Cosmic Ray Anisotropy

What's in the literature?
How does Peter/Roman's fit compare with other Measurements?

Brenda Dingus
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Abstract: Peter provided me with an "unexamined" fit of Milagro's observed background anisotropy. I show various plots of this fit and then compare it to some measurements from the literature. This fit compares well with the published results. Peter, however, considers such a comparison premature. I mention some of the explanations of the anisotropy, but in general these are not very quantitative.

Peter/Roman's "Unexamined" Fit

For the plots of our data I use the example of the "unexamined" fit of Peter/Roman to 3 harmonics for their analysis of the no X2 cut data. The amplitude and phase of the 3 harmonics are given by the following code, which is a linear function with declination. There are a total of 12 parameters in the fit. I believe these are the same numbers shown by Peter at the Asilomar meeting.

```
double E1  = 50.2;              /* constant terms for phase  */
double E2 = -88.05;
double E3  = -17.90;
double F1 = -1.003;                     /* slopes for phase */
double F2  = 0.2265;
double F3 = 0.451;

double G1 = 4.5E-4;          /* constant terms for amplitude */
double G2 = 9.6E-4;
double G3 = 2.2E-4;
double H1 = 0.04E-4;               /* slopes for amplitude */
double H2  = -0.137E-4;
double H3 = 0.01E-4;

A1 = G1 + (H1 * Dec);               /* Dec in degrees */
A2 = G2 + (H2 * Dec);
A3 = G3 + (H3 * Dec);

RA1 = E1 + (F1 * Dec);
RA2 = E2 + (F2 * Dec);
RA3 = E3 + (F3 * Dec);

y = 1.0 + A1 * cos(       DEG_TO_RAD*(RAslosh - RA1)) + \
            A2 * cos(2.0 * DEG_TO_RAD*(RAslosh - RA2)) + \
            A3 * cos(3.0 * DEG_TO_RAD*(RAslosh - RA3));
```

Figure 1 shows Peter's functional fit at Dec=10 to 60 deg in steps of 10 deg. I only show this range of Dec, because Peter only fit this range of Dec for our data. Figure 2 is an Aitoff plot of this fit with RA=0 degrees at the center increasing to the left and Figure 3 is an Aitoff plot with RA=180 degrees also increasing to the left. I also show the Galactic plane which seems to follow a broad excess that we see (or maybe it's just because we see a deficit somewhat near to the North Galactic pole). Finally Figure 4 is an Aitoff plot in Galactic coordinates with the b=0 at the center and increasing to the left.

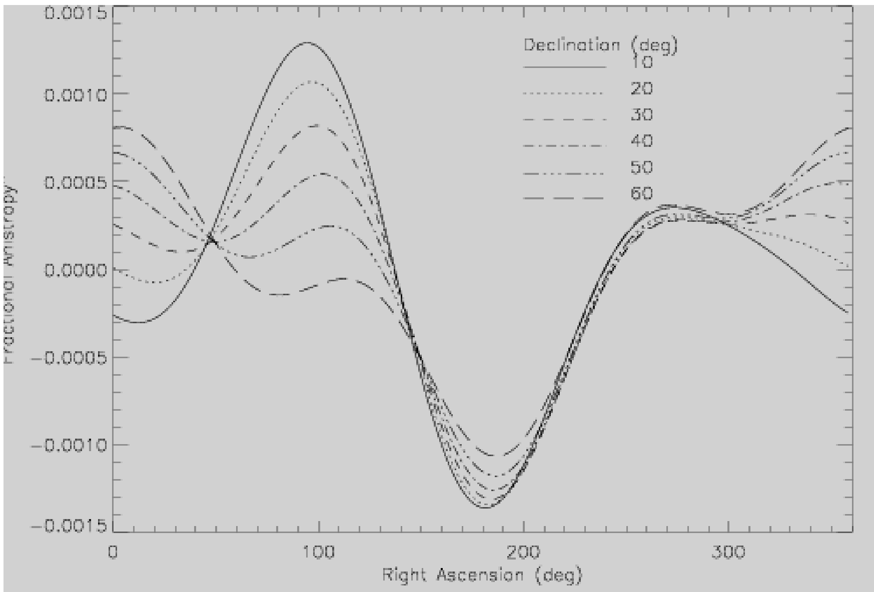

Figure 1: Plot of function with the terms cos(R.A.), cos (2*R.A.) and cos(3*R.A.) where the phases and amplitudes are described above.

