Voyager 2 Observations of the Anisotropy of Anomalous Cosmic Rays in the Heliosheath

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Alternate title: Where and How are ACRs accelerated?

Introduction

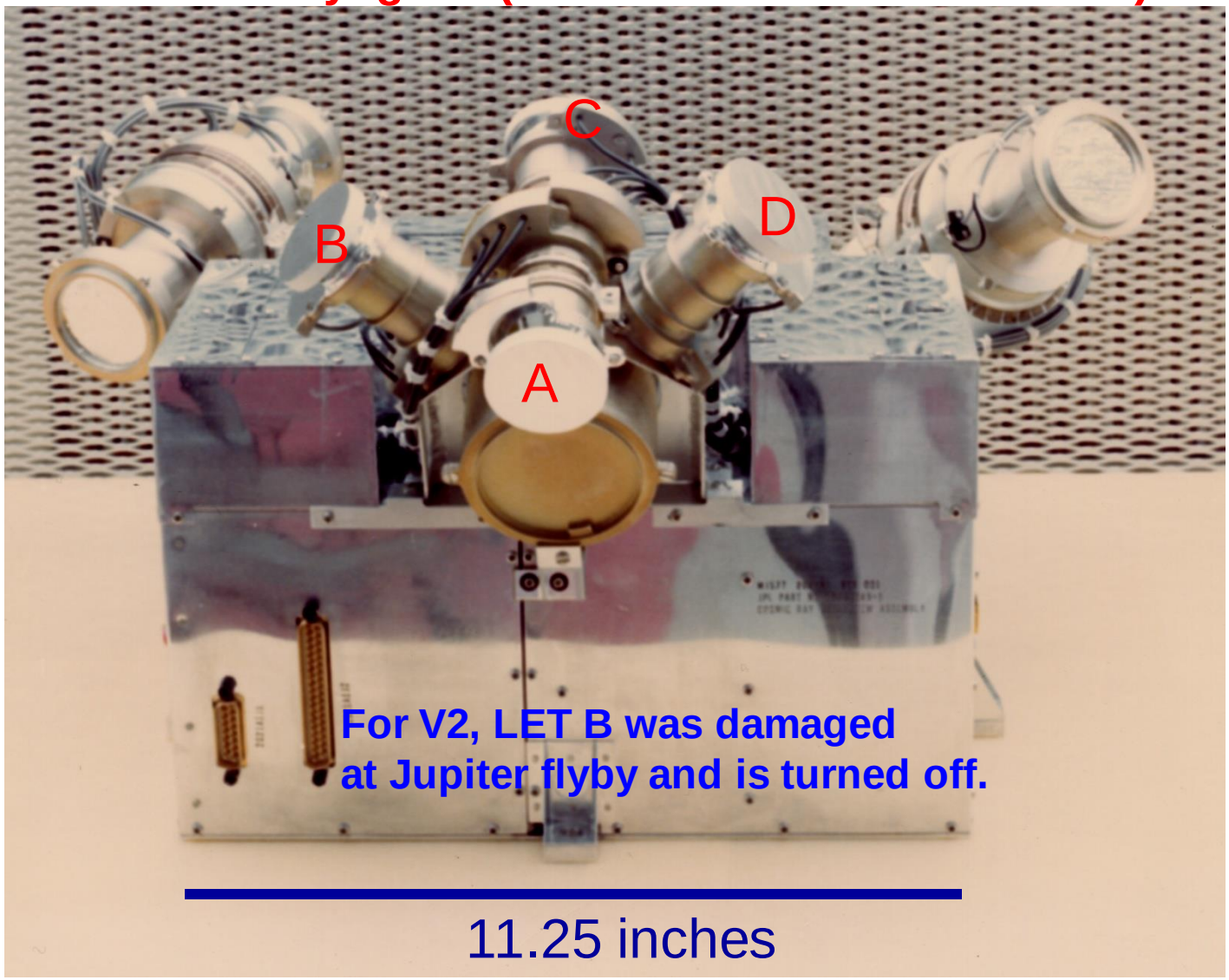
- **Brief review:**
  - **ACRs begin as neutral atoms in the interstellar medium; they drift into the heliosphere; become ionized; picked up by the magnetic field lines frozen into the expanding solar wind and accelerated somewhere in the heliosphere by some process – everyone agrees on this scenario.**
- **Prior to the termination shock (TS) crossing by V1 on 16 December 2004, almost everyone thought the TS was the place where the acceleration occurred via diffusive shock acceleration.**
- **Neither V1 nor V2 observed the expected energy spectrum from DSA at the TS.**
- **Instead, the energy spectra unfolded to the expected shape as the Voyagers moved deeper into the inner heliosheath.**
- **Among the theories that ensued, one noted that it still could be the TS doing the work via DSA, but doing it further back along the flank or tail where the magnetic field line Voyager is on would be connected to the shock long enough to accelerate the particles to ACR energies and where the injection energy could be lower. (McComas & Schwadron, 2006; Kota, 2008; Kota and Jokipii, 2006)**
- **The unfolding spectra would result from a diffusive flow of these flank/tail ACRs towards the nose region where the Voyagers are located.**
- **If so, one would expect to observe an anisotropy in the intensity: $J_A = Jo*(1 + \delta_f \cdot A)$, where A denotes a particular telescope's boresight vector (LET A in this case).**
  - **(this δ_f denotes direction particles are coming from and is the way the analysis was done; $\delta_{true} = -1.193*\delta_f$ is direction of flow and the 1.193 corrects for wide opening angle of telescopes)**
- **The diffusive anisotropy δ_d would be obtained from $\delta_d = \delta_{true} - \delta_{CG}$, where δ_{CG} is the solar wind convective anisotropy due to the Compton-Getting effect.**

Introduction (continued)

- $\delta_{CG} = < (2 - 2\gamma)/v) > V$ **where the average is over the energy spectrum, dJ/dE = AE$^{\gamma}$, v = particle speed, and V = solar wind speed.**

