Title
Part IV. Neutrino astrophysics

Journal
Physics Reports, 227(1-5)

ISSN
0370-1573

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Publication Date
1993-05-01

DOI
10.1016/0370-1573(93)90063-j

Peer reviewed

PHYSICS REPORTS (Review Section of Physics Letters) 227, Nos. 1–5 (1993) 149–155.
North-Holland

PHYSICS REPORTS

PART IV. NEUTRINO ASTROPHYSICS

Supernova dynamics and nucleosynthesis as a probe of closure mass neutrinos

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Abstract:

We discuss how the neutrino material-heating rate and electron fraction in the region above the neutrino-sphere in a nascent type II supernova become very sensitive to neutrino flavor mixings. Matter-enhancement effects would ensure that a ν_μ or ν_τ (hereafter, ν_τ) neutrino with a vacuum mass of roughly 10 to 100 eV would have a mass-level-crossing with a light ν_e in this region. Coincidently, this is the neutrino mass range which is sometimes conjectured to provide the closure density for the universe. Since the supernova ν_τ neutrinos have considerably higher average energies than do the ν_e, transformations between these species at the level crossings result in more energetic electron neutrinos. This would imply an enhanced ν_e capture rate which, in turn, would result in a higher heating rate and would tend to increase the electron fraction, reducing the neutron excess. For a vacuum mixing angle between ν_τ and ν_e of $\theta > 10^{-4}$ the increase in early heating results in roughly a factor of two increase in supernova explosion energy, which may help solve the explosion-mechanism problem. However, late neutrino flavor conversion will drive the ejected material proton-rich and a promising site for r-process nucleosynthesis may be lost unless it is also true that $\theta < 10^{-3}$.

1. Introduction

In this paper we examine the effects on supernova models of transformations between closure mass ν_τ or ν_μ neutrinos and electron neutrinos in the region between the neutrino-sphere and the shock in a nascent type II supernova. Hereafter when we refer to ν_τ it should be understood that we mean either ν_τ or ν_μ unless explicitly stated otherwise. We will explore the sensitivity of supernova dynamics and nucleosynthesis to neutrino flavor mixing with the intent of assessing whether this process may play a role in the explosion mechanism and to place broad constraints on closure mass neutrinos. Willy Fowler has shown repeatedly how accurate knowledge of nuclear reaction rates gives vital insight into astrophysical phenomena. In that spirit we explore how fundamental uncertainties in weak interaction physics (neutrino masses and the extent of weak flavor mixing) impacts several outstanding problems in modern astrophysics: the supernova explosion mechanism problem, heavy element nucleosynthesis, and the dark matter problem.

Neutrinos dominate the current picture of supernova dynamics. In this picture the progenitors of type II supernovae are massive stars which evolve to the point of Fe-core collapse. In the collapse of the core to become a neutron star 95% or more of the gravitational binding energy released ($\approx 10^{53}$ erg s) is transformed into ν_e, ν_μ, ν_τ and associated anti-neutrino seas. Neutrinos are trapped in the low-entropy infall phase of collapse (duration < 1 s) but diffuse out of the core after bounce on a timescale of a few seconds [cf. Colgate and White 1966, Mazurek 1975, Sato 1975; cf. Arnett 1977 and Bethe et al. 1979 for an overview of the supernova core collapse problem].

Hydrodynamic bounce of the core generates a shock which begins to move out but suffers energy loss as nuclei are photodisintegrated in the higher entropy post-shock environment. In some numerical calculations the shock remains viable and explodes the star with an energy of $\approx 10^{51}$ erg, while in recent studies with neutrino losses (especially for massive stars $M \geq 15\, M_\odot$)

the shock stalls and evolves into an accretion shock [Cooperstein and Baron 1990, see also Wilson 1982, Baron, Cooperstein, and Kahana 1985, Burrows and Lattimer 1987]. In the latter case it has been hoped that neutrinos emitted from a "neutrino-sphere" near the edge of the proto-neutron star can re-energize the shock [Wilson 1982, Lattimer and Burrows 1984, Bethe and Wilson 1985, hereafter BW85; Colgate 1991]. The energy of the resulting supernova explosion in these "late-time", or delayed-mechanism models may be low, however, being less than $\sim 10^{51}$ erg [BW85, Mayle 1990; but note also that some recent calculations give energies near 10^{51} erg].

It has been shown [Fuller et al. 1992] that a ν_μ or ν_τ neutrino with a cosmologically significant mass (10–100 eV) and a small mixing (vacuum mixing angle $\theta > 10^{-4}$) with a light ν_e would result in a matter-enhanced MSW resonant transformation between these species in a region above the neutrino-sphere but below the stalled shock during the re-heating phase of a type II supernova. The neutrino heating behind the shock is due to charged current ν_e and $\bar{\nu}_e$ captures. Since the ν_μ and ν_τ have considerably higher average energies than do the ν_e, neutrino flavor mixing would result in higher effective ν_e energies behind the shock and a concomitant increase in the heating rate.