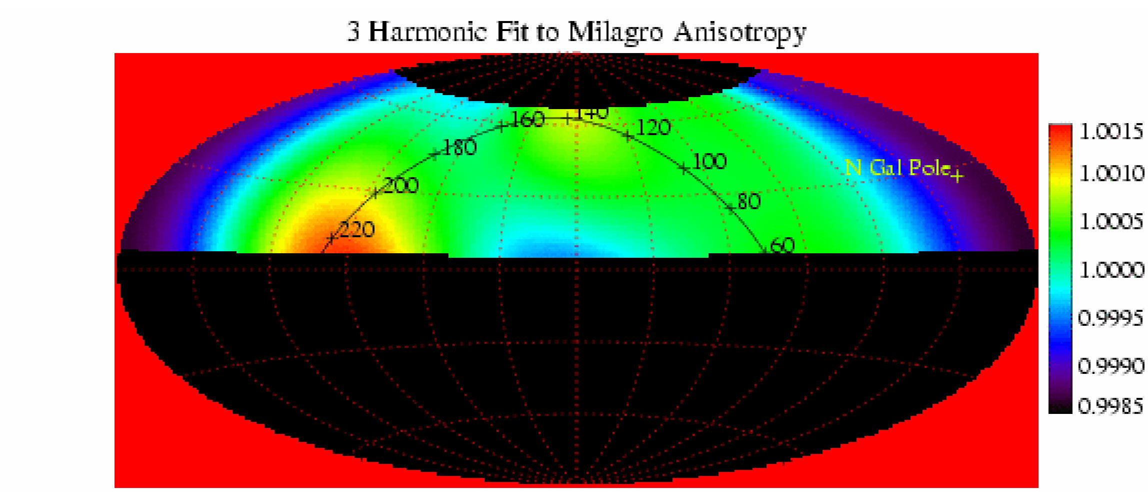

Figure 2: Aitoff plot in R.A. and Dec. of the same function. Astronomers' convention is used for plotting R.A. (i.e. R.A.=0 at the center and negative to the right, positive to the left). The line is the Galactic plane with the numbers indicating the Galactic longitude.

