National Centre for Radio Astrophysics
TATA INSTITUTE OF FUNDAMENTAL RESEARCH
PUNE UNIVERSITY CAMPUS, GANESHKHIND, PUNE 411007, INDIA

NCRA • TIFR

Guidelines for Graduate Studies by Research Scholars

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1 Introduction

The Graduate Programme at the National Centre for Radio Astrophysics (NCRA), Pune, involves both coursework and research work in the areas of observational astronomy and theoretical astrophysics, with an emphasis on radio astronomy. There are also courses on basic physics and mathematical methods relevant for astronomy and astrophysics.

The normal duration of the Programme, including the doctoral research, is five years for Regular Ph.D. students and six years for Integrated Ph.D. ("Int-Ph.D.") students, within which the student is expected to submit a thesis for a Ph.D. degree to the Tata Institute of Fundamental Research (TIFR), a deemed University, or any other University/Institution with whom NCRA has a formal arrangement. Details regarding the requirements of the University/Institution can be obtained from the Joint Secretariat at NCRA.

The Graduate Programme is monitored by the Academic Affairs Committee (AAC). The Convenor of this committee has the overall responsibility for the programme. The academic activities of all Ph.D. students are monitored by the AAC, who will work in co-ordination with the Ph.D. supervisor and a Thesis Committee (TC), which is set up for each student. The student's supervisor will be a member of his/her TC, along with one member of the AAC, and one member of the NCRA faculty.

Policies and guidelines concerning various aspects of the Graduate Programme are described below. Further information and recent updates are available on the NCRA and the TIFR web pages (`http://www.ncra.tifr.res.in` and `https://www.tifr.res.in/academics/index.php`, respectively). We emphasize that various rules applicable to NCRA students, such as leave rules, stipends, rules governing the use of the contingency grant, etc., may be revised from time to time by TIFR. In case of such changes, the currently applicable rules (which may be obtained from the Joint Secretariat) would take precedence over what is described below.

2 Admission to the Graduate Programme

2.1 Normal Procedure

The normal route for admission to NCRA's Graduate Programme is via either the TIFR Graduate School (GS) written test or the Joint Entrance Screening Test (JEST). These are announced through advertisements placed in several national newspapers and on the NCRA web page, as well as notifications sent to different educa-

Before joining NCRA		**Programme in NCRA**		
Previous degree	**Years**	**Name of the programme**	**Number of credits in the coursework**	**Degree(s) awarded**
B.Sc. (Physics, Maths, Astronomy)	3	Int-Ph.D.	100	M.Sc. in Physics + Ph.D. in Physics
B.E./B.Tech. (any subject *except Engineering Physics*)	4	Int-Ph.D.	100	M.Sc. in Physics + Ph.D. in Physics
B.Sc./B.S. (Physics, Maths, Astronomy)	4	Int-Ph.D.	80	M.Sc. in Physics + Ph.D. in Physics
B.E./B.Tech. (Engineering Physics)	4	Int-Ph.D.	80	M.Sc. in Physics + Ph.D. in Physics
M.Sc. (Physics, Maths, Astronomy)	2	Ph.D.	60	Ph.D. in Physics
Int.-M.Sc. (Physics, Maths, Astronomy)	5	Ph.D.	60	Ph.D. in Physics

Table 1: **Summary of the eligibility criteria, credit requirements, and awarded degrees at NCRA.**

tional/research institutions. Based on their performance in the written test, candidates are invited for interviews, usually at TIFR-Mumbai. Candidates who clear these interviews are selected to join NCRA's Graduate Programme as Research Scholars, in either the Regular Ph.D. or Int-Ph.D. programmes (see below).

Research Scholars may also be pre-selected for the Ph.D. or Int-Ph.D. programmes from the Visiting Students' Research Programme (VSRP), conducted each summer at NCRA. Students may apply for the VSRP directly to NCRA, via an online application portal which is open from around mid-January to mid-February every year. Students who are entering the final year of an M.Sc., Int.-M.Sc., B.E., B.Tech. or four-year-B.Sc. programme are eligible for the VSRP. Selected VSRP students spend about two months during the summer working on a project at NCRA. Based on their performance during the VSRP, which includes a project seminar and interviews, students may be pre-selected to join NCRA's Graduate Programme after they satisfactorily complete their M.Sc., Int.-M.Sc., B.E., B.Tech. or four-year-B.Sc. course.

Depending on the nature and the duration of the qualifying degree, students would be admitted to the Ph.D. or the Int-Ph.D. programmes. Table 1 summarizes the various possibilities:

The category of a student who does not clearly belong to one of the above categories will be determined by the Dean, NCRA Faculty, in consultation with the Convenor of the AAC, and the Dean of Graduate Studies at TIFR-Mumbai. Note that "Int.-M.Sc." is used here to refer to all 5-year integrated Master of Science programmes, including the "B.S.-M.S." degree.

For brevity, Int-Ph.D. students who are required to complete 100 credits during their coursework will be referred to henceforth as "Int-Ph.D. (100 credits)", while those who are required to complete 80 credits will be referred to as "Int-Ph.D. (80 credits)".

3 The Structure of the NCRA Graduate Programme

Research Scholars in the Ph.D. programme are normally required to join the Institute on or before August 1 every year, while Research Scholars in the Int-Ph.D. programme are normally required to join the Institute on or before July 15 every year.

- *The Int-Ph.D. students who are required to complete 100 credits* would undergo one year of coursework at the Physics Department of the Savitribai Phule Pune University (hereafter, the Physics Department), followed by a short summer project with an NCRA faculty member, and then a ear of courses in the NCRA Graduate School. These students would also have to carry out two 3-month research projects in the first half of their third year.

- *The Int-Ph.D. students who are required to complete 80 credits* would do one year of courses in the NCRA Graduate School, followed by two 3-month research projects in the first half of their second year. In the second half of their second year, these students will be required to take two advanced courses and, finally, carry out one more 3-month research project.

- *The Regular Ph.D. students who are required to complete 60 credits* would do one year of courses in the NCRA Graduate School, followed by two 3-month research projects in the first half of their second year.

A summary of the detailed course and project structure for each of the above three programmes (essentially, combining Tables 3, 4, 5, and 6), is provided in Appendix 1.

Research Scholars would be allowed to register for a Ph.D. degree with the TIFR Deemed-to-be University, once they successfully clear all requirements of the NCRA Graduate School concerning the courses and the research projects. These requirements are detailed in Section 4.2.

The broad structure of the programme for the different categories of students is indicated below. It should be kept in mind that the actual duration of a semester may vary based on whether the student is doing courses or projects. Also, if a student is unable to clear the usual courses, s/he will have to spend additional time repeating them; however, the total duration of the Ph.D. or Int-Ph.D. programme will remain unchanged.

The Graduate Programme in NCRA consists of different types of courses and research projects. Their description, along with the grading procedures, are given below.

Grading System for the NCRA Graduate School			
% Marks	Letter Grade	Grade Point	Interpretation
$0 \leq \%\text{Marks} < 40$	F	0	Fail
$40 \leq \%\text{Marks} < 45$	P	4	Pass
$45 \leq \%\text{Marks} < 55$	C	5	Average
$55 \leq \%\text{Marks} < 65$	B	6	Above average
$65 \leq \%\text{Marks} < 75$	B+	7	Good
$75 \leq \%\text{Marks} < 85$	A	8	Very good
$85 \leq \%\text{Marks} < 95$	A+	9	Excellent
$95 \leq \%\text{Marks} \leq 100$	O	10	Outstanding

Table 2: **The grading system for the NCRA Graduate School.**

3.1 Percentage marks, letter grades and grade points

For the courses and research projects in the Graduate School, the student will be given a mark between 0% and 100%, called the percentage mark. This mark will be converted to a letter grade and a grade point using the mapping in Table 2. For each course, the final transcript will only contain the letter grade.

The grade point is used for evaluating the overall performance of the student. The relevant quantity is the Cumulative Grade Point Average (CGPA), which is calculated as follows:

$$\text{CGPA} = \frac{\sum_i \text{ credits for course } i \times \text{ grade point obtained in course } i}{\sum_i \text{ credits for course } i} ,$$

where the sum over i runs over all courses and research projects under consideration.

3.2 Coursework in the NCRA Graduate School

- **Description:** The coursework in the NCRA Graduate School (which, for some courses, is run jointly with IUCAA) consists of 15 courses distributed over two semesters, with each semester lasting for about 4.5 months. During the coursework, Research scholars undertake a combination of foundational and advanced courses that equip them with the knowledge and techniques necessary to pursue their Ph.D. thesis projects at NCRA.

- **Structure:** The structure of the Graduate School coursework, along with the credit structure, is given in Table 3.

  The detailed syllabi of the courses are listed in Appendix 2. Note that it is possible that the ordering of the courses in the Graduate School may be altered (with formal approval from the Dean, NCRA Faculty), in rare and unavoidable circumstances. The students will be notified well in advance in case such a situation arises. A course may be given as a reading course if there are only one or two students taking the course.

- **Evaluation and performance requirements:** The performance of the students in the courses will be evaluated on the basis of a combination of written test(s), home assignments, classroom discussions, and/or seminars. For every course, the instructor would give each student a numerical percentage mark between 0% and 100%, depending on his/her performance in the course. The percentage mark will be converted to a letter grade and a grade point by NCRA (see Table 2). A student must obtain a grade point ≥ 4 (grade P or better) to pass a course. Students are normally expected to clear all the courses at the first attempt. However, in case the student fails in one or more courses at the first attempt, s/he will be given a second chance to clear the courses in the subsequent year(s). The AAC would guide the student(s) regarding this. For each course, the final transcript will only contain the final letter grade.

Structure of the IUCAA-NCRA Coursework		
No.	Course	Credits
Semester I: Early August to mid-December		
PHY-231.3	Introduction to Astronomy & Astrophysics	4
PHY-232.3	Radiative Processes	4
PHY-233.3	Astronomical Techniques	4
PHY-234.3	General Relativity	2
PHY-235.3	Computational Astrophysics	2
PHY-236.3	The Radio Sky	2
Semester II: Early January to mid-May		
PHY-331.3	Fluids & Plasmas	2
PHY-332.3	Galaxies & ISM - I	2
PHY-333.3	Cosmology	2
PHY-334.3	Active Galactic Nuclei	2
PHY-335.3	Radio Telescopes	2
PHY-336.3	Radio Interferometry	2
PHY-337.3	Galaxies & ISM - II	2
PHY-338.3	Time-domain Astronomy	2
PHY-300.3	Research & Publication Ethics	2
	Total Credits	36

Table 3: **The structure of the coursework in the NCRA Graduate School**

- **Exemption:** Normally, no student will be exempted from completing the course requirements. However, if a student feels that s/he is thoroughly familiar with the material in a particular course in the Graduate School, s/he may request the lecturer to exempt him/her from attending the lectures and to evaluate him/her directly. It is up to the lecturer to decide whether such an exemption should be granted.

- **Feedback:** At the end of each semester in the NCRA Graduate School, students will be given an opportunity to anonymously evaluate the courses and course instructors in a prescribed form. All students of a given year should put their *unsigned* feedback forms into a single envelope, seal the envelope, and then sign across the seal. Even if a student does not wish to fill out the feedback form, s/he should sign across the seal of the envelope; this is to preserve confidentiality in the evaluation. Submission of the evaluation forms is *mandatory*; a student will be considered to have cleared a course only if the corresponding evaluation form has been submitted. The evaluation forms will be sent to the Directors of IUCAA and NCRA, and will be treated as confidential.