These numerical calculations suggest that this effect results in a 60% increase in the supernova explosion energy, possibly helping to solve the energy problem of delayed-mechanism supernova models. The increased heating associated with ν_e captures is accompanied by an increase in the electron fraction of the heated material. Since the nucleosynthesis yields from the re-heating region are particularly sensitive to the electron fraction (through the neutron-to-proton ratio), we can look for nucleosynthetic limits on the allowable degree of neutrino conversion. In section 2 we will discuss neutrino conversion above the neutrino-sphere and material heating at the shock-reheating epoch of 0.1 to 0.6 s after core bounce. In section 3 we will concentrate on the effects of neutrino transformation on nucleosynthesis at 4 to 6 s after core bounce.

2. Neutrino transformation, material heating, and shock revival

Matter enhanced neutrino oscillations have been extensively considered (cf. Wolfenstein 1978, 1979, Mikheyev and Smirnov 1985, Bethe 1986, Haxton 1986, Parke and Walker 1986]. Resonant neutrino oscillations in supernova cores were treated by Fuller et al. [1987] (hereafter FMWS87; see also Fukugita et al. [1988]). FMWS87 suggested that neutrino oscillations above the neutrino sphere but below the stalled shock could be important for the shock energetics. We might expect a matter enhanced level crossing between ν_e and ν_τ if the vacuum masses obey the condition $m_{\nu_\tau} > m_{\nu_e}$. In this case there are no transformations among the anti-neutrinos.

As a neutrino propagates through the stellar material its forward scattering on the ambient lepton seas via e^- or ν_e exchange generates an effective potential. This potential is equivalent to an effective mass for the neutrino. Since ν_e have an interaction (charged current exchange on electrons) which ν_τ lack they acquire larger effective masses. Fuller et al. [1992] showed that the contribution to this effective potential from forward scattering on the nearly radially free-streaming neutrinos in the region above the neutrino-sphere is negligible at large enough radius. Roughly speaking, when the effective-plus-vacuum mass of the electron neutrino matches the effective-plus-vacuum mass of the ν_τ there is a mass level crossing, or resonance, between them. The density at which the level crossing occurs is

$$\rho_{\rm res} \approx (2.108 \times 10^{10}\ {\rm g\,cm^{-3}}) \left(\frac{0.5}{Y_e}\right) \left(\frac{\Delta}{1600\ {\rm eV}^2}\right) \left(\frac{\rm MeV}{E_\nu}\right), \tag{1}$$

where E_ν is the energy of the neutrino and Y_e is the number of electrons per baryon. The probability that a ν_τ transforms to a ν_e, and vice versa, depends on a comparison of the oscillation length at resonance to the density scale height there.

The oscillation length at resonance is

$$L_{\rm res} = \frac{4\pi E_\nu}{\Delta \sin 2\theta} \approx \frac{0.1575\ {\rm cm}(E_\nu/{\rm MeV})}{(\Delta/1600\ {\rm eV}^2)\sin 2\theta}\,, \tag{2}$$

while the resonance "width" [Bethe 1986] is

$$\delta r = (\rho^{-1}\,{\rm d}\rho/{\rm d}r)^{-1}\tan 2\theta\,. \tag{3}$$

In these expressions $\Delta \equiv m_1^2 - m_2^2$ is the difference of the squares of the *vacuum* mass eigenvalues, while θ is the *vacuum* mixing angle of the ν_τ and ν_e. The criterion for complete transformation between neutrino flavors in the region of the resonance, the adiabatic condition, is that $L_{\rm res} \ll \delta r$.

The crucial time for the early re-heating of the shock is about 0.1 to 0.6 s after the bounce, when the neutrino-sphere has a radius of about 45 km and the shock is out beyond 500 km. From eq. (1) it can be seen that a level crossing of ν_e with ν_τ occurring above the neutrino-sphere but below the shock would require a vacuum mass difference corresponding to $\Delta \approx 10^2$–$10^4\ {\rm eV}^2$, which, if m_{ν_e} is negligible, corresponds to mass $m_{\nu_\tau} \approx 10$–100 eV. If we define Ω_ν to be the fraction of the closure density of the universe contributed by neutrinos then the m_{ν_τ} must be

$$m_{\nu_\tau} \approx (96\ {\rm eV})\left(\frac{H_0}{100\ {\rm km\,s^{-1}\,Mpc^{-1}}}\right)^2\left(\frac{2.7\ {\rm K}}{T_\gamma}\right)^3\Omega_\nu\,, \tag{4}$$

where H_0 is the Hubble constant and T_γ is the present cosmic microwave background temperature. Reasonable ranges of H_0 and Ω_ν then yield a cosmologically interesting mass range for m_{ν_τ} which is subsumed by the level crossing range implied by the dimensions of the re-heating region. A light neutrino as a dark matter candidate particle is still an actively debated issue [cf. Cowsik and McClelland 1972, Gunn et al. 1978, Tremaine and Gunn 1979, Bond, Estathiou and Silk 1980, Blumenthal et al. 1984].

