Detection of anisotropies in the arrival directions of 300 GeV – 10 TeV cosmic rays with the ARGO-YBJ experiment

presented by R. Iuppa

University of Rome Tor Vergata
INFN, sez.ne “Tor Vergata”

on behalf of the ARGO-YBJ collaboration

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Outline

- What we expect: isotropy of cosmic rays
- Observations of CR anisotropies
- The ARGO-YBJ experiment
- The large scale anisotropy
- The intermediate scale anisotropy
- Conclusions
What is expected: isotropy

The galactic magnetic field is thought to be the superposition of a “regular” and a “chaotic” component (with intensities $B_{\text{reg}} \sim 2 \mu\text{G}$ and $B_{\text{ch}} \sim 0.5\div2 \mu\text{G}$ respectively).

The gyroradius of a particle of rigidity $R$ TeraVolt is:

$$r = \frac{p}{Z e B} \approx R[TV] \times 5 \times 10^{-4} \, pc \approx R[TV] \times 100 \, A.U.$$ 

Cosmic rays interact with the interstellar medium (ISM), the interactions further scattering their trajectories (minor effect w.r.t. that of B).
What the observation of CR anisotropies might suggest

- there are sources nearby.
- the galactic magnetic field is not what we think (only if the effect is due to charged cosmic rays):
  - the role of the Solar wind as well as the magnetic field in the solar system may be non-negligible.
  - there might be local (or non-local) magnetic field structures focusing CRs up to the Solar System.
  - the chaotic component of the magnetic field may overwhelm the regular one.
- any combination of the two facts above.
Observations of CR anisotropies

Super-Kamiokande – ICRC 2007 Proceedings


ICE-CUBE - 2010 *ApJ* 718 L194

G. Guillian et. al. 2007 PRD

The ARGO-YBJ experiment

Altitude 4300 m a.s.l.
Longitude 90°31’ 50” East
Latitude 30°06’ 38” North

Astrophysical Radiation with Ground-based Observatory at YangBaJing
Operation modes

**Shower mode**

Trigger: number of fired pads \( (N_{pad}) \) within 420 ns on the central carpet

for \( N_{pad} \geq 20 \), rate \( \sim 3.5 \text{ kHz} \) \( \sim \) 220 GBytes/day

Detection of Extensive Air Showers (direction, size, core ...)

Aims: cosmic-ray physics (threshold \( \sim 1 \text{ TeV} \))
VHE \( \gamma \)-astronomy (threshold \( \sim 300 \text{ GeV} \))
gamma-ray bursts

**Scaler mode**

counting rates \( (\geq 1, \geq 2, \geq 3, \geq 4 \) coincidences) for each cluster

Aims: detector and environment monitor
flaring phenomena (gamma ray bursts, solar flares) with a threshold of few GeV
Space pixel: single strip (7×62 cm²)
Time pixel: pad (56×62 cm²) is the OR of 8 strips, with a resolution of ~ 1.8 ns
Dynamical range for protons by means of pads, strips and big pads: ~ 1 - 10⁴ TeV

Excellent operating performance since November 2007.

Duty cycle > 85% →

←Rate stability 0.5% (intrinsic)
Data analysis

DATA SET:
2008-2010 data
N_{str} > 40
Zenith angle < 50°

\textbf{1.4 \textit{10}^{11} \textit{events}}

NO SELECTION CUT APPLIED

\textbf{Background estimation methods:}

- Up to 45°-wide structures:
  - Time swapping/scrambling (3 hrs, N_{off}/N_{on}=10)
  - Direct integration (3 hrs)
    - (consistent each other within 7. \textit{10}^{-6})
- For larger scales: equizenith method
The large scale anisotropy as observed by ARGO-YBJ

All-data sky-map. Analysis optimized to look at large scale anisotropies ("all-distance" equizenith background estimation technique).
Energy spectrum of the large scale anisotropy

In agreement with standard diffusion models, where the anisotropy increases with the energy.
Large scale anisotropy: possible interpretations

What we see is the combination of a Uni-Directional Flow and a Bi-Directional Flow (along the magnetic field arm). The characteristic lengths are so small that a local low-density feature must be advocated: the Local Interstellar Cloud (93 pc³).

