Nanyang Technological University
Division of Physics and Applied Physics

Academic Year	2022/23	**Semester**	1
Course Coordinator	Dr. Leek Meng Lee		
Course Code	PH3403		
Course Title	Astrophysics and Cosmology		
Pre-requisites	PH1107 Relativity & Quantum Physics and PH2101 Quantum Mechanics 1 and PH2103 Thermal Physics		
No of AUs	4 AU		
Contact Hours	3 hr – lecture; 1 hr – tutorial		
Proposal Date	04 May 2022		

Course Aims

This is a first course in cosmology which covers various astrophysical phenomena and fundamental aspects of standard cosmology. The required background tools such as Special and General Relativity are covered to make the module self-contained. The astrophysics topics covered include properties and structure of stars; stellar evolution and end-stage stellar remnants; binary systems and coalescing binaries which emit gravitational waves; gaseous interstellar medium; and basic properties of galaxies. Then we will expand to the entire universe and discuss about its evolution which is known as cosmology. The topics covered in cosmology include the discussion of the cosmological principle that leads to the derivation of the Friedmann-Robertson-Walker (FRW) metric. Then the kinematics and dynamics of the FRW metric will be discussed and the course closes with the problems in the FRW model and a brief mention of the solutions by postulating an inflationary era during the early evolution of the universe. Throughout this course, you will also appreciate the multi-disciplinary nature of this subject.

Intended Learning Outcomes (ILO)

Upon the successful completion of this course, you (as a student) would be **able to**:

1. state and explain how Einstein arrived at the various equivalence principles.
2. state and explain how non-uniform gravitational field can be viewed as curved spacetime.
3. manipulate tensors in the context of special relativity.
4. explain the geometrical construction of tensors on differentiable manifolds
5. state and explain the concept of parallel transport on differentiable manifolds
6. explain and derive the geodesic equation
7. state the Bianchi Identity and derive the contracted Bianchi Identity which gives the left-hand-side (LHS) of Einstein equation
8. state and explain the conservation law of the energy-momentum tensor on curved spacetime which gives the right-hand-side (RHS) of Einstein equation
9. derive the Einstein equation by combining the LHS and RHS of Einstein equation with physical justifications
10. derive the Newtonian limit of Einstein equation
11. state and derive the basic equations for modelling stellar structures
12. state and derive the basic properties of white dwarfs and neutron stars
13. derive the basic properties of a static, spherically symmetric black hole from the Schwarzschild metric
14. state and derive the basic equations of celestial mechanics
15. state and derive the equations for gravitational waves emitted from orbiting/coalescing neutron stars/black holes
16. state and derive the Jeans criteria for the collapse of gaseous interstellar clouds
17. state and derive basic properties of galaxies
18. state and explain how the cosmological principle leads to the FRW metric.
19. derive the kinematical properties of the FRW metric
20. derive the dynamical equations of the FRW metric by assuming a perfect fluid
21. derive several analytical models of cosmology
22. deduce the problems that exist in the standard FRW models of cosmology

23. explain qualitatively how these problems can be resolved by postulating an inflationary era during the early stage of the evolution of the universe

Course Content

Equivalence principles
Parallel transport
Geodesic equation
Einstein equation
Hydrostatic equilibrium
Stellar models
Degenerate pressure in white dwarfs and neutron stars
Event horizon of a black hole
Kepler's laws
Virial theorem
Gravitational waves
Jeans instability
Spiral density wave
Galaxy rotation curve
Cosmological principle
FRW geometry
Friedmann equations
Cosmic expansion and big bang theory
Age of the universe
The horizon problem
Inflationary era

Assessment (includes both continuous and summative assessment)

Component	Course LO Tested	Related Programme LO or Graduate Attributes	Weighting	Team / Individual	Assessment Rubrics
1. Final Examination	All	Competence 1,2,3,4,5 Communication 1	40%	Individual	Point-based marking (not rubric-based)
2. Midterm Test I	Range 1-10	Competence 1,2,3,4,5 Communication 1	20%	Individual	Point-based marking (not rubric-based)
3. Midterm Test II	Range 11-20	Competence 1,2,3,4,5 Communication 1	20%	Individual	Point-based marking (not rubric-based)

4. Homework (5 problem sets)	All	Competence 1,2,3,4,5 Creativity 2 Communication 1	20%	Individual	Point-based marking (not rubric-based) Open-ended marking scheme[1]
Total			100%		

Formative feedback

Formative feedback is given through discussion within tutorial lessons, a discussion after the midterm, and an examiner's report for the final exam.

Learning and Teaching approach

Approach	**How does this approach support students in achieving the learning outcomes?**
Problem solving (tutorial and lecture)	Develop competence and perseverance in solving physics problems
Peer Instruction (during lecture)	Develop communication skills and competence in physics.
Lectures	Warm-up questions will be raised first, followed by lectures that further explain the physics based on the questions. Then wrap-up questions will also be provided.
Tutorial	You will review main concepts learned in lectures. This helps them to digest and understand better.
Homework	The homework comprises standard textbook practice questions that are covered during tutorial.

