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A SUMMARY OF THEORETICAL PREDICTIONS CONCERNING SUPERNOVA NEUTRINO DETECTION

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ABSTRACT

Predominantly to resolve the solar neutrino problem, massive detectors are being placed deep underground that will constitute a formidable array of supernova neutrino telescopes. In this paper, I summarize the signals that we may expect from a galactic core collapse in the various detectors and motivate my contension that SN1987A was not the last word concerning supernova neutrino astronomy, but a tantalizing beginning.

1. Introduction

More than five years ago, SN1987A confirmed that supernova explosions, the death of massive stars, and neutrino bursts are connected (Hirata et al. 1987 (KII); Bionta et al. 1987 (IMB); Burrows 1990; Arnett et al. 1989). The energetics, the duration, and the significant anti-electron neutrino ($\overline{\nu}_e$) content of that burst were verified to be consistent with the models developed in the 1980's (Burrows and Lattimer 1986; Bruenn 1987; Mayle, Wilson, and Schramm 1987; Woosley, Wilson and Mayle 1986). However, the important details of those models could not be identified in the mere nineteen events gathered by the IMB and Kamiokande II detectors. SN1987A was mute on the unique neutrino diagnostics that attend such phenomena as shock breakout, convection, accretion, explosion, long-term core cooling, and transparency (Burrows 1990). We still have no neutrino data on the supernova mechanism itself. Furthermore, no neutral-current, mu-neutrino (ν_μ) or tau-neutrino (ν_τ) signatures were identified, despite the prediction that these neutrino species (and their anti-particles) carry away the bulk of the neutron star binding energy. IMB and KII (now KIII) are not sensitive to these flavors.

However, there is now being assembled on three continents an international network of deep underground neutrino telescopes whose collective sensitivity to a galactic neutrino burst will be unprecedented. Joining the KIII (to be upgraded to "Super" Kamiokande (SK)) and Baksan (Alekseev et al. 1987) this decade are the Sudbury Neutrino Observatory (SNO, Ewan 1990), the Large Volume Detector (LVD, Hafen 1990), and the Monopole, Astrophysics,

and Cosmic Ray Observatory (MACRO, Barish 1990). Detectors that are now in the planning or development phases and that may join this constellation are the SuperNova Burst Observatory (SNBO, Cline 1990), the Imaging of Cosmic And Rare Underground Signals detector (ICARUS, Park 1990), the Liquid Scintillation Neutrino Detector (LSND, Burman 1990), the CalTech Scintillator (Boehm 1990), the Homestake ^{127}I radiochemical detector (Lande 1990), and Borexino (Raghavan and Pakvasa 1988).

2. Detectors

Thousands of events can be anticipated from a galactic stellar collapse which should resolve many of the outstanding questions in supernova and protoneutron star theory and constrain or measure the properties of the three flavors of neutrinos (mass, oscillation angles, decay, magnetic moment, etc.) more cheaply than can now be done in the laboratory. In this paper, we summarize the results obtained by Burrows et al. (1992) for a generic collapse at 10 kpc. For further details, it is suggested that the reader consult that work.

Supernova neutrino detectors require obvious characteristics that nevertheless bear listing. Foremost among these is great mass (M) which is a direct consequence of the small neutrino-matter cross sections (σ_ν). An estimate of the total number of events (N_ν) that register in a detector is $\sigma_\nu \times F \times N_A M/A$, where F is the neutrino fluence, N_A is Avogadro's number, and A is the molecular weight per target. If we want N_ν to be ~1000 and take A for protons in H_2O (9), an average σ_ν of 10^{-41} cm^2 (10^{-17} barns!) for the $\overline{\nu}_e + p \rightarrow n + e^+$ process, and a $\overline{\nu}_e$ fluence from the galactic center of 10^{11} cm^{-2} requires M to be of order 10 kilotonne. For H_2O(liq.), this is equivalent to a cube 20 meters on a side. In addition, the detector must be shielded from cosmic rays by at least 10^3 meters-of-water-equivalent (mwe) to provide low backgrounds in the 10–100 MeV per event range. Hence, the detectors must be deep underground. Low U/Th/K content in the adjacent rock and equipment is desirable, but not as crucial since natural radioactivity keeps below ~9.0 MeV per radiation and supernova neutrinos are in the 10–30 MeV range. Nevertheless, a low-energy trigger threshold of at most 10 MeV is desirable and this requires "radiation-quiet" environments.

