Particle acceleration - a solar/solar-terrestrial perspective

Prasad Subramanian

Indian Institute of Science Education and Research (IISER), Pune, India

Motivation - I

- This winter school is mostly about energetic particles in space

Motivation - I

- This winter school is mostly about energetic particles in space
- Accelerated particles, *cosmic rays*, to be precise

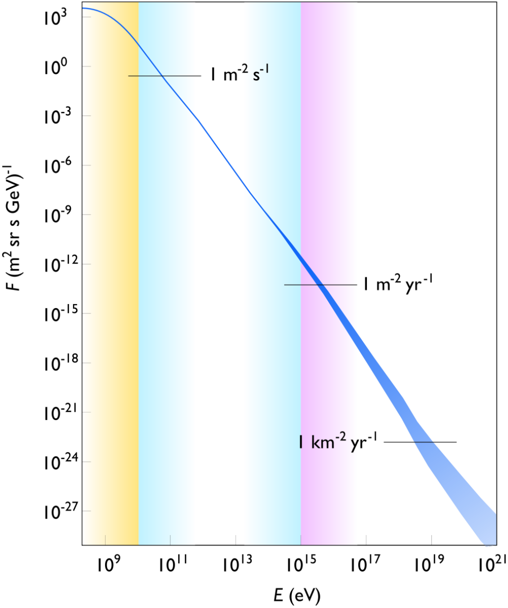
Motivation - I

- This winter school is mostly about energetic particles in space
- Accelerated particles, *cosmic rays*, to be precise
- Although cosmic rays have been discovered long ago, (1911, Victor Hess) we don't quite yet know where they come from and what accelerates them to such high energies!

Motivation - I

- This winter school is mostly about energetic particles in space
- Accelerated particles, *cosmic rays*, to be precise
- Although cosmic rays have been discovered long ago, (1911, Victor Hess) we don't quite yet know where they come from and what accelerates them to such high energies!
- All we know is that they are (mostly) galactic in origin, and that we are bathed in a steady, (almost) isotropic rain of cosmic rays

Galactic Cosmic rays



Motivation - II

- Turns out our own Sun is an (occasional) emitter of high energy particles

Motivation - II

- Turns out our own Sun is an (occasional) emitter of high energy particles
- Not nearly as energetic as galactic CRs, but

Motivation - II

- Turns out our own Sun is an (occasional) emitter of high energy particles
- Not nearly as energetic as galactic CRs, but
- Its much closer, so we are in a much better position to observe them/

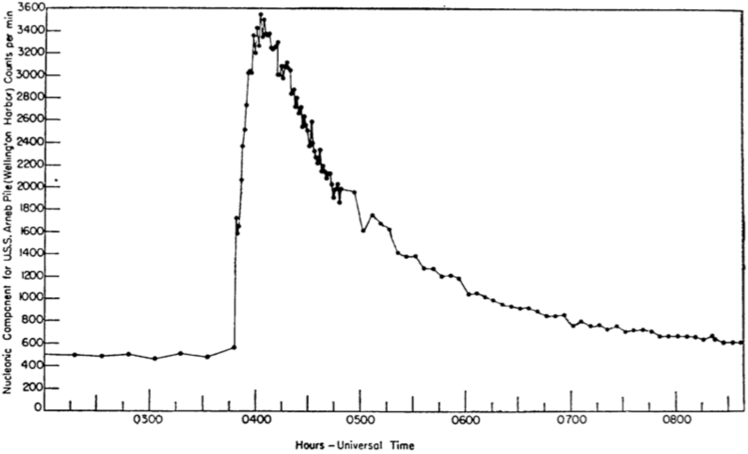
Motivation - II

- Turns out our own Sun is an (occasional) emitter of high energy particles
- Not nearly as energetic as galactic CRs, but
- Its much closer, so we are in a much better position to observe them/ understand how they are generated

Motivation - II

- Turns out our own Sun is an (occasional) emitter of high energy particles
- Not nearly as energetic as galactic CRs, but
- Its much closer, so we are in a much better position to observe them/ understand how they are generated
- It can provide a good template for understanding the origin of galactic CRs

Solar cosmic rays are very transient..



1. Neutron Monitor increase after the big flare of February 23, 1956, as detected on board of U.S.S. "Arneb" anchored in Wellington Harbor, New Zealand. (Ref. MEYER, PARKER and SIMPSON, 1956).

Solar cosmic rays are much “softer”

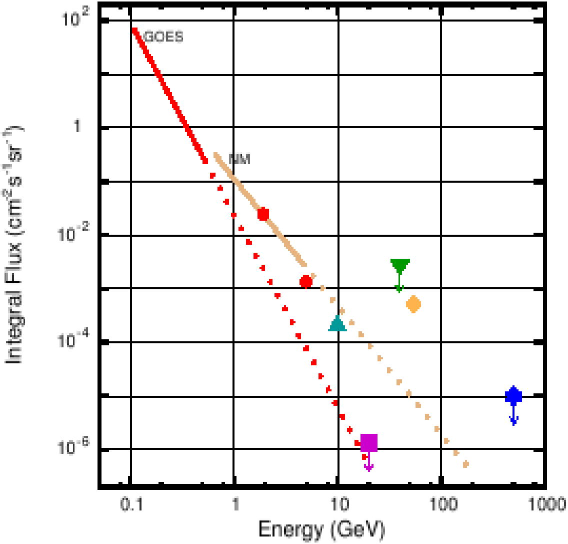


FIG. 11: Integral flux of protons with energy on 28 October 2003; a) Based on 100-600 MeV GOES-10/11 and sub-GeV balloon data. b) World-

Plan for the rest of the talk(s)

- ...so in these two talks, we will
  - Do a quick recap of what the words "accelerated particles" means

Plan for the rest of the talk(s)

- ...so in these two talks, we will
  - Do a quick recap of what the words "accelerated particles" means
  - Briefly review observations of solar energetic particles (SEPs)

Plan for the rest of the talk(s)

- ...so in these two talks, we will
  - Do a quick recap of what the words "accelerated particles" means
  - Briefly review observations of solar energetic particles (SEPs)
  - Briefly overview the phenomenon of magnetic reconnection

Plan for the rest of the talk(s)

- ...so in these two talks, we will
  - Do a quick recap of what the words "accelerated particles" means
  - Briefly review observations of solar energetic particles (SEPs)
  - Briefly overview the phenomenon of magnetic reconnection
  - ..and comment on some interesting solar effects on *galactic* CRs observed at the Earth

Accelerated particles

- Before delving into the subject, lets ask:
- ..what does the phrase “accelerated particles” mean to you?