3.3 Courses Outside NCRA

- **Description:** The Int-Ph.D. (100 credits) students will do the first year of courses at the Physics Department, Savitribai Phule Pune University.

- **Structure:** The details of the Int-Ph.D. (100 credits) courses are given in Table 4.

- **Evaluation and performance requirements:** It is the responsibility of the students to satisfy the requirements for passing the courses (e.g., attendance, registering for the examinations on time, payment of fees, etc.), as applicable at the Physics Dept.. The evaluation for these courses will be done entirely by the institution running the courses, i.e. by the Physics Dept., based on their rules and regulations. The resulting marks will be forwarded to NCRA at the end of each semester. The percentage mark sent by the Physics Dept. will be converted to a letter grade and a grade point by NCRA (see Table 2). A student

Structure of Courses Outside NCRA		
No.	Course	Credits
Semester - I: Mid-July to early December		
PHY-101.3	Electronics	3
PHY-103.3	Mathematical Methods in Physics	4
PHY-104.3	Classical Mechanics I	4
PHY-106.3	Quantum Mechanics I	4
PHY-108.3	General Laboratory⋆	3
Semester - II: Early January to early May		
PHY-105.3	Statistical Mechanics	4
PHY-116.3	Quantum Mechanics II	4
PHY-107.3	Electrodynamics I	4
PHY-111.3	Atoms, Molecules and Solids	3
PHY-110.3	Computer Laboratory⋆	3
	Total Credits	36

⋆ The General Laboratory and the Computer Laboratory courses can be interchanged for some students as per the Physics Dept. norms. The listed courses are based on the 2017 programme at the Physics. Dept.; the exact courses may vary in different years, but the broad structure would be similar. If there are any changes in the course structure, the students should convey this to the AAC.

Table 4: **The structure of external courses (at the Physics Dept.), for Int-Ph.D. (100 credits) students.**

must obtain a grade point ≥ 4 (grade P or better) to pass a course. Students are normally expected to clear all the courses at the first attempt. However, in case a student fails in one or more courses at the first attempt, s/he will be given a second chance to clear the courses in the subsequent year(s). The AAC would guide the student(s) regarding this. For each course, the final transcript will only contain the final letter grade.

3.4 Advanced Courses

- **Description:** The NCRA Graduate School also offers Advanced Courses covering various topics in Astronomy and Astrophysics. These are primarily meant for students of the Int-Ph.D. (80 credits) programme. Such students will be allowed to choose two courses from a set of eight courses listed in Table 5, and described in detail in Appendix 3. It is possible that some of the courses may not be offered in a particular year due to the non-availability of instructors. In such a situation, the AAC will advise the students on possible alternatives.

- **Structure:** The Advanced Courses are listed in Table 5. Depending on the number of students attending, the instructor may choose to offer the course as a reading course.

- **Evaluation and performance requirements:** The grading procedure will be decided by the instructor, on the basis of assignments, tests, seminars, classroom discussions, etc. The final percentage mark will be a number between 0% and 100%. This percentage mark will be converted to a letter grade and a grade point by NCRA (see Table 2). A student must obtain a grade point ≥ 4 (grade P or better) to pass a course. In case a student fails one of the Advanced Courses, s/he would be allowed to take a third Advanced Course, also of 3-month duration, over the period July 1–October 1 of the same year.

3.5 3-month Research Projects (Research Methodology)

- **Description:** Every NCRA doctoral student is required to do at least two 3-month research projects with different NCRA faculty members as part of the Graduate School, to test their research abilities and to

List of the Advanced Courses		
No.	Course	Credits
PHY-401.3	Advanced Radio Astronomy	6
PHY-402.3	Radio Instrumentation	6
PHY-403.3	Cosmology and Structure Formation	6
PHY-404.3	Advanced Interstellar Medium	6
PHY-405.3	Advanced course on Galaxies: Their Structure, Formation and Evolution	6
PHY-406.3	Advanced Course on Pulsars	6
PHY-407.3	Solar and Heliospheric Physics	6
PHY-408.3	Active Galactic Nuclei	6

Schedule for the Advanced Courses				
No.	Course	Start date	End date	Credits
PHY-4XX.3	Advanced Course I	February 15	May 15	6
PHY-4XX.3	Advanced Course II	February 15	May 15	6
	Total Credits			12

Table 5: **The list of the Advanced Courses and their schedule, for Int-Ph.D. (80 credits) students. The students will choose two courses from the courses listed here.**

allow them to explore different research areas before choosing a Ph.D. topic and Ph.D. supervisor. These projects are formally known as **Research Methodology-I** and **Research Methodology-II**. One of these projects must be based on the observational or instrumentation facilities operated by NCRA, i.e. the Giant Metrewave Radio Telescope (GMRT), the Ooty Radio Telescope (ORT), the 15-m telescope, new hardware, or facilities in the Radio Physics Laboratory (RPL), etc. The project may include the analysis of GMRT, ORT, or 15-m data, as well as the development of software tools or hardware instrumentation for the different facilities.

- **Structure:** The schedule of these projects is given in Table 6.
- **Evaluation and Performance requirements:** Students will have to give a seminar at the end of each project and submit a formal project report. If the project seminar and report are not submitted by the stipulated date, the student will be deemed to have failed the course.

Details of the 3-month Research Projects (Research Methodology)					
No.	Project	Start date	End date	Seminar & report deadline	Credits
PHY-387.3	Research Methodology I	June 15	September 15	September 30	12
PHY-388.3	Research Methodology II	October 15	January 15	January 31	12
PHY-389.3	Research Methodology-A*	February 15	May 15	May 31	12
PHY-461.3	Research Methodology III†	June 1	August 31	September 15	8
PHY-462.3	Research Methodology-B‡	October 1	December 31	January 15	8

*Research Methodology-A provides a safety net for doctoral students who have either failed in either Research Methodology I or II, or not obtained the minimum average grade in Research Methodology I and II.

†Research Methodology III and Research Methodology-B are only for Int-Ph.D. (80 credits) students.

‡Research Methodology-B provides a safety net for an Int-Ph.D. (80 credits) student who has failed to obtain the minimum required grade point of 6 in Research Methodology III.

Table 6: Details of the 3-month Research Projects (Research Methodology)

For each project, students will receive a percentage mark that is the average of the percentage marks from three components: their seminar (evaluated by NCRA faculty members), their project report (evaluated by the AAC), and their performance during the project (evaluated by the project supervisor). Each of these three components will carry an equal one-third weightage.

This percentage mark will be converted into a letter grade and a grade point by NCRA. Students must obtain a grade point ≥ 4 (grade P or better) to pass the Research Methodology I and II, and (if needed) a grade point ≥ 6 (grade B or better) to pass Research Methodology III. In addition, the Grade Point Average (GPA) over Research Methodology I and II, calculated as

$$\text{GPA} = \frac{\text{grade point in Research Methodology I} + \text{grade point in Research Methodology II}}{2},$$

must be ≥ 6.0.

If a doctoral student fails in either of Research Methodology I or II, but clears the other one, or if his/her GPA over Research Methodology I and II is < 6.0, s/he will be allowed to carry out an additional 3-month project (Research Methodology-A), allowing an additional chance to satisfy the Graduate School requirements. This extra project may not be a continuation of either of the earlier two projects and should be done with a faculty member different from those supervising Research Methodology I and II. In such circumstances, the student's GPA in the Research Methodology courses will be computed based on the two highest grades obtained in the three projects.

If an Int-Ph.D. (80 credits) student fails to get the minimum grade point of 6 in Research Methodology III, s/he will be allowed to carry out an additional 3-month project (Research Methodology-B) to satisfy the Graduate School requirements. Again, her/his extra project may not be a continuation of the student's earlier projects.

- **Assigning the projects:** Students are encouraged to approach faculty members for prospective projects well in advance. Once a project is finalised with a faculty member, the student should submit a title and abstract, summarizing the project's scope and content, to the AAC by May 15 for *both* Research Methodology I and II (beginning in June and October of the year, respectively). The description should clearly state whether the project is classified as an "NCRA facilities" project. If a student cannot identify a guide by May 1, they should contact the AAC, who will help find a guide before the May 15 deadline.

  For Research Methodology-A, where there is often limited time between projects, the student should provide a brief description of the new project to the AAC by February 7 for a project starting on February 15 of that year.

  Finally, for Research Methodology III, the student must submit the project description to the AAC by May 1 for projects starting on June 1 of that year. For Research Methodology-B, the student should provide the project description to the AAC by September 22, a week before the project's start date.

3.6 RPL or Experimental/Reading Project

- **Description:** All Int-Ph.D. (100 credits) students will carry out either a short project in NCRA's RPL, or an experimental or reading project with an NCRA faculty member, during the summer of their first year. The content of the project will be decided by the supervisor; a brief description of the project should be provided by the supervisor to the AAC by May 1 (i.e. 2 weeks before the beginning of the project).

- **Structure:** The project will run for ~ 6 weeks between mid-May and mid-July; the exact dates can be tuned to match the convenience of the supervisor and the student. This project will carry 4 credits.

- **Evaluation and performance requirements:** The grading procedure for this project will be decided by the supervisor, who will provide a percentage mark between 0% and 100% to NCRA, based on the student's performance in the project; this percentage mark will be converted by NCRA to a letter grade, and then to a grade point. Students must obtain a grade point ≥ 4 to pass the project. In case an Int-Ph.D. (100 credits) student fails this project, s/he must repeat it either in the next summer, or after completing the other requirements of the Graduate School. This will be done under the supervision of the AAC.

4 Evaluation in the Graduate School

4.1 Cumulative Grade Point Average (CGPA)

Evaluation in the NCRA Graduate School is based on the Cumulative Grade Point Average (CGPA), which is calculated from the marks obtained in the courses and research projects as follows:

$$\text{CGPA} = \frac{\sum_i \text{ credits for course } i \times \text{ grade point obtained in course } i}{\sum_i \text{ credits for course } i} ,$$

where the sum over i runs over all courses and research projects under consideration.

4.2 Graduate School Performance Requirements

A student must satisfy the following conditions in order to satisfactorily complete the requirements of the NCRA Graduate School. If a student fails to satisfy the above criteria at the end of the coursework (i.e., at the end of two years for Regular Ph.D. students and at the end of three years for Int-Ph.D. students), s/he would be asked to leave NCRA.

- The student should pass all courses, i.e., s/he should obtain a grade point ≥ 4 in all courses (both courses and research projects), within the period of his/her coursework (two years for Regular Ph.D. students and three years for Int-Ph.D. students).
- The student must get a CGPA of ≥ 6.0 over all courses, including advanced courses.
- The student must get a Grade Point Average (GPA) of ≥ 6.0 in the two Research Methodology projects.
- Int-Ph.D. (80 credits) students must obtain a Grade Point ≥ 6 in the Research Methodology III project.

Students would be required to leave NCRA under the following circumstances:

1. If a student fails to meet the performance criteria listed above at the end of the Graduate School, s/he would be required to leave NCRA.
2. If a student fails to achieve a CGPA of ≥ 6.0 at the end of each semester (whether or not s/he has failed some courses), s/he would be required to leave NCRA.
3. If a student fails in more than three courses (i.e. in four or more courses) at any point in the coursework, s/he would be required to leave NCRA.
4. If a student obtains a grade point < 4 in both of the initial 3-month research projects (Research Methodology I and II), s/he would be required to leave NCRA.