A massive detector must be composed of cheap, but high-neutrino-cross-section, material. Hence, the selection over the years of proton-rich materials, such as H_2O and liquid scintillator ("CH_2"), and isotopes such as ^{37}Cl (Davis 1978), ^{40}Ar (Cline 1987), ^{127}I (Haxton 1988, Engel 1991, Lande 1990), and ^{11}B (Raghavan 1988) with large ν_e cross sections. The SNO collaboration has selected heavy water (D_2O) to achieve high sensitivity to all neutrino species via the neutral-current break-up reaction on deuterium: $\nu_i + d \rightarrow n + p + \nu_i$. Beyond material, mass, and depth, a supernova neutrino telescope must have buffers adequate to handle high throughput (>1024), short dead-times (<1 millisecond), accurate absolute and relative timing, good energy resolution, low maintenance costs, and a high duty cycle. Furthermore, there should be some coordination between facilities to provide redundancy and constant surveillance (Cline 1990). These criteria may seem obvious, but have not all been achieved by any extant or past detector.

In water Čerenkov detectors, a large volume of clear water is put under constant surveillance by a dense array of inward-looking phototubes for

the characteristic transient cone of Čerenkov light from relativistic electron or positron secondaries. These detectors can infer particle energies from the integrated Čerenkov light and by the pattern of illuminated phototubes can reconstruct the electron angles.

The foremost light-water exemplar of this detector technology is Kamiokande III (soon to be Super Kamiokande), with a current fiducial masses for supernova detection of 2140 tonnes (soon to be ~40,000 tonnes).

The major interactions of supernova neutrinos with light water are,

$$\overline{\nu}_e + p \rightarrow n + e^+ \qquad \text{(C.C.)} \tag{1}$$

$$\nu_e + e^- \rightarrow \nu_e + e^- \qquad \text{(N.C.} + \text{C.C.)} \tag{2a}$$

$$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^- \qquad \text{(N.C.} + \text{C.C.)} \tag{2b}$$

$$\nu_\mu(\nu_\tau) + e^- \rightarrow \nu_\mu(\nu_\tau) + e^- \qquad \text{(N.C.)} \tag{2c}$$

where C.C. and N.C. stand for charged-current and neutral-current, respectively, and reaction (1) has far and away the highest cross section.

The only heavy-water detector on the horizon is the Sudbury Neutrino Observatory (SNO) now being constructed in Sudbury, Ontario (Ewan 1990, Mak 1988). It will consist of one kilotonne of heavy water surrounded by 4 meters of light water (with a fiducial H_2O mass for supernova detection of approximately 1.6 kilotonnes). Designed primarily to detect solar neutrinos, it is uniquely suited to detect $\nu_\mu(\overline{\nu}_\mu)$'s and $\nu_\tau(\overline{\nu}_\tau)$'s via the neutral-current break-up reactions of deuterium,

$$\nu_i + d \rightarrow n + p + \nu_i \quad (\epsilon_{th} = 2.22\,\text{MeV}) \tag{3a}$$

$$\overline{\nu}_i + d \rightarrow n + p + \overline{\nu}_i \quad (\epsilon_{th} = 2.22\,\text{MeV}) \tag{3b}$$

The secondary neutrons will be detected through the Čerenkov light from the pair cascades of the gamma-rays ($\Sigma E_\gamma \sim 8.6\,\text{MeV}$) from neutron capture on the ^{35}Cl salted throughout the D_2O in the form of NaCl (2.5 tonnes) or with ^{3}He counters suspended in the D_2O tank (Beier 1991). Whichever neutron detection scheme is employed, SNO can not measure energy or angles for reactions 3(a) and 3(b), but can measure event times.