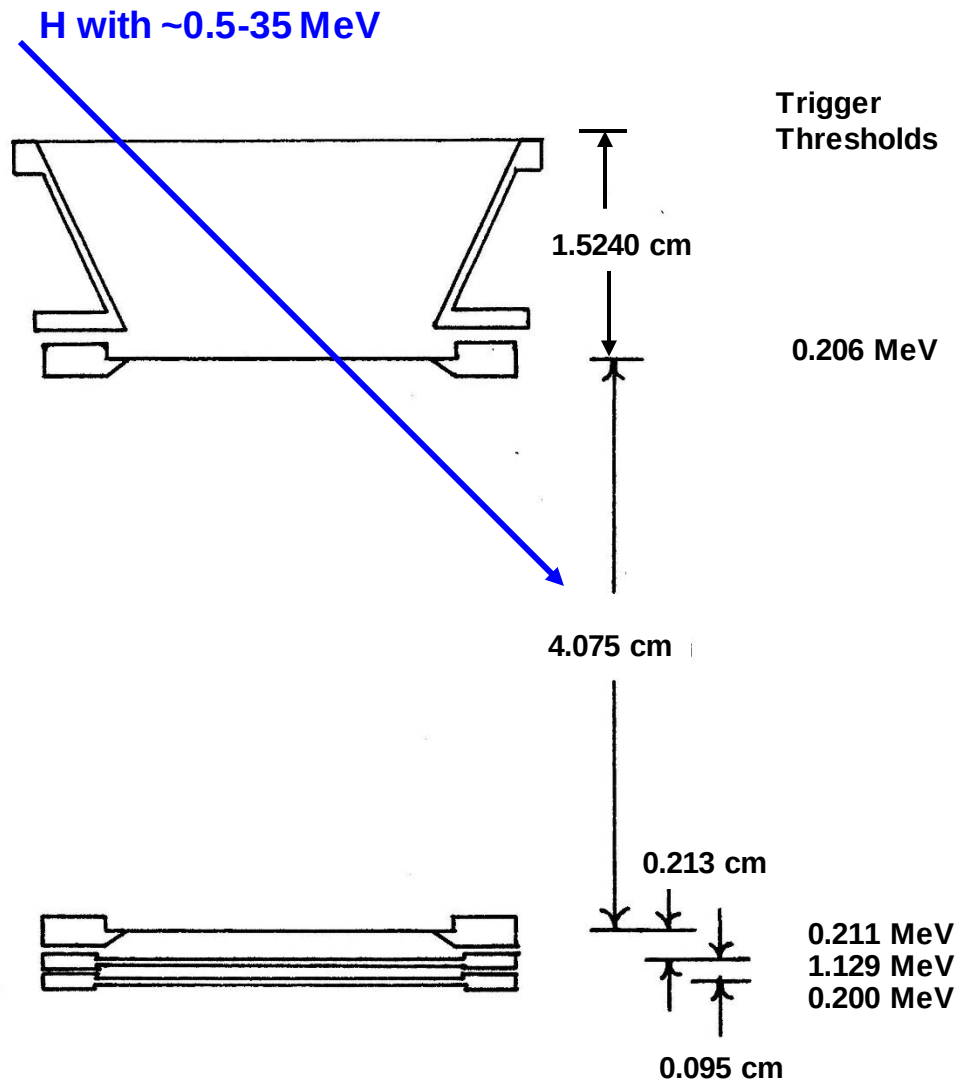
- **Result: We do find a diffusive anisotropy of 0.5-35 MeV protons, consistent with a flow from the flank or tail of the heliosphere towards the nose.**

CRS on Voyager 1 (identical for LETs A-D on V2)



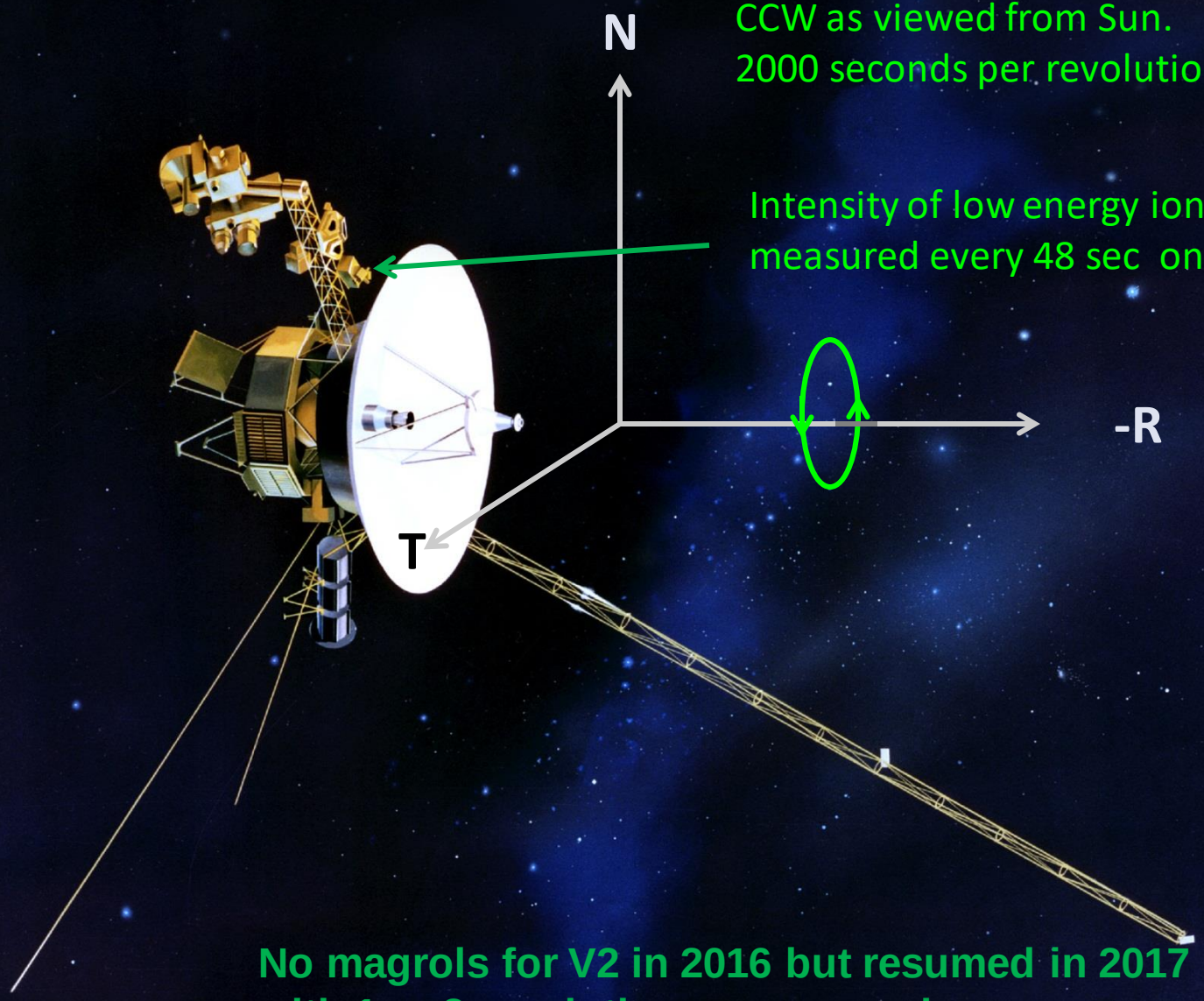
LET A telescope on Voyager 2

detector	Perpendicular thickness	radius
window	3 μm Al (3.47 μm Si)	1.7695 cm
L1	33.53 μm Si	0.9471 cm
L2	35.34 μm Si	0.9491 cm
L3	447.9 μm Si	1.1263 cm
L4	448.6 μm Si	1.1332 cm



