



UNI
GRAZ

ICAM



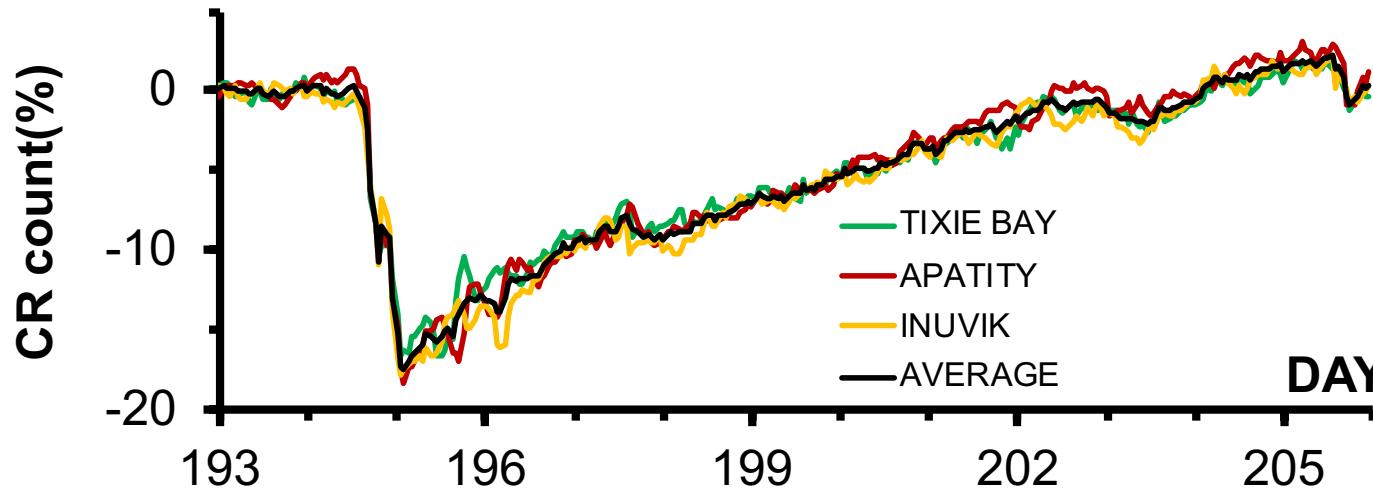
Forbush decrease model for expanding CMEs (ForbMod)

Mateja Dumbović

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Institute of Physics, University of Graz, Austria

What are Forbush decreases?

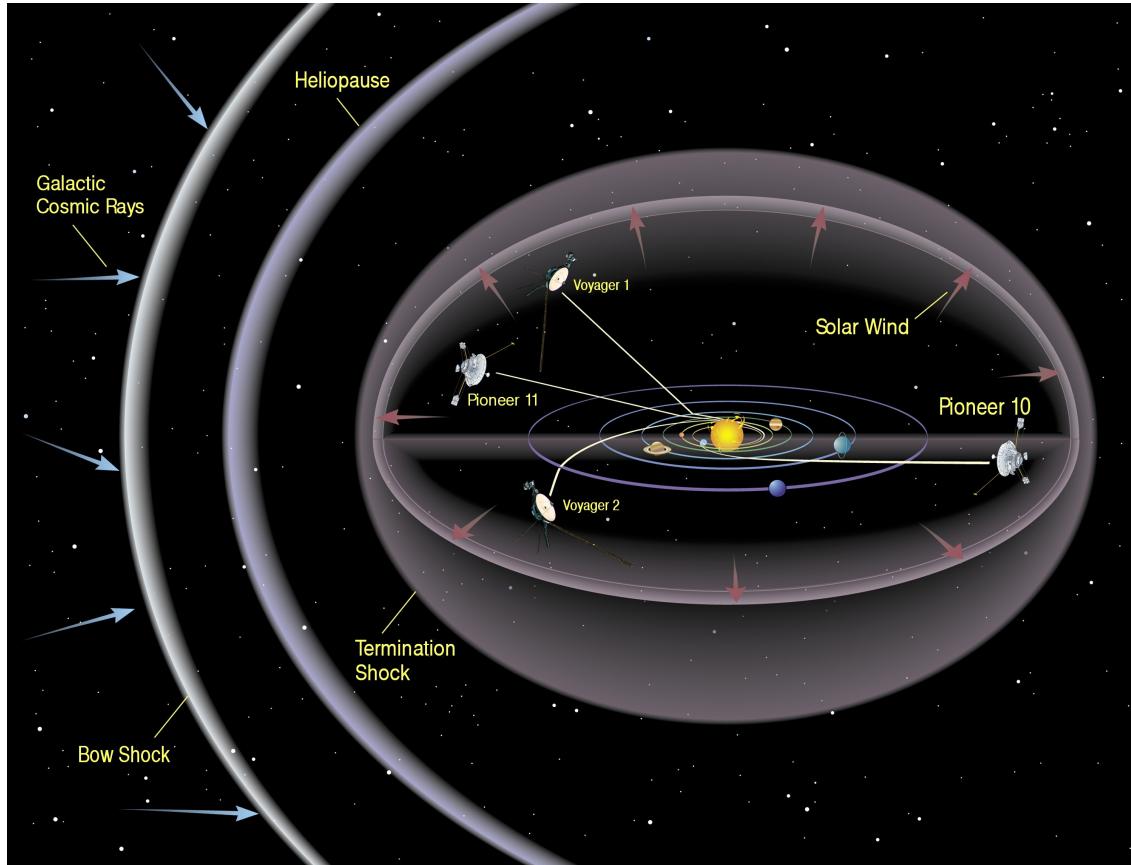


Dumbovic PhD thesis, 2015

First observed by Forbush, 1937 and Hess & Demmelmaier, 1937

Short term decreases in galactic cosmic ray count
Typical duration several days
Typical amplitudes several %
(depends on the detector)

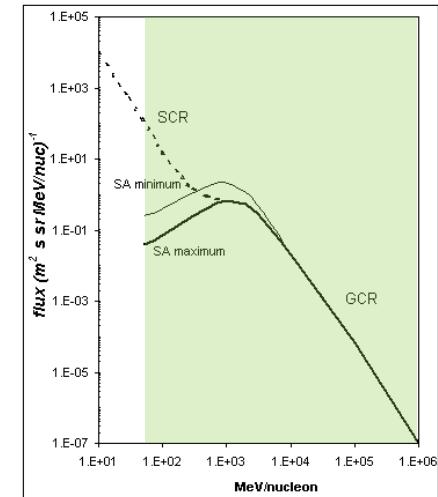
Cosmic rays in Heliosphere – in general



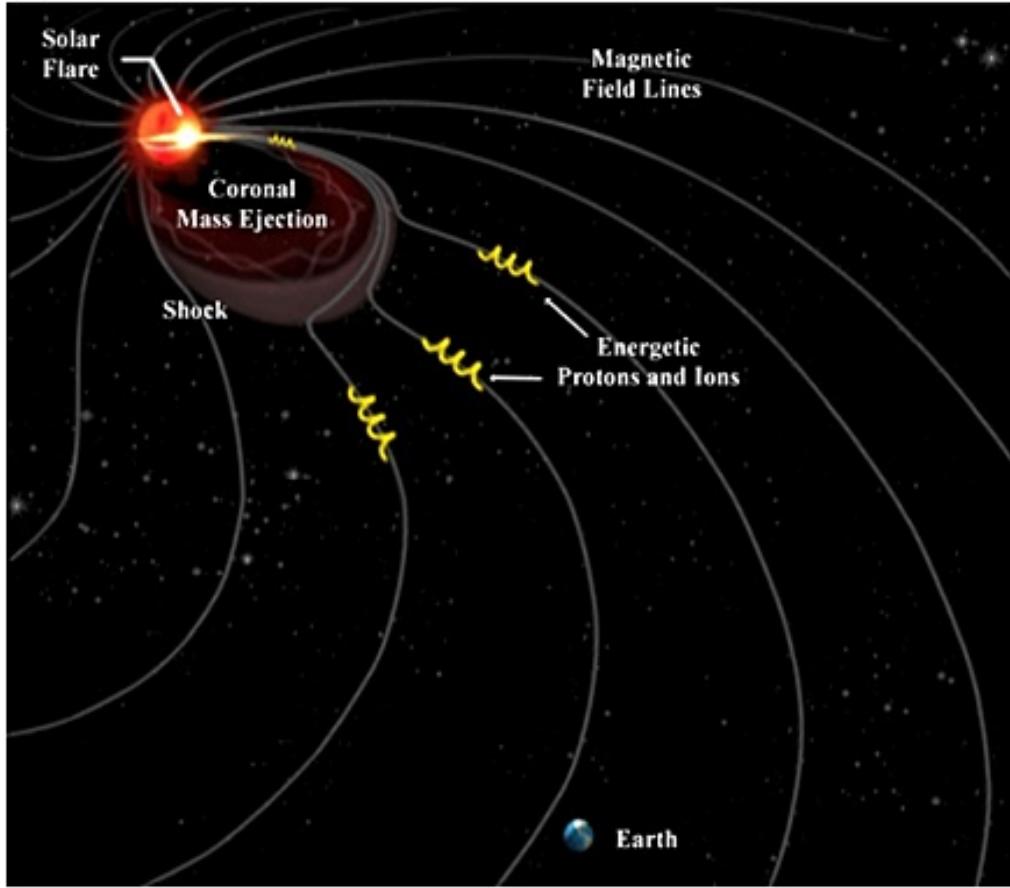
www.nasa.gov

THREE COMPONENTS:

- 1) Galactic cosmic rays



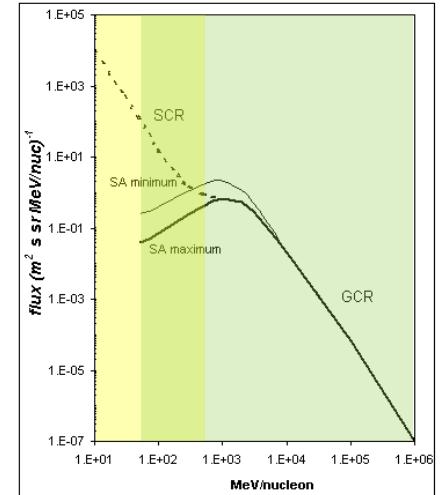
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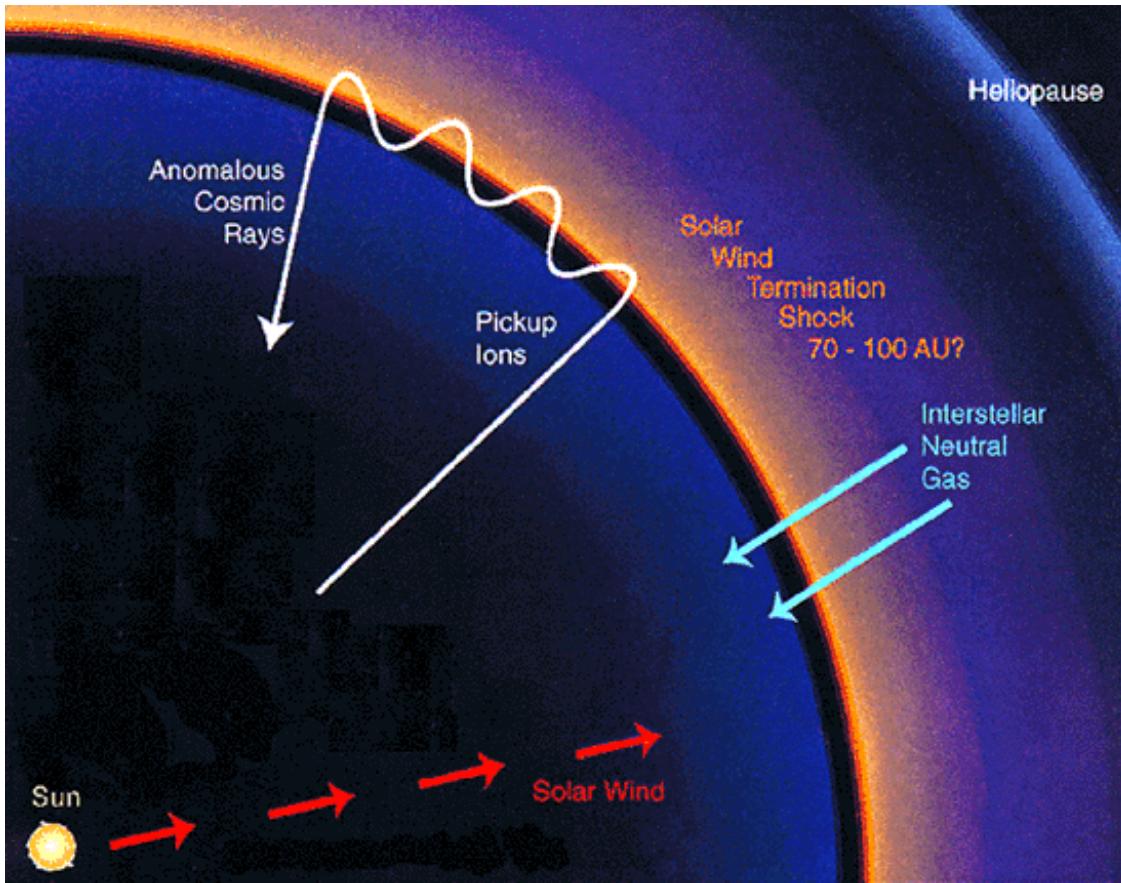
www.spaceweather.uma.es

