Protoneutron stars and constraints on maximum and minimum mass of neutron stars

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Abstract. Constraints on minimum and maximum mass of ordinary neutron stars are imposed by the consideration of their early evolution (protoneutron star stage). Calculations are performed for a realistic standard model of hot, dense matter (Lattimer & Swesty 1991) valid for both supranuclear and subnuclear densities. Various assumptions concerning protoneutron star interior (large trapped lepton number, no trapped lepton number, isentropic, isothermal) are taken into account.

1. Introduction

The heavy-element core of massive, evolved stars ($M_{\text{star}} > 8 \, M_\odot$) is believed to collapse either directly to a black hole (BH) or to a metastable protoneutron star (PNS). The newborn neutron star does not resemble the cold ordinary neutron star (NS). It is a very hot object, with temperature $T > 10$ MeV and radius significantly larger than that of a cold neutron star with the same number of baryons. In contrast to ordinary cold NS it is rich in leptons: electrons and trapped degenerate or non-degenerate neutrinos. A few seconds after birth $t \approx 2 - 4 \, \text{s}$ the matter in the core of a hot neutron star has almost constant lepton fraction ($Y_l = 0.3 - 0.4$) and entropy per baryon ($s = 1 - 2$ in unit of the Boltzmann constant $k_B$) (Burrows & Lattimer 1986). PNS evolves either to BH or to stable NS depending on its total number of baryons. A hot neutron star transforms into NS on a timescale 20-30 s.

Constraints on maximum mass of neutron stars imposed by composition and equation of state (EOS) of hot dense stellar interior were studied by numerous authors (e.g. Takatsuka 1995, Bombaci et. al 1995, Bombaci 1996, Prakash et al. 1997). For low densities of PNS they took EOS of cold matter (at $T=0$). In contrast to them we use a unified hot dense matter model, which holds for both supranuclear and subnuclear densities. We find the position of the neutrinosphere in a self-consistent way (Gondek et al. 1997, hereafter G97). These refinements enable us to study properties of PNS with arbitrary mass (also with small mass, which consists essentially of subnuclear density envelope alone) and find constraints on minimum and maximum mass of NSs assuming conservation of the total baryon number of the star during 3-30 seconds of its life (Bombaci 1996).
2. Physical model of protoneutron star

Our models of PNS are composed of a hot, neutrino-opaque interior, separated from much colder, neutrino-transparent envelope by the neutrinosphere. We consider two limiting thermal states of the hot interior (see G97): isentropic, with entropy per baryon \( s = 1 \) and \( s = 2 \); and isothermal, with \( T_\infty = T e^{\nu(r)/2} = \text{const.} \), where \( \nu(r) \) is the metric function (Zeldovich et al. 1971), \( T_\infty \) and \( T \) are the values of the temperature, measured by an observer at infinity and by a local observer respectively. We chose \( T = T_b = 15 \) MeV at the edge of the hot isothermal core. The first case, characteristic of a very initial state of a PNS corresponds to a significant trapped lepton number \( (Y_l = 0.4) \). The second case corresponds to situation after the deleptonization \( (Y_\nu = 0) \) of a PNS. In both cases the EOS of hot dense matter is determined using the moderately stiff model of Lattimer and Swesty (1991)(LS). This is a standard model of dense matter, composed of nucleons and leptons. For high densities we supplemented the LS model with contributions resulting from the presence of neutrinos and antineutrinos of three flavours.

We consider PNS as an isolated, non-rotating, spherically symmetric object, which has no magnetic field. Under these assumptions the structure of the star is solved numerically using TOV equations (Tolman 1939, Oppenheimer & Volkoff 1939) for a given EOS. Global parameters and static stability criteria of PNS are discussed by G97.

3. Results

Static neutron stars with central density lower than central density of the star with minimum mass \( M_{\text{max}} \), but greater than central density of the star with minimum mass \( M_{\text{min}} \) are stable and can exist (Harrison et al. 1965). In our case of moderately stiff equation of state \( M_{\text{max}}(\text{NS}) = 2.044M_\odot \) and \( M_{\text{min}}(\text{NS}) = 0.054M_\odot \). However, NS formed from PNS can have a gravitational mass in significantly narrower region. Since accretion on the forming protoneutron star ceases \( \sim 3 \) s after birth (Chevalier 1989) it is a good approximation to assume that during transformation of PNS into NS (3-30 seconds after birth) the total baryon number \( A \) in the star is conserved. We compare NSs and PNSs by fixing the total baryon (rest) mass of a star \( M_{\text{bar}} = Am_0 \), where \( m_0 \) is the mass of the hydrogen atom.

