Appendix A
TABLES OF EOSs IN NEUTRON STAR CRUST

In this Appendix we present tables of the EOS for the ground-state matter in the neutron star crust for $\rho > 10^7$ g cm^{-3}. At lower densities, the EOS can be influenced by the presence of strong magnetic fields (Chapter 4) and by the thermal effects (Chapter 2). The analytical description of properties of atomic nuclei in neutron star crusts is given in the Appendix B, and the analytic parameterization of the EOS is presented in the Appendix C.

The outer crust. Up to $\rho \simeq 10^{11}$ g cm^{-3}, the EOS in the outer crust is determined by experimental masses of neutron rich nuclei. This fact was exploited by Haensel & Pichon (1994, referred to as HP), who made maximal use of the experimental data. At higher densities, they used the semiempirical massformula of Möller (1992).[1] The HP EOS is given in Table A.1 for the same pressure grid as in the tabulated EOS of Baym *et al.* (1971b, referred to as BPS), except for the last line, which corresponds to the neutron drip point. The EOS in Table A.1 is very similar to the BPS one; typical differences in density at the same pressure do not exceed a few percent. One can refine the EOS by introducing density discontinuities which accompany changes of nuclides. It can be done by inserting additional pairs of lines (n_i, ρ_i, P_i), $(n_{i+1}, \rho_{i+1}, P_i)$, corresponding to the density jumps given in Table 3.1. This would complicate the integration of the equations of hydrostatic equilibrium while constructing neutron star models. On the other hand, these weak first-order phase transitions soften the EOS. The softening is well reproduced by interpolation between tabulated points in Table A.1, which leads to a smoothed EOS, easy to use in calculations. The analytical representation of such a smoothed EOS is given in the Appendix C.

The inner crust. Out of several existing EOSs of the inner crust, we selected a recent SLy model of Douchin & Haensel (2001). This EOS is given in Table A.2. For a better presentation of this EOS in the vicinity of neutron drip density $\rho_{\rm ND}$ and the crust-core interface, $\rho = \rho_{\rm cc}$, Table A.2 is somewhat extended, using the SLy model to $\rho < \rho_{\rm ND}$ and $\rho > \rho_{\rm cc}$.

The EOSs in Tables A.1 and A.2 are based on different dense-matter models and give different neutron drip points. Because $\rho_{\rm ND}({\rm SLy}) < \rho_{\rm ND}({\rm HP})$, we recommend to use $\rho_{\rm ND} = \rho_{\rm ND}({\rm SLy})$. At the first glance, the SLy EOS for $\rho < \rho_{\rm ND}({\rm SLy})$ nearly coincides with the HP one. Let us remind, however, that the SLy EOS (as well as the FPS one) has been calculated within the Compressible Liquid Drop Model, with no shell or pairing effects. Therefore, the density there is a smooth function of the pressure, except for a narrow vicinity of the neutron drip point and the crust-core transition. Except for these two narrow regions, it can be nicely fitted by analytical functions, as described in the Appendix C.

[1] After this book was almost completed, new EOSs of the outer crust appeared (Rüster *et al.*, 2006), based on different nuclear models and up-to-date experimental data for very neutron rich nuclei. There are some model-dependent differences in (Z, A) at higher densities, but the smoothed EOSs of Rüster *et al.* (2006) and HP are very similar.

Table A.1. The EOS of the outer crust derived by Haensel & Pichon (1994). The last line with a nucleus observed in laboratory and present in the ground state of dense matter, as well as the line corresponding to the neutron drip point, are printed in boldface.

ρ (g cm^{-3})	P (dyn cm^{-2})	n_{b} (cm^{-3})	ρ (g cm^{-3})	P (dyn cm^{-2})	n_{b} (cm^{-3})
3.303E7	3.833E24	1.991E31	2.091E10	1.938E28	1.257E34
6.592E7	1.006E25	3.973E31	2.533E10	2.503E28	1.522E34
1.315E8	2.604E25	7.926E31	3.315E10	3.404E28	1.991E34
2.625E8	6.676E25	1.581E32	4.174E10	4.628E28	2.507E34
3.305E8	8.738E25	1.991E32	5.039E10	5.949E28	3.025E34
5.239E8	1.629E26	3.156E32	6.619E10	8.089E28	3.973E34
8.303E8	3.029E26	5.001E32	8.337E10	1.100E29	5.002E34
1.0455E9	4.129E26	6.296E32	**9.631E10**	**1.450E29**	**5.777E34**
1.212E9	5.036E26	7.299E32	1.091E11	1.495E29	6.545E34
1.606E9	6.860E26	9.667E32	1.4155E11	2.033E29	8.485E34
2.545E9	1.272E27	1.532E33	1.701E11	2.597E29	1.0195E35
4.166E9	2.356E27	2.507E33	2.096E11	3.290E29	1.256E35
6.606E9	4.362E27	3.974E33	2.730E11	4.473E29	1.635E35
8.031E9	5.662E27	4.830E33	3.325E11	5.816E29	1.990E35
1.011E10	7.702E27	6.081E33	4.188E11	7.538E29	2.506E35
1.319E10	1.048E28	7.930E33	4.299E11	7.805E29	2.572E35
1.661E10	1.425E28	9.982E33	**4.321E11**	**7.857E29**	**2.585E35**

Table A.2. The SLy EOS of the ground state of the inner crust, together with the adjacent segments of the SLy EOS of the outer crust and the core (calculated by Douchin & Haensel, 2001). The first and last lines corresponding to the inner crust are printed in boldface.

$n_{\rm b}$ (cm^{-3})	ρ ($\mathrm{g\ cm}^{-3}$)	P ($\mathrm{dyn\ cm}^{-2}$)	$n_{\rm b}$ (cm^{-3})	ρ ($\mathrm{g\ cm}^{-3}$)	P ($\mathrm{dyn\ cm}^{-2}$)
1.7590E35	2.9398E11	5.0926E29	7.6609E35	1.2831E12	1.3370E30
1.8297E35	3.0582E11	5.3344E29	1.2616E36	2.1141E12	2.1547E30
1.9024E35	3.1800E11	5.5843E29	1.8947E36	3.1766E12	3.4272E30
1.9772E35	3.3052E11	5.8426E29	2.6726E36	4.4827E12	5.2679E30
2.0540E35	3.4338E11	6.1094E29	3.6062E36	6.0511E12	7.7976E30
2.0791E35	3.4759E11	6.1968E29	4.7097E36	7.9058E12	1.1147E31
2.0823E35	3.4810E11	6.2078E29	7.4963E36	1.2593E13	2.0894E31
2.0905E35	**3.4951E11**	**6.2150E29**	1.1197E37	1.8824E13	3.5841E31
2.1604E35	3.6121E11	6.3573E29	1.5999E37	2.6920E13	5.7611E31
2.2306E35	3.7296E11	6.4675E29	2.2073E37	3.7170E13	8.8117E31
2.3114E35	3.8650E11	6.5813E29	2.9477E37	4.9677E13	1.2947E32
2.4014E35	4.0158E11	6.6998E29	4.2684E37	7.2017E13	2.1620E32
2.4997E35	4.1805E11	6.8228E29	6.2200E37	1.0509E14	3.8475E32
2.6426E35	4.4199E11	6.9945E29	7.3174E37	1.2372E14	5.0462E32
3.0533E35	5.1080E11	7.4685E29	**7.5959E37**	**1.2845E14**	**5.3711E32**
3.5331E35	5.9119E11	8.0149E29	7.7100E37	1.3038E14	5.3739E32
4.0764E35	6.8224E11	8.6444E29	9.7100E37	1.6441E14	9.2059E32
4.6800E35	7.8339E11	9.3667E29	1.1710E38	1.9854E14	1.5028E33
5.3414E35	8.9426E11	1.0191E30	1.3710E38	2.3281E14	2.3136E33
6.0594E35	1.0146E12	1.1128E30	1.5710E38	2.6722E14	3.4072E33

Appendix B
ANALYTICAL MODELS OF NUCLEAR DENSITY PROFILES

Here we present analytical formulae which fit the results of calculations of microscopic density profiles of neutrons and protons, associated with nuclear structures in the ground state of a neutron star crust. These formulae were derived and used by Kaminker *et al.* (1999) (although not published there) and elaborated further. They are useful, for instance, for calculating neutrino emission or electron transport properties of crustal matter which depend on proton charge distribution within atomic nuclei (e.g., Kaminker *et al.* 1999; Gnedin *et al.* 2001). We can warn the reader that the formulae are not meant to be used for constructing any EOS of dense matter.

The higher the density in the neutron star crust, the more important finite nuclear sizes. Near the crust bottom, the shape of the nuclei may change from roughly spherical to cylindrical or plane-parallel (Chapter 3). Let us consider local density profiles of neutrons and protons within the nuclei, $n_n(r)$ and $n_p(r)$, where r is the distance either from the center of a spherical nucleus, or from the symmetry axis of a cylindrical nuclei, or from the symmetry plane of a slablike nucleus. Let $n_j^{\rm out}$ be the number densities of neutrons or protons (for $j = n$ or p) outside the nucleus. The mean-square radii of the neutron and proton distributions are

$$\overline{r_j^2} = \frac{\int_0^{r_{\rm c}} (n_j(r) - n_j^{\rm out}) r^{d+1}\,{\rm d}r}{\int_0^{r_{\rm c}} (n_j(r) - n_j^{\rm out}) r^{d-1}\,{\rm d}r}, \tag{B.1}$$

where $r_{\rm c}$ is the Wigner-Seitz cell radius (Chapter 3), and d is the space dimension of the nuclear phase ($d = 3, 2$, and 1 for spherical, cylindrical, and plane nuclei, respectively). Let us remind that for simple three-dimensional crystals and liquids, $r_{\rm c}$ equals the ion-sphere radius $a_{\rm i}$.

B.1. Steplike profile model

Far from the bottom of the inner crust, at densities much below the nuclear saturation density, a steplike approximation of the nucleon density profile may be good,

$$n_j(r) = \begin{cases} n_j^{\rm in} & \text{at} \quad r < r_j, \\ n_j^{\rm out} & \text{at} \quad r \geq r_j, \end{cases} \tag{B.2}$$

where $n_j^{\rm in}$ are the number densities of neutrons or protons (for $j = n$ or p) inside a nucleus, and r_n and r_p are the radii of neutron and proton distributions, respectively. In the case of spheres, the form factor for the steplike profile $n_p(r)$ is

$$F_q = \frac{3}{(qr_p)^3} \left[\sin(qr_p) - qr_p \cos(qr_p)\right]. \tag{B.3}$$

The mean-square radius (for any d) equals

$$\overline{r_j^2} = \frac{d}{d+2}\, r_j^2. \tag{B.4}$$

In the outer crust (at $\rho \lesssim \rho_{\rm ND}$), the radii of the nuclei are unaffected by the pressure of ambient medium and one can use the standard formula $r_p = 1.15\,A^{1/3}$ fm (e.g., Pethick & Ravenhall 1995). At higher densities, the values of r_p obtained numerically (Negele & Vautherin, 1973) can be approximated as $r_p = 1.83\,Z^{1/3}$ fm (Itoh & Kohyama, 1983).

The importance of the nuclear size effects depends on the fraction of volume the nuclei occupy. A relevant parameter is the ratio of the proton core radius to the Wigner-Seitz cell radius,

$$x_{\rm nuc} = r_p/r_{\rm c}. \tag{B.5}$$

For spherical nuclei, we have

$$x_{\rm nuc} = \begin{cases} 0.00155\,(A/Z)^{1/3}\,x_{\rm r} & \text{at} \quad \rho < \rho_{\rm ND}, \\ 0.00247\,x_{\rm r} & \text{at} \quad \rho > \rho_{\rm ND}, \end{cases} \tag{B.6}$$

where $x_{\rm r}$ is the relativity parameter defined by Eq. (2.2).

