Galactic Cosmic-Ray Anisotropy During Forbush Decreases: Evidence for Diffusive Barriers and Large-Scale Flow

G. D. Ihongo[1,2], D. Ruffolo[1], A. Sáiz[1], U. Tortermpun[1], J. W. Bieber[3], and A. C.-L. Chian[4].

1. *Mahidol University, Thailand.*
2. *Benue State University, Nigeria*
3. *University of Delaware, USA.*
4. *University of Adelaide, Australia.*

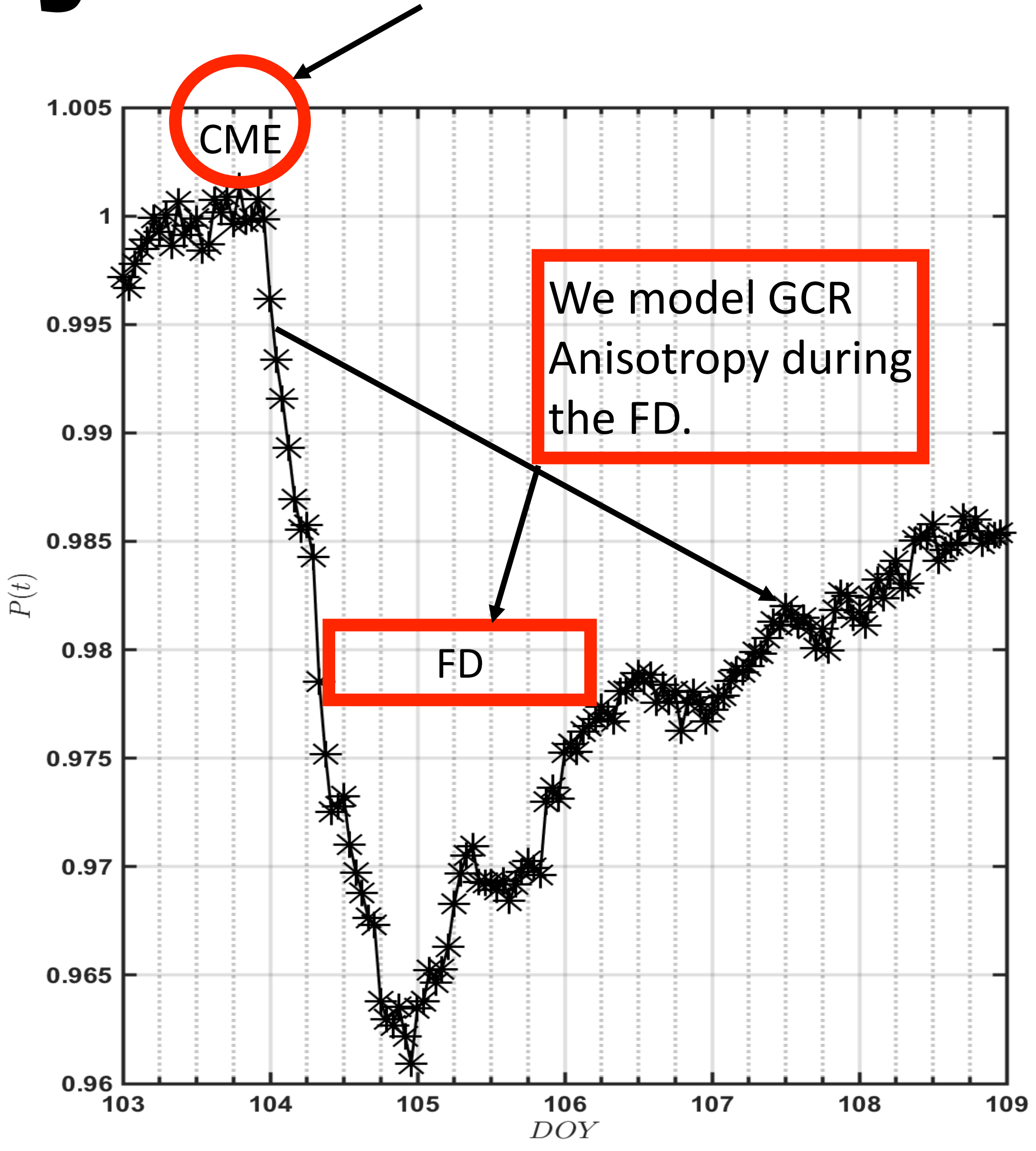
SPONSORS

MAHIDOL UNIVERSITY
Wisdom of the Land

36th International Cosmic Ray Conference - ICRC2019- July 29th, 2019
Madison, WI, U.S.A.

GCR Anisotropy

- The variation in the distribution or flux of GCR during a Forbush decrease (FD).
- It is caused by a shock due to the arrival of a Coronal mass ejection(CME) at Earth.



GCR Anisotropy

- What can cause GCR anisotropy during a FD?
- If “conical” flux rope, drifts can pull GCRs into one leg, push out of the other
  - Unidirectional parallel anisotropy in the flux rope: Krittinatham and Ruffolo [2009]
- Diffusive anisotropy due to turbulent magnetic fluctuations
  - Parallel to B (scattering)
  - Perpendicular to B: Shalchi [2010], Ruffolo et al [2012]
  - Increasing perpendicular diffusion with increasing $\Delta B/B$
  - Independent of sign of B

Data Information

- GCR counts were obtained from Neutron Monitor Database:

