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NEUTRINO ASTROPHYSICS

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Neutrino Astrophysics

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Abstract

Neutrino physics and astrophysics are in a ferment not experienced since the detection of neutral currents and the ascendency of the Electro-Weak theory almost twenty years ago. Whether there is a sea change in our conception of the neutrino in the next few years or merely glorious disappointment in the theoretical ranks will depend in no small measure on the outcome of numerous astronomical and laboratory experiments now underway. With the detection of solar, supernova, and atmospheric neutrinos, neutrino astronomy has come of age. In this brief report, I catalogue the astronomical sites and contexts where neutrinos are important and reflect on the astronomical neutrino's new status as an engine of scientific progress.

1. INTRODUCTION

Traditionally, we studied the neutrino indirectly via the beta decay of isolated isotopes [1] or more directly via the interaciton of accelerator beam dump neutrinos [2] or reactor neutrinos [3] with well-characterized targets. Currently, the crucial questions are whether neutrinos have mass [4], experience vacuum flavor oscillations [5], undergo MSW-like flavor conversions [6], or are of Majorana-type [7]. The putative detection by Simpson [8] and others in beta experiments of a massive neutrino at ~17 keV, new double β-decay measurements and bounds [9], tritium end-point experiments [10], disappearance experiments [11], and Z^o width measurements at LEP [12], are currently pacing the field. Frustratingly, much of what has been derived are upper limits or exclusion regions in Δm_ν^2–$\sin^2 2\theta_\nu$ space. We can not yet say that neutrinos are anything but classic, massless, Dirac particles.

However, many astronomical objects are powerful sources of neutrinos. A useful fraction of these objects can be detected on Earth. Neutrinos from the sun [13], SN1987A [14], and cosmic-rays in the atmosphere [15] have already been detected. Ultra-high energy (UHE) neutrinos from beam dumps thought by some to exist in AGN's or in various galactic X-ray sources (Cyg X-3?), stellar neutrinos, big-bang neutrinos, and the various other neutrino backgrounds may or may not soon be detected, but are of intense theoretical interest. Crucial to the future progress of neutrino astronomy is the extensive underground network of massive detectors that is being established. Facilities such as SNO [16], LVD [17], MACRO [18], Super Kamiokande [19], Baksan [20], Homestake

[21], Frejus [22], ICARUS [23], NUSEX [24], Borexino [25], GRANDE [26], DUMAND [27], and SNBO [28], among others, are already or may soon be the telescopes in this new and exciting astronomical enterprise. This expansion underground is driven by the philosophy that these detectors might illuminate not only astrophysics, but fundamental neutrino physics as well. In what follows, I briefly summarize the role of the neutrino in astrophysics and the larger role of neutrino astronomy in physics.

2. SOLAR NEUTRINOS

Our sun is an average star, but its proximity allows us to test both stellar and neutrino theory. The lion's share of the fusion ν_e's issuing from the $T_c \sim 1.3\,\mathrm{keV}$ solar core are from the pp chain and are below the energy threshold of the pioneering ^{37}Cl experiment of R. Davis [29] and the follow-on Kamiokande (KII) experiment [30]. Rare ($\sim 10^{-4}$) and very temperature sensitive ($\sim T_c^{18}$) side reactions are responsible for what they should see. That they see only 1/2–1/3 of what is predicted is the much-discussed "solar neutrino problem." The two classes of proposed solutions involve either altering the astrophysics (material mixing, opacities, etc.) or altering the neutrino physics (magnetic moments, neutrino oscillation, etc.). It is the latter possibility that has galvanized the particle community. Personally, I find it reassuring and a bit surprising that KII and Homestake are as close as they are to the standard model prediction. The severe core temperature dependence and small branching ratios for the production of the dominating ^{8}B neutrinos argue that factors of 1/2–1/3 are of order unity. Can we really presume to know T_c to 4%? Nevertheless, most of the cognoscenti argue that the discrepancy is real and perplexing. Perhaps it is real, and it is certainly perplexing. Might neutrino propagation effects and/or the MSW conversion of ν_e's into ν_μ's (or ν_τ's) be the answer [31]?