B.2. Smooth Composition Model

At $\rho \gtrsim 10^{13}$ g cm^{-3} the nucleon density profiles deviate significantly from the steplike distribution (Chapter 3). Oyamatsu (1993) calculated the local neutron and proton number density distributions within a Wigner-Seitz cell and fitted them in the form

$$n_j(r) = \begin{cases} \left(n_j^{\rm cen} - n_j^{\rm out}\right)\left[1 - (r/R_j)^{t_j}\right]^3 + n_j^{\rm out} & \text{at} \quad r < R_j, \\ n_j^{\rm out} & \text{at} \quad r \geq R_j, \end{cases} \tag{B.7}$$

where $n_j^{\rm cen}$, $n_j^{\rm out}$, t_j, and R_j are the fit parameters. The parameter t_j controls the sharpness of the local density profile, while R_j determines the size of a nucleus. These parameters, as well as the sizes of Wigner-Seitz cells, are presented in Table 6 of Oyamatsu (1993) for several values of the mean baryon number density $n_{\rm b}$ (for spherical and nonspherical nuclei). With increasing $n_{\rm b}$ the profiles become smoother, approaching the limit of uniform matter; therefore, the parameters t_j decrease.

Real local density distributions of neutrons and protons are not cut off at a certain distance from the center. Therefore, R_n and R_p can be treated only as convenient fit parameters. Near the bottom of the crust, the local density distribution is rather smooth, and the boundary between the free neutrons and the neutrons bound within the nuclei becomes rather uncertain. On the other hand, while describing properties of neutron star crust, one often uses such quantities as the radii of neutron and proton distributions (r_n and r_p) and the number of nucleons within a nucleus (A). To determine them, let us consider a nucleus as a combination of imaginary neutron and proton spheres of *equivalent radii* r_n and r_p and *equivalent neutron and proton densities* $n_n^{\rm in}$ and $n_p^{\rm in}$. We define the equivalent radius r_j as the radius of the imaginary steplike density distribution that reproduces the mean-square radii (B.4) of the real distribution. In this case $r_j = [(1+2/d)\overline{r_j^2}]^{1/2}$. For the distribution (B.7), the equivalent radii become

$$\begin{aligned} r_j \quad &= \quad \left[1 - 3\,\frac{d+2}{d+2+t_j}\,\gamma_j^{t_j} + 3\,\frac{d+2}{d+2+2t_j}\,\gamma_j^{2t_j} - \frac{d+2}{d+2+3t_j}\,\gamma_j^{3t_j}\right]^{1/2} \\ &\times \left[1 - \frac{3d}{d+t_j}\,\gamma_j^{t_j} + \frac{3d}{d+2t_j}\,\gamma_j^{2t_j} - \frac{d}{d+3t_j}\,\gamma_j^{3t_j}\right]^{-1/2} \gamma_j R_j, \end{aligned} \tag{B.8}$$

where $\gamma_j = r_j^{\rm max}/R_j$ and $r_j^{\rm max} = \min(R_j, r_{\rm c})$. The parameter γ_j equals 1 (and can be dropped out) in all the cases except for the case where the fit parameter R_j exceeds the Wigner-Seitz cell radius r_c, that may happen near the crust-core boundary. In the latter case, the local density profile (B.7) must be truncated at $r = r_c$, and we get $\gamma_j < 1$. Our model satisfies the natural requirement that the equivalent radii r_j are smaller than r_c.

We define the equivalent neutron and proton densities within the nucleus in such a way to reproduce the total number of nucleons (protons or neutrons) implied by Eq. (B.7):

$$\begin{aligned} n_j^{\rm in} &= n_j^{\rm out} + \frac{d}{r_j^d} \int_0^{r_j^{\max}} (n(r) - n_j^{\rm out})\, r^{d-1}\, \mathrm{d}r \\ &= n_j^{\rm out} + \left[1 - \frac{3d}{d+t_j}\,\gamma_j^{t_j} + \frac{3d}{d+2t_j}\,\gamma_j^{2t_j} - \frac{d}{d+3t_j}\,\gamma_j^{3t_j}\right] \frac{R_j^d}{r_j^d}\,(n_j^{\rm cen} - n_j^{\rm out}). \end{aligned} \quad \text{(B.9)}$$

The steplike profile of the previous section is recovered from Eqs. (B.7)–(B.9) in the limit of $t_j \to \infty$.

B.2.1 Spherical nuclei in the inner crust

Oyamatsu (1993) presented the fit parameters for spherical nuclei in the ground-state matter at three values of the mean baryon number density n_b= 0.01, 0.03, and 0.055 fm^{-3} (i.e., $\rho = 1.66 \times 10^{13}$, 4.98×10^{13}, and 9.13×10^{13} g cm^{-3}) in the inner crust of a neutron star. These parameters are quite consistent with those presented by Negele & Vautherin (1973) for nearly the same n_b. Some of these parameters can also be deduced from Figs. 3 and 4 and from Table 3 of Negele & Vautherin (1973) for several other values of n_b in the inner crust. The parameters appear to be smooth functions of n_b, and we interpolated them between the given points at $\rho_{\rm ND} \leq \rho \leq 1.4 \times 10^{14}$ g cm^{-3}. We present r_c and the parameters of Eq. (B.7) as functions of the dimensionless argument

$$\nu = \ln(n_b \times 100\ \mathrm{fm}^3).$$

The interpolation reads

$$r_c = (31.68 - 8.4\,\nu - 0.238\,\nu^2 + 0.1152\,\nu^3)\ \mathrm{fm}, \quad \text{(B.10a)}$$
$$t_n = (0.2027 + 0.004\,506\,\mathrm{e}^{\nu})^{-1}, \quad \text{(B.10b)}$$
$$R_n = (9.406 + 1.481\,\nu + 0.4625\,\nu^2 + 0.057\,38\,\nu^3)\ \mathrm{fm}, \quad \text{(B.10c)}$$
$$n_n^{\rm cen} - n_n^{\rm out} = (0.097\,61 - 0.013\,22\,\nu - 0.005\,544\,\nu^2 - 7.624 \times 10^{-4}\,\nu^3)\ \mathrm{fm}^{-3}, \quad \text{(B.10d)}$$
$$t_p = (0.1558 + 0.002\,225\,\nu + 9.452 \times 10^{-4}\,\nu^2)^{-1}, \quad \text{(B.10e)}$$
$$R_p = (8.345 + 0.7767\,\nu + 0.1333\,\nu^2 + 0.008\,707\,\nu^3)\ \mathrm{fm}, \quad \text{(B.10f)}$$
$$n_p^{\rm cen} = (0.0404 - 0.010\,97\,\nu - 7.23 \times 10^{-4}\,\nu^2 + 2.25 \times 10^{-4}\,\nu^3)\ \mathrm{fm}^{-3}. \quad \text{(B.10g)}$$

This interpolation smears out the jumps in the nuclear composition with increasing ρ, but it allows one to calculate the parameters of spherical nuclei at any density in the ground-state matter of the inner crust.

The number of protons (Z) and the total number of nucleons (A) within a nucleus are most easily found using the equivalent radii and densities defined by Eqs. (B.8) and (B.9) with $d = 3$:

$$Z = \frac{4\pi}{3}\, r_p^3\, n_p^{\rm in}, \quad A = Z + \frac{4\pi}{3}\, r_n^3\, n_n^{\rm in}. \quad \text{(B.11)}$$

Now the parameter $n_n^{\rm out}$ is determined from the relation

$$A' = A + \frac{4\pi}{3}\,(r_c^3 - r_n^3)\, n_n^{\rm out} = \frac{4\pi}{3}\, r_c^3 n_b, \quad \text{(B.12)}$$

where A' is the number of nucleons within a Wigner-Seitz cell.

The nucleus mass is assumed to be $m_i = A m_n + Z m_p$.

B.2.2 Spherical nuclei in the outer crust

Making use of the results of Haensel & Pichon (1994), we have also obtained an analytic description of atomic nuclei in the ground-state matter for lower densities,

$$10^8 \text{ g cm}^{-3} \le \rho \le \rho_{\rm ND}.$$

We have adopted the same parameterization (B.7) and constructed analytic expressions for the nuclear parameters versus

$$\nu = \ln[1 + 2\, n_{\rm b}/(10^{-8} \text{ fm}^{-3})].$$

These expressions read:

$$R_n = (5.788 + 0.020\,77\,\nu + 0.014\,89\,\nu^2) \text{ fm}, \tag{B.13a}$$
$$n_n^{\rm cen} = (0.0808 + 1.688 \times 10^{-4}\,\nu + 9.439 \times 10^{-5}\,\nu^2) \text{ fm}^{-3}, \tag{B.13b}$$
$$R_p = 5.688 + 0.026\,28\,\nu + 0.009\,468\,\nu^2 \text{ fm}, \tag{B.13c}$$
$$n_p^{\rm cen} = (0.0738 + 1.22 \times 10^{-4}\,\nu - 1.641 \times 10^{-4}\,\nu^2) \text{ fm}^{-3}, \tag{B.13d}$$
$$n_n^{\rm out} = n_p^{\rm out} = 0, \tag{B.13e}$$
$$t_n = t_p = 6. \tag{B.13f}$$

Equation (B.13f) just formally sets t_j values at $\rho < \rho_{\rm ND}$ close to those at $\rho = \rho_{\rm ND}$. In many applications it is sufficient to use steplike profiles (i.e., $t_j \to \infty$) at $\rho \le \rho_{\rm ND}$.

The free nucleons outside nuclei are absent in this regime, $n_n^{\rm out} = n_p^{\rm out} = 0$, and the Wigner-Seitz radius is

$$r_{\rm c} = \left(\frac{4\pi}{3} \frac{n_{\rm b}}{A} \right)^{-1/3}, \tag{B.14}$$

A and Z being determined by Eq. (B.11).

At low densities in the outer crust, Eqs. (B.13) reproduce the parameters of ^{56}Fe-nuclei.

B.2.3 Exotic nuclei

According to model I of Oyamatsu (1993), the phase with spherical nuclei in the inner crust is realized up to a density $n_{\rm b} = 0.0586$ fm^{-3} ($\rho = 0.973 \times 10^{14}$ g cm^{-3}). It is followed by the phase with rodlike nuclei up to $n_{\rm b} = 0.0749$ fm^{-3} ($\rho = 1.24 \times 10^{14}$ g cm^{-3}) and the phase with slablike nuclei (up to $n_{\rm b} = 0.0827$ fm^{-3}, $\rho = 1.37 \times 10^{14}$ g cm^{-3}). Subsequently there are two phases with the roles of nuclear matter and neutron matter reversed, the rodlike one (up to $n_{\rm b} = 0.0854$ fm^{-3}, $\rho = 1.42 \times 10^{14}$ g cm^{-3}), and the "Swiss cheese" (inverted-spheres) one, which is the analog of the phase with spherical nuclei and is the last phase in the neutron star crust (up to $n_{\rm b} = 0.0861$ fm^{-3}, $\rho = 1.43 \times 10^{14}$ g cm^{-3}). At higher densities the nuclei dissolve into the uniform matter of the neutron star core.