THREE COMPONENTS:

- 1) Galactic cosmic rays
- 2) Solar cosmic rays (solar energetic particles, SEPs)



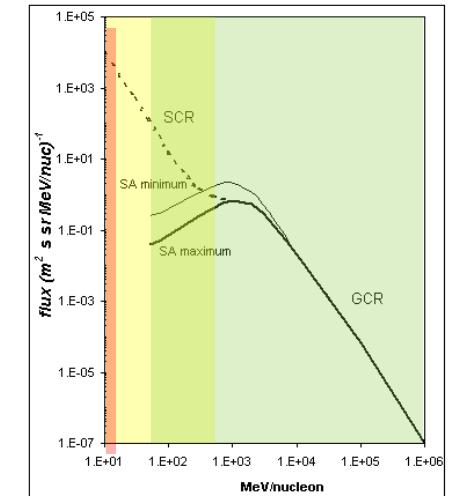
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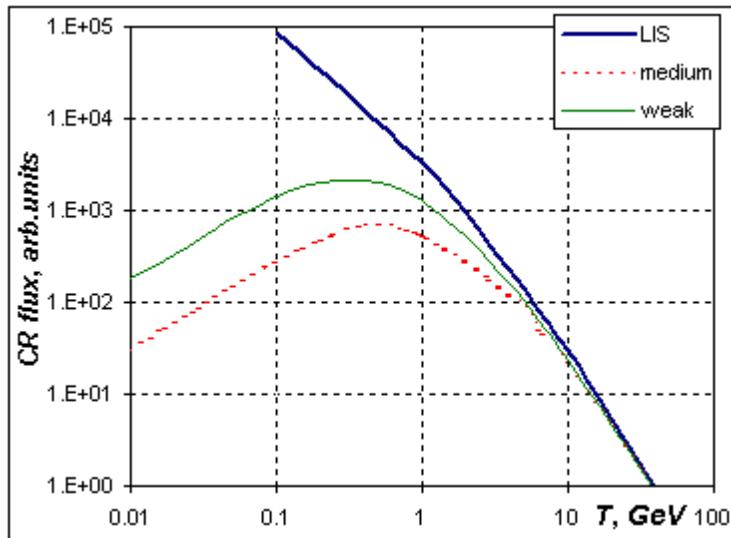
www.nasa.gov

THREE COMPONENTS:

- 1) Galactic cosmic rays
- 2) Solar cosmic rays (solar energetic particles, SEPs)
- 3) Anomalous cosmic rays



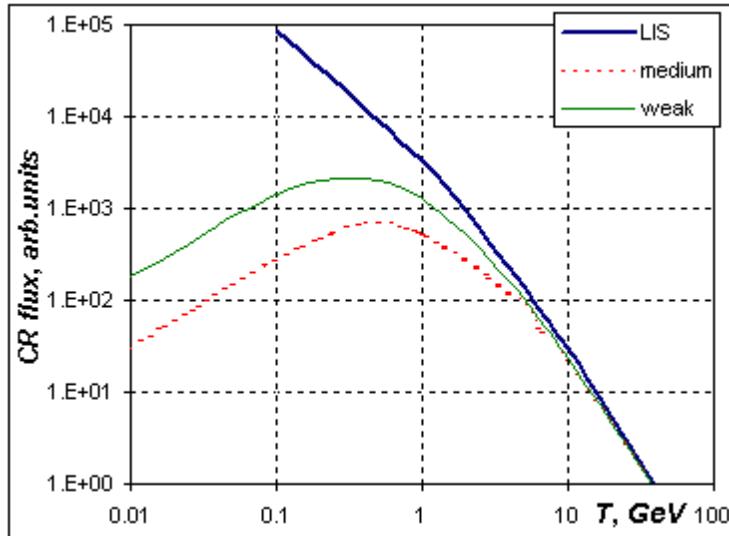
Modulation of Galactic Cosmic Rays (GCRs) in Heliosphere



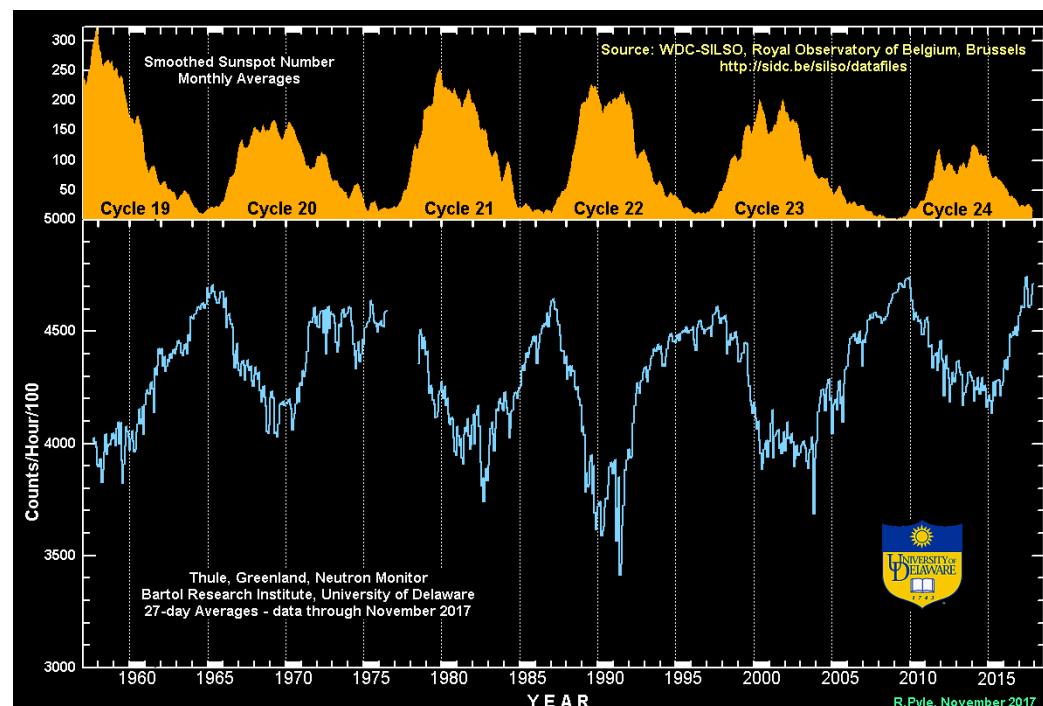
GCRs delayed or even prevented from reaching Earth

Mursula & Usoskin lectures, 2003, Uni. Oulu

Modulation of Galactic Cosmic Rays (GCRs) in Heliosphere



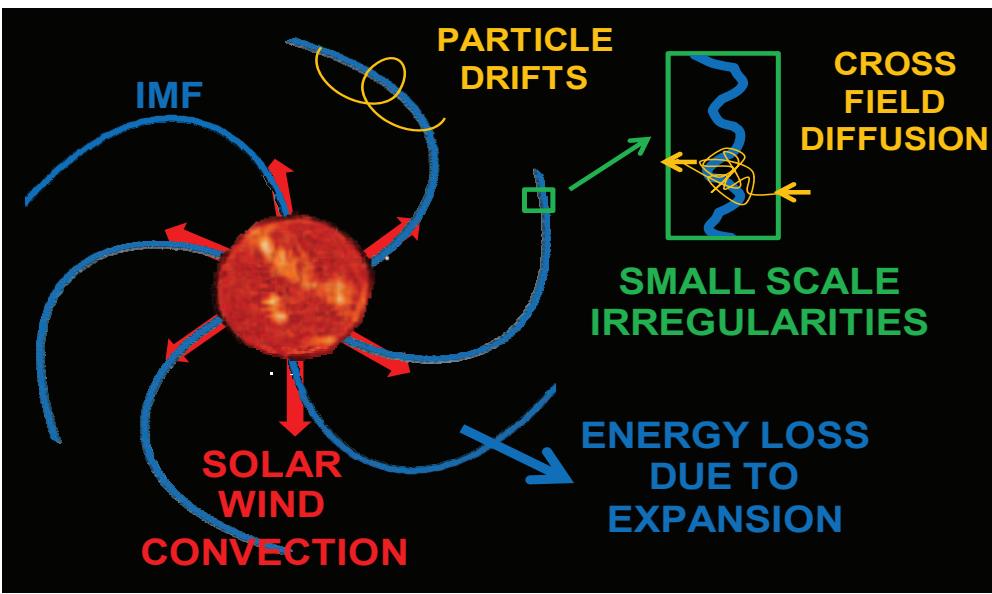
GCRs delayed or even prevented from reaching Earth



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GCR flux anticorrelated with solar activity

Modulation of Galactic Cosmic Rays (GCRs) in Heliosphere



Dumbovic PhD thesis, 2015

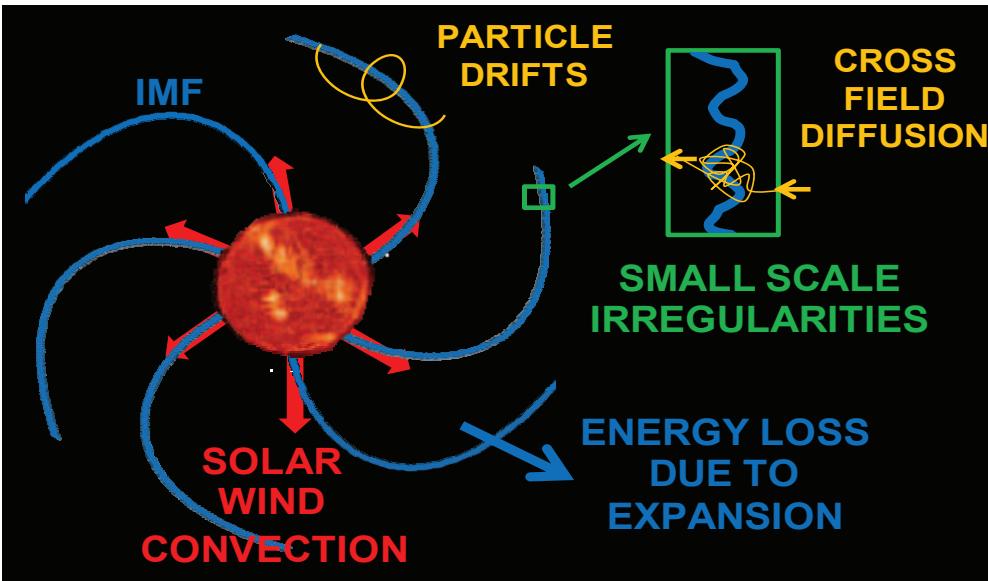
PARTICLE TRANSPORT EQUATION
Parker, 1965

$$\frac{\partial f}{\partial t} = -(\underbrace{\mathbf{V}}_a + \langle \mathbf{v}_d \rangle) \cdot \nabla f + \underbrace{\nabla \cdot (\mathbf{K}_s \cdot \nabla f)}_c + \frac{1}{3} (\nabla \cdot \mathbf{V}) \underbrace{\frac{\partial f}{\partial \ln P}}_e,$$

Arrows point from the terms to their descriptions:

- Term **a**: GCR phase-space distribution function $F(P, t, r)$
- Term **b**: drifts
- Term **c**: diffusion
- Term **d**: convection
- Term **e**: Adiabatic cooling

Modulation of Galactic Cosmic Rays (GCRs) in Heliosphere



Dumbovic PhD thesis, 2015

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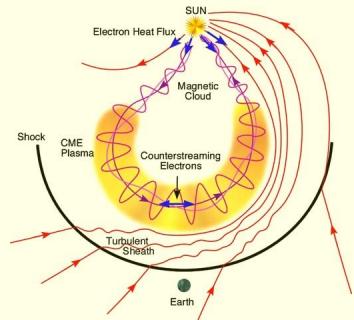
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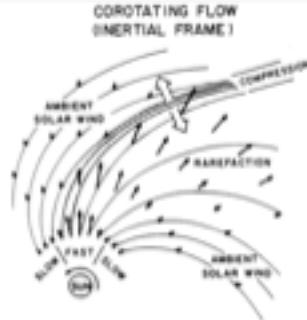
- Term a: GCR phase-space distribution function $F(P,t,r)$
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What are Forbush decreases?

