Proceedings of *RAGtime 17–19, 17–19/23–26 Oct., 1–5 Nov., 2015/2016/2017, Opava, Czech Republic*
Z. Stuchlík, G. Török and V. Karas, editors, Silesian University in Opava, 2017, pp. 23–32

Innermost stable circular orbits around compact stars: Terms that are quadratic in spin

Kateřina Goluchová[1], Gabriel Török[1,a] Martin Urbanec[1], Gabriela Urbancová[1,2] and Eva Šrámková[1]

[1] Institute of Physics and Research Centre for Computational Physics and Data Processing, Faculty of Philosophy & Science, Silesian University in Opava, Bezručovo nám. 13, CZ-746 01 Opava, Czech Republic
[2] Astronomical Institute, Boční II 1401/2a, CZ-14131 Praha 4 – Spořilov, Czech Republic
[a] gabriel.torok@gmail.com

ABSTRACT
Orbital motion close to a rotating compact star is largely affected by strong gravity. Location of the innermost stable circular orbit (ISCO) is determined trough interplay between the effects of general relativity and the effects of Newtonian physics that are associated to oblateness of the compact star. The Keplerian frequency at this orbit may increase as well as decrease when the compact star angular momentum increases. In this context we explore behaviour of the ISCO frequency for compact star models calculated within the Hartle–Thorne spacetime approximation.

Keywords: X-Rays: Binaries — Accretion, Accretion Disks — Stars: Neutron

1 INTRODUCTION

The Keplerian circular trajectories of test particles orbiting at external radii $r \in (r_{\rm NT}, \infty)$ around a spherical central body of mass M and radial extension $r_{\rm NT}$ in Newtonian theory poses monotonic behaviour of the angular momentum ℓ,

$$\frac{\partial \ell^2}{\partial r} > 0\,. \tag{1}$$

This inequality implies that the trajectories are stable to small radial perturbations (the Rayleigh and Solberg criterion, Rayleigh, 1917; Solberg, 1936; Abramowicz et al., 1984). When such trajectories are investigated in general relativistic approach the $\ell^2(r)$ curve is no longer found to be monotonic since a minimum of the angular momentum occurs. This minimum is associated with the presence of the well–known marginally stable circular orbit, $r = r_{\rm ms}$. For $r < r_{\rm ms}$ only unstable circular orbits may exist (e.g., Bardeen et al. (1972)). When dealing with both test particle and fluid motion, $r = r_{\rm ms}$ is often considered

978-80-7510-257-7

as the innermost stable circular orbit (ISCO) of an accretion disc that orbits a black hole (BH) or a relativistic compact star (CS),

$$r_{\rm ISCO} = r_{\rm ms}\,. \tag{2}$$

Spacetimes around slowly rotating CSs and the associated frame–dragging effects are frequently approximated using the Lense–Thirring, also called linear–Hartle, metric (Lense and Thirring, 1918; Hartle and Sharp, 1967; Hartle, 1967). Kluzniak and Wagoner (1985) discussed a relativistic formula for the Keplerian orbital frequency at $r_{\rm ISCO}$ expressed in the units of Hertz,

$$\nu_{ISCO} \equiv \nu_K(r_{\rm ISCO}) = \frac{c^3 M_\odot}{2\pi G M M_\odot}\,(1 + 0.75\,j)\,. \tag{3}$$

This formula, which is linear in j, can equivalently be written in the familiar form as

$$\nu_{ISCO} = \frac{2200 M_\odot}{M}\,(1 + 0.75\,j)\,[\mathrm{Hz}], \tag{4}$$

with the compact object mass being given in the solar mass units. For its simplicity and robustness it is often used within miscellaneous astrophysical applications.

The ISCO is commonly seen as a unique prediction of Einstein general relativity. It has however been pointed out that it also appears around highly elliptic bodies described within purely Newtonian approach (Gondek-Rosińska et al., 2001; Zdunik and Gourgoulhon, 2001; Amsterdamski et al., 2002; Kluźniak and Rosińska, 2013; Klużniak, 2014). In that context the ISCO frequency behaviour for rotating CSs can be understood in terms of interplay between the effects of general relativity and the effects of Newtonian physics that are associated to the CS oblateness. Such interplay affects outcomes of precise computations of rotating CS models and related ISCO frequencies.