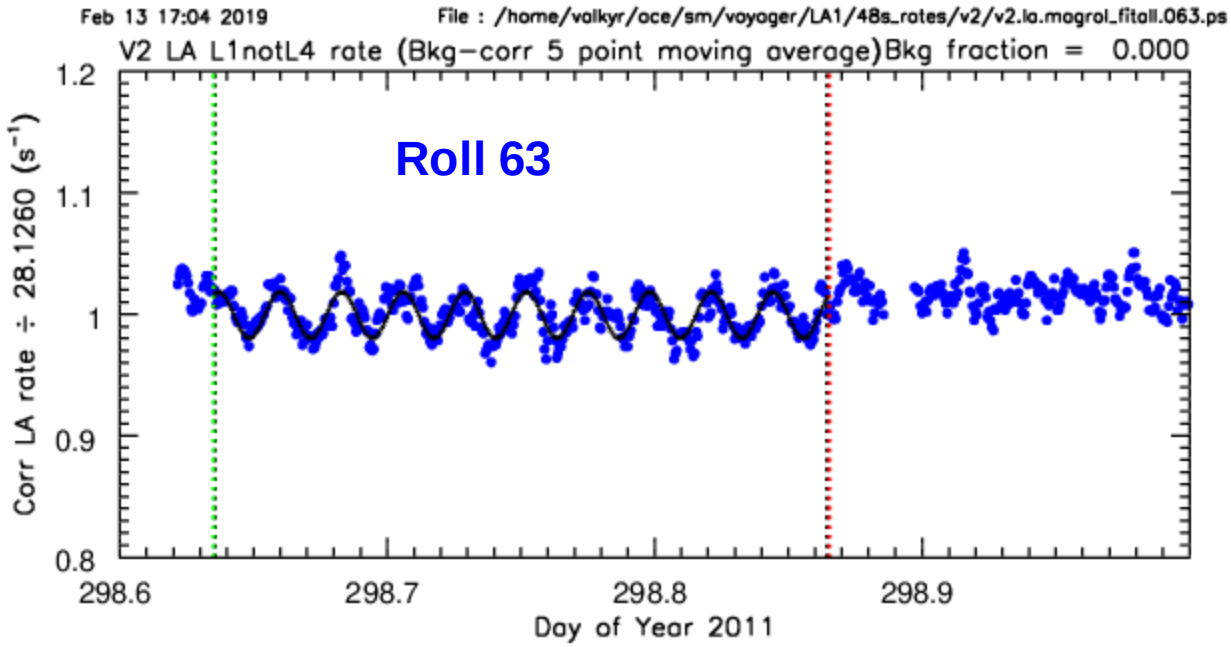
Coincidence equation for rates used in magrols is often window.L1.L4 but sometimes window.L1.

”magrols” = 1-10 revolutions about R axis CCW as viewed from Sun. 2000 seconds per revolution.

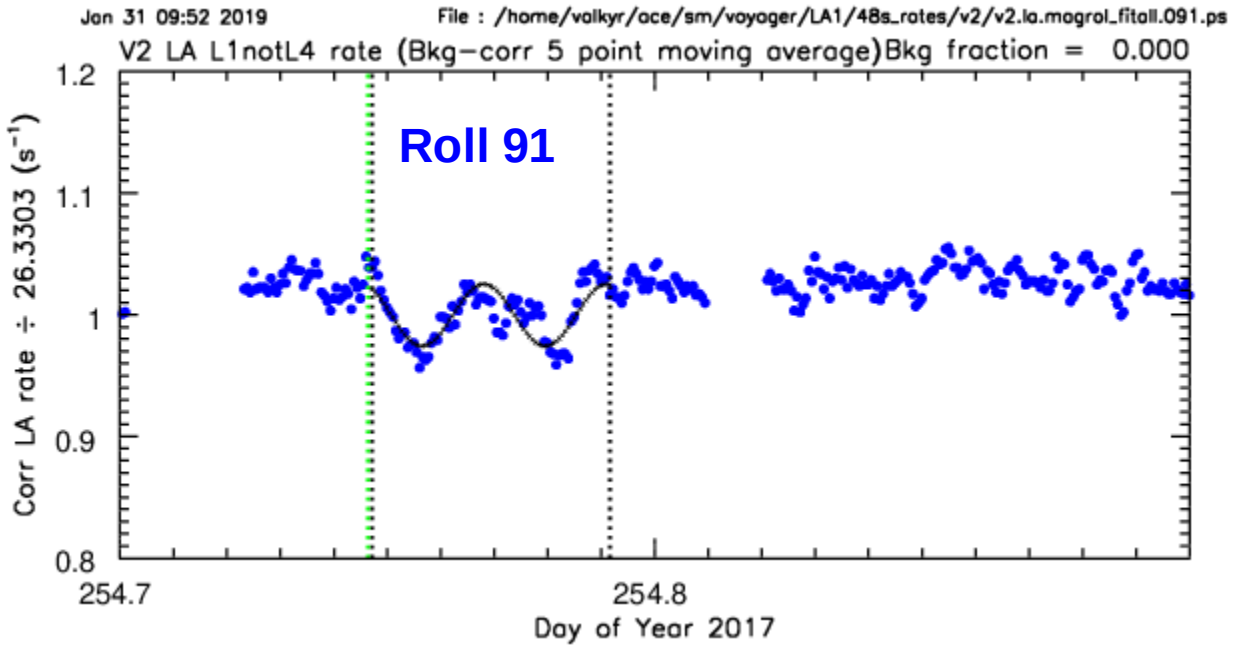


Intensity of low energy ions measured every 48 sec on CRS.

