Simulating the transport of high energy solar protons during historic GLE events

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Ground level enhancement (GLE) events

- Relativistic solar particle events (protons >500 MeV) can be detected on Earth in ground level enhancement (GLE) events
- These high energy events can lead to potentially harmful levels of radiation as well as damage to modern technology
- Understanding more about what causes GLEs is therefore crucial and will aid in the forecasting of these events at Earth
- We have simulated over 15 historic GLE events from 1978-2017
- This work focuses on the influence the heliospheric current sheet (HCS) has on relativistic proton propagation during GLE events

The heliospheric current sheet (HCS)

- The heliospheric current sheet has previously been suggested to affect the transport of solar energetic particles within the heliosphere, e.g. Augusto et al. 2018, Battarbee et al. 2018
- The events are chosen to ensure a range of current sheet configurations are covered; e.g. a flare location far from or close to the HCS, etc
- Events occurring under both A- and A+ IMF configurations are also chosen, where an A+ polarity has magnetic field lines pointing outwards in the northern hemisphere
- This polarity of the field relative to the current sheet has been seen to affect the direction of particle drift in previous simulations, e.g. Battarbee et al. 2018

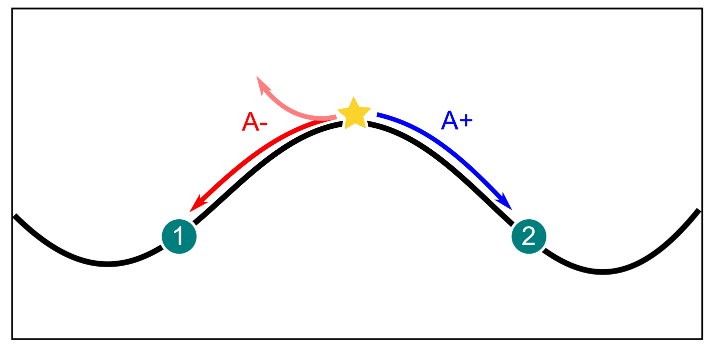

Diagram illustrating the direction of particle drift from a source region (star) towards an observer (1, 2) depending on the IMF configuration

An A+ configuration causes drift towards the HCS and to the West. An A- configuration leads to Easterly drift along the CS as well as some drift away from the sheet

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- The events are modelled with a 3D test particle model (Dalla & Browning 2005, Battarbee et al. 2018) which includes: drifts due to curvature and gradient of the Parker spiral and HCS drift – important at the high energies typical of GLE events. No perpendicular transport associated with turbulence is included
- For each event, 3 million protons (300<E<1200 MeV) are instantaneously injected at the flare location and allowed to propagate through the heliosphere for 72 hours
- Each simulation includes a HCS configuration, based off a fit to the neutral line of the relevant source surface map (obtained from the Wilcox Solar Observatory)
- The historic GLEs are modelled both with and without a current sheet to see the effect on particle propagation between a solar source region and 1AU

Example event with flare close to HCS: GLE 42 (29 September 1989)

