Exam Astroparticle Physics

Master Physics and Astronomy June 2021

The course was taught by prof. Dirk Ryckbosch (UGent) and prof. Stijn Buitink (VUB). They each gave you an article related to a subject from the class. You got 10-15 minutes to prepare for an article, then about 15-20 minutes for the exam itself and then you went on to the other professor. Articles are included by link or at the end after the questions.

Student 1 (11/06)

Stijn Buitink:
Article: from BBC, about the Xenon1 experiment that had found an excess
Questions: about axions, wimps, direct detection (solar modulation) and so on

Dirk Ryckbosch:
Article: about ^{60}Fe and how it is accelerated
Questions: about Fermi acceleration, random walk, spallation, ACE detector (why is it in the air and not on the ground? → mass information is lost once the particle hits the atmosphere) and so on

Student 2 (11/06)

Stijn Buitink:
Article: Dark matter hunt yields unexplained signal (or see below if the link doesn't work)
Questions: Why are WIMPs such attractive candidates? How do we get to axions?
Detour to inflation: Why do we need inflation? What does it do? How does the inflaton field work? How does it lead to the formation of structure?

Dirk Ryckbosch:
Article: Observation of the ^{60}Fe nucleosynthesis-clock isotope in galactic cosmic rays

Student 3 (21/06)

Dirk Ryckbosch:
Article: Searches for neutrinos from cosmic-ray interactions in the Sun using seven years of IceCube data
Questions: Start by explaining some of the things you notice in the article connected to the materials of the course (e.g. neutrino creation mechanism in the earth atmosphere). Why does the article say the creation of neutrinos and gamma rays are linked? Where

else (than in the sun and earth atmospheres) do you expect neutrinos and gamma rays to be produced? (supernovae) What is special about the spectrum of these particles? (power law instead of thermal spectrum) Up to what energies can supernovae accelerate these particles/ can the galaxy contain these particles? How long can the galaxy contain these particles and why? What produces the particles with even higher energies that we see? Other than the sun and the earth atmospheres, what produces high energy neutrinos? (AGNs, ...) How does IceCube detect neutrinos? What are the main backgrounds in IceCube?

Stijn Buitink:
Article: Dark matter hunt yields unexplained signal
Questions: First give a short recap of the article. What are axions? What are the main detection strategies for dark matter particles? Do you expect the annual modulation here? Why are axions considered as DM candidates if neutrinos are not due to being too light, when axions are even lighter? What are WIMPS? Explain the picture in the middle of the article, why is this evidence for dark matter?

Student 4 (21/06)

Stijn Buitink:
Article: Dark matter hunt yields unexplained signal

Dirk Ryckbosch:
Article: 260 B. KLECKER, R.A. MEWALDT, ET AL.

Student 5 (21/06)

Stijn Buitink:
Article: Dark matter hunt yields unexplained signal

Dirk Ryckbosch:
Article: Detection of very high-energy gamma-rays from GRBs

Student 6 (21/06)

Stijn Buitink:
Article: Dark matter hunt yields unexplained signal

Dirk Ryckbosch:
Article: Indications of intermediate-scale anisotropy of cosmic rays with energy greater

than 57 EeV in the northern sky measured with the surface detector of the Telescope Array experiment

Articles

Dark matter hunt yields unexplained signal

By Paul Rincon
Science editor, BBC News website

17 June 2020

The Xenon1T detector was installed at Italy's Gran Sasso lab from 2016 to 2018

An experiment searching for signs of elusive dark matter has detected an unexplained signal.

Scientists working on the Xenon1T experiment have detected more activity within their detector than they would otherwise expect.

This "excess of events" could point to the existence of hypothesised particles called axions, some of which are candidates for dark matter.

Dark matter comprises 85% of matter in the cosmos, but its nature is unknown.

Whatever it is, it does not reflect or emit detectable light, hence the name.

There are three potential explanations for the new signal from the Xenon1T experiment. Two require new physics to explain, while one of them is consistent with the existence of solar axion particles.

The findings, which have not been peer reviewed, **were published on the Arxiv pre-print server.**

So far, scientists have only observed indirect evidence of dark matter. A definitive, direct detection of dark matter particles has yet to be made.

- **Dark matter becomes less 'ghostly'**
- **Dark matter map yields first results**

There are several theories to account for what that particle might be like. The most favoured one has been the WIMP, or Weakly Interacting Massive Particle.

