Constraints on the Star Formation Rate from Supernova Relic Neutrino Observations

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ABSTRACT

We discuss the implication of the observation of supernova relic neutrinos on the study of the star formation rate (SFR) in galaxies. The limit recently obtained at Super-Kamiokande (SK) is already marginally significant: The SFR we derived \(\psi(t_0) < 0.040M_\odot\text{yr}^{-1}\text{Mpc}^{-3}\) (at a 90\% CL) is about twice the SFR estimated from radio observations, and five times the rate from \(H_0\) allowing for uncertainties in the model supernova neutrino flux.

Key words: stars: formation – cosmology:observation – neutrino – supernovae:general.

1 INTRODUCTION

Neutrinos emitted from stellar core collapse fill the universe as a diffuse background radiation. The feasibility for the detection of these neutrinos has been considered by many authors (Bisnovatyi-Kogan & Seidov 1982, Krauss, Glashow & Schramm 1984, Totani, Sato & Yoshii 1996, Malaney 1997, Hartmann & Woosley 1997, Kaplinghat, Steigman & Walker 2000, Ando, Sato & Totani 2002). While estimates of the expected neutrino flux depend much upon authors, the authors are generally negative regarding the feasibility of their detection. The problem is large backgrounds from solar and reactor (anti)neutrinos at low energies and atmospheric neutrinos at high energies; a possible window in between (say, the neutrino energy \(E_\nu = 15\text{-}50\text{ MeV}\)) is masked by a large background from electrons produced by decay of low energy muons that escape detection in the water Čerenkov detector (Zhang et al 1998). The decayed electron spectrum from muons, however, is precisely known, and the Super-Kamiokande (SK) group has demonstrated that this background can be subtracted (Totsuka 2001). The limit derived on the neutrino event rate in the 18-50 MeV range is close to the value indicated by some optimistic estimates of the supernova relic neutrino flux, which encourages us to scrutinize the problem.

A major uncertainty in the calculation of the supernova relic neutrino flux is in the star formation rate (SFR) and its evolution towards the past. The work with high redshift galaxies over the last five years, however, has provided us with significant insight on the evolution of the global SFR. The estimates include the use of UV emissivity (Madau et al 1996, Lilly et al 1999, Connolly et al 1997, Steidel et al 1999, Trever et al 1998, Sullivan et al 2000, Wilson et al 2002), \(H_0\) fluorescent emission (Gallego et al 1995, Tresse et al 2002), Glazebrook et al 1999, Sullivan et al 2000, radio emission (Sericani, Gruppioni & Oliver 2002, Haarsma et al 2000) and far-infrared emission (Flores et al 1999). Most of the estimates of the SFR are convergent to \(\approx 0.2\) dex among different authors, if the same observational techniques are used. The large uncertainty, however, resides in which techniques are to be used; Current estimates show an uncertainty of a factor of \(\approx 6\) (0.8 dex). In particular, the SFR estimated from UV depends largely on extinction corrections. Madau et al (1998) took \(E_{B-V} = 0.1\), Steidel et al (1999) indicated 0.15 and Sullivan et al (2000) derived 0.13. This corresponds to an uncertainty of 0.36 dex in the SFR. The prime purpose of this paper is to consider whether we can obtain any meaningful constraints on the SFR from the current observation of the supernova relic neutrinos.

Another focus of this paper is to derive a lower limit on the relic neutrino event rate expected in the SK detector under reasonable assumptions on the input to the calculation. The calculation of the event rate suffers from uncertainties besides the SFR. Among the most important uncertainties are those in the spectrum of neutrinos. In this paper we try to reduce the uncertainty in the neutrino spectrum using observation of neutrinos from SN1987A as a constraint. We may assume that it is typical of type II supernovae, since we expect that the physics of core collapse is similar even if the optical appearance may have a wide variety. The other uncertainty concerns neutrino oscillation, in which \(\nu_e\) and \(\nu_\mu\) partly interchange during propagation through vacuum and Earth. Recent neutrino oscillation experiment showed unambiguously the presence of neutrino oscillation.
and determined the oscillation parameters [Fukuda et al. 1998, Ahmad et al. 2001, Fukuda et al. 2001]. We can now calculate accurately the effect of oscillation both in vacuo and in Earth. This is no longer a source of uncertainties.

Throughout this paper we adopt the natural units, $c = h = 1$, and the Boltzmann constant $k_B = 1$.