Accelerated particles

- Before delving into the subject, lets ask:
- ..what does the phrase “accelerated particles” mean to you?
- In fact, its often used to denote a particle distribution that is *non-thermal*; i.e.,one that is not Maxwellian

Accelerated particles

- Before delving into the subject, lets ask:
- ..what does the phrase “accelerated particles” mean to you?
- In fact, its often used to denote a particle distribution that is *non-thermal*; i.e.,one that is not Maxwellian
- In fact, you already knew this - the energy spectra we saw earlier hardly looked like a thermal/Maxwellian distribution

Accelerated particles

- Before delving into the subject, lets ask:
- ..what does the phrase “accelerated particles” mean to you?
- In fact, its often used to denote a particle distribution that is *non-thermal*; i.e.,one that is not Maxwellian
- In fact, you already knew this - the energy spectra we saw earlier hardly looked like a thermal/Maxwellian distribution
- ..so they were clearly produced by a body that was not simply “very hot”;

Accelerated particles

- Before delving into the subject, lets ask:
- ..what does the phrase “accelerated particles” mean to you?
- In fact, its often used to denote a particle distribution that is *non-thermal*; i.e.,one that is not Maxwellian
- In fact, you already knew this - the energy spectra we saw earlier hardly looked like a thermal/Maxwellian distribution
- ..so they were clearly produced by a body that was not simply “very hot”; they have to be produced via other means

Accelerated particles

- Before delving into the subject, lets ask:
- ..what does the phrase "accelerated particles" mean to you?
- In fact, its often used to denote a particle distribution that is *non-thermal*; i.e.,one that is not Maxwellian
- In fact, you already knew this - the energy spectra we saw earlier hardly looked like a thermal/Maxwellian distribution
- ..so they were clearly produced by a body that was not simply "very hot"; they have to be produced via other means
- Typically, one invokes an acceleration mechanism comprising scattering centers, and is phenomenologically called *Fermi* acceleration

Where does the Maxwellian distribution come from? I

Consider first the collisionless Boltzmann equation

$$\frac{Df}{Dt} = \dot{f} + \dot{\mathbf{x}}\,\nabla\, f + \dot{\mathbf{u}}\,\nabla_u\, f = 0$$

The distribution function f represents the probability of finding a given particle in a given element of position-velocity phase space $d^3x\, d^3u$. The total number of particles is

$$n = \int f\, d^3x\, d^3u$$

$\dot{f} \rightarrow$ the creation/destruction of particles, $\dot{\mathbf{x}} \rightarrow$ the time evolution of the space-coordinate and $\dot{\mathbf{u}} \rightarrow$ the time evolution of the velocity-coordinate. The collisionless Boltzmann eq simply says that the number of particles in an elemental volume of phase space $d^3x\, d^3u$ (even as its deformed with time) is conserved.

Where does the Maxwellian distribution come from? II

- Any initial distribution will eventually relax to a Maxwellian when RHS of Boltzmann eq $= 0$. Viewed another way, the LHS has to be zero for a gas in *equilibrium* $\rightarrow$ Maxwellian

Where does the Maxwellian distribution come from? II

- Any initial distribution will eventually relax to a Maxwellian when RHS of Boltzmann eq $= 0$. Viewed another way, the LHS has to be zero for a gas in *equilibrium* $\rightarrow$ Maxwellian
- Even if the RHS were not 0; i.e., if there were collisions that take particles in and out of an elemental phase space volume,

Where does the Maxwellian distribution come from? II

- Any initial distribution will eventually relax to a Maxwellian when RHS of Boltzmann eq $= 0$. Viewed another way, the LHS has to be zero for a gas in *equilibrium* $\rightarrow$ Maxwellian
- Even if the RHS were not 0; i.e., if there were collisions that take particles in and out of an elemental phase space volume,
    - for a given number, momentum and energy, the Maxwellian distribution occupies the maximum phase space volume

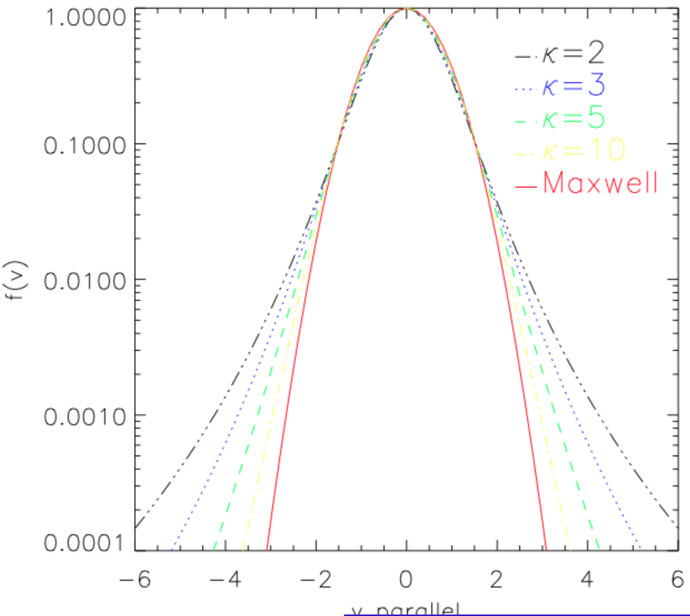
Where does the Maxwellian distribution come from? II