Physicists working on the Xenon series of experiments have spent more than a decade hunting for signs of these WIMPs. But the search has been fruitless.

But Xenon1T, the most recent iteration was also sensitive to other candidate particles.

Background noise

The experiment was operated deep underground at the Gran Sasso facility in Italy, from 2016 to 2018.

Its detector was filled with 3.2 tonnes of ultra-pure liquefied xenon, two tonnes of which served as a "target" for interactions between the xenon atoms and other particles that were passing through.

When a particle crosses the target, it can generate tiny flashes of light and free electrons from a xenon atom.

Most of these interactions - also known as events - are with particles we already know about, such as muons, cosmic rays and neutrinos. This constitutes what scientists refer to as the background signal.

NASA / ESA / CXC / M BRADAC / S ALLEN

Indirect evidence for dark matter: the titanic collision of two galaxy clusters separates dark matter (blue) from ordinary matter (pink)

A potential signal from an undiscovered particle needs to be strong enough to rise above this background noise.

Scientists carefully estimated the number of background events in Xenon1T. They expected to see roughly 232, but the experiment instead saw 285 - an excess of 53 events.

One explanation could be a new, previously unconsidered source of background contamination, caused by the presence of tiny amounts of tritium in the Xenon1T detector.

It could also be due to neutrinos, trillions of which pass through your body, unhindered, every second. One explanation could be that the magnetic moment (a property of all particles) of neutrinos is larger than its value in the Standard Model, which categorises the elementary particles in physics.

New physics

This would be a strong hint that some other new physics is needed to explain it.

However, the excess is most consistent with a signal from axions, a very light as-yet undetected class of particle. In fact, the excess of events has an energy spectrum similar to that expected from axions produced in the Sun.

While these solar axions are not dark matter candidates, axions produced in the early Universe could be a source of dark matter.

In statistical terms, the solar axion hypothesis has a significance of 3.5 sigma.

While this significance is fairly high, it is not large enough to conclude that axions exist. Five sigma is generally the accepted threshold for a discovery.

The significance of both the tritium and neutrino magnetic moment hypotheses corresponds to 3.2 sigma, meaning that they are also consistent with the data.

Scientists working on the Xenon collaboration are currently upgrading to a different iteration called Xenon-nT. With better data from this future version, they are confident they will soon find out whether the excess is a statistical fluke, a background contaminant, or something far more exciting.

Observation of the ^{60}Fe nucleosynthesis-clock isotope in galactic cosmic rays

Science 06 May 2016:
Vol. 352, Issue 6286, pp. 677-680
DOI: 10.1126/science.aad6004

Abstract

Iron-60 (^{60}Fe) is a radioactive isotope in cosmic rays that serves as a clock to infer an upper limit on the time between nucleosynthesis and acceleration. We have used the ACE-CRIS instrument to collect 3.55×10^5 iron nuclei, with energies ~195 to ~500 mega–electron volts per nucleon, of which we identify 15 ^{60}Fe nuclei. The ^{60}Fe/^{56}Fe source ratio is $(7.5 \pm 2.9) \times 10^{-5}$. The detection of supernova-produced ^{60}Fe in cosmic rays implies that the time required for acceleration and transport to Earth does not greatly exceed the ^{60}Fe half-life of 2.6 million years and that the ^{60}Fe source distance does not greatly exceed the distance cosmic rays can diffuse over this time, $\lesssim$1 kiloparsec. A natural place for ^{60}Fe origin is in nearby clusters of massive stars.

Signature of recent nucleosynthesis

The radioactive isotope ^{60}Fe [which decays by β^- decay with a half-life of 2.62×10^6 years (*1*)] is expected to be synthesized and ejected into space by supernovae, and thus could be present in galactic cosmic rays (GCRs) near Earth, depending upon the time elapsed since nucleosynthesis and the distance of the supernovae. ^{60}Fe is believed to be produced primarily in core-collapse supernovae of massive stars with mass $M > \sim 10$ solar masses ($M_\odot$), which occur mostly in associations of massive stars (OB associations). It is the only primary radioactive isotope with atomic number $Z \leq 30$ [with the exception of ^{59}Ni, for which only an upper limit is available (*2*)] produced with a half-life long enough to potentially survive the time interval between nucleosynthesis and detection at Earth. (Primary cosmic rays are those that are synthesized at the GCR source, as opposed to secondary cosmic rays, which are produced by nuclear interactions in the interstellar medium.) ^{60}Fe is difficult to measure with present-day instruments because of its expected extreme rarity, based on nucleosynthesis calculations for supernovae (*3*, *4*). The detection of ^{60}Fe in cosmic rays would be a clear sign of recent, nearby nucleosynthesis. The long period of data collection (17 years) achieved by the Cosmic Ray Isotope Spectrometer (CRIS) aboard NASA's Advanced Composition Explorer (ACE) (*5*), the excellent mass and charge resolution of the CRIS instrument, and its capability for background rejection have enabled us to detect ^{60}Fe.

