1 Introduction

Efforts are underway to qualitatively improve the instruments that can push astronomy beyond GeV photon energy, to wavelengths smaller than $10^{-14}$ cm, and map the sky in neutrinos and EeV cosmic rays as well as gamma rays. New gravitational wave detectors will explore wavelengths much larger than those of radio astronomy. While particle astrophysics may be easily mistaken for astronomy, I notice that most participants at this meeting are card-carrying particle physicists, born and raised near accelerators. Particle astrophysics presents particle physics with extraordinary opportunities. With neutrino mass, the cosmological constant and dark matter as some of the topics dominating this meeting, the case is self-evident.

Particle physics forms a basic framework which has allowed us to launch some of the most far-reaching excursions of the mind into the structure of matter and of the Universe. Further progress will come both from pushing the high energy and high sensitivity limits at accelerators, and from vigorously exploring the interfaces with other fields. Particle astrophysics has been one of the more successful of these multidisciplinary ventures.

The symbiosis of particle physics and astrophysics is even more intimate when it comes to instrumentation. The construction of dark matter detectors, earth- and space-based gamma ray telescopes, giant natural neutrino detectors and state-of-the-art air shower detectors, is immersed in technology developed for accelerator experiments. Particle physicists should not be reluctant in entering these new interdisciplinary ventures which touch astronomy,
astrophysics and cosmic ray physics using instrumentation that is a direct spin-off from techniques developed at great effort and expense in our accelerator laboratories. Second generation particle astrophysics experiments will require frontier technology, even by particle physics standards.

Cosmic beams of photons and protons have been detected with energies far exceeding those within reach of accelerators. How and where Nature accelerates particles to these energies is still a matter of speculation. We have learned that the sun does indeed emit a few percent of its energy in neutrinos. What were at first routine studies of cosmic ray interactions in the atmosphere, produced indications that neutrinos have mass. Supernova 1987A told us that we do understand stellar collapse, and also delivered a limit on the mass of the electron-neutrino similar to laboratory experiments. Its observation severely constrained the mass of the axion. Atmospheric Cherenkov telescopes have unambiguously detected several sources in gamma rays of energies between 1 and 10 TeV and are now providing a new window on the most violent sites in the cosmos. Finally, novel techniques developed by particle physicists at Berkeley produced evidence for a cosmological constant in observations of high red-shift supernovae.

Future goals hold promise beyond past achievements with, for instance, the possibility of detecting the particles which constitute the dark matter. The apparent relationship between the electroweak scale and the mass density of a flat universe is one of the most intriguing hints in contemporary science. The search for the particle nature of dark matter and the study of high energy neutrinos are examples of many common intellectual endeavors of particle physics and particle astrophysics. Also, the large neutrino detectors which have yielded tantalizing hints of new physics in the atmospheric neutrino beam, possibly neutrino mass, are complemented by new, giant detectors which are, hopefully, large enough to study neutrino sources far beyond our own galaxy. Gauge theory, which is the basic framework of modern particle physics, suggests topological structures which can only be probed in non-accelerator experiments. Such topological defects may manifest themselves both in cosmology (for instance, generating structure in the cosmic microwave background and the large scale distribution of galaxies) and in the acceleration of the highest energy cosmic rays.

Doing particle physics beyond the boundaries of the accelerator laboratories, for instance in space, at the South Pole or in the deep ocean, will inspire future generations of scientists and the public at large.

I will briefly summarize the excursions into particle astrophysics emphasized at this meeting:

1. **neutrinos**: first evidence for oscillations, and first light for first-generation
neutrino telescopes,

2. **gamma rays**: first light for next generation ground-based detectors using solar power stations and for the MILAGRO detector,

3. **EeV-protons**: the particles that do exist, but shouldn’t,

4. **cosmology and gravity**: $\Omega = 1$, but $\Omega_{\text{matter}} \simeq 0.4$ — the cosmological constant, eighty years later,

5. **dark matter**: the particles that should exist, but don’t.

It would be unwise however for the uninitiated observer to try to summarize the imaginative and sometimes heroic incursions of the theorists into the astrophysics of neutrinos. I especially enjoyed the discussions of neutrino magnetic moments, and of the collective interactions of neutrinos in astronomical plasmas.