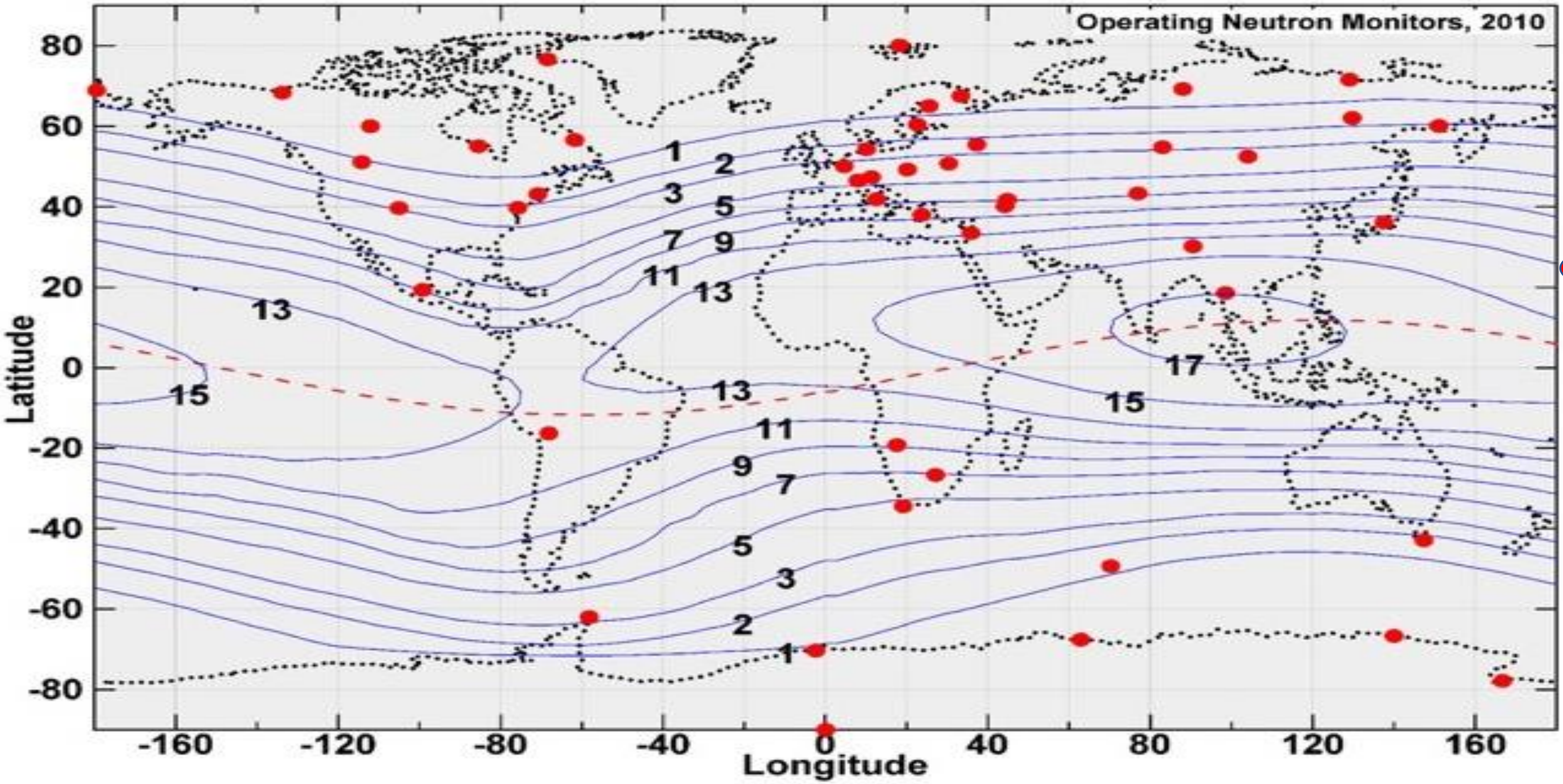
  htp://www.nmdb.eu

- Level 2 data from ACE for the solar wind speed, magnitude (B) and geocentric

  solar-ecliptic (GSE) components of the IMF:

  htp://http://www.srl.caltech.edu/ACE/ASC.

Operating NM Stations as of 2010



KEY

NM Stations

Credit: Pyle

Method

- The first order anisotropy of GCRs (δ) can be determined from the count rate of NM station n at a given time (t), using the following general equation

$$A_n(t) = \sum_{l=0}^{8} w_l \int_{P_{min,n,l}}^{P_{max}} \left(\frac{-dN(P_c)}{dP_c} |_P \right) T_{n,l}(P) \frac{P}{D(t)+P} \times \{1 + [\delta_x(t) + \chi_x(t,P)] n_{n,l,x}(t,P) + \left[\delta_y(t) + \chi_y(t,P)\right] n_{n,l,y}(t,P) + [\delta_z(t) + \chi_z(t,P)] n_{n,l,z}(t,P)\} dP$$

- Where l is the sum over 9 directions with weights; 1/2 for vertical direction and 1/16 for the other 8 directions, $N(P_c)$, is the NM response function, $T(l,P)$ is the transmission function,

Method

- δ_x, δ_y, and δ_z are the first order anisotropy in GEOx, GEOy , and GEOz-components respectively.
- χ is the Compton-Getting anisotropy, and is defined as

$$\boxed{\chi(P) = \gamma(P)\frac{\boldsymbol{u}}{v}, \text{ and } \gamma(P) \equiv \frac{\mathrm{dlog}f}{\mathrm{dlog}P}.}$$

- And $\boldsymbol{n}(t, P)$ for the asymptotic directions of GCRs at NM stations.
- We first normalize the count rates to pre-Forbush decrease event.
- Determine the North-south anisotropy in GEO Coordinates, using normalized count rates at Thule (T(t)) and Mcmurdo (M(t)) from

