LENSE-THIRRING PRECESSION IN STRONG GRAVITATIONAL FIELDS

By

CHANDRACHUR CHAKRABORTY (PHYS05201004002)

Saha Institute of Nuclear Physics, Kolkata India

> A thesis submitted to the Board of Studies in Physical Sciences In partial fulfillment of requirements for the Degree of

DOCTOR OF PHILOSOPHY

of HOMI BHABHA NATIONAL INSTITUTE



January, 2015

STATEMENT BY AUTHOR

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at Homi Bhabha National Institute (HBNI) and is deposited in the Library to be made available to borrowers under rules of the HBNI.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgement of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the Competent Authority of HBNI when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

DECLARATION

I, hereby declare that the investigation presented in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree / diploma at this or any other Institution / University.

List of Publications arising from the thesis

Journal

- 1. Dragging of inertial frames inside the rotating neutron stars
 - C. Chakraborty, K.P. Modak, D. Bandyopadhyay, Astrophys. J. 790, 2 (2014)
- 2. Inner-most stable circular orbits in extremal and non-extremal Kerr-Taub-NUT spacetimes

C. Chakraborty, Eur. Phys. J. C 74, 2759 (2014)

3. Strong gravity Lense-Thirring Precession in Kerr and Kerr-Taub-NUT spacetimes

C. Chakraborty, P. Majumdar, Class. Quantum Grav. 31, 075006 (2014)

- 4. Lense-Thirring Precession in Plebański-Demiański spacetimes
 C. Chakraborty, P. Pradhan, *Eur. Phys. J.* C 73, 2536 (2013)
- Anomalous Lense-Thirring precession in Kerr-Taub-NUT spacetimes
 C. Chakraborty, arXiv:1407.6294v2 [gr-qc]

"जननी जन्मभूमिश्च स्वर्गादपि गरीयसी...."

(Mother and Motherland are greater than even 'Heaven')

Dedicated To

My Mother and Motherland

ACKNOWLEDGEMENTS

"Comrade of the road, Here are my traveller's greetings to thee..." — Rabindranath Tagore

My sincere gratitude and indebtedness to my thesis supervisors Prof. Dr. Debades Bandyopadhyay and Prof. Dr. Parthasarathi Majumdar for providing their sincere help and guidance during the entire period of my research. They have always motivated me and incessantly encouraged me to pursue my own line of thinking. I am grateful to them for their patience and boosting my confidence from time to time. Academic and nonacademic discussions with them also help to boost up my mental strength and to grow up my knowledge in General Relativity as well as in Astrophysics.

I wish to express my warm and sincere thanks to Prof. Dr. Parthasartahi Mitra, Prof. Dr. Pijushpani Bhattacharjee, Prof. Dr. Debasish Majumdar and Prof. Dr. Ambar Ghosal for extending all kinds of help and support throughout my thesis work.

Immediate next name that comes to my mind is my friend, Kamakshya P. Modak who helped me all through my research days at SINP. I am grateful to him for collaborating with me in a project which constituted my thesis in turn and also for helping me to acquire programming skills. I am also grateful to Dr. P. P. Pradhan for collaborating with me in an another project which is also a part of my thesis.

Thanks to all of my seniors; Rana, Srijit, Pritibhajan, Abhishek (Majhi), Lab, Tapan, Niladri, Abhishek (Chowdhury), Swapan for helping me through various ways in my research career. Special thanks due to Parijat, Chiranjib, Amit, Prasanta, Satyajit, Abhik, Goutam, Kuntal, Apurba, Aminul, Anshu, Mithun, Palash, Biswarup, Tanmay, Uttam, Kalyanmoy, Atanu, Rajani, Souvik for their constant support and encouragements by maintaining an ambient atmosphere around my workplace. Thanks also to Bijoy and Nilanjan for their help and support in official purposes. I express my indebtedness to my very special friends Sutapa, Moumita, Kamakshya and Tapas for their love, youthful company and real friendship. I also want to thank all the members (teaching, nonteaching, JRFs, SRFs, RAs of Physics and Bio-physics divisions) of SINP to maintain the pleasant atmosphere at the institute. I am grateful to Dept. of Atomic Energy (DAE, Govt. of India) for the financial assistance in my Ph.D career.

