Planet-sized Detectors for Ultra-high Energy Neutrinos & Cosmic Rays

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Extragalactic astronomy with photons ends at 0.1 PeV, but we know there are astrophysical sources for seven more decades of energy beyond this. To probe the highest energy sources and particles in the universe, new messengers, such as neutrinos, and detectors with planet-sized areas are required. This note provides a glimpse of the possibilities.

1. Introduction. The Askaryan effect, first described in 1962 [1], in which selective scattering and absorption processes in a high energy particle cascade lead to a net negative charge excess and resulting coherent radio Cherenkov emission, has now been conclusively observed in a Stanford Linear Accelerator (SLAC) experiment [2]. This result has led to renewed interest in the wider particle and astroparticle physics communities in the technique of radio-frequency detection of cascades from high energy neutrinos and other high energy particles of cosmic origin [3]. In the four years since the confirmation of this process, a series of both satellite [4] and ground-based experiments [5, 6] have now yielded the best current limits on neutrino fluxes in hitherto unexplored energy regimes from $10^{15}$ eV to $10^{22}$ eV. Planned experiments and missions, including the NASA-sponsored Antarctic Impulsive Transient Antenna (ANITA) Long Duration Balloon (LDB) Mission [7] will extend the sensitivity 2-3 orders of magnitude from current levels, and may be expected to achieve detection of the baseline cosmogenic ultra-high energy neutrino flux [8] at EeV ($10^{18}$ eV) energies, an important milestone in establishing the origin of the highest energy particles in the universe. A summary of the current state of the field is shown in Fig. 1.

One of NASA’s primary goals, the establishment of telescopes and observatories in the space or near-space environment when such environments are fundamentally required for the exploration of our universe, is well-served by these efforts. In fact, we cannot afford to ignore the development of capabilities for astronomical observations above $10^{15}$ eV (1 PeV) by a simple and compelling argument: we know there are sources of particles of energies up to $10^{24}$ eV (1 ZVeV), and our traditional messengers for the unbiased identification and characterization of such sources—photons—cannot propagate beyond the very local universe, a few tens of Mpc at most. This is the result of the interaction $\gamma \gamma \rightarrow e^- e^+$, where first the infrared (IR) and then 3K microwave background photons provide pair-production targets for the high energy gamma-rays. Thus astronomy that is confined to the electromagnetic (EM) spectrum cannot directly observe the highest energy sources in the universe, over a range of order 7 decades of energy. To illustrate the relative magnitude of this exclusion, one might ask the question: where would our understanding of current extragalactic sources be if we were to remove observations over any 7 decades of the current electromagnetic spectrum, for example, from the near IR up to MeV photons, or from meter wavelengths to the near IR?

2. Ultra-high Energy Neutrino Astronomy. To ZeV astronomy thus requires new neutral, unattenuated messengers, with neutrinos the leading candidate. It also requires radically new techniques for detectors and telescopes. At these energies the cubic-kilometer-scale of target volumes planned for lower-energy neutrino telescopes currently under construction falls far short of what is needed. The more relevant scale is a Teraton, or 1000 km$^3$ water-equivalent mass. When particles of these energies interact in such volumes they produce sub-nanosecond highly polarized radio impulses of macroscopic energies, with kilowatt peak powers at the high end of the spectrum; such emission is detectable from even orbital distances. Thus if the interaction media are transparent over some range of the secondary emission spectrum, particle detection and estimation of the arrival direction are possible.