Within the linear approximation (4) the ISCO frequency increases with growing j. This agrees with the behaviour of ISCO known for BHs that are described by Kerr geometry. The effects of Newtonian physics, on the other hand, influence the ISCO frequency in the opposite way. This leads us to an immediate question: How important are the terms which are quadratic in j ?

2 THE HARTLE-THORNE APPROXIMATION

In order to investigate the main trends in the ISCO frequency behaviour we use the Hartle–Thorne (HT) approximation of the CS spacetime in its usual form, which involves the first– and second–order terms in j and the first–order terms in the CS quadrupole moment q. The ISCO radius can be expressed in the units of the compact object gravitational mass as (e.g. Abramowicz et al., 2003)

$$\begin{aligned} r_{\rm ISCO} &= 6\left[1 - j\,\frac{2}{3}\sqrt{\frac{2}{3}} + j^2\left(\frac{251647}{2592} - 240\ln\frac{3}{2}\right) + q\left(-\frac{9325}{96} + 240\ln\frac{3}{2}\right)\right] \\ &\approx 6\left[1 - 0.54\,j - 0.23\,j^2 + 0.18\,q\right]. \end{aligned} \tag{5}$$

The ISCO frequency can then be written in the units of Hertz in the form

$$
\begin{aligned}
\nu_{\scriptscriptstyle ISCO} =& \frac{2200 M_\odot}{M}\left[1+\frac{11 j}{6^{3/2}}+\frac{1}{864} j^2\left(-160583+397710 \ln \frac{3}{2}\right)\right. \\
&\left.+\frac{5}{32} q\left(1193-2946 \ln \frac{3}{2}\right)\right] \\
&\approx \frac{2200 M_\odot}{M}\left[1+0.75\, j+0.78\, j^2-0.23 q\right] . \qquad (6)
\end{aligned}
$$

In Figure 1 we illustrate the dependence of $\nu_{\scriptscriptstyle ISCO}$ on j and q. In this Figure we also include the dependency of $\nu_{\scriptscriptstyle ISCO}$ on a scaled quadrupole moment $\tilde{q} \equiv q/j^2$. One may now introduce a quadratic correction to the linear relation (4) given by coefficient

$$
\delta \simeq 0.78-0.23 \tilde{q} \qquad (7)
$$

and rewrite equation (6) as

$$
\nu_{\scriptscriptstyle ISCO} \approx \frac{2200 M_\odot}{M}\left(1+0.75 j+\delta j^2\right) . \qquad (8)
$$

2.1 The Maximal ISCO frequency

For fixed values of $\tilde{q}$ in relation (8), one can find a maximal frequency,

$$
\nu_{\scriptscriptstyle ISCO}=\nu_{\scriptscriptstyle ISCO}^{\max } \Leftrightarrow \frac{\partial \nu_{\scriptscriptstyle ISCO}}{\partial j}=0, \qquad (9)
$$

which arises for

$$
j_{\max }=-\left(\frac{11 \sqrt{6}}{72}\right) \frac{1}{\delta} \approx-\frac{0.375}{\delta} . \qquad (10)
$$

We illustrate the existence and behaviour of $\nu_{\scriptscriptstyle ISCO}^{\max}$ in Figure 1b. The physical nature of this non–monotonicity follows from the qualitative difference between the influence of the effects of general relativity and Newtonian physics (Kluźniak and Rosińska, 2014) reflected by a decrease of $r_{\scriptscriptstyle ISCO}$ with increasing j and its increase with increasing q. As discussed by Török et al. (2014), the $r_{\scriptscriptstyle ISCO}(j)$ function has a minimum when j and q are related as follows

$$
j_{\min } \approx \frac{0.27}{-0.23+0.18\, \tilde{q}_{\min }} . \qquad (11)
$$

The minimal allowed ISCO radius is then given by

$$
r_{\scriptscriptstyle ISCO}^{\min }=6-2 j_{\min } \sqrt{2/3}\,, \qquad (12)
$$

and the ISCO frequency corresponding to this radius is

$$
\nu_{\scriptscriptstyle ISCO}^{\min } \approx \frac{2200 M_\odot}{M}\left[1+0.41 j_{min}+0.49 j_{min}^2\right] . \qquad (13)
$$

