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Evolutionary Sequences of Rotating Protoneutron Stars with Hyperons

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Abstract Escape of the trapped neutrinos from a protoneutron star might cause a phase transition from a core nucleonic neutron star to a core hyperonic neutron star, which leads to the softening of the equation of state. We study the effects of the phase transition on the rotational evolution of a protoneutron star. It is found that the star keeps shrinking and spinning up until all the trapped neutrinos escape. If the hyperonic star is metastable, its rotational frequency accelerates distinguishedly before it collapses to a black hole.

Key words: stars: interior — stars: neutron — stars: rotation

1 INTRODUCTION

Core collapse supernovae (SNe) is one of the most violent catastrophic events in our Universe. Even though the observations of supernovae date back to ancient time, their explosion mechanism is still mystrious to us (Burrows 2000; Janka el al. 2001; Yuan 2005). As first pointed out by Baade & Zwicky (1934), it is generally believed that SNe are exploding stars whose cores collapsed to form small, dense neutron stars (NSs). Immediately after its birth, the NS is hot and lepton-rich because the core is opaque to neutrinos. The nascent object is called a protoneutron star (PNS). Roughly speaking, the SNe are powered by the iron core collapse of their progenitors that exhaust their nuclear fuel. Since the pioneering work of Colgate & White (1966), most of recent numerical simulations with up-to-date microphysics have shown not only the failure of the prompt shock, but the failure of its revival by the delayed neutrino emission from the PNS. Explosion or not sensitively depends on the input microphysics, especially on the evolution of the PNS.

Since the seminal work by Burrows & Lattimer (1986), nonrotating PNSs have been investigated in detail. Previous works have shown that as compared with the cold NSs, the trapped neutrinos significantly change the chemical equilibria between baryons and leptons, the fractions of all the compositions, thus the equation of state (EOS) (Keil & Janka 1995; Pons et al. 1999; 2001a, b). Therefore, the Kelvin-Helmholtz epoch of the evolution of the PNS, during which the PNS changes from a hot and lepton-rich compact star to a cold and neutrino-free case, is the most important evolutionary stage of the PNS (The typical time scale of this process is about 10 s).

After its birth, the NS generally rotates fast initially, even near to the breakup rotational angular velocity, $\Omega_{\rm K}$. The stellar rotation plays a key role at the global properties of PNSs. Even for cold NSs, it is complicated to deal with the rotation of a NS with an arbitray angular velocity in the framework of general relativity. If the angular velocity Ω is small compared to the breakup angular velocity, then the stellar rotation is treated as a perturbation to the metric of the nonrotation case. This is the essential idea of the Hartle's perturbation theory (Hartle 1967; Hartle & Thorne 1968). Glendenning & Weber (1992a, b) improved Hartle's method by considering the effects of centrifugal stretching and frame dragging. On the other hand, there have existed several independent numerical codes for obtaining accurate models of rotating NSs in fully general

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relativity (e.g. Stergioulas 2003), such as the KEH code (Komatsu et al. 1989a, b). In this work, using Stergioulas & Friedman's KEH code, which is available as public domain code (Stergioulas & Friedman 1995), we investigate the rotational evolution of PNSs (Yuan & Heyl 2005). Last but not the least, Lai et al. (1993) developed the Newtonian ellipsoidal rotating models by generalizing Chandrasekhar's work on the incompressible rotating configurations to compressible solutions. The advantages of Lai's model come from its simplicity and each term in all equations is physically transparent.

For studying the evolution of PNSs, the main difficulty stems from the complexity of the neutrino transport in more than one dimension. In this work, we simplify the rotational evolution of PNS with hyperons by studying a stationary axisymmetric space-time with a rigidly rotating perfect fluid.

2 EQUATION OF STATE

The equation of state (EOS) of dense matter near and beyond the nuclear density is the fundamental input for investigating the gross properties of compact stars. Comparing to the symmetric nuclear matter on earth, the superdense matter in the stellar interior is highly iso-spin asymmetric and contains possibly net strangeness in form of either strange quarks or hyperons. Therefore, the EOS of the interior dense matter is completely uncertain due to two reasons. First, the composition of the matter in the interior of NSs might be some exotic states, such as hyperonic matter, quark matter, kaon condensation, pion condensation, or even the mixed phase of nuclear matter and quark matter or kaon condensation (Cheng, Yuan, & Zhang 2002 and references therein). Second, even if the interior components are known, it is uncertain how to describe the superdense matter. For instance, either the non-relativistic Schrodinger based treatments or relativistic field theoretical ones has been applied to describe the dense matter with highly iso-spin asymmetry, and many kinds of many-body technique have been developed to study the interaction between interior particles (Glendenning 2000).

