RICAP-07: Summary Comments

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Abstract

The Roma International Conference on Astroparticle Physics covered gamma-ray astronomy, air shower experiments and neutrino astronomy on three successive days. I organize my brief summary comments into four topics that cut across these three techniques. They are detector calibration, galactic sources, extra-galactic sources and cosmology.

Key words: Cosmic rays, gamma-ray astronomy, neutrino astronomy

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1. Introduction

A main theme of the conference was the multi-messenger approach to the origin of cosmic rays. The conference had a local flavor that illustrates the strong Italian contributions to major experimental activities in all three fields, gamma-ray astronomy, cosmic-ray experiments and neutrino astronomy. In these brief remarks I will point out some common techniques and approaches and focus on a few important questions being addressed by current experiments in particle astrophysics. I make no attempt to give a balanced and systematic review of the field here.

2. Calibration

One can distinguish two aspects of calibration. One is to determine the response of a detector to a given beam or spectrum of particles. The other is to evaluate the level at which a source can be seen above background and make sure the search algorithms would find a sufficiently strong source if it is present. Computer simulations and test beams play a central role in both cases. For example, the Large Area Telescope (LAT) team on GLAST uses GEANT 4 to simulate the full detector based on exposure of each component to accelerator beams. The simulation is tuned to data from further exposures of prototype assemblies to accelerator beams. To address the other aspect, a simulated sky has been created consisting of various likely sources superimposed on the background of the Milky Way and an extra-galactic diffuse flux, as shown in Table 1.

| Galactic Sources       | Number | Extra-galactic Sources | Number |
|------------------------|--------|------------------------|--------|
| Milky Way              | 1      | Diffuse Extra-galactic | 1      |
| Moon                   | 1      |                        |        |
| Pulsars                | 414    | Bright variable AGN    | 204    |
| Plerions               | 7      | Faint steady AGN       | 900    |
| SNR                    | 11     | GRB                    | 134    |
| XRB                    | 5      | GRB afterglow          | 9      |
| OB associations        | 4      | PBH                    | 1      |
| Small mol. cloud       | 40     | Galaxy clusters        | 4      |
| Dark Matter            | ~2     | Galaxies               | 5      |
| ‘Other 3EG’            | 120    |                        |        |
| Solar flare            | 1      |                        |        |

Pointing accuracy and angular resolution can be determined with data from a known source. Gamma-ray telescopes typically use the Crab Nebula (e.g. VERITAS) as a calibration source. The shadow of the Moon can also be used, particularly for ground arrays operating at higher energy and with smaller statistics (e.g. ARGO-YBJ).

Angular resolution can also be determined by measuring the same events with two different detectors. An example...
of this is a sub-array analysis with an air shower detector such as IceTop [5]. The “checkerboard” analysis of the ARGO-YBJ carpet is another example.

For IceCube, the same principle can be used to check the pointing and angular resolution of the neutrino telescope, to the extent that high-energy muons in air shower cores tagged by IceTop are similar in the detector to upward-moving neutrino-induced muons. For air showers above the threshold for IceTop, one can compare the direction reconstructed with the surface array with the direction of the same event reconstructed independently by the deep array. Since the surface array can be surveyed directly, this comparison checks pointing as well as angular resolution. Limitations are that showers above the threshold for IceTop typically have several muons at the depth of the deep detectors of IceCube and that coincident events that pass through both detectors are nearly vertical. To address the multiplicity problem, one can also use lower-energy events that trigger only a single, inner IceTop station on the surface and compare the line from that station to the center of the deep event with the direction reconstructed by the IceCube reconstruction algorithm. In her talk on KM3NeT, the project to build a cubic kilometer neutrino detector in the Mediterranean [6], Els de Wolf pointed out the possibility of deploying, perhaps temporarily, a floating air-shower detector above the deep-sea neutrino telescope. Such a detector could have a variable spacing tuned to be able to reconstruct small showers likely to produce a single muon that penetrates to the deep array. It could also be moved to expand the range of angles explored.

Apart from coincident events, the energy spectrum and angular distribution of atmospheric muons and neutrinos are now rather well known in the TeV range. Measuring and reconstructing both these distributions is an important benchmark for neutrino telescopes. The spectrum of diffuse neutrinos in AMANDA [7] has been measured to approaching 100 TeV [8] and agrees reasonably well with expectation. Some atmospheric neutrinos have been identified with 9-string IceCube during 2006 [10]. The first physics-quality data with IceCube is expected from the 22-string detector currently operating in 2007 and in early 2008. The next version of IceCube, including the new strings of IceCube detectors to be deployed during the 2007/2008 season, is scheduled to start a new run in April, 2008. Antares has reported a preliminary measurement of the zenith angle distribution of muons as shown in Fig. 2 [11]. Although there is not yet a comparison with the expected angular distribution of atmospheric muons and neutrinos, the apparent emergence of neutrino-induced muons slightly above the horizon is impressive. If this interpretation of the plot is correct, it indicates good angular resolution at the depth of 2050-2400 meters in the Mediterranean Sea.