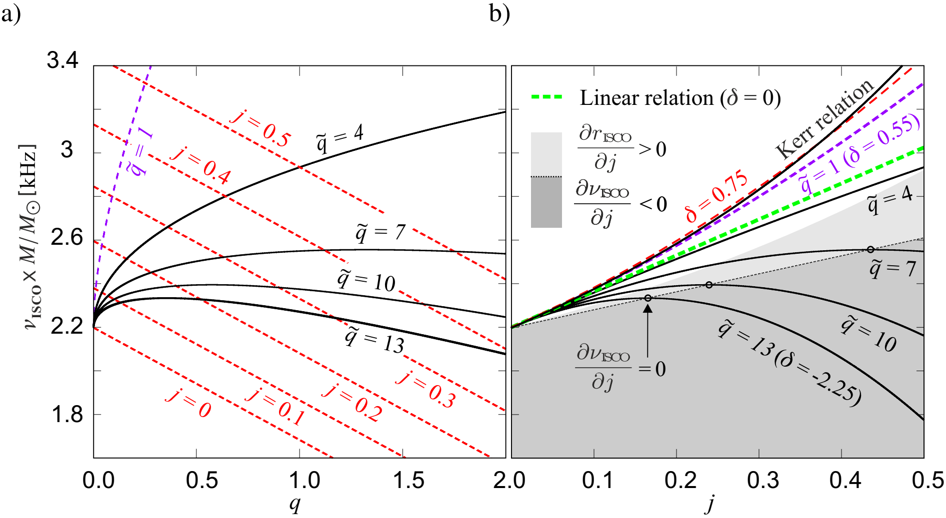

Figure 1. Dependence of the ISCO frequency $\nu_{\rm ISCO}$ on the CS angular momentum j and the scaled quadrupole moment, $\tilde{q} = q/j^2$. a) The $\nu_{\rm ISCO}(q)$ curves drawn for constant values of j (the red curves) and $\tilde{q}$ (the black curves) including the Kerr limit, $\tilde{q} = 1$ (the purple line). b) The $\nu_{\rm ISCO}(j)$ curves drawn for constant values of $\tilde{q}$ from panel a), the linear dependency (4), the $\nu_{\rm ISCO}(j)$ function calculated for Kerr spacetime and relation (8) for $\delta = 0.75$. The shaded area indicates the region corresponding to equation (10) where, in a qualitative disagreement with the relativistic relation (4), the value of $\nu_{\rm ISCO}$ decreases and value of $r_{\rm ISCO}$ increases with increasing j. The light shadow region indicates the region where both $r_{\rm ISCO}$ and $\nu_{\rm ISCO}$ increase with increasing j.

This frequency is however not the highest allowed ISCO frequency for a given $\tilde{q}$. For a fixed orbital radius and q, there is $\partial\nu_K/\partial j > 0$. The maximum of $\nu_{\rm ISCO}$ for a given value of $\tilde{q}$ therefore occurs for a somewhat higher value of j given by relation (10),

$$j_{\rm max} \approx -\frac{0.375}{0.78 - 0.23\tilde{q}_{\rm min}}. \tag{14}$$

The corresponding ISCO radius is now given by

$$r_{\rm ISCO}^{\rm max} = 6\left[1 - 0.25\, j_{max} + 0.38\, j_{max}^2\right], \tag{15}$$

and the maximal ISCO frequency can be expressed as

$$\nu_{\rm ISCO}^{\rm max} = \frac{2200 M_{\odot}}{M}\left[1 - \left(\frac{11\sqrt{6}}{72}\right)^2 \frac{1}{\delta}\right] \approx \frac{2200 M_{\odot}}{M}\left[1 - \frac{0.375^2}{0.78 - 0.23\tilde{q}}\right]$$
$$= \frac{2200 M_{\odot}}{M}\left[1 + 0.375\, j_{\rm max}\right]. \tag{16}$$