In each crystalline phase of matter the Wigner-Seitz cell has its own geometry, but we assume that in the phases of (body centered cubic) crystals of ordinary or inverted spherical nuclei it may be approximated by a sphere, and in rodlike phases by a right circular cylinder. Let the nucleon density distributions be described by Eq. (B.7). In the phases with rods and slabs, $n_p^{\rm out} = 0$, $n_n^{\rm out}$ describes the number density of free neutrons, and the region $r < R_n$ is occupied by the nucleus itself (with $n_n^{\rm cen} > n_n^{\rm out}$). In the two "bubble" phases with the roles of nuclear matter and neutron matter reversed, $n_p^{\rm out} \neq 0$, and $n_j^{\rm out} > n_j^{\rm cen}$, i.e., the local number density of neutrons and protons increases with increasing distance r from the center of the Wigner-Seitz cell. We interpolate the parameters of Eq. (B.7) as functions of $n_{\rm b}$ within each phase separately. In the rest of this Appendix, we introduce

$$\nu \equiv n_{\rm b} \times \text{fm}^3. \tag{B.15}$$

Rodlike nuclei. For the cylindrical nuclei, we have

$$
\begin{aligned}
r_{\rm c} &= (8.3014 + 764.026\,\nu - 16\,827.2\,\nu^2 + 100\,759\,\nu^3)\ \text{fm}, && \text{(B.16a)}\\
t_n &= -0.122\,016 + 163.6626\,\nu - 2\,751.439\,\nu^2 + 15\,238.15\,\nu^3, && \text{(B.16b)}\\
R_n &= (-40.383\,47 + 2\,328.248\,\nu - 37\,345.32\,\nu^2 + 207\,924.7\,\nu^3)\ \text{fm}, && \text{(B.16c)}\\
n_n^{\rm cen} &= (0.11371 - 0.611\,5979\,\nu + 9.431\,739\,\nu^2 - 63.742\,37\,\nu^3)\ \text{fm}^{-3}, && \text{(B.16d)}\\
n_n^{\rm out} &= (-0.019\,130\,93 + 1.706\,435\,\nu - 12.511\,92\,\nu^2 + 59.524\,78\,\nu^3)\ \text{fm}^{-3}, && \text{(B.16e)}\\
t_p &= -2.521\,390 + 304.3897\,\nu - 4966.492\,\nu^2 + 25\,571.19\,\nu^3, && \text{(B.16f)}\\
R_p &= (-41.773\,61 + 2331.504\,\nu - 37674.33\,\nu^2 + 212\,689.7\,\nu^3)\ \text{fm}, && \text{(B.16g)}\\
n_p^{\rm cen} &= (11.371 - 0.611\,5979\,\nu + 9.431\,739\,\nu^2 - 63.742\,37\,\nu^3)\ \text{fm}^{-3}, && \text{(B.16h)}\\
n_p^{\rm out} &= 0. && \text{(B.16i)}
\end{aligned}
$$

The numbers of protons and nucleons (Z and A) inside a nucleus, and the total number of nucleons A' *per unit length* of a cylindrical Wigner-Seitz cell equal

$$
Z = \pi r_p^2 n_p^{\rm in}, \quad A = Z + \pi r_n^2 n_n^{\rm in}, \quad A' = A + \pi(r_{\rm c}^2 - r_n^2) n_n^{\rm out}, \qquad \text{(B.17)}
$$

where r_p, $n_p^{\rm in}$, r_n, and $n_n^{\rm in}$ are defined by Eqs. (B.8) and (B.9) with $d = 2$.

Slablike nuclei. For the plane-parallel nuclei,

$$
\begin{aligned}
r_{\rm c} &= (-245.4595 + 11\,168.62\,\nu - 157\,290.7\,\nu^2 + 722\,159\,\nu^3)\ \text{fm}, && \text{(B.18a)}\\
t_n &= -267.2904 + 10\,459\,\nu - 135\,445.7\,\nu^2 + 585\,206\,\nu^3, && \text{(B.18b)}\\
R_n &= (9\,831.081 - 371\,401.1\,\nu + 4\,675\,343\,\nu^2 - 19\,591\,770\,\nu^3)\ \text{fm}, && \text{(B.18c)}\\
n_n^{\rm cen} &= (0.247\,6255 - 6.583\,347\,\nu + 91.630\,22\,\nu^2 - 425.2562\,\nu^3)\ \text{fm}^{-3}, && \text{(B.18d)}\\
n_n^{\rm out} &= (-0.805\,9552 + 31.998\,28\,\nu - 401.3776\,\nu^2 + 1\,723.221\,\nu^3)\ \text{fm}^{-3}, && \text{(B.18e)}\\
t_p &= 0.002\,725\,985 + 253.6894\,\nu - 5\,499.141\,\nu^2 + 33\,259.03\,\nu^3, && \text{(B.18f)}\\
R_p &= (-714.6039 + 28\,584.02\,\nu - 380\,503.3\,\nu^2 + 1\,703\,796\,\nu^3)\ \text{fm}, && \text{(B.18g)}\\
n_p^{\rm cen} &= (0.082\,536\,46 - 2.548\,742\,\nu + 31.836\,15\,\nu^2 - 147.7704\,\nu^3)\ \text{fm}^{-3}, && \text{(B.18h)}\\
n_p^{\rm out} &= 0. && \text{(B.18i)}
\end{aligned}
$$

The numbers of protons and nucleons (Z and A) inside a nucleus, and the total number of nucleons A' *per unit surface area* of a slablike Wigner-Seitz cell equal

$$
Z = 2\,r_p n_p^{\rm in}, \quad A = Z + 2\,r_n n_n^{\rm in}, \quad A' = A + 2\,(r_{\rm c} - r_n)\,n_n^{\rm out}, \qquad \text{(B.19)}
$$

where r_p, $n_p^{\rm in}$, r_n, and $n_n^{\rm in}$ are defined by Eqs. (B.8) and (B.9) with $d = 1$.

Cylindrical "bubbles". For the phase of "inverse cylindrical" nuclei,

$$r_{\rm c} = (430.966\,65 - 9\,710.2218\,\nu + 56\,422.005\,\nu^2)\ \text{fm}, \tag{B.20a}$$
$$t_n = 64.947\,03 - 1\,034.690\,\nu + 3\,501.129\,\nu^2, \tag{B.20b}$$
$$R_n = (271.654 - 6\,015.092\,\nu + 35\,000.53\,\nu^2)\ \text{fm}, \tag{B.20c}$$
$$n_n^{\rm cen} = (0.443\,7022 - 9.905\,772\,\nu + 65.004\,63\,\nu^2)\ \text{fm}^{-3}, \tag{B.20d}$$
$$n_n^{\rm out} = (-0.323\,9546 + 9.926\,548\,\nu - 59.979\,51\,\nu^2)\ \text{fm}^{-3}, \tag{B.20e}$$
$$t_p = 94.08485 - 1\,457.401\,\nu + 4\,499.405\,\nu^2, \tag{B.20f}$$
$$R_p = (441.3152 - 10\,140.12\,\nu + 60\,000.7\,\nu^2)\ \text{fm}, \tag{B.20g}$$
$$n_p^{\rm cen} = 0, \tag{B.20h}$$
$$n_p^{\rm out} = (-0.077\,336\,78 + 2.235\,163\,\nu - 15.000\,97\,\nu^2)\ \text{fm}^{-3}. \tag{B.20i}$$

The number of protons outside the "bubbles" and the total number of nucleons (Z and A') *per unit length* of a cylindrical Wigner-Seitz cell equal

$$Z = \pi(r_{\rm c}^2 n_p^{\rm out} + r_p^2 n_p^{\rm in}), \quad A' = Z + \pi r_{\rm c}^2 n_n^{\rm out} - \pi r_n^2\,(n_n^{\rm out} - n_n^{\rm in}), \tag{B.21}$$

where r_p, $n_p^{\rm in}$, r_n, and $n_n^{\rm in}$ are defined by Eqs. (B.8) and (B.9) with $d = 2$. In this case, $n_p^{\rm in}$ is negative, which corresponds to a deficit of protons inside the bubble relative to the surrounding medium. Contrary to the case of the ordinary nuclei, the proton core radius r_p is now greater than r_n, since the skin of the neutron bubble remains composed of neutrons, as in ordinary nuclei.

Spherical "bubbles". For the "inverse spherical" nuclei,

$$r_{\rm c} = (36.6584 - 248.1623\,\nu)\ \text{fm}, \tag{B.22a}$$
$$t_n = 73.420\,26 - 830.003\,\nu, \tag{B.22b}$$
$$R_n = (10.989\,02 + 50.06982\,\nu)\ \text{fm}, \tag{B.22c}$$
$$n_n^{\rm cen} = (-0.039\,683\,58 + 1.299\,808\,\nu)\ \text{fm}^{-3}, \tag{B.22d}$$
$$n_n^{\rm out} = (0.235\,124 - 1.749\,754\,\nu)\ \text{fm}^{-3}, \tag{B.22e}$$
$$t_p = 105.9954 - 1\,204.998\,\nu, \tag{B.22f}$$
$$R_p = (2.004\,501 + 150.005\,8\,\nu)\ \text{fm}, \tag{B.22g}$$
$$n_p^{\rm cen} = 0, \tag{B.22h}$$
$$n_p^{\rm out} = (0.033\,66631 - 0.350\,0152\,\nu)\ \text{fm}^{-3}. \tag{B.22i}$$

The number of protons Z outside the "bubbles" and the total number of nucleons A' in a Wigner-Seitz cell equal

$$Z = (4\pi/3)(r_{\rm c}^3 n_p^{\rm out} + r_p^3 n_p^{\rm in}), \quad A' = Z + \frac{4\pi}{3} r_{\rm c}^3 n_n^{\rm out} - \frac{4\pi}{3} r_n^3 (n_n^{\rm out} - n_n^{\rm in}), \tag{B.23}$$

where r_p, $n_p^{\rm in}$, r_n, and $n_n^{\rm in}$ are defined by Eqs. (B.8) and (B.9) with $d = 3$. As for cylindrical "bubbles", $n_p^{\rm in}$ is negative and $r_p > r_n$.

Thus, we have a simple analytic description of the neutron and proton local density profiles for the ground-state matter throughout the outer and inner neutron star crusts including nonspherical phases of atomic nuclei. This description is referred to as the *smooth composition model* (SCM) of ground-state matter.

Appendix C
ANALYTICAL REPRESENTATIONS OF UNIFIED EOSs

EOSs are usually tabulated, and subsequently interpolated between mesh points in computer codes. Interpolation introduces ambiguities in calculated parameters of neutron star models. Moreover, interpolation should respect exact thermodynamic relations which turned out to be especially serious in high-precision two-dimensional modeling of rapidly spinning neutron stars (Nozawa *et al.*, 1998). In three-dimensional calculations of stationary configurations in a close neutron star binary one needs derivatives of the pressure with respect to the enthalpy; tabulated EOSs become even less useful (see, e.g., Gourgoulhon *et al.* 2001). The problems of using tabulated EOSs are particularly serious for the EOSs constructed by matching different EOS segments (e.g., the crust and the core).

In view of all these problems, it is of great interest to derive analytical representations of EOSs. They introduce no ambiguity of interpolation; the derivatives can be precisely calculated; they can be constructed fulfilling exactly the thermodynamic relations. Here we present, following Haensel & Potekhin (2004), analytical representations of two *unified* EOSs, FPS and SLy (see Chapters 3 and 5).

The outer and inner crusts as well as the inner crust and the core of a neutron star are separated by phase transitions. There may also be phase transitions in the core (Chapter 7) and weak density jumps between layers containing different nuclei in the crust (Chapter 3). These weak jumps in the crust will be neglected; the EOSs we consider do not contain any phase transitions in the core. We will approximate the EOSs by fully analytical functions. However, the different character of the EOS in the outer crust, inner crust and the core is reflected by the complexity of the fit, which consists of several fractional-polynomial parts, matched together by virtue of the function

$$f_0(x) = \frac{1}{\mathrm{e}^x + 1} \ . \tag{C.1}$$

We employ two tabulated unified EOSs, FPS[1] or SLy, at $\rho > 5 \times 10^{10}$ g cm^{-3}. At lower densities, 10^8 g cm$^{-3} \lesssim \rho < 5 \times 10^{10}$ g cm^{-3}, the crustal matter is described by the EOS of Haensel & Pichon (1994) (HP94), based on experimental nuclear data. This EOS is supplemented by the BPS EOS for cold catalyzed matter at $\rho \lesssim 10^8$ g cm^{-3}(Chapter 3). The lowest-density parts of the tables at $\rho < 10^5$ g cm^{-3} have not been used in the fitting. At such low ρ the EOS is no longer one-parametric, but depends also on temperature (see Fig. 1.3).

[1]The FPS table has been kindly provided by N. Stergioulas.