2 THE LOCAL SUPERNOVA RATE AND THE LOCAL STAR FORMATION RATE

A number of extragalactic supernova surveys (van den Bergh & McClure 1994, Cappellaro et al. 1995, Tammann et al. 1994) yield the local supernova rate in units of SNe, i.e., the number of supernovae per $10^{50} L_B(0)$ per 100 year for each morphological type of galaxies. We translate it into the rate per unit cube of spatial volume, by averaging over morphological fractions of nearby galaxies E/S0 : Sa-Sb : Sbc-Sd = 0.32 : 0.28 : (Fukugita, Hogan & Peebles 1998, hereafter FHP), and by multiplying the $B$ band local luminosity density of the universe $L_B = 2.4 \pm 0.4 \times 10^{8} h L_\odot$ Mpc$^{-3}$ [Blanton et al. 2001, Yasuda et al. 2001], where $h$ is the Hubble constant in units of 100 km s$^{-1}$Mpc$^{-1}$. Counting both type Ia and Ic in addition to type II as core-collapse supernovae, we obtain the supernova rate $\dot{R}_{SN}$ as $1.98 \times 10^{-4}$, $2.11 \times 10^{-4}$ and $4.44 \times 10^{-4} h^2$yr$^{-1}$Mpc$^{-3}$ for the three surveys. We take the geometric mean of the three values and refer to the largest and smallest of the three as the allowed range: $2.65^{+1.76}_{-0.67} \times 10^{-4} h^2$yr$^{-1}$Mpc$^{-3}$. This is compared with a similar estimate $4.7 \times 10^{-4} h^2$yr$^{-1}$Mpc$^{-3}$ by [Madura et al. 1998].

For a given star formation rate $\psi(t)$ (in units of $M_\odot$ yr$^{-1}$Mpc$^{-3}$) $\dot{R}_{SN}$ is calculated as

$$\dot{R}_{SN} = \psi(t) \int_0^m \frac{m \phi(m)}{m} \frac{dm}{d\psi(m)},$$

(1)

where $\phi(m)$ is the initial mass function (IMF) of stars, for which we take the Salpeter form $\phi(m) \sim m^{-1.35}$ for $m > 1 M_\odot$ and continue to the IMF of [Gould, Bahcall & Flynn 1996] for a low mass (see FHP) so that the integral in the denominator is extended to zero mass. We set $m_u = 100 M_\odot$. Since the Salpeter IMF has been adopted in virtually all literature that derived SFRs, our calculation of SFR can be directly compared to those, only with a downward correction of a factor of 1.65 that arises from the difference between the genuine Salpeter IMF with a lower cut off of 0.1$M_\odot$ and our prescription. We take the critical mass for type II supernovae $m_c$ to be between 8 and 10 $M_\odot$ according to [Nomoto 1984].

The local star formation rate derived from is $\dot{\psi}(t) = \log \psi(t)(M_\odot)$yr$^{-1}$Mpc$^{-3}$) = $-2.09^{+0.22}_{-0.13}$, where we take $h = 0.72$. This may be compared with the SFR from an H$a$ survey $-2.11 \pm 0.04$ [Tresse et al. 2002, Glazebrook et al. 1994; we take their independent data points].

3 STAR FORMATION RATE AND THE RELIC NEUTRINO EVENT RATE IN THE DETECTOR

Figure 1. Star formation rate (SFR) inferred from H$a(\beta)$ (filled squares), UV emissivity (open and filled triangles), far-infrared (filled circles) and radio (crosses) observations as a function of lookback time. The SFR estimated from the local supernova rate is shown by open circle at 0 Gyr. The two dashed lines denote the 90% SK limits for the case of the minimum event rate (the conservative limit; hatching attached) and for the case of maximum event rate within uncertainties of the model supernova neutrino flux. The dotted line is fit [2]. All data use the modified Salpeter IMF described in the text.

In Figure 1 we present estimates for the SFR as a function of the lookback time ($= t_0 - t$ with $t_0$ the present time, in units of Gyr). The data are taken from [Glazebrook et al. 1994, Sullivan et al. 2000, Tresse et al. 2002, Steidel et al. 1999 and Haarsma et al. 2000], which cover most of the SFR work to date We include in the Figure the UV estimates of [Wilson et al. 2002] (filled triangles with thin drawings). These data, however, largely disagree with other estimates and the reasons are unknown: so we do not refer them further in this paper. We take the cosmology of $\Omega_0 = 0.3$ and $\lambda = 0.7$ with $h = 0.72$ to draw this figure. The solid points are the SFR from H$a$ (and H$\beta$) with the extinction estimated using the Balmer decrement, and the open points refer to the values from UV emissivity assuming zero extinction corrections. Radio observations are denoted by crosses. The grey points are obtained from far-infrared (ISO) observations. The SFR estimate from the supernova rate is shown at the zero lookback time. We also show the constraint from the supernova relic neutrino observations obtained from the present calculation given below.