Method

$$\frac{T(t)-M(t)}{2P_t(t)} = \frac{\sum_{l=0}^{8} w_l \int_{P_{min,n,l}}^{P_{max}} \left(\frac{-dN(P_c)}{dP_c}|_P\right) T_{n,l}(P) \frac{P}{D(t)+P} [\delta_z(t)+\chi_z(t,P)]\left[n_{T,l,z}(t,P)-n_{M,l,z}(t,P)\right] dP}{2\sum_{l=0}^{8} w_l \int_{P_{min}}^{P_{max}} \left(\frac{-dN(P_c)}{dP_c}|_P\right) dP}$$

- And we simultaneously fit all the station to determine the GEOx and GEOy components

$$\frac{C_n(t)}{C_{n,d}(t)} = \frac{A_n(t)}{B_n(t)}$$

Where

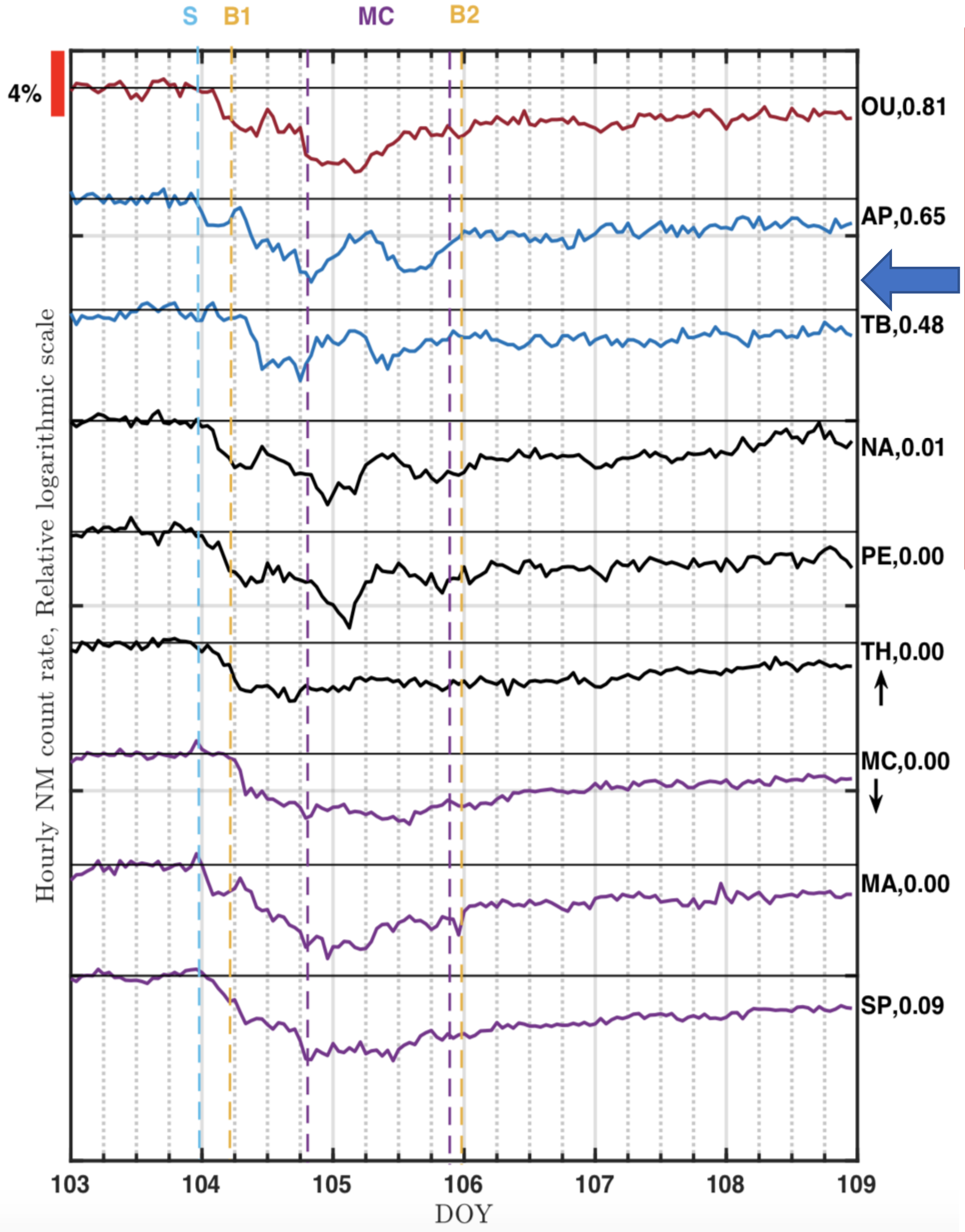
$$C_{n,d}(t) = \frac{1}{2}[C_n(t) + \left(\frac{C_n^{-}(t)+C_n^{+}(t)}{2}\right) - \frac{1}{4}\left(\frac{C_n^{--}(t)+C_n^{++}(t)}{2} - C_n(t)\right)],$$

$$B_n(t) = \sum_{l=0}^{8} w_l \int_{P_{min,n,l}}^{P_{max}} \left(\frac{-dN(P_c)}{dP_c}|_P\right) T_{n,l}(P) \frac{P}{D(t)+P} \times \{1 + [\delta_z(t)+\chi_z(t,P)] n_{n,l,z}(t,P)\} dP.$$