Constraints on maximum mass of neutron stars

In Fig. 1a, we plot gravitational mass as a function of the baryonic mass for stable massive NSs and PNSs. We see that the baryonic mass \( M_{\text{bar, max}} \) corresponding to the maximum gravitational mass \( M_{\text{max}} \) is the largest one for the static NSs (this is consistent with results of Takatsuka 1995 and Bombaci 1996 for a conventional equation of state). For PNSs with isentropic core (dashed and dotted-dashed lines) \( M_{\text{bar, max}} \) (PNS) is significantly lower than \( M_{\text{bar, max}} \) (NS). In our case a newborn isentropic PNS with the maximum gravitational mass transforms, due to deleptonization and cooling, into a cold NS with gravitational mass of 1.88-1.9 \( M_\odot \) (points a, b at Fig. 1a). NS with \( M_{\text{bar}}(\text{NS}) > M_{\text{bar, max}} \) (PNS) cannot be formed from a PNS. The maximum mass of a NS obtained from evolution is smaller than \( M_{\text{max}} \) (NS).
Figure 1. a) Gravitational mass versus baryonic mass for massive protoneutron stars and neutron stars. The long dashed and dash-dotted lines correspond to isentropic PNS stage ($t \sim 2 - 4$ s). The dotted line represents isothermal PNS ($t \sim 10 - 20$ s) and the solid line corresponds to the final NSs. The crosses correspond to maximum allowable masses for a given equation of state. The maximum baryon mass for a PNS is smaller than the maximum allowed baryon mass for a static NS. The points a and b represent NSs which has evolved from isentropic PNSs with the maximum possible mass assuming conservation of the total baryonic mass during evolution. b) Same as Fig. 1a, but for low massive protoneutron stars and neutron stars. The crosses correspond to minimum allowable masses of PNSs. The minimum baryon mass for a PNS is greater than the minimum allowed baryon mass for a static NS ($M_{\text{bar}, \text{min}}(\text{NS}) = 0.055 M_\odot$). The points a, b, c represent NSs which has evolved from PNSs with the minimum possible mass assuming conservation of the total baryonic mass.

from neutron stars model by $\sim 0.15 M_\odot$ (for comparison Takatsuka 1995 obtained 0.05-0.07 $M_\odot$).

Constraints on minimum mass of neutron stars In Fig. 1b, we compare the $M$ versus $M_{\text{bar}}$ between low mass PNSs and NSs. The baryonic mass $M_{\text{bar}, \text{min}}$ corresponding to the minimum gravitational mass $M_{\text{min}}$ is the lowest one for static neutron stars $M_{\text{bar}, \text{min}}(\text{NS}) = 0.055 M_\odot$. We consider two scenarios: an isentropic PNS transforms directly to a NS or undergoes through a hot isothermal state. In the first case the minimum gravitational mass for NS is $0.54 - 0.65 M_\odot$ depending on the value of entropy in isentropic core of a PNS, in the second case it is $0.84 M_\odot$. Therefore NS with $M < 0.54 M_\odot$ ($M < 0.84 M_\odot$ if the PNS goes through the hot isothermal like configurations) do not exist.
4. Conclusions

We have constrained the minimum and maximum masses of NSs by the considerations of their initial hot stage. All calculations were done for a standard, moderately stiff dense matter equation of state. We show that the minimum gravitational mass of a NS is by about $0.5M_\odot$ greater than $M_{\text{min}}(\text{NS})$ in a static NS model, while the maximum gravitational mass of a NS is by $\sim 0.15M_\odot$ smaller than $M_{\text{max}}(\text{NS})$. The latter result seems to be characteristic for a standard model of dense matter, composed of nucleons and leptons (e.g. Takatsuka 1995, Bombaci 1996). The conclusions are different when we take into account existence of an exotic components (hyperons, pions or kaons condensate or quark matter) at high densities (Bombaci et al. 1996). The scenario of transformation of a PNS into a NS could be strongly influenced by a phase transition in the central region of the star. Appearance of exotic matter could dramatically soften the EOS of dense matter, lowering maximum allowable mass of NSs. In the case of $K^-$ condensation, the maximum baryon mass of PNS is larger by $\sim 0.2M_\odot$ than that of cold neutron stars (Brown & Bethe 1994) and the maximum mass of a NS is that one determined from a static NS model. The deleptonization and cooling of PNSs of baryon mass exceeding the maximum allowable baryon mass for NSs, would lead to their collapse into BH.

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