Reading and References

a. Kolb E.W. and Turner M.S., *The Early Universe*, Perseus 1994, ISBN: 0201626748
b. Linde A., *Particle Physics and Inflationary Cosmology*, Taylor and Francis, 1990, ISBN: 3718604906
c. Peebles P.J.E., *Principles of Physical Cosmology*, Princeton, 1993, ISBN: 0691019339
d. Peacock J.A., *Cosmological Physics*, Cambridge, 2015, ISBN: 0521422701
e. Ryden B.S., *An introduction to cosmology*, Addison-Wesley, 2003, ISBN: 0805389121
f. Dodelson S., *Modern Cosmology*, Academic Press, 2003, ISBN: 0122191412
g. Trodden M. and Carroll S.M., *TASI lectures: Introduction to Cosmology*, http://arxiv.org/abs/astro-ph/0401547, 2004.

[1] There are homework questions in which you are expected to synthesize various concepts you encounter in the course to present solutions to modern problems in cosmology.

Baumann D., *TASI lectures: On cosmology*, http://arxiv.org/abs/0907.5424, 2009.

Course Policies and Student Responsibilities

Absence Due to Medical or Other Reasons

If you are sick and unable to attend your class / Mid-terms, you have to:

1. Send an email to the instructor regarding the absence and request for a replacement class and make-up mid-terms.
2. Submit a copy of your Medical Certificate* or official letter of excuse to administrator.
3. Attend the assigned replacement class (*subject to availability*) and make-up mid-terms.

* The medical certificate mentioned above should be issued in Singapore by a medical practitioner registered with the Singapore Medical Association.

Academic Integrity

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values.

As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Course Instructors

Instructor	Office Location	Phone	Email
Dr. Leek Meng Lee	PAP-03-10	+65 6592 7810	mlleek@ntu.edu.sg

Planned Weekly Schedule

Week	Topic	Course LO	Readings/ Activities
1	Introduction and course overview Introduce the physics of General Relativity which are the equivalence principles. Recasting special relativity into the language of tensor calculus	1, 2, 3	References and lecture notes
2	Basic differential geometry and construction of tensors on differentiable manifolds	4	References and lecture notes
3	Concept of parallel transport and derivation of geodesic equation	5, 6	References and lecture notes
4	Curvature tensor and its Bianchi identity. Then the contracted Bianchi identity is derived.	7	References and lecture notes

5	Energy-momentum tensor and its conservation in curved spacetime. Justification for Einstein equation and checking its Newtonian limit.	8, 9, 10	References and lecture notes
6	Stellar properties and modelling stellar structures. Remnants of stellar evolution: white dwarfs, neutron stars and black holes	11, 12, 13	References and lecture notes Midterm Test 1
7	Gravitational waves from orbiting/coalescing neutron stars/black holes	14, 15	References and lecture notes
8	Jeans criteria for the collapse of interstellar clouds Basic properties of galaxies	16, 17	References and lecture notes
9	Cosmological principle leading to the construction of the FRW metric Kinematical properties of the FRW metric	18, 19	References and lecture notes
10	Dynamical properties of the FRW metric (under the assumption of a perfect fluid)	20	References and lecture notes
11	Derive several analytical models of cosmology	21	References and lecture notes Midterm Test 2
12	Discussion of the problems within the standard FRW framework	22	References and lecture notes
13	Qualitatively understand how these problems are resolved by introducing an inflationary era in the early stage during the evolution of the universe	23	References and lecture notes

Graduate Attributes
What we want our graduates from Physics and Applied Physics to be able to do:

Upon the successful completion of the PHY, APHY, PHME, PHMP and PHMS programs, graduates should be able to:

Competency	1	demonstrate a rigorous understanding of the core theories and principles of physics involving (but not limited to) areas such as classical mechanics, electromagnetism, thermal physics and quantum mechanics [PHMS only] demonstrate a rigorous understanding of the core theories and principles of mathematical sciences involving (but not limited to) areas such as analysis, algebra and statistical analysis
	2	read and understand undergraduate level physics content independently;
	3	make educated guesses / estimations of physical quantities in general;
	4	apply fundamental physics knowledge, logical reasoning, mathematical and computational skills to analyse, model and solve problems;
	5	develop theoretical descriptions of physical phenomena with an understanding of the underlying assumptions and limitations;
	6	critically evaluate and distinguish sources of scientific/non-scientific information and to recommend appropriate decisions and choices when needed;
	7	demonstrate the ability to design and conduct experiments in a Physics laboratory, to make measurements, analyse and interpret data to draw valid conclusions.

Creativity	1	propose valid approaches to tackle open-ended problems in unexplored domains;
	2	offer valid alternative perspectives/approaches to a given situation or problem.

Communication	1	describe physical phenomena with scientifically sound principles;

	2	communicate (in writing and speaking) scientific and non-scientific ideas effectively to professional scientists and to the general public;
	3	communicate effectively with team members when working in a group.

Character	1	uphold absolute integrity when conducting scientific experiments, reporting and using the scientific results;
	2	readily pick up new skills, particularly technology related ones, to tackle new problems;
	3	contribute as a valued team member when working in a group.

Civic Mindedness	1	put together the skills and knowledge into their work in an effective, responsible and ethical manner for the benefits of society.