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DUMAND

A Deep Undersea Muon and Neutrino Detection Project

Beginning Neutrino Astronomy in the Ocean Depths

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A group of physicists from laboratories around the world plan a deep ocean laboratory near Hawaii in order to begin seeing the universe in a new light. The "light" will not be ordinary light composed of photons, as with normal telescopes, but stable elementary constituents of the universe, possibly even more numerous than photons, called neutrinos. The project, named DUMAND for Deep Undersea Muon and Neutrino Detection, will come into operation near Hawaii in 1993.

Neutrinos are nearly massless, have no charge, travel at the same speed as light, and have the remarkable property of penetrating almost all thicknesses of matter completely unscathed. This fact means that one can receive information from almost anyplace in the universe, no matter how densely shrouded, and it means that one can employ the earth as a filter, since the only particles coming through the earth are neutrinos. The other side of the coin, however, is that the neutrinos generally pass through undetected: they mostly go right on through the earth, one's detector, and even people without doing anything we can sense. Fortunately they do occasionally collide with the quarks and electrons in ordinary matter, and we can sense the energy transferred and the direction of the neutrino.

It is as though one had an invisible queue ball on a billiard table, and one could only see the numbered balls. It is easy to imagine that one could calculate the initial direction of the invisible queue ball by looking at the scattered directions and speeds of the balls struck. Relativity helps too, because at speeds nearer the speed of light, as is the case for neutrino detection, all particles move in directions near the neutrino direction. One of the most effective ways to detect high energy neutrinos (we shall discuss what we mean by high energies soon) is via the situation when a neutrino exchanges a charge with a quark and becomes a particle we call a muon. At the energies of interest this muon will travel within one degree of the original direction of the incident neutrino.

Because the muon has an electric charge it is easy to detect by the disturbance this moving charge makes when traversing matter. The simplest detection employs a transparent medium, clear water for example, in which the charge causes the atoms along the track to radiate photons. Light in a medium such as water travels more slowly in water than in a vacuum (in fact photons in water travel at 75% of the speed they make in air). Because of the muon travelling at the full speed of light, it outraces the disturbance it creates and leaves a cone of radiated light, moving outwards from the track at 42 degrees. This Cherenkov Radiation (named for the Russian physicist who discovered it), is very blue in color, and produces an extremely short pulse in optical sensors (a few billionths of a second, nanoseconds). One thus detects the passage of a muon through the DUMAND array by noting the rapid sequence of pulses in a set of light detectors spread throughout a volume of deep ocean water (discussed more below). These pulses are digitized and sent to shore where computers can reconstruct the original muon's trajectory, and hence calculate the original direction of the unseen neutrino to a precision of about a degree.

The light detectors consist of 16 inch diameter photomultiplier tubes, a device to catch individual photons of light and turn them into electrical pulses, placed in spherical glass housings which withstand the ocean pressure. At the depth of DUMAND operation, 4.8 km (15,000 feet), the pressure is about 500 atmospheres, so pressure resistance poses a major engineering challenge, now well in hand. The optical detectors will be placed in vertical instrument strings 350 m tall (1000 feet), floating up from the ocean bottom. The array now being built will have nine strings, eight around a (imaginary) cylinder 100 m (300 feet) in diameter, and one in the center. There will also be 45 hydrophones, for purposes of acoustically surveying thee array (and listening for some rare phenomena), and 15 laser calibration units, needed to monitor the sensitivity of the optical detectors and to calibrate their timing to nanosecond levels. The various modules in a string all communicate via fiber optic links to an electronics package at the bottom of each instrument string. This unit will contain a specially made digitizing chip which will record the arrival of light pulses with a precision of one nanosecond. The data and other control signals from an entire string then get multiplexed onto one single mode fiber link to shore.