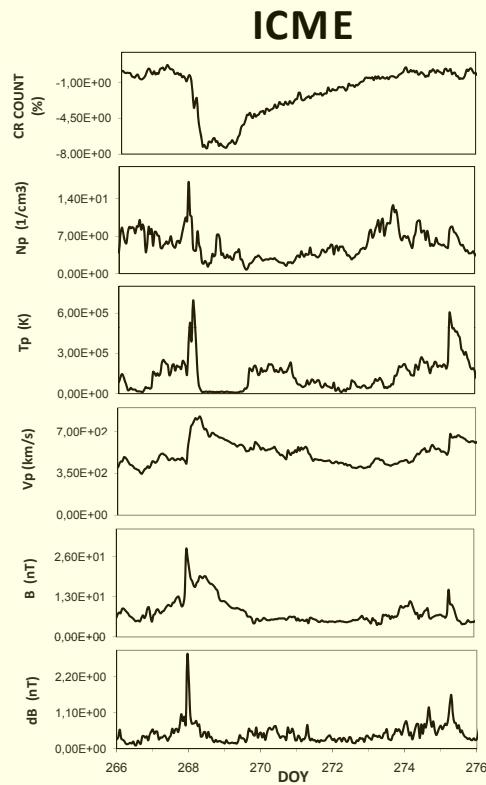
What causes Forbush decreases?



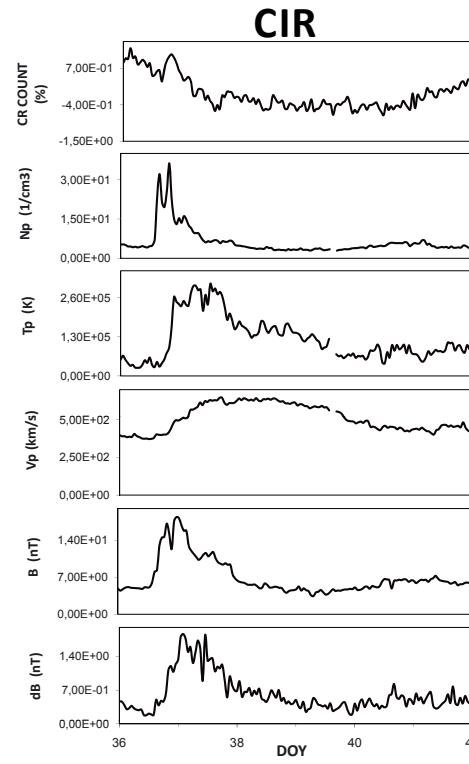
Zurbuchen&Richardson, 2006



Gosling&Pizzo, 1999



Dumbovic+, 2012



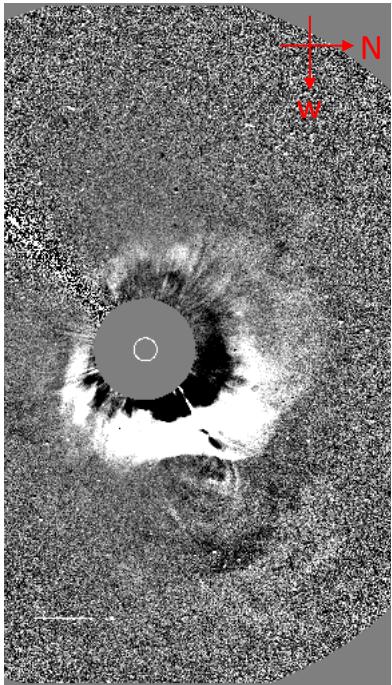
Various shapes and sizes



Various interplanetary transients

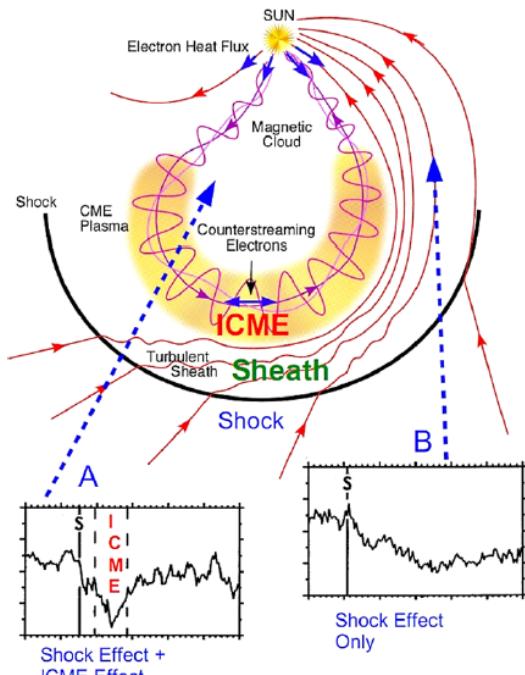
Forbush decreases caused by Interplanetary Coronal Mass Ejections (ICMEs)

REMOTE OBSERVATION

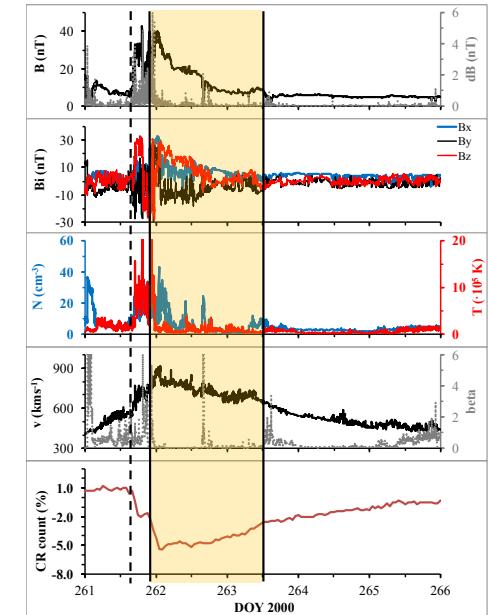


VISUALISATION

Adapted from Richardson & Cane, 2011, *SolPhys*



IN SITU MEASUREMENTS



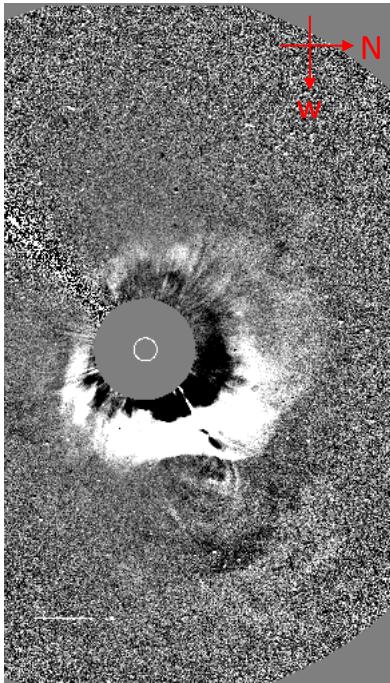
ICME detected in situ by Wind

2000 September 17
Shock arrival at 17:00

+
2step Forbush decrease detected by NMAs at Earth
adapted from Dumbovic+, 2011, *A&A*

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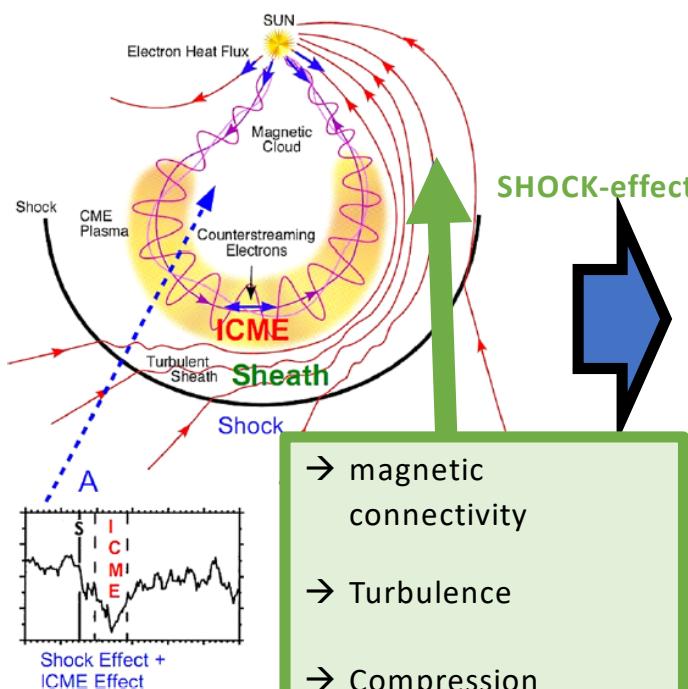
REMOTE OBSERVATION



CME in SOHO/LASCO C3
2000 September 16 06:18 UT
First C2 detection at 05:18

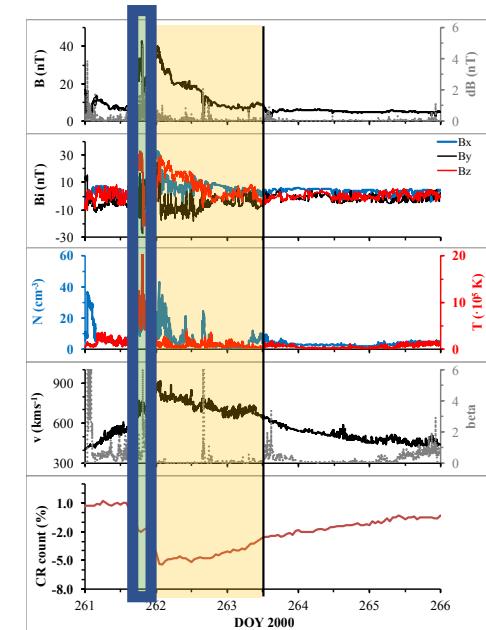
VISUALISATION

Adapted from Richardson & Cane (2011)