The current target medium of choice is polar ice, with areas exceeding $10^7$ km$^2$ on earth. In the 0.1-1GHz range, cold ice is likely the most transparent solid on earth, with attenuation lengths exceeding 1 km. From 37km balloon altitudes,

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$\geq 10^6$ km$^2$ of ice can be monitored; from low-earth orbit (LEO) and above, the entire Antarctic or Greenland ice sheet is simultaneously observable. The challenge for such instruments is thus not so much the attainment of sufficient monitored target volume, but rather to achieve maximal sensitivity in the presence of the 240K thermal noise levels of the ice. In this area the high level of development of antenna and radio-frequency amplifier and receiver technology is a tremendous benefit. In addition, the development of unmanned aerial vehicles (UAVs) or balloons with trajectory control that could keep station above the deepest portions of the Antarctic ice sheet at altitudes of 20-40 km would greatly enhance experiments such as ANITA, which are limited primarily by dwell time above deep ice. With station-keeping, several orders of magnitude improvement in sensitivity are possible.

3. Ice Planets as Detectors. Looking forward over the next several decades, we can envision the passive use of large bodies of solar-system ice (water or hydrocarbons) as target masses for exploration of what can be termed the high energy electro-weak spectrum, as particle physicists generalize it in the current theories that unify the neutrino weak interactions with the EM spectrum. Although the surface irregularities of bodies such as Europa pose a complication to the characterization of events, it is a tractable one, and will become more refined as the exploration and mapping of the bodies themselves improves. We can expect that if bodies of water ice several km deep or more are confirmed among the Jovian or Saturnian moons, their extremely low temperature (90K typical) will result in unmatched radio clarity compared even to the remarkable transparency of Antarctic ice, as the microwave data from Europa measurements already indicate [1]. An all-sky neutrino mapper, using a planetoic moon such as Europa for the telescope, is a vision perhaps not as far-flung as it first sounds, particularly if the thick-shell models for Europa (10-20 km ice layer) are correct.

The information content of the secondary RF emission from a cascade is distributed in the polarization angle vs. location along the radio Cherenkov cone; in the intrinsic radio spectrum observed, and its spatial gradient; and in the time structure of the impulse. To improve the detection signal-to-noise ratio and the measurement precision, a close (several km) formation of several satellites, able to perform polarimetry and pulse-phase interferometry over more than a single location of the Cherenkov cone of the emission would have significant advantages for any of the methods envisioned here.

3. Cosmic Ray Detection from Orbit. Several proposed missions [14, 15] have already advanced the concept of extending ground-based ultra-high energy cosmic ray optical fluorescence detection to an earth-orbiting platform, to observe cosmic ray air showers over very wide areas of the earth’s atmosphere ($\sim 10$ m water equivalent). Other planetary surface materials, such as the lunar regolith, while not as radio-transparent as ice, can still be observed to depths of several tens of m, and thus even a lunar orbiter may have access to many Teratons of target material. In addition, the lack of an atmosphere on objects such as the Moon mean that other particle species that cascade close to the surface, such as the ultra-high energy cosmic rays, are also in principle observable, since they also produce coherent radio emission via the Askaryan process. For example, an orbiter (or again a compact formation-flying satellite group) at 1 lunar radius above the Moon’s surface would synoptically observe 10$^2$ km$^2$ of regolith, over which there is of order 10$^{21}$ ultra-high energy cosmic ray events per year above 10$^{21}$ eV. Such events, each dumping more than 160 Joules of electromagnetic energy into the top few m of regolith, will produce strong coherent RF impulses which should be straightforward to detect at the maximum 3000 km distance from the horizon to such an orbiter or formation. This principle has already been applied to searches for ZeV neutrino interactions in the lunar regolith by the GLUE experiment and others [6].

4. Conclusions. The latter half of the twentieth century has seen NASA develop the means to explore the solar system and beyond using direct spacecraft travel, and orbiting telescopes created to exploit the pristine environment of space. If we are to further our exploration of the frontier of ultra-high energies to its currently known limits, we will need to move beyond the pure electromagnetic spectrum, and synthesize new kinds of telescopes, some the size of entire planets. This methodology draws upon the same kind of vision that led to the 20th century confirmation of the theory of general relativity, using the gravitational influences of the sun and planets: to see the planetary system itself as a rich scientific resource enabling us to look far beyond its limits, leading to entirely new kinds of astronomy, and new windows on the extreme universe.

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