2 Neutrinos

Neutrino astronomy was born with the sun in a series of pioneering efforts starting with the first observation in the Homestake mine and culminating with the GALLEX and SAGE experiments which detected the dominant solar source of neutrino production by proton-proton fusion. With the present emphasis on (and sometimes controversy surrounding) “the deficit”, the primary achievement of these historic experiments to see the sun in neutrinos should not be forgotten. Consolidation of the speculations that the solar deficit indicates a non-vanishing mass of the $\nu_e$ requires help from experiment which may very well come from SuperKamiokande. Supporting evidence may come as a distortion of the neutrino energy spectrum, or a daily or seasonal variation of the flux. The case for a particle, rather than astrophysical solution, has been boosted by ever more precise helioseismology. A lineup of new solar neutrino detectors lead by SNO and Borexino is ready to tackle the problem. A second-generation GALLEX experiment was discussed at this meeting.

While many now feel that neutrino mass has been finally established, the evidence came from elsewhere. Pathological behavior of the neutrinos produced in cosmic ray interactions with atmospheric nuclei, has been established for some time. The observed ratio of neutrinos of electron and muon type in the atmospheric beam disagrees with a very solid theoretical prediction. While this discrepancy can be readily accommodated by assuming oscillation of the neutrino beam, first support for this interpretation came from the SuperKamiokande experiment with a most striking and straightforward observation: there are fewer muon neutrinos produced in the earth’s atmosphere below our feet than above their head, a reduction in relative flux of more than 6 $\sigma$. 

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So, the anomalous ratio of electron and muon neutrinos can be traced to a reduction of the muon neutrino flux which travelled 12500 km from the other end of the earth, relative to the flux produced in the upper atmosphere overhead which travelled, on average, 25 km. Supporting observations by SuperK and other experiments confirm this interpretation; none are however compelling.

The data is described by a mixing angle near unity and a mass difference $\Delta m^2$ of a few times $10^{-3}$ eV$^2$. What now? Clearly some, waiting for decades for a crack in the harness of the Standard Model, have already built houses of cards. Even by the most conservative interpretation, this result must have truly fundamental implications. One can accommodate the mass by adding a right-handed singlet to the Standard Model fermion multiplet as in its SO(10) extension. A mass term is added to the Lagrangian which represents new physics with a coupling $\lambda$ given by

$$m_\nu = \lambda v^2 \simeq 0.1 \text{ eV}^2.$$  

With a Standard Model vacuum expectation value of 250 GeV, this calls for new physics at an energy scale $M$

$$\lambda = M^{-1} = 6 \times 10^{14} \text{ GeV}^{-1},$$  

possibly larger, and not too far from the Planck scale. With sub-eV masses, neutrinos are not dark matter, mixed or not. Remember however that even a conservative house of cards is a house of cards and that the experiments measure $\Delta m^2$ and not $m$.

Unusually fundamental results require confirmation of unusual quality: possibly, observing the reappearance of the $\nu_\mu$ beam as $\nu_\tau$'s. Long-baseline experiments provide the best hope, although present results call for a baseline in excess of 1000 km which none of the present proposals deliver. This number does have a large uncertainty. If everything else fails, one may have to look elsewhere, for instance lowering the threshold of high energy neutrino telescopes.

This speculation is no longer unrealistic: first neutrino events emerged from Lake Baikal water and South Pole ice. Construction and calibration of their first-generation instruments was completed in the months preceding this meeting. First calibration of the respective experimental techniques using the atmospheric neutrino beam is now possible. There already are immediate implications beyond the obvious: relatively shallow experiments can handle the large cosmic ray muon backgrounds, and one can reconstruct tracks in ice opening the possibility of commissioning a kilometer-scale detector in the near future. A wide variety of estimates indicate that this is the size of detector required to do the science. Consisting of several hundred optical modules
deployed in natural water or ice which acts as a Cherenkov medium, these detectors are optimized for large effective area rather than low threshold (10 GeV or higher, even for the present smaller versions).

These instruments are complementary to SuperK and exploiting them to confirm their atmospheric neutrino results will be challenging. Lowering the threshold by redesigning the telescope architecture is not, and can be achieved by reducing the spacings of the optical modules in all, or part of the detector. Doing this may not further their astronomical mission, but will turn these instruments into better atmospheric neutrino detectors, good enough to probe the SuperK signatures for neutrino mass. The South Pole experiment would also have the right baseline to receive an accelerator beam.