The following safety nets have been provided for students failing to clear the requirements of the Graduate School at the first attempt:

- Regular Ph.D. students have to maintain a CGPA ≥ 6.0 at the end of each semester. A student may fail at most three courses during the 1-year duration of the coursework. Students who have failed in four or more courses would have to leave NCRA. Students who have failed one or more, but fewer than four, courses will have to clear these courses by the end of the second year in the programme. By the end of 2 years, a Regular Ph.D. student should satisfy all the criteria listed above, otherwise s/he will have to leave NCRA.

- Int-Ph.D. students have to maintain a CGPA $\geq$ 6.0 at the end of each semester. A student may fail at most three courses during the entire two-year duration of the coursework. Students who have failed in four or more courses will have to leave NCRA. Students who have failed one or more, but fewer than four, courses will have to clear these courses by the end of their third year in the programme. At the end of the third year, Int-Ph.D. students should satisfy all the criteria listed above, else s/he would have to leave NCRA.

- In case a student obtains a grade point < 4 in Research Methodology-I or Research Methodology-II, or if his/her average GPA on these two Research Methodology projects is < 6.0, s/he would be allowed to carry out an additional 3-month Research Methodology project ("Research Methodology-A") to satisfy the Graduate School requirements. This extra project may not be a continuation of either of the earlier two projects and will run from February 16 to May 15; the seminar must be completed and the project report submitted by May 31. If a student is required to carry out a third Research Methodology project, the GPA on the research projects will be computed based on the two highest grades obtained in the three projects.

- In case an Int-Ph.D. (80-credits) student fails to obtain a GPA $\geq$ 6 on Research Methodology-III, s/he would be allowed to carry out an additional 3-month Research Methodology project ("Research Methodology-B") to satisfy the Graduate School requirements. The new project may not be a continuation of any of the earlier Research Methodology projects, and will run from October 1 to December 1; the seminar must be completed and the project report submitted by January 15. If a student is required to carry out a Research Methodology-B project, the GPA on the third research project will be the higher of the two grades obtained in Research Methodology-III and Research Methodology-B.

5 Requirements for Ph.D. Registration

Research Scholars may register for a Ph.D. after successful completion of their Graduate School (i.e. courses and research projects). Note that the stipend of Regular Ph.D. and Int-Ph.D. students would be raised after two and three years, respectively, provided their Graduate School studies have been completed satisfactorily, their progress is assessed to be satisfactory, and they have registered for the Ph.D. degree. Research Scholars are required to register for a Ph.D. within two years (Ph.D. students) or three years (Int-Ph.D. students), as per the TIFR rules. In case a student has not registered within the prescribed period, s/he may be given an extension of six months to complete the registration procedure by the Dean, NCRA Faculty, in consultation with the Convenor of the AAC and the Dean of Graduate Studies of TIFR-Mumbai. Students who have not registered for a Ph.D. within 2.5 years (Ph.D.) or 3.5 years (Int-Ph.D.) will be required to leave NCRA.

5.1 M.Sc. Degree for Int-Ph.D. students

Students in the Int-Ph.D. (80 credits) or Int-Ph.D. (100 credits) programmes should register for an M.Sc. degree with the TIFR Deemed-to-be University after joining NCRA as Research Scholars. The additional credits obtained by these students (20 and 40 extra credits, respectively) are considered by the TIFR Deemed-to-be University to be equivalent to the course requirements of an M.Sc. degree. Such students would be granted their M.Sc. degrees along with the Ph.D. degrees, based on the NCRA Graduate School requirements, *unless they leave NCRA without completing a Ph.D. degree*. If an Int-Ph.D. student leaves NCRA after completion of the NCRA Graduate School requirements but before completion of the Ph.D. degree (either due to not meeting the Graduate School requirements or if s/he wishes to leave NCRA), s/he would be allowed to obtain an M.Sc. degree from the TIFR Deemed-to-be University. However, this would require him/her to carry out an additional 6-month research project with an NCRA faculty member, in order to qualify for the M.Sc. degree. Int-Ph.D. students who wish to leave NCRA without the Ph.D. degree should consult with the Convenor of the AAC or the Dean, NCRA Faculty, about the requirements to obtain an M.Sc. degree.

5.2 Thesis Advisor Selection for Research Scholars

Registration for a Ph.D. degree requires the identification of a thesis supervisor (an academic member of NCRA with the rank of Reader or higher) for the candidate. Keeping this in mind, students are encouraged to get acquainted with the research areas at NCRA as early as possible and to interact personally with NCRA Faculty members to find out their research interests and availability as guides. Finding an advisor who is willing to supervise the work of a student is solely the responsibility of the student. However, s/he will be advised and assisted by the AAC, whenever required.

Ideally, the student should have identified a supervisor by the end of the Graduate School courses and projects. Within one week of completing the Graduate School projects, they are required to inform the Convenor of the AAC and the Dean, NCRA Faculty, of their thesis plans by e-mail, specifying the supervisor with whom they intend to work for the Ph.D. degree. In case a student has failed to identify an advisor by then, s/he should inform, again by e-mail, the Convenor of the AAC and the Dean, NCRA Faculty, of her/his plans to identify a supervisor. The latter students will be allowed until the end of the academic year (which would correspond to the end of the second year in NCRA for Regular Ph.D. students, and the end of the third year for Int-Ph.D. students) to identify a Ph.D. supervisor. If the student is unable to find an advisor at this time, his/her Research Scholarship would be terminated, except in cases of an appeal to the Dean, NCRA Faculty. In the latter cases, the Dean, NCRA Faculty, may, in consultation with the Convenor of the AAC and the Dean of Graduate Studies at TIFR-Mumbai, allow an extension of up to six months to complete the registration procedure.

The name of the supervisor and the broad area of research must be provided to the NCRA Joint Secretariat before a student is allowed to register for a Ph.D.. In addition, an abstract of the Ph.D. project must be uploaded directly to the TIFR Datanet2 system (`https://datanet2.tifr.res.in/ncra`), after which it will be processed for approval by the relevant authorities.

5.3 Thesis Committee (TC)

When a Research Scholar registers for the Ph.D. degree, a Thesis Committee (TC) will be set up for her/him, consisting of at least three faculty members, to monitor her/his progress until the completion of the Ph.D.. The TC will consist of the student's supervisor, a member of the AAC, and an additional NCRA Faculty member. The TC will monitor the performance of the student at least once every year, typically in May or June, and make recommendations concerning the renewal or termination of the student's Research Scholarship. Students should feel free to approach members of their TC for advice during the year, in case of any problems.

5.4 Premature Exit Options

Any student in the Ph.D. or Int-Ph.D. programme can at any time resign his/her position, obtain a 'No Dues' certificate, and leave NCRA without a degree. If such a student wishes to obtain a degree based on the work done by her/him at NCRA, s/he should check the options available from the TIFR Subject Board of Physics, at `https://www.tifr.res.in/academics/academic_procedures.php?t=cat5`. Such students are also encouraged to discuss their options with the Convenor of the AAC and the Dean, NCRA Faculty.

6 Stay in NCRA

6.1 Monitoring the Progress of a Student

The appointment of a Research Scholar is for one year at a time, with an extension every year subject to satisfactory performance. The progress of all Research Scholars is reviewed by either the AAC (before Ph.D. registration) or their respective TCs (after Ph.D. registration) every year. The schedule of the reviews is summarized in Table 7.

Annual reviews for Ph.D. students in and after the third year, and for Int-Ph.D. students in and after the fourth year, will be based on:

Academic Year*	**Review to be held before**	**Nature of Review**	**Maximum Extension†**
Int-Ph.D. I	July 10	Meeting with the AAC	1 year
Int-Ph.D. II / Ph.D. I	July 10	Meeting with the AAC	1 year
Int-Ph.D. III / Ph.D. II	July 10	Work report + meeting with the TC (or AAC if TC not formed)	6 months
Int-Ph.D. IV / Ph.D. III	December 10	Work report + seminar + meeting with the TC	6 months
	July 10	Work report + seminar + meeting with the TC	1 year
Int-Ph.D. V / Ph.D. IV	July 10	Work report + seminar + meeting with the TC	1 year
Int-Ph.D. VI / Ph.D. V	July 10	No review if synopsis submitted, else work report + seminar + meeting with the TC	1 year (with reduced/no salary)

*: The Academic Year runs from August 1 of a given year to July 31 of the following calendar year.
†: The committee may recommend termination if the student's performance is poor, or suggest a shorter extension period if closer monitoring is needed. For more details, please refer to the main text.

Table 7: Schedule of the Annual Reviews.

- A detailed report by the student summarizing the work carried out since the previous review, as well as plans for the future. This should include details of projects, publications, proposals, work-related travel, plans for the timeline of the Ph.D., and anything else that the student or supervisor feel is relevant to her/his research performance.
- An open seminar (of duration ~ 50 minutes) given by the student and graded by NCRA faculty members, in which s/he describes the work done since the previous review. The student may also choose to describe proposals, publications, and plans for the future in the talk.
- A discussion with the TC on the work done and the student's plans for the future; this would usually take place just after the above review seminar. In the course of the review, the TC would also meet with the student in the absence of the Ph.D. supervisor. This is to provide students with an opportunity to share any concerns with the TC members confidentially, should they wish to do so.

The review seminar will be evaluated by the NCRA faculty members who attend the talk. This evaluation will be based on a range of factors, such as the quantity and the quality of the work, the clarity of the presentation of the talk, the understanding of the field, the quality of the slides or presentation materials, the handling of questions during and after the talk, etc. Each faculty member will provide a mark on the talk on a scale of $1-10$, with a higher number indicating a better talk, and a mark of 6 indicating a satisfactory, but marginal, talk. Faculty members may provide comments on areas where they feel that the student might improve and also areas where they feel that the student has done well. The marks of all faculty members who evaluate the talk will be averaged together to obtain the final seminar grade, out of 10.

The TC will then separately evaluate the student based on the submitted report, any issues arising from the seminar, inputs from the guide, and a discussion with the student. The evaluation will be based on a number of factors, such as the quality and quantity of work done since the previous review, the number of successful proposals and published papers led by or contributed to by the student, the motivation, conscientiousness, and commitment shown by the student, etc. The TC may also discuss with the student the comments of the faculty members on the talk, to try to help the student improve on her/his work and presentation skills. Any problems that the student might have faced during the review period should also be brought up, so that these can be discussed; the TC will attempt to come up with solutions or suggestions. The TC members will then provide individual evaluations of the student's performance over the year, again on a scale of $1-10$, with a higher number indicating better performance and a mark of 6 indicating a satisfactory, but marginal, performance.

These will be averaged together to obtain the final TC grade. The final review grade will be the arithmetic mean of the final seminar grade and the final TC grade.

Based on all these inputs, the TC will recommend an extension of the Research Scholarship, or a termination of the student's Research Scholarship. In normal circumstances, the TC will recommend an extension of one year when the final review grade is significantly higher than 6 out of 10. The TC may recommend a six-month extension followed by a mid-term review in cases where closer monitoring is felt to be necessary, either because the review grade is marginal, or for any other reason. A final review grade significantly lower than 6/10 is likely to result in a recommendation for termination of the Research Scholarship, unless the TC feels that there are extenuating circumstances that warrant an extension.