^{60}Fe has been detected in other samples of matter. Measurements of diffuse γ-rays from the interstellar medium (ISM) by the spectrometer on the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) spacecraft have revealed line emission at 1173 and 1333 keV from ^{60}Co, the daughter product of ^{60}Fe decay, clear evidence that "nucleosynthesis is ongoing in the galaxy" (*6*). As expected, this emission is diffuse instead of point-like, since the ^{60}Fe lifetime is sufficiently long to allow it to diffuse over distances that are large compared to the size of a supernova remnant. This is one of many strong connections between γ-ray astronomy and direct cosmic-ray studies (*7*).

Searches for neutrinos from cosmic-ray interactions in the Sun using seven years of IceCube data

Journal reference: JCAP02(2021)025
DOI: 10.1088/1475-7516/2021/02/025

1 Introduction

Neutrinos can be produced as a result of cosmic-ray interactions in the solar atmosphere. Cosmic rays interact with nuclei in the solar atmosphere, producing particle showers including pions and kaons. The decays of these mesons produce so called "Solar Atmospheric Neutrinos" (SAνs). Theoretical flux predictions of SAνs and detailed process discussions have been given in [1–8]. The neutrino production process in the solar atmosphere is similar to that of the terrestrial atmospheric neutrinos, with the notable difference that mesons generated in the solar atmosphere tend to decay before they can re-interact or lose a significant fraction of their energy, due to the larger and thinner atmosphere. As a result, the neutrino spectrum from the solar atmosphere is expected to be harder compared to that from the Earth, where the spectrum is steepened due to interactions of the secondary mesons, see e.g. [9]. This difference makes the spectra distinguishable and is used as a main criteria in our search for the SAν flux. A search for solar atmospheric neutrinos has never been experimentally performed and this work is the first of its kind.

The production process of SAνs is closely connected to that of gamma-rays through the decays of neutral pions and other mesons. Evidence for solar gamma rays was first reported in a re-analysis of EGRET data [10]. Recently, the Fermi-LAT Collaboration reported the ob- servation of a steady gamma-ray emission from the solar disk with energies up to 10 GeV [11].

In addition to the solar disk emission predominantly due to neutral pion decays from cosmic-ray interactions in the solar atmosphere, an extended inverse Compton signal from cosmic-ray electron interactions with the solar photon field was also observed. A follow- up analysis on the solar disk emission based on six years of public Fermi-LAT data has shown that the energy spectrum extends beyond 100 GeV and anticorrelates with the solar activity [12]. This was confirmed with an extended nine year analysis [13]. The magnetic field near the Sun is complex and strongly time-dependent. Gamma-ray production is expected to be significantly enhanced above 10 GeV in case of a more intense magnetic field. However, the effects on the neutrino production are found to be negligible [14]. Further, the observed gamma-ray spectrum shows a potential dip [15] and points to an inhomogeneous emission between the equatorial plane and the polar region of the Sun [13]. Unexpectedly, the observed gamma-ray flux is about six times higher [12, 13] than theoretical predictions [1]. The High Altitude Water Cherenkov (HAWC) gamma-ray observatory has searched for gamma rays beyond the energies accessible by Fermi-LAT. HAWC reported no evidence of TeV gamma- ray emission in three years data and has set flux bounds [16]. The recent observation of gamma-ray emission from the Sun makes the search for solar atmospheric neutrinos very timely. The combined gamma-ray and neutrino data are expected to be vital to understand the solar atmospheric processes and cosmic-ray transport in the inner solar system [1, 17].

