Anisotropy and Corotation of Galactic Cosmic Rays

(*The Chinese collaboration team at YangBaJing Cosmic Ray Observatory*)

Based on some 40 billion cosmic ray events collected from 1997 to 2005 by the Tibet Air Shower Array experiment (a major scientific collaboration between China and Japan) operating at the YangBaJing Cosmic Ray Observatory (90.522 E, 30.102 N; 4300 m above sea level) near Lhasa in Tibet, a two-dimensional cosmic-ray intensity map in the sky was obtained with very high directional granularity and unprecedented precision in intensity at a level of 10-4. A new anisotropy component towards the Cygnus arm direction is uncovered and the source compactness may favor an interpretation of γray emissions. With a moderate energy resolution in the teraelectronvolt (TeV) range, cosmic-ray intensity maps are obtained for several different energy bands. For energies up to several hundred TeV, the intensity map becomes consistent with an isotropic distribution, indicating a corotation of cosmic rays with local Galactic magnetic environment along with the heliosphere. These frontier research results were published as a Research Article in Science 314, 2006, 439—443.

The Milky Way where we live contains thousands of billions of shining stars gathered by gravity in a gigantic disk with spiral arms. The Galaxy spans a radius of hundreds of thousands of light years (one light year is the distance that light travels in a year) and is permeated with very thin magnetized thermal gaseous materials and very high energy particles traveling around with speeds close to the speed of light. These high-energy particles including atomic nuclei and electrons are referred to as cosmic rays. Cosmic rays were first discovered by Austrian physicist Victor Hess in 1912 in a series of experiments. However, nobody knew where and how such cosmic rays were generated and gained their high energies in early times. Through years of investigations, there is a general concensus that cosmic rays with energies up to about one thousand TeV are mainly created by supernova explosions. Due to the presence of interstellar magnetic field of the order of a few to tens of micro Gauss, cosmic rays are largely confined within the Galaxy. Studies on the composition and energy distribution of cosmic rays, as well as their intensity variation from different directions can provide rich and valuable information for the origin, the propagation of cosmic rays, and the structure of Galactic magnetic field.

For exploring mysteries of cosmic rays, generations of Chinese physicists have faced various challenges and made a great effort over the past five decades. With the important initial support from the Chinese Academy of Sciences (CAS) and the National Natural Science Foundation of China (NSFC), collaborative physicists in China and Japan were able to successfully construct the YangBaJing International Cosmic Ray Observatory in early 90 s of last century. This Observatory is at longitude 90.522 E, latitude 30.102N, 4300 m a.s.l., and about 90 kilometers to the northwest of the capital city Lhasa of Tibet. Figure 1 shows a panoramic view of the Observatory. The Chinese co-spokesman was Professor Y.H. Tan from the Institute of High Energy Physics (IHEP) and the Japanese co-spokesman was Professor T. Yuda from the Institute for Cosmic Ray Research (ICRR) of Tokyo University until their retirement at the beginning of 21 century. The Observatory has earned a high reputation in the world scientific community. It was listed as one of the twenty five Chinese scientific bases and one of the six planned major projects in China by Science magazine in 1995[1]. It was also commended as the highest quality ground based cosmic-ray observatory by Professor James Cronin, a laureate of Nobel Prize in physics from the University of Chicago in the U.S.[2]

Currently, the YangBaJing Cosmic-Ray Observatory is hosting two collaborative experiments. One is the Sino-Japanese extensive air shower array (i.e., Tibet Air Shower Array, abbreviated as ASγ and shown as the white detector array in front of Fig. 1) which has a modal energy of about 3 TeV and the other is the Sino-Italian experiment ARGO-YBJ (Astrophysical Radiation Ground-based Observatory at YangBaJing, seen as the blue roof building to the upper right of Fig. 1) which is expected to decrease the threshold energy to about 300GeV. Both experiments have the advantage in a wide field of view and long duty cycle to monitor fascinating phenomena of high-energy cosmic rays occurring in the northern sky. The ASγ experiment has been operating for 17 years and went through 3 major upgrades; many unique and beautiful results were obtained. Since 2000, the ARGO-YBJ apparatus has been gradually installed and systematically tested. The construction was completed in the summer of 2006 and its successful operation will further enhance the capability of cosmic ray frontier research at YangBaJing Observatory.