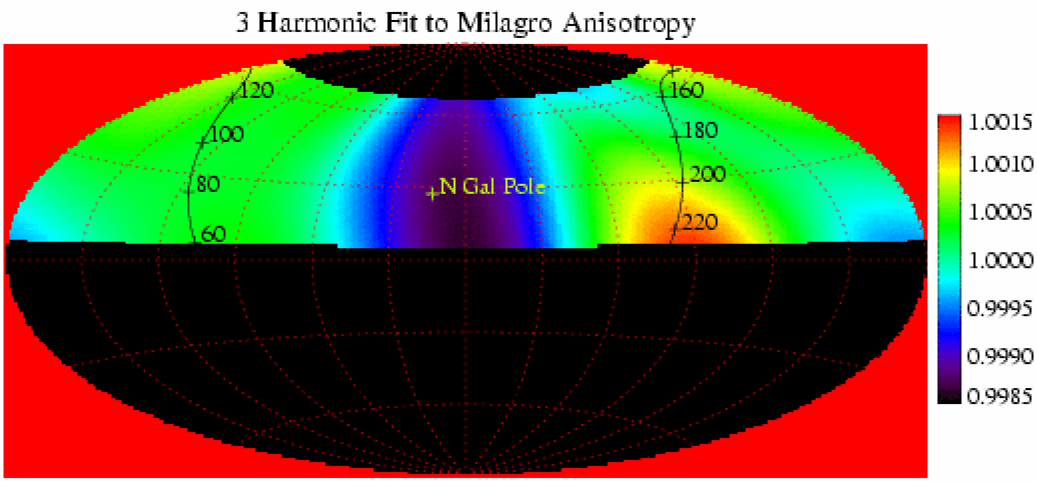

Figure 3: Same as Figure 2 but rotated by 180 degrees so that R.A. = 0 is at the right and R.A. =180 in the center and R.A.=360 is at the left.

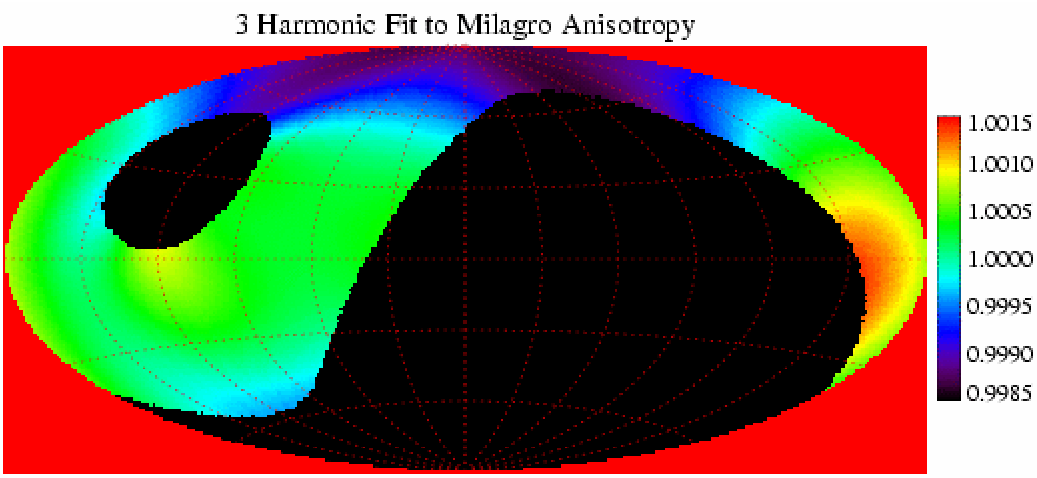

Figure 4: Now plotted in Galactic coordinates with the Galactic center in the center of the plot and l=180 on the left and l=-180 on the right.

Comparing Peter's Fit with Other Published Data

Some of the literature is from the 1970s, and many of the papers are in the Journal of Geophysical Research http://www.agu.org/journals/ja/, which is accessible from LANL. If you use VPN to connect to LANL, you can access all journals to which LANL has electronic subscriptions.

Data in our energy range:

D.L. Hall et al. JGR, Vol 104 A4 6737-6749 1999
http://www.agu.org/journals/ja/ja9904/1998JA900107/0.html

They fit the count rate in 46 underground muon telescopes (called Two Hemisphere Network THN) to 2 Guassian functions. One Guassian is a source and the other is a sink. The THN is sensitive to cosmic-rays of rigidity 140-1400 GV. Figure 5 is the contour plot and caption from Figure 5 of this paper.

The amplitudes of the 2 Guassians vary with energy to a power with a larger variation in the source than in the sink. There are a total of 13 parameters in this fit. I show in Figure 6 the plot of Peter's fit (solid line) compared with this paper's fit at 2 energies. Our average energy must change with Dec., but I haven't tried to figure that out.