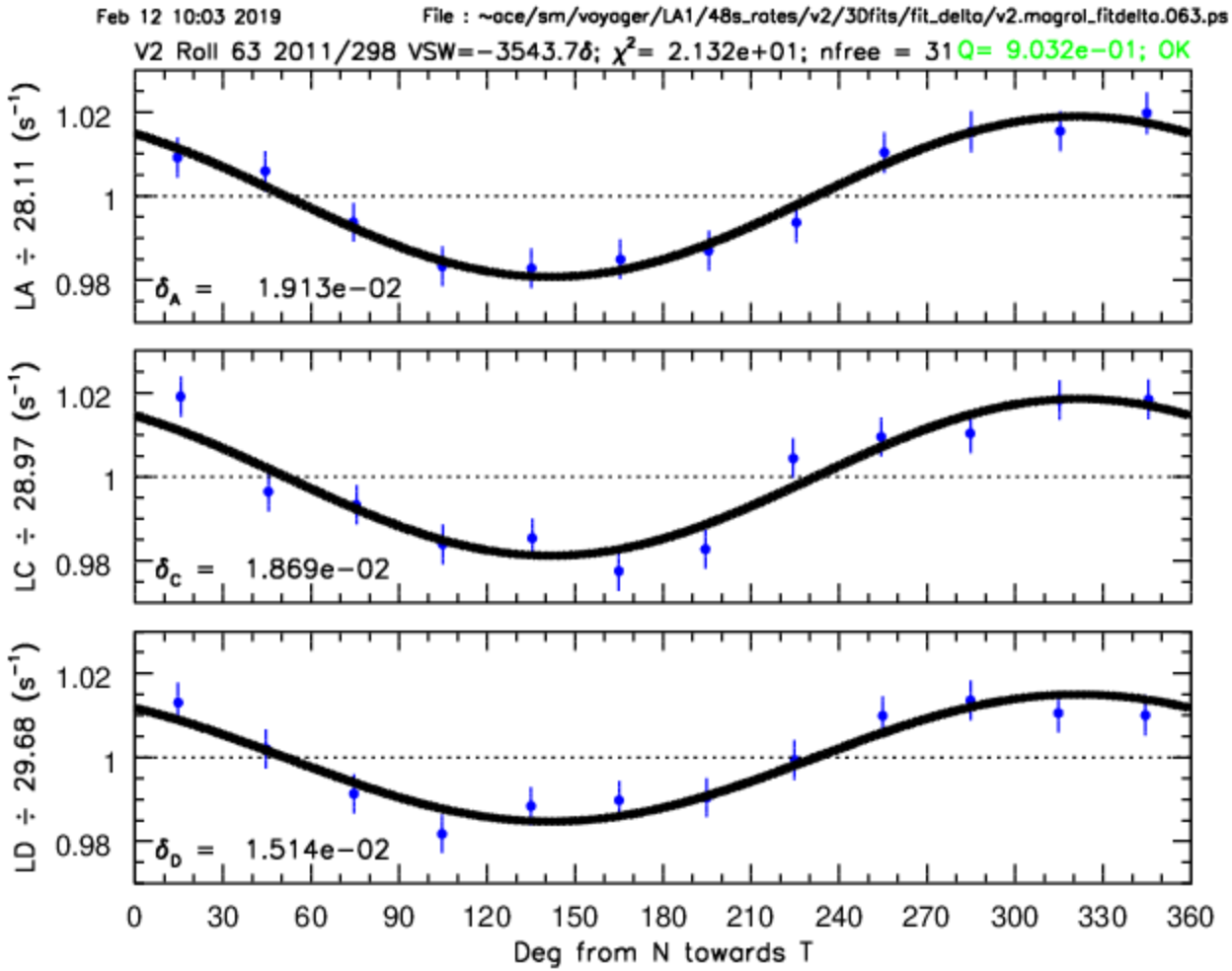
No magrols for V2 in 2016 but resumed in 2017 – 2019 with 1 or 2 revolutions per magrol maneuver.



Typical 10-roll maneuver in 2011 in LET A telescope.



Typical 2-roll maneuver in 2017. Roll modulation still evident and usable.



Param	Value	sig−	sig+
Jo	2.843e+01	4.404e−02	4.403e−02
δ_R	−2.734e−02	(assumed; in S/C frame)	
δ_T	−1.294e−02	1.306e−03	1.306e−03
δ_N	1.635e−02	1.303e−03	1.302e−03
κC	1.007e+00	1.743e−03	1.743e−03
κD	1.025e+00	1.768e−03	1.768e−03

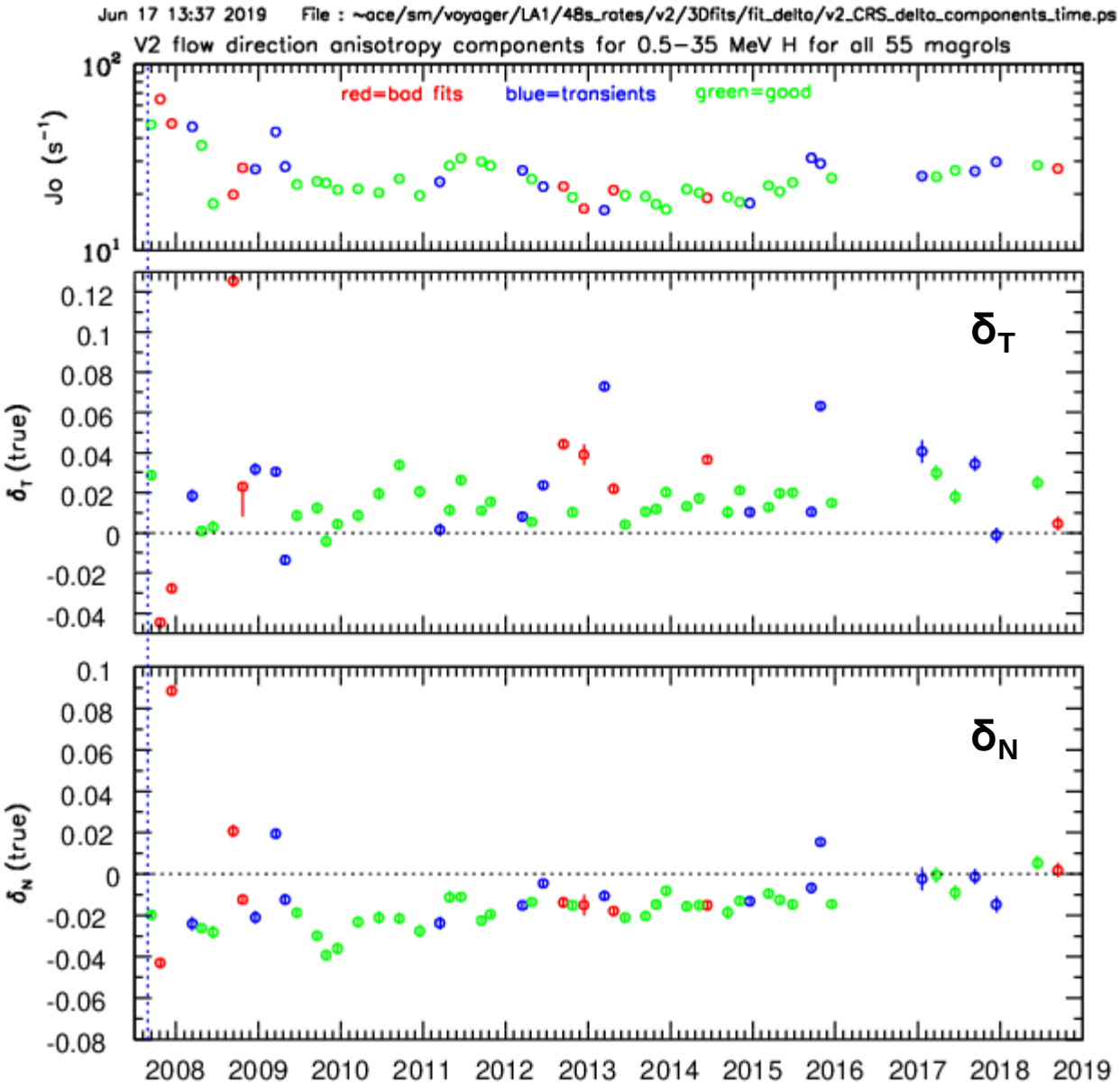
Param	Value	sig−	sig+
δ	3.438e−02	–	–
θ (w/r R)	142.7	–	–
β (N−>T)	321.6	–	–
V_R (km/s)	96.9	(assumed; in S/C frame)	
V_T (km/s)	45.9	4.6	4.6
V_N (km/s)	−57.9	4.6	4.6