There are two general experimental approaches being pursued to resolve the solar neutrino puzzle: the gallium radiochemical extraction experiments, SAGE [32] and GALLEX [33], that are sensitive to the dominant pp neutrinos, and real-time experiments, such as SNO, Super Kamiokande, and Borex(ino), that are sensitive to the higher energy ($\gtrsim$4 MeV) neutrinos. SNO and Borex(ino), in particular, have good neutral-current and, hence, ν_μ and ν_τ, response. They can detect the neutrinos into which the ν_e's might be oscillating. These are indeed heady times in solar neutrino research. If the gallium experiments unambiguously detect less than $\sim$80 SNU's of the $\sim$132 SNU's of the standard model, then either the sun is not a thermonuclear furnace or new neutrino physics is at work. If the latter, astrophysics will have midwifed a revolution in particle physics. The first SAGE results [34] including data through 15–8–91 imply only $\sim 20 \pm 20$ SNU with an upper limit of $\sim$80 SNU's (90% CL). If true, and that is a big IF, new neutrino physics is indicated, as the MSW plots in Figure 1 from Chen and Cherry [35] imply (The large cross in Figure 1 is the Bahcall and Bethe [36] prediction.). One eagerly anticipates the drop of the next shoe (the GALLEX shoe) and the completion of SNO, Borex(ino), and Super Kamiokande.

3. ATMOSPHERIC NEUTRINOS

Cosmic rays, predominantly protons and alpha particles between $\sim$1 GeV and 10^{11} GeV, collide with the Earth's atmosphere and produce showers of particles that are regularly detected around the world by the light they generate in the air, the "pancakes"