- magnetic connectivity
- Turbulence
- Compression
- Prolonged effect

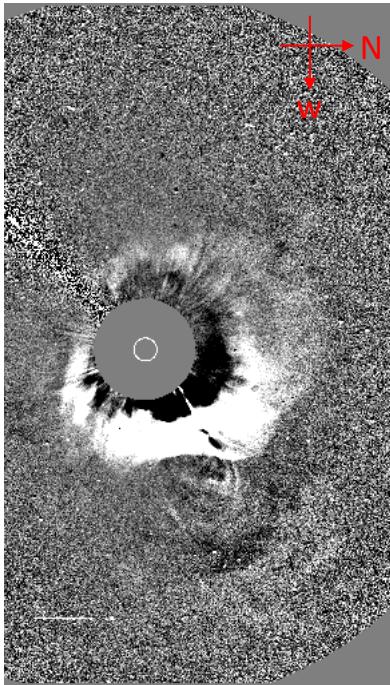
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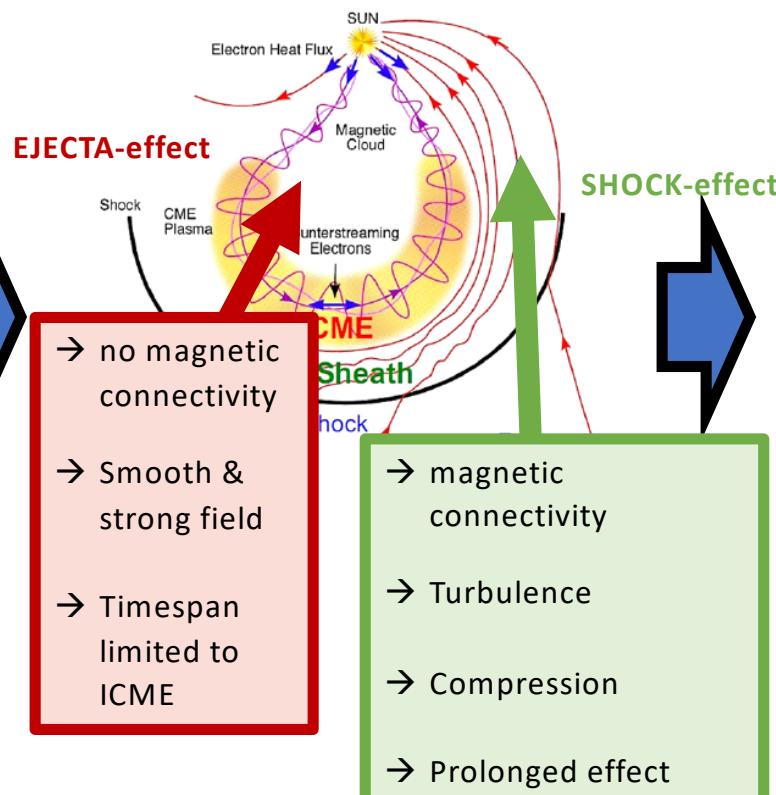
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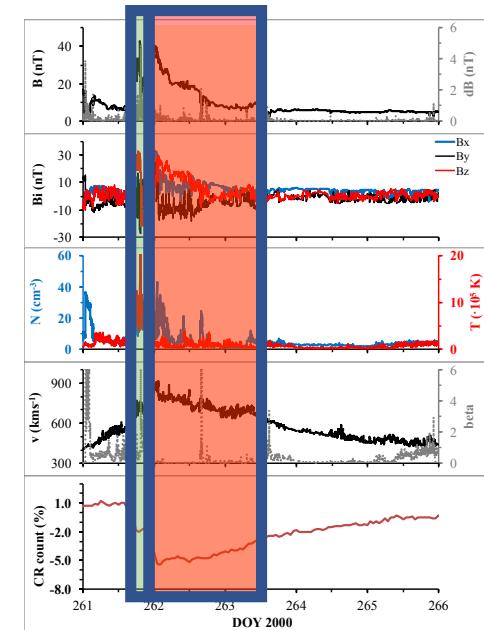
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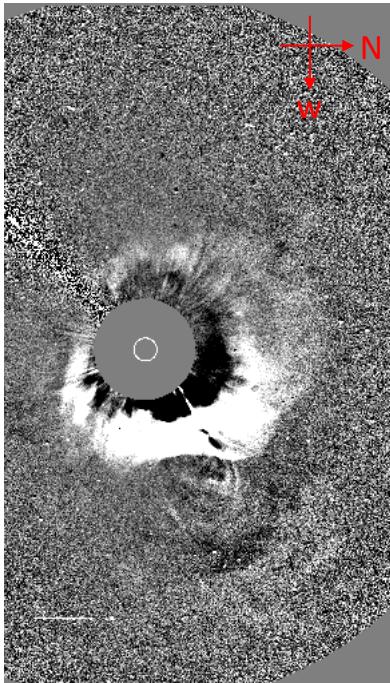
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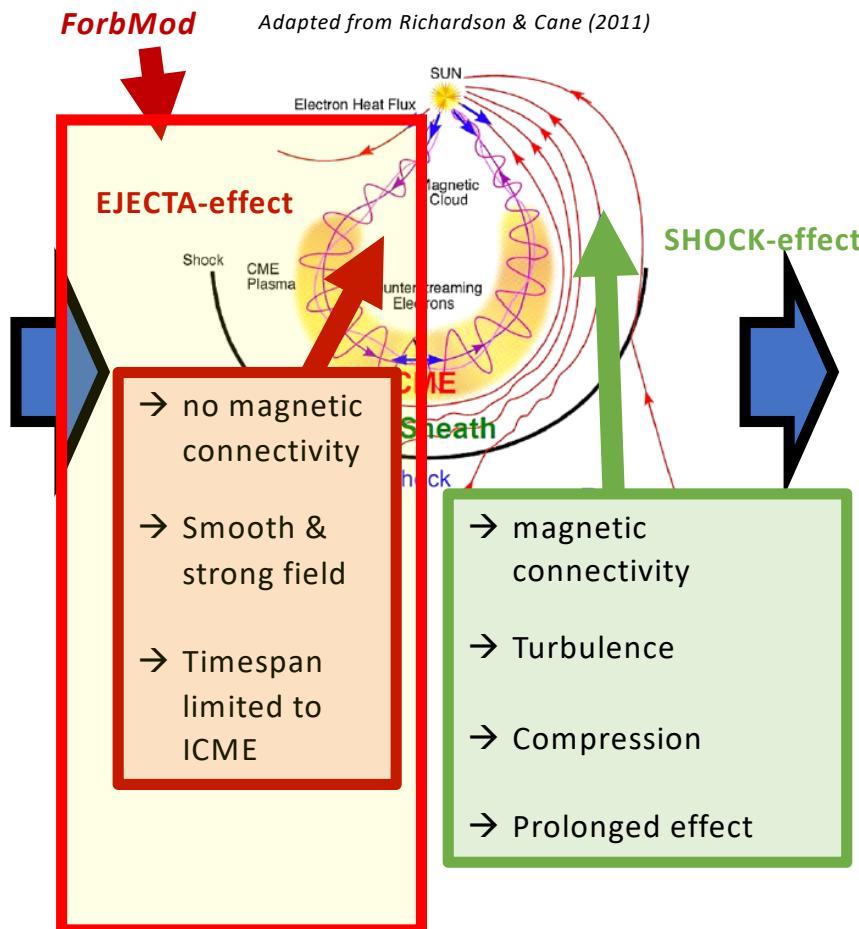
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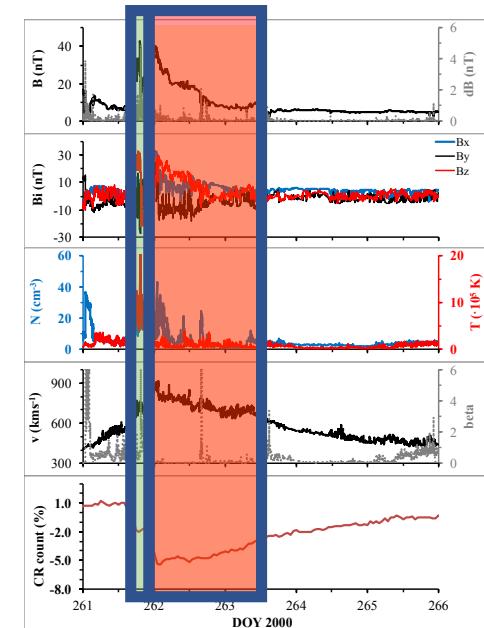


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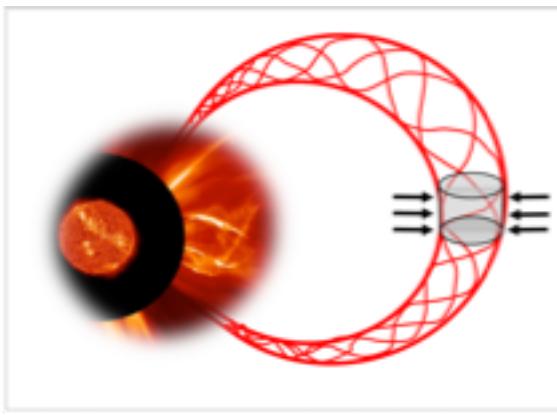


IN SITU MEASUREMENTS



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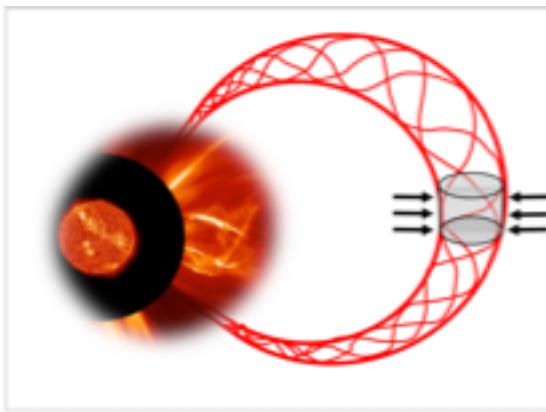
ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes



- a closed magnetic structure
 - Initially empty of GCR
 - Locally of cylindrical form
- Moves with constant velocity

First proposed by Morrison, 1956, PhysRev

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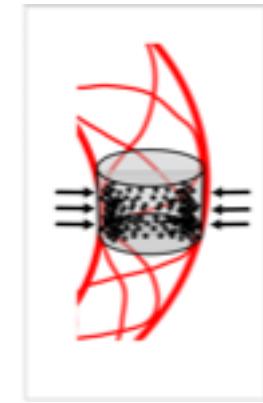
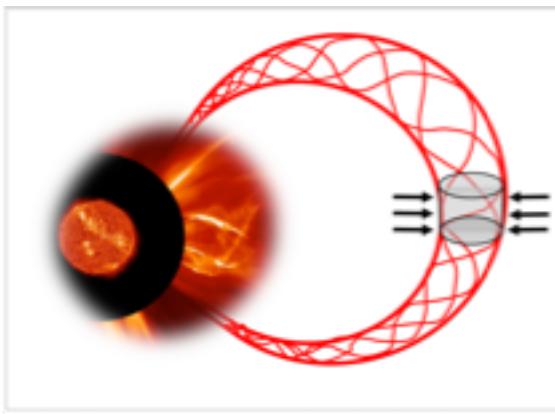


- a closed magnetic structure
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- particles enter by perpendicular diffusion and slowly fill the structure

First proposed by Morrison, 1956, PhysRev

Similar to e.g. Cane+, 1995, ICRCproc;
Quenby+, 2008, JGR

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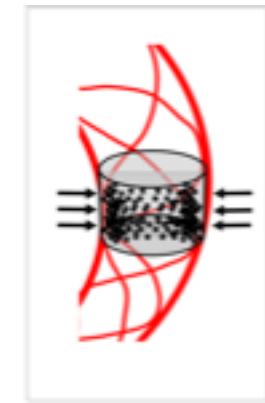
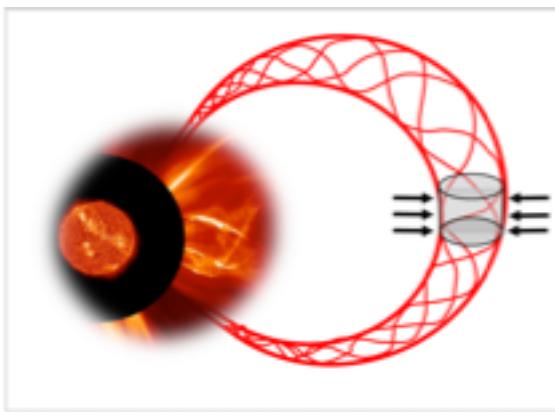
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$$U(r, t) = U_0 \left(1 - J_0(\alpha_1 r) e^{-\alpha_1^2 f(t)} \right)$$

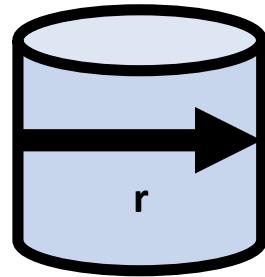
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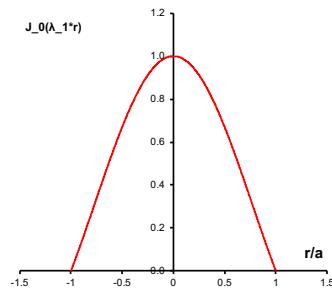