Showing fitting results for all three telescopes binned in N-towards-T angle for roll on 2011/298.

Fitting procedure for anisotropy vector components has 5 free parameters: Jo, delta_T, delta_N, and two intensity normalization factors between the three telescopes.

delta_R is derived from PLS observation of V_R and converted via Compton-Getting factor.

Components in N-T plane are very insensitive to choice of delta_R.



Flow direction results in N-T plane for all 55 magrols.

Some fits, in red, don't satisfy a good-fit criterion (9).

Transients, in blue, identified by examining the 3 rates involved and requiring they look "typical" of an undisturbed time (14).

32 good fits, in green, no transients.

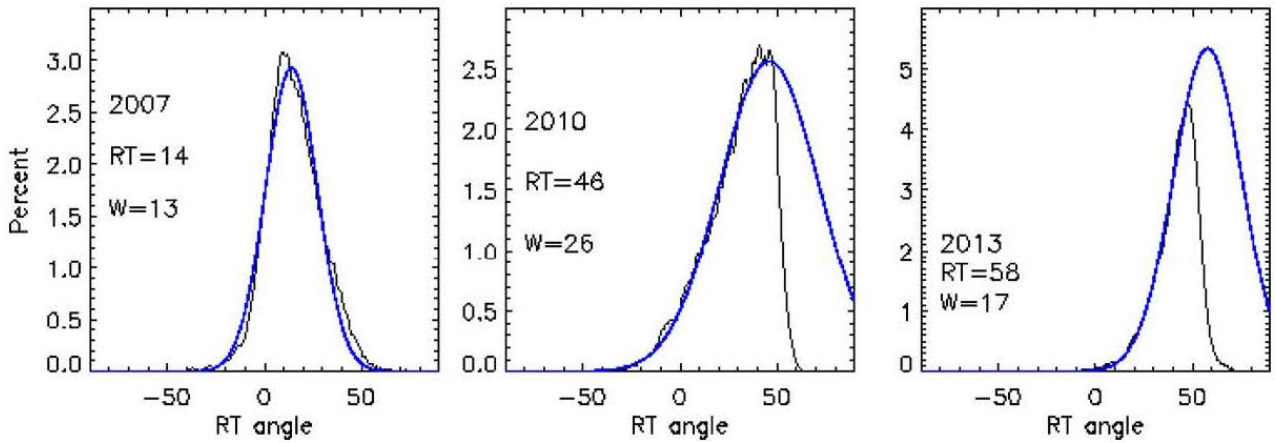


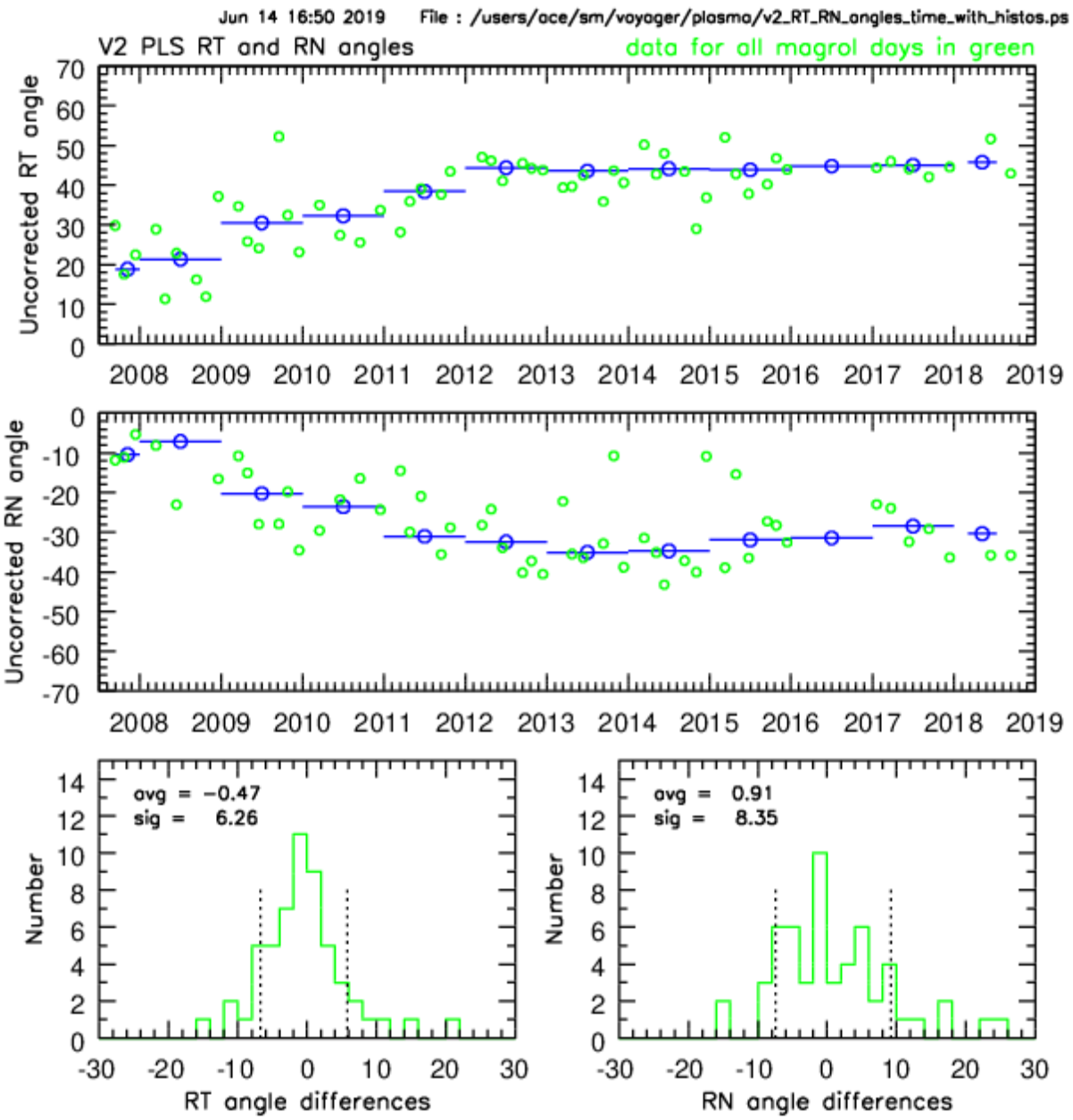