- Any initial distribution will eventually relax to a Maxwellian when RHS of Boltzmann eq $= 0$. Viewed another way, the LHS has to be zero for a gas in *equilibrium* $\rightarrow$ Maxwellian
- Even if the RHS were not 0; i.e., if there were collisions that take particles in and out of an elemental phase space volume,
  - for a given number, momentum and energy, the Maxwellian distribution occupies the maximum phase space volume
  - Generalized entropy argument: $H = \int f \ln f d^3u$ always $\downarrow$ with time, and the minimum is achieved by the Maxwellian

Where does the Maxwellian distribution come from? II

- Any initial distribution will eventually relax to a Maxwellian when RHS of Boltzmann eq $= 0$. Viewed another way, the LHS has to be zero for a gas in *equilibrium* $\rightarrow$ Maxwellian
- Even if the RHS were not 0; i.e., if there were collisions that take particles in and out of an elemental phase space volume,
  - for a given number, momentum and energy, the Maxwellian distribution occupies the maximum phase space volume
  - Generalized entropy argument: $H = \int f \ln f d^3 u$ always $\downarrow$ with time, and the minimum is achieved by the Maxwellian
- So any distribution eventually relaxes to a Maxwellian

Partice distribution



Collisions

- RHS of Boltzmann eq need not be zero; there can be collisions which move particles in and out of $d^3x\, d^3u$.

Collisions

- RHS of Boltzmann eq need not be zero; there can be collisions which move particles in and out of $d^3x\, d^3u$. The RHS (the collision operator) is an integral over velocities which involves the distribution function

Collisions

- RHS of Boltzmann eq need not be zero; there can be collisions which move particles in and out of $d^3x\, d^3u$. The RHS (the collision operator) is an integral over velocities which involves the distribution function
- When the collisions are Coulomb in nature, a Maxwellian f makes the RHS $= 0$

Collisions

- RHS of Boltzmann eq need not be zero; there can be collisions which move particles in and out of $d^3x\, d^3u$. The RHS (the collision operator) is an integral over velocities which involves the distribution function
- When the collisions are Coulomb in nature, a Maxwellian f makes the RHS $= 0$
- Coulomb collisions $\rightarrow$ heating ; T $\uparrow$ leads to $\uparrow$ in width (variance) of Maxwellian

Collisions

- RHS of Boltzmann eq need not be zero; there can be collisions which move particles in and out of $d^3x\, d^3u$. The RHS (the collision operator) is an integral over velocities which involves the distribution function
- When the collisions are Coulomb in nature, a Maxwellian f makes the RHS $= 0$
- Coulomb collisions $\rightarrow$ heating ; T $\uparrow$ leads to $\uparrow$ in width (variance) of Maxwellian
- Even with non-Coulomb collisions, non-Maxwellian distributions eventually relax to a Maxwellian, provided there's enough time. Else, the distribution could be non-thermal/accelerated.

The "collisional" Boltzmann equation

$$\frac{Df}{Dt} = -C_{\mathrm{out}} + C_{\mathrm{in}} = \left.\frac{\partial f}{\partial t}\right|_{\mathrm{c}}$$

The “collisional” Boltzmann equation

$$\frac{Df}{Dt} = -C_{\mathrm{out}} + C_{\mathrm{in}} = \left.\frac{\partial f}{\partial t}\right|_{\mathrm{c}}$$

If the cumulative effect of small collisions/deflections is dominant, the RHS integral (collision term) can be Taylor expanded to first order to yield the Fokker-Planck form (“friction” + diffusion in velocity space)

The "collisional" Boltzmann equation

$$\frac{Df}{Dt} = -C_{\rm out} + C_{\rm in} = \frac{\partial f}{\partial t}\Big|_{\rm c}$$

If the cumulative effect of small collisions/deflections is dominant, the RHS integral (collision term) can be Taylor expanded to first order to yield the Fokker-Planck form ("friction" + diffusion in velocity space)

$$\frac{\partial f}{\partial t}\Big|_{\rm c} = -\frac{\partial}{\partial u}\Big(Af\Big) + \frac{1}{2}\frac{\partial^2}{\partial u^2}\Big(Bf\Big)$$

The Fokker-Planck form

• The Fokker-Planck form of the collision integral can also be heuristically derived by considering a particle in a *dilute* gas that experiences a large number of small amplitude, stochastic "kicks"

The Fokker-Planck form

• The Fokker-Planck form of the collision integral can also be heuristically derived by considering a particle in a *dilute* gas that experiences a large number of small amplitude, stochastic "kicks"

• Random walk of tip of velocity (or momentum) vector represents "diffusion" in velocity/momentum space

The Fokker-Planck form

• The Fokker-Planck form of the collision integral can also be heuristically derived by considering a particle in a *dilute* gas that experiences a large number of small amplitude, stochastic "kicks"

• Random walk of tip of velocity (or momentum) vector represents "diffusion" in velocity/momentum space

• Drag due to motion through dilute gas → "friction" term.

$$\frac{\partial f}{\partial t}\bigg|_{\rm c} = -\frac{\partial}{\partial u}\Big(Af\Big) + \frac{1}{2}\frac{\partial^2}{\partial u^2}\Big(Bf\Big)$$

The "diffusion" term

$$\frac{\partial f}{\partial t} = D\frac{\partial^2 f}{\partial v^2}$$

The "diffusion" term

$$\frac{\partial f}{\partial t} = D\frac{\partial^2 f}{\partial v^2}$$

Solution (for constant D):

$$f = \left(\frac{D}{4\pi t}\right)^{1/2} \exp\left(-\frac{v^2}{4Dt}\right)$$

The “diffusion” term

$$\frac{\partial f}{\partial t} = D \frac{\partial^2 f}{\partial v^2}$$

Solution (for constant D):

$$f = \left(\frac{D}{4\pi t} \right)^{1/2} \exp\left(- \frac{v^2}{4Dt} \right)$$

• Gaussian broadens and gets shallower with time $\rightarrow$ diffusion in velocity space.