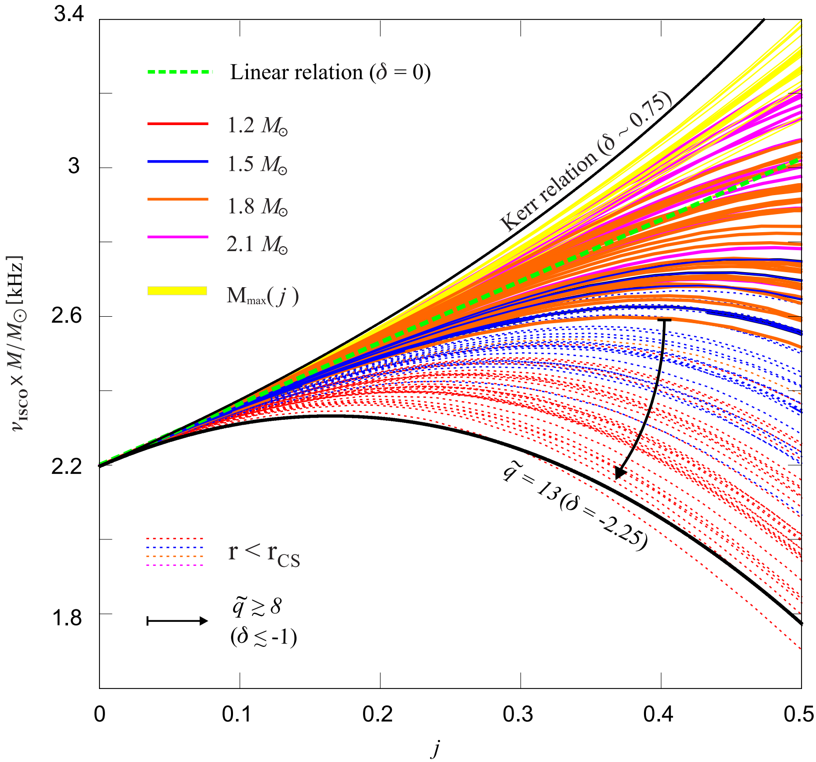

Figure 2. The $\nu_{ISCO}(j)$ dependence calculated assuming the HT approximation for 37 EoS and four different CS masses M that are colour–coded. The set of yellow curves is drawn for the case of maximal mass, $M_{\rm max} = M_{\rm max}(j,\ {\rm EoS}) > 2.1 M_\odot$.

The maximal allowed ISCO frequency is therefore dedined by a linear function of j. We note that this limit exists only for $\tilde{q} \gtrsim 3.4$. In Figure 1b we denote the regions in the j–ν_{ISCO} plane corresponding to $\partial r_{ISCO}/\partial j > 0$ and $\partial \nu_{ISCO}/\partial j < 0$.

3 THE SCENARIO IMPLIED BY MODELS OF A ROTATING CS

The quadrupole moment of a rotating CS occurs due to rotationally induced CS oblateness. In the case of numerical models of rotating CSs associated with a given equation of state (EoS), the effects described in the previous Section therefore manifest themselves through a certain type of ν_{ISCO} behaviour. Figure 2 displays the $\nu_{ISCO}(j)$ behaviour for several values of M and the maximal allowed gravitational masses $M_{\rm max}$ for a large set of EoS, which are listed in table 1. The Figure is based on calculations following the approach of Hartle and Sharp (1967), Hartle (1967), Miller (1977), Urbanec et al. (2013), and Török et al. (2016).

3.1 Compactness vs. oblateness

For $\tilde{q} \doteq 3.4$ we have $\delta = 0$ and the quadratic relation (8) merges with the linear term (4). For $\tilde{q} < 3.4$ the ISCO frequency monotonically increases with growing j (see Figure 1b). The values of $\tilde{q} \in (1, 3)$ correspond to very compact CSs with the highest possible ρ and M that can be achieved by assuming modern EoS (see, e.g., Urbanec et al., 2013). Typical values of M are around $\sim 2M_{\odot}$ but they strongly depend on the specific form of EoS and j. The behaviour of $\nu_{\rm ISCO}$ in this situation is illustrated in the yellow region of Figure 2. In the limit of $\tilde{q} = 1$, the CS (HT) spacetime approaches (up to the second–order in j) the Kerr spacetime. One may therefore write $\delta \doteq 0.55$ and

$$\nu_{\rm ISCO} = \frac{2200M_{\odot}}{M}\left(1 + 0.75j + 0.55j^2\right) . \tag{17}$$

Considering $\delta = 0.75$ one can write

$$\nu_{\rm ISCO} = \frac{2200M_{\odot}}{M}\left[1 + 0.75\left(j + j^2\right)\right] . \tag{18}$$

This simple relation almost exactly matches the ISCO frequency in Kerr spacetimes for j up to ~ 0.5 (see Figure 1b). It has been suggested as a rough upper limit for the ISCO frequencies for CSs (Török et al., 2010).

A qualitatively different situation occurs for $\tilde{q} \gtrsim 3.4$. In such case, when the less compact CSs posses a large influence of the CS oblateness, we have

$$\delta < 0 \tag{19}$$

and $\nu_{\rm ISCO}$ is not a monotonic function of j. Inspecting the curves drawn in Figure 2 for different EoS, we in many cases find a non–monotonic $\nu_{\rm ISCO}$ behaviour analogic to that shown in panel b) of Figure 1.