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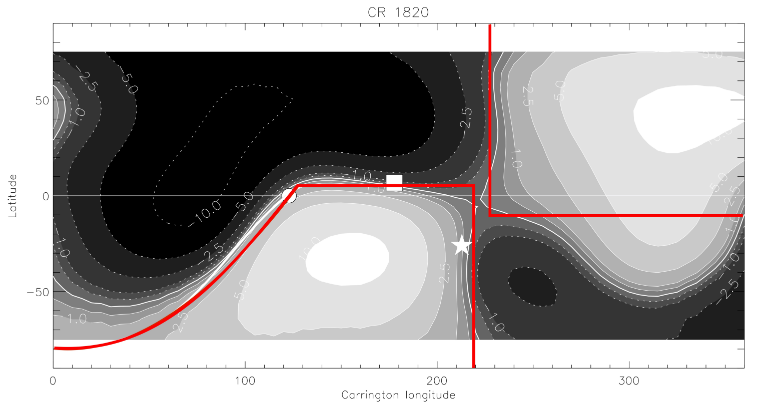
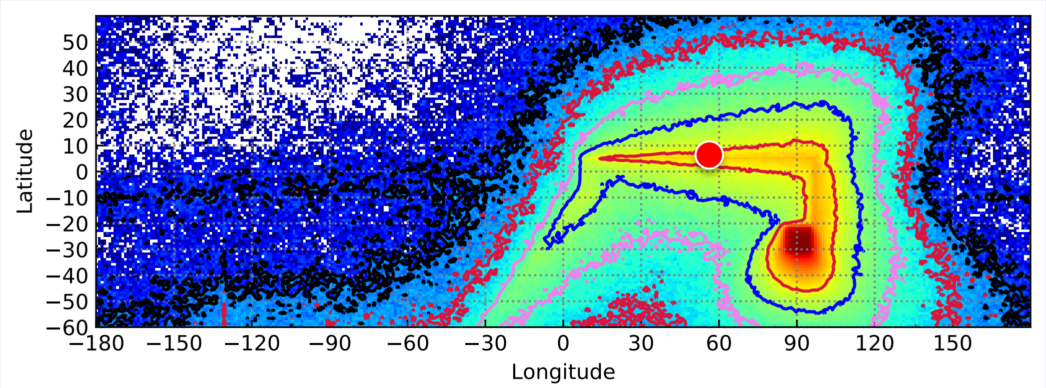
- GLE 42 had a flare site within 5 degrees of the HCS and a longitudinal separation between the flare and Earth's footpoint of >30 degrees
- 1AU cumulative crossing map (below) shows significant drift along the CS towards the East
- Earth footpoint (●) is favourably located within this region
- A- polarity also causes gradient and curvature drift away from the HCS towards the poles



Source surface map for CR 1820 with flare (star) and Earth footpoint (square) locations. Fit to the HCS is shown in red. (Circle: central meridian at time of flare)

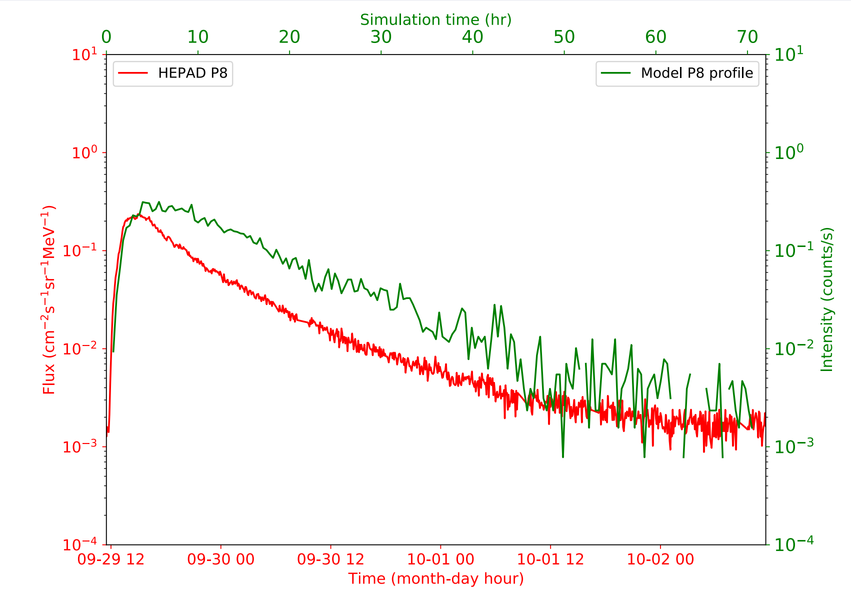
Simulation parameters:
Injection location: [90,-26]
Number of particles: 3 million
E range: 300-1200MeV
Power law index: 1.5
Vsw: 500 km/s



