

TeV Particle Astrophysics II: Summary comments¹

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Abstract. A unifying theme of this conference was the use of different approaches to understand astrophysical sources of energetic particles in the TeV range and above. In this summary I review how gamma-ray astronomy, neutrino astronomy and (to some extent) gravitational wave astronomy provide complementary avenues to understanding the origin and role of high-energy particles in energetic astrophysical sources.

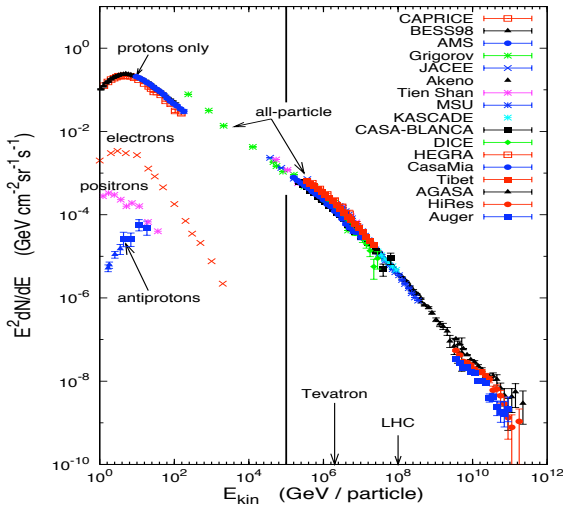


Figure 1. The $\nu F(\nu)$ plot for cosmic rays.

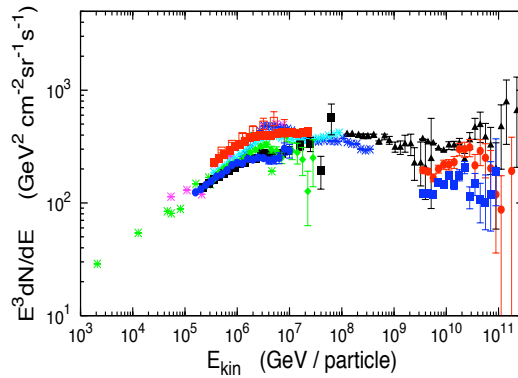


Figure 2. The differential primary spectrum multiplied by E^3 (see text).

1. Introduction: the cosmic-ray spectrum

Figure ?? shows the energy spectrum of cosmic rays in the form of a " $\nu F(\nu)$ " plot. Multiplying the differential energy spectrum by two powers of energy gives a plot that shows the energy content per logarithmic interval of energy. Most of the energy is carried by particles with energies below 100 GeV. In this energy range, detailed measurements with magnetic spectrometers in balloons or spacecraft above the atmosphere are possible. Spectrometer measurements of protons, electrons, positrons and antiprotons are shown on the plot. Not shown are the measurements of individual nuclear species, such as lithium, beryllium, boron, carbon, oxygen etc. from which we have the basic information about the lifetime of cosmic-rays in our galaxy and the power needed to maintain them in equilibrium. In his talk in parallel session IV, Swordy summarized the current status of this field [?].

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Above several hundred GeV, direct measurements are typically made with calorimeters. The charges of individual nuclei can still be determined, but the systematics of the energy determination is not as good. Above about 100 TeV (marked by the vertical line in Fig. ??), the flux becomes so low that large air shower detectors on the ground must be used. From the ground only secondary cascades are measured, so only indirect and very approximate measurements of the primary composition are possible.² With an enclosed area of 3000 km² the Auger Project [?] currently has the largest acceptance of any cosmic-ray detector. First results with the partially completed Auger detector were presented at the 2005 Cosmic Ray Conference [?] and are included in Fig. ?. In his talk at this conference [?], Cronin pointed out that (except possibly at the very highest energies) the spectra measured by AGASA [?], Hi-Res [?] and Auger [?] can be brought into close agreement by a systematic shift in energy of the order of 25%.

Figure ?? shows the same data as in Fig. ?? in the form conventionally used for discussion of the spectrum of ultra-high energy cosmic rays. Such a plot was shown and discussed by Blasi [?] in his talk at this conference. He noted several features in the spectrum:

- The knee around 3×10^{15} eV,
- A second knee above 10^{17} eV,
- A dip just below 10^{19} eV and
- A GZK feature in the decade above 10^{19} eV.

Except for the “second knee”, these features are clearly visible in the data collected in Fig. ?. The first “knee” is a steepening of the spectrum from a differential index of ≈ -2.7 below 10^{15} eV to ≈ -3 for $E > 10^{16}$ eV.

