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Supernova neutrinos: The accretion disk scenario

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Neutrinos from core collapse supernovae can be emitted from a rapidly accreting disk surrounding a black hole, instead of the canonical protoneutron star. For galactic events, detector count rates are considerable and in fact can be in the thousands for Super-Kamiokande. The rate of occurrence of these accreting disks in the Galaxy is predicted to be on the order of $\sim 10^{-5}$ yr^{-1}, yet there is little observational evidence to provide an upper limit on their formation rate. It would therefore be useful to discriminate between neutrinos which have been produced in a protoneutron star and those which have been produced accretion disks. In order to distinguish between the two scenarios, either the time profile of the neutrino luminosity, total energetics, or the relative fluxes of different neutrino flavors may be considered. The flavor content would clearly point to one scenario or the other.

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Recent advances in the theory of gamma ray bursts (GRBs) have pointed to rapidly accreting disks surrounding black holes (AD-BH) because this configuration is a natural one for producing massive energy generation. Simulations of neutron star mergers and core collapse supernovae have indeed found that, under certain conditions, these disks can form [1–3]. Spectra from x-ray afterglows of long duration bursts have indicated that the bursts are associated with Type Ib/Ic supernovae, suggesting massive stellar core collapse as the origin. The rate of gamma ray bursts in the galactic region is estimated to be approximately 10^{-5} yr^{-1} with approximately $2/3$ of these being long duration events [4]. This is roughly 0.1% of the core collapse supernova rate. Disks which produce enough energy for a burst must have fairly high accretion rates in the range of $0.1 M_\odot$/s to $1.0 M_\odot$/s. Observations of short bursts suggest that they are associated with compact object mergers, neutron-star–neutron-star, or black-hole–neutron- star [5].

Hypernovae are very energetic core collapse supernova. The rate of Type Ic supernovae in an average galaxy is about 10^{-3} yr^{-1}, whereas the inferred hypernova rate is about 10^{-5} yr^{-1} [4]. A limited data set of Type Ic hypernovae and supernovae shows that supernovae which come from progenitors above $\sim 20 M_\odot$ show evidence for two branches with a few stars at high energy $\sim 10^{52}$ ergs, and one at low energy $\sim 10^{50}$ ergs [6]. One can speculate that the more luminous events are produced by an accretion disk and the less luminous event is not.

It would be useful to translate these limits on hypernovae and gamma ray bursts into limits on the AD-BH formation rate. Not every AD-BH may make a hypernova or GRB. An observationally based upper limit can be made from the ratio of black holes to neutron stars. In the case of low-mass x-ray transients, the observations will support turning every star above $\sim 20 M_\odot$ into a black hole [7], producing a rate of 10% or even greater.

In this paper we point out that the next galactic supernova may produce neutrinos from an AD-BH. Baumgarte [8] discussed the neutrino signal from a collapsing protoneutron star, which cut off the flux of all flavors of neutrinos. Here we discuss an object where the protoneutron star (PNS) has collapsed and an accretion disk around a black hole remains, and emits neutrinos. It is possible that the PNS may collapse to a black hole essentially immediately, so the only neutrinos that are produced will come from the AD-BH. On the other hand, there may be a stage where the accretion disk and the PNS exist at the same time, so that the neutrinos will be emitted from both simultaneously. Another possibility is that there will be a two stage scenario, where the PNS collapses, but only after it has had time to release substantial numbers of neutrinos, leaving behind an AD-BH which continues to emit. Even if the supernova light curve is observed (unfortunately the optical signal is not likely to be visible as most of the Galaxy is obscured by dust), it would be difficult to use this to determine whether a PNS or an AD-BH is at the core. We show that the emitted neutrinos may be used to immediately and directly make this distinction.

Detectors that will observe neutrinos from the next galactic supernova are currently Super-Kamiokande [9], KamLAND [10], MiniBooNE [11], SNO [12], and the future Borexino [13]. A protoneutron star event will produce thousands of events in SuperK, and hundreds in KamLAND and MiniBooNE. At least one count from an AD-BH supernova may occur in Super-Kamiokande even if the event is 3 Mpc away [14].