The “diffusion” term

$$\frac{\partial f}{\partial t} = D\frac{\partial^2 f}{\partial v^2}$$

Solution (for constant D):

$$f = \left(\frac{D}{4\pi t}\right)^{1/2} \exp\left(-\frac{v^2}{4Dt}\right)$$

- Gaussian broadens and gets shallower with time $\rightarrow$ diffusion in velocity space.
- But mean velocity still increases! (why?)

The "diffusion" term

$$\frac{\partial f}{\partial t} = D\frac{\partial^2 f}{\partial v^2}$$

Solution (for constant D):

$$f = \left(\frac{D}{4\pi t}\right)^{1/2} \exp\left(-\frac{v^2}{4Dt}\right)$$

• Gaussian broadens and gets shallower with time $\rightarrow$ diffusion in velocity space.

• But mean velocity still increases! (why?)

• This is second order acceleration, typically due to stochastically moving scattering centers.

Nonthermal, power law spectrum: an example

Consider only the "diffusion" term,

$$\frac{\partial f}{\partial t} = -\frac{1}{v^2}\,\frac{\partial}{\partial v}\left(-v^2\,\mathcal{D}(v)\,\frac{\partial f}{\partial v}\right),$$

Nonthermal, power law spectrum: an example

Consider only the "diffusion" term,

$$\frac{\partial f}{\partial t} = -\frac{1}{v^2}\,\frac{\partial}{\partial v}\left(-v^2\,\mathcal{D}(v)\,\frac{\partial f}{\partial v}\right),$$

with

Nonthermal, power law spectrum: an example

Consider only the "diffusion" term,

$$\frac{\partial f}{\partial t} = -\frac{1}{v^2}\,\frac{\partial}{\partial v}\left(-v^2\,\mathcal{D}(v)\,\frac{\partial f}{\partial v}\right),$$

with

$$\mathcal{D}(v) = D_0\,v^2\,,$$

where D_0 is a constant.

Nonthermal, power law spectrum: an example

Consider only the "diffusion" term,

$$\frac{\partial f}{\partial t} = -\frac{1}{v^2}\,\frac{\partial}{\partial v}\left(-v^2\,\mathcal{D}(v)\,\frac{\partial f}{\partial v}\right),$$

with

$$\mathcal{D}(v) = D_0\,v^2\,,$$

where D_0 is a constant.
The steady-state solution is $f \propto v^{\alpha}$; i.e., a power-law (clearly non-thermal) particle spectrum.

Nonthermal, power law spectrum: an example

Consider only the "diffusion" term,

$$\frac{\partial f}{\partial t} = -\frac{1}{v^2}\frac{\partial}{\partial v}\left(-v^2\,\mathcal{D}(v)\,\frac{\partial f}{\partial v}\right),$$

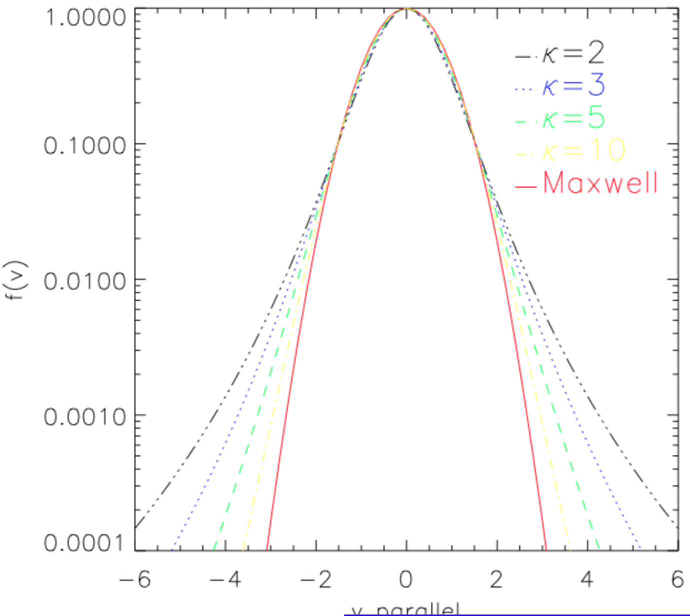
with

$$\mathcal{D}(v) = D_0\,v^2\,,$$

where D_0 is a constant.
The steady-state solution is $f \propto v^{\alpha}$; i.e., a power-law (clearly non-thermal) particle spectrum.

This is an example of a particular kind of second-order Fermi acceleration. So the name of the game would be to find physical situations that yield a particular form for the diffusion coefficient $\mathcal{D}(v)$.

Partice distribution



Observations of solar energetic particles

- Energetic particles on the Sun are typically observed as a consequence of

Observations of solar energetic particles

- Energetic particles on the Sun are typically observed as a consequence of
- Flares, and

Observations of solar energetic particles

- Energetic particles on the Sun are typically observed as a consequence of
- Flares, and
- Coronal Mass Ejections

Observations of solar energetic particles

- Energetic particles on the Sun are typically observed as a consequence of
- Flares, and
- Coronal Mass Ejections
- Both are generally termed as *eruptive phenomena* in the solar corona

Observations of solar energetic particles

- Energetic particles on the Sun are typically observed as a consequence of
- Flares, and
- Coronal Mass Ejections
- Both are generally termed as *eruptive phenomena* in the solar corona
- Most of the time one observes radiation from the accelerated/nonthermal particles, not the particles themselves

Observations of solar energetic particles

- Energetic particles on the Sun are typically observed as a consequence of
- Flares, and
- Coronal Mass Ejections
- Both are generally termed as *eruptive phenomena* in the solar corona
- Most of the time one observes radiation from the accelerated/nonthermal particles, not the particles themselves
- ...although, for very energetic eruptions, one does observe accelerated particles (or byproducts thereof) with detectors on the Earth

