DOI: 10.12871/978883339517320

Thinking Big: How Large-scale Detectors Set the Stage for the Emergence of Astro-particle Physics. A Short Survey

Luisa Bonolis – Max Planck Institute for the History of Science, Berlin – lbonolis@mpiwg-berlin.mpg.de
Juan-Andres Leon – Max Planck Institute for the History of Science, Berlin – jaleon@mpiwg-berlin.mpg.de

Abstract: The emergence of particle astrophysics was shaped by the growing symbiotic relationship between cosmic-ray and elementary-particle physics, high-energy astrophysics and cosmology during the 1970s/1980s. Detecting techniques grew in size from small Geiger-Müller counters up to giant detector arrays distributed over areas measured in square kilometers, to compensate with a large monitoring surface the low probability of ultra-high energy events. The same well-established practice for studying rare events — *a large-scale detector* — has been transferred to experiments hunting for solar neutrinos, to ground-based gamma-ray astronomy and to experiments transforming fresh water, ice and sea water into *both* targets and detectors for cosmic neutrinos, proton decay, dark matter candidates and other exotic particles relics of the early Universe. At the intersection of different research areas, material cultures, detection approaches and communities of practitioners, astro-particle physics got its modern identity and created a new unconventional breed of 'astronomers'. Through the early decades of these developments, the theoretical insights and proposed experiments of Bruno Pontecorvo proved particularly fertile and often provided the model for inquiry in this new field.

Keywords: Astroparticle physics, Detectors, Neutrinos, Astronomy.

1. Astro-particle physics: a unified view of the macro- and the micro-cosmos

Historically, particle physics, cosmology and astrophysics developed more or less independently, but they became interwoven again in the new field of astroparticle physics emerging in the period going from the mid-1970s to the second half of the 1980s. This is the period when new theoretical aspects and observational questions related to different scales of the Universe began to merge in a context more and more shared by several fields. New disciplines such as neutrino and gamma-ray astronomy presented from the outset a close link to particle physics, as had been the case with cosmic-ray studies since the very beginning. In this short note, we pick up a very selected number of examples which are especially relevant in showing how experiments on diverse research channels, combined with many theoretical conceptual frameworks — like the inflationary Universe, the cold-dark matter paradigm, neutrino oscillations, the hypothetical existence of exotic relics of the early Universe predicted by Grand Unified Theories (GUT) — contributed to materialize a new research field in which investigations of the most perplexing cosmic and astrophysical phenomena at a cosmological scale are inextricably intertwined with the quantum world of elementary particles. All this turned the Universe into a huge laboratory complementary to accelerator and non-accelerator experiments to explore fundamental physics at a microscopic and macroscopic scale.[1] Astroparticle physics is currently an interdisciplinary field lying at the intersection of particle physics, cosmology and astrophysics that is concerned with subatomic particles of cosmic origin and their relevance to astrophysics and cosmology. Given its interdisciplinary approach and the overlap of different disciplines, a concise definition of which experiments are to be considered 'astroparticle physics' is difficult. For example, as messengers from the high-energy Universe, gravitational wave research shows similar detection and scaling challenges in its development, around the same time. Several aspects of these connections can be traced far back in time, but the active process materialized in earnest towards the mid-1970s. At the time, the theoretical expectation coming from GUTs that unification of strong and electroweak forces should reveal itself at the extremely high energies and particle densities available in the first instants of the Universe, was deeply connecting astrophysics and particle physics with physical cosmology. Within the framework of the Hot Big Bang model the laws of particle physics could be applied in an attempt to trace the evolution of the Universe at very early times. But astroparticle physics also emerged in connection with the *experimental search* of effects, particles and entities predicted by such new theoretical frameworks. This gave a new impetus to traditional investigations on the origin of cosmic rays — eventually leading to high-energy gamma-ray astronomy — but also especially gained strength the most successful quest leading to astroparticle physics, and one that best represented the potential for observations leading to radical shifts in our understanding of fundamental physics: the detection of astrophysical neutrinos, which became entangled with the very nature of this unique particle and with new physics beyond the Standard theory of particle physics. The kinds of observations typical of astroparticle physics, require high sensitivity to the signal and high background rejection rate, that are both crucial for the search of rare events. The rarity of events or the elusiveness of particles, typically require massive detectors, often located underground to filter most of the unwanted background. The first of such detectors, and archetype for a successful astroparticle experiment/observatory, was built by Raymond Davis in the 1960s, at nearly 1500 m underground in the Homestake gold mine in South Dakota.