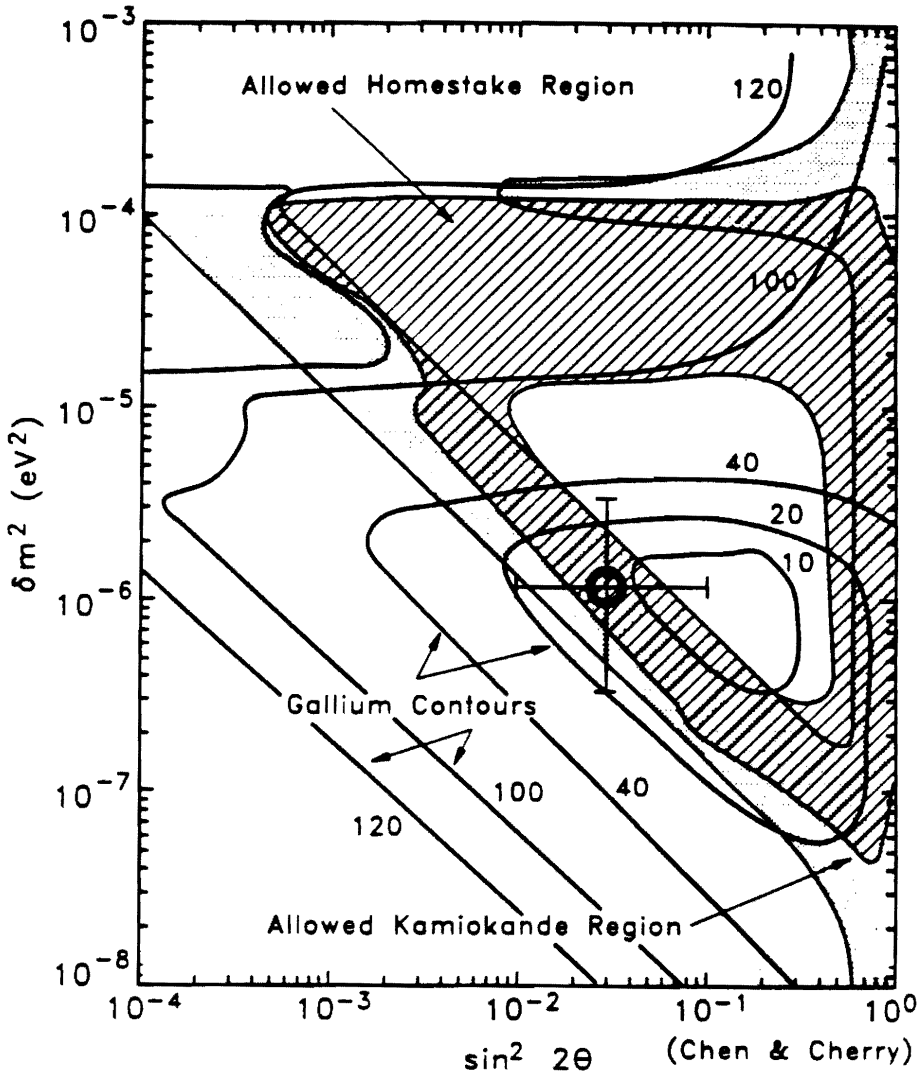

Figure 1. Taken from reference 35, this figure depicts the regions in the MSW $\delta m^2(\mathrm{eV}^3)$ versus $\sin^2 2\theta$ space still allowed by the Kamiokande (stippled) and Homestake (diagonal) solar neutrino data. The lines marked "Gallium Contours" are iso-SNU lines in the gallium detectors. The intersection of these lines with the shaded regions are allowed by the MSW solution. The circle and error bar cross near the center of the plot denote the regions predicted for the gallium experiments in reference 36.

of γe^+e^-'s that reach the Earth's surface, and the muons from the decay of spallation pions and kaons. Before accelerators, cosmic-ray studies led the way in particle physics research. Now, these "beam dump" neutrinos from the decay of the shower mesons and muons provide a means to answer basic questions in neutrino physics. An average of 10–100 atmospheric neutrino events are culled every year in each deep neutrino detector. Such neutrinos are a background for proton-decay studies, show latitude dependences and energy cutoffs that reflect geomagnetic effects on the primary, can be generated by rock interactions ("rock amplification"), and are detected moving both up and down.

About 1000 atmospheric neutrinos events have thus far been identified underground [37]. Their theoretical spectrum is shown in Figure 2 from Totsuka [37] and compared to the spectra from other astrophysical neutrino sources. Figure 2 is a nice summary of the neutrino sky. Note that atmospheric neutrinos should dominate above ~50 MeV.