1. Introduction

R.A. Mewaldt, B. Klecker, and A.C. Cummings

During the twenty five years since the discovery of anomalouscosmic rays (ACR) there has been enormous progress in delineating their observed properties and in deducing the processes bywhich they originate (see e.g., reviews by Biswas et al., 1993; Klecker, 1995; and Simpson, 1995). As a result of this progress it is now firmly established that the bulk of ACRs result from interstellar neutrals that have been swept into the heliosphere and ionized to become pickup ions (Fisk et al., 1974). These pickup ions are then convectedinto the outer heliosphere, where they are accelerated to energies of 1 to 100 MeV/nuc, presumably at the solar wind termination shock (Pesses et al., 1981). The ACR component is now generally agreed to include the elements H, He, C, N, O, Ne, and Ar.

A number of observations have now verified key aspects of this basic picture. The composition of solar wind pickup ions has been measured directly (e.g. Geiss et al., 1994, and references therein), and neutral interstellar He was observed streaming into the heliosphere (Witte et al., 1993). It has also been demonstrated that the bulk of ACRs are singly-charged (Adams et al., 1991;Klecker et al., 1995), which distinguishes them from other particle components such as solar energetic particles (SEP) and galactic cosmic rays (GCR).

During the past several years of solar minimum conditions several new observations have intensified interest in ACRs, and raised a number of new questions about their origin. In the outer heliosphere the spectra of ACR He and O are unfolding with time and/or distance and the evolving spectral shapes have been used to estimate the location and strength of the termination shock (Cummings and Stone, 1996). Observations by SAMPEX have shown that at energies 20 MeV/nuc most ACRs are no longer singly charged as at lower energies (16 MeV/nuc); rather, they have charge states of 2, 3 and higher (Mewaldt et al., 1996b), which has implications for the nature of the acceleration process (Jokipii, 1996). In addition, Ulysses data haveshown that there are apparently additional sources of pickup ions, at least in the innerheliosphere (Geiss etal., 1995), andthere is evidence from Wind and Geotail for an enhancement in the low-energy sulfur spectrum similar to that of ACR species (Reames et al., 1996; Takashima et al., 1997).

Detection of very high-energy gamma-rays from GRBs

11/20/2019 1 Comment

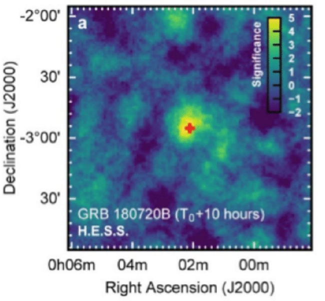
This is one of these rare moments: after decades of (quite often rather frustrating) searches we finally did it!

What did we do?

We detected very high-energy emission from a gamma-ray burst (GRB). These extremely energetic cosmic explosions typically lasting for only a few tens of seconds. They are the most luminous explosions in the universe. The burst is followed by a longer lasting afterglow mostly in the optical and X-ray spectral regions whose intensity decreases rapidly. The prompt high energy gamma-ray emission is mostly composed of photons several hundred-thousands to millions of times more energetic than visible light, that can only be observed by satellite-based instruments. Whilst these space-borne observatories have detected a few photons with even higher energies, the question if very-high-energy (VHE) gamma radiation (at least 100 billion times more energetic than visible light and only detectable with ground-based telescopes) is emitted, has remained unanswered until now.On 20 July 2018, the *Fermi Gamma-Ray Burst Monitor* and a few seconds later the *Swift Burst Alert Telescope* notified the world of a gamma-ray burst, GRB 180720B. Immediately after the alert, several observatories turned to look at this position in the sky.

For H.E.S.S. (High Energy Stereoscopic System), this location became visible only 10 hours later. Nevertheless, the H.E.S.S. team decided to search for a very-high-energy *afterglow* of the burst. After having looked for a very-high-energy signature of these events for more than a decade, the efforts by the collaboration now bore fruit.

A signature has now been detected with the large H.E.S.S. telescope that is especially suited for such observations. The data collected during two hours from 10 to 12 hours after the gamma-ray burst showed a new point-like gamma-ray source at the position of the burst. While the detection of GRBs at these very-high-energies had long been anticipated, the discovery many hours after the initial event, deep in the afterglow phase, came as a real surprise. The discovery of the first GRB to be detected at such very-high-photon energies is reported in a publication by the H.E.S.S. collaboration et al., in the journal 'Nature' on November 20, 2019.