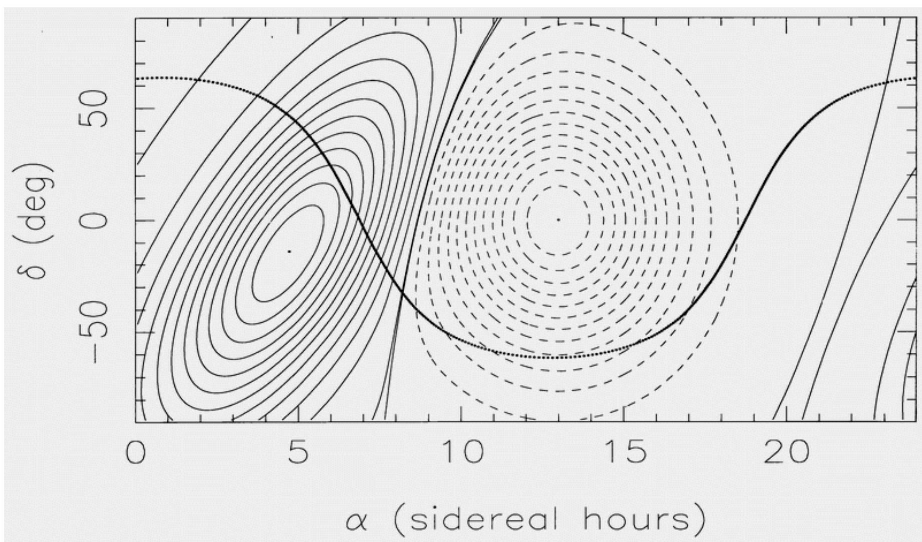

Figure 5: Caption from paper is "Contours of the values of anisotropy calculated from Equation (6) at 500 GV. The solid contours indicate the tail-in anisotropy (positive values of ξ) and the dashed contours indicate the loss cone anisotropy (negative values of ξ). The bold dotted line is the galactic equator. The contours range between 0.072% and -0.077% in steps of 0.006%."