4 DISCUSSION AND CONCLUSIONS

Our results regarding the ISCO frequency behaviour obtained for the HT spacetimes demonstrate the importance of the second–order terms in j. The non–monotonicities of $r_{\rm ISCO}$ and $\nu_{\rm ISCO}$ determined by relations (11) and (14) can be of clear astrophysical relevance (e.g. Török et al., 2014). It is therefore important that, as demonstrated in Section 3, these non–monotonicities arise for given CS models calculated within the HT approximation.

The outcomes based on the HT approximation should be compared to outputs of exact calculations assuming numerical spacetimes. In Figures 3 and 4 we present several results that were obtained using the LORENE code (Gourgoulhon et al., 2016). These are drawn for a particular ApR EoS. Figure 3 illustrates the behaviour of $\nu_{\rm ISCO}$ for two sequences of rotating CSs calculated for a fixed central CS density ρ. Remarkably, the exact results are in good agreement with those obtained within the HT approximation. We note that the non–monotonicity of $\nu_{\rm ISCO}$ in this case arises mainly due to the increase of M implied by the CS rotation. Figure 4 includes a similar consideration, but for a fixed M. Although there is no obvious maximum here we can see that $\partial\nu_{\rm ISCO}/\partial\nu_{\rm S}$ vanishes when $r_{\rm ISCO}$ approaches $r_{\rm CS}$ (see panel d of Figure 4).

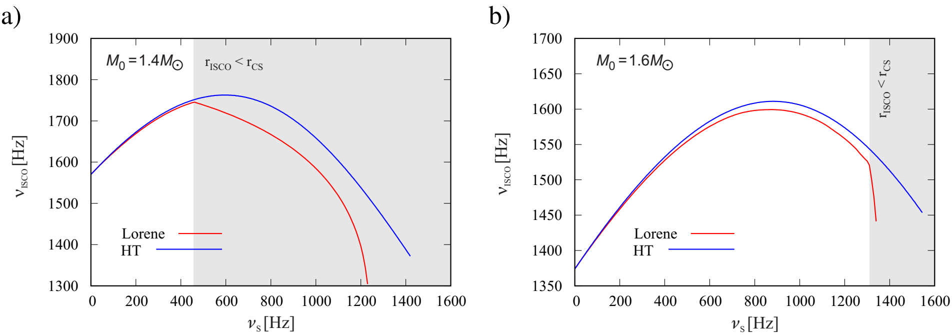

Figure 3. Behaviour of ν_{ISCO} (and the frequency of the CS surface rotation). The exact curves (the red colour) obtained using the LORENE numerical code are compared to those based on the HT approximation (the blue colour). The APR EoS and a fixed central density ρ_c are considered here. a) Plotted for a non–rotating CS mass $M_0 = 1.4M_\odot$. b) For a non–rotating CS mass $M_0 = 1.6M_\odot$. The maximum of ν_{ISCO} occurs close to $\nu_S = 800$Hz.