Figure 5. Distribution of angles in the RT plane in 2007, 2010, and 2013 (white lines) and Gaussian fits to these distributions (blue lines). The average RT angle and the width of the distribution, both from the Gaussian fits, are given in each panel.

(A color version of this figure is available in the online journal.)

To get diffusive anisotropy we need to get Compton-Getting anisotropy and for that we need to know the N and T components of solar wind speed. As the flow turns away from the radial direction in the heliosheath, that gets to be a problem due to PLS instrument response, as shown above.

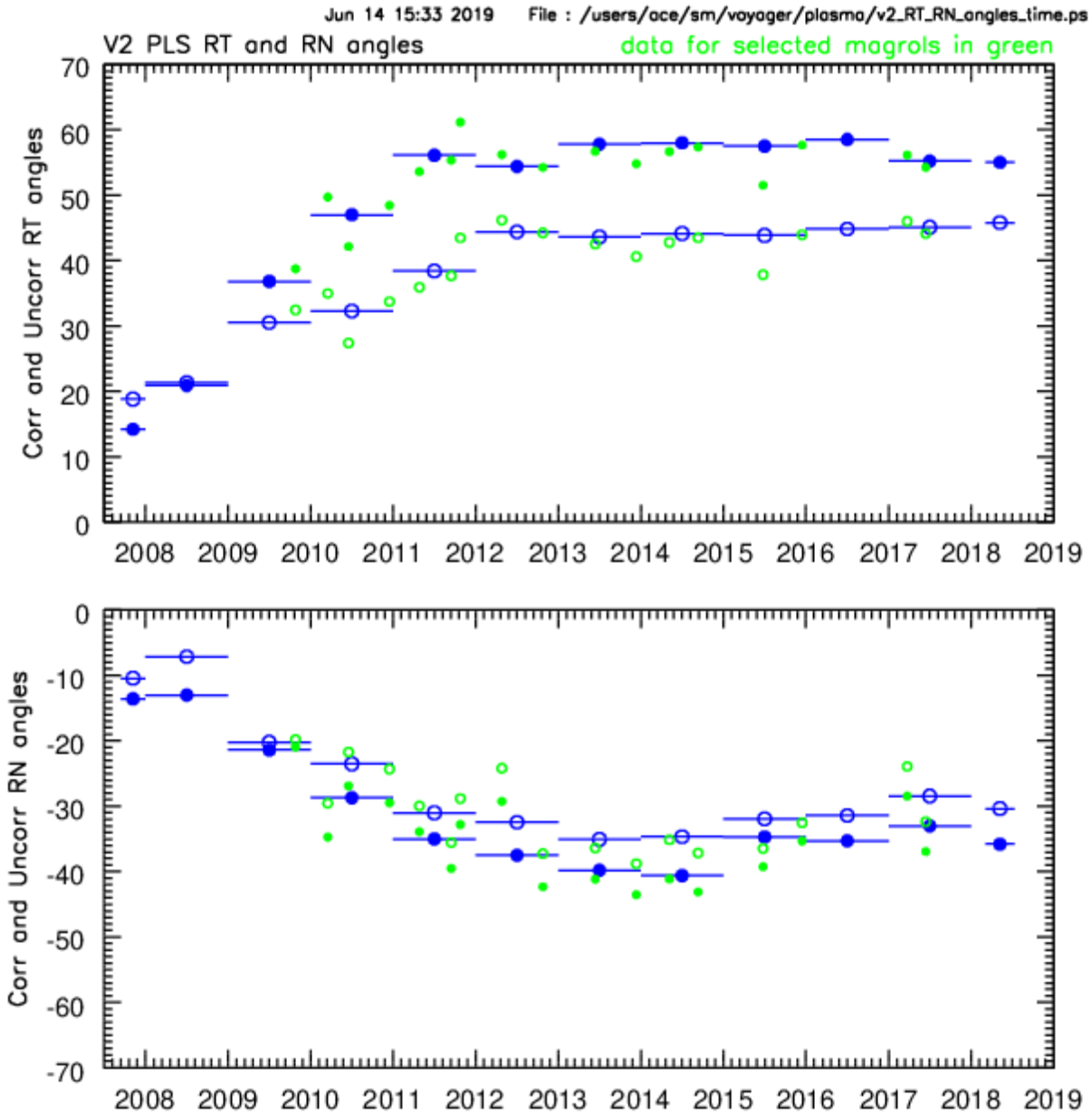
PLS can determine the angle correction needed only for long time averages, not for the day of the roll as would be ideal.

We have applied an angle correction for the day of the roll based on selecting days with RT and RN angles that reasonably match the long term averages. That selection reduced the number of rolls from 32 to 17.