While the student reviews are typically held once a year, it is strongly recommended that the student or supervisor should bring any problems in the student's progress (either apparent or envisaged, and including any inter-personal problems that are affecting the work) to the attention of the TC as early as possible so that these, along with possible solutions, can be discussed. If needed, these discussions could include the Convenor of the AAC and the Dean, NCRA Faculty. The students are especially advised to not wait until the annual review to take up such issues, but to bring them up with the TC as soon as possible.

The minutes of the review will be provided to the student within ≈ 2 weeks of the review. If a student feels for any reason that the minutes are not a fair representation of what transpired during the seminar or review, or feels that the review process has not been fair, s/he should discuss the matter with the advisor and/or the TC, and may request another meeting with the TC. If the student is not satisfied with the outcome of this meeting, s/he may make a representation to the Dean, NCRA Faculty, or to the Centre Director (in cases where the Dean, NCRA Faculty, is a member of the TC).

6.2 Salary, Travel Grant, and Contingency Grant

All NCRA Ph.D. and Int-Ph.D. students are provided a scholarship to support them during their Ph.D. research, as well as an annual contingency grant. The details of the scholarship and the contingency grant can be found at `https://www.tifr.res.in/academics/academic_procedures.php?t=cat2`. We emphasize that all scholarships and grants are subject to revision by the Department of Atomic Energy and TIFR from time to time.

A description of the items that may be purchased with the contingency grant, along with various norms, is provided at `https://www.tifr.res.in/academics/academic_procedures.php?t=cat2`. The purchase of other items required for research purposes may also be permitted, based on the recommendations of the guide or, for students who have not yet registered for the Ph.D., by the Convenor of the AAC.

The contingency grant is maintained on the basis of the academic year, i.e. August to July, and is non-cumulative. However, if a specific item (e.g., a laptop) costs more than the total annual contingency grant, students may be permitted to combine the grants from two or more years in order to purchase the item. This would require a formal application from the student to the Dean, NCRA Faculty, before the purchase of the item, and would only be allowed as per the TIFR norms. In case a student wishes to use the contingency grant of a given academic year to purchase an item in the following year, along with the grant of the following year, s/he must send in a formal request for "blocking" the grant of the current academic year for this purchase before the end of the academic year, i.e. by July 31.

The contingency grant of a given academic year may also be used to support travel for conferences, workshops, schools, observing runs, etc, in the following academic year, again with the approval of the Dean, NCRA Faculty, as per the TIFR norms. All such requests for "blocking" the contingency grant of an academic year for use in the following academic year must be made before July 31 of the academic year of the contingency grant, and must explicitly state what the grant will be used for (e.g. the conference name, dates, and venue, if the grant is to be used for a conference). If the request is made after the above deadline of July 31, the request will be denied. Similarly, if a student would like part of a particular bill to be covered with the contingency grant of a future academic year, the request for this must be made *before* submitting the bill, and the approval note should be attached to the submission. It would not be possible to process requests made after the bill has been submitted and cleared.

In addition, Regular Ph.D. and Int-Ph.D. students will be provided with a research and travel support grant of INR 2.25 lakhs during the course of the Ph.D. (as of August 2025) to enable them to attend international research conferences, workshops, or schools, carry out international research collaborations, travel for observations or experiments with international research facilities, etc. Formal approval of the Ph.D. supervisor (or of the Convenor of the AAC for students who have not yet registered for a Ph.D.) for such travel should be obtained when submitting the relevant application forms (available at the Joint Secretariat). The final permission for such travel must in all cases be obtained well in advance of the travel from the Centre Director, NCRA.

6.3 Leave of Absence for Research Scholars

During the courses of the Graduate School, students will not be allowed to take leave from NCRA except in circumstances such as illness or emergencies. In any event, absence from NCRA during the Graduate School period will be permitted only with the recommendation of the Convenor of the AAC and approval from the Dean, NCRA Faculty.

Students attending Graduate School are generally not expected to go out of station to attend scientific conferences or workshops, or to go on deputation. An exception to this norm would require the recommendation of the Convenor of the AAC, and approval from the Dean, NCRA Faculty.

Research Scholars are not permitted to go on vacation while their courses are in progress. Vacation can be taken only during the breaks in the Graduate School.

Once the courses are over, students are entitled to seventy days of leave in a year, provided the leave is taken during the vacation period (October 1 to October 31, December 16 to January 14, and April 1 to July 31). The detailed leave rules applicable at any time may be obtained from the Joint Secretariat. All requests for leave must be approved in advance, first by the Ph.D. supervisor (or, for students who have not yet registered for a Ph.D., by the Convenor of the AAC), and finally by the Dean, NCRA Faculty.

6.4 Support Activities

All Research Scholars are strongly encouraged to take part in support activities, especially in the observatory, to enrich their experience and learning, and also to contribute to the Centre. These support activities include Science Day activities, GMRT test and upgrade activities, acting as a teaching assistant in a lecture course, etc..

6.5 Seminars and other Academic Activities

Research Scholars are expected to participate in academic activities, such as seminars, colloquia, informal discussion meetings, etc. Besides the annual review seminar, every Research Scholar is required to give an additional talk, typically at the NCRA Academic Day(s), during each academic year. Research Scholars are also strongly encouraged to give more seminars, both at NCRA and at other institutes.

6.6 National Eligibility Test (NET)

It is strongly recommended that NCRA Research Scholars pass the CSIR/UGC National Eligibility Test (NET) at the earliest opportunity. While this test is not required by NCRA or the TIFR Deemed-to-be University, it is an important qualifier for faculty positions at Indian universities, and experience has shown that it is far easier to clear this test when candidates have recently cleared the M.Sc. examination.

7 Requirements and Procedures for a Ph.D. Degree

The year-by-year structure of the programmes for Int-Ph.D. (100 credits), Int-Ph.D. (80 credits), and Regular Ph.D. students is summarized in Table 8.

Programme (Credits)		Duration											
	Years	I		II		III		IV		V		VI	
	Semesters	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Int-Ph.D. (100)		C*	C*	C	C	C	R	R	R	R	R	R	T
Int-Ph.D. (80)		C	C	C	C	R	R	R	R	R	R	R	T
Ph.D. (60)		C	C	C	R	R	R	R	R	R	T		

C*: Coursework (outside NCRA)
C: coursework (including research projects) in NCRA
R: Research work
T: Thesis preparation

Table 8: The overall structure of the Ph.D. and Int-Ph.D. programmes.

7.1 Duration of Ph.D. Programme

A Regular Ph.D. student is expected to submit his/her Ph.D. thesis to the TIFR Deemed-to-be University or the University at which s/he is registered within five years of the date of joining the NCRA Ph.D. Programme (i.e. including the Graduate School). The corresponding limit for Int-Ph.D. students is six years. Research Scholars who fail to complete their work within these periods will have to request an extension. In such cases, the student's Thesis Committee would refer the matter to the Dean, NCRA Faculty, along with a justification for the extension. The Dean will review such cases and recommend an extension, if felt appropriate, to the NCRA Centre Director. Such extensions to the thesis submission deadline may be granted for up to a year, with approval from the NCRA Centre Director. However, the scholarship amount will reduce to half of the regular scholarship, for the months of the extension. In addition, the sum of all *extensions with scholarships* in a batch containing M students would be at most $N = 3 \times M$ months. This means that, if all students of a batch require an extension, each student would be given a half-pay extension for 3 months. After this period, no scholarship would be paid to the students, although they may continue to work on the thesis. We emphasize again that such extensions are not guaranteed and require the approval of the NCRA Centre Director. Including such extensions, the total duration of the thesis should not be more than six years for Regular Ph.D. students and seven years for Int-Ph.D. students. Extensions beyond these limits will be allowed only in rare and exceptional cases, based on a written application from the advisor.

We emphasize that the monthly salary of the student would be reduced to half during the period of the extension, with the sum of all extensions for a batch of M students being $3 \times M$ months (as per the TIFR norms). Further, the contingency grant will not be available during the extension period, except for cases where it has been "blocked", with approval, from the previous academic year.

7.2 Basic Requirements for a Ph.D. Thesis

The requirements for an NCRA Ph.D. from the TIFR Deemed-to-be University are set by the TIFR Subject Board of Physics. Essentially, the thesis must demonstrate that the candidate has done a significant amount of original work in the chosen subject. A necessary criterion for this is that at least some part of the thesis, where the candidate has made a significant contribution, should be published or accepted for publication in a peer-reviewed journal, at the time of the submission of the synopsis. Further details are provided at the website of the TIFR Subject Board of Physics `https://www.tifr.res.in/~sbp/new2015/thesis.htm`.

7.3 Synopsis Seminar

When the student has completed his/her research work to the satisfaction of the supervisor, s/he is required to give a "synopsis seminar" on the work on which the thesis is based. The NCRA Joint Secretariat will make arrangements for this synopsis seminar. The synopsis evaluation committee will consist of five faculty members, including one external member. The evaluation committee, including the external member, would be finalised by the Dean, NCRA Faculty, in consultation with the supervisor and/or the Convenor of the AAC.

The synopsis is a PDF document, of length not fewer than 10 pages and not more than 15 pages, legibly typed on A4-size pages in 12-pt. font size, with 1.5 pt. spacing and with 1 inch margins (see `https://www.tifr.res.in/~sbp/new2015/synopsis.htm`). Apart from text, it may contain figures, tables, sections of computer code, and a short bibliography. An extra page should be attached to the synopsis, listing publications from the thesis. A copy of the synopsis must be submitted to the Joint Secretariat for circulation to the evaluation committee at least one week before the synopsis seminar. If the title of the thesis has been changed from the one submitted at the time of registration, an additional sheet must be attached to the synopsis, requesting approval of the change in the title. This sheet must be signed by both the Ph.D. student and the Ph.D. supervisor.

The synopsis and the synopsis seminar will be evaluated by the evaluation committee (see above), and the numerical marks given by members of the evaluation committee will be recorded in the file of the candidate. If the average numerical mark of the committee is lower than 60%, the thesis will not be forwarded to the TIFR Deemed-to-Be University. In such situations, the students would be required to resubmit the synopsis, and repeat the synopsis seminar. The recommendations of the synopsis evaluation committee should be taken into account by the student, and the synopsis (and possibly, the thesis) revised accordingly before the final submission. Any significant changes in the thesis from the content described in the approved synopsis would require a resubmission and re-approval of the synopsis.

7.4 Synopsis and Thesis Submission

After the synopsis and the synopsis seminar have been approved by the evaluation committee, the student may submit the final synopsis of her/his Ph.D. thesis to the TIFR Deemed University. The procedure for this may be obtained from the NCRA Joint Secretariat, or from the website `https://www.tifr.res.in/academics/academic_procedures.php`. Finally, the Ph.D. thesis may be submitted to the TIFR Deemed-to-be University at any time following the submission of the synopsis, up to a maximum of six months from the date of submission of the synopsis. If the thesis has not been submitted within six months of the synopsis submission, the synopsis would have to be resubmitted and re-evaluated.

7.5 Visiting Fellowship After Submission of Thesis

The norms of the Department of Atomic Energy (DAE) require candidates for a post-doctoral fellowship to have at least a provisional Ph.D. degree. As such, Ph.D. students who have obtained their provisional Ph.D. degrees may, *on application*, be offered a short-term Research Associate position at NCRA for up to 6 months, to allow completion of ongoing research projects.