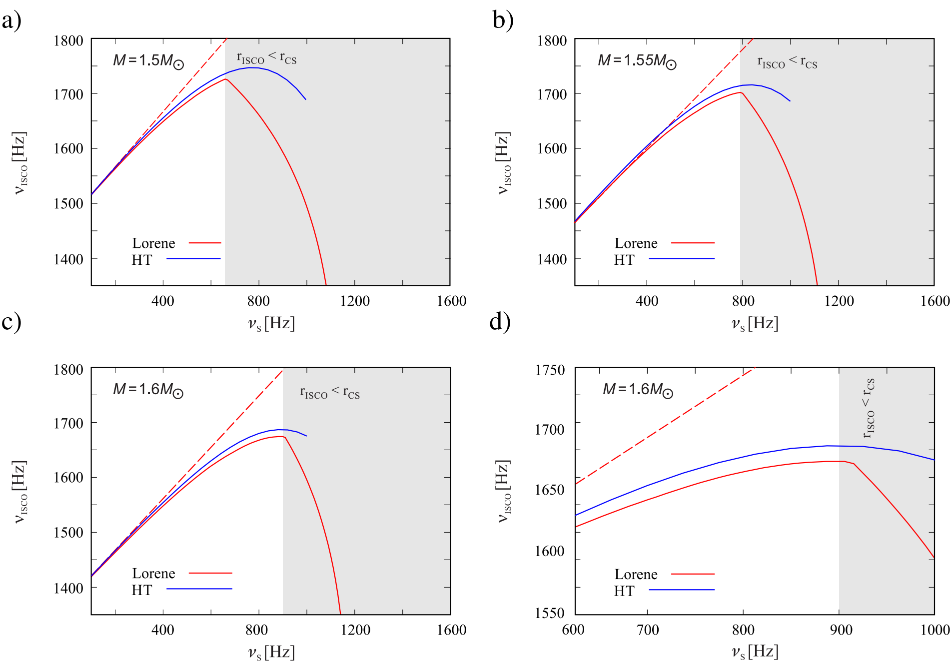

Figure 4. Behaviour of ν_{ISCO} (and the frequency of the CS surface rotation). The exact curves (the red colour) obtained using the LORENE numerical code are compared to those based on the HT approximation (the blue colour). The APR EoS and a fixed gravitational mass M are considered here. a) Plotted for a gravitational mass $M = 1.5M_\odot$. b) For a gravitational mass $M = 1.55M_\odot$. c) For a gravitational mass $M = 1.6M_\odot$. d) An enlarged view of panel c.

Table 1. The EoS assumed in this study. Along with relevant references the individual columns indicate for each EoS the maximal mass and the corresponding radius, and the central baryon number density.

EoS	$M_{\rm max}^{j=0}$ $[M_\odot]$	R [km]	$n_{\rm c}$ $[fm]^{-3}$	$\mathcal{R}_{1.4}$	$M_{\rm max}^{\nu_{\rm S}=600}$ $[M_\odot]$	Ref.
L	2.66	13.63	0.65	5.18	2.72	Arnett and Bowers (1977)
GLENDNH3	1.96	11.38	1.05	4.90	2.00	Glendenning (1985)
SkI5	2.18	11.29	0.97	4.88	2.21	Rikovska Stone et al. (2003)
SV	2.38	11.95	0.80	4.78	2.42	Rikovska Stone et al. (2003)
N	2.63	12.77	0.72	4.77	2.68	Arnett and Bowers (1977)
SkI2	2.11	11.00	1.03	4.70	2.14	Rikovska Stone et al. (2003)
Gs	2.08	10.77	1.08	4.58	2.11	Arnett and Bowers (1977)
l	1.92	11.33	1.04	4.48	1.96	Urbanec et al. (2010)
SGI	2.22	10.93	1.01	4.46	2.25	Rikovska Stone et al. (2003)
QMC700	1.95	12.57	0.61	4.45	2.02	Rikovska Stone et al. (2007)
O	2.38	11.51	0.89	4.43	2.41	Arnett and Bowers (1977)
nocross	2.39	12.48	0.67	4.42	2.44	Urbanec et al. (2010)
J35L80	2.05	10.50	1.13	4.38	2.08	Newton et al. (2013)
UBS	2.20	12.08	0.67	4.36	2.24	Urbanec et al. (2010)
PNML80	2.02	10.41	1.16	4.35	2.04	Newton et al. (2013)
SkO	1.97	10.27	1.19	4.31	2.00	Rikovska Stone et al. (2003)
SkT5	1.82	9.95	1.31	4.23	1.84	Rikovska Stone et al. (2003)
SkO’	1.95	10.06	1.24	4.19	1.97	Rikovska Stone et al. (2003)
C	1.85	9.92	1.31	4.11	1.87	Arnett and Bowers (1977)
APR	2.21	10.16	1.12	4.10	2.23	Akmal et al. (1998)
Gandolfi	2.20	9.82	1.16	4.06	2.22	Gandolfi et al. (2010)
NRAPR	1.93	9.85	1.29	4.06	1.95	Steiner et al. (2005)
SLy4	2.04	9.95	1.21	4.03	2.06	Rikovska Stone et al. (2003)
KDE0v1	1.96	9.72	1.29	3.98	1.98	Agrawal et al. (2005)
BBB2	1.92	9.49	1.35	3.84	1.94	Baldo et al. (1997)
UU	2.19	9.81	1.16	3.84	2.21	Wiringa et al. (1988)
WS	1.84	9.52	1.38	3.77	1.86	Wiringa et al. (1988)
FPS	1.80	9.27	1.46	3.75	1.82	Lorenz et al. (1993)
AU	2.13	9.38	1.25	3.59	2.14	Wiringa et al. (1988)

Our overall conclusion is that the second–order terms in j are clearly important, but further systematic studies will be necessary before making key statements on the HT approximation applicability.