For obtaining information from the neutrino signal, the first observables that come to mind are total energetics and time scale of emission. The energy released in neutrinos is very likely to differ between the AD-BH and the PNS. Uncertainties exist, however, in the total energy emitted in each case. For example in the protoneutron star, the canonical neutrino signal involves equipartition of 3×10^{53} erg of gravitational binding energy between the six neutrino flavors. However, factors such as collapse of the PNS to a black hole and/or fallback onto the PNS could change the total energy considerably. More uncertainty exists in the case of accretion disks where the accretion rate can differ by more than an order of magnitude. Physics not yet included in the calculations may produce different predictions, see e.g. [15] for model discussion. However, we note that the gravitational binding energy potentially available, given a $3M_\odot$ black hole, is $9(M/M_\odot) \times 10^{53}$ ergs, where M is the mass of material processed by the disk and some fraction will be radiated in the form of neutrinos. For the models we study, we find that roughly 20% of this gravitational binding energy is released in the form of neutrinos for disks of $1.0M_\odot/\mathrm{s}$ and 5% in the case of $0.1M_\odot/\mathrm{s}$, which is consistent with those calculated in [16,17]. Similar issues are present when considering time scale of emission. However, the often assumed time scale for neutrino emission through the protoneutron star is about 10 s, with an exponentially decaying luminosity so that most of the neutrinos are emitted in the first three seconds. If an accretion disk is steady state, the neutrino luminosity will not fall off but will be approximately constant, although deviations from steady state will likely occur. While time scale and total energy should certainly be measured and used as constraints to the extent possible, it is desirable to look for a more robust test.

Common to all models of core collapse AD-BH is their inability to produce significant numbers ν_μ and ν_τ in comparison to ν_e. This is illustrated in Fig. 1, where we show the ratio of ν_μ, ν_τ relative to ν_e production. Also plotted are the three disk models that we are use here [16–18]. We show for comparison two numerical models [1,19]. As can be seen in the figure, the ratio of production of ν_μ and ν_τ to ν_e is low everywhere. Emission rates differ from production rates when neutrinos are trapped though, and significant emission of ν_μ and ν_τ relative to ν_e will occur where the ν_μ and ν_τ types are trapped. As can be seen from the figure this occurs in the PNS but not in any AD-BH scenarios proposed for core collapse. Trapping for the ν_e and $\bar{\nu}_e$ occurs only in fast accretion rate disks. We show the trapped region of an $1M_\odot/\mathrm{s}$ disk and compare it with the trapped regions of the PNS in Fig. 2. This relatively small emission of ν_μ and ν_τ in comparison with the PNS suggests a robust test, in the form of flavor ratios, to determine whether the origin of a future neutrino signal is an AD-BH or a PNS. We use the standard symbol ν_x for ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$ since these flavors are emitted with essentially the same spectra in the types of environments we are considering here.

To proceed, we first determine the energy spectra of the emitted neutrinos. Spectra for two different AD-BH models (which differ by an order of magnitude in accretion rate) as well as the PNS are shown in Fig. 3. Over the trapping surface in the $\dot{M} = 1M_\odot/\mathrm{s}$ AD, the energies are in the range of $\langle E_{\nu_e}\rangle \sim 13$ MeV to $\langle E_{\nu_e}\rangle \sim 14$ MeV and $\langle E_{\bar{\nu}_e}\rangle \sim 16$ MeV to $\langle E_{\bar{\nu}_e}\rangle \sim 18$ MeV [18]. The models used for these calculations have been modified from those found in [16,17] to take account of a finite height neutrino surface and electron fractions that differ from 0.5. In more slowly rotating, optically thin disks, the average energy of the neutrinos comes close to tracking the average thermal energy of the electrons and positrons.

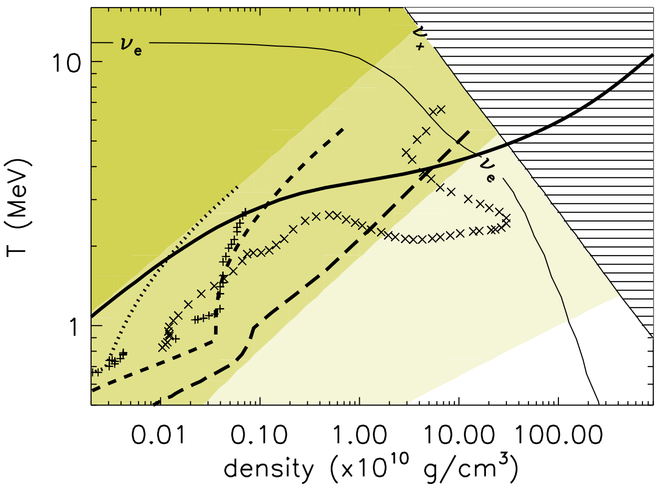

FIG. 1 (color online). Shaded regions show the ratio of ν_μ, ν_τ production relative to ν_e. The darkest shaded region shows a ratio of 0.1 to 0.2, the lightest shaded region shows rations of 10^{-5} to 0.1, and the white region shows ratios below 10^{-5}. The production ratios are only relevant where the neutrinos are not trapped. The trapped region of ν_e occurs above the line labeled ν_e. The ν_μ and ν_τ emission is only significant relative to ν_e in the region where ν_μs and ν_τs are trapped which is shown as the hashed area. One can see that neither the calculations used here (dotted and dashed lines, corresponding from left to right to accretion rates of $0.01M/M_\odot$, $0.1M/M_\odot$, $1.0M/M_\odot$) nor numerical models such as those in [1,19] (crosses) ever enter that trapped region. In contrast, all types of neutrinos are trapped in the protoneutron star (solid line) [27] and significant ν_μ and ν_τ emission occurs.