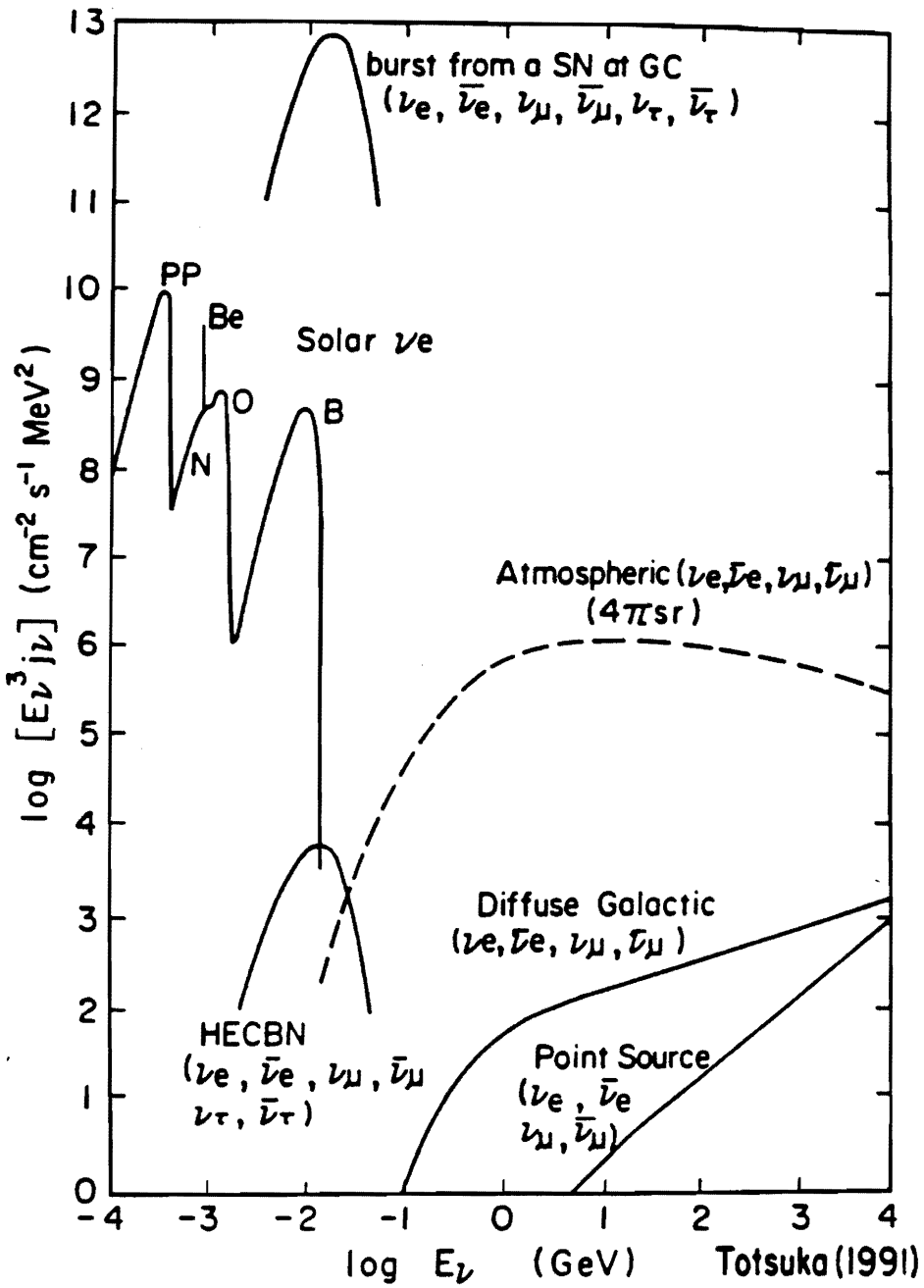

Figure 2. Taken from reference 37, this figure portrays the neutrino sky due to the sun, the atmosphere, the universal diffuse background, an hypothetical UHE point source, the universal supernova background (HECBN) and a supernova at the galactic center (GC). j_ν is in #/(cm^2·s·MeV) and E_ν is in GeV.

However, not all the data are consistent with standard shower calculations, and therein lies another neutrino puzzle. The ratio of $R_{\mu e}$, the ratio of the observed ν flux to the theoretical Monte Carlo flux, for ν_μ's and ν_e's is not one in all the underground detectors. KII saw $0.61^{+0.09}_{-0.08} \pm 0.05$, IMB saw $0.67 \pm 0.09 \pm 0.08$, Frejus saw $1.06^{+0.19}_{-0.16} \pm 0.08$, and NUSEX saw $0.99^{+0.35}_{-0.25}$. That the two largest detectors, IMB and KII, obtained anomalous results is intriguing. Can the ν_μ deficit be real and be a signature of neutrino oscillation? If the solar deficit is explained by MSW conversion from ν_e to ν_μ, the same oscillations can not explain the atmospheric deficit. However, this deficit could be explained by ν_μ–ν_τ oscillations [38–40]. Again, basic particle physics may be illuminated by neutrino astronomy.