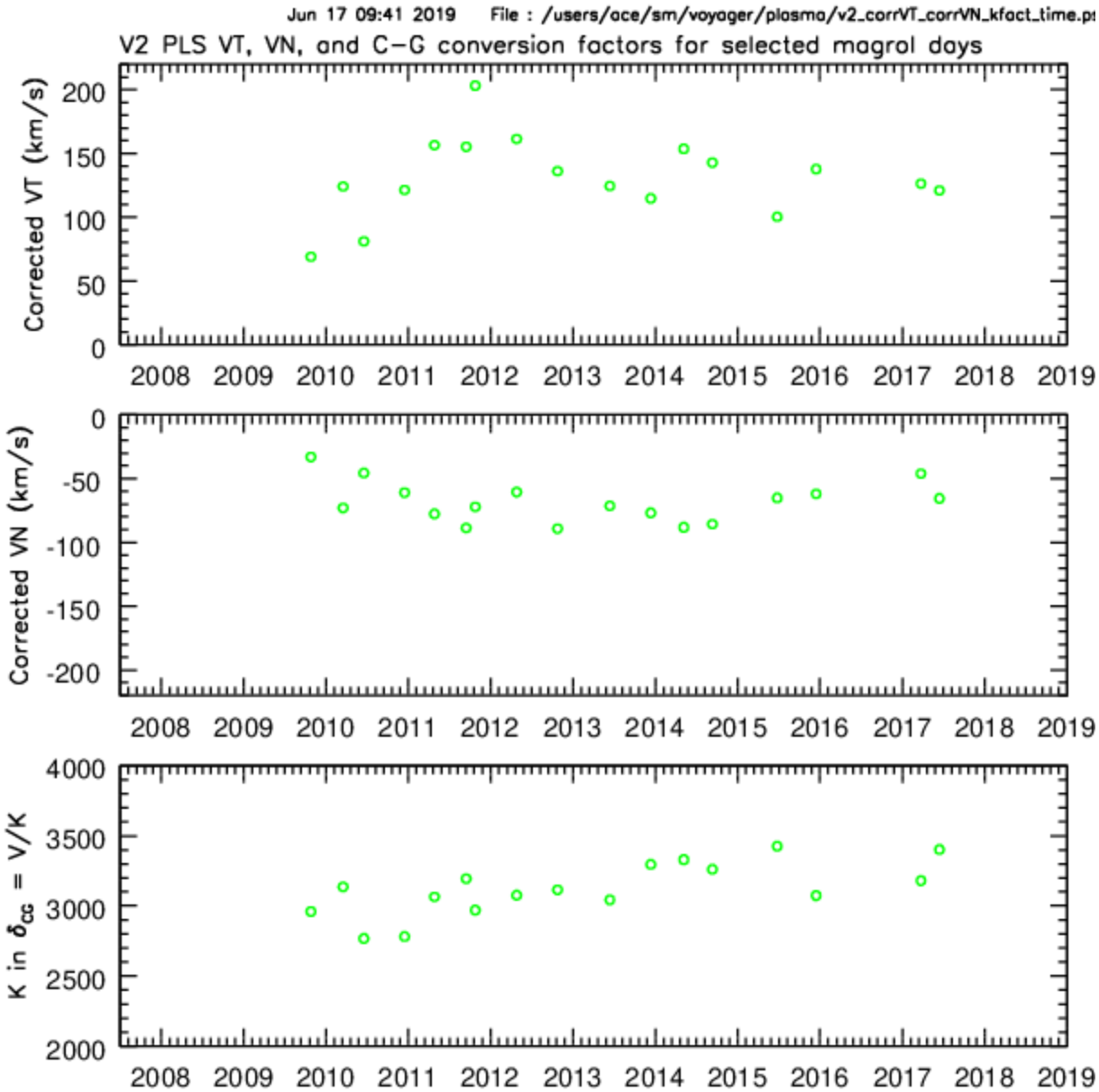
Uncorrected RT angle and RN angle vs time – long period averages in blue, data for all 55 magrol days in green.

Histograms of the angle differences, days of roll – long term averages. Selected only roll days within 1-sigma of the mean.



Uncorrected and Corrected RT and RN angles vs time for both long term averages and the 17 selected roll days.

For roll days, correction is long-term correction applied for the time the roll day falls into.



But, what we need is VT and VN, the corrected solar wind speeds.