8 Students or Guides Affiliated to Other Institutions

8.1 Students working at NCRA

Students affiliated to an institution other than TIFR but desirous of working at NCRA for extended periods must have a guide and a research problem clearly identified in their parent institution. Such a collaborative effort, in which an NCRA staff member is interested in partially supervising the student, would contribute to increasing the academic activities at NCRA. However, the following norms should be followed:

1. The NCRA staff member with whom the student is working, and who is responsible for the student, should be clearly identified.

2. The total duration of such visits by one student should not exceed six months in a calendar year. In exceptional circumstances, this could be extended to at most nine months, with approval of the NCRA Faculty.

3. The total number of such external students visiting NCRA at any given time will be determined by the available infrastructure. If such a student wishes to visit NCRA, s/he should write to the Dean, NCRA Faculty (dean_nf@ncra.tifr.res.in), requesting permission for the visit, well in advance.

4. Such visits should be mentioned in the NCRA Faculty meetings as an informational item. The students should also be encouraged to give a talk at the end of each visit.

5. The students are expected to be financially supported by their parent institute or their own research grants. However, efforts will be made to provide logistical support. Students from India and abroad will be treated at par.

6. Accomodation in the NCRA hostel or guest house will be provided to such students depending on availability, and following the NCRA norms.

8.2 NCRA Members Guiding Students Working Elsewhere

Occasionally, an NCRA member may be requested to be the Ph.D. guide of a student who intends to carry out doctoral work at another institution. NCRA imposes no constraints on this activity, except that the thesis may not be submitted through NCRA. The doctoral research of such students will be governed entirely by the rules and regulations of his/her institution. However, the NCRA Joint Secretariat should be informed about such cases.

Appendix 1: Summary of the course and project structure for the three NCRA Ph.D. and Int-Ph.D. programmes

Course Outline for Regular Ph.D. Students (60 Credits)		
No.	Course	Credits
Semester I: Early August to mid-December		
PHY-231.3	Introduction to Astronomy & Astrophysics	4
PHY-232.3	Radiative Processes	4
PHY-233.3	Astronomical Techniques	4
PHY-234.3	General Relativity	2
PHY-235.3	Computational Astrophysics	2
PHY-236.3	The Radio Sky	2
Semester II: Early January to mid-May		
PHY-331.3	Fluids & Plasmas	2
PHY-332.3	Galaxies & ISM - I	2
PHY-333.3	Cosmology	2
PHY-334.3	Active Galactic Nuclei	2
PHY-335.3	Radio Telescopes	2
PHY-336.3	Radio Interferometry	2
PHY-337.3	Galaxies & ISM - II	2
PHY-338.3	Time-domain Astronomy	2
PHY-300.3	Research & Publication Ethics	2
Semester III, Term I: Mid-June to mid-September		
PHY-387.3	Research Methodology I	12
Semester III, Term II: Mid-October to mid-January		
PHY-388.3	Research Methodology II	12
	Total Credits	60

Table 9: Courses and Projects for Regular Ph.D. Students

Course Outline for Integrated Ph.D. Students (80 Credits)		
No.	Course	Credits
Semester I: Early August to mid-December		
PHY-231.3	Introduction to Astronomy & Astrophysics	4
PHY-232.3	Radiative Processes	4
PHY-233.3	Astronomical Techniques	4
PHY-234.3	General Relativity	2
PHY-235.3	Computational Astrophysics	2
PHY-236.3	The Radio Sky	2
Semester II: Early January to mid-May		
PHY-331.3	Fluids & Plasmas	2
PHY-332.3	Galaxies & ISM - I	2
PHY-333.3	Cosmology	2
PHY-334.3	Active Galactic Nuclei	2
PHY-335.3	Radio Telescopes	2
PHY-336.3	Radio Interferometry	2
PHY-337.3	Galaxies & ISM - II	2
PHY-338.3	Time-domain Astronomy	2
PHY-300.3	Research & Publication Ethics	2
Semester III, Term I: Mid-June to mid-September		
PHY-387.3	Research Methodology I	12
Semester III, Term II: Mid-October to mid-January		
PHY-388.3	Research Methodology II	12
Semester IV, Term I: Mid-February to mid-May		
PHY-4XX.3	Advanced Course I	6
PHY-4XX.3	Advanced Course II	6
Semester IV, Term II: Early-June to end-August		
PHY-461.3	Research Methodology III	8
	Total Credits	80

Table 10: Courses and Projects for Integrated Ph.D. Students (80 Credits)

Course Outline for Integrated Ph.D. Students (100 Credits)		
No.	Course	Credits
Semester I: Early August to early December (Physics Dept.)[1]		
PHY-101.3	Electronics	3
PHY-103.3	Mathematical Methods in Physics	4
PHY-104.3	Classical Mechanics I	4
PHY-106.3	Quantum Mechanics I	4
PHY-108.3	General Laboratory*	3
Semester II: Early January to early May (Physics Dept.)[1]		
PHY-105.3	Statistical Mechanics	4
PHY-116.3	Quantum Mechanics II	4
PHY-107.3	Electrodynamics I	4
PHY-111.3	Atoms, Molecules and Solids	3
PHY-110.3	Computer Laboratory*	3
Summer Project: Mid-May to mid-July (NCRA)		
PHY-109.3	RPL or Experimental/Reading Project	4
Semester III: Early August to mid-December (IUCAA/NCRA)		
PHY-231.3	Introduction to Astronomy & Astrophysics	4
PHY-232.3	Radiative Processes	4
PHY-233.3	Astronomical Techniques	4
PHY-234.3	General Relativity	2
PHY-235.3	Computational Astrophysics	2
PHY-236.3	The Radio Sky	2
Semester IV: Early January to mid-May (IUCAA/NCRA)		
PHY-331.3	Fluids & Plasmas	2
PHY-332.3	Galaxies & ISM - I	2
PHY-333.3	Cosmology	2
PHY-334.3	Active Galactic Nuclei	2
PHY-335.3	Radio Telescopes	2
PHY-336.3	Radio Interferometry	2
PHY-337.3	Galaxies & ISM - II	2
PHY-338.3	Time-domain Astronomy	2
PHY-300.3	Research & Publication Ethics	2
Semester V, Term I: Mid-June to mid-September (NCRA)		
PHY-387.3	Research Methodology I	12
Semester V, Term II: Mid-October to mid-January (NCRA)		
PHY-388.3	Research Methodology II	12
	Total Credits	100

[1]These courses are listed according to the curriculum followed in 2017 at the Physics Dept.; the exact listing of courses may vary.

* The General Laboratory and the Computer Laboratory courses may be interchanged for some students as per the Physics Dept. norms.

Table 11: Courses and Projects for Integrated Ph.D. Students (100 Credits)

Appendix 2: Syllabi for the NCRA Graduate School Courses

PHY-231.3: Introduction to Astronomy & Astrophysics [4 credits]

Astronomical Measurements: celestial sphere, RA/DEC coordinates, Galactic coordinates, luminosity/flux magnitude scale, apparent/absolute magnitude, electromagnetic wavebands, spectroscopy, Astronomical Unit, parsec, standard candles, distance measurement by geometric means (parallax, distances to open clusters), radial velocity, binaries (visual, eclipsing, spectroscopic)

Radiation: radiative transfer equation and line formation, opacity and extinction, photon diffusion and scattering, LTE, departure from LTE

Sun and solar system: Sun as a star (qualitative): Solar spectrum, photospheric absorption lines, limb darkening; energy source: Kelvin time scale, nuclear fusion; energy transport - radiation and convection; photosphere, chromosphere, transition region, corona; X-ray emission, magnetic fields, Sunspots

Planets and extrasolar planets: Different types of planetary system; Detection mechanism of extrasolar planets; concept of orbital resonance

Stellar structure and evolution: Observed stellar properties: stellar classification based on spectra, HR diagram, main sequence, luminosity dependence on mass, Saha ionisation equation, and star clusters; Stellar models: hydrostatic equilibrium, gas/radiation pressure; theoretical main sequence: energy balance, constitutive relations and detailed stellar structure, convective instability. Convection zones in stars; Nuclear energy production: binding energy per nucleon, efficiency of fusion, calculation of nuclear reaction rates, tunneling in Coulomb barrier, Gamow peak. important nuclear reactions in stars: pp chain, CNO cycle, triple alpha reaction, nuclear resonances and elementary particle production; Pre-main sequence evolution: Jeans instability, star formation, Initial Mass Function, Hyashi track, massive stars; Post-main sequence evolution: Core He burning, shell burning, red giant phase, stellar winds, Parker's model for solar wind, planetary nebulae, compact objects (white dwarfs, neutron stars & pulsars, black holes); Binary system evolution: effective potential in rotating frame, Lagrange points, Roche lobe, mass overflow, Type la supernovae, X-ray binaries and accretion disk

Extragalactic astronomy: Inter-stellar medium (ISM): Multi-phase structure, HII region, heating and cooling mechanisms, dust and molecular clouds, basics of Circumgalactic medium; Galaxies: morphology, surface brightness profiles, colour-magnitude diagram, stellar population, kinematics, high redshift galaxies, Active galaxies; Cosmology & Structure Formation: groups, clusters and filaments, Big Bang nucleosynthesis, CMB, thermal history

Reference books:

1. The Physical Universe: An Introduction to Astronomy: Frank H. Shu
2. Observational Astrophysics: Robert C. Smith
3. An introduction to Modern Astrophysics: B. W. Carroll, D. A. Ostle
4. Theoretical astrophysics. Vol.1: Astrophysical processes: T. Padmanabhan
5. Methods of celestial mechanics: D. Brouwer, G. M. Clemence
6. Envisioning Exoplanets: Searching for Life in the Galaxy: Michael Carroll
7. An introduction to the study of stellar structure: S. Chandrasekhar
8. The Sun: An Introduction: Michael Stix (2004 edition).
9. Stellar structure and evolution: R. Kippenhahn and A. Weigert
10. Black holes, white dwarfs, and neutron stars: the physics of compact objects: S.L. Shapiro and S. A. Teukolsky
11. Galaxies and the universe: Allan Sandage, Mary Sandage, Jerome Kristian
12. Nucleosynthesis and Chemical Evolution of Galaxies: Bernard E. J. Pagel
13. Principles of Physical Cosmology: P.J.E. Peebles

PHY-232.3: Radiative Processes [4 credits]

Radiative Transfer: Specific intensity and its moments, optical depth and radiative transfer - simple approximate solutions, Thermal Radiation and Local Thermodynamic Equilibrium, scattering effects, radiative diffusion.

Basic theory of radiation fields: electromagnetic waves, radiation spectrum, polarisation and Stokes parameters, geometrical optics

Radiation from non-relativistic moving charges: Single moving charges - Lienard-Wiechart potentials, velocity and radiation fields; radiation from non-relativistic system of particles, radiation reaction, radiation from harmonically bound charges.

Continuum radiation: Bremsstrahlung, Cyclotron and Synchrotron radiation, Comptonisation, Cerenkov radiation, Curvature radiation, plasma effects.

Attenuation of radiation: interaction of radiation with atoms, molecules and dust grains - reddening and extinction curves (Galactic, SMC/LMC, Starbursts), interaction of high energy radiation with matter - photoelectric absorption, Thomson and Compton scattering, pair production and pair annihilation, polarization.

