukunen et al. (2018); (9) Gopalswamy et al. (2005).
d Ellison et al. (1961) and Obayashi (1962) report a large amplitude SC at ~10:22 UT on November 13 that is not included in Mayaud’s (1973) list.
e Modulation of the >30 MeV proton time profile is not clearly related to the SC.
f All onset times from Cliver et al. (1982) and Cliver (2006).
g References: (1) SC from Švestka & Simon (1975), no SC reported by Mayaud (1973) on November 21, GLE time profile from https://gle.oulu.fi; (2) SC and >30 MeV time profile from SGD; (3) SC and >30 MeV profile from NOAA (see above).
h The shock is presumably not associated with the listed flare but modulates the GLE time profile at certain stations.
i Mboum reported an SC at 21:18 UT on March 30.
j The shock ends a slight enhancement on the >30 MeV time profile.
k SCs reported at Hyderabad and Port Moresby at 07:32 UT on September 26 but an SC is not included in the listing of Romaná.
l The >30 MeV time profile drops by a factor of ~3 at the shock, near the end of the event.
m Modulation of >30 MeV time profile not related to time of SC.

60% of the total. In all five cases, the ESP contribution to $F_{30}$ was dominant by factors of ~2–3 or more. In contrast, only three of the eight far western (>W100) GLEs in Table 1 had confirmed associated SCs and the delay from the flare for these three events ranged from ~50 to 80 hr (Table 2(b)). Effects on the >30 MeV proton time profile at the time of shock arrival at Earth for these events were weak or absent.

### 3. Discussion

After an extended debate (e.g., Reames 2015), it is generally accepted that large solar proton events are primarily due to diffusive shock acceleration (DSA; Desai & Giacalone 2016) at shocks driven by coronal mass ejections (CMEs) rather than to a flare-resident process. If there is a remaining area of uncertainty, it is for the highest-energy proton events (McCracken et al. 2008; Moraal & McCracken 2012; Klein et al. 2014; Cliver 2016; Klein & Dalla 2017). The comprehensive characterization of GLEs by Raukunen et al. (2018) following the work of Tylka & Dietrich (2009) permits further investigation of this question.

The distribution of source longitudes for the highest-fluence GLEs in Figure 1(a) argues against a picture in which high-energy protons are accelerated locally in a solar flare. In such a picture, one would expect the strongest GLEs to be preferentially produced near W60 with proton fluxues falling
off with distance from this location. Instead, the distribution in Figure 1(a) is skewed toward disk center with only 5 of 24 such GLEs originating from W40 to 80. The broad distribution of source longitudes in Figure 1(a), with the bulk of large GLEs having sources from ~E20 to W100, corresponds to the $\gtrsim 120^\circ$ angular span in latitude for powerful CMEs originating at the solar limbs (Gopalswamy et al. 2015), supporting the CME-driven shock picture for high-energy proton acceleration. Figure 2 shows that it is the third of GLEs with the lowest $F_{\text{430}}$ values that are primarily responsible for the broad W20–100 peak in the overall distribution of source longitudes. Apparently, these weaker GLEs (Figure 1(b)) benefit from the proximity of their source to the $\sim$W55 footprint of the magnetic field-line connected to Earth.

In the CME-driven shock picture of high-energy proton acceleration, we would expect GLE spectra to result from some combination of quasi-perpendicular and quasi-parallel shock acceleration. Figure 3 gives hints as to how this apportionment occurs with source longitude. Quasi-perpendicular shock acceleration, in which the shock is propagating perpendicularly to the ambient magnetic field, is a special case of DSA (Jokipii 1982, 1987; Tylka et al. 2005; Zank et al. 2006) that produces a harder spectrum than quasi-parallel acceleration. The quasi-perpendicular contribution to GLEs having sources from $\sim$SI30/200 peak in the overall distribution of source longitudes.

Earth, it can produce an ESP event due either to local acceleration (Reames 2013) or a magnetically trapped population (Lario & Deckter 2002). Because the CME-driven shock will decelerate and weaken over time, proton acceleration at the bow shock will produce a progressively softer spectrum at Earth during the time that the shock is connected to the magnetic spiral to Earth—a time that will naturally be greater for central meridian eruptions than for those from beyond the west limb. The resulting soft proton spectra for these various processes make bow shocks from central meridian CMEs the principal candidate for the cause of the broad peak in $\sim$SI30/200 from $\sim$E20 to W20 in the scatter plot in Figure 3.

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