The array will be lowered one string at a time from a surface research vessel, and connected to a cable to shore by a manned research submarine. The junction box at the end of the cable will have various instrumentation, including television to monitor emplacement and connection activity. The shore cable will be layed in late 1992. It will come ashore at the Natural Energy Laboratory of Hawaii, located on the Western most point of thee Big Island of Hawaii, near the town of Kona. There, in a modest laboratory the data will be received from the 10 data carrying fibers at 625 megabaud (million bits per second), typical of state of the art fiber optic communication networks. The data will be filtered by special computers to find the interesting events, which will then be sent to general purpose computers running physicist written programs to reconstruct such things as the neutrino celestial direction.

Power will be sent down the 1.5 cm diameter armored cable at high voltage, DC, delivering 5.5 kilowatts to the array. The fibers carry commands out to the array as well as data and status information back to shore, one color going out and another color coming back. Because the array will contain about 250 network linked computers, which can control many functions such as voltages and switches, the array can be remotely tuned and even reprogrammed to cope with the unexpected, or to deal with failures (strings can be replaced in case of major failures, but this is expensive). The array will be operated sequentially by teams of physicists taking their turns "on shift" in Hawaii, Japan, Europe and the mainland U.S., operating the experiment via high speed computer network. Data will be passed immediately to all the collaborators so that analysis may be done at the home institutions on-line.

So, why would one want to "see" the universe in this peculiar light? What would one see? Where do the neutrinos come from? Who cares? These are all good questions, the answers to which fill a book, so we will only outline the motivations of the physicists and astronomers for trying to begin what is essentially a new science.

First, there is the question of why one should bother. The motivation for the undertaking of neutrino astronomy generally stems from the same drive as to do any astronomy, cosmology and elementary particle physics: we want to understand the universe around us, where it has come from, how it got here, what it is made of, and where it will end. Many times people attempt to justify fundamental science for the many fringe benefits generated, both from technology and newly found processes, which fringe benefit while realized statistically cannot be predicted or counted upon in individual research projects. A more honest reason comes from the deep human need to understand our environment down to fundamental constituents, and hardly anything more basic exists than neutrinos.

Neutrinos exist in staggering numbers in the universe: about a hundred million billion (10^{17}) neutrinos per second go through your body, without a trace! These are the neutrinos left over from the Big Bang, the neutrino flash. They are (so far) hopelessly undetectable because their energies are so low that they seldom interact, end even when interacting the result is pitifully feeble. Fortunately for would-be neutrino astronomers, the interaction probability gets stronger with energy, and the results become truly spectacular at high energies. By high energies here we mean energies typical of the highest energy man made particle accelerators, machines which can accelerate a proton to a thousand times it's rest mass (10^{12} eV, or 1 TeV, a factor of 10^{16}, ten million billion, bigger than the Big Bang neutrinos). At these energies the detector described below can sense neutrino interactions from throughout a volume of about 1/10 cubic kilometer, a hundred million ton target volume! (For scale, the biggest detectors at accelerator laboratories have target volumes of a thousand tons, though with much finer resolution, which DUMAND trades off for gross size).

Neutrinos will result from almost all energetic processes in the universe, but only some may be detectable. The sun produces as much energy in neutrinos as in the light and heat we all see and feel. The sun is just barely detectable in neutrinos, because of the relatively low energy (the energy of neutrinos from nuclear burning as in the sun is in millions of eVs, MeV, a factor of a million less than the design of DUMAND aims at). (In fact an exciting story about the partly missing solar neutrinos has been unfolding over the last few years, but that does not concern us here). Another favorite neutrino source that physicists have dreamed of observing occurs when a star of mass somewhat greater than our sun runs out of nuclear fuel and lacking the heat to keep it inflated, collapses to a neutron star (or maybe even a black hole). The resulting supernova may be brighter in photons than a whole galaxy for a few months. The neutrinos do not linger though and come out in a mind boggling burst from the initial collapse, perhaps even being responsible for blowing off the stellar mantle producing the spectacular fireworks. Fortuitously the first supernova visible to the naked eye in several hundred years took place several years ago (23 March 1987), and it showed up in neutrino interactions two large underground detectors, one in Japan, one in the U.S. This supernova (SN1987A, in astronomer nomenclature) was the beginning, and end (so far), of neutrino astronomy from outside the solar system.