Observations of solar energetic particles

- Energetic particles on the Sun are typically observed as a consequence of
- Flares, and
- Coronal Mass Ejections
- Both are generally termed as *eruptive phenomena* in the solar corona
- Most of the time one observes radiation from the accelerated/nonthermal particles, not the particles themselves
- ...although, for very energetic eruptions, one does observe accelerated particles (or byproducts thereof) with detectors on the Earth but the Earth needs to be (magnetically) well "connected" to the eruption site in order to observe the particles

Particle acceleration in the solar corona - physical processes

- We have talked about particle acceleration in bits and pieces so far

- We have talked about particle acceleration in bits and pieces so far
- ...talking about what it means to call a particle distribution nonthermal/accelerated

Particle acceleration in the solar corona - physical processes

- We have talked about particle acceleration in bits and pieces so far
- ...talking about what it means to call a particle distribution nonthermal/accelerated
- ...talked a bit (mostly in generic terms) about how a thermal distribution comes about, and

Particle acceleration in the solar corona - physical processes

- We have talked about particle acceleration in bits and pieces so far
- ...talking about what it means to call a particle distribution nonthermal/accelerated
- ...talked a bit (mostly in generic terms) about how a thermal distribution comes about, and
- ...how a nonthermal/accelerated distribution can be produced

Particle acceleration in the solar corona - physical processes

- We have talked about particle acceleration in bits and pieces so far
- ...talking about what it means to call a particle distribution nonthermal/accelerated
- ...talked a bit (mostly in generic terms) about how a thermal distribution comes about, and
- ...how a nonthermal/accelerated distribution can be produced
- Briefly reviewed observations of accelerated particles in the solar corona

Particle acceleration in the solar corona - physical processes

- We have talked about particle acceleration in bits and pieces so far
- ...talking about what it means to call a particle distribution nonthermal/accelerated
- ...talked a bit (mostly in generic terms) about how a thermal distribution comes about, and
- ...how a nonthermal/accelerated distribution can be produced
- Briefly reviewed observations of accelerated particles in the solar corona
- ...and now we will focus on the physical basis of it all - magnetic reconnection

Reconnection - “cut-and-paste” field lines

- From $\nabla \,.\, \mathbf{B} = 0$, we know that there can’t be any cutting of magnetic field lines

Reconnection - “cut-and-paste” field lines

- From $\nabla . \mathbf{B} = 0$, we know that there can’t be any cutting of magnetic field lines
- But more generally, there is a concept of conservation of helicity

Reconnection - "cut-and-paste" field lines

- From $\nabla \,.\, \mathbf{B} = 0$, we know that there can't be any cutting of magnetic field lines
- But more generally, there is a concept of conservation of helicity (similar to flux conservation, which follows from flux freezing)

Reconnection - "cut-and-paste" field lines

- From $\nabla . \mathbf{B} = 0$, we know that there can't be any cutting of magnetic field lines
- But more generally, there is a concept of conservation of helicity (similar to flux conservation, which follows from flux freezing) which prohibits such cut-and-paste situations

Reconnection - “cut-and-paste” field lines

- From $\nabla \,.\, \mathbf{B} = 0$, we know that there can’t be any cutting of magnetic field lines
- But more generally, there is a concept of conservation of helicity (similar to flux conservation, which follows from flux freezing) which prohibits such cut-and-paste situations
- in ideal MHD

Reconnection - “cut-and-paste” field lines

- From $\nabla . \mathbf{B} = 0$, we know that there can’t be any cutting of magnetic field lines
- But more generally, there is a concept of conservation of helicity (similar to flux conservation, which follows from flux freezing) which prohibits such cut-and-paste situations
- in ideal MHD
- ...so an violation should involve a violation of some of the tenets of MHD -

Reconnection - “cut-and-paste” field lines

- From $\nabla \,.\, \mathbf{B} = 0$, we know that there can’t be any cutting of magnetic field lines
- But more generally, there is a concept of conservation of helicity (similar to flux conservation, which follows from flux freezing) which prohibits such cut-and-paste situations
- in ideal MHD
- ...so an violation should involve a violation of some of the tenets of MHD - specifically, finite resistivity effects

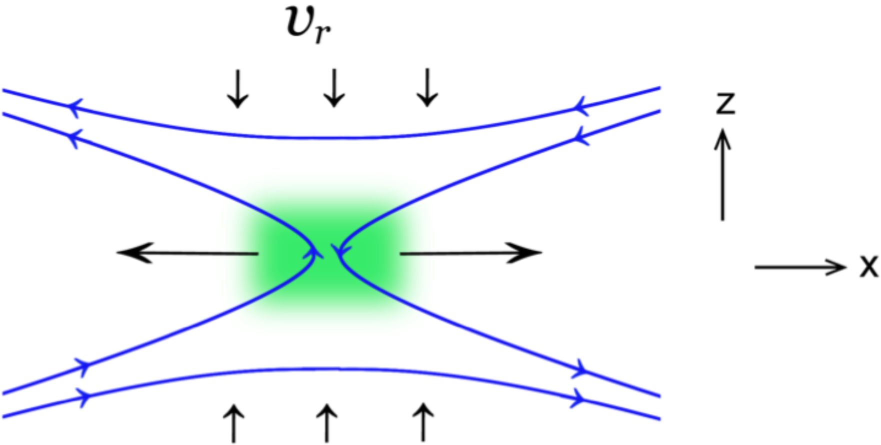
Reconnection - "cut-and-paste" field lines

- From $\nabla \, . \, \mathbf{B} = 0$, we know that there can't be any cutting of magnetic field lines
- But more generally, there is a concept of conservation of helicity (similar to flux conservation, which follows from flux freezing) which prohibits such cut-and-paste situations
- in ideal MHD
- ...so an violation should involve a violation of some of the tenets of MHD - specifically, finite resistivity effects
- But first, lets look at what happens when (oppositely directed) magnetic field lines approach each other;

Reconnection - "cut-and-paste" field lines

- From $\nabla \cdot \mathbf{B} = 0$, we know that there can't be any cutting of magnetic field lines
- But more generally, there is a concept of conservation of helicity (similar to flux conservation, which follows from flux freezing) which prohibits such cut-and-paste situations
- in ideal MHD
- ...so an violation should involve a violation of some of the tenets of MHD - specifically, finite resistivity effects
- But first, lets look at what happens when (oppositely directed) magnetic field lines approach each other; due to some reason - maybe the velocity field is doing it..