TIME PART

Axial symmetry



Bessel function 0th order



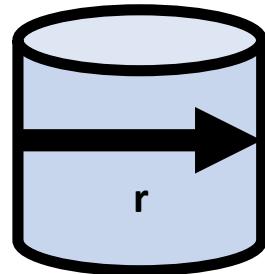
Symmetric + normalized

ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes

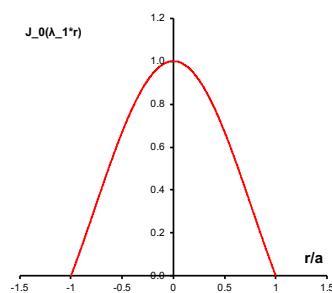
$$U(r, t) = U_0 \left(1 - J_0(\alpha_1 r) e^{-\alpha_1^2 f(t)} \right)$$

SPACE PART

Axial symmetry

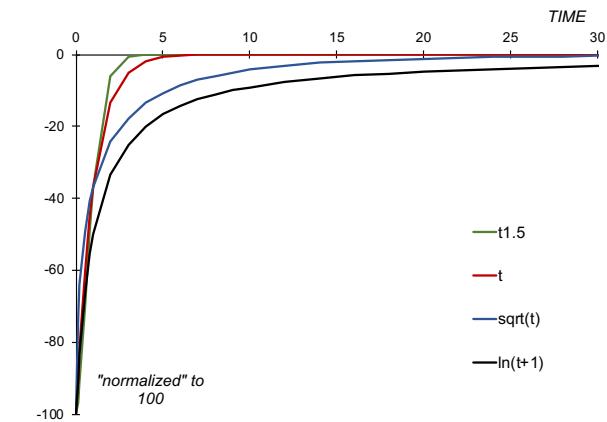


Bessel function 0th order



Symmetric + normalized

TIME PART



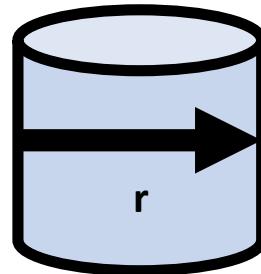
Exponential function of time

ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes

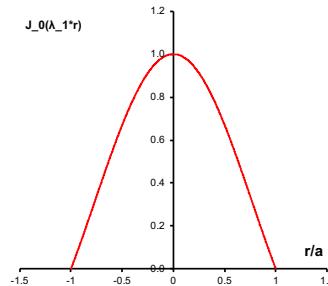
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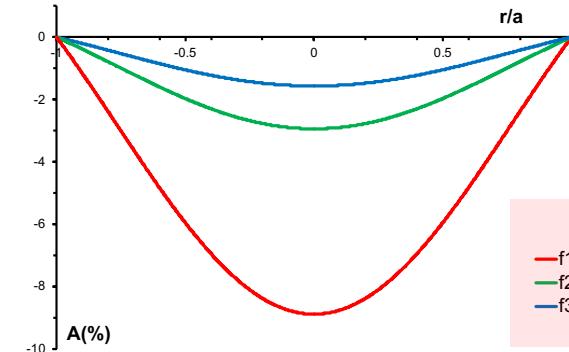
Axial symmetry



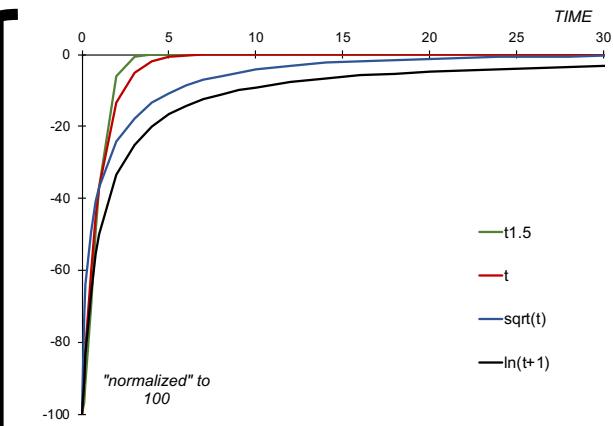
Bessel function 0th order



Symmetric + normalized



TIME PART



Exponential function of time

ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes

$$f(t) = \int D(t)/a(t)^2 dt$$

ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes

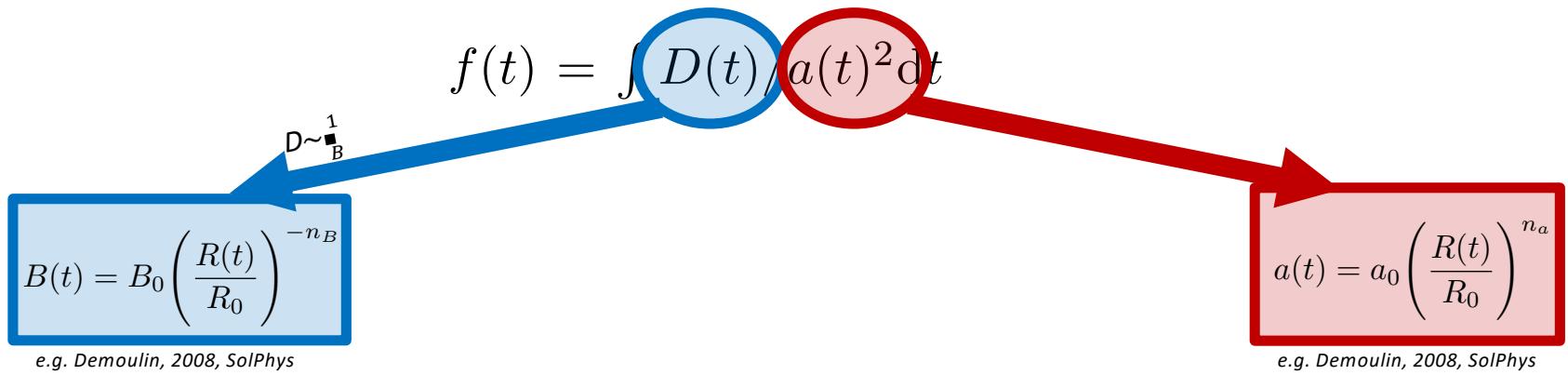
$$f(t) = \int D(t)/a(t)^2 dt$$

$$D \sim \frac{1}{B}$$

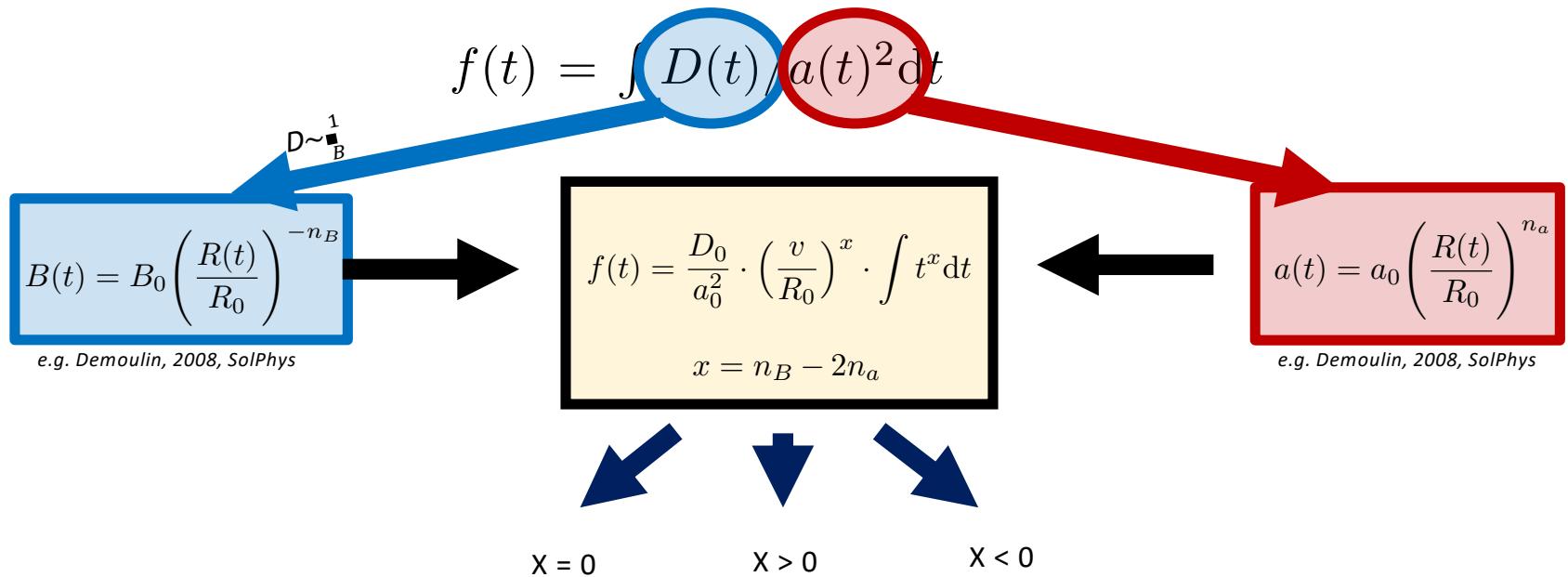
$$B(t) = B_0 \left(\frac{R(t)}{R_0} \right)^{-n_B}$$

e.g. Demoulin, 2008, SolPhys

ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes



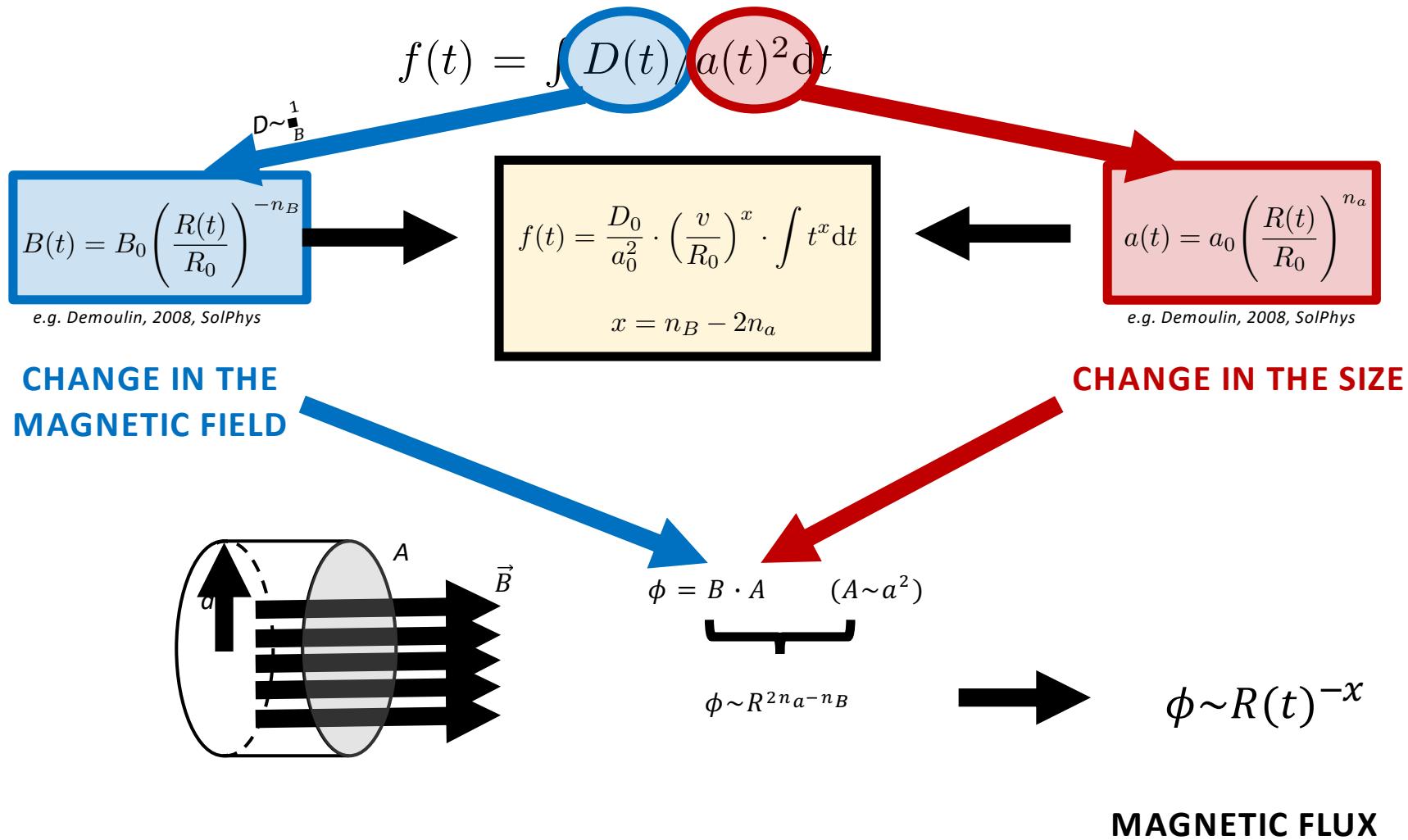
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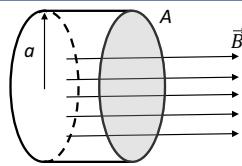
COMPETITION