Physicists learned much from the event, and the numbers bore out the expectations for a gravitational collapse to a degree unprecedented in astrophysics. (The observations agreed with predictions within a factor of two, in a field where a factor of ten is considered not bad!).

Sadly, the rate of supernovae within a distance detectable by detectors that one might afford probably does not exceed one per 10 years, and could be one per 50 years! The impracticality of such research on a human time scale drives us to the higher energies of DUMAND as a place to begin neutrino astronomy. Of course eventually, perhaps well along in the 21st century by our scientific great grandchildren, we shall want to press downwards in energy, and perhaps observe (almost daily) the neutrino bursts from supernova occurring throughout our galactic cluster.

DUMAND aims for catching neutrinos of a million times higher energy than the supernova neutrinos. We know about the general situation of where such neutrinos may originate: a beam of particles, probably protons, accelerated near an object such as a neutron star or a gigantic black hole in a galactic nucleus, smashes into a disk of matter surrounding the object, or a surrounding gas cloud, or even a companion star, and the resulting spray of particles decay to neutrinos in abundance (with perhaps 10% of the initial energy going into neutrinos). We know that protons and nuclei get accelerated to amazingly high energies (so far unaccountably) because of the nearly uniform rain of them (the cosmic rays) impinging upon the earth's atmosphere (with directions well stirred by magnetic fields throughout the galaxy). In contrast, neutrinos go straight across the universe from their origins, perhaps to be detected by us, but not interfered with by intervening clouds, stars, or magnetic fields. Once we have the ability to see this light we will then be able to peer into the inner regions of the most energetic regions of the universe.

Physicists have worked hard at predicting how many of these neutrinos there should be from various sources. They get caught however in a kind of Catch 22, in that if we knew the answer the question would not be so interesting! The list of suspects for sources of neutrinos encompasses all the bizarre and luminous sources that astronomers have observed or hypothesized in recent decades, such as neutron stars, black holes, active galactic nuclei, and quasars. If history teaches us anything, however, the calculations predict little and the most interesting objects detected will be things unforeseen.

Thus while high energy neutrinos surely exist, we do not know exactly how big an instrument we need to get into business. Hence the strategy of incremental exploration, stepping up in size as technology and budgets permit. DUMAND II, described below, will make an increase of about a factor of 100 in sensitivity over the now largest neutrino detectors, based in mines (one is driven to the oceans, because much larger mine cavities will collapse due to earth pressure). The betting has it that DUMAND II should detect the first point sources of high energies, but we shall have to wait until about 1995 when the array will be running and have a goodly amount of data analyzed to know for sure.

The results of these first explorations will not be pictorially spectacular, as with the lovely photographic plates from optical telescopes. As an example, the neutrino data can be used to make a sky map. The normal cosmic rays which hit the atmosphere produce a steady background of neutrinos, randomly distributed across the neutrino sky. A celestial point source will consist of a cluster of ten or so neutrinos within about one degree of celestial arrival directions. Since the earth turns in 24 hours the neutrino detector also rotates. Cosmic rays also produce numerous downgoing muons in the atmosphere, which muons penetrate to the deepest mines and into the ocean depths. Thus only sidegoing or upcoming muons signal neutrinos that have traversed the earth: the earth is our background (cosmic ray muon) filter. (Of course, one persons background may be another's object of study, and the cosmic ray muons may yield interesting results in themselves, providing PhD dissertation topics for quite a few students!). One can picture the neutrino detector as a huge rotating fish-eye camera, detecting a most dim light. It is such a faint picture that it may take years to develop the image of the neutrino sky. You can be sure that the physicists will be pouring over every grain of the exposure, and may learn much from the nature of the neutrinos, their energies and timing (if associated with pulsars for example).