The charged current reactions,

$$\nu_e + d \rightarrow p + p + e^- \quad (\epsilon_{th} = 1.44\,\text{MeV}) \tag{4}$$

and

$$\overline{\nu}_e + d \rightarrow n + n + e^+ \quad (\epsilon_{th} = 4.03\,\text{MeV}), \tag{5}$$

are at least as important in SNO as neutral-current reactions. SNO's sensitivity to ν_μ's, ν_τ's, and ν_e's, its low anticipated detection threshold of 5 MeV, its great depth of 6000 m.w.e., and its H_2O/D_2O design will make it a premier supernova burst sentinel when it goes on line in 1995 or 1996.

Another important class of massive underground detectors is the scintillators. In these, some of the energy of an event is converted into light that is detected by phototubes arrayed around the active liquid or connected to

the liquid by light pipes of various designs. Since the amount of scintillation light collected is proportional to the deposited energy, the total event energy can be measured. No angle information is extracted. The foremost virtues of scintillation detectors, vis-a-vis water Čerenkov detectors, are their proton-richness ($\sim 1.3 \times H_2O$) and efficient light production. This makes them quite sensitive to $\overline{\nu}_e$'s via reaction (1). In principle, the high light yields can result in detection thresholds that are superior to those in Čerenkov detectors. The 2.22 MeV photon from the capture of the neutron liberated in reaction (1) is also detectable, and the coincidence of the e^+ and the neutron signals is a powerful signature of $\overline{\nu}_e$'s. The LVD is expected to have an efficiency for the detection of the neutron capture of $\sim$70% (Hafen 1990).

The well-developed scintillator technology is employed in a variety of detectors that are built, being built, or proposed. Among these are the LVD (Pless 1988, Hafen 1990) (1800 tonnes of "$C_{10}H_{22}$") and MACRO (Barish 1990) (1000 tonnes) in the Gran Sasso Tunnel in Italy, Baksan (Alekseev 1987) (200 tonnes) in the Soviet Caucasus, the LSND (Burman 1990) (200 tonnes) at Los Alamos; and Borexino (Raghavan 1988) (200 tonnes), planned for Gran Sasso. The latter is a boron-rich scintillator [trimethoxyboroxine: $(BO)_3(OCH_3)_3$] that would have both good neutral-current and good charged-current response. (The masses accompanying the detectors are proposed, and not necessarily, current masses.) Though these detectors are motivated primarily for neutrino oscillation, monopole, or solar neutrino studies, each has great potential as a supernova neutrino telescope in the informal international burst network.

The LVD and MACRO, in particular, with estimated completion dates near 1993–1994, promise sensitivity competitive with that of SNO, KII, and IMB. MACRO is being equipped with dedicated supernova electronics that can provide an early warning within one hour of detection (Barish 1990). By 1995, the continents of North America, Europe, and Asia should be well instrumented for a supernova neutrino burst "watch."

Though Čerenkov and scintillation detectors are the flagships of this network, other approaches for supernova neutrino detection are being pursued. Among these are ICARUS (Cline 1987, Park 1990), a 3.6 ktonne drift chamber with pure liquid ^{40}Ar, the ^{37}Cl and ^{127}I radiochemical detectors in the Homestake Mine (Davis 1978, Lande 1990, Haxton 1988, Engel 1991), the ^{37}Cl detector at Baksan (Gavrin 1991), SNBO (Cline 1990), a massive rock detector that would be instrumented with numerous cheap BF_3 neutron counters.

ICARUS is most sensitive to ν_e's through the charged-current reaction on ^{40}Ar (see Fig. 2),

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-; \qquad {}^{40}\mathrm{K}^* \rightarrow {}^{40}\mathrm{K} + \gamma(5\,\mathrm{MeV}), \tag{6}$$

but has little neutral-current or $\nu_\mu(\nu_\tau)$ capability. Its most positive feature from the supernova perspective is its competitive sensitivity to the shock breakout ν_e burst.

3. Some Generic Theoretical Expectations

Though the neutrino emissions during the first hundred millseconds after bounce are rich with diagnostic features, by then only 10–20% of the neutron star's binding energy has been radiated. The energy sources for the

middle phase that includes and continues the first 100 ms are not only the gravitational binding energy of the outer mantle of the protoneutron star, which due to the loss of entropy and lepton number collapses quasi-statically, and the accretion energy, but, quite possibly, also the "convective" overturn of the mantle. The latter is driven by the unstable entropy and lepton gradients dynamically impressed on the protoneutron star periphery by a stalling shock. The nature and neutrino signatures of these instabilities are not yet known, but are under active investigation and may prove to be crucial to the supernova mechanism itself (Burrows 1987, Burrows and Lattimer 1988, Burrows and Fryxell 1992, Herant, Benz, and Colgate 1992).