GRB 180720B in very-high-energy gamma light, 10 to 12 hours after the burst as seen by the large H.E.S.S. telescope. The red cross indicates the position of GRB 180720B, determined from the optical emission of the GRB.

Who is "we"?

The results were obtained using the High Energy Stereoscopic System (H.E.S.S.) telescopes in Namibia. This system of four 13 m diameter telescopes surrounding the huge 28 m H.E.S.S. II telescope is the world's most sensitive very high-energy gamma ray detector. The H.E.S.S. telescopes image the faint, short flashes of bluish light emitted when energetic gamma rays interact with the Earth's atmosphere (so-called Cherenkov light), collecting the light with big mirrors and focusing it onto extremely fast reacting sensitive cameras. These Cherenkov images allow H.E.S.S. to reconstruct the properties of the interacting gamma-rays and ultimately detect their sources.

The High Energy Stereoscopic System (H.E.S.S.) team consists of over 200 scientists from Germany, France, the United Kingdom, Namibia, South Africa, Ireland, Armenia, Poland, Australia, Austria, the Netherlands, Japan and Sweden, supported by their respective funding agencies and institutions.

Author

Myself ;-)

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While I was not personally involved in the data analysis for this particular event, I am responsible for the searches for transient (i.e. rapidly fading) phenomena within the H.E.S.S. collaboration (technically speaking I am the convener of the "Transient" working group). Among the various topics covered in this group, searches for emission from GRBs have always been (and will obviously remain) the highest priority. Other searches include the quest for gamma-ray emission associated to Gravitational Waves, high-energy neutrinos, Fast Radio Bursts, Novae and Supernovae as well as flares from AGN, stars, magnetars, etc.

What does this mean and what is next?

The very-high-energy gamma radiation which has now been detected not only demonstrates the presence of extremely accelerated particles, but also shows that these particles still exist or are created a long time after the explosion. Most probably, the shock wave of the explosion acts here as the cosmic accelerator. Before this H.E.S.S. observation, it had been assumed that such bursts likely are observable only within the first seconds and minutes at these extreme energies.

At the time of the H.E.S.S. measurements the X-ray afterglow had already decayed very considerably. Remarkably, the intensities and spectral shapes are similar in the X-ray and gamma-ray regions. There are several theoretical mechanisms for the generation of very-high-energy gamma light by particles accelerated to very high energies. The H.E.S.S results strongly constrain the possible emission mechanisms, but also present a new puzzle, as they request quite extreme parameters for the GRB as a cosmic accelerator.

Together with the observations of very-high-energy gamma radiation following later GRBs with MAGIC (published in the same edition of Nature on Nov. 20, 2019) and again with H.E.S.S. (GRB190829A), this discovery provides deeper insights into the nature of gamma-ray bursts and opens the window for deeper observations and further studies.

For more than a decade, Cherenkov telescopes such as H.E.S.S., MAGIC and VERITAS have searched for very-high-energy gamma radiation from GRBs and continuously improved their observation strategies. Now several GRBs have been detected at very high energies within a very short time, and we now know that these bursts are emitting at extreme energies for many hours. This opens entirely new perspectives for further observations with the current instruments and is even more promising for the successor instrument, the Cherenkov Telescope Array, which will enable us to study these stellar explosions in much more detail.

A few highlights of the media coverage:

- A very-high-energy component deep in the γ-ray burst afterglow; H.E.S.S. collaboration; *Nature 575*, 464-467 (2019); https://www.nature.com/articles/s41586-019-1743-9 also available on the arXiv: https://arxiv.org/abs/1911.08961
- Teraelectronvolt emission from the gamma-ray burst GRB 190114C, *Nature* 575, 455-458 (2019); https://www.nature.com/articles/s41586-019-1750-x
- Observation of inverse Compton emission from a long gamma-ray burst, *Nature* 575, 459-463 (2019); https://www.nature.com/articles/s41586-019-1754-6
- Nature editorial by Bing Zhang
- Fait marquant de l'IRFU

For this blog. I reused text prepared within the H.E.S.S. collaboration. See H.E.S.S

Tweet

1 Comment

The Astrophysical Journal Letters, 790:L21 (5pp), 2014 August 1 doi:10.1088/2041-8205/790/2/L21

INDICATIONS OF INTERMEDIATE-SCALE ANISOTROPY OF COSMIC RAYS WITH ENERGY GREATER THAN 57 EeV IN THE NORTHERN SKY MEASURED WITH THE SURFACE DETECTOR OF THE TELESCOPE ARRAY EXPERIMENT