(Note: Astrophysical application should be included wherever possible.)

Reference books:

1. Radiative Processes in Astrophysics: G. B. Rybicki, A. P. Lightman
2. High Energy Astrophysics: Longair, Malcolm S.
3. Classical Theory of Fields: L. D. Landau, E. M. Lifshitz
4. Astrophysics of Gaseous Nebulae and Active Galactic Nuclei: D. E. Osterbrock, G. J. Ferland

PHY-233.3: Astronomical Technique [4 credits]

Celestial sphere, astronomical coordinates and time

Astrophysical information carriers and their importance: Electromagnetic radiation, neutrinos and cosmic rays, gravitational waves

Earth's atmosphere: Effects at different bands, Extinction and reddening, ground and spaced-based telescopes

Optical/UV/IR: Telescopes: collecting area, field of view, diffraction limit, seeing and point spread function; Detectors; Turbulent atmosphere and adaptive optics; Techniques: Photometry, Spectroscopy, Timing and Polarimetry; Major Telescopes in visible/UV/IR.

Radio Astronomy: Basic Fourier optics; Signal detection at radio wavelengths - dipoles, phased arrays and single dish; Two element interferometer and aperture synthesis; Antenna electronics (LO and digitizer); Correlator and beamformer; Calibration - Hamaker-Bregman-Sault measurement equation; Imaging and deconvolution; Time domain astronomy; Polarimetry.

High Energy Astronomy: Detectors and Telescopes: X-ray/gamma-ray detectors; Source localization - collimators, coded-aperture masks, X-ray optics; Techniques: Imaging, Spectroscopy, Timing, Polarisation (optional); Major Telescopes in X-ray/gamma-ray.

Gravitational waves: Observational methods for gravitational waves, Michelson and Fabry Perot interferometers, Effect of gravitational waves on matter and corresponding response of a Michelson interferometer (optional), Ground-based laser interferometers as gravitational wave detectors - choice of various parameters, namely, arm length, mirror mass, laser power, vacuum level, suspensions and seismic isolation.

Reference books:

1. Astronomical Optics: D. J. Schroeder
2. Optical, Infrared and Radio Astronomy: From Techniques to Observation: R. Poggiani
3. Physical principles of Astronomical Instrumentation: Ade, Griffin, Tucker
4. Observational Astrophysics: P. Léna (Author), D. Rouan, F. Lebrun, F. Mignard, D. Pelat
5. High Energy Astrophysical Techniques: R. Poggiani
6. Handbook of X-ray Astronomy: Edited by K. Arnaud, R. Smith, A. Siemiginowska
7. The fourier transform and its applications: Ronald N. Bracewell
8. Tools of radio astronomy: Thomas L. Wilson, Kristen Rohlfs, Susanne Hüttemeister
9. Interferometry and Synthesis in radio astronomy: A. Richard Thompson, James M. Moran, George W. Swenson Jr.
10. Fundamentals of Interferometric Gravitational Wave Detectors, 2nd Edition, Peter Saulson, World Scientific (2017)
11. General Relativity and Gravitational Waves: Essentials of Theory and Practice, Dhurandhar & Mitra, Springer (2022)

PHY-234.3: General Relativity [2 credits]

- Equivalence principle and physical basis for GR
- Tensor analysis
- Geodesics, connection and curvature
- Energy-momentum tensor
- Einstein equations
- Schwarzschild metric: orbits and classical tests of GR
- Linearized gravity

Reference books:

1. A First Course in General Relativity: B. Schutz
2. Gravity: An Introduction to Einstein's General Relativity: J. Hartle
3. Gravitation: C. W. Misner, K. S. Thorne, J. A. Wheeler
4. A Relativist's Toolkit: E. Poisson

PHY-235.3: Computational Astrophysics [2 credits]

Probability and Statistics: discrete and continuous distributions, Bayes' theorem, moment and cumulant generating Functions, multivariate Gaussian statistics, non-Gaussian distributions, Central Limit Theorem

Python revision: Numpy and Scipy, data structures and precision

Random number generation

Statistical tests of randomness: Kolmogorov-Smirnov, Chi-squared, mean and variance of a data set

Basic parameter inference: least squares fitting, linear Gaussian problem in Bayesian framework, model comparison theory

Differential equations: basic finite differencing schemes, implementation of one of the methods [first and second order Runge Kutta, Crank Nicholson], PDE solvers, implementation of one of the methods [method of characteristics, LAX]

Fourier techniques: FFT and DFT

Reference books:

1. Data Reduction and Error Analysis: P. R. Bevington, D. K. Robinson
2. Probability, Random Variables and Stochastic Processes: A. Papoulis, S. U. Pillai
3. The Art of Computer Programming, vol. 1: fundamental algorithms: D. E. Knuth
4. Numerical Methods that (usually) Work: Forman S. Acton
5. Numerical Recipes: W. H. Press, B. P. Flannery, S. A. Teukolsky, W. T. Vetterling
6. Bayesian methods in Cosmology: Roberto Trotta, online notes - https://arxiv.org/pdf/1701.01467.pdf
7. The Fourier Transforms and its Applications: Ronald N. Bracewell

PHY-236.3: The Radio Sky [2 credits]

Radio continuum emission: Synchrotron emission, Brehmsstrahlung emission, Gyro-synchrotron emission, Electron-cyclotron maser emission

Radio spectral lines: The HI 21cm line, The CO rotational lines, The CII 158 micron line, Other radio lines (OH, HCO, H2O, NH3, CI, etc).

The constituents of the radio sky: The Sun and the planets, Galactic HII regions and supernova remnants, The Galactic Centre, Pulsars and fast radio bursts, Radio galaxies and active galactic nuclei, Normal galaxies, Other sources (e.g. extra-solar planets, stars, gamma-ray bursts, slow transients, etc).

Radio source counts

Reference Books:

1. Essential Radio Astronomy (Condon and Ransom)
2. Tools of Radio Astronomy (Wilson, Rohlfs, and Huttemeister)
3. Introduction to Radio Astronomy (Burke, Graham-Smith, and Wilkinson)
4. Radio Astronomy (Kraus)
5. Fundamentals of Radio Astronomy: Astrophysics (Snell, Kurtz, and Marr)

PHY-331.3: Fluids & Plasmas [2 credits]

Ideal Fluids: Definition of fluid as continuum, mean free path, collision time, local thermal equilibrium, perfect gas equation of state, convective/Lagrangian derivative, Euler equation, fluid equations in conservation form, vorticity, circulation theorems, Hydrostatic equilibrium of plane parallel atmosphere: isothermal, isentropic; Fluid equations in rotating reference frames

Linear Waves and Instability: Sound, Internal gravity, Surface gravity, Schwarzschild criterion for convective instability, Rayleigh-Taylor and Kelvin-Helmholtz instabilities, Jeans instability

Non-ideal fluids: Energy equation, Navier-Stokes equations, Boundary layers, Reynolds number, Stokes flow, Molecular origin of viscosity

Turbulence: transition to turbulence, homogeneous and isotropic turbulence: Kolmogorov (K41) phenomenology

Supersonic Flows: Hydrodynamic shocks, Rankine-Hugoniot jump conditions

Plasma: Definitions of cold and warm plasmas, Plasma orbit theory: magnetic mirrors, gradient drift, curvature drift, 2-component plasmas, Debye length, Cold plasma oscillations

Kinetic theory: Distribution functions, Vlasov Equation, Landau Damping (collisionless plasma)

Magnetohydrodynamics: regime of its validity, induction equation, flux freezing, MHD waves

Solar winds: Parker spiral

Reference books:

1. Elementary Fluid Dynamics: D J Acheson
2. Physics of Fluids and Plasmas: A R Choudhuri
3. Fluid Mechanics: Landau & Lifshitz
4. Physics of Plasmas: TJM Boyd & J J Sanderson
5. Introduction to Plasma Physics and Controlled Fusion: F F Chen
6. Magnetohydrodynamics (of Laboratory and Astrophysical Plasmas): H Goedbloed, R Keppens, S Poedts
7. Principles of Astrophysical Fluid Dynamics: C Clarke & B Carswell
8. Astrophysical Flows: J Pringle & A King

PHY-332.3: Galaxies & ISM - 1 [2 credits]

Milky Way and its neighbourhood: Basic structure of our Galaxy, solar neighbourhood, Andromeda and their satellites e.g., LMC, SMC

Galaxy morphology: Classification of galaxies: spirals, ellipticals, lenticulars, irregulars, dwarfs, peculiar galaxies; Active galactic nuclei, Hubble sequence and Hubble Types; Methods of galaxy classification: visual inspection, colour-based

Photometry and Surface Brightness distribution: Basic filter system; photometry; Point spread function; Surface brightness profiles: radial and vertical; colors, colour-bimodality, colour-magnitude diagram

Stellar population: Simple stellar population models; mass-to-light ratio estimation; stellar mass estimation

Potential of galaxies: Solving Poisson equation for spherical galaxy models; Kuzmin disk and exponential disk models

Kinematics: Galaxy spectra; Rotation curve - ionized gas and stellar rotation, cold HI 21 cm, CO rotation; Modelling dark matter profiles; stellar velocity dispersion and its measurement.

Interstellar medium (ISM) Overview: Multi-phase structure of ISM

Basics of interstellar dust: Extinction and reddening of star light; Galactic reddening correction, extinction curve

HII regions: Ionization structure: static; heating and cooling; Nebular diagnostic: BPT diagram; Hot gas: heating and cooling curve

Hl clouds: Two-phase medium: 21 cm line; Hl distribution: in-plane and perpendicular to the plane - bending and breathing waves, corrugation

Reference books:

1. Galaxies in the Universe: An Introduction: L. S. Sparke, J. S. Gallagher
2. Galactic Astronomy: Binney, Merrifield
3. Theoretical Astrophysics Vol. 3, Galaxies & Cosmology: T. Padmanabhan
4. Galaxy Formation and Evolution: H. Mo, F. van den Bosch, S. D. M. White
5. Galactic Dynamics: Binney, Tremaine
6. Galaxies and cosmology: F. Combes, P. Boisse, A. Mazure, A. Blanchard, M. Seymour
7. Physical Processes in the Interstellar Medium: L. Spitzer Jr.
8. Astrophysics Of Gas Nebulae and Active Galactic Nuclei: D. E. Osterbrock, G. J. Ferland
9. Physics of the Interstellar and Intergalactic Medium: B. T. Draine

PHY-333.3: Cosmology [2 credits]

Expanding Universe: Cosmological principle, homogeneity and isotropy, maximally symmetric spaces with and without curvature, Friedmann Lemaitre Robertson Walker (FLRW) metric, expansion of the Universe, redshift and distances in an expanding Universe - angular diameter distance, luminosity distance

FLRW Dynamics: Einstein tensor of the FLRW metric, Energy-momentum tensor of dust, Friedmann equations, critical density of the Universe, special case solutions, horizons in the Universe, standard model of Cosmology

Brief thermal history of the Universe from $T = 1$ GeV to $T = 900$ K: number density, energy density, pressure and entropy density of particles in thermal equilibrium, relativistic and nonrelativistic limits, effective number of degrees of freedom and its evolution, particle freeze out, temperature of decoupled relativistic species, cosmic neutrino background, Big Bang nucleosynthesis, Helium abundance, cosmic microwave background (CMB) and discovery of temperature fluctuations

Observational evidence for dark matter: Kinematics of galaxies in galaxy clusters, rotation curves of galaxies, growth of structure.