Cumulative proton crossing map over 72 hours at 1AU

Simulated intensity profile at Earth for GLE 42

- Intensity profiles at Earth's footpoint are produced for each event, GLE 42 shown below (green)
- The proton intensity profile is shown for the 330-450 MeV channel, corresponding to the GOES HEPAD P8 channel
- The observed HEPAD P8 intensity profile is overlaid (red) for a 72 hour period following flare onset
- Model and simulation results agree well for this event



1AU modelled intensity profile at Earth's location

Example event with flare far from HCS: GLE 65 (28 October 2003)

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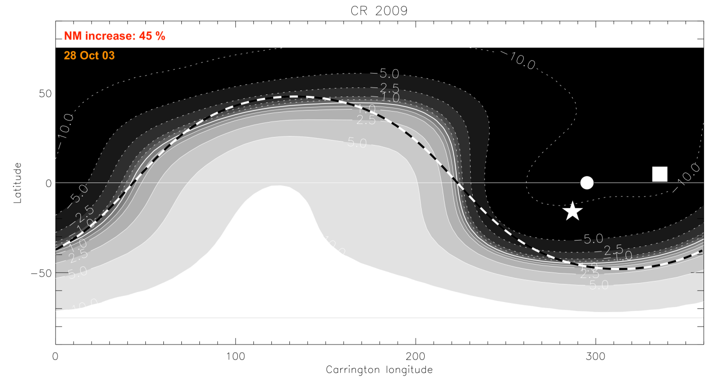
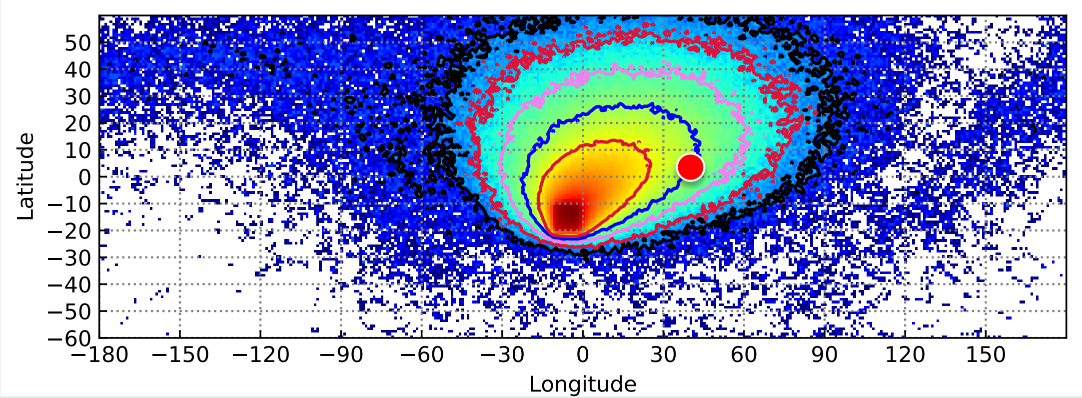
- GLE 65 had a flare site >30 degrees away from the HCS and a longitudinal separation between the flare and Earth's footpoint of >40 degrees
- 1AU cumulative crossing map shows minimal drift along the CS, the pattern is due to the gradient and curvature drift towards the pole
- Despite this (and the Eastern flare location), Earth footpoint (●) is favourably located within this drift region and a GLE still occurred
- Inclusion of the HCS for this event makes no difference



Source surface map for CR 2009 with flare (star) and Earth footpoint (square) locations. Fit to the HCS is shown as dashed line. (Circle: central meridian at time of flare)