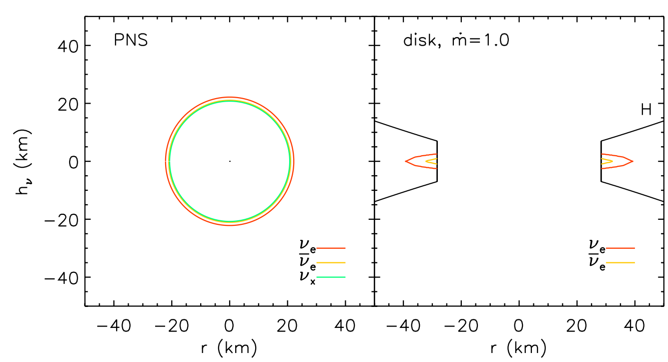

FIG. 2 (color online). Shows the neutrino surfaces for a protoneutron star and a $1M_\odot/\mathrm{s}$ accretion disk from [18].

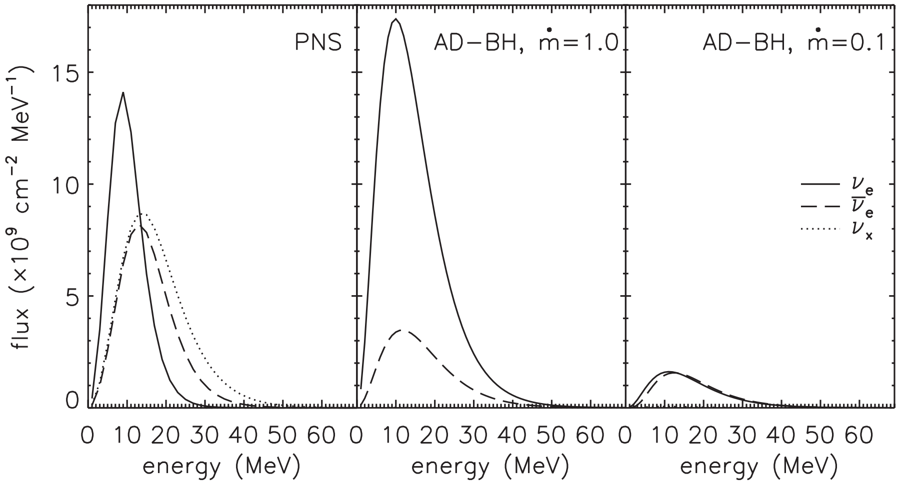

FIG. 3. Shows the neutrino spectra for the PNS and AD-BH, in the absence of oscillations, at a distance of 10 kpc from the center of the object. The AD-BH neutrino spectra were calculated by summing over the entire surface of the disk including both trapped and untrapped regions, as described in [18,28]. The spectral parameters for the PNS were taken from [23]: $T_{\nu_e} = 2.6$, $\eta = 3.0$, $T_{\bar{\nu}_e} = 4.0$, $\eta = 2.8$, and $T_{\nu_\mu,\nu_\tau} = 5.0$, $\eta = 1.8$, with an energy partition of L_{ν_e}:$L_{\bar{\nu}_e}$:$L_{\nu_{\mu,\tau}}$ of 1:1.3:7.7.

In both the PNS and AD-BH, the neutrinos are emitted from a place of relatively high density, where they are matter suppressed and essentially coincident with matter eigenstates. As the neutrinos proceed to the outer edges of the star, which is at relatively low density, they pass through two potential resonance regions and emerge as mass eigenstates, see e.g. [20]. The lower density resonance, at $\sim 10\ \mathrm{g\,cm^{-3}}$, is governed by δm_{12}, and θ_{12} both of which have been measured by solar and reactor neutrino experiments. The higher density transition, at $\sim 10^3\ \mathrm{g\,cm^{-3}}$ is governed by δm_{13} and θ_{13}. The former parameter is known except for a sign (leaving the neutrino mass hierarchy unknown) while the latter is constrained by reactor neutrino experiments $\sin^2\theta_{13} < 0.1$ [21]. There is some uncertainty regarding how the neutrinos will behave due to unknown neutrino parameters such as the hierarchy, θ_{13} and the density profile of the star. There are two possible hierarchies: normal and inverted, but this leads to five different cases, because of the unknown density profile at the two resonances. If either neutrinos or antineutrinos proceed adiabatically through the higher density resonance (i.e. the hopping probability is zero) most of the original ν_e or $\bar{\nu}_e$ will be converted to a combination of ν_μ and ν_τ or $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$. We label these cases as H in the tables, and note the hierarchy with which they correspond. If the neutrinos proceed adiabatically through the lower