Structure Formation: Linear growth of perturbations, Nonlinear evolution of perturbations - Zeldovich approximation, spherical top hat, basic idea of simulation results

Brief introduction to physics of galaxy formation

Basic discussion of cosmological observations: geometrical probes, CMB anisotropies, late-time cosmic web, intergalactic medium

Reference books:

1. An Introduction to Cosmology: J. V. Narlikar
2. Cosmology: J. A. Peacock
3. Theoretical Astrophysics Vol. 3, Galaxies & Cosmology: T. Padmanabhan
4. The Early Universe: E. Kolb, M. Turner
5. Physical Cosmology: P. J. E. Peebles

PHY-334.3: Active Galactic Nuclei [2 credits]

Taxonomy and history of Active Galactic Nuclei (AGN): Seyfert galaxies, Quasars, Fanaroff-Riley Radio Galaxies, LINERS, BL Lac objects, Optically Violent Variables

The supermassive black hole paradigm: accretion disk structures

Continuum emission: UV-optical continuum, High energy X-ray & gamma-ray emission, Radio continuum, Synchrotron emission, Free-free emission, Thermal & Inverse-Compton emission

Broad and Narrow emission line regions (BLR, NLR): Photoionization, Electron densities, Electron temperatures, Reverbertion mapping

Jets in AGNs: Radio-loud & Radio-quite Divide, Fanaroff-Riley Divide

Unified models of AGNs: Successes & Failures, Evolution with Redshift

Environments of AGNS: AGN Feedback

AGN surveys: UV/optical, Radio, X-rays

Quasar luminosity functions: Log N - Log tests, Luminosity-Volume tests, AGN Evolution

Quasar absorption lines: Absorption-Line Physics, Lyman-alpha forest systems, Broad absorption line (BAL) systems, Damped Lyman-alpha absorbers, 21cm absorbers, Gunn Peterson test

Recent developments in AGN science: Discovery of high-energy neutrinos, High-resolution VLBI in Optical and Radio from VLTI and EHT, Multi-messenger astronomy.

Reference books:

1. ”An Introduction to Active Galactic Nuclei” by Bradley M. Peterson.
2. ”Active Galactic Nuclei: From the Central Black Hole to the Galactic Environment” by Julian H. Krolik.
3. ”The Physics of Extragalactic Radio Sources” by David de Young.
4. ”Active Galactic Nuclei” by Volker Beckmann & Chris Shrader.
5. ”The Physics and Evolution of Active Galactic Nuclei” by Hagai Netzer.
6. ”Quasars and Active Galactic Nuclei: An Introduction” by A. K. Kembhavi & J. V. Narlikar.

PHY-335.3: Radio Telescopes [2 credits]

Types of Radio Telescopes: Single dish, interferometric arrays, all-sky arrays, space radio telescopes, and special radio telescopes - their uses and applications - radio continuum imaging, spectral line imaging and spectroscopy, pulsars and transients, VLBI. Radio telescopes from around the world.

Antennas for Radio Telescopes: Radiation fields around an antenna, reciprocity theorem, near and far fields, the Hertzian dipole. Antenna and feed types: prime and secondary focus, offset parabolic, cylindrical and dipole array. Dish antenna geometry: deep and shallow dishes, their applications. Apertures and radiation patterns, directivity, illumination, beam patterns, and pattern shaping.

Receiver and Signal Theory: Random signals and noise, their statistics. Analog receivers, superheterodyning, sampling and digitization. Effects of sampling and digitization: aliasing and quantization noise. Detection of radio signals, square law detection, and bolometric detectors. Spectrometers (autocorrelation and Fourier), polarimeters and pulsar backends.

Sensitivity: Radiometers, the radiometer equation, gain (G), antenna temperature, and system temperature (T_sys), system equivalent flux density (SEFD), sensitivity of single-dish radio telescopes, relationship between G/T_sys and SEFD. Linearity, dynamic range, and source confusion. Comparing different single dish radio telescopes.

Observational Techniques: Calibration with noise sources, Dicke switching, frequency-switching, position-switching, and calibrator sources. Single dish spectrometer for galactic kinematics and line spectroscopy, Velocity frames, and Doppler corrections. Pulsar observations (with a few applications) and observing techniques. Imaging with single-dish telescopes. Phased arrays and beamformers. VLBI observations.

Reference books:

1. Tools of Radio Astronomy (Wilson, Rohlfs & Huttemeister)
2. Essential Radio Astronomy (Condon & Ransom)
3. Radio Telescopes (Christiansen & Hogbom).
4. Fundamentals of Radio Astronomy: Observational Methods (Snell, Kurtz & Marr)
5. Antennas (Kraus, J.D.)
6. Single Dish Radio Astronomy: Techniques and Applications (Eds: Stanimirovic, Altschuler, Goldsmith & Salter)

PHY-336.3: Radio Interferometry [2 credits]

Review of basic aspects of Radio Astronomy: Antennas, receivers, sensitivity: Flux density and brightness temperature; Coherence in radio astronomy

Fundamentals of Interferometry: Limitations of single dish astronomy: The need for interferometry; The two element interferometer - monochromatic and quasi-monochromatic; Delay tracking, fringe rotation; Coordinate system for imaging, antenna spacings and u,v,w coordinates; Correlation and correlators; Array design and aperture synthesis; UV coverage.

Modern radio interferometers: The GMRT: Low frequency: GMRT, VLA, LOFAR, MWA, ASKAP, MeerKAT; High frequency: ALMA, NOEMA, EHT, VLA; Introduction to the GMRT: Frequencies, UV coverage, Correlator.

Sensitivity and Errors: Point source and surface brightness sensitivity of an interferometer; The GMRT sensitivity; Time and frequency averaging; Dynamic range: Issues that limit the sensitivity; Radio Frequency Interference; Flux density, phase, and bandpass calibrators; Identifying problems-I: Bad data in the visibility domain; Planning an observing run: Sensitivity calculators, selecting calibrators, etc.

Calibration, Imaging, and Deconvolution: Calibration formalism and methods - amplitude and phase, antenna pointing, gain, delay, bandpass and polarization calibration, closure quantities; Identifying problems-II: Inspecting the antenna-based gains and bandpasses; Imaging - sampling function, weighting functions and gridding of visibility data; Deconvolution - CLEAN and its variants, non-uniqueness of solutions and missing information; Identifying problems-III: Artefacts in the image domain; Self-calibration; Imaging wide fields-of-view: The w-term; Imaging wide bandwidths: Multi-frequency synthesis.

Special topics: Spectral Line imaging and Polarization: Important radio spectral lines; Continuum subtraction; Spectral cubes; Moment images: Intensity, Velocity field, Velocity dispersion; Polarized radio emission; The Stokes parameters; Measuring polarization: circular or linear? Polarization calibration; Beam polarization; The Jones matrix.

Reference Books:

1. Essential Radio Astronomy (Condon and Ransom)
2. Interferometry and Synthesis in Radio Astronomy (Thomson, Moran, Swenson)
3. Synthesis Imaging in Radio Astronomy - II (eds. Taylor, Carilli, Perley)
4. Low-frequency Radio Astronomy (eds. Chengalur, Gupta, Dwarakanath).

PHY-337.3: Galaxies & ISM - II [2 credits]

Galaxies as Collisionless system: Stellar encounters; Concept of relaxation and its time scale for different stellar systems. Jeans theorem and its application; moments of CBE - Jeans equation, tensor virial theorem and their application to galaxies; Dynamical friction and its application

Galaxy environment: Local group and beyond; groups and clusters of galaxies; filament and voids. Tidal interaction and application to binary galaxy interaction; Impact of environment on galaxy properties

Galaxy morphology: Quantitative morphology; morphology density relation and its application to nearby cluster of galaxies; Galaxy luminosity function

Stellar population and stellar mass: Spectra energy distribution (SED) and its modelling. Star formation rate and star-formation history; Star-formation law

Scaling relations: Tully-Fisher relation, Faber-Jackson relation; Kormendy relation; Fundamental plane relation

Kinematics and dynamics of Galaxies: Stellar orbits; Schwarzschild modelling; Disk dynamics. Bars and spiral structures, disk instability.

Galaxy formation and Evolution: Angular momentum problem; SMBH-galaxy connection; high-redshift galaxies; top-down and bottom-up scenario

ISM dust: Composition and geometry of interstellar dust; extinction curve revisited; Scattering of optical and UV photons by dust grains; emission of infrared, submillimeter, and microwave radiation by dust; the evolution of interstellar dust.

HII regions: Ionization structure - dynamics

Magnetic field: Faraday rotation; cosmic rays

Supernovae: Three phase model; shocks; supernovae remnants; acceleration of cosmic rays by shock waves;

Nebular diagnostics: planetary nebulae, chemical enrichment; alpha abundance; Gas phase metallicity: methods to measure metallicity and its distribution in the galaxy

Molecular hydrogen: Formation and destruction; UV radiation from OB associations; turbulence in interstellar clouds; giant molecular clouds - star-formation

Initial Mass Function: Salpeter, Kroupa; connection to metallicity; massive star formation including Pop-III models.

(40% of the topics will be included in any given year.)

Reference books:

1. Galactic Dynamics: Binney, Tremaine
2. Galaxies in the Universe: An Introduction: L. S. Sparke, J. S. Gallagher
3. Galactic Astronomy: Binney, Merrifield
4. Theoretical Astrophysics Vol. 3, Galaxies & Cosmology: T. Padmanabhan
5. Galaxy Formation and Evolution: H. Mo, F. van den Bosch, S. D. M. White
6. Galaxy formation: M.S. Longair
7. Principles of stellar dynamics: S. Chandrasekhar
8. Astrophysics Of Gas Nebulae and Active Galactic Nuclei: D. E. Osterbrock, G. J. Ferland
9. Physics of the Interstellar and Intergalactic Medium: B. T. Draine
10. The Origin of Cosmic Rays: V. L. Ginzburg and S.I. Syrovatskii

PHY-338.3: Time-domain Astronomy [2 credits]

Time-domain sources with their observational properties, emission models, etc: Pulsars, Millisecond pulsars, Rotating Radio Transients (RRATS), Magnetars, Fast Radio Bursts (FRBs), Ultra Long-period transients, Gamma-Ray Bursts (GRBs), Other transient/variable sources (Stellar flares, Exoplanets, TDEs, Supernovae, Sun, etc.)

Multi-wavelength study of time-domain sources (Radio, Optical, X-ray, Gamma-ray)

Key facilities for time-domain radio astronomy: Interferometers (GMRT, LOFAR, MeerKAT, ASKAP, CHIME, SKA), Single dishes: (Parkes, GBT, FAST, Arecibo)

Overview of major time-domain radio surveys and their prerequisites:

Observational techniques for time-domain radio astronomy: Single-dish vs. interferometric detection, Single-dish surveys, Real-time detection with radio interferometers, Wide-field surveys (e.g., CHIME/FRB, ASKAP, DSA), Data processing: RFI mitigation, search (both single pulse search and periodicity search with acceleration correction for binaries), timing and imaging analysis

Time-domain sources as probes: Probing ISM with pulsars, Gravitational wave detection with pulsars, Gravity tests with pulsars, Probing IGM, cosmology with FRBs

Reference books:

1. Pulsar Astronomy by Andrew G. Lyne and Francis Graham-Smith
2. Handbook of Pulsar Astronomy by Duncan R. Lorimer and Michael Kramer
3. Pulsars by R. N. Manchester and J. H. Taylor
4. Astrophysics of Neutron Stars by Vladimir M. Lipunov
5. Rotation And Accretion Powered Pulsars by Pranab Ghosh
6. The Physics of Fast Radio Bursts by Bing Zhang

PHY-330.3: Research & Publication Ethics [2 credits]

The scientific process: Philosophy: E.g. Popper versus Kuhn. How does one actually carry out research? (literature survey, defining a research problem, proposal and grant writing, actually doing the work, writing up the result for publication, giving talks to describe the results, refine understanding of the research problem, ...). How does one choose an advisor? Evaluation and practices. Reading papers and understanding talks.