The figure shows that the SFR obtained from a single indicator exhibits nearly an exponential dependence as a function of the lookback time, at least for $z \leq 1$, as expected in the closed box model and also in CDM model calculations (e.g. [Nagamine et al. 2001]). For example the SFR for $1 < t_0 < 7$ Gyr obtained from H$a$ is fitted well with

$$\log \psi(t)_{H_a} = (-1.96 \pm 0.04) + \log h + 0.216 h(t_0 - t).$$

(2)
We allot a 20% error to this estimate. The mean energy observed neutron stars takes a universal value of 1.4 MeV, which is of our current concern, and we do not need to specify any accurate functional form, as we will see below. We take $\psi(t_0)$ as a parameter. Alternatively, we may use $E_{B-V}$ as a parameter taking $\log \psi_{UV}(t_0) = -2.45$ from UV emissivity with zero extinction as a fiducial value.

Neutrino spectrum from type II supernovae

We must deal with the uncertainty of the neutrino flux emergent from type II supernovae. The dominant neutrino emission arises from pair creation in the optically thick object. Hence the luminosity of each species of neutrinos is approximately equal, as demonstrated by many neutrino transport calculations given in Table 1. The total neutrino luminosity is close to $3 \times 10^{53}$ erg, since the mass of all observed neutron stars takes a universal value of $1.4 M_\odot$. We allot a 20% error to this estimate. The mean energy of neutrinos depends on details of calculations, e.g. ranging from 12 to 20 MeV for $\bar{\nu}_e$. The mean energy neutrinos satisfy $\langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_e} \rangle < \langle E_{\nu_{\tau}} \rangle$, where $\nu_{\tau}$ includes $\nu_\mu$, $\nu_\tau$ and their antiparticles. Neutrino transport calculations give $E_{\bar{\nu}_e}/E_{\nu_e} = 1.6$; see Table 1. We take this ratio to be 4/3, but the result of our calculation is not sensitive to this ratio once we introduce the observational constraint.

The model neutrino spectrum from supernovae is somewhat deviated from the zero-chemical potential Fermi distribution. It is usually parametrised by introducing an effective chemical potential $\eta$, i.e., $f = \exp(E_{\nu_i}/T_{\nu_i} - \eta) + 1\rbrack^{-1}$ with $\eta = 1 - 3$ [Janka & Hillebrandt 1984].

For water Čerenkov neutrino detectors the only reaction we must consider is $\nu, p \rightarrow e^+ n$. The cross section of $\nu_e^{16}O$ is $> 20$ times smaller. There is, however, an important contribution from $\bar{\nu}_e \rightarrow e^-$ due to neutrino oscillation. Recent solar neutrino experiments at Sudbury and SK show that the mixing between $\nu_\mu$ and $\nu_\tau$ is nearly maximal. With the matter effect the neutrinos emerging from a supernova are $\nu_2 = -\sin \theta_{\nu_2} \nu_\mu + \cos \theta_{\nu_2} \nu_\tau$ and $\nu_1 = \cos \theta_{\nu_2} \nu_\mu + \sin \theta_{\nu_2} \nu_\tau$, which are the mass eigenstates. The $\bar{\nu}_e$ detected in detectors are therefore $\cos^2 \theta$ times the $\bar{\nu}_e$ flux and $\sin^2 \theta$ times the $\bar{\nu}_\mu$ flux where $\sin^2 2\theta > 0.96$ [Ahmad et al. 2001, Fukuda et al. 2001]. This in principle increases the neutrino detection rate due to higher energies of the $\bar{\nu}_e$ flux.

The matter effect of Earth somewhat modifies the mixing ratio for the neutrino flux that passes through Earth. This effect is calculated assuming Earth as a sphere of a constant matter density, $\rho_0$ (Earth) $\approx 3.2$ g/cm$^3$.

### Constraints from SN1987A

At the epoch of SN1987A Kamiokande [Hirata et al. 1987] and Irvine-Michigan-Brookhaven Collaboration (IMB) [Bionta et al. 1987] detected neutrinos from core collapse. The gross characteristics of these neutrino events agree with what are expected. Here we use the detection of neutrino events at IMB, which has a larger fiducial volume and is more sensitive to rare, higher-energy neutrino events, to constrain the higher energy spectrum of supernova neutrinos. We estimate the event number $N_{\text{IMB}}$ at IMB (5 kton water) as

$$N_{\text{IMB}} = 3.3 \times 10^{32} \int_{30 \text{MeV}}^{60 \text{MeV}} dE_{\nu_i} \sigma_i(E_{\nu_i}) F_{\nu_i}(E_{\nu_i}) x(E_{\nu_i}),$$

where $\sigma_i(E_{\nu_i})$ is the cross section for $\nu, p \rightarrow e^+ n$ with the neutrino energy $E_{\nu_i}$, $x(E_{\nu_i})$ is the trigger efficiency, and $F_{\nu_i}$ is the $\nu_i$ flux at the IMB detector.