TABLE I. Integrated counts in various detectors. The columns represent the same oscillation scenarios as in Table II. All accretion disk rates may be scaled by $(M/M_\odot)$ where M is the mass of material processed by the disk. OMNIS rates are quoted for 1 kt of lead perchlorate only. More detailed discussions of count rates for the PNS are in, e.g. [12,24–26].

	Normal hierarchy H				Normal hierarchy LA				Normal hierarchy LNA				Inverted hierarchy H, LA				Inverted hierarchy H, LNA			
		$\dot{m}$				$\dot{m}$				$\dot{m}$				$\dot{m}$				$\dot{m}$		
	PNS	1.0	0.1	0.01	PNS	1.0	0.1	0.01	PNS	1.0	0.1	0.01	PNS	1.0	0.1	0.01	PNS	1.0	0.1	0.01
SuperK																				
$\bar{\nu}_e + p \rightarrow n + e^+$	7000	2800	1400	50	7000	2800	1400	50	7000	2800	1400	50	10 000	10	50	2	10 000	10	50	2
$\nu + ^{16}0$	30	20	3.0	0.3	30	20	3.0	0.3	30	20	3.0	0.3	30	20	3.0	0.3	30	20	3.0	0.3
SNO																				
$\nu_e + d \rightarrow p + p + e^-$	170	0.2	0.8	0.04	130	80	10	0.2	80	180	20	0.4	130	80	10	0.2	80	180	20	0.4
$\bar{\nu}_e + d \rightarrow n + n + e^+$	70	30	0.2	0.4	70	30	15	0.4	70	30	6	0.4	100	0.1	0.5	0.02	100	0.1	0.5	0.02
$\nu + d \rightarrow p + n + \nu$	330	140	30	0.7	330	140	30	0.7	330	140	30	0.7	330	140	30	0.7	330	140	30	0.7
KamLAND																				
$\bar{\nu}_e + p \rightarrow n + e^+$	280	110	50	2	280	110	50	2	280	110	50	2	380	0.5	3	0.1	380	0.5	3	0.1
$\nu + p \rightarrow \nu + p$	500	200	44	1	500	200	44	1	500	200	44	1	500	200	44	1	500	200	44	1
OMNIS																				
$\nu_e + \mathrm{Pb} \rightarrow e^- + n + \mathrm{Bi}$	210	0.1	0.9	0.2	150	90	10	0.1	80	190	30	0.3	150	90	10	0.1	80	190	30	0.2
$\nu + \mathrm{Pb} \rightarrow \nu + \mathrm{Pb} + n$	40	16	4	0.04	40	16	4	0.04	40	16	4	0.04	40	16	4	0.04	40	16	4	0.04

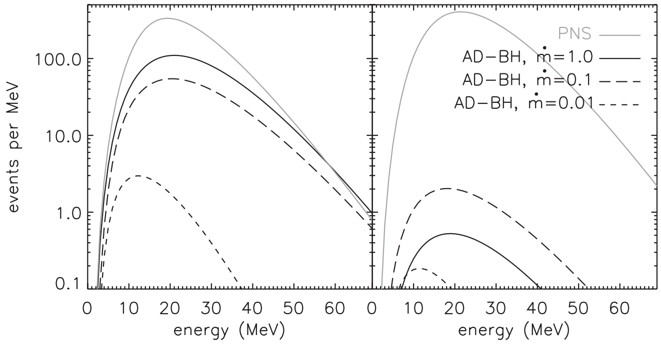

FIG. 4. Comparison between the counts for $\bar{\nu}_e + p \rightarrow e^+ + n$ at Super-Kamiokande as a function of positron energy for the two oscillation scenarios. Plotted are the signals from the protoneutron star and accretion disks ranging from $0.01 M_\odot$/s to $1.0 M_\odot$/s. With a normal hierarchy and nonadiabatic second resonance (LNA) (left panel), a fraction of the neutrinos originally emitted as $\bar{\nu}_e$s are measured as $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$s at the detector. With an inverted hierarchy and an adiabatic θ_{13} H resonance (right panel), almost all the neutrinos originally emitted as $\bar{\nu}_e$s are measured as $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$s at the detector. For the PNS this makes relatively little difference as originally emitted $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$s are also converted to $\bar{\nu}_e$.

density resonance, then we label this case as LA. If instead the neutrinos pass nonadiabatically through the lower density resonance, we label that situation as LNA. For a more complete discussion of neutrino oscillations and how to calculate hopping probabilities, see e.g. [20,22].