Significant transformation of the ν_τ to ν_e in the re-heating region would require $\theta > 10^{-4}$. We note that this is an extremely small lower limit for the vacuum mixing angle required for neutrino transformation. In other words there will be significant neutrino flavor conversion if the vacuum mixing of ν_τ and ν_e flavor states is larger than one part in a hundred million! If this occurs it would result in considerably higher energy ν_e in the region between the neutrino-sphere and the shock, since the energy of the ν_τ at the neutrino-sphere exceeds the energy of the ν_e. Neutrino heating of the material behind the shock is principally due to charged current ν_e capture on neutrons and $\bar{\nu}_e$ capture on protons, so that higher energy ν_e should imply more heating and a reduced neutron fraction. The results of Fuller et al. [1992] showed that this process gives about a factor of two increase in the local heating rate and a 60% overall increase in the supernova energy. Bethe [1992] estimates that other heating processes such as ν_e capture on alpha particles give another 12% increase in heating over that found in the calculation of Fuller et al. [1992] which neglected such effects.

We note that Mayle and Wilson's [1991] hydrodynamics-neutrino-transport code has undergone some improvements in energy transport since Fuller et al.'s [1992] calculations were performed. In particular we have reason to believe that the neutrino transformation processes now

may yield somewhat more than a 60% energy increase. The physics of convective overturn under the neutrino-sphere is quite controversial and difficult to handle, but seems to be required to get a delayed-mechanism explosion. It would be particularly significant if the neutrino transformation process could obviate the need for this overturn. In the calculations of Fuller et al. [1992] convective overturn under the neutrino-sphere was still required to obtain an explosion. However, Mayle and Wilson have made many improvements in their code since these calculations were done. They find improved neutrino heating efficiency in recent calculations and this, combined with the detailed results of our neutrino-transformation runs with the old code, lead us to believe that when neutrino conversion is included in the new code we will see an explosion without convection under the neutrino-sphere. A definitive answer, however, awaits the results of the numerical calculations.

Previous studies have attempted to constrain neutrino transformations by comparison of predicted neutrino energy spectra from supernova models with the 19 neutrino-induced events in the IMB and Kamiokande detectors for SN1987a [cf. Arafune et al. 1987, Lagage et al. 1987, Kuo and Pantaleone 1988, Nötzold 1987]. All of these studies assume, however, that the first two events in Kamiokande are ν_e–e scattering events and that the ν_e involved come from a distinct "neutronization pulse". These are both questionable assumptions (cf. Rosen [1988] for a discussion of the probability that the first two Kamiokande events are due to scattering; see also Burrows [1989] and Mayle [1990] for a general discussion of neutrinos from SN1987a), so that any conclusions drawn are at best model dependent and therefore cannot exclude the parameter space of interest for neutrino-oscillation-enhanced re-heating. Kielczewska [1990] has pointed out another possible, more promising, constraint on oscillation parameters from observations of supernova neutrinos. This constraint is based on the backward peaked nature of the ν_e-charged-current capture on ^{16}O [Haxton 1987, 1988] in water detectors like Kamiokande or IMB. Though the effective threshold for this capture process is high ($E_{\nu_e} > 30$ MeV to access substantial weak strength), the cross section rises very rapidly with energy due to the opening of extra forbidden-strength capture-channels at high daughter-nucleus excitation energy (Haxton [1987, 1988], see also the discussion of angular distributions in neutrino capture in Fuller and Meyer [1991]). Recently Qian and Fuller [1992] have examined the expected supernova burst signals in water detectors from capture on ^{16}O and conclude that neutrino flavor transformations could not have been reliably detected in IMB or Kamiokande for SN1987a, but are probably readily detectable for a galactic supernova with some of the proposed next generation water detectors.