Results

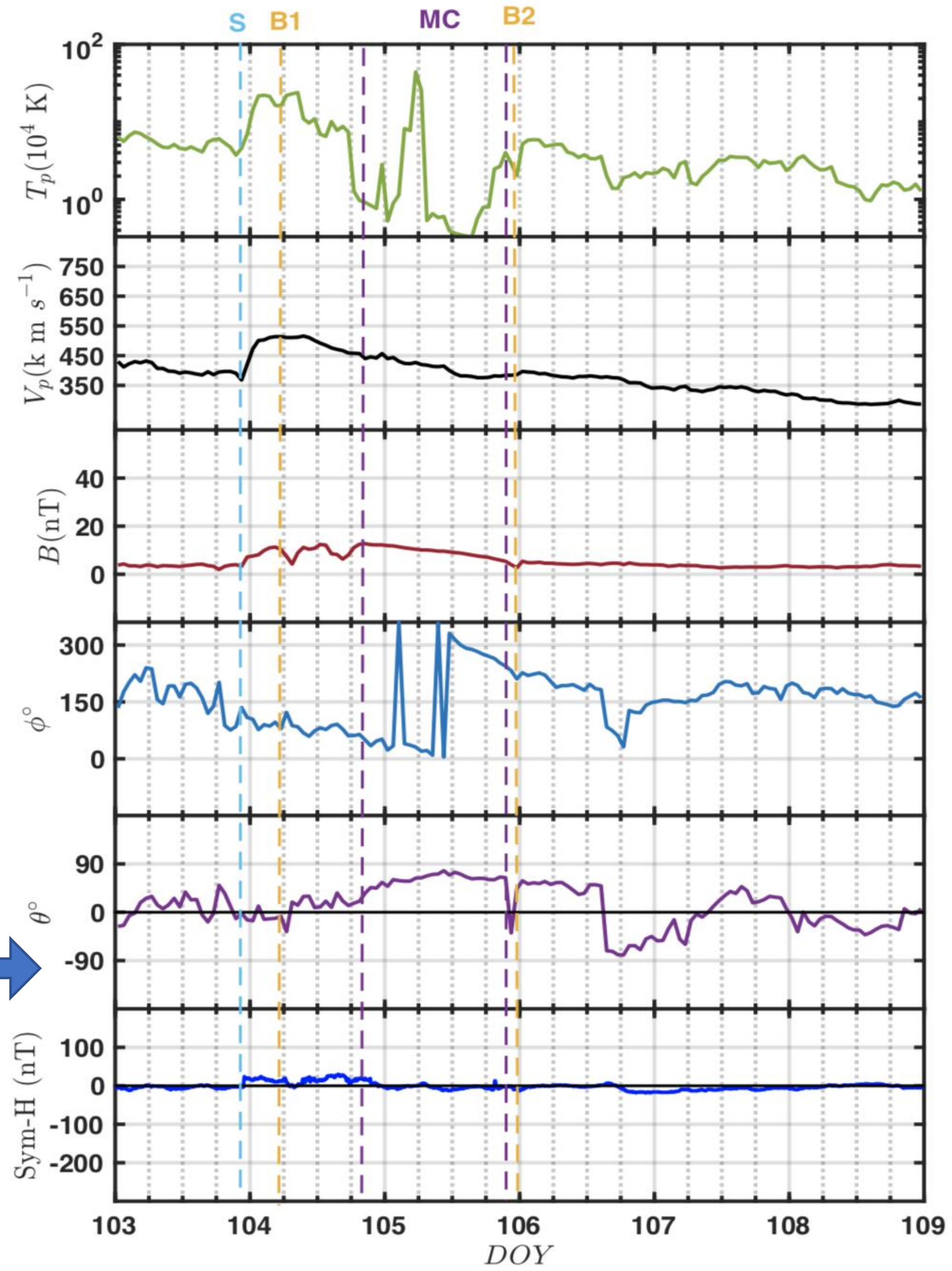
- In order to accurately interpret our results;
- We first analyze plasma and magnetic field data to identify the distinct structures in the interplanetary coronal mass ejections (ICMEs)
- Alongside hourly count rates from NM stations before, during and after the Forbush decrease.
- The figures in the next slides shows the results of our analysis for the Forbush decreases starting April 13, 2013 and February 17, 2011

