Observation of CR anisotropy with ARGO-YBJ

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On behalf of the ARGO-YBJ Collaboration
CRs below $10^{18}$ eV are predominantly galactic.

The bulk of CR is produced by shock acceleration in SN explosions.

Diffusion of accelerated CRs through non-uniform, non-homogeneous ISM.

At 1 TeV, $B \sim 1 \mu G$, Gyro-Radius $\sim 200$ AU, 0.001 pc

Galactic CRs are expected to be highly isotropic scrambled by galactic magnetic field over very long time.
An-isotropy observed

- **Anisotropy** of arrival direction of CRs observed since 80's
- 10's GeV - 100's TeV in μ detector, surface arrays and ν detectors
- Observed anisotropy of about $10^{-3} - 10^{-4}$

- Tail-in feature directed towards the heliospheric tail peak located at RA $\sim 6h$ ($\sim 90^\circ$).
- Amplitude and phase change with latitude
- North-South asymmetry
- Tail-in modulated in time: max in Dec. and min in June

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TAUP 2011 - Sept. 05, 2011
2D measurement of CR anisotropy

Super-K
- 2.1×10^8 events bet. 1996 - 2001
- Angular resolution < 2°
- Median energy ~ 10 TeV

Milagro
Abdo et al., arXiv:0806.2293
- 9.6×10^{10} events bet. 2000-2007
- Angular resolution < 1°
- Median energy ~ 6 TeV

Tibet Array
- 3.7×10^{10} events bet. 1997-2005
- Angular resolution < 1°
- Median energy ~ 6 TeV

Icecube - 59
- 34 × 10^9 events
- Angular resolution ~ 3°
- Median energy ~20 TeV
**The ARGO-YBJ experiment**

An unconventional EAS-array exploiting the full coverage approach at very high altitude to detect small air showers at an energy threshold of a few hundreds of GeV.

Longitude 90° 31’ 50” East
Latitude 30° 06’ 38” North
90 Km North from Lhasa (Tibet)

4300 m above the sea level ~ 600 g/cm²

Wednesday, 7 Sept. 2011
16:50: “Highlights from ARGO-YBJ” by I. De Mitri
The basic concepts

...for an unconventional air shower detector

HIGH ALTITUDE SITE
(YBJ - Tibet, 4300 m a.s.l, ~ 600 g/cm²)

FULL COVERAGE
(RPC technology, 92% covering factor)

HIGH SEGMENTATION OF THE READOUT
(small space-time pixels)
  Space pixels: 146,880 strips (7×62 cm²)
  Time pixels: 18,360 pads (56×62 cm²)

... in order to:
  ◼ image the shower front
  ◼ get a energy threshold of a few hundreds of GeV
Current Status

- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- The average duty cycle ~ 85%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- Dead time 4%
- 220 GB/day transferred to China (IHEP) / Italy (CNAF) data centers
Moon shadow analysis

A tool to evaluate the detector performance

- Pointing accuracy
- Angular resolution
- Absolute energy calibration

N_{pad} > 100, 71 s.d.

The energy scale uncertainty is estimated to be smaller than 13\% in the energy range \(1 \text{ – } 30 \text{ (TeV/Z)}\).
Long-term stability

- $N_{\text{pad}}>100$: 10 s.d./month
- A tool to monitor the stability of the data and reconstruction
- Right figures: one point per month!
- Position stable at a level of 0.1°
- Angular resolution stable at a level of 10%
**DATA SET:**
November 2007 - May 2011 data (~1300 days)
\[ \text{N}_{\text{str}} > 25, \text{Zenith angle} < 45^\circ, \ 2.2 \times 10^{11} \text{ events} \]
NO gamma/hadron discrimination technique applied.

**Background estimation methods:**

- Equi-zenith angle method
- Up to 45°- wide structures:
  - Time swapping/scrambling (3 hrs, \( \text{N}_{\text{off}}/\text{N}_{\text{on}} = 10 \))
  - Direct integration (3 hrs)
    (consistent each other within 0.3 s.d.)