The properties of non-rotating PNSs that contain only ordinary nuclear matter or some exotic states, such as hyperonic matter, quark matter, kaon condensation, and the quark-hadron phase transition, on the evolution of PNSs both have also been investigated in detail (Takatsuka 1994; Bombaci et al. 1995; Prakash et al. 1997; Hashimoto et al. 1994; Goussard et al. 1997, 1998; Strobel et al. 1999; Sumiyoshi 1999). Because the trapped neutrinos increase the chemical potential of electrons, the common consequence of the inclusion of the possible exotic states that contain negatively charged components in the PNS is the existence of a metastable star, whose mass is larger than the maximum mass for a cold NS (Prakash et al. 1997). Inevitably, the metastable PNS will collapse to a black hole at some time during the Kelvin-Helmholtz epoch, which would lead to the sudden cease of neutrino emission. In princple, the delayed collapse could be detected by the future neutrino telescope (Pons et al 1999; 2001a, b).

In this work, we contrast the rotational evolution of hyperonic PNSs with ordinary PNSs to check whether the PNS with hyperons spins up at the end of its Kelvin-Helmholtz epoch. In order to describe the hyperonic matter with trapped neutrinos, the relativistic mean field theory (RMFT) has been generally applied (Walecka 1974; Chin 1977; Serot 1979; Serot & Walecka 1986; Muller & Serot 1996; Prakash 1997; Yuan & Zhang 1999; Glendenning 2000). Since the previous works have indicated that the effect of the trapped neutrinos dominates over that of temperature on the internal composition and EOS (Prakash et al. 1997). Thus, for simplicity, we use the RMFT to describe the dense nuclear matter with hyperons at zero temperature. As the neutrinos escape, their fraction relative to the baryons $Y_{\nu_e} \equiv n_{\nu_e}/n_{\rm B}$ decreases with time. Because our purpose in this work is to explore the rotational behavior of the PNS as the neutrinos escape, we study the rotational angular velocity and other interesting quantities as a function of Y_{ν_e}. The ratio of the number fraction of electron neutrinos to its initial value ($f_{\nu_e} = Y_{\nu_e}/Y^i_{\nu_e}$) is assumed to be a constant with baryon number density in the neutrino opaque core, for a given time. Due to the uncertainty of the value of $n_{\rm env}$, the baryon number density at the the bottom of the neutrinosphere, in this work, we treat it as a free parameter and choose the latter modest value, i.e. $n_{\rm env} \simeq 6 \times 10^{-4}$ fm^{-3}. Before the neutrinos escape, we set the electronic lepton per baryon $Y_{\rm L_e} = 0.4$ inside the neutrino ellipsoid, below the density of the neutrino ellipsoid, we simply assume that it is neutrino free.

Figure 1 shows the evolution of the composition of matter in the stellar interior which contains hyperons. The subfigures in Figure 1 are the results for $Y_{\nu_e}/Y^i_{\nu_e} = 100\%, 60\%, 20\%, 0$, respectively. As noticed in previous work, the neutrino trapping causes the following results: (1) muons do not appear; (2) the number density of electrons and protons increases significantly; (3) the onset of the negatively charged hyperons

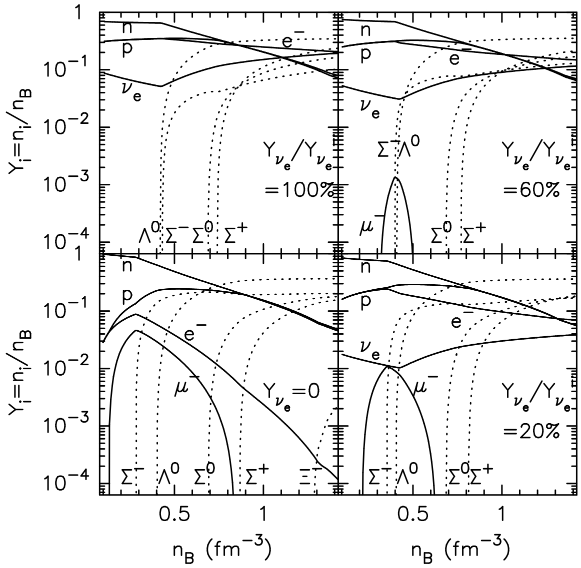

Fig. 1 The relative compositions (Y_i) as a function of the baryon number density ($n_{\rm B}$) at the different values of $Y_{\nu_e}/Y^i_{\nu_e}$ in the hyperonic matter.

takes place at higher baryon number density, chargeless hyperons appear at nearly the same baryon number density, while the onset of positively charged hyperons occurs at lower density. The whole effect is that the EOS of the hyperonic matter becomes stiffer at high density. With the escape of the trapped neutrinos, muons begin to appear and Σ^- particles appear at lower density.

3 EVOLUTIONARY SEQUENCES OF ROTATING PNSS WITH HYPERONS

As indicated in the above section, the global structure of the PNS changes in different ways as the neutrinos escape depending on whether hyperons exist in the core. This may affect the rotational evolution of the PNS. During the evolution of the PNS, the baryonic mass is fixed, if there is no accretion. Neglecting the loss of angular momentum due to the radiation of gravitational and electromagnetic waves, the loss of the total angular momentum of the PNS only results from the escaping of the neutrinos. To determine how the loss of angular momentum carried away by the neutrinos affects the rotational evolution, we also assume that the neutrinos do not carry any angular momentum as they escape. Because it is a formidable work to investigate the neutrino transfer rigorously. In our scenario, we simply assume that all emitted neutrinos escape from the surface of the neutrino ellipsoid. Before their escape, they are coupled to the dynamical motion of the fluid. As the neutrinos de-coupled from the dynamical motion of the fluid, they carry the energy and angular momentum away from the star, which lead to the decrease of the gravitational mass and the total angular momentum.