Taking the advantage of large field of view and the availability of a very large data sample (about 40 billions of cosmic ray events) collected from decade long stable operation, ASγ experiment is able to measure in two dimensions with unprecedented precision, at a level of one per mill, that the cosmic ray intensities are different for different directions in multi-TeV energy range (see Figs. 2a and 2b). This anisotropy of cosmic ray intensity is analogous to winds in the air. Near the ground, the atmosphere is in general attached to the Earth surface, but winds may be formed as a result of the temperature and pressure differences in the atmosphere caused by the solar radiation. The intensity of an air flow is higher when facing against the wind direction but less stronger when

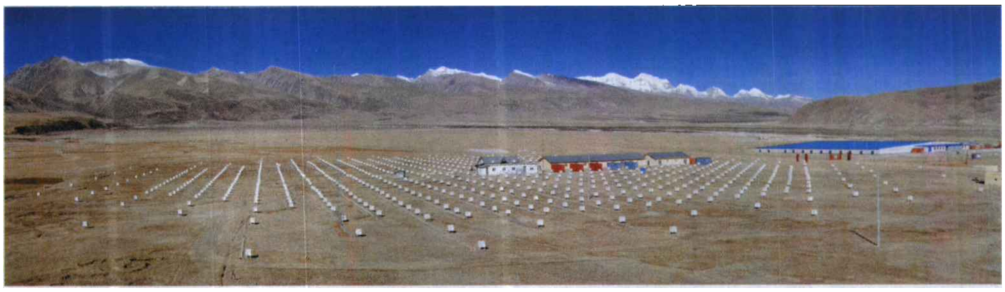

Figure 1 The panorama of the YangBaJing International Cosmic Ray Observatory

The white scintillation detector array in front is the Sino-Japanese collaborative experiment Asγ; it occupies an area of 270 m by 270 m. The building of blue roof with a size of 100 m by 100 m to the upper right is the experimental hall for the Sino-Italian collaborative experiment ARGO-YBJ, equipped with a full coverage of RPC detectors.

following the wind direction. For example, in the case of cosmic rays, the Galactic magnetic field makes the path easier if cosmic rays propagate along the field line direction but more difficult if cosmic rays travel in a transverse direction; this may lead to the anisotropy of cosmic ray intensity. Besides the high precision measurement, a new anisotropic component (region III in both Fig. 2a and 2b) is discovered in our research and its compact structure indicates that the enhancement is likely coming from neutral particles, e.g., γray photons. If this is true, it implies that not far from the solar system (e.g., about hundred of light years), there exist cosmic ray sources which are accelerating high-energy cosmic rays. Further investigations are now being carried out in world-wide experiments.

When going to higher energies (—300 TeV), an interesting phenomenon appears. The intensity of cosmic rays tends to be isotropic. In other words, no "wind" of cosmic rays is detected. There is thus no relative motion between an observer and cosmic ray plasma, or cosmic rays corotate with the heliosphere around the Galactic center. Our experimental result shows the first corotation evidence for Galactic cosmic rays ever since A. H. Compton (Nobel laureate in physics) and I. A. Getting initiated such a pioneer exploration in 1935.