Table C.1. Parameters of the fit (C.2)

i	a_i(FPS)	a_i(SLy)	i	a_i(FPS)	a_i(SLy)
1	6.22	6.22	10	11.8421	11.4950
2	6.121	6.121	11	-22.003	-22.775
3	0.006004	0.005925	12	1.5552	1.5707
4	0.16345	0.16326	13	9.3	4.3
5	6.50	6.48	14	14.19	14.08
6	11.8440	11.4971	15	23.73	27.80
7	17.24	19.105	16	-1.508	-1.653
8	1.065	0.8938	17	1.79	1.50
9	6.54	6.54	18	15.13	14.67

C.1. Representation convenient for non-rotating stars

For non-rotating star, it is instructive to parameterize the pressure as function of density. Let us introduce $\xi = \lg(\rho/\text{g cm}^{-3})$ and $\zeta = \lg(P/\text{dyn cm}^{-2})$. Then the parameterization reads

$$\begin{aligned}\zeta &= \frac{a_1 + a_2\xi + a_3\xi^3}{1 + a_4\,\xi}\, f_0(a_5(\xi - a_6)) + (a_7 + a_8\xi)\, f_0(a_9(a_{10} - \xi)) \\ &\quad + (a_{11} + a_{12}\xi)\, f_0(a_{13}(a_{14} - \xi)) + (a_{15} + a_{16}\xi)\, f_0(a_{17}(a_{18} - \xi))\,. \qquad \text{(C.2)}\end{aligned}$$

The parameters a_i for the FPS and SLy EOSs are given in Table C.1. The typical fit error of P is (1–2)% (for $\xi \gtrsim 5$). The maximum error is associated with the phase transitions available in the original tabulated EOSs but smoothed by the fit (C.2). For the FPS EOS, the maximum error is 3.6% at $\xi = 14.22$ (the crust-core interface). For the SLy EOS, the maximum error is 2.9% at $\xi = 8.42$ (the ^{62}Ni-^{64}Ni phase transition in the HP94 table).

The overall EOS throughout the neutron star is presented in Fig. 1.3 in Chapter 1. The figure shows $\log P$ against $\log\rho$ ($\log \equiv \lg \equiv \log_{10}$) for the tabulated EOSs (symbols) and the corresponding fit (the solid line). Triangles correspond to the BPS data, stars to HP94, and dots to the SLy data. By construction, the fit is accurate at $\rho \gtrsim 10^5$ g cm^{-3}. As stated above, at lower ρ the EOS becomes temperature-dependent. This is illustrated by the dashed lines, that show the OPAL EOS of iron plasma (Rogers *et al.* 1996; see § 2.4) for $T = 10^6$, 10^7, and 10^8 K. However, a reasonable continuation of the fit to lower densities can be constructed by a simple interpolation. For instance, the dotted line in Fig. 1.3 corresponds to $P = 10^\zeta + P_0$, where ζ is given by Eq. (C.2) (and ξ should be positive), and $P_0 = 3.5 \times 10^{14}\,\rho$ approximates the OPAL EOS for $\rho \sim \rho_\text{s}$ at $T = 10^7$ K (P is in dyn cm^{-2}, ρ in g cm^{-3}, and $\rho_\text{s} = 7.86$ g cm^{-3} is the lowest density in the BPS table).

In Fig. C.1 we compare the FPS and SLy EOSs. Symbols on the top panel show the data (triangles, stars, dots, and open circles for BPS, HP94, SLy, and FPS, respectively) and lines show the fits (the solid line is for SLy and the dot-dashed line for FPS). In order to make the differences between the data and fits and between SLy and FPS EOSs visible, we plot the *difference* $\log P - 1.4\log\rho$, where P is in dyn cm^{-2} and ρ in g cm^{-3}. The bottom panel shows the relative difference between the tabulated and fitted EOSs (solid and dot-dashed lines for SLy and FPS, respectively). It illustrates the accuracy of the fit (C.2).

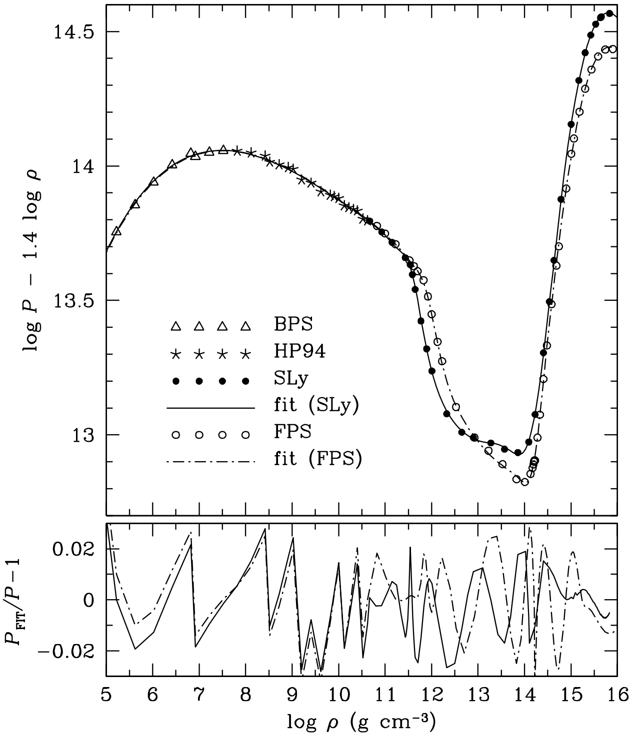

Figure C.1. Comparison of the data and fits for the SLy and FPS EOSs (Haensel & Potekhin, 2004). *Top*: Rarefied tabular data (symbols) and the fit (C.2) (lines). *Bottom*: Relative difference between the data and fit. Filled dots and the solid line are for the SLy EOS; open circles and the dot-dashed line are for the FPS EOS (triangles and stars on the top panel are the BPS and HP94 data at $\rho < 5 \times 10^{10}$ g cm^{-3}).

Now the baryon number density $n_{\rm b}(\rho)$ can be easily obtained from the integral form of Eq. (5.97):

$$\ln\left(\frac{n_{\rm b}}{n_{\rm bs}}\right) = c^2 \int_{\rho_{\rm s}}^{\rho} \frac{{\rm d}\rho'}{P(\rho') + \rho' c^2} , \tag{C.3}$$

where $\rho_{\rm s}$ and $n_{\rm bs}$ are the values of ρ and $n_{\rm b}$ at some low-density ("surface") point. Substituting $P(\rho')$ from Eq. (C.2), we recover the original tabular values with maximum errors $< 0.4\%$ and $< 0.12\%$ for the FPS and SLy EOSs, respectively.

In some applications, it may be convenient to use $n_{\rm b}$ as an independent variable, and treat ρ and P as functions of $n_{\rm b}$. For this purpose one can use the fit:

$$\begin{aligned} \frac{\rho}{n_{\rm b} m_0} \quad &= \quad 1 + \frac{p_1 n_{\rm b}^{p_2} + p_3 n_{\rm b}^{p_4}}{(1 + p_5 n_{\rm b})^2}\, f_0(-p_6(\log n_{\rm b} + p_7)) \\ &\quad + \frac{n_{\rm b}}{8 \times 10^{-6} + 2.1\, n_{\rm b}^{0.585}}\, f_0(p_6(\log n_{\rm b} + p_7)) , \end{aligned} \tag{C.4}$$

Table C.2. Parameters of the fits (C.4) and (C.5)

i	p_i(FPS)	p_i(SLy)	q_i(FPS)	q_i(SLy)
1	0.320	0.423	0.608	0.183
2	2.17	2.42	2.41	1.26
3	0.173	0.031	2.39	6.88
4	3.01	0.78	3.581	3.612
5	0.540	0.238	1.681	2.248
6	0.847	0.912	0.850	0.911
7	3.581	3.674	11.64	11.56

where $n_{\rm b}$ is in fm^{-3} and $m_0 = 1.66 \times 10^{-24}$ g. The inverse fit $n_{\rm b}(\rho)$ is given by

$$\begin{aligned} \frac{x}{n_{\rm b}} &= 1 + \frac{q_1 x^{q_2} + q_3 x^{q_4}}{(1+q_5 x)^3}\, f_0(q_6(q_7 - \log\rho)) \\ &+ \frac{x}{8\times 10^{-6} + 2.1\, x^{0.585}}\, f_0(q_6(\log\rho - q_7)), \end{aligned} \tag{C.5}$$

where $x = \rho/m_0$ and ρ is in g cm^{-3}. Coefficients p_i and q_i of the fits (C.4) and (C.5) are given in Table C.2. The difference $(\rho - n m_0)$ is approximated by these equations with the error of a few percent.

It should be stressed that thermodynamics requires Eq. (5.97) to be satisfied exactly. To achieve this, one should not totally rely on the fits (C.4) and (C.5); otherwise thermodynamic consistency will be violated on the scale of fit errors (a fraction of percent). Thus, if ρ is used as an input, then $n_{\rm b}(\rho)$ should be calculated from Eq. (C.3). Alternatively, if the input is $n_{\rm b}$, then, after calculating $\rho_{\rm fit}(n_{\rm b})$ from Eq. (C.4) and $P(n_{\rm b}) = P(\rho_{\rm fit}(n_{\rm b}))$ from Eq. (C.2), one should refine $\rho(n_{\rm b})$ using the relation

$$\frac{\rho(n_{\rm b})}{n_{\rm b}} = \frac{\rho_{\rm s}}{n_{\rm bs}} + \int_{n_{\rm bs}}^{n_{\rm b}} \frac{P(n'_{\rm b})}{{n'_{\rm b}}^2 c^2}\, {\rm d}n'_{\rm b}\,, \tag{C.6}$$

which also follows from Eq. (5.97).

C.2. Representation convenient for rotating stars

For rotating stars, it is most useful to parameterize the density and pressure as functions of the pseudo-enthalpy H, Eq. (6.99). The latter can be written in terms of the enthalpy per baryon h according to Eq. (6.102). Let us define $\eta \equiv h/m_0c^2 - 1$. In view of the relation (6.101), the function $\xi(\eta)$ (to be parameterized) is not independent of the function $\zeta(\xi)$ parameterized by Eq. (C.2). In order to fulfill Eq. (6.101) as accurately as possible, we first calculate $\eta(\xi)$ using Eqs. (C.2) and (6.101) and then find the inverse fit $\xi(\eta)$. The best fit reads:

$$\begin{aligned} \xi &= \left(b_1 + b_2 \lg\eta + \frac{b_3 \eta^{b_4}}{1 + b_5\eta}\right) f_0(b_6(\lg\eta - b_7)) \\ &+ \frac{b_8 + b_9 \lg\eta + (b_{10} + b_{11}\lg\eta)(b_{12}\eta)^7}{1 + b_{13}\eta + (b_{12}\eta)^7} f_0(b_6(b_7 - \lg\eta)) \\ &+ b_{14}\, f_0(b_{15}(b_{16} - \lg\eta))\,, \end{aligned} \tag{C.7}$$

Table C.3. Parameters of the fit (C.7)

i	b_i(FPS)	b_i(SLy)	i	b_i(FPS)	b_i(SLy)
1	5.926	5.926	9	11.97	34.96
2	0.4704	0.4704	10	15.432	15.328
3	19.92	20.13	11	0.6731	0.621
4	0.2333	0.2347	12	49.4	63.1
5	2.63	3.07	13	11.47	68.5
6	54.7	97.8	14	1.425	2.518
7	-1.926	-2.012	15	3.0	2.6
8	36.89	89.85	16	0.913	1.363

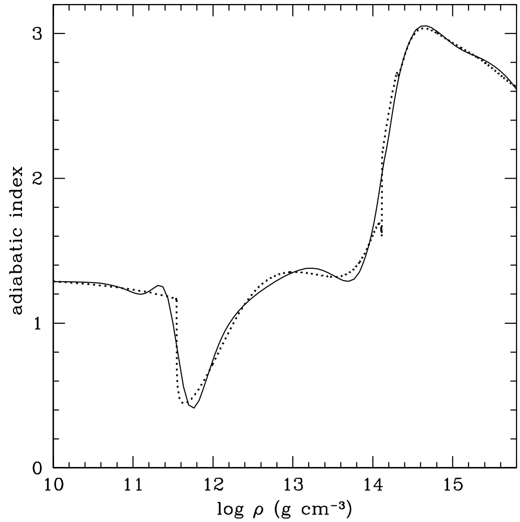

Figure C.2. Adiabatic index for the SLy EOS. The solid line is the fit, the dotted line shows precise values.

where the parameters b_i are given in Table C.3. The typical fit error of ρ, provided by Eq. (C.7), is about 1% at $\eta \gtrsim 10^{-7}$ (i.e., at $\xi \gtrsim 3$); the maximum fit error $< 4\%$ occurs near the neutron drip and near the crust-core interface.