Reconnection - 1D



Reconnection - some general issues

- Most generally, reconnection is a matter of changes in field line topology

Reconnection - some general issues

- Most generally, reconnection is a matter of changes in field line topology
- Most simply visualized in 1D - field lines on two sides are antiparallel, *current sheet* in between

Reconnection - some general issues

- Most generally, reconnection is a matter of changes in field line topology
- Most simply visualized in 1D - field lines on two sides are antiparallel, *current sheet* in between
- As the field lines approach closer, the current sheet gets thinner and thinner, until finite resisitivity effects become important at the neutral/X point

Reconnection - some general issues

- Most generally, reconnection is a matter of changes in field line topology
- Most simply visualized in 1D - field lines on two sides are antiparallel, *current sheet* in between
- As the field lines approach closer, the current sheet gets thinner and thinner, until finite resisitivity effects become important at the neutral/X point
- The ideal MHD frozen-in condition doesn't hold anymore near the X-point, and "cutting/pasting" of field lines is allowed

Reconnection - some general issues

- Most generally, reconnection is a matter of changes in field line topology
- Most simply visualized in 1D - field lines on two sides are antiparallel, *current sheet* in between
- As the field lines approach closer, the current sheet gets thinner and thinner, until finite resisitivity effects become important at the neutral/X point
- The ideal MHD frozen-in condition doesn't hold anymore near the X-point, and "cutting/pasting" of field lines is allowed
- So the original configuration is altered, and the new configuration "snaps apart" -

Reconnection - some general issues

- Most generally, reconnection is a matter of changes in field line topology
- Most simply visualized in 1D - field lines on two sides are antiparallel, *current sheet* in between
- As the field lines approach closer, the current sheet gets thinner and thinner, until finite resisitivity effects become important at the neutral/X point
- The ideal MHD frozen-in condition doesn't hold anymore near the X-point, and "cutting/pasting" of field lines is allowed
- So the original configuration is altered, and the new configuration "snaps apart" - and the whole process has to satisfy mass conservation -

Reconnection - some general issues

- Most generally, reconnection is a matter of changes in field line topology
- Most simply visualized in 1D - field lines on two sides are antiparallel, *current sheet* in between
- As the field lines approach closer, the current sheet gets thinner and thinner, until finite resisitivity effects become important at the neutral/X point
- The ideal MHD frozen-in condition doesn't hold anymore near the X-point, and "cutting/pasting" of field lines is allowed
- So the original configuration is altered, and the new configuration "snaps apart" - and the whole process has to satisfy mass conservation - not flux conservation.

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing -

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy (over and abovethe minimum energy/potential) configuration)

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy (over and abovethe minimum energy/potential) configuration) that is stored in the twisted/stressed fields is released during the reconfiguration

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy (over and abovethe minimum energy/potential) configuration) that is stored in the twisted/stressed fields is released during the reconfiguration
- The energy released in reconnection is held responsible for a variety of phenomena -

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy (over and abovethe minimum energy/potential) configuration) that is stored in the twisted/stressed fields is released during the reconfiguration
- The energy released in reconnection is held responsible for a variety of phenomena - from solar coronal eruptions

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy (over and abovethe minimum energy/potential) configuration) that is stored in the twisted/stressed fields is released during the reconfiguration
- The energy released in reconnection is held responsible for a variety of phenomena - from solar coronal eruptions (flares, coronal mass ejections), to "flares" in (extragalactic) active galactic nuclei,

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy (over and abovethe minimum energy/potential) configuration) that is stored in the twisted/stressed fields is released during the reconfiguration
- The energy released in reconnection is held responsible for a variety of phenomena - from solar coronal eruptions (flares, coronal mass ejections), to "flares" in (extragalactic) active galactic nuclei, to phenomena near the geotail, and a whole lot more

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy (over and abovethe minimum energy/potential) configuration) that is stored in the twisted/stressed fields is released during the reconfiguration
- The energy released in reconnection is held responsible for a variety of phenomena - from solar coronal eruptions (flares, coronal mass ejections), to “flares” in (extragalactic) active galactic nuclei, to phenomena near the geotail, and a whole lot more
- Particle acceleration - due to direct **E** field acceleration in the current sheet,

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy (over and abovethe minimum energy/potential) configuration) that is stored in the twisted/stressed fields is released during the reconfiguration
- The energy released in reconnection is held responsible for a variety of phenomena - from solar coronal eruptions (flares, coronal mass ejections), to “flares” in (extragalactic) active galactic nuclei, to phenomena near the geotail, and a whole lot more
- Particle acceleration - due to direct **E** field acceleration in the current sheet, stochastic interaction with eddies in the turbulent reconnection outflow..