4. HIGH-ENERGY NEUTRINOS: POINT SOURCES AND DIFFUSE BACKGROUND

There is not now any evidence for high-energy neutrino point sources in the sky. However, some theories of AGN's and galactic gamma-ray sources (e.g. Cyg X-3, Her X-1, Vela X-1 ??) involve luminous particle beams and beam dumps. When hadronic beams intercept matter, both photon and neutrino beams are generated. Such neutrino beams might be detected on the Earth. It has even been suggested that neutrino beams in quasars can heat the stars in quasars, drive stellar winds, and thereby feed the central quasar engine [41]. Neutrino energies in the TeV, PeV, and even EeV (10^{18} eV) ranges have been discussed (Note that above $\sim$100 TeV, the Earth becomes opaque to neutrinos.). If there are point sources of energetic neutrinos in the galaxy and universe, very massive subsurface detectors such as DUMAND [42], AMANDA [43], GRANDE [44], and LENA [45] are required to see them. The detection of nearby point sources or the general diffuse background of point sources and "Griesen" neutrinos in the universe will speak volumes about fundamental astrophysical processes, but will ve bery difficult. Such work is complementary with ongoing Extensive Air Shower studies (e.g. Fly's Eye, CASA...). A fanciful theoretical spectrum ($<10^4$ GeV) of both the diffuse neutrino background and a point source is shown in Figure 2. Whether the actual spectra look anything like this one can only be determined by observation. I suspect some surprises are in store.

5. STELLAR NEUTRINO EMISSION (PAIRS)

All stars that burn hydrogen emit electron neutrinos because the various hydrogen fusion chains all contain weak interaction links. However, the neutrino losses of such stars amount to only a few percent of their total luminosity and, hence, such losses do not have significant evolutionary consequences. On the other hand, massive stars ($\gtrsim 8\,M_\odot$), whose cores have proceeded from hydrogen to heavy elements through successive thermonuclear burning stages, achieve near their deaths such high temperatures ($>10^9$ K) and densities ($>10^6$ gm/cm^3) that thermal neutrino pair emission dominates the star's luminosity. The most important processes are pair annihilation ($e^+ + e^- \rightarrow \nu\bar{\nu}$), plasmon decay ($\gamma_{pl} \rightarrow \nu\bar{\nu}$), and the photoneutrino process ($\gamma + e^- \rightarrow e^- + \nu\bar{\nu}$). During these later stages, it is the neutrino luminosity that carries away the thermonuclear heat and the surface photon luminosity becomes irrelevant to the subsequent evolution of the star's core. Indeed, just *before* stellar collapse to a protoneutron star and a supernova explosion, the neutrino luminosity can reach $\sim 10^{49}$ ergs/s, which is $\sim 10^{10}$ times

the Eddington photon luminosity. Such large neutrino luminosities are responsible for drastically accelerating the evolution of massive stars after carbon burning and for refrigerating their cores into quasi-degenerate "white dwarfs." Without these neutrino emissions, the white dwarf Chandrasekhar mass of $\sim 1.4\,M_\odot$ would not be the relevant mass scale of neutron stars formed from massive stars and we would not expect the observed neutron star masses to cluster as they do near $1.4\,M_\odot$. Indeed, it is possible that black holes, not neutron stars, would be the residue of collapse, because the cores of massive stars might otherwise accumulate masses before collapse ensues in excess of the maximum possible mass of a neutron star. In sum, the very existence of many neutron stars with masses near $1.4\,M_\odot$ may be due to significant neutrino emission before collapse. Unfortunately, even such large neutrino luminosities may be undetectable, since the average energy of the emitted neutrinos lies below $\sim$1 MeV. At such energies, the interaction cross sections are very low and most of the neutrinos are below detector thresholds. Furthermore, even 10^{49} erg/s is not adequate at the $\sim$150 parsec minimum distance from us of a massive star (Betelgeuse).