My sincere gratitude and indebtedness to Dr. Mani Bhaumik with whom I discuss many important academic and non-academic things. His valuable suggestions and advices help me a lot. I am also influenced by his life history which boosts up my mental strength. My sincere gratitude also to Dr. A. L. Bhaumik, Bhabes Pan, Debasis Bhattacharyya, Goutam Bhattacherjee, Indrani Chattopadhyay, Samit De and Sikha Roychoudhury for their various help and constant encouragement in my Ph.D life.

I wish to express my deep sense of gratitude to my parents and my brother (Indranil) for their immense patience, love, affection, encouragements and support. I am indebted to my parents for giving me the freedom to choose my own career and for constantly providing me the moral and emotional support at every stage of my life. I am also indebted to my uncle (Snehasis) and aunt (Aparajita) due to their valuable suggestions, advices and constant supports in the various stages of my life. Their appreciation of my works have boosted up my mental strength. Immense respect and best regards to my Grand Mother, maternal Grand Father and maternal Grand Mother whom I will never forget in my whole life. They were my primary 'guides' and they always used to inspire me to gain more and more knowledge. It is only because of their kind blessings that I could complete this work.

Finally, I bow down to Ishwarchandra Vidyasagar, Rabindranath Tagore, Swami Vivekananda and S. C. Bose whose lives and teachings have inspired me tremendously since my childhood and built up my character for which I could able to achieve this goal.

Contents

1	Introduction						
	1.1	Genera	al Introduction	15			
	1.2	Spin p	recession in curved spacetimes	16			
	1.3	Geode	tic precession	18			
	1.4	Lense-	Thirring precession	19			
		1.4.1	Lense-Thirring precession outside of a slowly rotating body	19			
		1.4.2	Measurement of LT precession: Gravity Probe B	22			
	1.5	Summ	ary	22			
2	General formulation of Lense-Thirring effect and its application to Kerr						
	spa	cetime		27			
	2.1	Introd	uction	27			
	2.2	Deriva	tion of Lense-Thirring precession frequency	28			
	2.3	Lense-	Thirring precession in Kerr spacetime	34			
		2.3.1	Weak field limit	36			
		2.3.2	Preliminary comparison with observational data	38			
	2.4	Summ	ary	41			
3	Lense-Thirring precession in Plebański-Demiański spacetime 4						
	3.1	Introd	uction	44			
	3.2	Non-e	xtremal case	46			
		3.2.1	Plebański-Demiański (PD) spacetimes	46			
		3.2.2	Special cases	48			
		3.2.3	Non-vanishing Lense-Thirring precession in 'zero angular momen-				
			tum' Plebański-Demiański spacetimes	50			
	3.3 Extremal case		nal case	53			
		3.3.1	Extremal Plebański-Demiański Spacetime	53			
		3.3.2	Extremal Kerr Spacetime	57			
		3.3.3	Extremal Kerr-Newman Spacetime	58			
		3.3.4	Extremal Kerr-de Sitter Spacetime	59			
		3.3.5	Extremal Kerr-Taub-NUT spacetime	60			
	3.4	Summ	ary	60			

4	Anomalous Lense-Thirring precession in Kerr-Taub-NUT and Taub-					
	NUT spacetimes					
	4.1	Introduction	62			
	4.2	4.2 Lense-Thirring precession in Kerr-Taub-NUT spacetime				
	4.3	.3 Results & Discussion				
	4.4 Lense-Thirring precession in Taub-NUT spacetime					
		4.4.1 Analytic extension of Taub-NUT spacetime	78			
	4.5	Digression : ISCOs in KTN spacetimes	80			
		4.5.1 Motivation	80			
		4.5.2 ISCOs for the null geodesics in Kerr-Taub-NUT spacetimes	84			
		4.5.3 ISCOs for the timelike geodesics in Kerr-Taub-NUT spacetimes	93			
	4.6	Summary	108			
5	Dragging of inertial frames inside the rotating neutron stars 111					
	5.1	Introduction				
	5.2	Basic equations of frame-dragging effect inside rotating neutron stars 114				
	5.3 Numerical method \ldots		118			
		5.3.1 Equation of state (EoS) of dense matter	120			
	5.4	Results and Discussion	121			
		5.4.1 Pulsars rotating with their Kepler frequencies $\Omega = \Omega_K$	121			
		5.4.2 Pulsars rotating with their frequencies $\Omega < \Omega_K$	127			
	5.5	Summary	129			
6	Conclusion & Outlook					
р:	Bibliography					