2. The prototype for large detectors: the radiochemical Chlorine-Argon method

The existence of a light neutral particle emitted in nuclear beta decay was suggested by Pauli and incorporated by Fermi in a quantitative theory in 1933. In 1934, Bethe and Peierls calculated that the cross section for the "inverse beta decay process" should be less than 10^{-44} cm^2. And so, the neutrino appeared to be "completely unobservable". In 1945,

---

[1] No literature will be cited, as this is meant as a very preliminary outline on some main aspects related to the emergence of astroparticle physics.

after about ten years, during which several attempts were made to detect this elusive particle, Pontecorvo suggested to look for processes directly created by free neutrinos using the inverse beta process in which a radioisotope is created by a neutrino interacting with stable nuclei. Observation of the resulting radioisotopes could thus be a direct proof of the neutrino existence. How to detect such rare events against the background? Based on his excellent expertise in the properties of radioactive and nuclear processes, Pontecorvo had the idea to use radiochemical methods: a neutrino impinging on a Chlorine 37 nucleus will transform a proton into a neutron, transmuting it into Argon 37, which has different chemical properties. Argon would decay emitting an Auger electron with a characteristic energy distribution and leaving enough time to collect and count with a proportional counter the few atoms resulting from neutrino interactions. The irradiated material should not be too expensive, *since large volumes are involved*, as Pontecorvo remarked, to balance the very small cross section of such processes. For this reason, he chose Carbon Tetrachloride (CCl4) a convenient chemical compound used for dry-cleaning.

3. Detecting neutrinos from nuclear reactors, the atmosphere and the cosmos

In 1956, after more than 25 years since Pauli's suggestion, Clyde Cowans and Frederick Reines, announced the detection of neutrinos using the intense beam from the Savannah River nuclear fission reactor, and two tanks with about 200 liters of water as targets and two giant liquid scintillation detectors viewed by photomultipliers to capture the signals emitted by secondary reactions, the characteristic signature of the inverse beta-decay process in their experiment. Since 1951, Raymond Davis, too, had tried to detect neutrinos from a reactor, but using Pontecorvo's Clorine-Argon radiochemical method. Interestingly, he did not get any positive results, hence demonstrating that neutrinos from a reactor are actually *anti*-neutrinos, implying that neutrinos emitted in beta$^-$ and beta$^+$ decays are different particles. Another obvious steady source of neutrino is the Sun, where a part of the energy is lost to the neutrinos. As emphasized by Pontecorvo, because of the small neutrino cross-sections, *a very large detector is required to observe astrophysical neutrinos*. Then, since early 1960s, Davis began to work on a solar neutrino experiment and in 1966 a large tank containing about 380 cubic meters of CCl4 was built at the deep underground Homestake gold mine located in South Dakota, where 1500 m of rock reduced the cosmic-ray background. He was supported by systematic theoretical calculations made by his greatest ally, the astrophysicist John Bahcall. Pontecorvo's method successfully worked and solar neutrinos were detected by Davis. But the first results released in 1968 gave a much lower flux than the one estimated by the Standard Solar Model. The Model was put in discussion. The experiment itself was questioned. But during the years neither the measured flux nor the predicted flux changed significantly and nothing wrong was found. This was the beginning of the *solar neutrino puzzle*.

3.1. The solar neutrino puzzle: large-scale detectors become standard practice

For a long time, the Homestake experiment was the only measurement of the solar neutrino flux, stubbornly continuing to be only around one third of the theoretical prediction.

These results launched almost three decades of scientific debates covering a wide range of epistemological questions, from the accuracy of the experimental system to the validity of the nuclear fusion theories of the Sun, and ultimately whether the problem may originate in the nature of neutrinos themselves. In 1967, *before* the first results were published by Davis, Pontecorvo had anticipated the solar neutrino problem pointing out that neutrinos could oscillate between different states, and thus electron solar neutrinos might transform into muon neutrinos during their journey from the Sun to the Earth: this phenomenon would lead *to an observed deficit of neutrinos in Chlorine-based experiments* able to detect only neutrinos of a specific lepton flavor, electron neutrinos. The issue of neutrino mass, which is related to the oscillation mechanism and the solar neutrino deficit, thus established itself as a fundamental question at the intersection of astrophysics and particle physics, hinting to new physics beyond the Standard Theory of Particle Physics. But to solve the solar neutrino paradox, another series of solar neutrino experiments was needed. Two new radiochemical experiments were planned at the end of the 1970s, using the much rarer substance of Gallium and employing a reaction whose lower energy threshold would allow detection of the most abundant but low-energy flux of neutrinos from the dominant *pp* chain, which were not accessible in Davis's experiment. GALLEX (built at the brand new Gran Sasso Underground Laboratory) and SAGE (built at the underground Baksan Neutrino Observatory in the Caucasus mountains), began operations at the end of the 1980s, and by 1994 were giving very similar results, providing additional evidence for electron neutrino disappearance and leaving neutrino flavor changes as the only viable possible consistent explanation. In the meantime, in 1987, the unexpected first ever detection of a burst of neutrinos from the explosion of a supernova had marked the birth of neutrino astronomy, involving a most relevant huge detector: KamiokaNDE.