Another classic stellar site where neutrino emissions dominate a star's evolution is the young ($\lesssim 10^4$ years) neutron star [46]. What we may some day see are the neutron star's surface X-rays, but during the first few thousand years, the evolution of its surface temperature ($\gtrsim 10^6$ K(?)) is tied to the neutrino cooling of its core. The dominant processes are thought to be the modified URCA process ($nn \rightarrow npe^- + \overline{\nu}_e$: $npe^- \rightarrow nn + \nu_e$), neutral current scattering (e.g., $nn \rightarrow nn + \nu\overline{\nu}$), and pair bremsstraulung ($e^- + (Z,A) \rightarrow e^- + (Z,A) + \nu\overline{\nu}$). If there are pions, kaons, or free quarks in "neutron" star cores, similar processes involving them will dominate. Again, these neutrino emissions themselves are detectable through their indirect influence on surface X-ray emissions, but they dominate what can be seen for thousands of years. Similarly, when white dwarfs are formed from stars with masses below $\sim 8\,M_\odot$, they lose their residual heat via neutrinos during the first $\sim 10^6$ years of life. The early evolution of a white dwarf's optical and ultraviolet surface emissions is paced by these neutrino losses.

6. COSMOLOGY

During the last ten years, particle physicists have claimed cosmology as their own. What cosmology can say about particle physics or what particle physics can contribute to our understanding of the universe is too large a subject to review or summarize here. However, from the beginnings of the emerging particle astrophysics symbiosis, the role of the neutrino has been central. If the universe underwent an inflationary epoch, Ω equals one. If the baryonic contribution to the universe is limited to $\Omega_B \lesssim 0.15$ by the standard deuterium nucleosynthesis arguments and what we see amounts to even less, there is non-baryonic dark matter. If the sum of the masses of the neutrinos that we know about is $\sim 100\ h^2\ eV/c^2$ $\sim$20–50 eV/c^2, big bang neutrinos are that dark matter. These arguments are old, but resilient. Furthermore, the gravity of such neutrinos would affect the power spectrum of density inhomogeneities by smoothing out perturbations on small scales (the so-called "Hot" dark matter scenario, that is not currently in favor). Their effect on Large-Scale Structure and galaxy clustering is measurable (even if they themselves are not). In addition, it has been shown [47] that the primordial ^{4}He abundance is sensitive to the number of light neutrinos and limited to be below 3.4 (i.e., = 3). This has recently been verified by LEP, which finds that $N_\nu = 2.99 \pm 0.05$ [12].

Cosmological arguments can also constrain the properties of Simpson's 17 keV beast [48]. That $\Omega \sim 1$ forces it to be unstable ($\tau < 10^{12}$ s) into much lighter species. Observations of density fluctuations on 5 Mpc/h scales and the theory that galaxy clustering requires a period of matter domination brings the decay time to below 10^6 s. Curiously, the upper limit to the mass of a Dirac neutrino derived from the SN1987A $\overline{\nu}_e$ signal is on the order of, but greater than, 20 keV [49] and this fails to eliminate Simpson's neutrino. However, if pion cooling is significant in protoneutron stars, this limit might be decreased substantially.

Cosmology is an arena in which the dialogue between neutrino physics and astrophysics has been most profitable and prolonged. This will no doubt fruitfully continue to be the case for the foreseeable future.

7. SUPERNOVA NEUTRINO BURSTS

Theory supposed that fabulous neutrino bursts accompany the death of massive stars, the birth of neutron stars, and most supernova explosions. The detection [50,51] of just such a burst from SN1987A seems to confirm this theory, though the residual neutron star has yet to be seen. Little can be said here about the neutrinos from 87A that hasn't been said in the one thousand or so readable papers on this subject generated over the last five years. The total radiated energy, average event energy, and duration fit the standard model developed during the eighties [52,53]. Limits have been obtained on the ν_e mass, the ν_e magnetic moment, the ν_e lifetime, the properties of axions, the weak principle of equivalence, and a variety of putative particle parameters [54]. On the whole, SN1987A has proven useful.