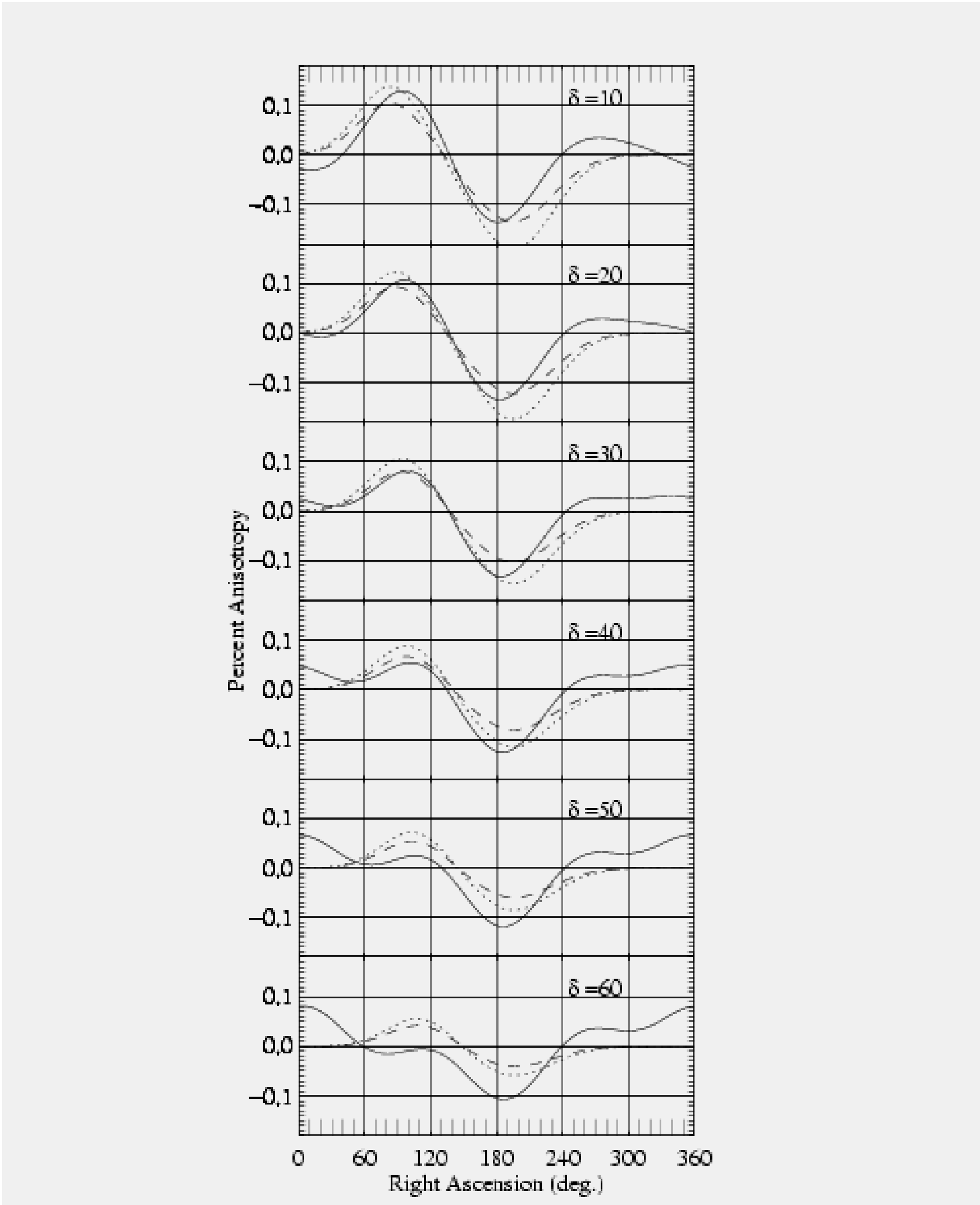

Figure 6: Comparison of Peter's fit (solid line) with the 13 parameter fit of this paper at 1.0 TeV (dotted line) and 1.5 TeV (dashed line).

Underground Muon data at higher energies

Kamiokande (mean Dec = 36.4 deg) published 2.8 sigma anisotropy for a mean energy of 12 TeV (Munakata, K. et al. Phys Rev D, Vol 56, No. 1, p. 23-26 (1997). They fit to the fundamental, $1 + r_o \cos(\text{R.A.} + \alpha)$, where r_o=(5.6+-1.9)e-4 and α=8+-20 deg, i.e. also a minimum at ~180 deg.

MACRO (mean Dec = 37 deg) also has about a 3 sigma anisotropy for a mean energy of 30 TeV. Their paper (Ambosio, M. et al. Phys Rev D, Vol 67, 042002 (2003)) is very well written and gives a good description about the various tests and why this anisotropy is not Compton Getting. Specifically, they show there data modulated by the "pseudosideral day" of 24 hours plus 3 min 57 sec (one sidereal day is 24 hours minus 3 hours 57 sec). The beating of any solar effects (i.e. day/night) will be observed with the same amplitude in the "pseudosidereal" modulated data as in the sidereal modulated data. MACRO sees a pseudosidereal modulation consistent with 0, so they conclude that the sidereal modulation is not a solar effect. There anisotropy has amplitude of (8.2+-2.7)e-4 and phase of 348+-20 degrees.

Super K has an internal memo, and their fit to the fundamental is consistent with MACRO and Kamiokande. They detect a seasonal effect with a larger anisotropy in winter. This is expected from a heliospheric phenomenon because in winter the Earth is closer to the direction of motion of the Sun and therefore closer to the heliomagnetosphere (see Figure 8). This effect is discussed by Nagashima, K., Fujimoto, K.,& Jacklyn, R.M. JGR Vol 103, A8 44 (1998). More about the Nagashima paper below.

EAS data at higher energies

A Bulgarian group with 4 sets of Geiger-Muller counters of area 2.5 m^2 situated at the corners of 8m x 8m square measured the anisotropy at Musala peak (lat=42 deg). They (Gombosi, Kota, Somogyi, Varga, Betev, Katsarsky, Kavlakov & Khirov) published their results in Nature, 255, 687 (1975). The elevation was almost 3000 m a.s.l. so the mean energy was ~ 60 TeV at Dec. =42.