However, after the accretion/mantle collapse/"convective" phase and after the supernova is truly launched, a more staid protoneutron star cooling phase commences. Though the first second of protoneutron star life described above may have been vigorous and luminous, the long-term phase that follows may account for most of the energy emitted. Generically, the emissions break up into the two phases expected: the middle accretion/mantle cooling phase with a decay constant near one second and the long-term cooling phase with a much longer duration ($\tau \gtrsim 4$ seconds) that smoothly matches onto the middle phase., In fact, the luminosities during the long-term phase do not decay exponentially, but as power laws (index $\sim 1 \pm 0.5$) that indirectly reflect the nonlinear nature of neutrino transport (Bludman and Schinder 1988). The long duration of the late core cooling phase is a consequence of the high densities and neutrino energies ($\rightarrow$ high opacities) in the protoneutron star interior that is now the source of the neutrino emissions. Though KII and IMB detected neutrino events during the first $\sim$10 seconds, we expect that the thousand or so events anticipated from a galactic collapse will be spread out over many *tens* of seconds to a minute. It should be remembered though that during the long-term phase the neutrino spectra gradually soften and that a larger and larger fraction of the emitted neutrinos are shunted below the detector thresholds of $\sim$5–10 MeV.

The importance of the $\overline{\nu}_e p \rightarrow n e^+$ channel in all the detectors is manifest. While it is overwhelmingly important in KIII (and SK), in LVD a nontrivial fraction ($\sim$6%) of the total signal comes from the neutral-current reaction on ^{12}C. At 10 kpc, this represents $\sim$20 events that should stand out clearly near 15.11 MeV. SNO is sensitive to ν_e's, $\overline{\nu}_e$'s, and "ν_μ"'s via both charged-current and neutral-current processes. More than 25% of its supernova signal is expected to be from "ν_μ"'s, while 35% is via the neutral-current break-up reactions. The precise percentages depend on the hardness of the ν_μ spectrum. Our numbers reflect the new, softer ν_μ spectra of Bruenn (1989) and Myra and Burrows (1989). Importantly, $\sim$10% of the total signal ($\sim$20% of the signal in the heavy water alone) is due to the charged-current reaction of ν_e's on deuterium. As many as 80 events at 10 kpc are expected in SNO via this channel alone. This ν_e sensitivity is unique among the telescopes now under construction, though the 3.6 kilotonne ICARUS and the 40 kilotonne SK would be competitive in this regard. As a consequence, a break-out ν_e flash at 10 kpc is expected to produce $\sim$13 events in SNO's inner 1000 tonnes. This is comparable to the entire number of events captured from SN1987A by either IMB or KII. Estimates of the total number of events at 10 kpc due to the shock break-out ν_e flash in KIII, LVD, SK, SNO, and ICARUS are 1, 1, 15, 13, and 9, respectively.

Many of the characteristics of supernova emissions—the rapid turn-on,

the oscillations, the explosion pulse, the long decay—will stand out clearly in the detectors. In KIII, after 50–100 milliseconds, the $\overline{\nu}_e$ signal may climb to ~600 Hz, roughly one event every 2 milliseconds at 10 kpc. A ~80 millisecond modulation of the $\overline{\nu}_e$ signal occasioned by the ringing of the outer mantle of the protoneutron star might involve excursions in the count rate of ±50–100 Hz. This is equivalent to a bunching of ~5–10 events per pulse and may be discernible. The decay of the count rate during the first 0.5 seconds is made more gradual than the corresponding decay of the $\overline{\nu}_e$ luminosity because of the simultaneous secular hardening of the spectrum. The halting of the pulsations at explosion is easily identified near 500 milliseconds, the average count rate dropping after a burst of 10–20 counts from ~350 Hz to ~100 Hz within 150 milliseconds. It should be remembered that the theoretical oscillation period can range from 10 to 100 milliseconds and that the explosion may commence after, not 0.5 seconds, but a few seconds. It is the qualitative nature of the generic features that we emphasize, not any specific and rigid model.