However, there is an agonizingly long list of questions concerning supernova and protoneutron star physics that were left unresolved. What is the mechanism of the explosion? Are ν_μ's and ν_τ's in fact produced in generous amounts? Is there a shock break-out flash of ν_e's? Are protoneutron stars convective? How do the neutrino spectra evolve? How are the emissions in the various neutrino channels correlated? Does the neutrino luminosity fluctuate before explosion? What might be the role of neutrino oscillations and the MSW effect in supernovae? How long is the entire burst? What is the nuclear equation of state? These are only a few of the interesting and germane questions on which SN1987A was almost entirely mute. Fortunately, our ignorance needn't be permanent. The nineties will see the establishment of an international network of massive underground detectors with exquisite sensitivity to galactic neutrino bursts. The thousands of events anticipated in this collection of neutrino telescopes from a core collapse anywhere in our galaxy will provide not only a quantitatively, but a qualitatively, better view of supernova physics. Table 1 lists the facilities that are now either built, being built, or planned, along with some of their pertinent characteristics and estimates of the total number of events anticipated at 10 kiloparsecs. The latter should be contrasted with the total of 19 events from both KII and IMB.

I will not here repeat the detailed discussion of the potential of this network for supernova and neutrino science that is found in the recent paper by Burrows, Klein, and Gandhi [55]. Rather, I will illustrate only one small, but exotic, signature of a finite ν_e mass in the super massive "Super" Kamiokande (SK). Figure 3 depicts the early evolution of the spectrum of energies that could be detected by SK at 10 kpc if the electron neutrino mass were 8 eV/c^2. A generic model of the neutrino emissions constructed in reference 55 was employed, but the precise details of that model are not important. What are important are the striking characteristics of the spectra and their evolution from 50 milliseconds to 600 milliseconds. Not only is there a dramatic sweep

Supernova Neutrino Telescope Characteristics

Detector	Total Mass (tonnes) (Fiducial Mass (tonnes))	Composition	Depth (mwe)	Threshold (MeV)	# Events at 10kpc	*Resolution (e,t,a)
ČERENKOV:						
IMB3	8000 (6800)	H_2O	1570	10	940	e,t,a
KII	3000 (2140)	H_2O	2700	7	370	e,t,a
Super KII	40,000 (32,000)	H_2O	2700	7	5510	e,t,a,
SNO	1600/1000	H_2O/D_2O	6000	5	781	e,t,a (t for NC)
SCINTILLATION:						
LVD	1800 (1200)	Kerosene	3100–4000	5–7	375	e,t, (a?)
MACRO	1000	"CH_2"	3100–4000	10	241	e,t
Baksan	330 (200)	"White Spirits"	850	10	70	e,t
LSND	200	"CH_2"	-	5	70	e,t
Borex[ino]	1760[300]	$(BO)_3(OCH_3)_3$	3100–4000	4.7	~325[33]	e,t
CalTech	1000	-	?	2.8	290	e,t
DRIFT CHAMBER:						
ICARUS	3600	^{40}Ar	3100–4000	5	120	e,t,a
RADIOCHEMICAL:						
Homestake ^{37}Cl	610	C_2Cl_4	4200	0.814	4	
Homestake ^{127}I	1000	NaI	4200	0.664	~25	
Baksan ^{37}Cl	3000	C_2Cl_4	800	0.814	22	
EXTRAGALACTIC:						
SNBO	100,000	$CaCO_3$	?	-	10,000	t
JULIA	40,000	H_2O	?	-	10,000	e,t,a

*e, t, and a mean that the detector has or will have energy, time, or angle resolution.

with time from high average and minimum energies, but the predicted fluctuations in the *luminosity* versus time are echoed in the individual *spectra* at a given time. These remarkable signatures of a finite ν_e mass are only a few of the rich features and diagnostics that the new array of neutrino telescopes promises. We will just need a little luck.

CONCLUSION

I hope that this short article adequately conveys the variety of astrophysical contexts in which neutrinos play a central role and the usefulness to fundamental neutrino physics of an ongoing dialogue with astrophysics. Much has already been achieved at the interface between these disciplines. With the establishment of massive underground and underwater neutrino telescopes, this dialogue can only accelerate to mutual benefit.