Literature review and the use of scientific software

Scientific writing: Covers issues related to writing papers and telescope/funding proposals. Reference: Stephen Heard: The Scientist's Guide to Writing: How to Write More Easily and Effectively Throughout your Scientific Career. Savage & Yeh's 2019 Nature article.

Scientific presentations: Covers basic principles of scientific presentations, different types of presentations, etc.

Research ethics (lectures + group discussion sessions): Issues related to data handling, plagiarism, falsification of data, acknowledging use of other people's work, appropriate citation. Material will be pooled by different TIFR centres and schools in a common area.

PHY-121.3: Electrodynamics [Remedial]

Principle of relativity; Relativistic mechanics; Charges in electromagnetic (EM) fields; EM field equations; constant EM fields; EM waves; propagation of light; field of moving charges

References:

1. Classical Theory of Fields: Landau & Lifshitz vol 2. (chs 1-9)

PHY-122.3: Quantum Mechanics [Remedial]

Heisenberg uncertainty principle; Schrodinger's equation; 1-d potentials; Linear algebra, Hilbert spaces; Simple harmonic oscillator; Hydrogen-like atoms; Angular momentum algebra; Identical particles and symmetry, Pauli exclusion; Time-independent perturbation theory, Zeeman effect, Stark effect; Time-dependent perturbation theory, Fermi's golden rule, electric dipole transitions, Selection rules, Decays and lifetime, natural line-width, transition probability, Einstein coefficients.

References:

1. "Introduction to quantum mechanics", David J. Griffiths, Cambridge University Press
2. "Lectures on Quantum Mechanics", Ashok Das, World Scientific
3. "Quantum Mechanics Theory and Applications", Ajoy Ghatak and S. Lokanathan, Springer
4. "Physics of atoms and molecules", B. H. Bransden and C. J. Joachain, Pearson
5. "Modern Quantum Mechanics", J. J. Sakurai, Cambridge University Press
6. "The Physics of Astrophysics: Radiation", Frank H. Shu, Univ Science Books
7. "Principles of Quantum Mechanics", R. Shankar, Springer

PHY-123.3: Statistical Mechanics [Remedial]

Kinetic theory, Boltzmann equation, H-Theorem. Classical statistical mechanics, microcanonical, canonical, grand canonical ensembles, derivation of thermodynamics. Quantum statistical mechanics, density matrix, Bose and Fermi statistics, ideal gases; Photons and the Planck spectrum, Saha ionisation equilibrium, phase transitions, basic theory of white dwarfs.

References:

1. "Thermodynamics: Concepts and Applications" - Stephen R. Turns, Cambridge University Press
2. "Statistical Mechanics" - K. Huang, John Wiley & sons
3. "Statistical Mechanics"- R. K. Pathria, Butterworth Heinemann
4. "Fundamentals of Statistical and Thermal Physics", - F. Reif, McGraw Hill International Edition (1985)
5. "Introduction to Modern Statistical Mechanics" - David Chandler, Oxford University Press
6. "Equilibrium Statistical Physics" - M. Plischke and B. Bergersen, World Scientific
7. "Statistical Physics, Vol. 5 in Course in Theoretical Physics", L. D. Landau and E. M. Lifshitz, Elsevier
8. "Principles of Condensed Matter Physics", P. M. Chaikin and T. C. Lubensky, Cambridge University Press

Appendix 3: Syllabi for the Advanced Courses

The syllabi for the Advanced Courses offered to the Int-Ph.D. (80 credits) students are as follows:

PHY-401.3: Advanced Radio Astronomy [6 credits]

1. Wide-field, wide-band imaging
2. Data pre-processing and calibration
3. Propagation effects
4. Construction of sky models
5. Beam formation techniques
6. De-dispersion techniques
7. Pulsar search algorithms.

PHY-402.3: Radio Instrumentation [6 credits]

1. Types of antennas and feeds in radio astronomy, and their radiation patterns.
2. Signal amplification, transmission, and related analogue electronics.
3. Low noise radio frequency amplifiers and their design characteristics,
4. Working and design of a Superheterodyne radio receiver system (including the local oscillator, IF amplifier and baseband receiver).
5. Basics of fibre optics communication and servo systems.
6. Digital correlators: design principles and their implementation using both hardware- and software-based signal correlation.
7. Hands-on experiment with any two of the above 4 modules.

PHY-403.3: Cosmology and Structure Formation [6 credits]

1. Review of basic cosmology.
2. Cosmological perturbations.
3. Anisotropies in the Cosmic Microwave Background.
4. Gravitational collapse and formation of dark matter haloes.
5. Statistical properties of the cosmic density field.
6. Models of galaxy formation.
7. Numerical simulations.
8. The intergalactic medium.
9. The epoch of Reionization.
10. Dark energy.

PHY-404.3: Advanced Interstellar Medium [6 credits]

1. The distribution of neutral atomic hydrogen in the Milky Way
2. Dust models and emission processes
3. Polycyclic aromatic hydrocarbons
4. The hot ionized medium
5. Multi-phase models of the interstellar medium
6. Diffuse and dense molecular gas
7. The CO-to-H2 conversion factor

8. Determining physical conditions in the interstellar medium
9. Magnetic fields in the Milky Way and external galaxies
10. The interstellar medium in external galaxies.

PHY-405.3: Advanced course on Galaxies: Their structure, formation and evolution [6 credits]

1. The first galaxies
   (a) Collapse of density fluctuations
   (b) The role of cooling in galaxies and clusters
   (c) Major and minor mergers
2. Probing large-scale structure using galaxy tracers
   (a) Measurements of galaxy clustering and large-scale structure
   (b) Redshift surveys
   (c) Evolution of clustering
3. Galaxy properties
   (a) Modern view of the Hubble Sequence
   (b) Stellar populations.
   (c) Galaxy luminosity and mass functions
   (d) Properties of spiral, elliptical and dwarf galaxies.
   (e) Fundamental correlations and scaling relations.
   (f) Galaxy clusters.
   (g) High redshift galaxies.
4. Galaxy Evolution
   (a) Basic processes: secular and environment-dependent.
   (b) Deep galaxy surveys and selection effects.
   (c) Star formation and stellar mass.
   (d) Extragalactic Background Light.
   (e) Chemical evolution of galaxies.
   (f) Feedback processes.

PHY-406.3: Advanced Course on Pulsars [6 credits]

1. Introduction to Pulsars and Neutron stars.
2. Origin and evolution of pulsars.
3. Classes of Pulsars and Neutron Stars.
4. Observational properties of pulsars.
5. Instrumentation for pulsar observations.
6. Pulsar data analysis techniques: Searches, timing, imaging.
7. Pulsar emission mechanisms: theory and probes.
8. Pulsars as probes of the interstellar medium.
9. Binary and millisecond pulsars
10. Pulsars as probes of gravity
11. The equation of state of pulsars
12. Pulsars and their environments: Supernova remnnants, pulsar wind nebulae.
13. Pulsars in globular clusters.

PHY-407.3: Solar and Heliospheric Physics [6 credits]

1. Introduction to the Sun and the Heliosphere.
2. Electromagnetic emission from the Sun.
3. Solar radio emission mechanisms.
4. Solar flares.
5. Coronal mass ejections.
6. Coronal heating
7. Magnetic reconnection in the corona
8. Probes of the heliosphere.
9. The impact of the Sun on the Earth and Space Weather

PHY-408.3: Advanced Course on Active Galactic Nuclei [6 credits]

1. Active Galactic Nuclei (AGNs) across the electromagnetic spectrum.
   (a) Emission Mechanisms at different observing bands.
   (b) Spectral Modelling of AGNs.
2. The physics of black hole accretion.
3. The Broad and Narrow Line Regions:
   (a) Types of spectral lines and kinematics.
   (b) Determination of the black hole mass.
   (c) Reverberation mapping.
4. AGN Classification and Unification schemes.
5. Formation and evolution of AGNs.
6. AGN feedback and the AGN-Starburst connection.
7. Jets in AGNs: theoretical models and observational signatures.
8. The Black Hole - Disk - Jet connection in AGNs.
   (a) The Fundamental Plane.
   (b) The Quasar-Microquasar connection.
9. AGNs and Cosmology.
10. Open questions in AGN studies.

Appendix 4: Norms for NCRA staff members doing a Ph.D.

The norms for NCRA staff members who would like to register for a Ph.D. under the TIFR Deemed-to-be University are as follows:

1. The research ability of the candidate will be tested in an interview by an NCRA faculty committee before s/he begins graduate school studies. This interview could cover the technical skills of the candidate, his/her understanding of projects that have been done in the past as well as the area proposed for doctoral research, and his/her understanding of basic physics. The committee for this purpose will be constituted by the Dean, NCRA Faculty.

2. The academic requirements for obtaining the Ph.D. degree should be the same as those for Regular Ph.D. students in NCRA. Specifically, the staff member must complete all the required Graduate School courses and research projects. The points worth noting are (i) the staff members will be allowed two attempts at clearing each Graduate School course and (ii) staff members will have the same CGPA requirements for courses and projects as those for Regular students of the NCRA Graduate School. The CGPA for the staff members will be computed at the end of every 18 credits, which roughly corresponds to the number of credits per semester of the Graduate School. The detailed norms are outlined in Sections 3, 4, and 5 of this document.

3. Bearing in mind the fact that the staff members will have parallel observatory duties, they would be allowed to complete the Graduate School requirements in 5 years (as opposed to 2 years for Regular Ph.D. students).

4. Also, staff members will be allowed a maximum of 6 months in which to complete each "3 month" research project (Research Methodology).

5. It is possible that the staff members may not be able to attend classroom lectures for some or most of the graduate school courses, due to observatory duties at GMRT. Hence the staff member may be allowed to take the required courses as reading courses, if this is deemed appropriate by the review committee. The review committee should decide which courses should be taken as reading and classroom courses. For reading courses, all courses should not be taken under the guidance of a single faculty member; preferably, not more than 2-3 courses should be taken under a single faculty member. The performance in the reading courses should be evaluated as per the standard Graduate School norms, i.e. a combination of assignments, tests, seminars, and discussions, as deemed appropriate by the advisor. The member can also try to attend the lecture courses via a video link.

6. A review committee should be set up for the Ph.D. candidate, similar to the Thesis Committees of NCRA Ph.D. students. This committee should consist of the guide, a member of the AAC, and the candidate's reporting officer. In case the reporting officer is also the guide, the NCRA Dean should nominate an NCRA Faculty member to be on the review committee.

7. There will be a review of the candidate's performance every year, similar to the reviews of other NCRA Ph.D. students.