Peters showed long ago [?] that if the knee in the spectrum represents the transition from a low energy population of cosmic rays to a higher energy population with a harder spectrum, then one should see a characteristic sequence of changes in the elemental composition. The underlying assumption of his argument is that the spectral change is the result of a physical effect that depends on magnetic rigidity of the cosmic rays, which is the case for many models of propagation and acceleration. For example, for shock acceleration by supernova remnants, when the gyroradius of a particle exceeds the size of the remnant, it will escape from the acceleration region. Thus the criterion that determines the maximum energy is that the gyroradius of a particle should not exceed the radius of the remnant, R_{SN} [?]. This leads to

$$E_{\text{max}} = \xi\beta \times Z e B R_{\text{SN}}, \quad (1)$$

where $Z e$ is the charge of a nucleus of total energy E , B the magnetic field strength in the acceleration region and $\xi\beta$ the supernova shock velocity reduced by a numerical factor ξ . In this sequence, first protons would decrease in abundance, then helium ($Z = 2$) then the CNO group, etc.

Several air-shower experiments (e.g. Refs. [?, ?] and references therein) show a general trend of increasing mass through the knee region, but the KASCADE [?, ?] experiment is the first to see evidence of the sequence of steepening of individual spectra predicted by Peters. The KASCADE result, in common with all indirect determinations of the composition, is limited by uncertainties in the models of hadronic interactions used to interpret the data. Thus the fractions of the different groups of nuclei are less well established than the energy-dependence of the average mass, which becomes heavier through the knee region. Current experiments become statistically limited below 10^{17} eV. This is just the energy range one would like to

² Wakely’s talk [?] describes a method [?] that may be used to measure primary cosmic rays in the PeV range from the ground by detecting direct Cherenkov light before the primary nuclei disintegrate. The method works best if Z is not too small.

explore in more detail to look for signatures in composition of a transition to a new (presumably extra-galactic) population of particles at higher energy.

The location in energy of a transition from Galactic to extra-Galactic cosmic rays is a question of long standing. In the past, the dip was sometimes interpreted as the signature of the transition to an extra-galactic population [?]. More recent data from the HiRes experiment [?] seem to suggest a transition from mostly heavy nuclei (interpreted as the end of galactic cosmic rays) to mostly light nuclei (possibly extra-galactic) an order of magnitude or more lower in energy. This result would be consistent with the interpretation by Berezhinsky et al. [?] of the dip as a consequence of energy losses by protons producing electron-positron pairs in interaction with the cosmic background radiation.

If the extra-galactic component includes too large a fraction of heavy nuclei, however, the dip due to pair production is wiped out. A recent paper, [?] reported on at this conference by Busca [?], contrasts two models of extra-galactic cosmic rays. One is mostly protons, in which case the dip is explained by pair production and the transition to extra-galactic cosmic rays occurs at relatively low energy ($< 10^{18}$ eV). The other postulates a large fraction of heavy nuclei and interprets the dip as the signature of the onset of the extra-galactic component. In the latter case, one probably needs a special, high-energy galactic component (called “component B” by Hillas [?]) to fill in between conventional supernova origin and the extra-galactic component at ultra-high energy.

Composition in the intermediate region between the knee and the dip is an important unanswered question at present. First spectrum measurements from KASCADE-Grande extending to 10^{18} eV were shown at this conference [?], but not yet interpreted in terms of composition. The IceCube experiment [?], currently under construction at the South Pole, with its surface component IceTop will also be sensitive to primary composition up to 10^{18} eV. A low-energy extension of the telescope array is contemplated [?] to explore this energy region, and there are other possibilities [?], including use of the radio technique to detect showers by their geo-synchrotron radiation [?, ?].

2. Multi-messenger astronomy

The term “multi-messenger astronomy” was first used, as far as I can ascertain, by Steve Barwick during one of the committee meetings of the panel on Particle, Nuclear and Gravitational-Wave Astrophysics in the last decadal survey [?]. What was then to some extent a rhetorical device in our report is now coming closer to reality as neutrino telescopes approach the sensitivity needed to see neutrinos from established and likely TeV gamma-ray sources. Ideas for coordinating searches between gamma-ray and neutrino telescopes are now being proposed [?, ?]. Coincident observation of a gamma-ray burst by LIGO is also a possibility in the near future [?].

