

Cosmic-Ray Anisotropies

Gus Sinnis Los Alamos National Laboratory





Outline

- A brief history of anisotropy
- Current Status
 - Large-scale anisotropies
 - Small-scale anisotropies
- What do we really know?
- What else would we like to know?
- New explanations

THE PHYSICAL REVIEW A Journal of Experimental and Theoretical Physics

An Apparent Effect of Galactic Rotation on the Intensity of Cosmic Rays

ARTHUR H. COMPTON, University of Chicago and Oxford University AND IVAN A. GETTING, Oxford University (Received April 12, 1935)





While we must await some such measurements before we can consider the effect due to the rotation of the galaxy as established, the quantitative agreement with the predictions as shown in Fig. 2 gives a strong presumption in its favor. Its existence would imply that an important part of the cosmic rays originates outside of our galaxy. If its magnitude is found to be as great as we have predicted, it will imply that practically all the cosmic radiation has an extragalactic origin.

SECOND SERIES

Tibet Array: 2006



Hess and Steinmaurer data claimed 10σ in paper



Amenomori et al. Science 314 439, 2006

No evidence of Compton Getting effect associated with Galactic rotation

Large Scale Anisotropy Tibet



- Tibet Air shower data 1997-2005 (no time dependence observed)
- Amplitude of modulation ~0.1%
- >12 TeV anisotropy decreases
- Not observable at 300 TeV

Large Scale Anisotropy Milagro



- Median energy 6 TeV
- Phase and amplitude consistent with Tibet array
- Amplitude declination dependent 0.1%-0.3%
- Phase independent of declination

Milagro: Time Dependence of Amplitude



 $\supset 1$

2003

Year

2005

20

- chi-sq of straight line 86/6 dofs.
- chisq of best fit 4.4/5 dofs
- no trend seen in anti-sidereal time or UT
- no seasonal effect observed
- affect of solar cycle? (Tibet says no)

IceCube: Large Scale Anisotropy







- Broadly consistent with Tibet and Milagro.
 - Amplitude ~0.1%
 - Phase of minimum near 200° R.A.
- Phase changes at higher energies
- EAS-Top phase change occurs between 100 TeV and 370 TeV





- IC22 detector, <u>4 x 10⁹ events</u>, Median energy ~ <u>20 TeV</u>
- First indication of large scale $\sim 10^{-3}$ anisotropy observed in the South.
- Good match to observations in the North.

Higher Energies: IceTop



The Old Arrays

SUGAR 0 000 XXX 0 00 0 0 0 1 km 1968-1979 $\delta = -31.5$

Haverah Park



~2500 km² sr yr (77 yrs!)

Auger ~32,000 km² sr yr

TA ~6200 km² sr yr

Yakutsk

l973-2009 δ = 61.7

Volcano Ranch

1958-1973 $\delta = 32.2$

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Isotropy of the arrival directions of ultra high energy cosmic rays Linsley and Watson, Nature June 1974

- 87 events with energies above "few times 10¹⁹ eV" [filled symbols E>10²⁰ eV]
- Combined data from Sydney (50), Cornell (3), Haverah Park (20), and Volcano Ranch (14)
- "The data are clearly consistent with isotropy of arrival directions and show no evidence for the existence of point sources of ultra high energy cosmic rays."



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Table 1 Comparison of observed and predicted number of equi-event areas								
No. of	Observed no. of	Expected no. of						
events	squares assuming	squares assuming						
per square	Poissonian distribution	Poissonian distribution						
0	285	284.8						
1	67	66.5						
2	7	7.76						
3	1	0.6						
4	0	0.04						

Evidence of an anisotropy in the arrival direction of cosmic rays with energies above 10¹⁹ eV

Krasilnikov, Kuzmin, *Linsley*, Orlov, Reid, *Watson*, Wilson (J. Phys. A, Nov. 1974)

- Declination > 0 only
- Added Yakutsk data to previous paper
- Harmonic analysis yielded:
 - First harmonic amplitude 40% (p<2.6% all expts. combined)
 - First harmonic phase 13.5 ± 1.0 hr
 - Phases consistent across experiments
- "None of the individual sets separately gives an amplitude which is significant...Strikingly, however, the phases of the harmonics for the individual experiments are consistently in agreement..."