Combining the fits (C.2) and (C.7) with Eq. (C.3) or Eq. (C.5) we get the parameterizations of $\rho(H)$, $P(H)$, and $n_{\rm b}(H)$ needed for calculating stationary rotating neutron star models. In this case, the function $P(H) = P(\rho(H))$ obtained from Eqs. (C.2) and (C.7) reproduces the tabular values with a typical error $\sim$(1–2)% and with the maximum error within 10% near the crust-core interface.

The remark on the thermodynamic consistency, made at the end of § C.C.1, applies here as well. One should refine fitted values of either $n_{\rm b}$ or ρ, using the exact relations (C.3) or (C.6).

C.3. Adiabatic index

An important dimensionless parameter characterizing the stiffness of the EOS at a given density is the adiabatic index, defined by Eq. (5.109). Using our fit (C.2), we obtain the analytical expression

$$
\begin{aligned}
&(1+P/\rho c^2)^{-1}\gamma = \mathrm{d}\zeta/\,\mathrm{d}\xi \\
&= \left[\frac{a_2 - a_1 a_4 + 3a_3\xi^2 + 2a_3 a_4 \xi^3}{(1+a_4\xi)^2} - a_5\,\frac{1_1 + a_2\xi + a_3\xi^3}{1+a_4\xi}\, f_0(a_5(a_6-\xi))\right] f_0(a_5(\xi - a_6)) \\
&\quad + \sum_{i=2}^{4} f_0(a_{4i+1}(a_{4i+2}-\xi))\big[a_{4i} + a_{4i+1}(a_{4i-1} + a_{4i}\xi) f_0(a_{4i+1}(\xi - a_{4i+2}))\big]\,. \qquad \text{(C.8)}
\end{aligned}
$$

The behavior of γ in different neutron star layers is displayed in Fig. C.2. Precise values of γ calculated by Douchin & Haensel (2001) are shown by the dotted line, and the fit, given by Eqs. (C.2) and (C.8), is shown by the solid line.

Appendix D
SEMI-ANALYTICAL EOSs IN NEUTRON STAR CORES

In this Appendix we describe a class of EOSs for uniform matter in neutron star cores composed of nucleons, electrons and muons. These EOSs are based on analytic expressions for the energy per nucleon (excluding the rest-mass energy) quadratic in neutron excess,

$$E_{\rm N} = W(u) + S(u)\,(1-2x_p)^2\,, \tag{D.1}$$

where $u \equiv n_{\rm b}/n_0$ is the dimensionless baryon number density, $x_p = n_p/n_{\rm b}$ is the proton fraction; $W(u)$ and $S(u)$ are, respectively, the energy per nucleon in symmetric nuclear matter and the symmetry energy (assumed to be given by analytic functions). The total energy per nucleon is then $E = E_{\rm N} + E_{\rm N0} + E_e + E_\mu$, where $E_{\rm N0}$ is the nucleon rest-mass contribution, while E_e and E_μ are the electron and muon contributions (also given analytically because electrons and muons constitute almost free Fermi gases). In this case, the total energy E is presented in an analytic form which allows one to avoid ambiguities of interpolation (of otherwise tabulated values of $E_{\rm N}$) and to strictly satisfy thermodynamic relations and conservation laws.

The beta equilibrium conditions are given by relations between the chemical potential of nucleons and leptons,

$$\mu_n = \mu_p + \mu_e\,, \qquad \mu_e = \mu_\mu\,. \tag{D.2}$$

The local electric neutrality requires $x_p = x_e + x_\mu$, where $x_e = n_e/n_{\rm b}$ and $x_\mu = n_\mu/n_{\rm b}$. The electron and muon chemical potentials are equal to the appropriate Fermi energies,

$$\mu_e \approx c\,p_{{\rm F}e}\,, \qquad \mu_\mu = \sqrt{m_\mu^2\,c^4 + p_{{\rm F}\mu}^2 c^2}\,, \tag{D.3}$$

where $p_{{\rm F}j} = \hbar\,(3\pi^2 n_{\rm b} x_j)^{1/3}$ with $j = e$ or μ. At a fixed $n_{\rm b}$ under the natural simplified assumption that $m_p = m_n$ the beta equilibrium conditions reduce to a set of two equations

$$x_\mu + x_e - \frac{1}{2} + \mathcal{A}\,x_e^{1/3} \quad = \quad 0\,, \tag{D.4a}$$

$$x_e^{2/3} - x_\mu^{2/3} - \mathcal{B} \quad = \quad 0\,, \tag{D.4b}$$

where $\mathcal{A}$ and $\mathcal{B}$ are dimensionless functions of $n_{\rm b}$,

$$\mathcal{A} = \hbar c\,(3\pi^2 n_{\rm b})^{1/3}/(8S(n_{\rm b}))\,, \quad \mathcal{B} = (m_\mu c/\hbar)^2/(3\pi^2 n_{\rm b})^{2/3}\,. \tag{D.5}$$

Beta equilibrium depends on $S(u)$ but not on $W(u)$. For a given $n_{\rm b}$, one can easily solve Eqs. (D.4a) and (D.4b) and determine all particle fractions. After that one can use standard thermodynamic relations, derive the analytic expressions for the energy density (ρc^2) and the pressure, and calculate ρ and P at given $n_{\rm b}$ and the particle fractions. In this way one constructs a semi-analytical EOS; the only simple numerical procedure consists in solving Eqs. (D.4a) and (D.4b). The numerical accuracy of this EOS for an employed nuclear interaction model (D.1) can be formally very high.

Table D.1. Three sets of parameters for $W(u)$ models of Prakash *et al.* (1988)

K_0 MeV	A MeV	B MeV	B'	σ	C_1 MeV	C_2 MeV
120	75.94	–30.88	0	0.498	–83.84	23.0
180	440.94	–213.41	0	0.927	–83.84	23.0
240	–46.65	39.54	0.3	1.663	–83.84	23.0

The muons appear only in sufficiently dense matter in which $x_e > \mathcal{B}^{3/2}$. At lower densities the muons are absent ($x_\mu = 0$) and Eq. (D.4b) can be disregarded. Then Eq. (D.4a) reads $2\,x_e - 1 + 2\,\mathcal{A}\,x_e^{1/3} = 0$ and can be solved analytically. In this case the procedure of constructing the EOS becomes purely analytical.

Model PAL. Prakash *et al.* (1988) proposed a model (PAL) of $W(u)$ which fits experimental values of the energy per nucleon and the density of symmetric nuclear matter at the saturation point $u = 1$: $(\mathrm{d}W/\mathrm{d}u)_1 = 0$, $W(1) = -16$ MeV, and $n_0 = 0.16\ \mathrm{fm}^{-3}$. They suggested three versions corresponding to three values of the compression modulus at saturation, K_0=120, 180, and 240 MeV. The functional form of $W(u)$ is

$$W(u) = E_0^{\rm FFG} u^{2/3} + \frac{Au}{2} + \frac{Bu^\sigma}{1 + B'u^{\sigma-1}} + 3\sum_{i=1,2} C_i \alpha_i^3 \left[\frac{u^{1/3}}{\alpha_i} - \mathrm{Artan}\left(\frac{u^{1/3}}{\alpha_i}\right)\right], \quad \text{(D.6)}$$

where $\alpha_1 = 1.5$, $\alpha_2 = 3$, and the energy of free Fermi gas (FFG) is $E_0^{\rm FFG} = \frac{3}{5}\epsilon_{\rm F}(n_0) = 0.3\,p_{\rm N0}^2/m_n = 22.1$ MeV, where $p_{\rm N0} = \hbar\,(1.5\pi^2 n_0)^{1/3}$. The three sets of parameters for three models of $W(u)$ are given in Table D.1.

Prakash *et al.* (1988) proposed $S(u)$ of the form

$$S(u) = (2^{2/3} - 1)\,E_0^{\rm FFG}\left[u^{2/3} - F(u)\right] + S_0 F(u)\,. \quad \text{(D.7)}$$

Putting $F \equiv 0$ we recover the value of S for a free Fermi gas model, Eq. (5.103) (see a discussion following Eq. (5.103)). Actually, the function $F(u)$ is defined in such a way to reproduce the experimental value S_0, so that $S(1) = S_0$ and therefore $F(1) = 1$. Prakash *et al.* (1988) assumed $S_0 = 30$ MeV, and proposed three models (I,II, and III) of $F(u)$,

$$F_{\rm I}(u) = u\,, \quad F_{\rm II}(u) = 2u^2/(u+1)\,, \quad F_{\rm III}(u) = \sqrt{u}\,. \quad \text{(D.8)}$$

Thus, they get nine PAL EOSs, which differ in the stiffness and in the density dependence of the symmetry energy.

Model PAPAL. Page & Applegate (1992) proposed one very simple power-law density dependence of the symmetry energy

$$S(u) = 30u^{0.7}\ \mathrm{MeV}\,. \quad \text{(D.9)}$$

They combined the above model for $S(u)$ with $K_0 = 180$ MeV model for $W(u)$ of Prakash *et al.* (1988). Accordingly they obtained what we call the PAPAL EOS of the $npe\mu$ matter, which yields $M_{\max} = 1.7\ M_\odot$ and a direct Urca core for $M > 1.35\ M_\odot$. One can also implant this form of $S(u)$ into other PAL models, with $K_0 = 120$ and 240 MeV, and obtain thus softer and stiffer EOSs (see, e.g., Yakovlev *et al.* 2001).

Model HHJ. Heiselberg & Hjorth-Jensen (2000) constructed a two-parameter fit to the EOS of nuclear matter proposed by Akmal *et al.* (1998) (hereafter APR, with boost corrections and three-body forces; $V_{18} + \delta v + \mathrm{UIX}^*$),

$$W(u) = E_0\, u\, (2 + \delta - u)/(1 + \delta u)\ , \tag{D.10}$$

where δ is the "softness" parameter important for $u \gg 1$. By construction, $W(1) = E_0 = -15.8$ MeV (the value adopted by Akmal *et al.* 1998). The free parameter δ is related to the incompressibility of the symmetric nuclear matter at saturation point,

$$K_0 = 9 \left(\frac{\mathrm{d}^2 W}{\mathrm{d}u^2} \right)_{u=1} = \frac{18\, |E_0|}{1 + \delta}\ . \tag{D.11}$$

As far as the symmetry energy is concerned, Heiselberg & Hjorth-Jensen (2000) fitted the APR results with a simple formula of Page & Applegate (1992) type,

$$S(u) = 32\ u^\zeta\ \mathrm{MeV}\ . \tag{D.12}$$

Heiselberg & Hjorth-Jensen (2000) suggested the basic values $\delta = 0.2$ and $\zeta = 0.6$ which make their EOS similar to the APR EOS. In contrast to the PAL and PAPAL EOSs, which are largely phenomenological and relatively old, the HHJ EOS is based on the recent realistic APR EOS.

The HHJ EOS has a very simple analytic form and can be made slightly softer (or stiffer) by increasing (decreasing) the value of δ with respect to 0.2 (at a fixed ζ). Fixing δ one can regulate the symmetry energy (D.12) by increasing (decreasing) ζ with respect to $\zeta = 0.6$. This would slightly decrease (increase) the threshold density for opening the direct Urca process (Gusakov *et al.*, 2005).