In his review of ground-based gamma-ray astronomy, Eckart Lorenz [?] showed a sky plot with well over $30 \geq$ TeV γ -ray sources, including both galactic and extra-galactic objects. His map showed only a fraction of the sources newly discovered by H.E.S.S. [?] in the inner galaxy [?]. Several of these are supernova remnants, some of which are clearly better fit by hadronic models than by synchrotron-self-Compton models. An example is RXJ1713.7-3946, first reported in TeV by CANGAROO [?]. The results from H.E.S.S. observing the southern sky are making a breakthrough in VHE gamma-ray astronomy. VERITAS is now coming on line with four telescopes [?] and will have similar sensitivity for the northern sky. The recent observation by MILAGRO of an excess from the Cygnus region [?] of the galactic plane will be particularly interesting to investigate with VERITAS.

In his survey of astrophysical sources of neutrinos and expected rates [?], Dermer stated a rule of thumb for detectability of neutrino sources in kilometer scale neutrino telescopes. An energy fluence of 10^{-4} ergs/cm² is the criterion for detectability. The argument, which assumes

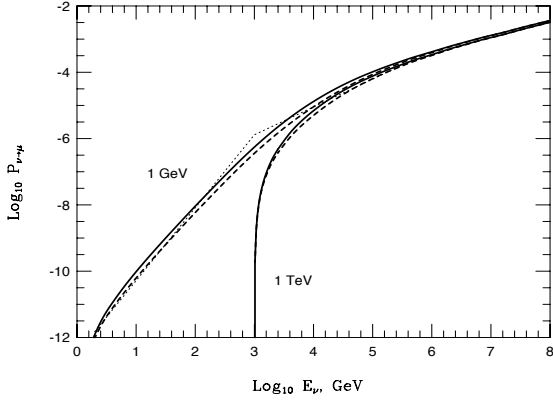


Figure 3. The probability $P_\nu(E_\nu)$ for detecting a muon neutrino (solid) or anti-neutrino (dashed) by the charged current interaction channel [?]. (See text.)

that muon neutrinos are the favored channel because of the large muon range, is illustrated in Figs. ??,??. The signal is the convolution of the neutrino flux, $\phi_\nu(E_\nu)$, with the probability $P_\nu(E_\nu)$ that a neutrino on a trajectory toward the detector will interact to produce a muon that reaches the detector with enough energy to be detected. In general, the detection efficiency will be an increasing function of energy. Figure ?? from Ref. [?] shows two extreme examples, step function thresholds at 1 GeV and 1 TeV.

Figure ?? shows the response function, $E_\nu \phi_\nu(E_\nu) \times P_\nu(E_\nu)$, for several examples. The response function is essentially $dN_{\text{signal}}/d\ln(E_\nu)$, so that equal areas on the plot correspond to equal contributions to the signal. Curves A and B refer to the spectral shape of RXJ1713.7-3946 as measured by H.E.S.S. [?], which shows evidence of steepening, consistent with an exponential cutoff above 10 TeV. The neutrino flux is normalized assuming all observed gamma-rays are from π^0 -decay without absorption in the source. The flux at Earth is reduced by a kinematic factor (≈ 0.85) that relates π^0 photons to $\nu_\mu + \bar{\nu}_\mu$ from the charged $\pi \rightarrow \mu \rightarrow e$ decay chain and by a factor of two to account for oscillations. Absorption of neutrinos in the Earth is unimportant below 100 TeV. The integrated energy fluence of $\nu_\mu + \bar{\nu}_\mu$ at Earth with these assumptions is $\approx 2 \times 10^{-4}$ erg/cm². Curve A corresponds to a requirement $E_\mu > 1$ TeV at the detector, while the threshold for curve B is taken as 100 GeV. These threshold are meant to bracket the true threshold for a kilometer-scale neutrino detector. The corresponding range of signals is ~ 2 to 4 events per square kilometer per year. These numbers are comparable to the atmospheric background within a cone of radius 1° .

Curve C is the response function for a neutrino spectrum with the same normalization as A at 1 TeV but with a hard differential spectral index of -2 and cutoff above 1 PeV. Such a situation is conceivable (though unlikely) if the gamma-ray cutoff is due to absorption at the source in a way that does not affect the neutrinos. Curve C also illustrates how detectors respond to different neutrino spectra. For example, for power-law spectra with differential indices of -3 , -2 and -1 , Becker [?] showed that the response for AMANDA peaks respectively at 0.5, 50 and 10^5 TeV.