Other research can be carried out with the neutrinos and muons, which we have not the space to delve into here. One fascinating possibility has resulted from the proposed construction of a new accelerator at Fermilab near Chicago. The new device, to be built by about 1995, could shoot a neutrino beam 6,000 km through the earth (at an angle of 30 degrees below the horizon) towards DUMAND II. The study of the thousand or so neutrinos observed in a six month run could reveal characteristics of neutrinos called oscillations (where one kind of neutrino turns into another as they fly along), which experiment cannot otherwise be done on earth. (There exist substantial reasons for suspecting such odd phenomena, in explanation of other results, among them the solar neutrino deficit). DUMAND can also explore for new types of particles coming form outer space, such particles as may be related to the controversy about the "missing mass" of the universe. (Various astronomical observations indicate that galaxies and stars orbit about masses unseen, and much larger than the amount that can be accounted for by the visible stars).

The group carrying out the DUMAND project consists of a team of about 25 PhDs, plus about an equal number of students, engineers and technicians from the Universities of Aachen (Germany), Bern (Switzerland), Boston University (Mass.), California at San Diego (Scripps), Hawaii (Manoa), Kiel (Germany), Kinki (Japan), Kobe (Japan), Tohoku (Japan), Tokyo (Japan), Vanderbilt (Tennessee), Washington (Seattle), Wisconsin (Madison). The group have mainly experience in high energy particle physics, of the sort conducted at accelerators, or in cosmic ray studies done in laboratories or on mountain tops. Going to sea to do very high technology research presented all kinds of new challenges, and has taken them 10 years of effort studying the environment and techniques, including several blind alleys and a couple of disappointing failures in tests, but finally successful overcoming of all technical hurdles in the last several years. DUMAND represents one manifestation of a much heralded convergence between particle physics as done at accelerators, probing the smallest scales, and astrophysics and cosmology examining the universe on the other extreme in size scale. As an unprecedented endeavor DUMAND has faced at first less than enthusiastic endorsement by skeptical colleagues, and penury from conservative funding agencies which favor sure-fire projects with predicable results, as opposed to risky explorations. A paragon of good science funding has been the High Energy Physics Division of the Department of Energy (which has a total budget of about $300 million per year for elementary particle physics in the U.S.), which has (albeit cautiously) permitted these physicists to demonstrate the viability of their ocean neutrino detector, finally approving construction of the DUMAND II in June 1990. Similar situations hold for the funding from Japan and Germany, which constitute substantial fractions of the approximately $10 million cost of the DUMAND II array. Substantial aid along the way has also come from many visionary scientists and engineers who have put their own time and resources into helping launch the project. (The Naval Ocean Systems Center in San Diego have been stalwarts particularly deserving of mention).

What of the future? DUMAND II must overcome substantial technical hurdles in the next few years (by late 1993), and we must be lucky enough to have encouraging signals inorder to proceed. DUMAND II has the lead, but several other projects may come to fruition by the middle of the decade, in the U.S., Europe, Russia, or perhaps even at the South Pole.

Regular neutrino astronomy, however, will require another jump in size of about one hundred most probably. For this we will need detectors with size measured in kilometers upon a side, and costs in the $100 million range (the detectors for the new accelerator in Texas will cost upwards of a billion dollars). Such detectors will doubtless be built by large international collaborations, and indeed are already under discussion. At this time we know of no other place to find the target volumes needed than in the deep ocean. Locations might be Hawaii (wonderfully clear stable deep water, not far from the equator giving good sky coverage), and perhaps in the Mediterranean. Detectors on opposite sides of the world provide whole sky coverage, permitting the full time observation for rare events.

For now, however, the entire energies of the DUMAND team focus upon building the initial 20,000 m^2 array, and getting it running well by late 1993. With luck the first celestial neutrino point sources will have been identified by 1994, heralding the true beginning of neutrino astronomy and opening a new window upon the universe.