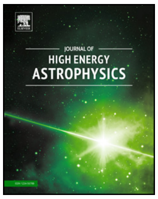
Journal of High Energy Astrophysics 1–2 (2014) 1–30

Contents lists available at ScienceDirect

Journal of High Energy Astrophysics

www.elsevier.com/locate/jheap



Review

Cosmic neutrino pevatrons: A brand new pathway to astronomy, astrophysics, and particle physics

Luis A. Anchordoqui [a,*], Vernon Barger [b], Ilias Cholis [c], Haim Goldberg [d], Dan Hooper [c,e], Alexander Kusenko [f,g], John G. Learned [h], Danny Marfatia [h], Sandip Pakvasa [h], Thomas C. Paul [a,d], Thomas J. Weiler [i]

[a] *Department of Physics, University of Wisconsin–Milwaukee, Milwaukee, WI 53201, USA*
[b] *Department of Physics, University of Wisconsin, Madison, WI 53706, USA*
[c] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[d] *Department of Physics, Northeastern University, Boston, MA 02115, USA*
[e] *Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[f] *Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1547, USA*
[g] *Kavli IPMU (WPI), University of Tokyo, Kashiwa, Chiba 277-8568, Japan*
[h] *Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA*
[i] *Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA*

ARTICLE INFO

Article history:
Received 25 December 2013
Accepted 30 January 2014

ABSTRACT

The announcement by the IceCube Collaboration of the observation of 28 cosmic neutrino candidates has been greeted with a great deal of justified excitement. The data reported so far depart by 4.3σ from the expected atmospheric neutrino background, which raises the obvious question: “Where in the Cosmos are these neutrinos coming from?” We review the many possibilities which have been explored in the literature to address this question, including origins at either Galactic or extragalactic celestial objects. For completeness, we also briefly discuss new physical processes which may either explain or be constrained by IceCube data.

Contents

---

* Corresponding author.

http://dx.doi.org/10.1016/j.jheap.2014.01.001
2214-4048/© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Neutrinos will serve as unique astronomical messengers. Except for oscillations induced by transit in a vacuum Higgs field, neutrinos propagate without interactions between source and Earth, providing powerful probes of high energy astrophysics. The neutrino's direction and energy (modulo the usual red-shifting due to expansion of the universe) are preserved, and the neutrino's flavor is altered in a calculable way. The potential power of neutrino astrophysics has been discussed in a number of review articles (Gaisser et al., 1995; Learned and Mannheim, 2000; Halzen and Hooper, 2002; Becker, 2008; Anchordoqui and Montaruli, 2010). In addition, the flavor composition of neutrinos originating at astrophysical sources can serve as a probe of new physics in the electroweak sector (Learned and Pakvasa, 1995; Beacom et al., 2003a, 2003b, 2004a, 2004b; Hooper et al., 2005a; Anchordoqui et al., 2005a). Furthermore, decays and annihilations of hypothetical dark matter particles accumulated in Sun are expected to produce a large flux of secondary neutrinos at energies far above the 1–20 MeV energies of neutrinos produced in solar burning (Silk et al., 1985; Srednicki et al., 1987; Halzen et al., 1992; Barger et al., 2002, 2010, 2011; Halzen and Hooper, 2006). Observation of such high energy neutrinos coming from the direction of the Sun would provide "smoking ice" for dark matter hunters (Aartsen et al., 2013a). However, neutrinos constitute something of a double-edged sword: they are excellent probes of astrophysics and particle physics because of their feeble interactions, but also extremely difficult to detect for the same reason.

Neutrino (antineutrino) interactions with matter can be reduced to two categories: (i) in charged current (CC) interactions the neutrino becomes a charged lepton through the exchange of a $W^\pm$ with some particle X, $\nu_\alpha(\bar{\nu}_\alpha) + X \to l^\pm_\alpha + \text{anything}$; (ii) in neutral current (NC) interactions the neutrino interacts via a Z transferring momentum to jets of hadrons, but producing a neutrino rather than an $l^\pm$ in the final state: $\nu_\alpha(\bar{\nu}_\alpha) + X \to \nu_\alpha(\bar{\nu}_\alpha) + \text{anything}$. Lepton flavor is labeled as $\alpha = e, \mu, \tau$ from here on. The neutrino–nucleon cross section rises roughly linearly with energy (Quigg et al., 1986; Reno and Quigg, 1988; Gandhi et al., 1996, 1998; Anchordoqui et al., 2006a; Cooper-Sarkar and Sarkar, 2008; Jeong and Reno, 2010; Block et al., 2010; Connolly et al., 2011; Illarionov et al., 2011; Cooper-Sarkar et al., 2011). For neutrino telescopes located on Earth, the detection probability is modulated by a combination of the neutrino energy E_ν and the arrival zenith angle θ. For $E_\nu \lesssim 10^5$ GeV, most neutrinos pass through the Earth unscattered, and thus in this energy range the detection probability rises with energy. At about 10^5 GeV, the interaction length of neutrinos is roughly equal to the Earth's diameter, and hence about 80% (40%) of ν_μ and ν_e with $\cos\theta = -1$ (-0.7) are absorbed (L'Abbate et al., 2005). For the case of the tau neutrino, there is a subtlety in its propagation through matter due to the short τ lifetime. A ν_τ propagating through the Earth can interact to generate a τ lepton which subsequently decays, producing a ν_τ of lower energy, a process referred to as the "regeneration effect" (Halzen and Saltzberg, 1998) (though this will generally have negligible consequence for steeply falling spectra).