Curve D in Fig. ?? shows the integrated diffuse flux corresponding to the MILAGRO gamma-ray spectrum for the Cygnus region. Averaged over a region of $\pm 3^\circ$ in galactic latitude and 20 degrees in galactic longitude, the integral gamma-ray intensity is 4×10^{-13} (cm²s)⁻¹ for $E_\gamma > 12.5$ TeV with an assumed differential spectral index of -2.6 . The corresponding upward muon signal would be ~ 3 per km²yr, under the same assumptions described above for relating neutrinos at Earth to the observed spectrum of photons. Because of the diffuse nature of the source, however, such a low signal would be hidden in the atmospheric background.

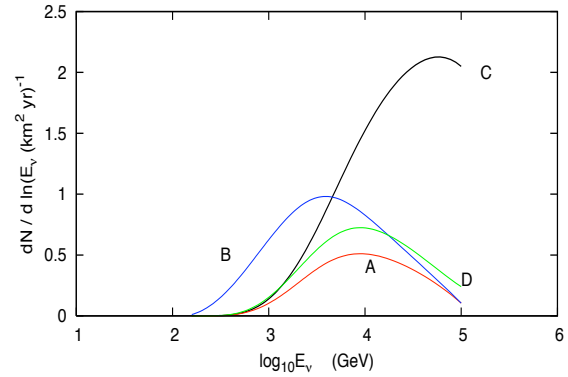


Figure 4. The differential response function for neutrino signals. Curves A, B, C and D correspond to different sources and assumptions as described in the text.

3. Concluding comments

In his summary [?], Dermer listed blazar active galaxies (“flat spectrum radio quasars, not BL Lacs”) and gamma-ray bursts as the most promising sources for kilometer-scale neutrino detectors. Finding the first signals from such sources, as well as from the kinds of Galactic sources mentioned above, by detecting upward neutrinos in the TeV-PeV range is the primary goal of IceCube, now under construction in Antarctica [?, ?], and of planned kilometer scale detectors in the Mediterranean [?]. The ability to distinguish between single muons and muon bundles with Antares [?] illustrates the merits of water as a detection medium. Good progress with construction of IceCube [?] and the successful performance of the first strings [?] show that the Antarctic ice sheet is also a suitable detection medium, The solid surface is convenient for deployment and readily accommodates the IceTop air shower array as an integral component of IceCube. The two large neutrino telescope projects are complementary in technique as well as sky coverage.

In view of the low level of expected signals, it is important to develop techniques for multi-messenger astronomy to help discriminate signals from background. In this respect, searching for neutrinos associated with identified gamma-ray burst events is attractive. More generally, finding a statistically proper way to define and search for coincidences between gamma-ray activity and neutrino signals should be helpful [?, ?]. Triple coincidences with gravitational wave detectors as well would be even better.

Yoshida [?] discussed GZK neutrinos as a probe of models of cosmic evolution and sources of ultra-high energy cosmic rays. Weiler [?] discussed the possibility of using precise measurements of neutrino flavor ratios to probe conditions in the acceleration region as well as looking for novel intrinsic neutrino properties. He also discussed using horizontal events to probe the neutrino cross section at ultra-high energy. To fully exploit the potential of UHE neutrino astronomy appears to require new techniques capable of seeing larger target volumes with more sparsely instrumented arrays. Ideas for radio and acoustic detection of neutrinos were reviewed by Varner [?] and Thompson [?] respectively. These techniques have higher energy thresholds (particularly the acoustic), so finding a way to cross-calibrate with other techniques is important and is a recognized goal.

A better understanding of hadronic interactions is important for interpreting the results of air shower experiments as well as for obtaining better estimates of the atmospheric muon and neutrino background in neutrino telescopes. Catanesi [?] described new measurements with fixed target experiments at CERN which should provide the basis for improving treatment of the low-energy interactions in calculations of air showers as well as the neutrino flux calculations. Processes of interest for particle physics in the LHC era have cross sections in the microbarn range and below [?]. As a consequence, despite their somewhat higher reach in energy, air shower experiments are unlikely to make important new discoveries in particle physics. On the other hand, any information about the fragmentation region of hadronic interactions forthcoming from forward detectors at the LHC will be of great value for interpreting ultra-high energy cosmic-ray cascades to determine primary composition.

The most profound problems addressed at the conference concern dark matter and the early universe. The WMAP data are described well by the Lambda Cold Dark Matter model [?], which requires both dark energy and cold dark matter. Cabrera [?] and Aprile [?] reviewed direct searches for dark matter. Ullio [?] reviewed the many ways hints of dark matter might show up indirectly in spectra of particles and radiation, the most striking of which would be a diffuse gamma-ray line, which would give a direct measure of the WIMP mass. Among the viable possibilities is a neutrino signal from WIMP capture and annihilation in the Sun large enough to be detected in AMANDA/IceCube.

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