Results: April 2013

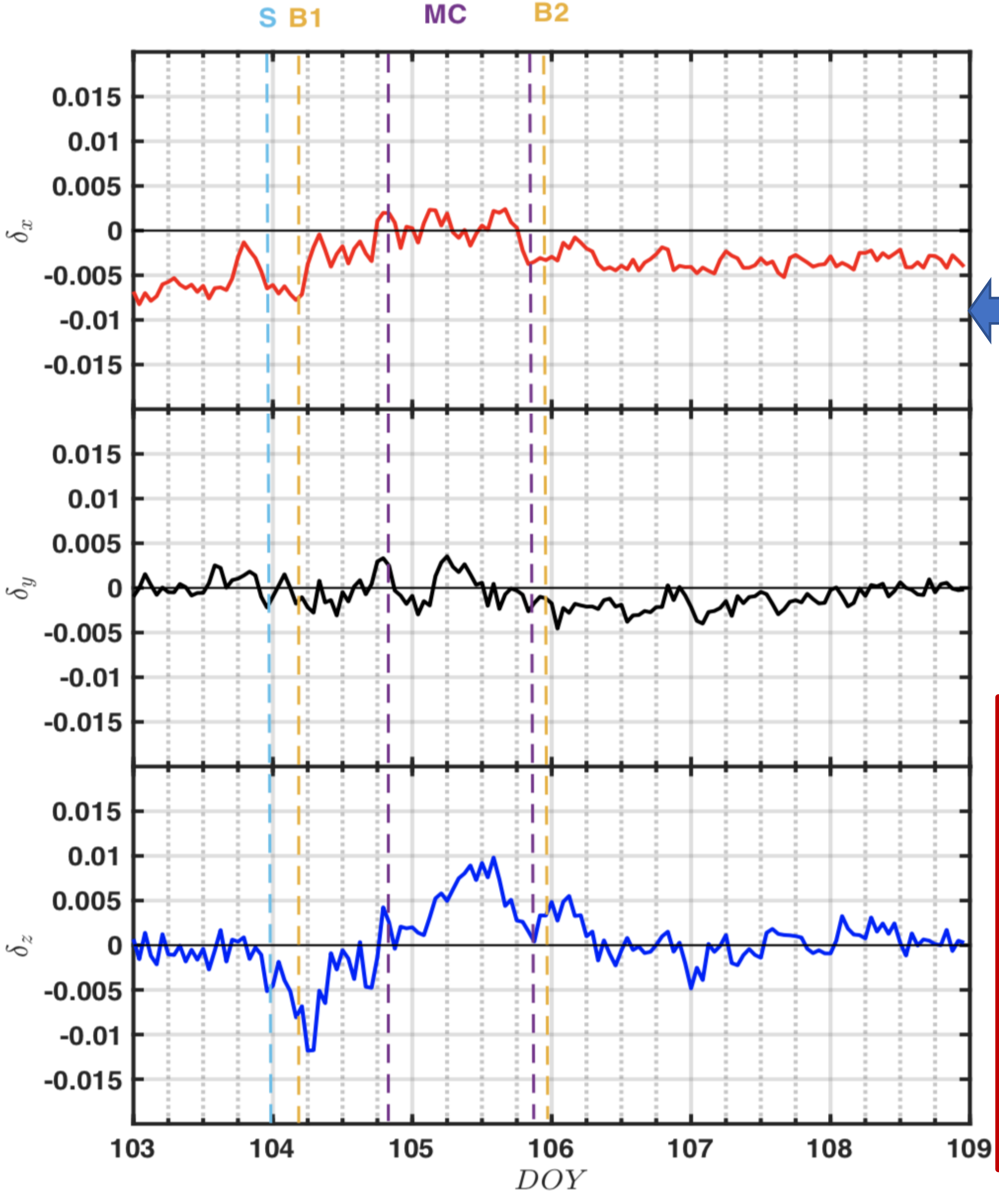


NM count rates before and after the Forbush decrease

Plasma and IMF parameters before and after the Forbush decrease