3.2. Kamioka Nucleon Decay Experiment

The beginning of the KamiokaNDE story dates back to the middle of the 1970's when particle physicists had started to discuss unification of the weak, electromagnetic and strong interactions. GUTs also predicted that the proton can decay with an estimated lifetime around 6×10^{30} years. The challenging experimental search for such a rare process required a comparable number of protons, and since 1000 tons of water contain about 6×10^{32} nucleons, Masatoshi Koshiba and his colleagues conceived a detector of about 2000 tons of water surrounded by about 1000 large photo-multiplier tubes to look for proton decay and test GUTs predictions. In early 1987, when Kamiokande-II started to take data with an improved detecting system, it immediately caught a neutrino burst from supernova SN1987A, also seen by the Baksan Neutrino Observatory and by the Irvine Michigan Brookhaven detector, all demonstrating the excellent capability of water Cherenkov detectors to measure low energy neutrinos. From then onwards, the neutrino background proved more interesting than the 'non-existence' signal of proton decay... The Supernova 1987A laid the foundation for the design of really large projects and also made some neutrino physicists move to the newborn field of astroparticle physics. After 1990, the emphasis in solar neutrino research shifted from solar physics to the particle physics realm, as the most likely cause of the missing electron neutrinos was new neutrino physics. Super-Kamiokande, the world largest imaging water Cherenkov detector

(50000 tons of water viewed by about 11000 photomultipliers), was planned to study three puzzles: Nucleon decay (still), solar neutrinos and atmospheric neutrinos. In 1998 it obtained compelling evidence of atmospheric neutrino oscillations. Then, in 2001, the Sudbury Neutrino Observatory *real-time* detector also established that solar neutrinos are oscillating, definitely providing a compelling evidence that neutrinos do have a non-zero mass.

3.3. Sea-water and transparent Antarctic ice as giant detectors for cosmic neutrinos

A brief mention for a meaningful project discussed since 1973, but having roots in visionary suggestions by Markov and Greisen in 1960: DUMAND, the Deep Underwater Muon And Neutrino Detector to catch high-energy neutrinos from gravitational collapse or other sources. It was never built, but it paved the way for underwater neutrino telescopes in the Mediterranean Sea, in the Lake Baikal (Russia), and for the Antarctic Muon and Neutrino Detector Array (AMANDA), the proof of concept for the kilometer-scale neutrino observatory IceCube, now at the forefront of multi-messenger astronomy.

4. High-energy cosmic rays and the birth of gamma ray astronomy

Cosmic ray studies constitute the oldest tradition dealing with astroparticles, and gave birth to two research fields which are now among the pillars of astroparticle physics: The search for ultra-high energy cosmic rays and ground-based Cherenkov gamma-ray astronomy. During the 1950s, when powerful accelerators had become the central tools of high-energy physics, radio astronomy was unveiling the existence of very high-energy processes in the Universe. The phenomenon of radio emission, explained as *non-thermal synchrotron radiation* generated by ultra-relativistic electrons spiraling in interstellar magnetic fields, implied energies well beyond those which can be produced by any conceivable thermal emission, typical of the light from hot astrophysical objects. While the discovery of quasars was triggering the advent of relativistic astrophysics, two still unanswered fundamental questions renewed interest towards cosmic-ray astrophysics: what is the origin of the primary cosmic radiation *and* how are cosmic-rays accelerated?