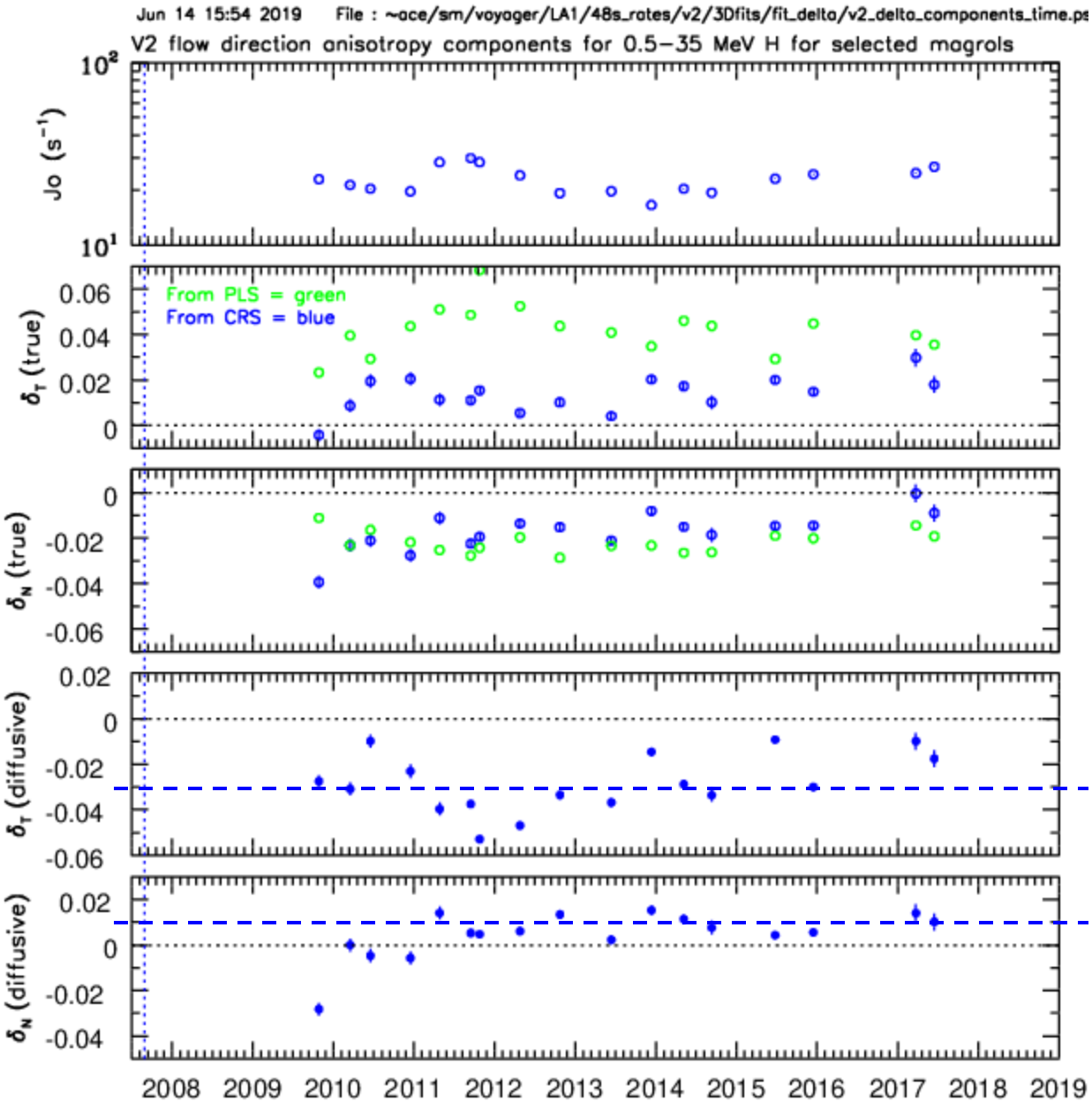
We get those from

VT = VR*tan(corrected RT angle)
and
VN = VR*tan(corrected RN angle)

These are the factors that convert speed to convective C-G anisotropy. Based on Forman, 1970:

$$\delta = < (2 - 2\gamma)/v) > V$$

where the average is over the energy spectrum, dJ/dE = AE$^{\gamma}$, v = particle speed, and V = solar wind speed. Monte-Carlo sim is used to get the average, with a 4-power-law fit to the energy spectrum for the day.



The result –bottom 2 panels.

Diffusive δ_T = -(3/v)K·grad U/U ~-0.03

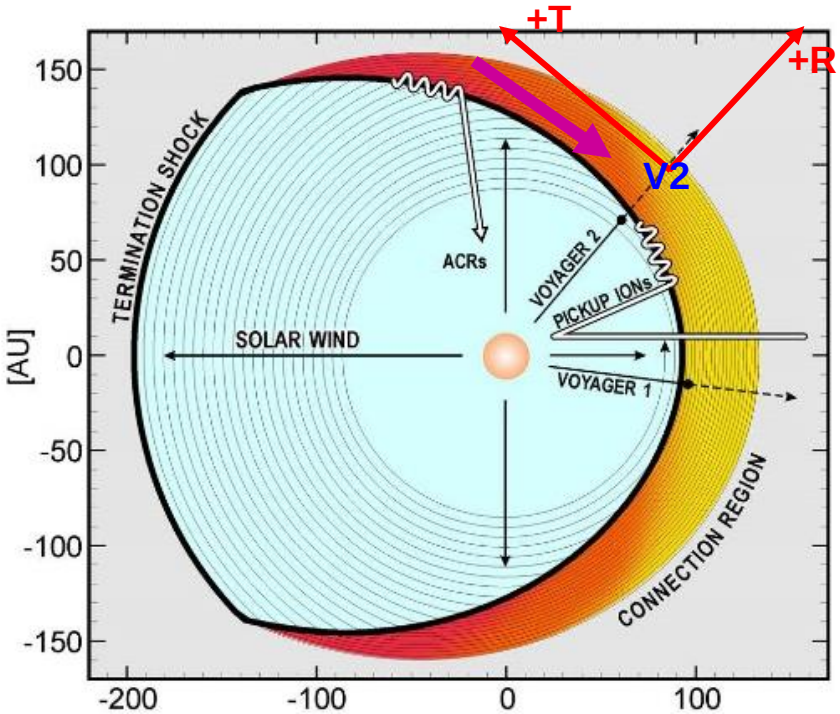
Diffusive δ_N = ~0.01

So, diffusive flow is equatorward and towards nose from flank or tail.

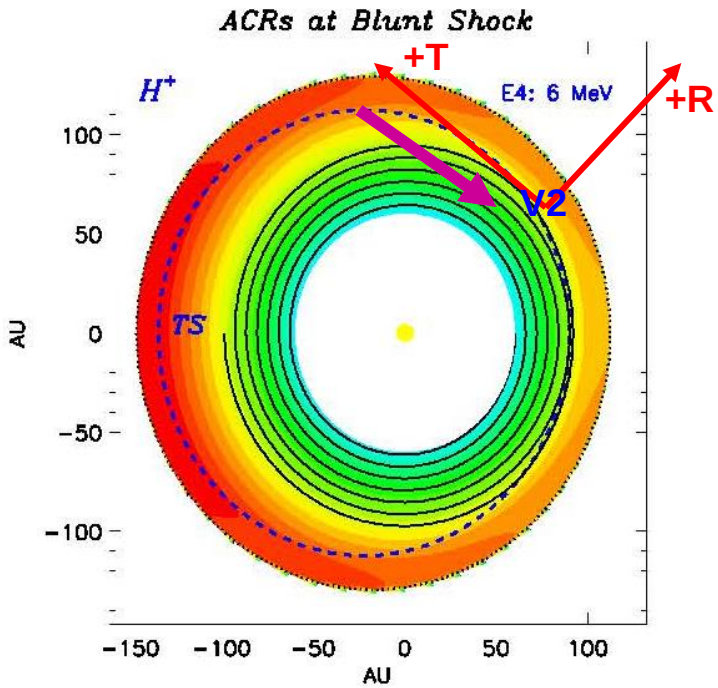
Summary

- **Observation of diffusive flow of ACRs from +T towards –T direction supports idea that ACRs are primarily accelerated back along flank or tail of termination shock.**
- **Supports picture of ACR acceleration and transport of McComas and Schwadron, 2006, Kóta and Jokipii, 2006, and Kóta, 2007.**
- **Further rolls on V2 are not expected to yield data useful to this study since now in LISM and ACRs are gone.**

McComas & Schwadron 2006



Kóta ICRC 2007



The End