The Auger Experiment: Harmonic Analysis



Abreu, et al., Astrophysical J. Lett. v762 (2013) and ICRC 2013

- 23,520 km² yr sr exposure 30 EeV (12/31/11)
- ~680,000 events as of 12/31/12
- No significant dipole/quadrupole: limits on first harmonic 2-10%
- Rule out Galactic proton sources



Auger: Status of Phase Alignment



- In 2011 established prescription to investigate apparent phase consistency with energy
- Above ~I EeV phases consistent with previous independent data set
- $\sim 10,000 \text{ km}^2 \text{ sr yr } (1/2 \text{ through prescribed time period})$
- Stay tuned 2015 prescribed period should end

Auger Phase results



UHECR: Correlations with AGN



- Clear prescription established by Auger
 - Energy > 55 EeV
 - Veron-Cetty & Veron Catalog (2006) of AGN < 75 Mpc
 - 3.1° radius circle





Current Status: Auger



- From 2011 ICRC
- Current situation ~unchanged (now have 110 events)
 - Correlating fraction now at 32% (21% is isotropy) and still ~2.8 σ

AGN Correlation: TA



- Applied Auger criteria
- Different sample of AGN (northern hemisphere)
- 17 of 42 events correlate
- Probability 1.4%



- Used the 2MASS Galaxy redshift catalog
- Propagated protons to earth including energy loss
- E>10 EeV consistent with isotropy
- E>57 EeV 2-3 sigma pre-trial rejection of isotropy

Mid-Scale Anisotropy: TeV Regime



- Milagro (2008) identified 2 regions with significant excess ~5 x 10⁻⁴ of CR flux (~1/10 of large scale anisotropy)
- 220 billion events collected
- Median energy I TeV



Energy Spectrum of Regions A&B



- Region A is hard spectrum $\sim E^{-1.5\pm0.5}$
- Region A exhibits cutoff between 5-20 TeV (1-σ band)
- Region B marginally consistent (0.6% probability) with constant amplitude vs. energy (i.e. CR spectrum)



Particle Nature of Excess



- Compactness consistent with soft spectrum gammas or hadrons
- Energy distribution inconsistent with soft spectrum source
- Gamma hypothesis strongly excluded for Regions A & B

Simultaneous fit of energy and compactness Region A: γ hypothesis $\chi^2 = 124/16$ proton $\chi^2 = 10/16$ Region B: γ hypothesis $\chi^2 = 85/16$ proton $\chi^2 = 19/16$

ARGO Anisotropy



- 200 billion events (11/2007 5/2011)
- I.8 TeV median proton energy
- Consistent with Milagro map perhaps new regions being seen
- Particle content assumed protons (no mechanism to test)

ARGO Energy Spectrum



- Region I (A) harder than CR spectrum
- Region 2 (B) similar to CR spectrum
- No evidence of a cutoff to 20 TeV

IceCube: Mid-Scale Anisotropy



- 56 billion events (downward muons)
- 20 TeV median energy
- 10° smoothing
- Similar amplitude as Milagro (few x 10⁻⁴)

Abbasi, et al., ApJ 740, p16 2011



Puzzles of Small-Scale Anisotropy

- 0.01 pc: Larmor radius of 10 TeV proton in 1 microGauss field
- 0.1 pc: Lifetime of 10 TeV neutron
- I pc: nearest star
- 200 pc: Geminga
- Source must be close and must have non-standard cosmic ray propagation
- Ideas:
 - Geminga (Salvati & Sacco 2008)
 - Magnetic bottle connected to CR sources (Drury & Aharonian 2008)
 - Magnetic reconnection in magnetotail (Lazarian & Desiati 2010)
 - Local structure of turbulent Galactic B-field (Giacinti & Sigl 2012)
 - Strangelets (Kotera, Perez-Garcia, & Silk arXiv:1303.1186)

Local Dark Matter Clump

Dark matter clump coupled to magnetic funnel (a la Drury & Aharonian)



- constraints
- Symbols: DM models

- Blue: 50 TeV Z⁰Z⁰
- Pink: 100 TeV bb

Pat Harding ArXiv:1307.6537

Dark Matter

- DM structure leads to sub-halos
- Protons from DM annihilation follow field structure to Earth
- Gamma source not aligned with protons
- Milagro not sensitive to gamma signal
- HAWC will be sensitive to gamma signal if clump in field of view.
- Signal does not violate any constraints



Summary: Large Scale Anisotropy





- Large scale anisotropy clearly observed from I TeV to 2 PeV
- Significant dipole and quadrupole components
- Time dependence of amplitude not confirmed
- Phase shifts between 20 TeV and 400 TeV
- Amplitude may increase between 400 TeV and 2 PeV
- Above 10¹⁶ eV anisotropy not established
 - No significant dipole or quadrupole components (but getting interesting)
 - Hints from phase alignment
- AGN correlation still at ~2.8 σ with 32% correlating fraction
 - TA sees ~1% probability of no correlation with same VCV parameters



- Structure detected at angular scales from ~7-20 degrees
- Amplitude ~few x 10⁻⁴
- Energy spectrum different for different structures
- Only Milagro has established hadronic nature of structures (Regions A & B)
- Future measurements:
 - Energy spectrum of all structures (IceCube/HAWC)
 - Composition (gamma fraction?) of structures (HAWC/LHAASO)
- Still a puzzle that's why we are here!

Backup