Received 2014 April 25; accepted 2014 June 26; published 2014 July 14

ABSTRACT

We have searched for intermediate-scale anisotropy in the arrival directions of ultrahigh-energy cosmic rays with energies above 57 EeV in the northern sky using data collected over a 5 yr period by the surface detector of the Telescope Array experiment. We report on a cluster of events that we call the hotspot, found by oversampling using 20◦ radius circles. The hotspot has a Li-Ma statistical significance of 5.1**σ**, and is centered at R.A. = 146. ◦ 7, decl. = 43. ◦ 2. The position of the hotspot is about 19◦ off of the supergalactic plane. The probability of a cluster of events of 5.1**σ** significance, appearing by chance in an isotropic cosmic-ray sky, is estimated to be 3.7 °ø 10^{-4} (3.4**σ**).

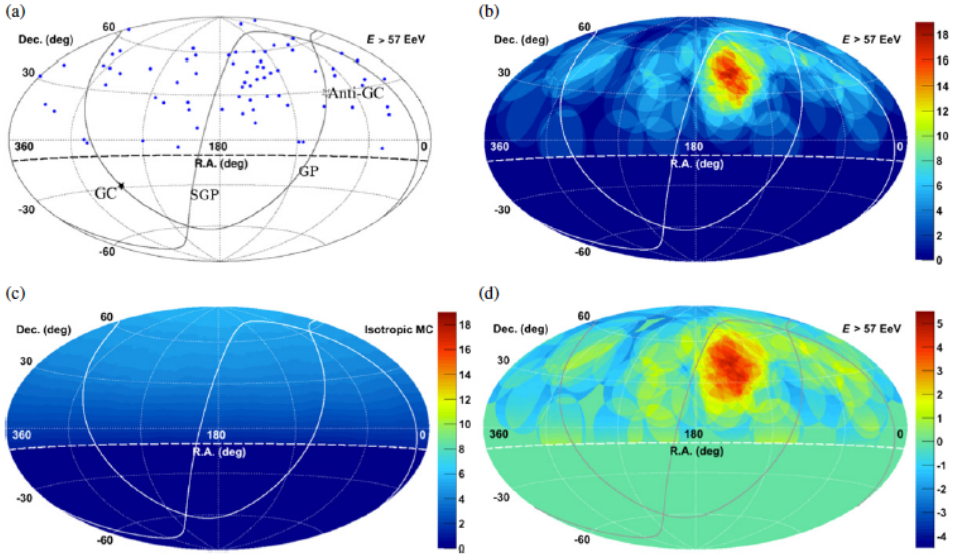

Figure 1. Aitoff projection of the UHECR maps in equatorial coordinates. The solid curves indicate the galactic plane (GP) and supergalactic plane (SGP). Our FoV is defined as the region above the dashed curve at decl. = −10°. (a) The points show the directions of the UHECRs $E > 57$ EeV observed by the TA SD array, and the closed and open stars indicate the Galactic center (GC) and the anti-Galactic center (Anti-GC), respectively; (b) color contours show the number of observed cosmic-ray events summed over a 20° radius circle; (c) number of background events from the geometrical exposure summed over a 20° radius circle (the same color scale as (b) is used for comparison); (d) significance map calculated from (b) and (c) using Equation (1).

5. DISCUSSION

There are no known specific sources behind the hotspot. The hotspot is located near the supergalactic plane, which contains local galaxy clusters such as the Ursa Major cluster (20 Mpc from Earth), the Coma cluster (90 Mpc), and the Virgo cluster (20 Mpc). The angular distance between the hotspot center and the supergalactic plane in the vicinity of the Ursa Major cluster is **~** 19◦ . Assuming the hotspot is real, two possible interpretations are that it may be associated with the closest galaxy groups and/ or the galaxy filament connecting us with the Virgo cluster (Dolag et al. 2004); or, if cosmic rays are heavy nuclei, they may originate close to the supergalactic plane and be deflected by extragalactic magnetic fields and the galactic halo field (Tinyakov & Tkachev 2002 ; Takami et al. 2012). To determine the origin of the hotspot,wewill need greaterUHECR statistics in the northern sky. Better information about the mass composition of the UHECRs, GMF, and IGMF would also be important.