$$F_{\nu_i}(E_{\nu_i}) = P_{\text{IMB}}(E_{\nu_i}) F_{\nu_i} + (1 - P_{\text{IMB}}(E_{\nu_i})) F_{\bar{\nu}_i},$$

where $P_{\text{IMB}}(E_{\nu_i})$ is the conversion probability for $\bar{\nu}_i \rightarrow \nu_i$ due to neutrino oscillation including matter effects of Earth and $\mathcal{F}_i$ is the neutrino flux for species $i$ without oscillation, for which we obtain

$$\mathcal{F}_i = 3.99 \times 10^{49} \text{cm}^{-2} \text{MeV}^{-1} \frac{E_{\nu_i}}{\text{MeV}} \times \left( \frac{T_{\nu_i}}{\text{MeV}} \right) \left( \frac{E_{\text{tot},i}}{10^{53} \text{erg}} \right) C(\eta)f(\eta,E_{\nu_i}).$$

where $E_{\text{tot},i}$ is the total neutrino energy, $T_{\nu_i}$ is temperature of neutrino for $i$th species and $C(\eta) = \int dE_{\nu_i} E_{\nu_i}^2 f(\eta,E_{\nu_i})/\int dE_{\nu_i} E_{\nu_i}^2 f(0,E_{\nu_i})$. The calculation of $P_{\text{IMB}}$ is standard and is carried out in a way similar to that in [Lunardini & Smirnov 2001], taking neutrino trajectory inside Earth for SN1987A. Applying Poisson statistics to 8 events observed at IMB, we obtain 90% confidence limits on $\langle E_{\nu_e} \rangle$ and $T_{\nu_e}$ as shown in Table 2. This constraint removes much of the uncertainty of the model neutrino flux; hence the result of our calculation in what follows depends only weakly on the assumptions on parameters we assumed for the model neutrino flux emergent from supernovae.

### Supernova relic neutrino flux

The neutrino flux $\mathcal{J}_{\nu_i}$ is calculated as

$$\mathcal{J}_{\nu_i}(E_{\nu_i}) = \int_0^{t_f} dz \frac{dE_{\nu_i}}{dz}(1+z) \mathcal{L}_{\nu_i}((1+z)E_{\nu_i}) R_{\text{SN}}(z),$$

where $t_f$ is the time of supernova explosion and $R_{\text{SN}}(z)$ is the rate of supernovae.

| $\eta$ | $\langle E_{\nu_e} \rangle$ (MeV) | $T_{\nu_e}$ (MeV) |
|-------|-----------------|-----------------|
| 0     | 10.5 – 14.9     | 3.33 – 4.72     |
| 1     | 11.0 – 15.3     | 3.31 – 4.60     |
| 2     | 11.4 – 15.8     | 3.16 – 4.39     |
| 3     | 12.0 – 16.4     | 3.01 – 4.11     |
where the neutrino luminosity $L_\nu$ is given by

$$L_\nu = E_{\nu} \frac{120}{7\pi^4} \frac{E_{\nu}^2}{T_{\nu}} C(\eta,E_\nu).$$

(8)

$z_f$ is the formation epoch of galaxies, but the integral is dominated by a low redshift region. The supernova rate is related with the SFR as,

$$R_{SK}(z) = 1.22 \times 10^{-2} \psi(z)/M_\odot (9)$$

for $m_\nu = 8M_\odot$. We remark that the flux $\psi$ is independent of the cosmology, since its dependence in $dt/dz$ is compensated by the volume factor of $\psi(z)$. We use for $\psi$ the exponential law for $z < 1$ and assume a constant for $z > 1$. We take $\psi(t_0)$ as a free parameter. This parameter is also translated to $E_{B-V}$, taking the SFR from UV emissivity with zero extinction as a fiducial. The extinction is written $\Delta \log \psi = 2.42E_{B-V}$ for $z < 1$ using the standard extinction law $\text{Seaton} 1979$ $\text{Cardelli et al} 1989$.