Several initiatives exist to develop the infrastructure and technologies for the deployment of a neutrino telescope in the Mediterranean basin. At this meeting the Antares collaboration revealed, after satisfactory initial tests, their plans to proceed with the deployment of a first string of optical modules in 99, the construction of a detector of 800 modules on 10~15 strings by 02, and a kilometer-scale detector by 06.

As with conventional telescopes, at least two are required to cover the sky. As with particle physics collider experiments, it is very advantageous to explore a new frontier with two or more instruments, preferably using different techniques. This goal may be achieved by exploiting the parallel efforts to use natural water and ice as the Cherenkov medium for particle detection. Let me conclude by trying to infuse some sanity in the non-debate on “water and ice”. It is a non-debate because, ideally, we want both. Given the pioneering and exploratory nature of the research, we most likely need both. Water and ice have complementary optical properties: while the “attenuation” lengths are comparable for the blue wavelength photons relevant to the experiments, attenuation is dominated by scattering in ice and by absorption in water. Both have a problem: scattering in ice, potassium decay and bioluminescence in water. Both problems can be solved as shown by the initial results.

3 Gamma Ray Astronomy on Earth and in Space

State-of-the-art particle physics technology has reached space with the AMS anti-matter spectrometer which made a successful flight on the NASA shuttle. The field of gamma ray astronomy is buzzing with activity to construct second-generation instruments. Space-based detectors are extending their reach from GeV to TeV energy with AMS and, especially, GLAST, while the ground-based Cherenkov telescopes are designing instruments with lower thresholds. In the not so far future both techniques should generate overlapping measurements in
the 10~10^2 GeV energy range. All ground-based experiments reach for lower threshold, better angular- and energy-resolution, and a longer duty cycle. One can identify a multi-prong attack, with different methods for improving air Cherenkov telescopes:

i. larger mirror area, exploiting the parasitic use of solar collectors during nighttime,

ii. better, or rather, ultimate imaging of the photon footprint in the atmosphere with the 17 m MAGIC mirror,

iii. larger field of view by using multiple telescopes.

At this conference the first results from the CELESTE instrument were reported. Atmospheric air showers initiated by photons are imaged using an abandoned solar power station in the French Pyrenees. Each heliostat is viewed by a photomultiplier via optics placed at the focus, in the tower where solar power was once harnessed. The technique has been demonstrated by observing the Crab supernova remnant with a threshold of 80 GeV using only 18 heliostats and 9 data acquisition channels triggering at 10 Hz. This threshold corresponds to only 4 photons per heliostat. The march to lower threshold is on track.

After two decades, ground-based gamma ray astronomy has become a mature science. Let me remind you that, although it has produced few sources by astronomical standards, their observation has produced spectacular results. Data taken on the flaring active galaxies Markarian 421 and 501 testify to this statement. The most prominent features are:

• a spectrum which extends beyond 30 TeV,

• emission of TeV-photons in bursts with a duration of order a few days,

• correlation between the optical and TeV variability,

• observation of a burst lasting only 15 minutes, suggesting emission from very localized regions of the galaxy, presumably the jet.

There is a dark horse in this race: Milagro. The Milagro idea is to lower the threshold of conventional air shower arrays to 100 GeV by uniformly instrumenting an area of 10^3 m^2 or more (no sampling!). For time-varying signals, such as bursts, the threshold could be even lower. One instruments a pond with photomultipliers (Milagro), or covers a large area with resistive plate chambers (ARGO), or even with muon detectors (Hanul) which identify point sources of muons produced in photon-induced air showers.
Around 1930 Rossi and collaborators discovered that the bulk of the cosmic radiation is not made up of gamma rays. This marked the beginning of what was then called “the new astronomy”, and we refer to as cosmic ray physics today. It is “astronomy” only above $5 \times 10^{19}$ eV or so, where the arrival directions of the charged cosmic rays are not scrambled by the ambient magnetic field of our own galaxy. We suspect that the bulk of the cosmic rays are accelerated in the blastwaves of supernovae exploding into the interstellar medium. This mechanism has the potential to accelerate particles up to energies of $10^3$ TeV where the cosmic ray spectrum suddenly steepens: the “knee” in the energy spectrum. We have no clue where and how cosmic rays with energies in excess of $10^3$ TeV are accelerated. We are not even sure whether they are protons or iron, or anything else. The origin of cosmic rays with energy beyond the “knee” is one of the oldest unresolved puzzles in science.