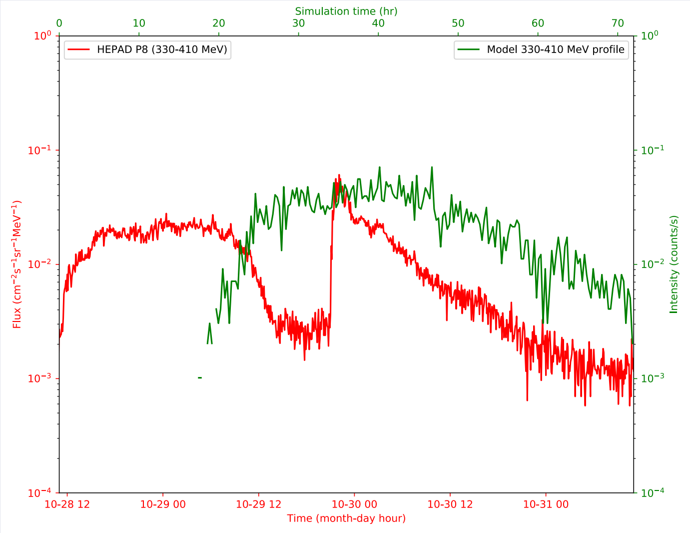
Simulation parameters:
Injection location: [-8,-16]
Number of particles: 3 million
E range: 300-1200MeV
Power law index: 1.5
Vsw: 700 km/s



Cumulative proton crossing map over 72 hours at 1AU

Simulated intensity profile at Earth for GLE 65

- Intensity profiles at Earth's footpoint for GLE 65 shown below (green), and the observed HEPAD P8 profile (red)
- Also visible in HEPAD data is GLE 66 (29th October 2003)
- Test particle model currently only handles a single injection of particles
- Shape of simulated and observed profiles are similar however there is a delay in onset for the simulated profile



1AU modelled intensity profile at Earth's location

The largest GLE events

- The proximity of the flare to the HCS in GLE 42 has a large role in transporting the particles to Earth's location
- Without the HCS in GLE 42, no particles reach Earth in our simulation
- Out of all the historic GLEs, those with a flare closest to the HCS have a greater longitudinal distribution of protons **and** the largest increases in neutron monitor data
- The table shows the 8 largest GLEs (excluding those from the 1950/60s)
- 7/8 of these GLEs had a flare within 10 degrees of the HCS
- 13/12/06 is the exception, whose flare was ~18 degrees away but with a smaller longitudinal separation between the flare and Earth
- This suggests a close proximity of the flare to the HCS strongly affects the severity of the event at Earth (even for flares originating outside the W40-W60 zone of good magnetic connection)

GLE	Flare loc	NM % inc	Approx. flare dist. from HCS / deg
20/01/05	N14W61	5500	<5
29/09/89	S26W>90	395	<5
15/04/01	S20W85	230	<10
22/10/89	S27W31	190	<10
13/12/06	S06W23	110	<20
16/02/84	S16W94	100	<10
24/10/89	S30W57	95	<10
19/10/89	S27E10	90	<10

The largest GLE events

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- Also of note is the on/behind the limb location for the GLEs occurring on 29/9/89 and 16/2/84
- Despite both events occurring in this poorly connected region they led to enormous events at Earth with percentage increases at neutron monitors >100%
- Both events had flares within 10 degrees of the HCS
- Since the mid 1970's, 6 GLEs have occurred behind the limb, all of which had flares close to the HCS

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13/12/06	S06W23	110	<20
16/02/84	S16W94	100	<10
24/10/89	S30W57	95	<10
19/10/89	S27E10	90	<10

Conclusions

- HCS plays a significant role in distributing energetic particles throughout the heliosphere
- Particle transport along the HCS is most efficient when the flare is within 10 degrees of the HCS
- The flare was closest to the HCS during the largest GLE's on record suggesting proximity of the flare to the HCS strongly affects the severity of the event at Earth
- Inclusion of the HCS significantly influences 75% of our simulated historic GLEs
- Our simulations enable us to produce model profiles at Earth that can be compared to existing HEPAD and neutron monitor observations, as well as for use in developing future forecasting models