The loss-cone is the signature of a “poloidal” component of the galactic magnetic field (in agreement with southern hemisphere data from IceCube). The “tail-in” and the “Cygnus” excess are both due to guiding by the magnetic fields along the local arm (the “tail-in” excess is slightly deformed by the Heliosphere).
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The loss-cone is a powerful probe for the exploration of the galactic magnetic field.

Mizoguchi et al. 31st ICRC 2009

Xiao-bo Qu et al 2011, arXiv:1101.5273
The intermediate scale anisotropy

MILAGRO: Discovery of Localized Regions of Excess 10-TeV Cosmic Rays

DATA SET:
Zenith angle < 45°

2.2 $10^{11}$ events
Median energy 1 TeV
NO GAMMA HADRON
DISCRIMINATING APPLIED

Background estimation technique:
direct integration method (2 hours intervals)
The intermediate scale anisotropy

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

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

Ra: 117°–131° | 131°–141°
Ra: 66°–76°

De: 15°–40° | 40°–50°
De: 10°–20°
The intermediate scale CR anisotropy as observed by ARGO-YBJ

All-data sky-map. Analysis optimized to look at small and medium scale anisotropies (direct integration and time-swapping background estimation technique). Several extended features are already visible at 1° scale.
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Equatorial coordinates: projection of the earth longitude and latitude
The intermediate scale anisotropy at 5°

Significance

SMOOTH RADIUS 5°

Ratio
The intermediate scale anisotropy at 5°
The intermediate scale anisotropy: focus on >5 s.d. significant regions

SMOOTH RADIUS 5°
 Ratio (> 5 s.d.)

GALACTIC ANTI-CENTER

Sub-structures?Cygnus region
New-structures?
Intermediate scale anisotropy
energy spectrum

**ARGO-YBJ**

- Region A
- Region B

**MILAGRO 2008**

- Fractional Excess ($\times 10^{-3}$)

Region A and region B defined as in slide 3
What is behind the intermediate scale anisotropies

The excesses are due to nearby sources (Geminga, Vela, Monogem...) emitting CR. In any case it looks as particular features of the local magnetic field are needed to bring us the radiation so beamed. The spectrum and the cut-off are explained with the age of the source.

Salvati & Sacco, Astronomy & Astrophysics 2008

Drury & Aharonian, Astroparticle Physics 2008
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**nearby sources of cosmic rays!**

What we see is the effect of magnetic reconnection in the heliotail. The spectrum and the cutoff are due to the efficiency of the process.


first look inside the heliotail!
Are we inside a CR “local bubble”? 

Cosmic ray energy-dependent escape from a super-nova remnant

Are these feature related to the positron excess observed by PAMELA?

All these violation of the standard CR model lay in the 100 GeV - 10 TeV interval. Notice that ARGO-YBJ measurements give localized excess.
Conclusions

- ARGO-YBJ observed either the large scale and the intermediate scale cosmic ray anisotropies.
- The observation of the large scale CR anisotropy is in agreement with the other experiments and provides useful data to constrain diffusion models.
- The 300 GeV - 3 TeV large-scale data form ARGO-YBJ may provide essential informations about the local and galactic magnetic field.
- The observation of the intermediate scale excesses showed several interesting features still uninvestigated. Anyway, each model would imply deep revisions of the standard model of cosmic rays:
  - Unexpected magnetic field configurations:
    - Magnetic lenses?
    - Helio-tail reconnection?
  - Nearby sources:
    - Geminga, Vela, Monogem → is there any connection with FERMI/PAMELA findings?
    - What are the implications on the fine structure of the CR spectrum? Is the CR “knee” a feature of the nearby source emission?
- The implications of such observations on the cosmic ray physics might be decisive, mostly as far as the medium scale features are concerned.