To illustrate the degree of desperation, it has been suggested that the highest energy cosmic rays are the decay products of $10^{24}$ eV (the GUT unification scale) topological defects such as a monopoles, strings. Topological structures are deeply connected to gauge theories and cannot be studied in accelerator experiments. Non-accelerator particle physics provides unique opportunities here. A topological defect will suffer a chain decay into GUT particles X,Y, which subsequently decay to the familiar weak bosons, leptons and quark-gluon jets. Cosmic ray protons are the fragmentation products of these jets.

If the sources of cosmic rays are beyond $10^2$ Mpc, conventional astronomy cannot identify them because of the absorption of the beam on the microwave background. Absence of an energy cutoff associated with this absorption (the Greissen-Kuzmin-Zatsepin cutoff) becomes a signature for distant sources. The main problem today is statistics. After particles with energies in the vicinity of 100 EeV were discovered at Haverah Park, we have accumulated some 10 events whose energy clearly exceed $10^{20}$ eV, using three different detectors: AGASA, Yakutsk and the Fly’s Eye. The latter is being replaced by a technologically superior instrument with larger collection area: the HIRES detector. Construction of a $10^4$ km$^2$ array, one hundred times larger than the AGASA array operating in Japan, has been proposed and will be launched soon as the “Auger” project.

The asymmetric collapse, e.g. of a rotating star, near the center of our galaxy will result in the supernova display astronomy is waiting for — the simul-
taneous observation of light, neutrinos and gravitational waves could be the scientific event of all times. If we make the optimistic assumption that a similar amount of energy is emitted in gravitational waves and in light, i.e. one hundredth of a solar mass, the new generation of gravitational antennas under construction in the US and Europe will detect a whopping signal of $\delta h = 10^{-18}$. This deformation of the transverse components of the space-time tensor $h_{\mu\nu}^{TT}(x-ct)$ is detected at Earth in the form of gravitational waves. Such endeavors have put general relativity back into the particle physicist’s bag of tools. We were reminded at this meeting that this, and other adventures involving the cosmological constant and dark matter, are built on a total faith of the framework.

Concerning gravity, theorists have been investigating the interesting suggestion that the Planck scale is of order the weak scale of 1 TeV. At the Planck, the other particle interactions cannot be separated from gravity: a particle’s Compton wavelength ($m^{-1}$) is of the same order of magnitude as its Schwarzschild radius ($G_N m$). The idea implies that particle interactions modify gravity for distances below 1 millimeter! It is amazing to realize that no experimental verifications of Newtonian gravity cover this regime (yet), and the Large Hadron Collider will study gravity.

Even with a Planck scale safely anchored at $10^{19}$ GeV, cosmology has become (too?) exciting. The convergence on a Standard Cosmology with a flat Universe with $\Omega = 1$ has been shattered by multiple blows: we now suspect that $\Omega \leq 1$ for matter and that the cosmological constant does not vanish. The latter is an awesome possibility. While we know the particle physics that rules the other great epochs of cosmology, nucleosynthesis and recombination, we do not know the physics that rules the expanding Universe we live in today, driven by a cosmological constant.

Although the evidence, presented here by two groups, emerged from measurements of the Hubble flow using supernovae as standard candles, corroborating evidence may be emerging from elsewhere. Recent South Pole measurements of the acoustic waves at the surface of last scattering (the so-called Doppler peak in the power spectrum), indicate that $\Omega = 1$. With $\Omega_{\text{matter}} \leq 1$, this leaves room for a cosmological constant closing the deficit.

We were reminded at this conference that the search for particle dark matter is still a main focus of particle physicists entering astroparticle physics. This search is reaching the critical point where the size and sensitivity of the experiments will reach the predictions of the most popular model: neutralino dark matter made of the lightest stable particle predicted by supersymmetry. Phonon, scintillation and other techniques are developed, often in experiments exploiting coincident signals. Where these experiment lose sensitivity with in-
creasing neutralino mass, the now-operating neutrino telescopes gain sensitivity all the way to TeV masses, the maximum allowed by Standard Cosmology. **High** mass neutralinos annihilate in sun and earth into **high** energy neutrinos which are easier to detect.

We feel that in astroparticle physics, like in astronomy, mother Nature is always more imaginative than scientists. The future of astroparticle physics is not only bright — I predict, with history on my side, that it will be brighter than we can imagine.

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