The essential problem for calibration of large air shower arrays is that reconstruction of the energy and mass of the primary cosmic-rays they are designed to measure depends on extrapolation of properties of hadronic interactions into regions inaccessible at accelerators. Calibration of the individual detectors on the ground is straightforward, either by exposing them to accelerator beams or by using abundant GeV cosmic-ray muons in situ. The real problem is that reconstructing the properties of the primary cosmic radiation from what is measured on the ground depends on comparison to simulations made with models of hadronic interactions extrapolated orders of magnitude beyond the regions of energy and phase space measured at accelerators. Use of fluorescence detectors has the advantage that the measurement of shower energy is more nearly calorimetric provided complications of viewing angle, Cherenkov
light background and variable atmospheric properties can be overcome (for example with laser calibration shots). But even in this case, there is a surprisingly large range of predictions for the correction that has to be made for dark energy in air showers (i.e. energy lost to neutrinos and energy carried into the ground by muons). In his talk on Auger, Alan Watson showed a 6-7% contribution to the 24% systematic uncertainty in the Auger fluorescence detector from this source.

3. Galactic sources

Perhaps the most remarkable discovery in particle astrophysics of the last few years is the large number of galactic sources observed in detail (including spatial structure) by H.E.S.S. and described in this meeting in [14]. The MILAGRO experiment reports structure reflecting several sources in the Cygnus region as well as a diffuse TeV gamma-ray background that is higher than expected [16]. The MILAGRO experiment reports structure reflecting several sources in the Cygnus region as well as a diffuse TeV gamma-ray background that is higher than expected [16]. Some of the H.E.S.S. sources are supernova remnants for which hadronic models seem likely [17] in view of measurements of strong magnetic fields, which make the electromagnetic interpretation more difficult, in particular RX J1713-3946, in which the gamma-ray spectrum is observed to 100 TeV [18].

The most direct signal of acceleration of protons as well as electrons in SNR would be observation of neutrinos. If the >TeV gamma-rays are decay products of neutral pions produced in hadronic interactions (\( p \rightarrow \pi^0 \rightarrow \gamma + \gamma \)), then one can calculate from kinematics the corresponding spectrum of neutrinos from \( p \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \). This has been done for several H.E.S.S. TeV gamma-ray sources in Ref. [18]. Optimistically, one expects to observe only a few neutrino-induced muons per year in a cubic kilometer detector, and atmospheric backgrounds in the search window are comparable or somewhat larger. In this situation, strategies such as source stacking can be helpful. Further references and discussion are given in Ref. [19].

In his talk on origin and acceleration of cosmic rays [20], Pasquale Blasi emphasized the role of magnetic field amplification and non-linear effects at strong shocks. There is evidence from X-ray observations of young supernova remnants for magnetic fields as high as 100 \( \mu \) Gauss, which allows acceleration of protons to \( > 10^{15} \) eV. Non-linear effects lead to differential spectra harder than \(-2\) at the source. The galactic spectrum with its observed differential index of \(-2.7\) must then be explained by a combination of several effects, including propagation and time evolution of the sources [21].

Developing a full model of galactic cosmic rays is a job that remains to be completed, but there is a growing consensus that the knee of the cosmic-ray spectrum must be associated with the beginning of the end of the spectrum of cosmic rays from sources in the Galaxy. If so, the spectrum is expected to become increasingly dominated by heavy primaries as the transition is approached. In his talk on KASCADE [22], Jörg Hörandel showed evidence for an increase in the relative proportion of heavy nuclei with increasing energy through the knee region. This analysis also brings up again the problem of how to extrapolate models of hadronic interactions correctly. The quantitative result of the analysis depends strongly on which event generator is used to interpret the KASCADE measurement of the ratio of \( \sim \) GeV muons to electrons in the shower front. Two event generators are compared (SIBYLL 2.1 and QGSJet 01). In both cases helium is apparently more abundant above \( 10^{15} \) eV than protons. However, the analysis with SIBYLL 2.1 shows the CNO group as the most abundant component, whereas with QGSJet 01 helium is significantly more abundant that the other components.