Appendix E
SCALING OF STELLAR MODELS FOR LINEAR EOSs

Let us outline scaling relations of stellar models built of the matter with the linear EOS of the form

$$P = ac^2(\rho - \rho_{\rm s}). \tag{E.1}$$

E.1. The causal limit EOS with $a = 1$

It is convenient to introduce the dimensionless variables,

$$\widetilde{\rho} = \frac{\rho}{\rho_{\rm s}}\,, \quad \widetilde{P} = \frac{P}{\rho_{\rm s}c^2} = \widetilde{\rho} - 1\,, \quad \widetilde{r} = \frac{r}{r_0}, \quad \widetilde{m} = \frac{m}{M_0}, \quad \widetilde{n}_{\rm b} = \frac{n_{\rm b}}{n_{\rm s}}, \tag{E.2}$$

where $r_0 = c/\sqrt{G\rho_{\rm s}}$, $M_0 = \rho_{\rm s} r_0^3$, and $n_{\rm s}$ is the value of the baryon number density at the stellar surface $\rho = \rho_{\rm s}$. These variables allow one to rewrite the relativistic equations of hydrostatic equilibrium, Eqs. (6.7)-(6.8), in a dimensionless form. Using the thermodynamic relation

$$\mathrm{d}\widetilde{\rho}/\,\mathrm{d}\widetilde{n}_{\rm b} = (\widetilde{P} + \widetilde{\rho})/\widetilde{n}_{\rm b}, \tag{E.3}$$

one gets

$$\widetilde{n}_{\rm b} = \left[2\widetilde{P} + 1\right]^{1/2} = (2\widetilde{\rho} - 1)^{1/2}\,. \tag{E.4}$$

Non-rotating stars. The dimensionless Tolman-Oppenheimer-Volkoff and mass-balance equations read

$$\begin{aligned} \frac{\mathrm{d}\widetilde{\rho}}{\mathrm{d}\widetilde{r}} &= -\frac{\widetilde{m}}{\widetilde{r}^2}\frac{(2\widetilde{\rho} - 1)}{(1 - 2\widetilde{m}/\widetilde{r})}\left(1 + 4\pi\widetilde{r}^3\frac{\widetilde{\rho} - 1}{\widetilde{m}}\right)\,, \\ \frac{\mathrm{d}\widetilde{m}}{\mathrm{d}\widetilde{r}} &= 4\pi\widetilde{r}^2\widetilde{\rho}\,. \end{aligned} \tag{E.5}$$

The boundary conditions are $\widetilde{\rho}(0) = \widetilde{\rho}_{\rm c}$ and $\widetilde{m}(0) = 0$. The radius $\widetilde{R}$ is determined by $\widetilde{\rho}(\widetilde{R}) = 1$ and the dimensionless total gravitational mass $\widetilde{M} = \widetilde{m}(\widetilde{R})$. The solutions of Eqs. (E.5) form a one-parameter family of configurations labeled by $\widetilde{P}_{\rm c} = \widetilde{\rho}_{\rm c} + 1$. The dependence $\widetilde{M}(\widetilde{P}_{\rm c})$ is shown in Fig. E.1. The dimensionless maximum mass is $\widetilde{M}^{\rm CL}_{\rm max} = 0.0851$; it is reached for $\widetilde{P}_{\rm c,max} = 2.03$ ($\widetilde{\rho}_{\rm c,max} = 3.03$). The corresponding mass-radius relation is shown in Fig. E.2. Numerical values of the surface redshift (Fig. E.3) are independent of the choice of units.

A mass-radius diagram at any given $\rho_{\rm s}$ can be obtained from Fig. E.2 by coming back to ordinary units. Consequently, the points of a curve obtained for a given $\rho_{\rm s}$ transform into points of a curve calculated for another $\rho'_{\rm s}$. For example, the $M'(R')$ curve is obtained via scaling of the $M(R)$ one, namely, $R \rightarrow R' = (\rho_{\rm s}/\rho'_{\rm s})^{-1/2}R$, $M \rightarrow M' = (\rho_{\rm s}/\rho'_{\rm s})^{-1/2}M$. In geometrical terms, $M - R$ curves are self-similar. Any extremum of an unprimed curve transforms into an

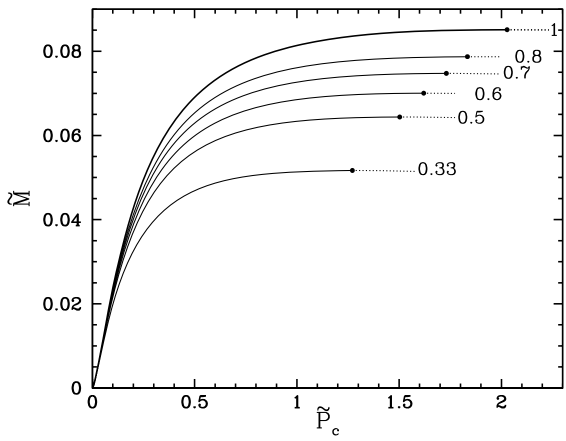

Figure E.1. The $\widetilde{M}(\widetilde{P}_{\rm c})$ curves labeled by the values of a. Filled circles mark maximum-mass configurations. Solid and dotted segments correspond to stable and unstable configurations, respectively. Prepared by J.L. Zdunik (2006, unpublished); with the kind permission of the author.

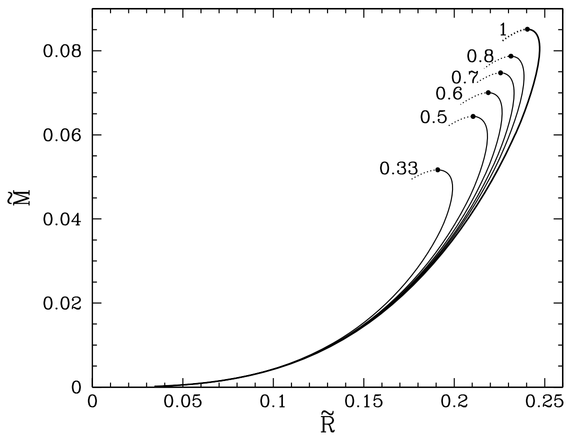

Figure E.2. The $\widetilde{M}(\widetilde{R})$ curves labeled by the values of a. Notations are the same as in Fig. E.1. Prepared by J.L. Zdunik (2006, unpublished); with the kind permission of the author.

extremum of a primed curve. In particular, the maximum mass configurations scale as

$$M_{\rm max}^{\rm CL} = M_0\ \widetilde{M}_{\rm max} = 2.116\ (\rho_{\rm s,15})^{-1/2}\ M_\odot\ , \tag{E.6a}$$

$$R_{M_{\rm max}}^{\rm CL} = r_0 \widetilde{R}_{M_{\rm max}} = 8.825\ (\rho_{\rm s,15})^{-1/2}\ {\rm km}\ , \tag{E.6b}$$

$$\rho_{\rm c,max}^{\rm CL}/\rho_{\rm s} = 3.03\ , \tag{E.6c}$$

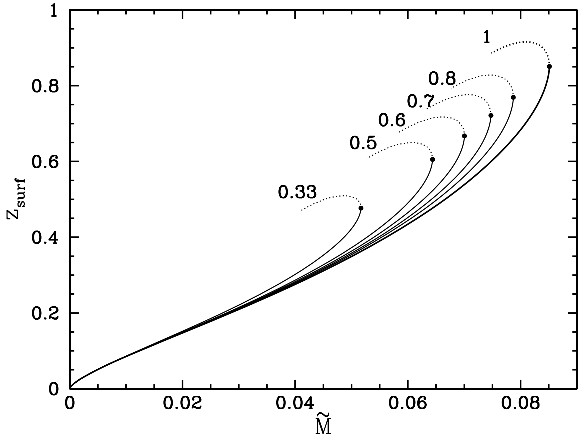

Figure E.3. The $z_{\rm surf}(\widetilde{M})$ curves labeled by the values of a. Notations are the same as in Fig. E.1. Prepared by J.L. Zdunik (2006, unpublished); with the kind permission of the author.

where $\rho_{\rm s,15} \equiv \rho_{\rm s}/10^{15}$ g cm^{-3}. The density contrast within stellar models based on the causal limit (CL) EOS is very low. Even at the maximum mass, the central density is only three times higher than the surface one.

The maximum surface redshift $z_{\rm surf}$ for stable configuration is reached at $M = M_{\rm max}$. It is independent of $\rho_{\rm s}$ and can be readily obtained from Eqs. (E.6a) and (E.6b),

$$z^{\rm CL}_{\rm max} = 0.8509 \; . \tag{E.7}$$

The equation which determines the moment of inertia for a slow rigid rotation, Eq. (6.65), can be written in a dimensionless form provided one expresses angular frequencies in $\sqrt{G\rho_{\rm s}}$. This form, together with the matching conditions explained in § 6.10.1, yields then the dimensionless moment of inertia $\widetilde{I}$, so that $I = M_0 r_0^2 \widetilde{I}$. The maximum moment of inertia for the CL EOS is given by

$$I^{\rm CL}_{\rm max} = M_0 r_0^2 \, \widetilde{I}^{\rm CL}_{\rm max} = 1.979 \; (\rho_{\rm s,15})^{-3/2} \;\; 10^{45} \; {\rm g \; cm}^2 \; . \tag{E.8}$$

The maximum of I is reached for M slightly (by $\sim$ 0.5%) lower than $M_{\rm max}$. The value of $I^{\rm CL}_{M_{\rm max}}$, which is lower than $I^{\rm CL}_{\rm max}$ by $\approx 1.6\%$, scales with $\rho_{\rm s}$ in the same way as $I^{\rm CL}_{\rm max}$.

Rotating stars. In order to transform Eq. (6.98), which describes the structure of a rotating star, into a dimensionless form one should supplement the dimensionless quantities (E.2) with the dimensionless frequencies

$$\widetilde{\Omega} = \Omega/\sqrt{G\rho_{\rm s}} \; , \qquad \widetilde{\omega} = \omega/\sqrt{G\rho_{\rm s}} \; . \tag{E.9}$$

In this way, one gets a dimensionless solution of Eq. (6.98). Solutions corresponding to any $\rho_{\rm s}$ can then be obtained by returning to physical units. Any two solutions for $\rho'_{\rm s}$ and $\rho_{\rm s}$ are self-similar. In particular, this is true for extremal configurations. For a rotating maximum-mass star one gets the same scaling as in the non-rotating case,

$$M^{\rm CL,rot\,\prime}_{\rm max} = M^{\rm CL,rot}_{\rm max} \; (\rho_{\rm s}/\rho'_{\rm s})^{1/2} \; . \tag{E.10}$$

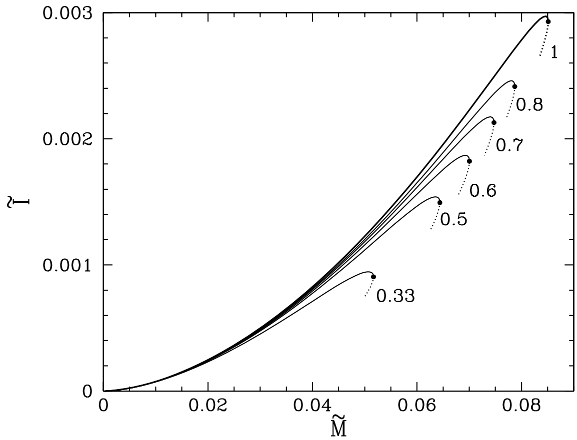

Figure E.4. The $\widetilde{I}(\widetilde{M})$ curves, labeled by the values of a. Notations are the same as in Fig. E.1. Prepared by J.L. Zdunik (2006, unpublished); with the kind permission of the author.

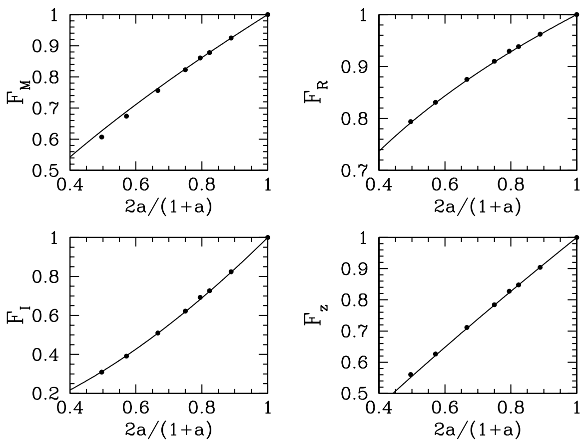

Figure E.5. Functions F_Q ($Q = M, R, z, I$) which determine the scaling for maximum-mass rotating stars with respect to variations of a. Filled circles show exact results, solid lines are the fits (E.17). Prepared by J.L. Zdunik (2006, unpublished); with the kind permission of the author.