Energy released in reconnection

- Energy released due to a reconfiguration of magnetic fields is conceptually appealing - excess energy (over and abovethe minimum energy/potential) configuration) that is stored in the twisted/stressed fields is released during the reconfiguration
- The energy released in reconnection is held responsible for a variety of phenomena - from solar coronal eruptions (flares, coronal mass ejections), to "flares" in (extragalactic) active galactic nuclei, to phenomena near the geotail, and a whole lot more
- Particle acceleration - due to direct **E** field acceleration in the current sheet, stochastic interaction with eddies in the turbulent reconnection outflow..
- Exactly how much excess magnetic energy is released depends upon the reconnection rate

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r;

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r; then $\dot{\phi} = B_i L v_r$

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r; then $\dot{\phi} = B_i L v_r$
- The quantity v_r is the all important reconnection speed

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r; then $\dot{\phi} = B_i L v_r$
- The quantity v_r is the all important reconnection speed (often called the reconnection rate)

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r; then $\dot{\phi} = B_i L v_r$
- The quantity v_r is the all important reconnection speed (often called the reconnection rate)
- Various reconnection theories predict numbers for v_r;

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r; then $\dot{\phi} = B_i L v_r$
- The quantity v_r is the all important reconnection speed (often called the reconnection rate)
- Various reconnection theories predict numbers for v_r; the issue is to account for observations which predict *fast* reconnection;

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r; then $\dot{\phi} = B_i L v_r$
- The quantity v_r is the all important reconnection speed (often called the reconnection rate)
- Various reconnection theories predict numbers for v_r; the issue is to account for observations which predict *fast* reconnection; a reasonable/popular guess in astrophysical situations is $v_r \approx 0.1 v_{\mathrm{A}}$

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r; then $\dot{\phi} = B_i L v_r$
- The quantity v_r is the all important reconnection speed (often called the reconnection rate)
- Various reconnection theories predict numbers for v_r; the issue is to account for observations which predict *fast* reconnection; a reasonable/popular guess in astrophysical situations is $v_r \approx 0.1 v_{\mathrm{A}}$
- Much of this depends upon the geometry of the reconnection region;

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r; then $\dot{\phi} = B_i L v_r$
- The quantity v_r is the all important reconnection speed (often called the reconnection rate)
- Various reconnection theories predict numbers for v_r; the issue is to account for observations which predict *fast* reconnection; a reasonable/popular guess in astrophysical situations is $v_r \approx 0.1 v_{\mathrm{A}}$
- Much of this depends upon the geometry of the reconnection region; how small it can get

The reconnection rate

- Field lines are "annhilated" at the reconnection/X-point
- So a measure of the (1D) reconnection rate is the rate of change of magnetic flux $\dot{\phi}$ ($\mathrm{G\,cm^{-2}\,s^{-1}}$ in cgs)
- Let the extent of the reconnection region $\perp$ the plane of the paper is L, B_i the average field strength in the "reconnection region" and the inflow speed v_r; then $\dot{\phi} = B_i L v_r$
- The quantity v_r is the all important reconnection speed (often called the reconnection rate)
- Various reconnection theories predict numbers for v_r; the issue is to account for observations which predict *fast* reconnection; a reasonable/popular guess in astrophysical situations is $v_r \approx 0.1 v_{\mathrm{A}}$
- Much of this depends upon the geometry of the reconnection region; how small it can get
- ...which in turn depends upon the (kinetic) microphysics that governs the collision rate/resistivity in the reconnection region

Solar transients and *galactic* cosmic rays

- We have discussed so far how particles are accelerated in the solar corona

Solar transients and *galactic* cosmic rays

- We have discussed so far how particles are accelerated in the solar corona
- ...the so-called "solar" cosmic rays or solar energetic particles

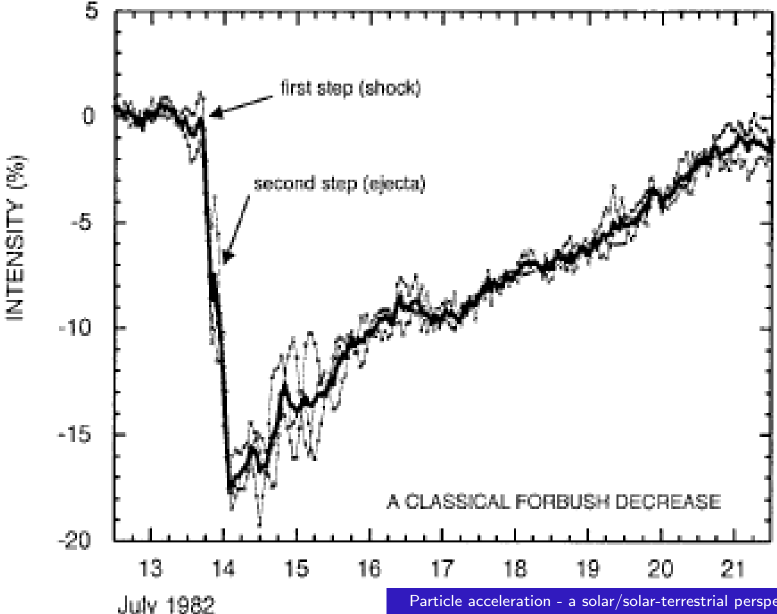
Solar transients and *galactic* cosmic rays

- We have discussed so far how particles are accelerated in the solar corona
- ...the so-called "solar" cosmic rays or solar energetic particles
- turns out solar eruptions also do interesting things to *galactic* cosmic rays

Solar transients and *galactic* cosmic rays

- We have discussed so far how particles are accelerated in the solar corona
- ...the so-called "solar" cosmic rays or solar energetic particles
- turns out solar eruptions also do interesting things to *galactic* cosmic rays
- ..under usual circumstances, we are bathed in a nearly isotropic, *constant* flux of galactic cosmic rays

Solar transients cause a decrease in GCR flux



Forbush decreases - Overview

- It has been recognized since ≈ 1930 that solar transients cause (temporal) changes in the galactic cosmic ray intensity detected at the Earth