3. Nucleosynthesis and constraints on closure mass neutrinos

By 4 to 6 s after core bounce the neutrino-sphere has moved in to about 12 km. The region above this has evolved to very low density and high entropy ($S/k \sim 400$ per baryon) through general expansion of the material behind the shock and accretion-driven neutrino heating. The composition of this material is mostly free neutrons and protons and alpha particles. The material is in steady state quasi-beta-equilibrium with the neutrino flux from the neutrino sphere. Since the average ν_e energy is ≈ 11.2 MeV while that of the $\bar{\nu}_e$ is ≈ 16.3 MeV the neutrino capture reactions have driven the material neutron rich ($Y_e \approx 0.45$). This is a potentially perfect site for r-process nucleosynthesis [Woosley and Hoffman 1992, Meyer et al. 1992]. Ejection of the material in this region would result in freeze-out from nuclear statistical equilibrium (NSE) in a high entropy neutron-rich environment (the r-process).

The neutrino transformation process outlined above for the early re-heating epoch at ~ 0.2 s post-bounce could aid this r-process scenario by increasing the entropy, as well as producing an

explosion! However, if transformation between ν_τ and ν_e is still going on at 4 s during the nucleosynthesis epoch then this promising site for the r-process could be lost. This is because the ν_τ leaving the neutrino-sphere have energies comparable to those of the $\bar{\nu}_e$, so that if they convert to ν_e the quasi-beta-equilibrium would shift to higher electron fraction and the material might be driven proton-rich ($Y_e \geq 0.5$). It is in fact inevitable that Y_e will be pushed up to at least 0.5, given the quasi-equilibrium of the material with the neutrino flux. Subsequent ejection of this material would result in a proton-rich freeze-out from NSE at high entropy. This would not be an r-process and it is possible that the nucleosynthesis yields in this case would contain unacceptable elemental abundances. Woosley and Baron [1992] have considered the collapse of bare white dwarfs to neutron stars and have discussed how nucleosynthesis of neutron-rich heavy elements can be used as a probe of the collapse physics.

Unacceptable nucleosynthesis from this epoch would allow us to put a stringent constraint on the vacuum mixing angle of a closure mass ν_τ with the ν_e. This would be a very important result (see the discussion of neutrino mixing in [Bludman, Kennedy and Langacker 1991]). Equations (1) and (2) show that the neutrinos will not be adiabatically transformed at the level crossings during the nucleosynthesis epoch so long as $\theta < 10^{-3}$. Note that the level crossings at this epoch have moved down to near the steep density gradient in the vicinity of the neutron star surface. In this region the density scale height is of only of order 0.5 km, hence the requirement of a larger mixing angle for transformation.

What about the effect of more energetic ν_e from neutrino flavor transformation on the ν-process of neutrino spallation-induced nucleosynthesis [Woosley et al. 1990]? This will probably be a relatively small second order effect as the primary channel for neutrino-induced spallation is neutral current scattering and hence is not flavor specific. However, more energetic electron neutrinos produced from neutrino flavor conversion would be expected to enhance the ν_e-charged-current-capture rates on heavy nuclei which will have the effect of spallation. This would give, roughly, a factor of two increase in the total neutrino-induced spallation cross-section.

4. Conclusion

We have discussed how type II supernova dynamics and nucleosynthesis depend sensitively on neutrino flavor mixing in the region between the neutrino-sphere and the shock. In turn, the mass of the ν_τ required to get a mass level crossing in this region is, coincidentally, the same as the mass which is interesting in the dark matter problem: 10 eV to 100 eV. A ν_μ or ν_τ neutrino with a mass in this range would produce significant effects in supernovae. If the vacuum mixing angle between this neutrino and the ν_e is $\theta > 10^{-4}$, then neutrino flavor conversion will produce increased material heating behind the shock which can effect a factor of two or so increase in the delayed-mechanism supernova model energies, which is certainly welcome. On the other hand the mixing angle must not exceed $\theta \approx 10^{-3}$ lest the material ejected by neutrino-driven winds at very late times be driven too proton-rich to yield a good r-process. This level of mixing is orders of magnitude smaller than anything that can be measured in the laboratory.

This later constraint does not of course constitute a hard and fast bound as there are competing sites and models for the r-process. However we argue that this is the best site for the r-process [cf. Woosley and Hoffman 1992]. The detailed nucleosynthesis of freezeout from nuclear statistical equilibrium at high entropy in marginally proton-rich conditions must be examined to see if there are any truly unacceptable nuclear abundances produced. If there are then the above bound on the mixing angle of closure mass neutrinos will become a severe constraint on particle physics and

cosmology. Willy Fowler imbued me with the spirit of adventure associated with connecting the universe to the micro-physics of nuclear and particle physics and for this I am very grateful. Thank you and happy birthday Willy.

Acknowledgements

We wish to acknowledge useful discussions and collaborations with B. Meyer, R. Mayle, J.R. Wilson, W. Haxton, D.N. Schramm, T.A. Weaver, and S.E. Woosley. This work was supported by NSF Grant No. PHY-9121623, California Space Institute Grant No. CS-56-91 at UCSD, and IGPP Grant 92-08.

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