BETWEEN **CHANGE IN THE MAGNETIC FIELD**
AND THE **CHANGE IN THE SIZE**

ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes



ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes

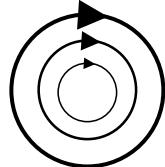


$$\phi \sim R(t)^{-x}$$
$$x = n_B - 2n_a$$

MAGNETIC FLUX

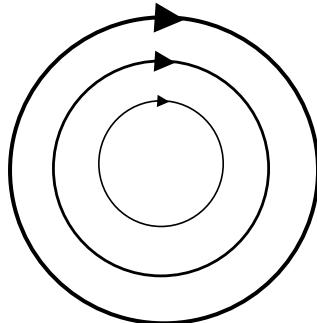
X = 0

(magnetic flux conserved)

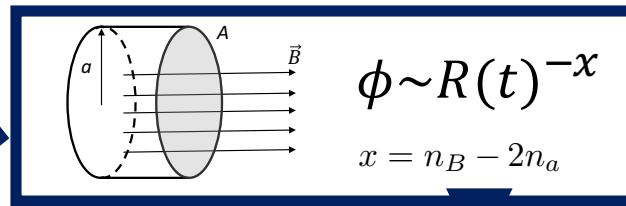


$$\phi_1 = \phi_2$$

Increase in A
countered by the
decrease in B



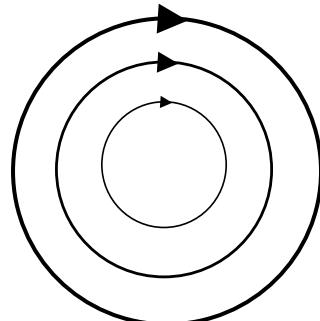
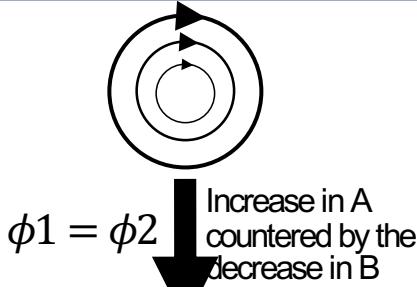
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MAGNETIC FLUX

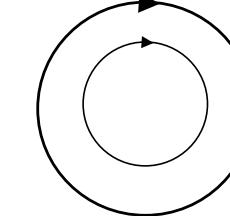
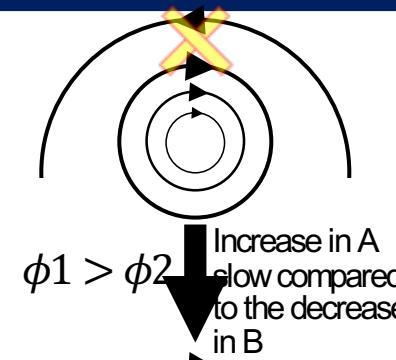
$X = 0$

(magnetic flux conserved)



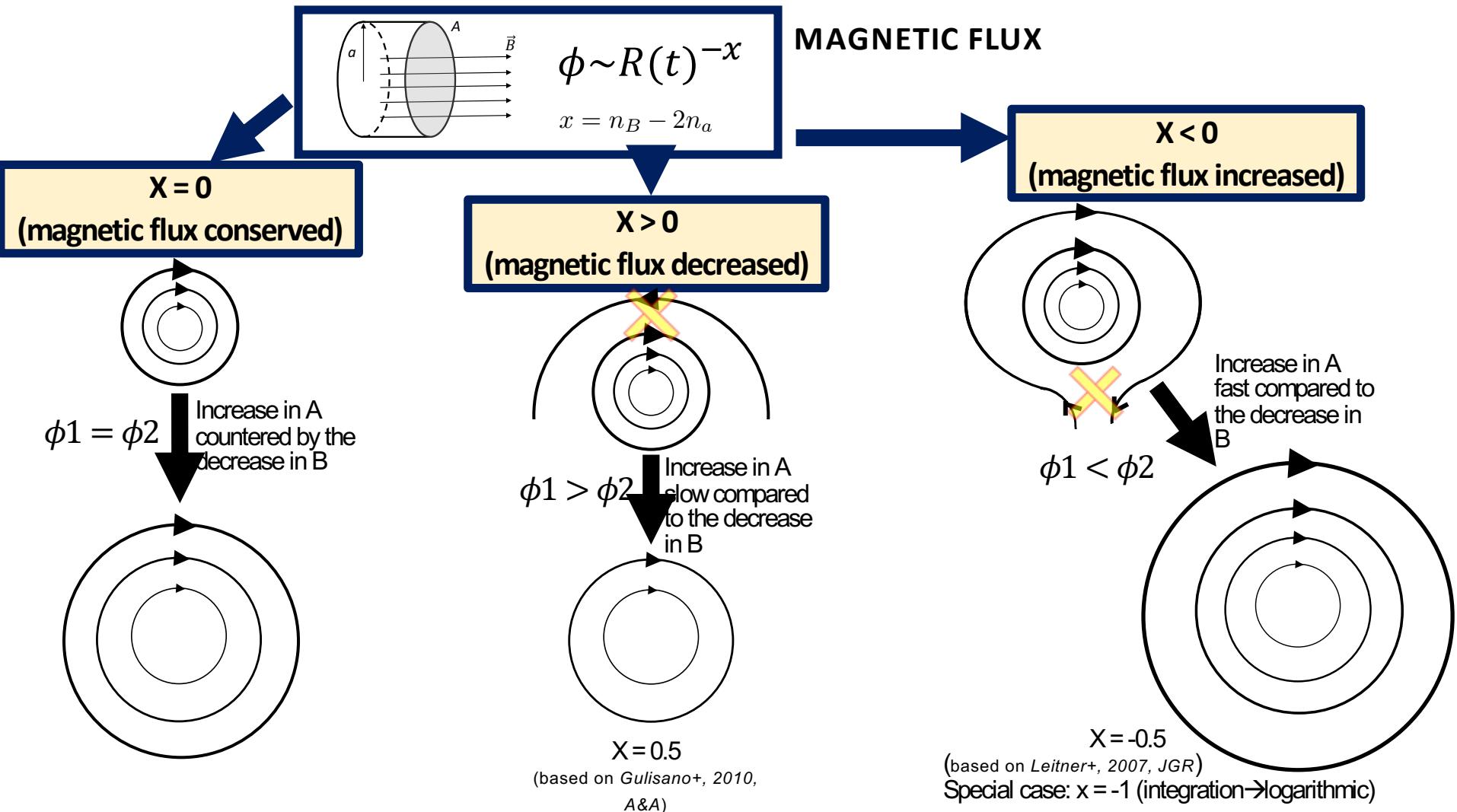
$X > 0$

(magnetic flux decreased)

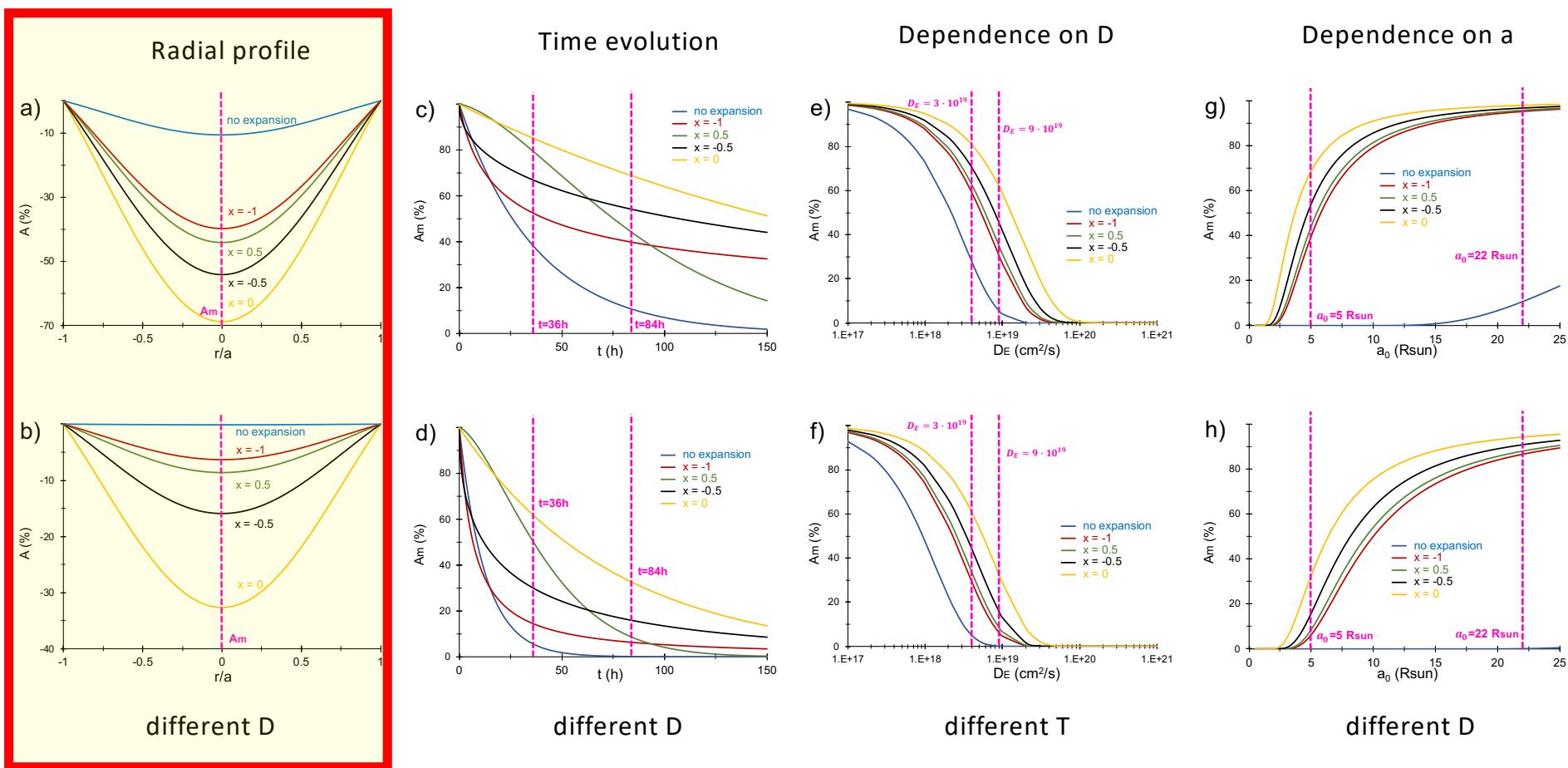


$X = 0.5$
(based on Gulisano+, 2010,
A&A)

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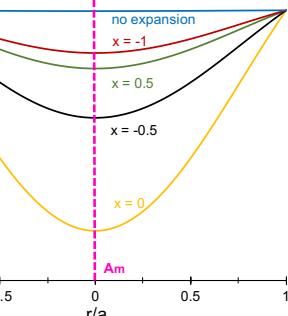
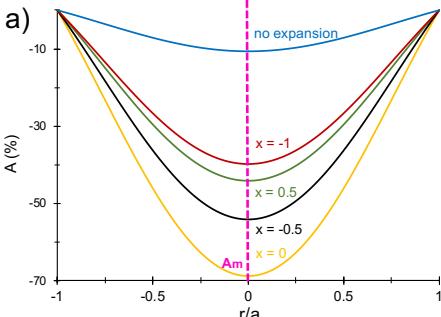