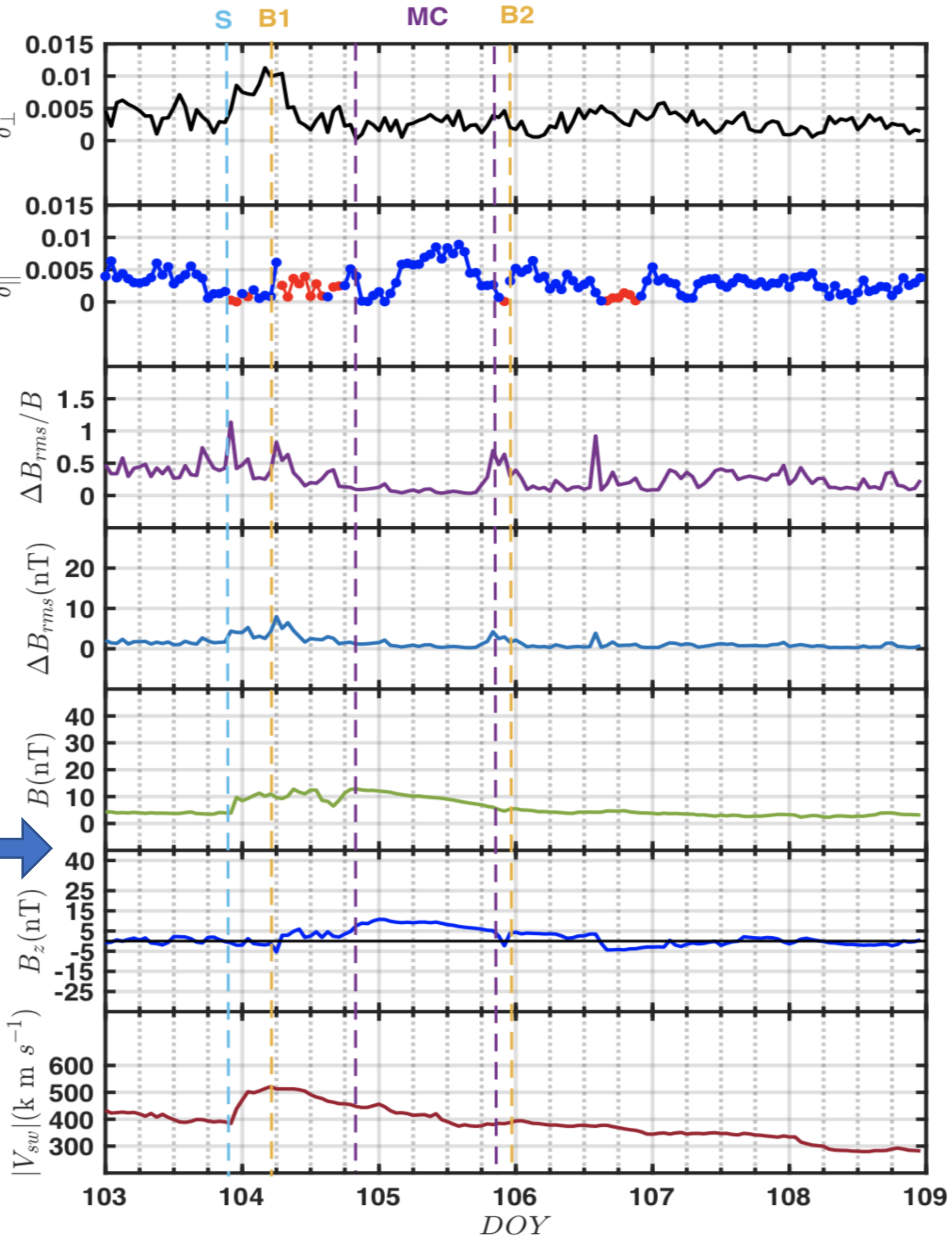


Results: April 2013

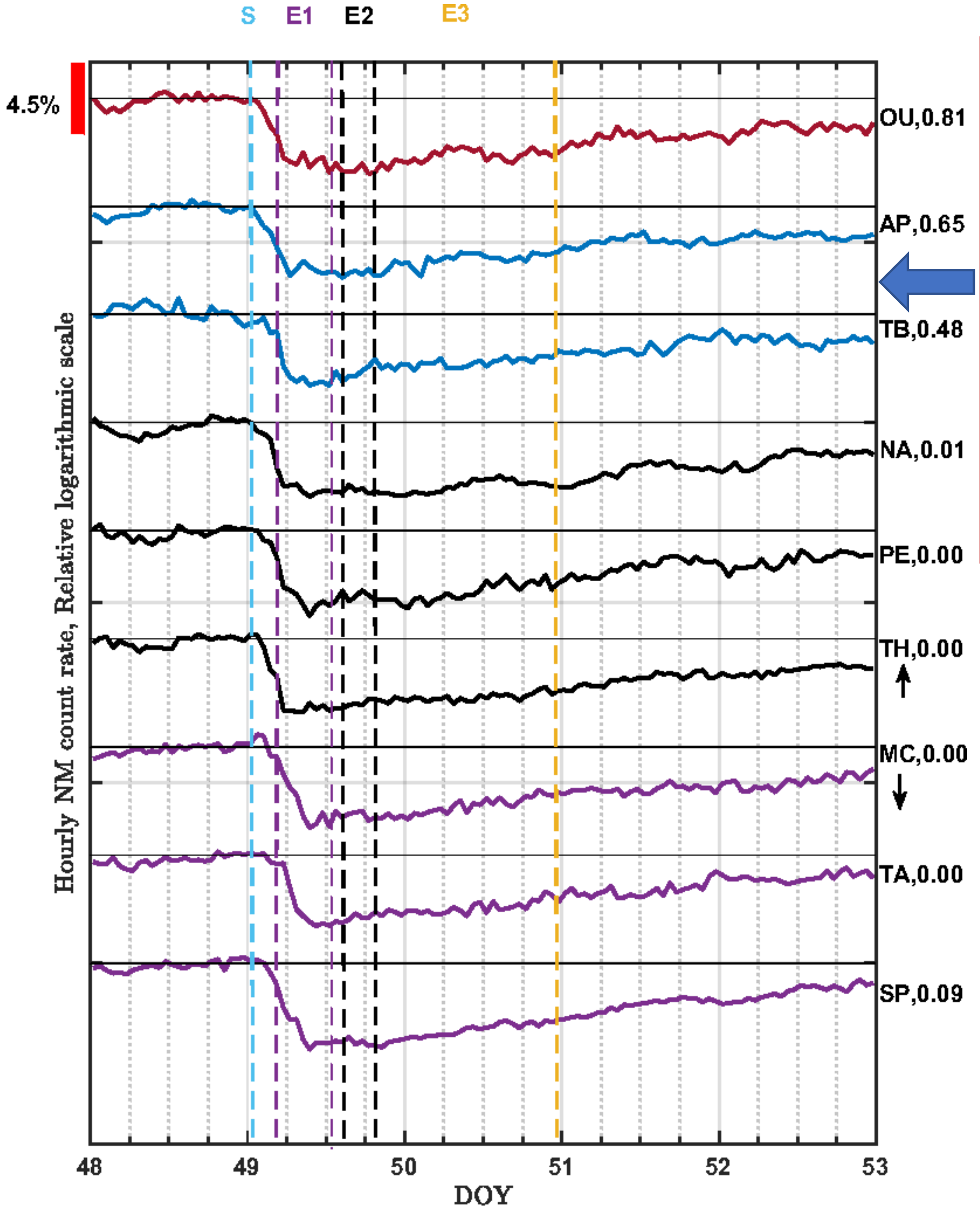


1st order anisotropy in the solar wind frame during 2013 April 13-18.