ACKNOWLEDGEMENTS

We would like to acknowledge the Czech Science Foundation grant No. 17-16287S, the INTER-TRANSFER project No. LTT17003, and the internal grant No. SGS /15/2016. GU acknowledges the Albert Einstein Center for Gravitation and Astrophysics supported by the Czech Science Foundation grant No. 14-37086G. We are grateful to Marek Abramowicz and Omer Blaes for useful discussions. Last but not least, we would like to acknowledge the hospitality of University of California in Santa Barbara, and to express our thanks to concierges of Mlýnská hotel in Uherské Hradiště, Czech Republic for their participation in organizing frequent workshops of Silesian University and Astronomical Institute of the Czech Academy of Sciences.

REFERENCES

Abramowicz, M. A., Almergren, G. J. E., Kluzniak, W. and Thampan, A. V. (2003), The Hartle-Thorne circular geodesics, *ArXiv e-prints: gr-qc/0312070*, arXiv: gr-qc/0312070.

Abramowicz, M. A., Livio, M., Piran, T. and Wiita, P. J. (1984), Local stability of thick accretion disks. I - Basic equations and parallel perturbations in the negligible viscosity case, *ApJ*, **279**, pp. 367–383.

Agrawal, B. K., Shlomo, S. and Au, V. K. (2005), Determination of the parameters of a Skyrme type effective interaction using the simulated annealing approach, *Pys. Rev. C*, **72**(1), 014310, arXiv: nucl-th/0505071.

Akmal, A., Pandharipande, V. R. and Ravenhall, D. G. (1998), Equation of state of nucleon matter and neutron star structure, *Phys. Rev. C*, **58**, pp. 1804–1828, arXiv: nucl-th/9804027.

Amsterdamski, P., Bulik, T., Gondek-Rosińska, D. and Kluźniak, W. (2002), Marginally stable orbits around Maclaurin spheroids and low-mass quark stars, *A&A*, **381**, pp. L21–L24, arXiv: astro-ph/0012547.

Arnett, W. D. and Bowers, R. L. (1977), A Microscopic Interpretation of Neutron Star Structure, *ApJ Supp.*, **33**, p. 415.

Baldo, M., Bombaci, I. and Burgio, G. F. (1997), Microscopic nuclear equation of state with three-body forces and neutron star structure, *A&A*, **328**, pp. 274–282, arXiv: astro-ph/9707277.

Bardeen, J. M., Press, W. H. and Teukolsky, S. A. (1972), Rotating Black Holes: Locally Nonrotating Frames, Energy Extraction, and Scalar Synchrotron Radiation, *ApJ*, **178**, pp. 347–370.

Gandolfi, S., Illarionov, A. Y., Fantoni, S., Miller, J. C., Pederiva, F. and Schmidt, K. E. (2010), Microscopic calculation of the equation of state of nuclear matter and neutron star structure, *MNRAS*, **404**, pp. L35–L39, arXiv: 0909.3487.

Glendenning, N. K. (1985), Neutron stars are giant hypernuclei?, *ApJ*, **293**, pp. 470–493.

Gondek-Rosińska, D., Bulik, T., Kluzniak, W., Zdunik, J. L. and Gourgoulhon, E. (2001), Innermost stable circular orbits around rotating compact quark stars and QPOs, in A. Gimenez, V. Reglero and C. Winkler, editors, *Exploring the Gamma-Ray Universe*, volume 459 of *ESA Special Publication*, pp. 223–225, arXiv: astro-ph/0012540.

Gourgoulhon, E., Grandclément, P., Marck, J.-A., Novak, J. and Taniguchi, K. (2016), LORENE: Spectral methods differential equations solver, Astrophysics Source Code Library, arXiv: 1608.018.

Hartle, J. B. (1967), Slowly Rotating Relativistic Stars. I. Equations of Structure, *ApJ*, **150**, p. 1005.

Hartle, J. B. and Sharp, D. H. (1967), Variational Principle for the Equilibrium of a Relativistic, Rotating Star, *Apj*, **147**, p. 317.

Klużniak, W. (2014), Exploring GR effects in Newtonian physics, in *XXXVI Polish Astronomical Society Meeting*, pp. 21–26.