For estimating whether one might generically expect sufficient count rates, we show Table I. We include models which differ over 2 orders of magnitude and we show several different detectors. All numbers must be scaled by $(M/M_\odot)$ where M is the amount of material cycled through the accretion disk. The number of counts depends on the time the disk is in existence. For example, for a $0.01 M_\odot$/s disk which processes $1 M_\odot$, the neutrino emission will be spread over 100 s. If one uses the time scale of a gamma ray burst as a guide to the time scale of existence of the central engine (and therefore the accretion disk), then 100 s is a reasonable upper limit. For comparison we show the expected count rates for the canonical PNS. The table shows that counts will be expected in the currently existing detectors for a wide range of models. Figure 4 shows the electron recoil energies for a number of AD-BH models in SuperK.

Since the ν_e, $\bar{\nu}_e$ will become mixed with ν_μ and ν_τ because of flavor transformation, the neutrinos which arrive at the detector will no longer be purely ν_e, $\bar{\nu}_e$. We therefore check that the flavor ratios will not masquerade as those which are expected from the PNS in Table II. In no case are all channels the same as the PNS. However, it is essential to have a good neutral current signal measurement, as this is how the total flux will be measured and it is also vastly preferable to have a way to measure both the ν_e and $\bar{\nu}_e$ flux if one wishes to distinguish between a PNS and an AD-BH.

We have discussed the observational consequences of the next galactic core collapse event forming at its center an accretion disk surrounding a black hole instead of, or after, a protoneutron star. This type of accretion disk will produce significant event rates in currently on-line neutrino detectors, with a time profile and total energetics that will likely differ from that of the canonical PNS. If the flavor content of the signal can be observed, it may be possible to determine the origin of core-collapse supernova neutrinos by inferring the ratio of the charged current flux to the total energy flux.

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TABLE II. Ratios of energy fluxes for various accretion disk models and oscillation scenarios as compared with the PNS. The PNS is calculated for the case of equipartition of energy between neutrino species, and for the luminosity ratios of Fig. 3. The quantity ν_x refers to the sum of the ν_μ, ν_τ and $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ luminosities.

	Normal hierarchy H			Normal hierarchy LA			Normal hierarchy LNA			Inverted hierarchy H, LA			Inverted hierarchy H, LNA		
	$\frac{\nu_e}{\text{total}}$	$\frac{\bar{\nu}_e}{\text{total}}$	$\frac{\nu_\mu+\nu_\tau+\bar{\nu}_\mu+\bar{\nu}_\tau}{\text{total}}$	$\frac{\nu_e}{\text{total}}$	$\frac{\bar{\nu}_e}{\text{total}}$	$\frac{\nu_x}{\text{total}}$	$\frac{\nu_e}{\text{total}}$	$\frac{\bar{\nu}_e}{\text{total}}$	$\frac{\nu_x}{\text{total}}$	$\frac{\nu_e}{\text{total}}$	$\frac{\bar{\nu}_e}{\text{total}}$	$\frac{\nu_x}{\text{total}}$	$\frac{\nu_e}{\text{total}}$	$\frac{\bar{\nu}_e}{\text{total}}$	$\frac{\nu_x}{\text{total}}$
PNS, equipart	0.19	0.15	0.66	0.16	0.15	0.67	0.13	0.15	0.71	0.16	0.19	0.63	0.13	0.19	0.67
PNS, from [23]	0.17	0.17	0.66	0.17	0.17	0.66	0.17	0.17	0.66	0.17	0.17	0.66	0.17	0.17	0.66
$\dot{m} = 1.0$ from [18]	∼0	0.13	0.85	0.25	0.13	0.62	0.56	0.13	0.31	0.25	∼0	0.76	0.56	∼0	0.43
$\dot{m} = 0.1$ from [18]	0.01	0.33	0.66	0.15	0.33	0.5	0.33	0.33	0.33	0.15	0.01	0.83	0.33	0.01	0.66
$\dot{m} = 0.01$ from [18]	0.02	0.37	0.59	0.13	0.37	0.05	0.26	0.37	0.36	0.13	0.02	0.83	0.26	0.02	0.71

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