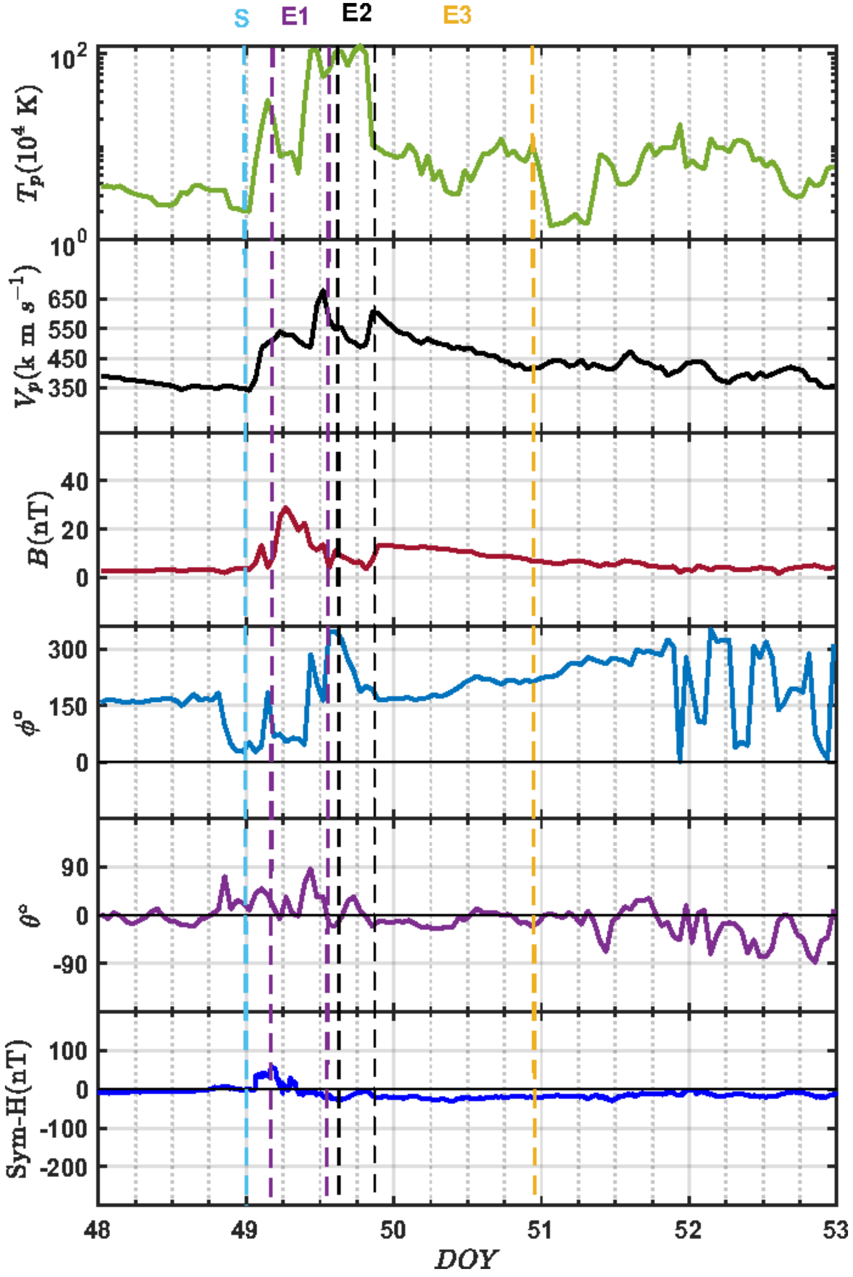
1st order anisotropy magnitude parallel and perp. to **B**