4.1. Extensive Air Showers (EAS) as a novel investigative tool: the astrophysical turn

Detailed analysis of the cascade processes in the atmosphere allowed to determine the energy of primary particles. The first large array for the study of EAS was built in 1959 at Volcano Ranch, by John Linsley and Livio Scarsi, of Rossi's cosmic-ray group at MIT. In early 1962 they announced observation of an air shower created by a primary particle with an incredible energy of 10^{20} eV, an event reinforcing interest in the challenging question: which astrophysical mechanisms can accelerate particles to such energies?

4.2. From cosmic-ray astrophysics to gamma-ray astronomy and astroparticle physics: the intriguing case of Cygnus X-3

As it is not possible for astrophysical objects to get hot enough to produce gamma rays, these, too, must be produced by *non-thermal* mechanisms, often connected with the presence of high-energy particles produced by some kind of cosmic accelerator. Being neutral, gamma rays can be used to trace such extreme astrophysical environments. Gamma-rays with energies greater than 10^{12} eV, whose low fluxes could not be directly caught by the small-size detectors used in satellites or balloons, could be studied from the ground with large air shower arrays spanning tens to hundreds of square meters. A reduced muon content, compared to a proton shower, was a criterion for identifying gamma-ray induced cascades, over the overwhelming hadron background resulting from charged primaries. In 1983, a cosmic-ray group in Kiel, Germany, claimed observation of a very high gamma ray outburst from the X-ray binary source *Cygnus X-3*. Although the statistical significance was low, such controversial detection was exciting because it implied that Cyg X-3 was producing ultra-high energy particles showing the way "towards a solution for the mystery of high-energy cosmic ray sources". On one hand, this claim (soon also announced by other experiments) reinforced cosmic-gamma-ray hunters' expectations, on the other hand, there was the puzzling phenomenon of an anomalous muon production apparently related to Cyg X-3, seen by several proton decay experiments. It was speculated that these events could even be initiated by unknown hypothetical exotic primaries. The 1983 Cyg X-3 event was never seen again with improved methods. Nevertheless, for a few years it had a tremendous impact and intrigued high-energy physicists working with accelerators: *Some new physics might be at work up there*. Several of them, notably the Nobel laureates Jim Cronin and Sam Ting, migrated to the new field with a vision for new experiments, such as very large air shower arrays or a space detector designed to explore fundamental issues as the origin of cosmic rays and dark matter.

4.3. Using the atmosphere as huge detector: imaging Air Cherenkov Technique for ground-based gamma-ray astronomy

From the mid-1980s, Monte Carlo simulations became very effective helping to select gamma ray events from the overwhelming hadron background, a main problem of ground-based gamma-ray astronomy. At the same time, following pioneering experiments in USSR and UK, a new experimental technique was developed since the early 1960s to detect the Cherenkov radiation emitted almost simultaneously by thousands of relativistic charged particles in the EAS. The successful development of the Imaging Cherenkov Telescope at Whipple observatory in US, allowed, after a 20-year-long effort, the first robust detection of the Crab Nebula as a steady source of gamma rays in the TeV range, reported in 1989 at 9.0-σ. Thanks also to the multifunction array HEGRA, built by the above-mentioned Kiel group, the establishment of the imaging technique, with significant improvements in flux sensitivity, led to the third generation of Cherenkov telescopes: H.E.S.S., MAGIC and VERITAS. With more than 100 next-generation telescopes located in two sites of the southern and northern hemisphere, the current project of the Cherenkov Telescope Array observatory, CTA, will be far more sensitive and have unprecedented accuracy in detection of gamma rays spanning a wide range of energies.

5. Hunting for GUT monopoles and other exotic astroparticles: the MACRO experiment at Gran Sasso underground Laboratories

Last but not least, we shall close this outline with the MACRO experiment, which started data taking with part of the apparatus in 1989 at Gran Sasso Underground Laboratories. In perfect harmony with the advent of astroparticle physics, MACRO was optimized to look for the supermassive magnetic monopoles predicted by GUTs, but was versatile enough to pick up signals from neutrinos, as well as cosmic rays, WIMPS and other exotic particles. Currently, several experiments are operated in what is still the largest underground laboratory in the world devoted to neutrino and astroparticle physics.

6. A dedicated journal for a brand new field

By the end of the 1980s, the new realm of astroparticle physics was being established as a rapidly developing and interdisciplinary field. As the historical roots of the different research areas were quite diverse, publications were scattered over a wide range of sources, and so, a new dedicated journal, the *Astrophysical Journal*, was founded in 1992. In providing a common platform to seemingly distant fields of physics, but having common research questions, it put a seal on the identity of the new field and favored its expansion.