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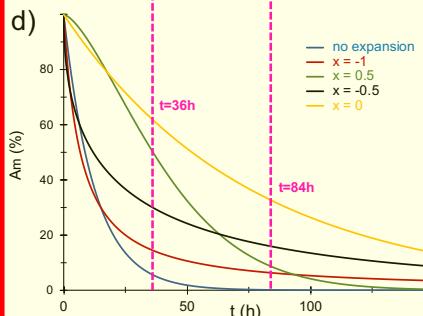
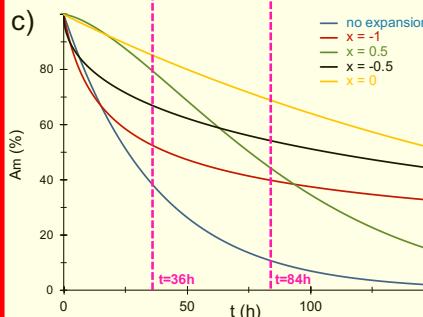
ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes

Radial profile



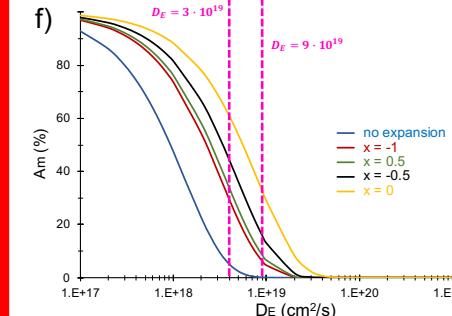
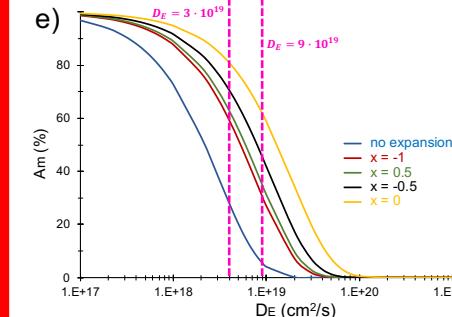
different D

Time evolution



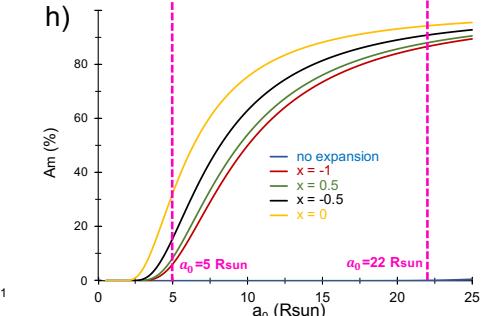
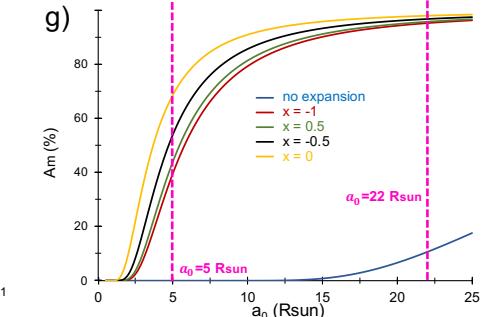
different D

Dependence on D



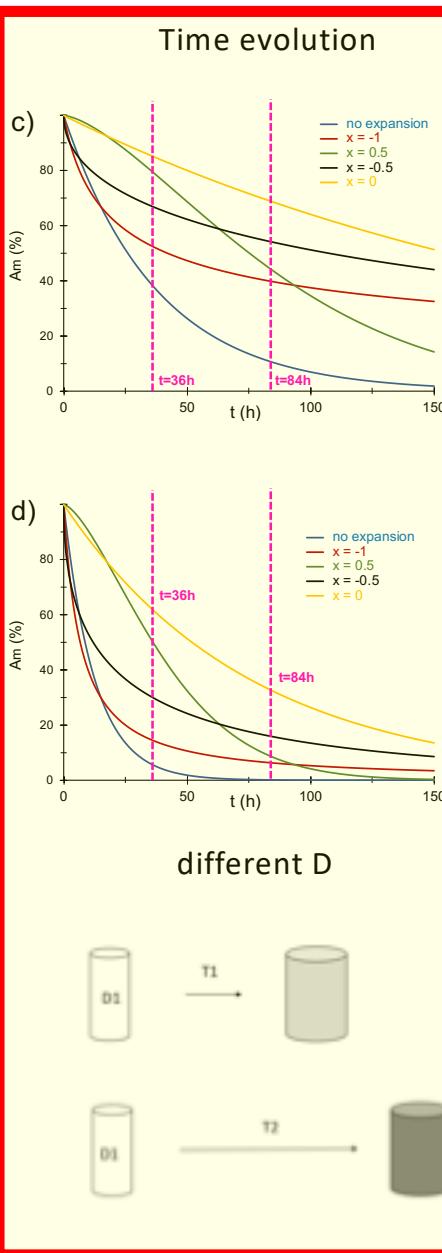
different T

Dependence on a



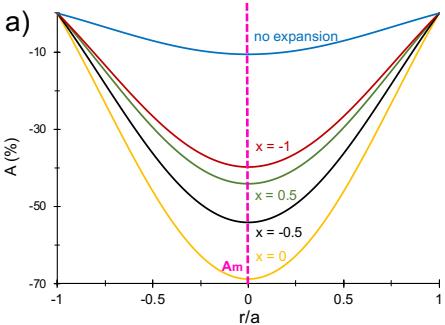
different D

**COMPLEX
INTERPLAY OF
DIFFUSION AND
EXPANSION**

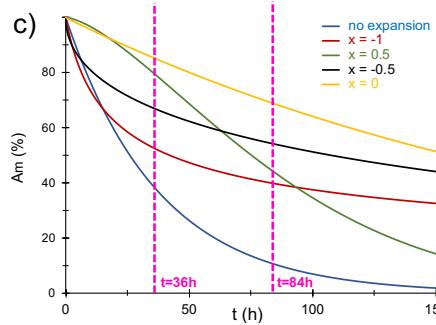


ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes

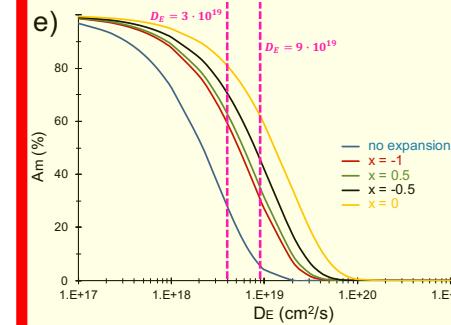
Radial profile



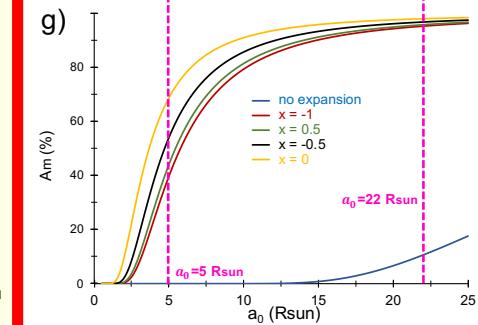
Time evolution



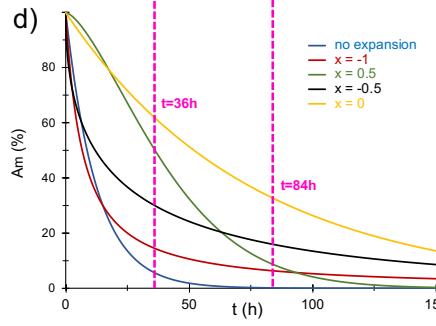
Dependence on D



Dependence on a

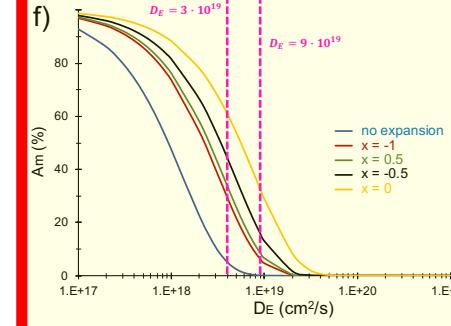


different D



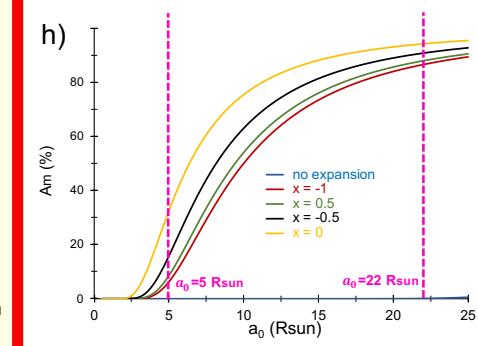
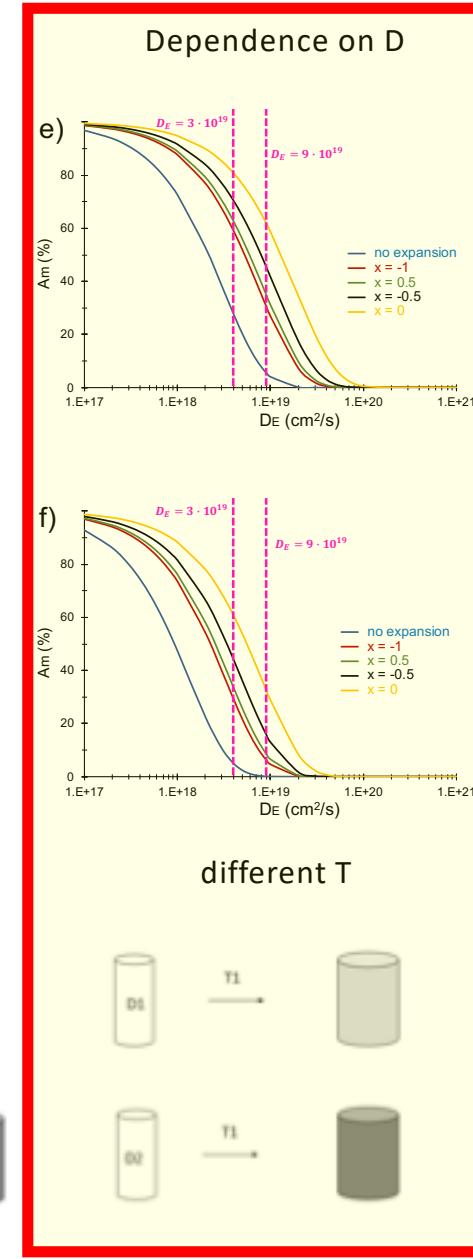
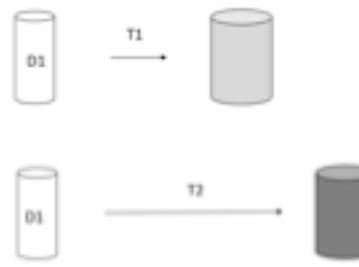
different D

different T



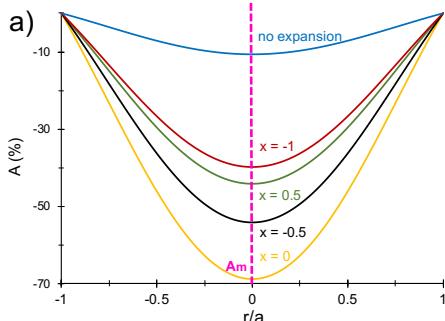
different D

COMPLEX INTERPLAY OF DIFFUSION AND EXPANSION

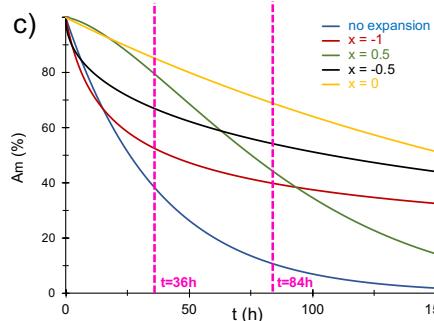


ForbMod = analytical diffusion-expansion model for Forbush decreases caused by flux ropes