Results: February 2011

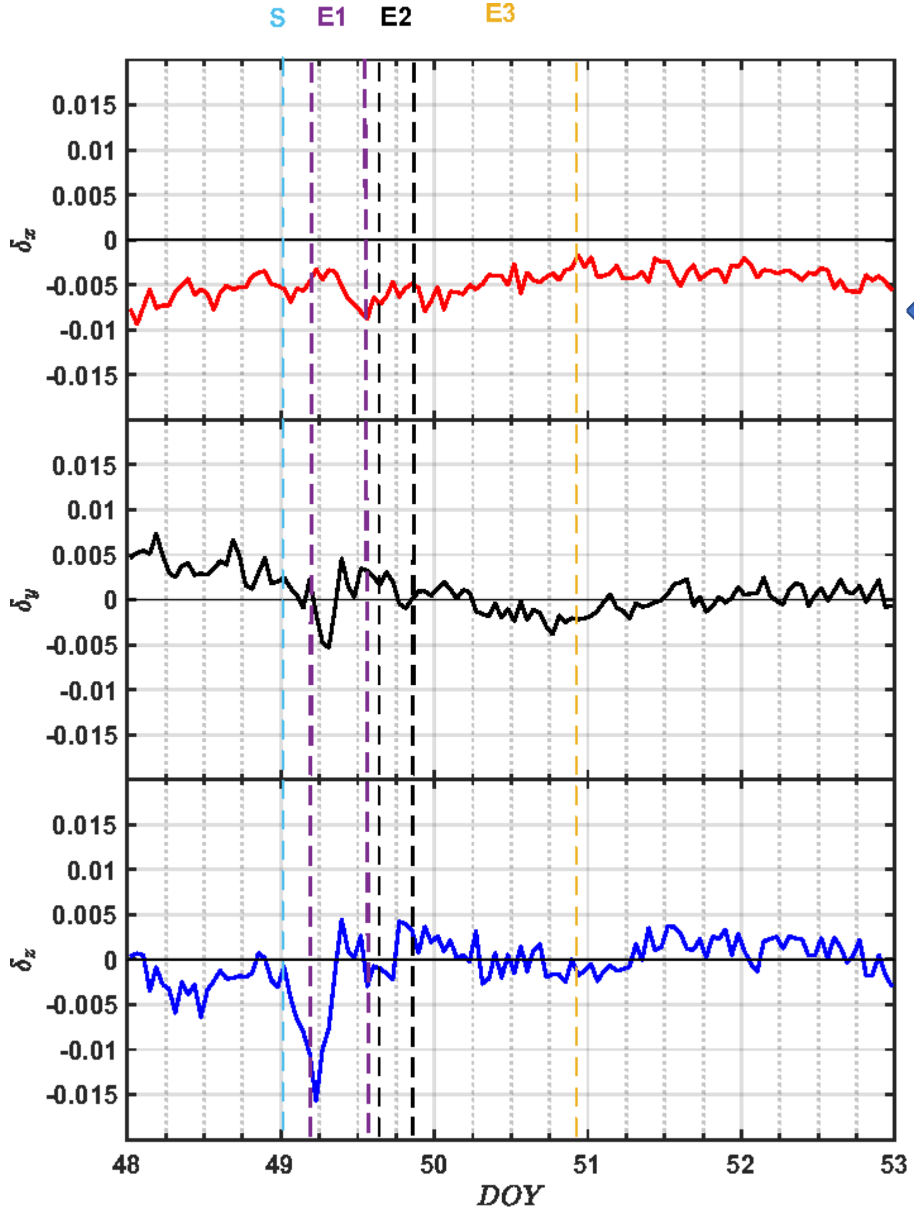


NM count rates before and after the Forbush decrease



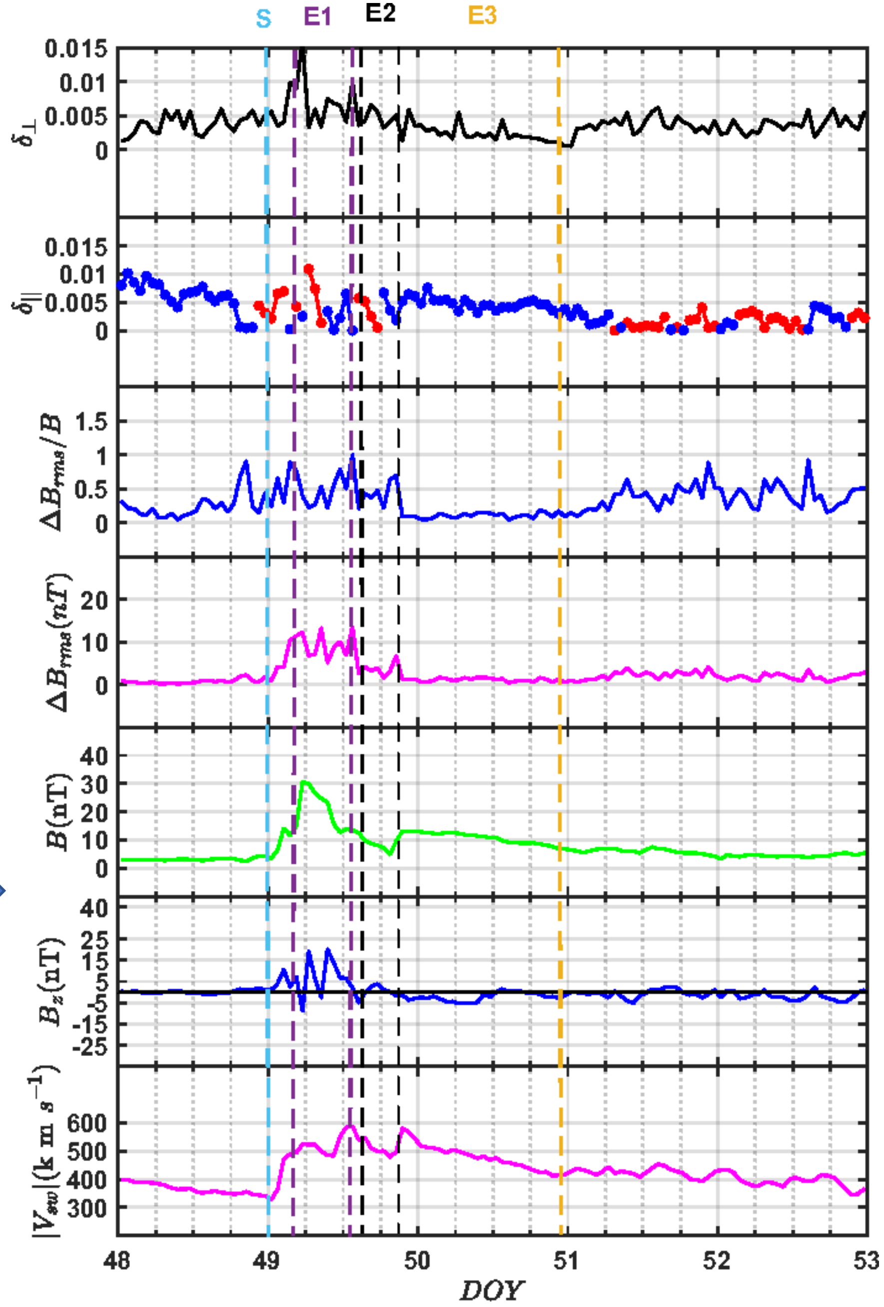
Plasma and IMF parameters before and after the Forbush decrease

Results: February 2011



1st order anisotropy in the solar wind frame during 2011 Feb. 17-21

1st order anisotropy magnitude parallel and perp. to **B**



Summary

- For the FD starting on 2013 April 13, we find that:
- There is an increase in $\delta_{\perp}$ at times with stronger rms fluctuation $\Delta B_{rms}/B$
- This is consistent with diffusive anisotropy and theories of perpendicular diffusion.
- In contrast, $\delta_{\parallel}$ was generally lower during times with stronger magnetic fluctuations and higher during times of weak fluctuations, for instance, within a CME flux rope where magnetic fluctuations are very weak.
- This is in good agreement with theoretical expectations that strong fluctuations can cause strong cosmic ray scattering leading to low parallel diffusion coefficient.

Summary

- This is also consistent with the idea that a parallel diffusive barrier is responsible for the decrease of cosmic ray flux in the sheath region.
- These results, along with the near constancy of parallel anisotropy across magnetic field reversals, are consistent with diffusive barriers causing the decrease in GCR flux before the arrival of the flux rope.
- Within the CME flux rope there was a strong parallel anisotropy in the direction predicted from a theory of drift motions into one leg of the magnetic flux rope and out the other Krittinatham and Ruffolo (2009), confirming that the anisotropy can remotely sense a large-scale flow of GCRs through a magnetic flux rope.

References

1. Tortermpun, U., Ruffolo, D. and Bieber J. W. 2018, The Astrophysical Journal Letters, 852: L26.
2. Forbush, S. E. 1937, Phys. Rev, 51, 1108.
3. Krittinatham, W., and Ruffolo, D. 2009, ApJ, 704, 831.
4. Shalchi, A. 2010, ApJL, 720, L127.
5. Ruffolo, D., et al 2012, ApJL, 747, L34.