Though 25%, 50%, and 75% of the total binding energy of 2.9×10^{53} ergs is radiated after 0.368 seconds, 1.65 seconds, and 11.3 seconds, respectively, in the generic model of Burrows, Klein,and Gandhi (1992) the integrated number of counts rises faster than the energy is radiated because the average neutrino energies are higher in the earlier phases. Since the interaction cross sections are increasing functions of neutrino energy, the signal is skewed to earlier times and a non-trivial fraction of the total burst energy can dribble out "unsensed." Nevertheless, we expect as many as ~40 events in KIII at 10 kpc after 10 seconds. This is ~10% of the signal and occurs when ~25% of the energy is emitted. Note also that even after 20 seconds we expect ~20 events in KIII at 10 kpc. No events were recorded in KII from SN1987A after 20 seconds. The precise times of the last events are determined by the actual rate at which energy is released from the core and, hence, by the specifics of neutrino transfer at nuclear and supranuclear densities (Burrows 1988). Note also that these counts and count rates are increased by a factor of ~15 for Super Kamiokande. This implies, among other things, that ~300 events are to be expected in SK at 10 kpc after 20 seconds.

SNO is usefully sensitive to all neutrino flavors. The "ν_μ" signal rate in SNO might average a full 200 Hz during the first half second, during which ~100 "ν_μ" events have accumulated. The ν_e break-out flash may reach 1200 Hz (but lasts only ~10 milliseconds). The 100–150 Hz ν_e event rate achieved before explosion is more than 10 times higher than the corresponding rate in MACRO, LVD, or KIII. A total of ~130 ν_e events register in SNO at 10 kpc during the entire neutrino burst, in contrast to 7.6 in KIII (but 113 in SK) and 9.3 in LVD. The large $\overline{\nu}_e$ count rate occurs predominantly in the outer 1600 tonnes of light water, but the charged-current reactions account for as many as 37 ($\overline{\nu}_e$) and 67 (ν_e) events in the inner 1000 tonnes of heavy water.

One prediction of the current theory of supernova neutrino bursts is that the "ν_μ" signals will be in phase with the $\overline{\nu}_e$ and ν_e signals. Though their spectra are a bit harder and the amplitudes of any signal modulation are a bit smaller, the emitted "ν_μ,'s" reflect the hydrodynamics, ringing, explosion, and cooling of the core in much the same way as do the electron types. Any statistically significant deviation from this behavior would imply that non-standard neutrino properties such as mass, flavor oscillation, and/or decay were at work.

4. Conclusions

Assuming that the components of a neutrino telescope network do indeed provide this information in a timely fashion, how accurately can a supernova's direction be ascertained? The low neutrino event yields from SN1987A rendered impossible any definitive, a priori association with the Large Magellanic Cloud. However, the 100's–1000's of events anticipated from a galactic stellar collapse bring the possibility of reconstructing direction within reach. There are two primary methods to achieve this: 1) using the anisotropic angle distributions of a subset of the detected events in detectors with angle information, or 2) using triangulation between at least 3 detectors. The latter method can include scintillation detectors that provide no angular information, but requires accurate absolute timing ($\ll 1$ ms). The former method relies on a minority of the events, such as those from $\nu - e^-$ scattering, but can be done by a single detector with angular resolution. Both methods require good statistics. Straggling confounds the first method, but in SNO pointing accuracies of $\sim$ 5–7° at 10 kpc might be achieved. Even in the massive SK, accuracies at that distance of only 3° can be contemplated. The second method of triangulation, say between KIII (SK), LVD, and SNO, might point to an accuracy of $\sim$ 10° (at 10 kpc).

An international network of massive underground neutrino detectors is being assembled that by the year 1997 will have an unprecedented sensitivity to a galactic neutrino burst. We surmise that this generation of detectors will not be the last and that a permanent scientific presence underground has begun. If this generation of neutrino telescopes does not catch a galactic burst, succeeding ones certainly will. We can now realistically predict that most of us will live to experience the science that this sea-change in capability implies.

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