Our research results were published in Science as a Research Article on October 20, 2006 as a milestone in cosmic-ray frontier research[3]. In the section of "Perspectives" on the same issue, Dr. M. Duldig of Australian Government Antarctic Division wrote an expert commentary and perspective article on our paper. In particular, he emphasizes the promising prospect of upgrading ASγ detectors in order to push forward frontier research further and to obtain new results of more significant impact[4]. As already proposed[5] by ASγ collaboration team, a simple and economic upgrading plan would make the array the most sensitive cosmic-ray telescope at 100 TeV energy range

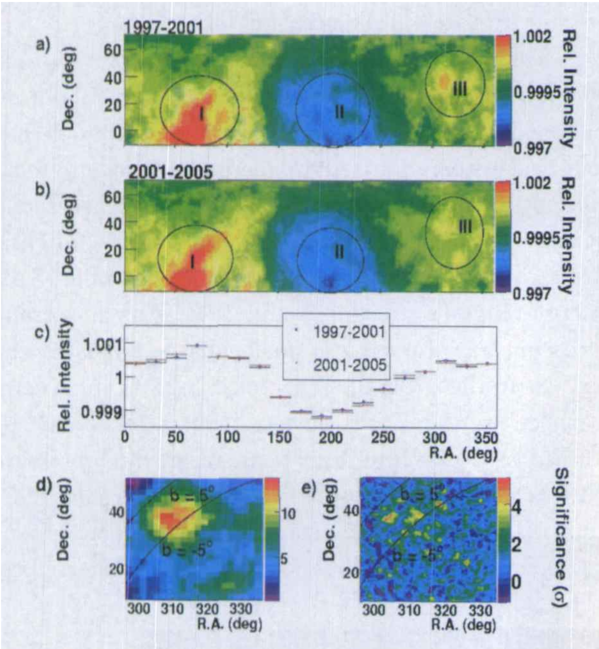

Figure 2 Panels a) and b) are intensity maps of cosmic rays in the equatorial coordinate system for two different periods of time as indicated

The red color in regions I and III represents intensity enhancements while the blue color in region II indicates a deficit of cosmic ray intensity. Panel c) shows that the anisotropy remains similar before and after the solar maximum and panel d) is an enlarged plot for region III with all data combined. Panel e) shows much more fine structures in region III and the compactness of cosmic ray excess, hinting at possible contributions from γray emissions.

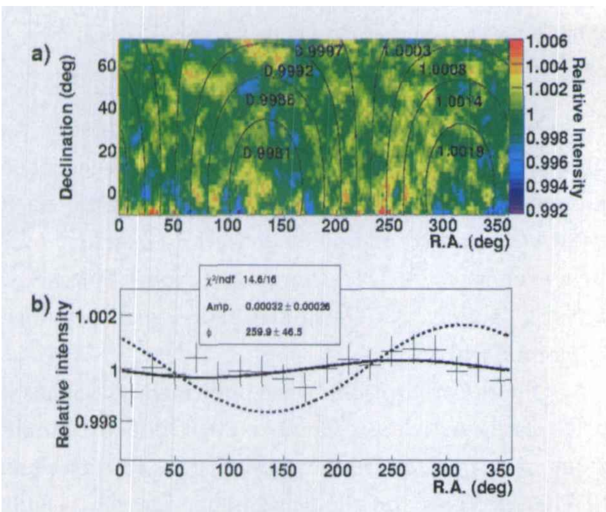

Figure 3 Panel a) displays the isotropic cosmic ray intensity at energy of 300 TeV in the equatorial coordinate system

If cosmic ray plasma stays at rest and does not rotate around the Galactic center, its motion relative to the solar system would cause the observer to experience a "wind" of cosmic rays, as shown by the contour plot. Our data show that such wind does not exist, indicating cosmic ray plasma actually co-rotates with the solar system around the Galactic center. In panel b), + signs indicate the measured results and the solid line is the best-fit curve projected to the R.A. direction. The dotted curve is the predicted intensity distribution in the absence of co-rotation.

in the world. Furthermore, by utilizing the high-altitude advantage and by decreasing the energy threshold to tens of GeV, we will be able to detect high-energy γray emissions from deep space and early universe and to broaden the horizon of astrophysics, cosmology and particle astrophysics[6,7].

Our scientific endeavors and achievements would be impossible without the prescient decision and sustained support from Chinese funding agencies, including the NSFC, the MOST and the CAS. The authors also wish to express their deep gratitude to the government of the Tibet autonomous region for various assistance over years.

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