There was another measurement at Norikura (lat=36 deg, E = 20 TeV) and Poatina (lat = -42 deg, E=1 TeV) reported in the XV ICRC. I got the numbers from a review paper by Kiraly, P., Kota, J., Osborne, J., Stapley, N.R. and Wolfendale, A.W. in Rivista del Nuovo Cimento Vol. 2, No. 7, 1, (1979). They also had updated numbers for Musala. Both Musala and Norikura do a 2 harmonic fit. I've plotted their anisotropy as well as ours for approximately the same Dec in Figure 7.

EAS Top (Dec= 42.5) also published an anisotropy (Aglietta, M. et al. ApJ 470, 501 (1996)) for 200 TeV of (3.73 +- 0.57)e-4 with phase of 27.3+-7.4 degrees. This is a 6.5 sigma effect, but they don't seem to fit to any higher harmonics. This fit is also in Figure 7.

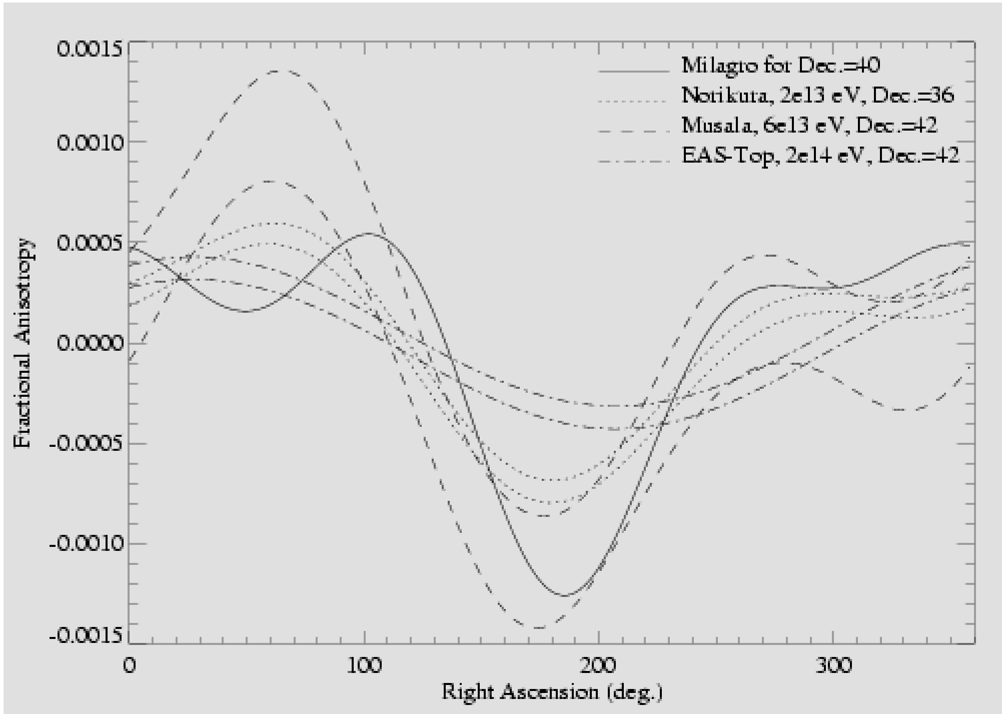

Figure 7: Anisotropy fit by Milagro at Dec=40 (solid line), Norikura (dotted line), Musala (dashed line), and EAS-Top (dash-dot line). When there are two lines, these are plus and minus one sigma on the fit parameters.

What's it mean?

Nagashima, K., Fujimoto, K.,& Jacklyn, R.M. JGR Vol 103, A8 44 (1998) in particular try to explain the data of the THN published by Hall. They interpret the Gaussian excess as due to a heliospheric effect and the Gaussian deficit as a galactic effect.