4. Extra-galactic sources

A major recent result is the observation of a steepening of the ultra-high energy cosmic ray spectrum above about \( 3 - 5 \times 10^{18} \) eV by Hi-Res [23] and Auger [13]. One question that arises is whether the spectrum steepens because accelerators are reaching their maximum energy or because of the effect of propagation and energy loss in the microwave background, the Greisen-Kuz’min-Zatsepin (GZK) effect. One way to confirm that it is the GZK effect is to measure the intensity of neutrinos in the EeV energy range. Predictions for the intensity of GZK neutrinos that would be produced by \( \sim 10^{20} \) eV protons during propagation depend on the cosmological evolution of the sources and their energy spectra, as discussed here by Todor Stanev [24]. The question arises how precisely and over what energy region it would be necessary to measure the spectrum of GZK neutrinos in order to unfold information about the history of cosmic-ray sources at large red shift and the source spectrum. The expected intensity of GZK neutrinos is such that a kilometer-scale detector might be expected to detect one or two per year. For this reason there is strong interest in using other techniques, such as radio [25] or acoustic [26], to achieve a significantly larger effective detector volume.

The most frequently mentioned possibilities for the sources of ultra-high energy cosmic rays are Gamma Ray Bursts and Active Galaxies. In either case, depending on the environment of the accelerator, a fraction of the energy could be lost in interactions of accelerated hadrons in or near their sources. If so, there could be correlated hadronic production of both >TeV gamma-rays and neutrinos [27,28].

The recent AMANDA limit on neutrino-induced muons from Northern Hemisphere GRBs [29] is close to the benchmark Waxman-Bahcall prediction [28], and IceCube is poised to extend the sensitivity significantly [30]. With AGILE already in orbit [31] and sensitive to GRBs on a range of time scales, and particularly next year when GLAST begins operation, there will be an increased number of tagged GRBs to define a time window in which to look for neutrinos. With time and direction windows de-
fined by an observed GRB, the background of atmospheric neutrinos is reduced to a very low level.

Leptonic models of TeV gamma-ray production in AGN are generally favored over hadronic models, in which case the connection between the observed intensity of TeV gamma-rays and possible neutrino fluxes would be lost. A recent addition to the arguments against hadronic models of AGN is the observation that new hadronic models come from the observation by MAGIC of a flare from Mrk-501 in which the higher energy photons arrive a few minutes after lower energy ones [32]. If the time delay reflects the time history of the accelerated charged particles, it has a natural explanation in the context of the electromagnetic, Synchrotron-Self-Compton Model; namely, that it may take longer to accelerate electrons to higher energy, so the higher energy Compton up-scattered photons would arrive later [33].

The branching ratio for this mode is likely to be small, but the signature is distinctive. In general, any gamma-ray product of dark matter interactions should point to regions of high mass concentration in the Galaxy.

Finally, I conclude with a reminder that the particle detectors PAMELA and AMS will make measurements of spectra of galactic cosmic rays with unprecedented precision. They will also map the effects of the Sun on cosmic rays and observe solar energetic particles. A nice example shown here was the spectrum of the December 13, 2006 solar flare observed with PAMELA [36].

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5. Cosmology

One motivation for the study of AGN spectra, apart from their intrinsic interest as compact, energetic astrophysical sources, is that they have the potential to probe the spectrum of extra-galactic background light in the infra-red which reflects the history of star formation in early epochs of the Universe [34]. The high-energy part of the spectrum is cutoff in the TeV range by $\gamma \gamma \to e^+e^-$ for sources with $z \sim 0.1$ and at lower energy for sources at larger redshift. The possibility of such a systematic study was emphasized here as one motivating factor in the proposal for a next generation gamma-ray telescope, CTA [35]. In his review of the subject [34], Stecker points out that cutoffs in the range of tens of GeV are expected in the spectra of AGNs with $z \sim 2$, a range accessible to GLAST.

Indirect detection of dark matter is a major goal of the satellite experiments discussed at this conference. The particle detectors (PAMELA [36], AMS [37]) will be searching for an excess of anti-matter over what is expected from cosmic-ray propagation through the interstellar medium. Such excesses would be a natural expectation, for example from WIMP pair annihilation in concentrations of dark matter, because particles and antiparticles would be produced in equal abundance. As emphasized in Roberto Batista’s talk [37], not only positrons and anti-protons could be observed, but also anti-deuterons. The latter would be a particularly clean signal of annihilation [38] because of the extreme difficulty of producing an anti-deuteron at low energy in the collision of a cosmic ray with an interstellar nucleus at rest. Because of the very high energy threshold for the process, any $d$ produced on a stationary target would be quite energetic.

Gamma-rays are also a potential signature of dark matter, particularly in the case where the signal produces a peak or line in the spectrum. The search for a signal of dark matter is among the principal goals of GLAST [3]. In his talk here, Lars Bergstrom [39] described the line signature from WIMP pair annihilation into $\gamma \gamma$ with $E_\gamma = M_{\text{WIMP}}$.

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