Figure 2 shows how the rotational angular velocity changes as the neutrinos escape from a PNS which contains only nucleons (NP model) and which contains hyperons as well (NPH model). Early in the Kelvin-Helmholtz epoch, the PNS always shrinks independently of the presence of hyperons, because as neutrinos escape the envelope. If the loss of the stellar angular momentum is ignored, the star spins up (see the dotted lines in Figure 2). Later in the evolution, roughly speaking, for the NPH model, the PNS spins up with the EOS in the stellar core becoming softer; while for the NP model, the PNS spins down with the EOS in the stellar core becoming stiffer. For $M = 2.0 M_\odot$, at the early stage of the evolution, the NPH spins down. Even though the increased number of hyperons make the EOS softer and the star contract, the loss of the stellar angular momentum tries to make the star slow down. These two effects compete with each other, the spin down results from the loss of the stellar angular momentum. If the PNS is metastable, the star keeps spinning up significantly, and then collapses to a black hole at the end of its life. It is clearly shown in

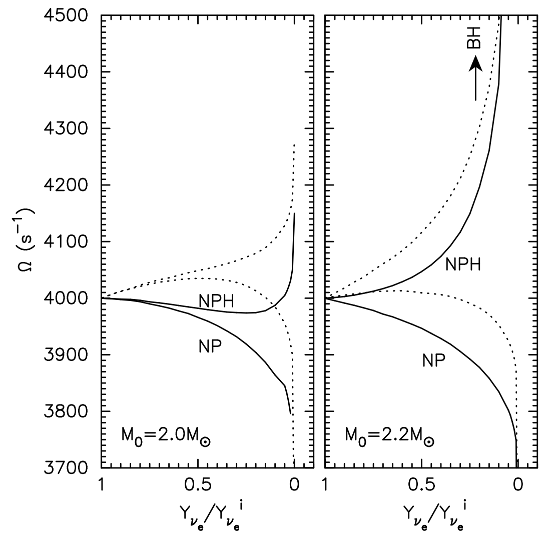

Fig. 2 The evolution of the rotational angular velocity of a PNS with hyperons or not at the different fixed rest masses of the star, $M_0 = 2.0, 2.2\,M_{\odot}$. The dotted lines represent the corresponding results for the cases in which the stellar angular momentum carried away by the escaped neutrinos is ignored.

Figure 2 that even though the escaped neutrinos carry away some of the angular momentum which decreases the rotational angular velocity of the PNS, the effect of the change of the global structure due to the escape of the neutrinos dominates the stellar rotational evolution.

The change of the rotational frequencies of the PNS after the neutrinos escape would change the initial distribution of the periods of neutron stars. Assuming the distribution at the beginnning of the Kelvin-Helmholtz epoch is uniform between zero and the Keplerian frequency, we find that for PNSs without hyperons, the range of the periods is somewhat narrower than before, but roughly speaking, the distribution is still almost uniform. For the PNS with hyperons, a significant number of slowly rotating PNSs shift to higher spins; consequently, the presence of hyperonic matter at the center of neutron stars will skew the distribution of initial spin periods toward shorter periods.

4 DISCUSSION

In this work, we investigate the rotational evolution of protoneutron stars which contain only nucleons with that of PNSs which contain hyperonic matter at zero temperature in full general relativity. It is found that PNSs contract and spin up at the early stage of its evolution as the trapped neutrinos escape. During this stage the contribution of leptons to the pressure in the stellar envelope dominates. As the neutrinos continue to escape, the evolution of the PNS mainly depends on the changing behavior of the EOS of the dense matter in the stellar core; therefore, it differs in the two different models. A PNS which contains only nucleons stops contracting and begins to expand because the EOS becomes stiffer as neutrinos escape from the core. PNSs that contain hyperonic matter keep shrinking, and their spin frequency increases because the EOS becomes softer with the escape of the neutrinos. At the end of the evolution, for PNSs without hyperons, the range of the spin periods becomes a little bit narrower than the initial one. However, the shape of the distribution of the spin periods is very similar to that of the initial distribution. For PNSs with hyperons, the distribution of the initial spin periods is skewed significantly toward shorter periods. If a PNS is metastable, it keeps spinning up significantly on the neutrino diffusion timescale before it collapses to a black hole.

In addition to the hyperonic matter, other exotic states, such as quark matter, kaon condensation and others might exist in the stellar core. Because the neutrino trapping makes the onset of these exotic states which contain negatively charged particles take place at the higher baryon number density, a PNS with such an exotic composition spins up as the neutrinos escape.

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