The heliospheric effect is called the "tail-in anisotropy" and is illustrated in Figure 8. The Earth is moving relative to the stars and relative to the local gas so the heliosphere is not spherical, but is closer to us in the direction of the motion. This reduced magnetic field in the tail direction gives us more cosmic rays. The tail direction relative to the stars is R.A. = 90 deg, Dec=-29 deg and relative to the gas is R.A.= 72, Dec=16 deg. The authors even argue that the anisotropy should be less when the earth is closest to the heliomagnetosphere in the winter and bigger in the summer. I don't understand this point very well because we only move 2 AU and the heliosphere is out at ~100AU, i.e. the figure is not to scale. This excess is energy dependent with the maximum anisotropy at ~1 TeV and disappearing by 10 TeV (maybe because the gyroradius exceeds the size of the tail region).

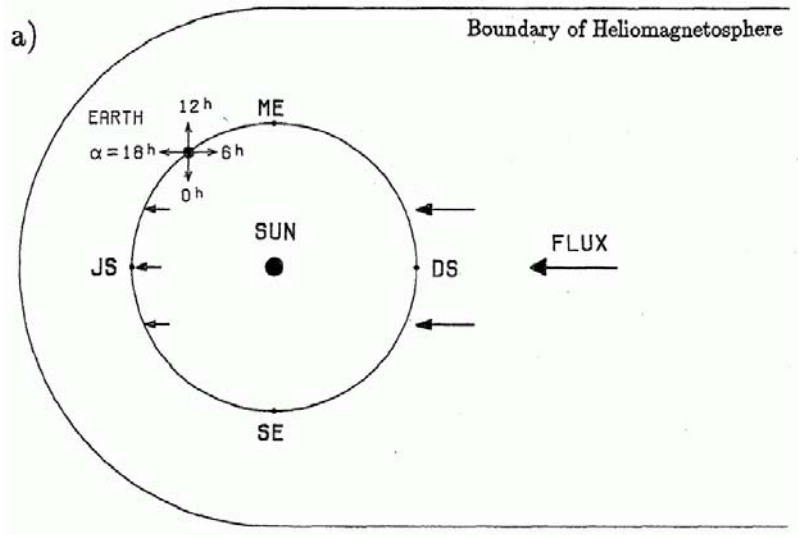

Figure 8: The direction of the excess flux is due to the distortion of the heliomagnetosphere due to the motion of the Sun relative to the local medium. ME and SE denote the March and September equinox and JS and DS correspond to the June and December solstice. Figure from Nagashima et al (1998).

The galactic effect is not energy dependent, having a similar shape from 60 GeV to > 10 TeV according to the THN data. While the paper does not mention it, it seems to me that it's significant that this deficit corresponds to the North Galactic Pole. If cosmic rays are created in the plane of the Galaxy and are diffusing to higher Galactic latitudes, there would be a net motion of cosmic rays towards the pole or a deficit in cosmic rays from the pole (as observed).

Finally this paper also argues that there is no Compton Getting effect based on this data. Therefore, the cosmic rays (at least below 10 TeV) are trapped by the local magnetic fields and travel with the Sun as it moves through the Galaxy.

Ptuskin, Jones, Seo, & Sina have a paper in the last ICRC (OG 1.3) explaining the effect of local sources on the cosmic ray anisotropy. Using the actual locations and ages of SNR they calculate the level of anisotropy expected. They find that sources could account for all of the anisotropy, and that there can't be many more undiscovered ones.

Conclusion:
We should talk with some heliospheric folks as well as galactic cosmic ray types. While our observations are similar to what other people have also observed, we probably will have smaller error bars. To further understand our data, we should consider the tests of "pseudosidereal" time and investigate the seasonal dependence of our anisotropy. If we could make an energy cut, we could also confirm the different energy dependence of the two Gaussian anisotropy. Specifically the Gaussian excess should diminish above ~10 TeV if it's heliospheric in origin.