The rate of interaction of ν_e, ν_μ, ν_τ, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$, with electrons is mostly negligible compared to interactions with nucleons. However, the case of $\bar{\nu}_e$ is unique because of resonant scattering, $\bar{\nu}_e e^- \to W^- \to \text{anything}$, at $E_\nu \simeq 6.3$ PeV. The W^- resonance in this process is commonly referred to as the Glashow resonance (Glashow, 1960). The signal for $\bar{\nu}_e$ at the Glashow resonance, when normalized to the total $\nu + \bar{\nu}$ flux, can be used to differentiate between the two primary candidates ($p\gamma$ and pp collisions) for neutrino-producing interactions in optically thin sources of cosmic rays (Anchordoqui et al., 2005b). In pp collisions the nearly isotopically neutral mix of pions will create on decay a neutrino population with the ratio $N_{\nu_\mu} = N_{\bar{\nu}_\mu} = 2N_{\nu_e} = 2N_{\bar{\nu}_e}$. On the other hand, in photopion interactions the isotopically asymmetric process $p\gamma \to \Delta^+ \to \pi^+ n$, $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$, is the dominant source of neutrinos so that at production, $N_{\nu_\mu} = N_{\bar{\nu}_\mu} = N_{\nu_e} \gg N_{\bar{\nu}_e}$.[1] Note that events at the Glashow resonance provide the only known physics calibration of neutrino detectors in this high energy range, always a worrisome problem (witness the difficulties with the highest energy air showers, as in the Piere Auger Observatory and Telescope Array (Anchordoqui et al., 2013a)).

At PeV energies neutrinos interact with nucleons with a cross section of about 1 nb ($1\ \text{b} = 10^{-24}\ \text{cm}^2$). Hence, for a detector medium with a density of about $N_A \simeq 6 \times 10^{23}$ nucleons per cm^3 we expect only a fraction $\mathcal{O}(10^{-5})$ of PeV neutrinos to interact within 1 km of the medium. If the medium is transparent, like water or ice, the fast-moving secondary charged particles created in these interactions can be observed via the resulting Cherenkov light emission. Assuming cosmic ray (CR) sources are optically thin, one can estimate the diffuse flux of extragalactic neutrinos from the observed cosmic ray flux, since the relevant particle physics is well-known. The only wiggle room is the efficiency of the energy transfer from protons to pions, ϵ_π. An upper bound on the flux ($\epsilon_\pi = 1$) was first obtained by Waxman and Bahcall (1999), Bahcall and Waxman (2001). For an estimate of ϵ_π based on our best current knowledge, the diffuse flux of extragalactic neutrinos would provide $\mathcal{O}(10^5)$ PeV neutrinos per year and km^2. Thus, observation of a few extragalactic PeV neutrinos per year requires neutrino telescopes with active detector volumes on the scale of cubic-kilometers. IceCube is the first observatory on this scale and we can hope that the European KM3-NET will soon join the club.

1.1. *Historical background*

The long road to developing the IceCube experiment has been thoroughly described in Halzen (2007), Spiering (2012). Here we recount some of the highlights. Early efforts concentrated on instrumenting large pre-existing volumes of water to produce giant Cherenkov detectors. The first major step from conceptual ideas to large-scale experimental efforts was taken by the Deep Underwater Muon and Neutrino Detector (DUMAND) project (Bosetti et al., 1980). In November 1987, the DUMAND Collaboration measured the muon vertical intensity at depths ranging between 2–4 km (in intervals of 500 m), with a prototype string of optical detectors deployed about 30 km off-shore the island of

---

[1] It has been noted that advanced civilizations across the Galaxy could use a monochromatic signal at the Glashow resonance for purposes of communication (Learned et al., 2009).