An effective high-pass filter for structures narrower than \( 3 \text{ hrs} \times 15^\circ/\text{hrs} = 45^\circ \) in R.A.
Large scale CR anisotropy

All-data sky-map. Analysis optimized to look at large scale anisotropies.

Tail-in excess region  Loss-cone deficit region

Cygnus region
The tail-in broad structure appears to dissolve to smaller angular scale spots.
Anisotropy seems to disappear.
The origin of the large scale anisotropy in the CR arrival direction is still unknown.

The structure of the local interstellar magnetic field is likely to have an important role.

However, the combined study of the anisotropy energy and angular dependency, its time modulation, and angular scale structure seem to suggest that the observation might be a combination of multiple superimposed effects, caused by phenomenologies at different distances from Earth.
Medium scale anisotropy by Milagro

Region B
12.4 s.d.
Fractional excess: \(4 \times 10^{-4}\)

Region A
15 s.d.
Fractional excess: \(6 \times 10^{-4}\)

Smoothing radius 10°

Medium scale anisotropy by ARGO-YBJ

Map smoothed with the detector PSF for CRs

If the optimal opening angle is looked for, the pre-trial max significance is 23 s.d.

Δt = 3 hr = 45°

Equatorial coordinates:
projection of the earth longitude and latitude

Cosmic rays excess
≈ 0.06%

≈ 0.1%

Post-trial
Proton median energy ≈ 1 TeV

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Galactic coordinates

GALACTIC ANTI-CENTER

ARGO–YBJ sky-map
N>25, PST–smoothed
Medium scale anisotropy

Crab Nebula
Energy spectra harder than isotropic CRs with cutoff around 8 and 2 TeV.

MILAGRO missed an important part of the medium scale anisotropy.

Energy spectrum calculation
The region is going to show quite a complex morphology with high statistical significance (more than 12 s.d.). That suggests that even more detailed studies will be possible in the next future.
The energy spectra of the two sub-regions are close to each other, suggesting that the nature of the diffuse emission might be the same all over 60 degrees in declination.
Intensity as a function of the Energy

$E_p^{50} = 680$ GeV

$E_p^{50} = 1.4$ TeV

$E_p^{50} = 3.4$ TeV

$E_p^{50} = 7.3$ TeV
Complete CR map of the entire TeV sky

ARGO-YBJ + IceCube-59

3 hr = 45°

PSF-Smoothed map

ARGO-YBJ 1 TeV

Smoothing radius 10°
There is currently no explanation for these local enhancements in the CR flux.

- **Composition:**
  - **Not photons or electrons** (Milagro)
  - Neutrons from a star? Unlikely → 10 TeV neutrons decay in 0.1 pc → much closer than the nearest star.
  - **Gyro-radius of a 10 TeV proton in a 2μG magnetic field is only ~0.005 pc (1000 AU).**
    - Magnetic field must connect us to the source and be coherent out to it (≥ 100 pc).

- **Tips:**
  - Connection to heliosphere ? Region 1 coincides with the direction of the heliotail.
  - The direction of both regions is nearly perpendicular to the expected Galactic magnetic field direction.

- **Multiple explanations were proposed:**
  - K. Munakata AIP Conf Proc Vol 932, page 283

young nearby SN ?
Conclusions

- ARGO-YBJ observed either the large scale and the intermediate scale CR anisotropies with high statistical significance.

- The observation of the large scale CR anisotropy up to about 25 TeV is in agreement with other experiments.

- The observation of an intermediate scale anisotropy shows evidence of several new features still uninvestigated.

- Deeper analysis with new techniques is under way.

- The possibility that a young nearby SN might have produced an anisotropic feature over the isotropic intensity of old CRs provides the possibility that the origin of CRs might be discovered through the study of their anisotropy.