A maximally rotating configuration has the shortest spin period $P = P_{\rm min}$ (the highest frequency $\Omega = \Omega_{\rm max}$) of all stably rotating configurations. This configuration is only slightly different from a maximum mass configuration. The shortest spin period $P_{\rm min}$ scales as

$$P_{\rm min}^{\rm CL\,\prime} = P_{\rm min}^{\rm CL}\,(\rho_{\rm s}/\rho_{\rm s}')^{1/2}\,. \qquad \text{(E.11)}$$

After integrating numerically the relevant dimensionless equations and returning to the ordinary physical units, we get the formulae for the CL EOS in an explicit form

$$\begin{aligned} M_{\max}^{\mathrm{CL,rot}} &= 2.75\ (\rho_{\mathrm{s},15})^{-1/2}\ M_\odot\ , && \text{(E.12a)}\\ P_{\min}^{\mathrm{CL}} &= 0.415\ (\rho_{\mathrm{s},15})^{-1/2}\ \mathrm{ms}\ . && \text{(E.12b)} \end{aligned}$$

E.2. The case of $a < 1$

The dimensionless form of the EOS is

$$\widetilde{P} = a(\widetilde{\rho} - 1)\ . \tag{E.13}$$

The formula for $\widetilde{n}_{\mathrm{b}}(P)$ can be derived using Eq. (E.3). One gets then a generalization of Eq. (E.4),

$$\widetilde{n}_{\mathrm{b}} = [(a+1)\widetilde{\rho} - a]^{1/(1+a)} = \left[(a+1)\widetilde{P}\,a^{-1} + 1\right]^{1/(1+a)}\ . \tag{E.14}$$

Non-rotating stars. The dimensionless equations read

$$\begin{aligned} a\frac{\mathrm{d}\widetilde{\rho}}{\mathrm{d}\widetilde{r}} &= -\frac{\widetilde{m}}{\widetilde{r}^2}\frac{[(1+a)\widetilde{\rho} - a]}{(1 - 2\widetilde{m}/\widetilde{r})}\left(1 + 4\pi\widetilde{r}^3 a\,\frac{\widetilde{\rho} - 1}{\widetilde{m}}\right)\ ,\\ \frac{\mathrm{d}\widetilde{m}}{\mathrm{d}\widetilde{r}} &= 4\pi\widetilde{r}^2\widetilde{\rho}\ . \end{aligned} \tag{E.15}$$

Now we get a dimensionless solution at any a. At a fixed a, the curves calculated using normal units and representing solutions with different ρ_{s} scale with the same power of ρ_{s} as in the case of $a = 1$. However, the numerical coefficients in these scaling relations depend on a. As shown by J.L. Zdunik (2006, unpublished), this dependence can be described by functions $F_Q(y)$, where $y = 2a/(a+1)$ is more convenient than just a, and $Q = M, R, z, I, \ldots$ In particular, the parameters of maximum-mass configurations are related to those obtained at $a = 1$ by

$$\begin{aligned} M_{\max} &= F_M(y)\ M_{\max}^{\mathrm{CL}}\ ,\quad R_{M_{\max}} = F_R(y)\ R_{M_{\max}}^{\mathrm{CL}}\ ,\\ z_{M_{\max}} &= F_z(y)\ z_{M_{\max}}^{\mathrm{CL}}\ ,\quad I_{M_{\max}} = F_I(y)\, I_{M_{\max}}^{\mathrm{CL}}\ . \end{aligned} \tag{E.16}$$

To a very good approximation (Fig. E.5), $F_Q(y)$ are simple power-laws (J.L. Zdunik, 2006, unpublished),

$$F_M(y) = y^{2/3},\quad F_R(y) = y^{1/3},\quad F_z(y) = y^{0.85},\quad F_I(y) = y^{5/3}\ . \tag{E.17}$$

The scaling with respect to $a \to a'$ takes simple form in the Newtonian limit. To make the equations of hydrostatic equilibrium independent of a, it is sufficient to "include" a into the gravitational constant G. Equilibrium configurations for any pair of values of a and ρ_{s} can then be obtained from the dimensionless solution (independent of a) by multiplying radius and mass by $a^{1/2}r_0$ and $a^{3/2}M_0$, respectively. This gives new scaling relations.

Rotating stars. Solutions of dimensionless equations of stationary motion depend parametrically on a. The power in the scaling under $\rho_{\mathrm{s}} \to \rho_{\mathrm{s}}'$ is the same as for $a = 1$, but the numerical prefactor is modified and depends on a.

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LIST OF SYMBOLS

This list is not comprehensive: for instance, we omit notations that are used only a few times in a particular section, and we do not list all notations which differ only by self-explanatory subscripts or superscripts. Standard mathematical notations (e, π, etc.) are also not listed.

A, A_i – ion mass number
$\boldsymbol{A}$ – vector potential
A' – effective mass number including bound and free neutrons in the inner crust (Chapters 2, 4)
A'' – number of free neutrons per nucleus in the inner crust (Chapter 2)
A_b – total number of baryons in the star
A_j – mass number of ions of species j
$a_0 = 0.5291772108 \times 10^{-8}$ cm – Bohr radius
a_i – ion-sphere radius
a_m – magnetic length
$\boldsymbol{B}$, B – magnetic field
$\mathcal{B}$ – bag constant
b – magnetic field in relativistic units (Chapter 4); binding energy per nucleon (Chapter 3)
C, C_V – heat capacity at constant volume
C_M – Madelung constant (Chapters 2, 3)
C_P – heat capacity at constant pressure
$c = 2.99\,792\,458 \times 10^{10}$ cm s^{-1} – speed of light in vacuum
d, D – distance
d – dimensionality of a nuclear phase (Chapter 3)
E – energy; energy per nucleon (Chapter 5)
E_κ – binding energy of a quantum state κ (Chapters 2, 4)
E_grav – gravitational energy
E_int – total internal energy of a star
E_rot – rotational energy
$\mathcal{E}$ – energy density
$e = 4.8032044 \times 10^{-10}$ esu – elementary charge
F – (Helmholtz) free energy (Chapters 2, 4)
F_id – ideal-gas free energy
F_ex – excess free energy

$F_{\rm q}$ – quantum (Wigner) correction to the free energy
$F_{\rm xc}$ – exchange-correlation contribution to the free energy
$f^{(0)}(\epsilon - \mu, T)$ – Fermi-Dirac distribution function
$G = 6.674 \times 10^{-8}$ cm^3 g^{-1} s^{-2} – gravitational constant
$G(k)$ – local field correction
$\hat{G}, G_{NN'}, G_{BB'}$ – G-matrix of the Brueckner-Bethe-Goldstone theory (Chapter 5)
g – gravitational acceleration
$g(r)$ – radial pair-correlation function
$g_e = 1.001\,159\,6522$ – electron gyromagnetic factor
$g_p = 5.585\,6947$ – proton gyromagnetic factor
$g_{\rm n}$ (n $= 1, 2, 3, \dots$) – Green's functions (Chapter 5)
$g_{\rm s}$, $g_{\rm v}$, g_ϕ, $\dots$ – coupling constants in a Lagrangian (Chapter 5)
g_κ – statistical weight of a quantum state κ
g_{ik} – spacetime metric tensor
H – Hamiltonian function; pseudo-enthalpy (§ 6.12.1, Appendix C)
$\hat{H}$ – Hamiltonian operator
$H_n(\xi)$ – Hermite polynomial (Chapter 4)
$\mathcal{H}_n(\xi)$ – harmonic-oscillator function (Chapter 4)
h – enthalpy per nucleon (Chapters 3, 6; Appendix C); gravitational wave strain (§ 6.11.2)
h_e – thickness of the electron surface of the strange star (Chapter 8)
h_{ij} – metric perturbation (Chapter 6)
$\hbar = 1.05457168 \times 10^{-27}$ erg s - Planck constant over 2π
I – moment of inertia
I_ν – Fermi-Dirac integral
J, $\boldsymbol{J}$ – angular momentum
$\hat{K}$ – kinetic energy operator
$\boldsymbol{K}$ – atomic pseudomomentum (Chapter 4)
K_c – critical value of the atomic pseudomomentum (Chapter 4)
K_0 – incompressibility of nuclear matter
$\boldsymbol{k}$ – wave vector
$k_{\rm B} = 1.380\,6505 \times 10^{-16}$ erg K^{-1} – Boltzmann constant
$k_{\rm F}$ – Fermi wavenumber
$k_{\rm TF}$ – Thomas-Fermi wave number
ℓ – leptons: electrons, muons
L – stellar luminosity
$\hat{\boldsymbol{L}}$ – orbital angular momentum operator (Chapter 5)
$L_{\rm Edd}$ – Eddington luminosity limit
$L_\odot = 3.846 \times 10^{33}$ erg s^{-1} – solar luminosity
$\mathcal{L}$ – Lagrangian density
l_κ – rms size of an atom or ion in a quantum state κ

M – stellar mass; gravitational stellar mass
$M_\odot = 1.9889 \times 10^{33}$ g – solar mass
m – mass of a particle; magnetic quantum number (Chapter 4); azimuthal mode number (Chapter 6)
$m = m(r)$ – gravitational mass inside a sphere with radial coordinate r
$m_e = 9.109\,3826 \times 10^{-28}$ g – electron mass
m^* – nucleon effective mass (Chapter 5)
m_e^* – effective dynamic mass of an electron
m_i – (mean) ion mass
m_j – mass of particle (species) j
$m_\mathrm{u} = 1.660\,5388 \times 10^{-24}$ g – unified atomic mass unit
$m_0 = 1.658\,610 \times 10^{-24}$ g – mass of the ^{56}Fe atom divided by 56
N_j – number of particles of type j
n – number density; pulsar braking index (Chapters 1, 9); polytropic index (Chapters 2, 6); Landau quantum number (Chapter 4)
n_b – number density of baryons
n_B – critical value of n_e in a strong magnetic field (Chapter 2); number density of baryon species B (Chapter 5)
$n_\mathrm{b,s}$ – baryon density at surface of bare strange star (Chapter 8)
n_c – baryon density at the stellar center
n_cc – baryon number density at the crust-core interface
n_e – the electron number density
n_j – number density of ions of species j
$n_\mathcal{N}$ – total number density of ions (atomic nuclei)
n_n – number density of free neutrons
n_s – number density of neutrons in the neutron skin (Chapter 3)
n_s – number density of strange quarks (Chapter 8)
n_0 – normal nucleon (baryon) density $= 0.16\ \mathrm{fm}^{-3}$
$\mathcal{N}_B(\epsilon)$ – n_e in the approximation of strong degeneracy (Chapter 4)
p, $\boldsymbol{p}$ – particle momentum
$\hat{\boldsymbol{p}}$ – momentum operator
$\tilde{p}_i$ – electron momentum components in relativistic units (Chapter 4)
P – pressure; star rotation period (Chapters 1, 9)
P_c – pressure at the stellar center
$P_\mathrm{id}^{(e)}$ – pressure of the ideal electron gas
$P_\mathrm{r} = 1.421\,775 \times 10^{25}\ \mathrm{dyn\ cm}^{-2}$ – relativistic unit of pressure
Q – neutrino emissivity (Chapter 1); critical wave number of density perturbations (Chapter 3)
q – particle charge
q_D – Debye wave number (Chapter 2)
q'_D – plasma screening wave number (Chapter 2)
$\boldsymbol{r}_c$ – guiding-center coordinate vector (Chapter 4)