Kluźniak, W. and Rosińska, D. (2013), Orbital and epicyclic frequencies of Maclaurin spheroids, *MNRAS*, **434**, pp. 2825–2829.

Kluźniak, W. and Rosińska, D. (2014), Kerr-like behavior of orbits around rotating Newtonian stars, in *Jour. of Phys. Conf. Ser.*, volume 496 of *Journal of Physics Conference Series*, p. 012016.

Kluzniak, W. and Wagoner, R. V. (1985), Evolution of the innermost stable orbits around accreting neutron stars, *ApJ*, **297**, pp. 548–554.

Lense, J. and Thirring, H. (1918), Über den Einfluß der Eigenrotation der Zentralkörper auf die Bewegung der Planeten und Monde nach der Einsteinschen Gravitationstheorie, *PZ*, **19**.

Lorenz, C. P., Ravenhall, D. G. and Pethick, C. J. (1993), Neutron star crusts, *PRL*, **70**, pp. 379–382.

Miller, J. C. (1977), Quasi-stationary gravitational collapse of slowly rotating bodies in general relativity, *MNRAS*, **179**, pp. 483–498.

Newton, W. G., Gearheart, M. and Li, B.-A. (2013), A Survey of the Parameter Space of the Compressible Liquid Drop Model as Applied to the Neutron Star Inner Crust, *Apj Supp.*, **204**, 9, arXiv: 1110.4043.

Rayleigh, L. (1917), On the Dynamics of Revolving Fluids, *Proceedings of the Royal Society of London Series A*, **93**, pp. 148–154.

Rikovska Stone, J., Guichon, P. A. M., Matevosyan, H. H. and Thomas, A. W. (2007), Cold uniform matter and neutron stars in the quark meson-coupling model, *Nuclear Physics A*, **792**, pp. 341–369, arXiv: nucl-th/0611030.

Rikovska Stone, J., Miller, J. C., Koncewicz, R., Stevenson, P. D. and Strayer, M. R. (2003), Nuclear matter and neutron-star properties calculated with the Skyrme interaction, *PRC*, **68**(3), 034324.

Solberg, H. (1936), Le mouvement d'inertie de l'atmosphere stable et son role dans le theorie des cyclones, in *Proces-Verbaux Tss. Meteor U.G.G.I 6 e Assemblee Generale (Edinburgh)*.

Steiner, A. W., Prakash, M., Lattimer, J. M. and Ellis, P. J. (2005), Isospin asymmetry in nuclei and neutron stars [review article], *Phys. Rep.*, **411**, pp. 325–375, arXiv: nucl-th/0410066.

Török, G., Bakala, P., Šrámková, E., Stuchlík, Z. and Urbanec, M. (2010), On Mass Constraints Implied by the Relativistic Precession Model of Twin-peak Quasi-periodic Oscillations in Circinus X-1, *AJ*, **714**, pp. 748–757, arXiv: 1008.0088.

Török, G., Goluchová, K., Urbanec, M., Šrámková, E., Adámek, K., Urbancová, G., Pecháček, T., Bakala, P., Stuchlík, Z., Horák, J. and Juryšek, J. (2016), Constraining Models of Twin-Peak Quasi-periodic Oscillations with Realistic Neutron Star Equations of State, *The Astrophysical Journal*, **833**, 273, arXiv: 1611.06087.

Török, G., Urbanec, M., Adámek, K. and Urbancová, G. (2014), Appearance of innermost stable circular orbits of accretion discs around rotating neutron stars, *A&A*, **564**, L5, arXiv: 1403.3728.

Urbanec, M., Běták, E. and Stuchlík, Z. (2010), Observational Tests of Neutron Star Relativistic Mean Field Equations of State, *Acta Astron.*, **60**, pp. 149–163, arXiv: 1007.3446.

Urbanec, M., Miller, J. C. and Stuchlík, Z. (2013), Quadrupole moments of rotating neutron stars and strange stars, *MNRAS*, **433**, pp. 1903–1909, arXiv: 1301.5925.

Wiringa, R. B., Fiks, V. and Fabrocini, A. (1988), Equation of state for dense nucleon matter, *Phys. Rev. C*, **38**, pp. 1010–1037.

Zdunik, J. L. and Gourgoulhon, E. (2001), Small strange stars and marginally stable orbit in Newtonian theory, *PRD*, **63**(8), 087501, arXiv: astro-ph/0011028.