Properties of Non-rotating and Rapidly Rotating Protoneutron Stars

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The aim of this paper was the investigation of the properties of rapidly rotating protoneutron stars (PNS's) consisting of nuclear matter (n, p, e^-, μ^-) under the influence of trapped neutrinos. We used a recently developed nuclear EOS for hot, dense matter in the nuclear Thomas-Fermi approach. The nuclear EOS was extended in this paper to subnuclear densities and to different compositions of PNS and hot neutron stars (HNS) matter (i.e. trapped neutrinos, constant entropy per baryon, ...). Our results for subnuclear densities are comparable to the results derived by Lattimer & Swesty used in the investigations of Goussard et al. and Gondek et al.. However, considerable deviations occur at densities around and above nuclear matter density, since the EOS of Lattimer & Swesty shows a smaller temperature dependence. In general, this difference to our results has only a small impact on the properties of PNS's, but impacts on HNS's with canonical mass. The impact becomes considerable for more massive stars.

An investigation of this kind should investigate the properties of PNS's and HNS's for the whole range of possible masses. So far lepton concentration profiles and entropy per baryon profiles were derived only for one fixed mass in simulations of PNS evolution. In our calculation, the extension to the whole range of masses was done by assuming that the lepton concentration and the entropy per baryon does not depend on the mass of the PNS.

As a result we find that the minimum gravitational mass of a NS is determined at the earliest stage of a PNS, so that the mass of a NS formed in a Type-II supernova is larger than 0.89-1.13$M_\odot$. The exact lower limit of the NS mass depends on the used entropy per baryon in the EPNS model. The quoted mass range was obtained by using $s = 4$ and $s = 5$ as lower and upper limit of the entropy per baryon in the envelope of the EPNS. The minimum mass of EPNS's is approximately by a factor of ten larger than the minimum stable mass of CNS's.

The maximum possible baryonic mass of a CNS is always larger than the maximum possible baryonic mass of the PNS's, this means that once a PNS was formed, it cannot collapse into a black hole, if further accretion is neglected. One exception is the case of the most massive stars rotating near or at its Kepler frequency, which possibly collapse to a black hole during their time evolution. This statement holds for stars with a pure nucleonic/leptonic composition . If one includes hyperons and/or quarks, the maximum baryonic mass of a CNS decreases and may be smaller than the maximum baryonic mass of a PNS. Then, a sufficiently massive PNS may collapse to a black hole during deloptonization. The maximum gravitational mass increases slightly with increasing entropy per baryon in contrast to the maximum baryonic mass.

It turned out that the influence of rotation has several impacts on properties of PNS's and NS's. Whereas the minimum mass changes only slightly due to rotation, the effect on the maximum mass is rather large, particularly for CNS's. The central baryon density is nearly unaffected by rotation at the early stages of the evolution, whereas the impact on the later stages is rather large. The effect on the circumferential radius decreases with increasing mass and the impact on (early) EPNS's and (late) LPNS's is slightly larger than the impact on (cold) CNS's.

We investigated th influence of different shapes of the neutrino sphere on the structure of LPNS's. As expected, we obtained considerable differences (up to 10 %) in the circumferential radii and, due to this, in the Kepler frequency. Other properties, as the central density, are barely changed by the location of the neutrino sphere. We have also considered different temperatures in the envelope of LPNS's and (hot) HNS's. If a very high temperature of 0.6 MeV is used in the envelope instead of a constant entropy per baryon, the gross properties of the LPNS change by less than 1 %. Larger deviations were obtained if the envelope is assumed to be cold. The finite temperature effects should therefore not be neglected in the envelope. Furthermore, we obtain that the thermal effects are comparable to the effects due to trapped neutrinos. This is in contrast to the results of Prakash et al., who found the thermal effects to be much smaller than the effect of high lepton numbers.

In our model we assumed that accretion onto the emerging NS stopped after the formation of the EPNS. Furthermore, we kept the angular momentum constant during the deleptonization and the thermal cooling period. Under these presumptions, we obtain a lower limit on the periods of young NS's with a typical baryonic mass of 1.6 $M_\odot$ between 1.56 and 2.22 ms, which is in accordance with similar values obtained by Goussard et al. These results support strongly the hypothesis that millisecond pulsars were accelerated due to accretion. With the same reasoning, one obtains an upper limit of the stability parameter $\beta \lesssim 0.082$, which is smaller, for almost all NS's, than the critical value for the onset of dynamical and secular instabilities. Kepler rotating massive CNS's possess stability parameter values up to $\beta \sim 0.13$ and might therefore be secular unstable against $m = 2$ and $m = 3$ non-axisymmetric perturbations.

Though we have assumed uniform rotation, it seems to be very reasonable that PNS's and young NS's rotate differentially. As it was found by Schaab and Goussard et al., differential rotation may considerably effect the structure of PNS's and NS's, and we will pursue our investigations to differential rotation in the future. Another issue that will be addressed in a future work is the effect of additional degrees of freedom (e.g. hyperons) on the evolution of PNSs.

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