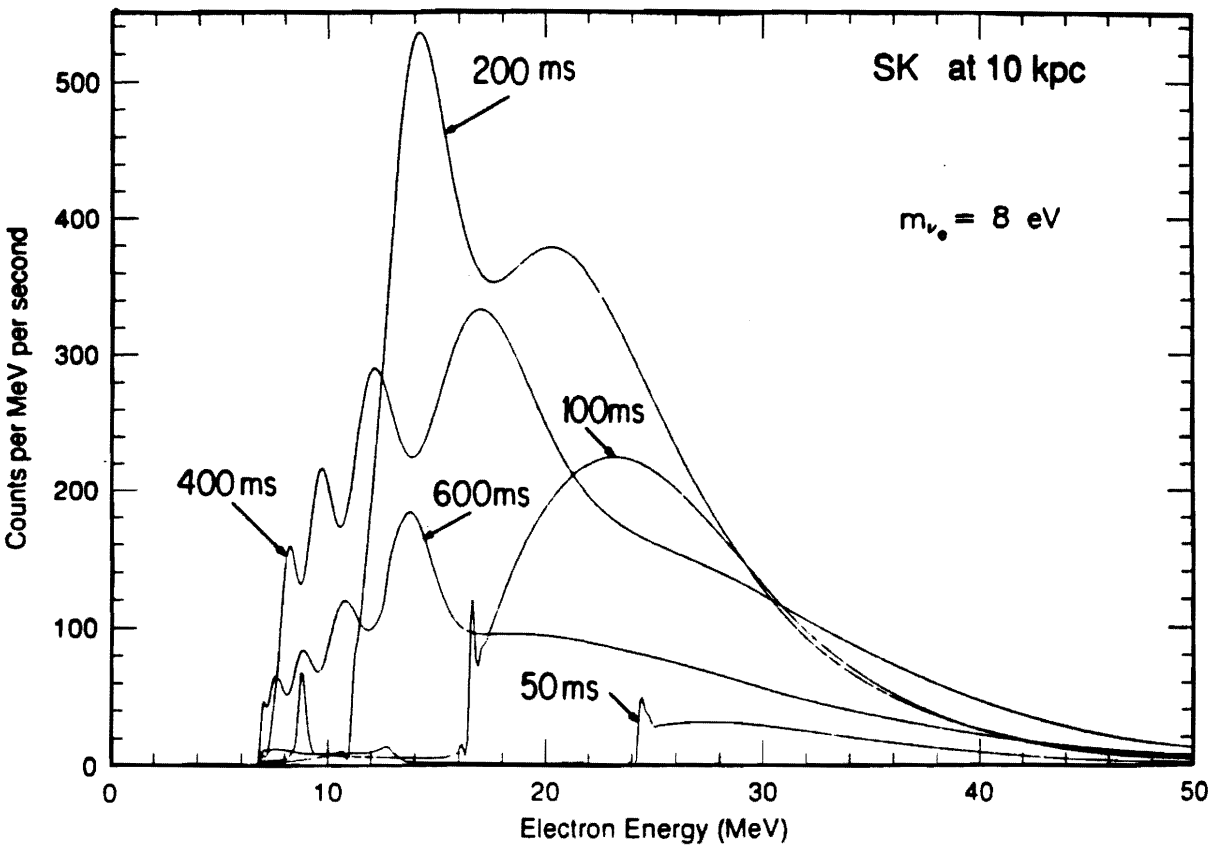

Figure 3. The number of counts per MeV per second in Super Kamiokande at 10 kpc versus the event electron energy in MeV for the generic neutrino burst model in reference 55 at 50, 100, 200, 400, and 600 milliseconds after core bounce. For illustration, an electron neutrino mass of 8 eV/c^2 and a detection threshold of 7 MeV was assumed. See text for discussion.

Acknowledgments

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