The calculation of supernova relic neutrino flux $J_{\nu}$ (after neutrino oscillation effect) is carried out in a similar way, with the modification that the Earth effect is integrated over all directions. The event rate with a fiducial volume of the 22.5 kton SK detector is calculated as

$$R_{SK} = 4.2 \times 10^{-3}\text{yr}^{-1}$$

$$\times \int_{E_{\nu_{\min}}}^{E_{\nu_{\max}}} \left(\frac{E_{\nu}}{\text{MeV}}\right)^2 \left(\frac{J_{\nu}(E_{\nu})}{\text{MeV}^{-1}\text{cm}^{-2}\text{sec}^{-1}}\right),$$

(10)

where $E_{\nu_{\min/\max}}$ is the minimum (maximum) energy of the neutrino detection, which we take $E_{\nu_{\min}} = 18$ MeV and $E_{\nu_{\max}} = 50$ MeV. Fig. 2 shows an example result for the neutrino event rate for SK as a function of $E_{B-V}$ for a typical parameter set indicated in the figure. It is seen that the event rate exceeds the current SK limit, 2.0 yr$^{-1}$ at 90% confidence for the $18 - 50$ MeV window $\text{Totsuka} 2001$, if $E_{B-V} > 0.4$. From this figure we can read the range of $E_{B-V}$ which is consistent with the SFR from H$\alpha$ at the zero redshift. The SFRs from H$\alpha$ and the local supernova rate are consistent.

Fig. 3 shows the relative importance of supernovae at different redshifts for neutrino events. The solid histogram corresponds to neutrino events with energy between 18 MeV and 50 MeV. It shows that half the events arise from low- $z$ supernovae ($z < 0.25$). If we decrease the energy of the detector window to $12 < E < 18$ MeV, non-zero redshift supernovae become more important. This means that we can learn the evolution of the SFR from gross spectroscopy of supernova relic neutrinos. This histogram also shows that the contribution from supernovae at $z > 1$ is insignificant in so far as our consideration is restricted to $E > 12$ MeV. The neutrino spectrum is presented in Figure 4.

**Constraint on the star formation rate**

We derive a constraint on the SFR by requiring that the supernova relic neutrino event should not exceed the SK limit allowing for uncertainty of the model neutrino flux shown in Fig. 2 the result is shown in Figure 4 above. The most conservative limit is obtained by taking $m_\nu = 10M_\odot$ and minimising the number of events at IMB for SN1987A. At a 90% confidence the limit means

$$\log \psi(t_0) \leq -1.40, \quad \text{or} \quad E_{B-V} \leq 0.48.$$  

(11)
The constraint derived here is about 5 times higher than the SFR obtained from Hα and far-infrared, and twice higher than the SFR from radio observations.

If we would take the opposite case, i.e., the maximum allowed flux (90% confidence for the IMB events) and $m_e = 8M_\odot$, the limit becomes stronger by a factor of 4; it nearly coincides with the SFR from Hα, and already overshoots the SFR from radio.

We emphasize that large uncertainties in the model supernova neutrino flux calculations are significantly reduced by empirical constraints derived from SN1987A. For instance an increase of $\eta$ is compensated by an increase of effective neutrino energy or else by an increase of neutrino luminosity, so that the neutrino flux in the energy range that concerns us changes little. Neutrino oscillation generically enhances the high energy tail of the neutrino spectrum. Under the empirical constraint, however, this is absorbed into the change of other parameters. As a result the prediction of supernova relic neutrinos at SK is modified little.

The lower limit of neutrino reaction rates at SK

Assuming $\log \psi = -2.15$, which is the lower value of SFR from Hα allowed within the error range (or SFR from UV with $E_{B-V} \geq 0.19$) and taking our minimum neutrino flux estimate and $m_e = 10M_\odot$, we obtain

$$R_{SK} \geq 0.40 \text{ yr}^{-1}.$$  \hfill (12)

A similar limit is derived if we take the lowest value of the supernova rate:

$$R_{SK} \geq 0.44 \text{ yr}^{-1}.$$  \hfill (13)

The SK should see the supernova relic neutrino events if they increase the sensitivity by a factor of 5.

4 CONCLUSIONS

The limit on the SFR derived from the supernova relic neutrino observation at SK is already marginally significant even if we include the uncertainty of the model supernova neutrino flux. With the current data we can conclude that $\psi(t_0) < 0.040M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$, which is 5 times the estimate from Hα ($0.0078 \pm 0.0008 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$) and twice that from radio observations. The SFR from local supernova surveys ($0.0081^{+0.0054}_{-0.0021} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$) is consistent with the estimate from Hα. For the SFR from UV emissivity, our result means $\langle E_{B-V} \rangle < 0.48$ with the standard extinction law. The increase of SK statistics by a factor of 5 should positively detect the supernova relic neutrino events.

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