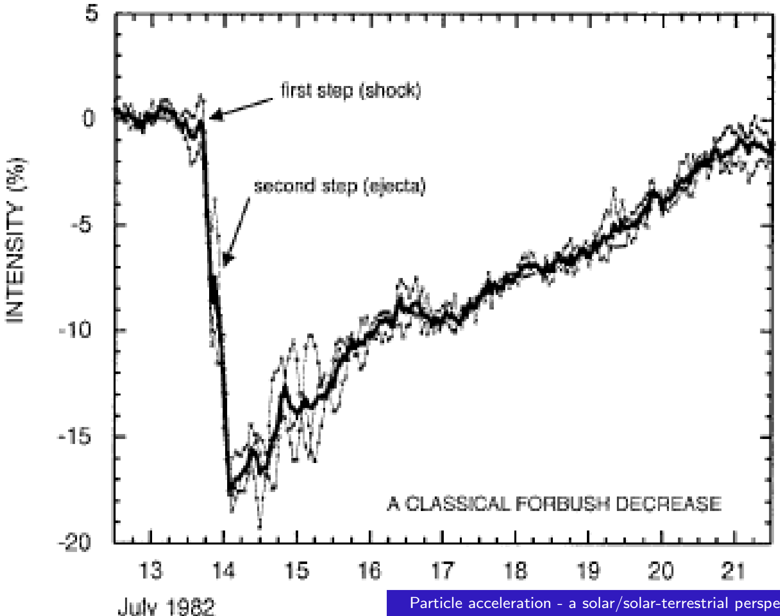
Forbush decreases - Overview

- It has been recognized since ≈ 1930 that solar transients cause (temporal) changes in the galactic cosmic ray intensity detected at the Earth
- Specifically, magnetic clouds/near-Earth CME manifestations and their associated shocks are known to cause Forbush decreases in the galactic cosmic ray intensity.

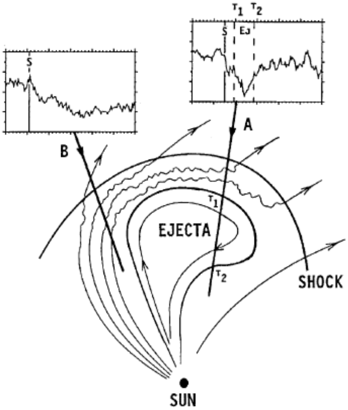
Forbush decreases - Overview

- It has been recognized since ≈ 1930 that solar transients cause (temporal) changes in the galactic cosmic ray intensity detected at the Earth
- Specifically, magnetic clouds/near-Earth CME manifestations and their associated shocks are known to cause Forbush decreases in the galactic cosmic ray intensity.
- More interestingly, precursors to Forbush decreases in galactic cosmic rays at the Earth provide advance information about parameters of the CME-associated shock, and hence the impending geomagnetic storm

Forbush decrease

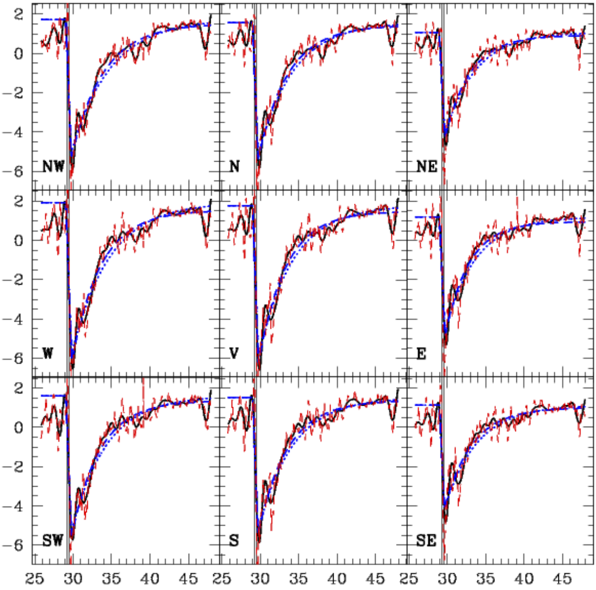


FDs are due to near-Earth CME/shock



Shock (magnetic "umbrella" against cosmic rays) + CME (low density cavity)

Forbush decrease observed by GRAPES-3



Forbush Decrease studies with GRAPES-3

- Conventional wisdom has it that the shock (propagating, diffusive barrier) and the CME (magnetic “bottle”) are both responsible for the observed Forbush decrease

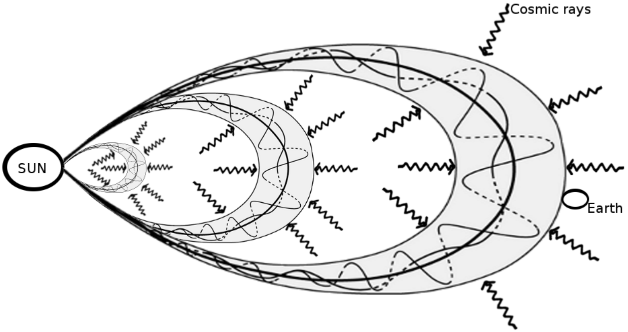
Forbush Decrease studies with GRAPES-3

- Conventional wisdom has it that the shock (propagating, diffusive barrier) and the CME (magnetic "bottle") are both responsible for the observed Forbush decrease
- At GRAPES-3 energies ($\approx 14 - 42$ GeV) we have shown (Arun Babu, PhD thesis) that the relatively empty magnetic bottle (the CME) is the primary cause of the Forbush decrease.

Forbush Decrease studies with GRAPES-3

- Conventional wisdom has it that the shock (propagating, diffusive barrier) and the CME (magnetic "bottle") are both responsible for the observed Forbush decrease
- At GRAPES-3 energies ($\approx 14 - 42$ GeV) we have shown (Arun Babu, PhD thesis) that the relatively empty magnetic bottle (the CME) is the primary cause of the Forbush decrease.
- We have derived tight constraints on the turbulence level (amplitude) in the vicinity of the CME (sheath region), especially with multi-rigidity data (Arun Babu, PhD thesis). We are also elucidating the role of cross-field diffusion in the presence of MHD turbulence.

Forbush decrease due to magnetic bottle



CME starts out almost devoid of CRs. CRs (cross-field) diffuse into it, but its still a depleted (CR) cavity @ Earth