R – stellar radius
R – circumferential radius of spherical star
$R_{\rm eq}$ – circumferential equatorial radius of rotating star
R_S – ion density parameter
$R_\odot = 6.960 \times 10^{10}$ cm – solar equatorial radius
R_∞ – apparent (radiation) stellar radius
$r_{\rm c}$ – equivalent cell radius (Chapter 3)
$r_{\rm D}$ – Debye length (Chapter 2)
$r_{\rm g}$ – gravitational (Schwarzschild) radius
r_e – electron screening length
$r_{\rm eq}$ – equatorial radial coordinate of rotating star (Chapters 6,8)
$r_{\rm pol}$ – radial coordinate of the pole of rotating star (Chapters 6,8)
$\mathcal{R}_{ik}$ – Ricci tensor
r_s – (plasma) density parameter
Ry $= 2.179\,872 \times 10^{-11}$ erg – Rydberg energy unit ($= 0.5$ Hartree)
S – entropy
s – spin quantum number (Chapter 4)
$S(q)$ – static structure factor (Chapter 2)
$S(\boldsymbol{q}, \omega)$ – dynamic structure factor (Chapter 2)
$\hat{\boldsymbol{S}}$ – total spin operator (Chapter 5)
$\hat{S}_{ij}$ – tensor coupling operator of ij nucleon pair (Chapter 5)
S_0 – symmetry energy at saturation density
T – temperature
$\hat{T}$, $T_{NN'}$ – in-medium T-matrix (Chapter 5)
$\hat{\boldsymbol{T}}$ – total isospin operator (Chapter 5)
T_B, $T_{\rm cycl}$ – critical values of T in a magnetic field (Chapter 2)
$T_{\rm c}$, $T_{\rm crit}$ – critical temperature of a phase transition
$T_{\rm F}$ – Fermi temperature
$T_{\rm l}$ – temperature of gas-liquid transition
$T_{\rm m}$ – melting temperature
$T_{{\rm p}e}$ – electron plasma temperature
$T_{\rm pi}$ – ion plasma temperature
$T_{\rm r} = 5.929\,889 \times 10^9$ K – relativistic temperature unit
$T_{\rm s}$ – effective surface temperature
$T_{\rm s}^\infty$ – $T_{\rm s}$ as detected by a distant observer
T_{ik} – stress-energy tensor
t – time variable
$t_{\rm p}$ – quantum plasma parameter (Chapter 2); pulsar age (Chapter 9)
$t_{\rm r}$ – temperature in relativistic units
U – internal energy; fluid velocity in the azimuthal direction (Chapter 6)
$\hat{U}$ – single-particle potential operator (Chapter 5)

$U(\sigma)$ – self-interaction contribution of σ field to Hamiltonian density (Chapter 5)
$\mathcal{U}$ – potential energy of an ensemble of particles
$\boldsymbol{u}$ – displacement vector (Chapter 3)
u_{ik} – components of the strain tensor (Chapter 3)
V – volume; potential function
$\hat{V}$ – potential energy operator
$V^{\text{eff}}(k)$ – Fourier transform of the Coulomb potential
$\hat{V}_{ijk}$ – three-nucleon interaction potential (Chapter 5)
v_{F} – Fermi velocity
$\hat{v}_{ij}$ – potential acting between a nucleon pair ij (Chapter 5)
v_{s} – speed of sound
$W_{\mathcal{N}}$ – energy of the nucleus
w – fraction of volume occupied by atomic nuclei
w_{κ} – occupation probability of a quantum state κ
X_{ν} – inverse function to the Fermi integral
x_B – relativity parameter in a quantizing magnetic field
x_{GR} – compactness parameter
x_j – fraction of ion species j
x_{r} – relativity parameter
Z, Z_{i} – ion charge number
$\mathcal{Z}$ – partition function
Z_{eff} – effective charge number
Z_j – charge number of ions of species j
z – gravitational redshift; proper depth (Chapter 6); starting energy parameter (Chapter 5)
z_{surf} – surface gravitational redshift (Chapter 6)
$\alpha_{\text{f}} = 0.007\,297\,352\,57$ – fine-structure constant
α_{s} – strong interaction (QCD) coupling constant
α_v – coupling strength of the vector field to nucleons
β_{r} – relativistic electron velocity parameter
Γ – ion Coulomb coupling parameter (Chapters 2, 4); Lorenz factor (Chapters 6,7,8)
Γ_e – (nondegenerate) electron Coulomb coupling parameter (Chapters 2, 4)
Γ_j – Coulomb coupling parameter for species j (Chapters 2, 4)
Γ_{m} – value of Γ at melting (Chapters 2, 4)
γ, γ_{ad} – adiabatic index (polytrope exponent)
γ – magnetic field in atomic units (Chapter 4); relativistic parameter of a binary system (Chapter 9)
γ_B – electron Lorentz factor in a quantizing magnetic field
γ_{r} – relativistic electron energy parameter (fiducial electron Lorentz factor)
Δ – superfluid energy gap (Chapters 1, 5, 7, 8); resonance (Chapters 5, 7)

δ – Dirac's delta function; neutron excess (Chapters 3, 5); quantum defect (Chapter 4)
ϵ – electron energy (Chapters 2, 4); oblateness parameter (Chapter 6); quark energy (Chapter 6)
$\epsilon_{\rm F}$ – Fermi energy
ϵ_k – kinetic energy of nucleon of momentum k (Chapter 5)
ε – dielectric (screening) function (Chapter 2)
ε_k – quasiparticle energy (Chapter 5)
ζ – bulk viscosity (Chapter 1); dimensionless coupling parameter (Chapter 8)
η – shear viscosity (Chapter 1); inverse quantum plasma parameter (Chapter 2)
θ – polar angle; electron degeneracy parameter (Chapter 2)
κ – thermal conductivity (Chapter 1); set of quantum numbers (Chapters 2, 4); surface curvature (Chapter 3)
$\lambda\!\!\!^{-}_{\rm C} = 3.86\,159\,268 \times 10^{-11}$ cm - Compton wavelength over 2π
$\lambda = \lambda(r)$ – metric function (Chapter 6)
λ – squared oscillation frequency (Chapter 6); relative density jump (Chapter 7)
λ_e – electron thermal wavelength (Chapters 2, 4)
$\lambda_{\rm H}$ – thermal wavelength of the H atom (Chapters 2, 4)
λ_j – thermal wavelength of particle species j (Chapters 2, 4); Lagrange multiplier (Chapter 5); jth eigenvalue of λ (Chapter 6)
λ_Q – critical wavelength of density perturbations (Chapter 3)
μ – chemical potential; shear modulus (Chapter 3)
$\mu_{\rm b}$ – baryon chemical potential
μ_e – electron chemical potential
ν – "longitudinal" quantum number (Chapter 4)
ξ^i – Lagrangian displacements in a perturbed star (Chapter 6)
ρ – mass density
$\rho_{\rm c}$ – mass density at the stellar center
$\rho_{\rm cc}$ – mass density at the crust-core interface
$\rho_{\rm m}$ – density at quantum melting
$\rho_{\rm s}$ – mass density at the surface of bare strange star (Chapter 8)
ρ_B – critical value of ρ in a strong magnetic field (Chapter 2)
$\rho_{\rm ND}$ – neutron-drip density
$\rho_0 = 2.8 \times 10^{14}$ g cm^{-3} – normal nuclear density
σ – electrical conductivity (Chapter 1); standard rms deviation (Chapters 6, 9)
σ, $\sigma_{\rm s}$ – surface tension (Chapter 7)
$\boldsymbol{\sigma}$ – spin
σ^k – Pauli matrix
σ_{ij} – stress tensor (Chapters 3, 6)
$\sigma_{\rm SB} = 5.67\,040 \times 10^{-5}$ erg cm^{-2} s^{-1} K^{-4} – Stefan-Boltzmann constant
$\sigma_{\rm T} = 6.652\,4587 \times 10^{-25}$ cm^2 – Thomson scattering cross section

$\boldsymbol{\tau}$ – isospin (Chapter 5)

τ – mean lifetime of a baryon (Chapter 5) or of a nuclear state (Chapter 7); local proper time (Chapter 6)

Φ, $\Phi(r)$ – ground-state wave-function (Chapter 5); metric function (Chapter 6)

$\Phi_{n,s}(r)$ – Landau function

ϕ – azimuthal angle

$\phi(r)$ – electrostatic potential (Chapter 2)

χ – normalized chemical potential of electrons; volume fraction of denser phase (Chapter 7)

χ_T, χ_ρ – temperature and density logarithmic derivatives of pressure

ψ_{ns} – basic bispinors (Chapter 4)

$\boldsymbol{\Omega}$, Ω – stellar spin frequency

Ω – thermodynamic potential (Chapters 4, 7)

ω – angular frequency of a stellar oscillation; single-particle energy (Chapter 5); spin frequency of the local inertial reference frame (§ 6.10); metric function (§ 6.12); photon frequency

$\overline{\omega}$ – local spin frequency of a star, as measured in a local inertial reference frame

ω_B – electron gyrofrequency

$\omega_{\rm c}$ – electron cyclotron frequency

$\omega_{\rm ci}$ – ion cyclotron frequency

$\omega_{{\rm c}p}$ – proton cyclotron frequency

$\omega_{\rm g}$ – electron gyrofrequency

$\omega_{{\rm p}e}$ – electron plasma frequency

$\omega_{\rm pl}$ – plasma frequency in quark matter (Chapter 8)

ω_∞ – proton frequency as measured by a distant observer

$\nabla_{\rm ad}$ – adiabatic gradient

LIST OF ABBREVIATIONS

APR – Akmal-Pandharipande-Ravenhall (EOS)
ALS – alternating-spin layers
AXP – anomalous X-ray pulsar
BB – baryon-baryon (interaction)
BZ – Brillouin zone
BBG – Brueckner-Bethe-Goldstone (theory)
BBP – Baym-Bethe-Pethick EOS; model; paper
bcc – body-centered cubic (crystal)
BCS – Bardeen-Cooper-Schrieffer (model, theory)
BPS – Baym-Pethick-Sutherland model; paper
CFL – color-flavor-locked (phase)
CFS – Chandrasekhar-Friedman-Schutz (instability)
CL – causality limit
CLDM – compressible liquid drop model
DFT – density functional theory
ee – electron-electron (interaction)
eip – electron-ion plasma
EOS – equation of state
ETF – extended Thomas-Fermi (approximation)
fcc – face-centered cubic (crystal)
FFG – free Fermi gas
FPS – Friedman-Pandharipande-Skyrme (model; EOS)
GFT – Green function theory
hcp – hexagonal close-packed (crystal)
HFB – Hartree-Fock-Bogoliubov (approximation)
HH – hyperon-hyperon (interaction)
HMXB – high mass X-ray binary
HNC – hypernetted chain (appoximation)
HP – Haensel-Pichon model; EOS; paper
ie – ion-electron (interaction)
ii – ion-ion (interaction)
IS – intermediate- and short-range (component of a potential)
LMXB – low mass X-ray binary
LOFER – Landau orbital ferromagnetism

MEM – Meson Exchange Model
NH – nucleon-hyperon (interaction)
NN – nucleon-nucleon (interaction)
NNN – three-nucleon (interaction)
npe-matter – uniform matter of neutrons, protons, and electrons
$npe\mu$-matter – uniform matter of neutrons, protons, electrons, and muons
OBE – one-boson-exchange
OCP – one-component plasma
OPAL – Opacity Library (project)
OPEP – one-pion exchange potential
PSN – pre-supernova
PWN – pulsar-wind nebula
QCD – quantum chromodynamics
QPO – quasiperiodic oscillation
RBHF – relativistic Brueckner-Hartree-Fock (approximation) $\equiv$ DBHF – Dirac-Brueckner-Hartree-Fock (approximation)
RETF – relativistic extended Thomas-Fermi (approximation)
RMF – relativistic mean-field (model)
RPA – random-phase approximation SGR – soft gamma repeater
SLy – Skyrme Lyon effective interaction; EOS model
SN – supernova
SNR – supernova remnant
SQM – strange quark matter (self-bound quark matter)
SXT – soft X-ray transient

SUBJECT INDEX