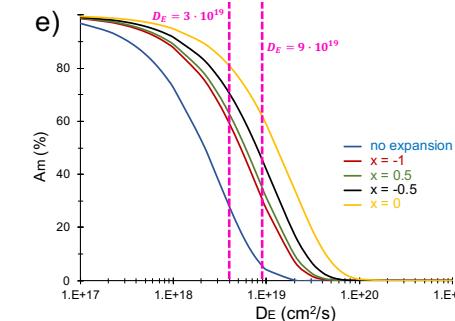
Radial profile



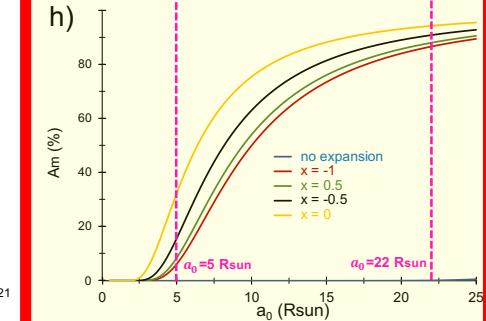
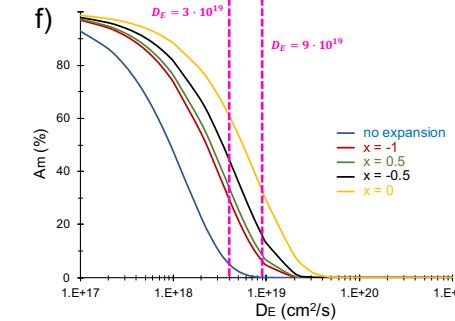
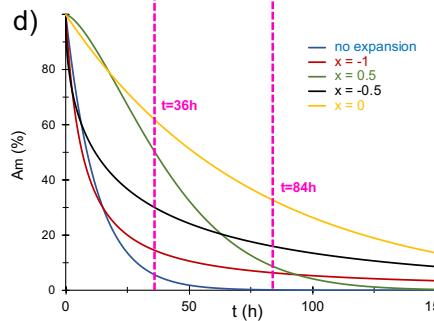
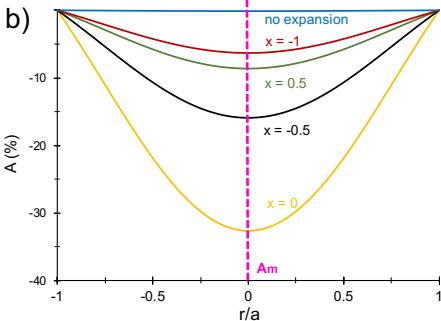
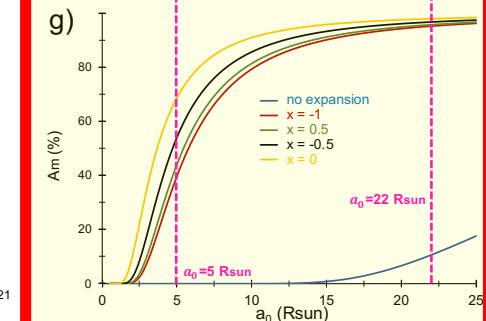
Time evolution



Dependence on D



Dependence on a



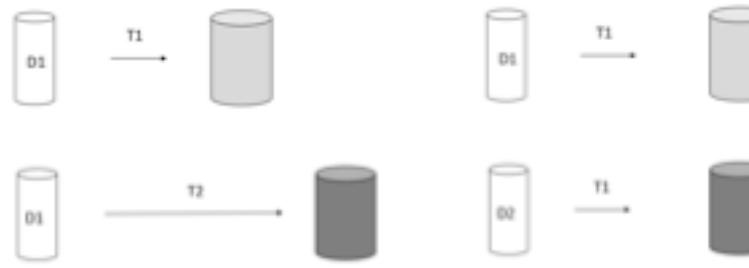
different D

different D

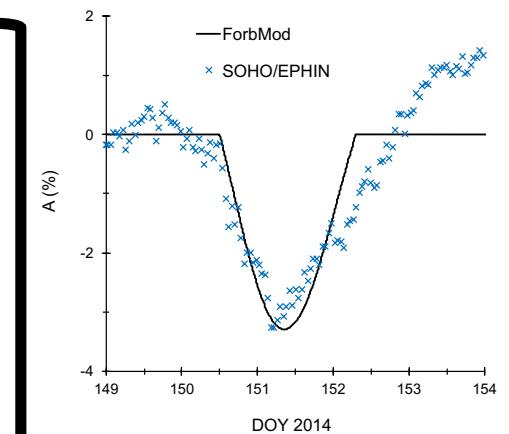
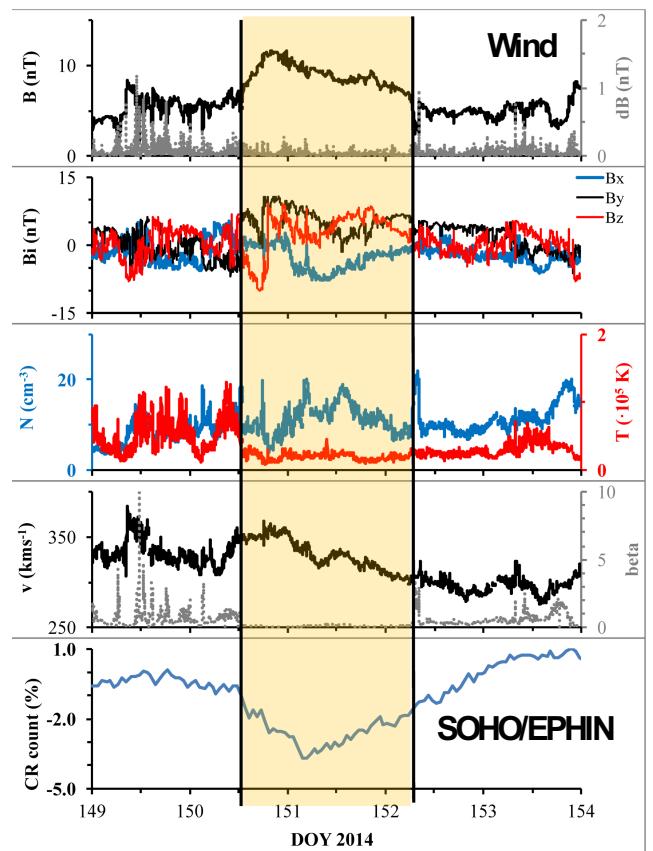
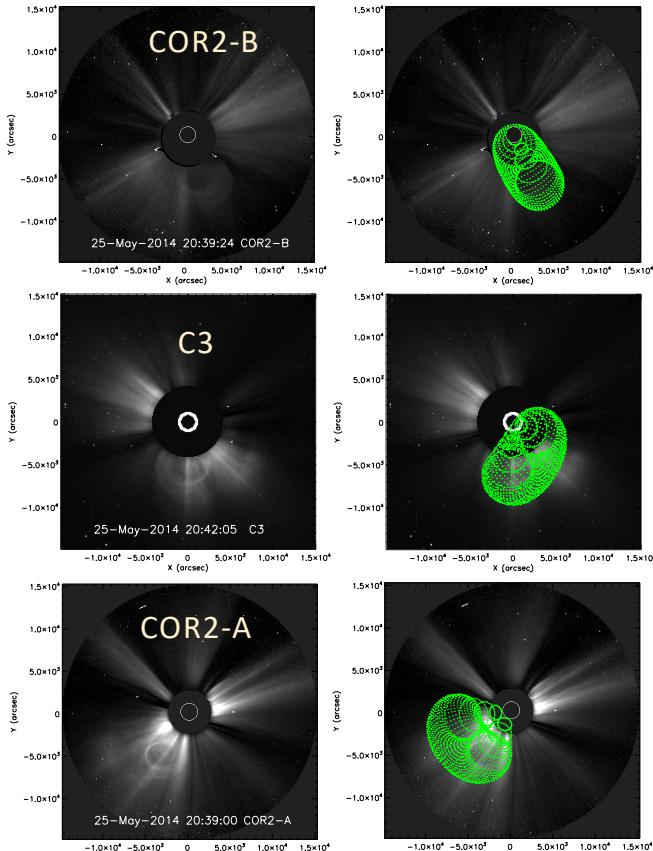
different T

different D

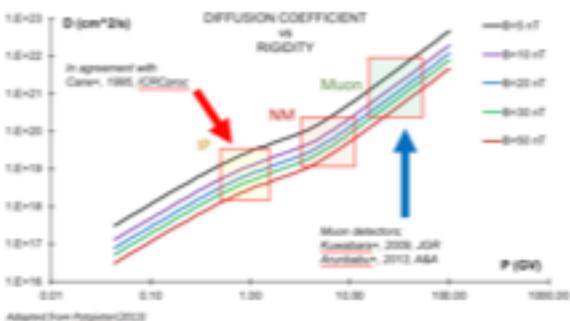
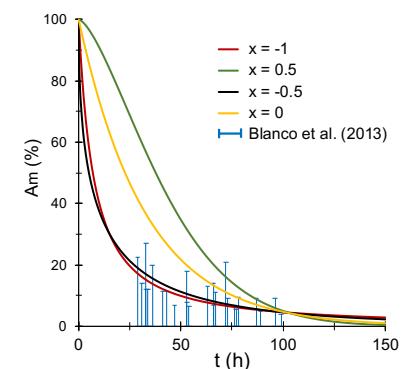
COMPLEX INTERPLAY OF DIFFUSION AND EXPANSION



THE CASE STUDY – TEST EVENT



BEST FIT
(diffusion coefficient free parameter)



TIME EVOLUTION
model compared to
observations from a
statistical study by
Blanco+, 2013
(error bars = possible
ejecta only FD range)

```

jupyter ForbMod.ipynb (ipykernel, started 2019-01-17 14:13:17) [autoreload]
File Edit View Insert Cell Kernel Widgets Help
In [1]: %matplotlib inline
In [2]: %pylab
Out[2]: 
In [3]: from scipy.special import *
In [4]: import math
In [5]: import numpy.linalg as np
In [6]: from decimal import Decimal

```

DEFINE INPUT AND MODEL PARAMETERS

```

In [7]: # # Parameters
1.0E-05 # A0000 initial density in kg/m^3
1.0E-05 # P0000 initial FD radius in solar radii
1.0E-05 # R0000 initial FD height in solar radii
0.0 # D0000 initial diffusion coefficient at Earth in cm/s
0.0 # T0000 initial temperature at Earth in K
0.0 # # Constants
1.0 # Lambda=pi/2*pi=0.5*pi after zero of the Bessel Function of the order 0
1.0 # mu=1.327714327896971E-05 in cm/s
1.0 # mu=1.490119717E-05 in m/s
1.0 # mu=1.490119717E-05 in m/s
# # CALCULATIONS INPUTS
1.0 # D0000 = 1.0E-05 # D0000 initial diffusion coefficient in cm/s
1.0 # T0000 = 1.0E-05 # T0000 initial temperature in K
1.0 # D0000 = 1.0E-05 # D0000 initial diffusion coefficient in cm/s for expansion cause 1 and 2
1.0 # D0000 = 1.0E-05 # D0000 initial diffusion coefficient in cm/s for expansion cause 3 and 4
1.0 # D0000 = 1.0E-05 # D0000 initial diffusion coefficient in cm/s for expansion cause 5 and 6
1.0 # D0000 = 1.0E-05 # D0000 initial diffusion coefficient in cm/s for expansion cause 7 and 8
1.0 # D0000 = 1.0E-05 # D0000 initial diffusion coefficient in cm/s for expansion cause 9 and 10
# # CALCULATING OUTPUTS
1.0 # F0000, F1000, F2000, F3000, F4000, F5000, F6000, F7000 = ((1/10)_i for i in range(10))
1.0 # time, F1mag1, F2mag1, F3mag1, F4mag1 = ((1/10)_i for i in range(5))

```

CONCLUSIONS & FUTURE WORK

- *ForbMod* is analytical diffusion-expansion model for ejecta-only FDs
- FD amplitude depends on the interplay of diffusion and expansion
- Qualitatively agrees with observation
- Case study indicates quantitative agreement
- **NEXT STEPS: testing and constraints using statistics, FR forward modeling and multispacecraft measurements**

Thank you for your attention!

Acknowledgements:



The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 745782.