**Department of Physics & Astronomy**
900 University Avenue
Riverside, CA 92521

May 2, 2022

**To:** Prof. Jason Stajich
Chair, Riverside Division

**From:** Prof. George Becker
Department of Physics and Astronomy

**RE:** **Ph.D. Program in Astronomy (Response to 2nd Round Review)**

Dear Chair Staijich,

We thank the Graduate Council once again for their comments on the Master's Degree. We have adopted their wording as suggested for Sections 2.3e and 2.9.

Sincerely,

Cc: K. Uhrich, Dean, CNAS
J. Wudka, Divisional Dean, CNAS
K. Barish, Chair, Department of Physics & Astronomy
T. Garland, Chair, CNAS Faculty Executive Committee

**Department of Physics & Astronomy**
900 University Avenue
Riverside, CA 92521

# A Proposal for a Program of Graduate Studies in Astronomy for the Ph.D. Degree

Prepared April 27, 2022

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## Executive Summary

We propose to establish a Ph.D. program in Astronomy at UC Riverside, to be hosted within the College of Natural Arts and Sciences and administered by the faculty and staff of the Department of Physics and Astronomy. Astronomy at UCR has grown considerably over the past several years. The Department now includes ten faculty members conducting research in observational and theoretical Astronomy, with additional faculty in closely related fields. A dedicated Ph.D. program in Astronomy will leverage UCR's expertise in the field, as well as UC's investment in world-leading observational facilities such as Lick Observatory, the Keck Telescopes and the Thirty Meter Telescope. The program will help attract world-class faculty and students, comprehensively train students for research careers in Astronomy, and enhance the overall academic excellence of the Department. The program will also allow UCR to become ranked among national Astronomy and Astrophysics programs, increasing its research profile and visibility.

Students entering the program will take a set of core courses in the first year and elective courses in the second year. The program will also provide early access to research, starting in the first year. To obtain the Ph.D., students must pass a comprehensive exam at the end of their first year, a qualifying exam detailing plans for their thesis by the end of their third year, and ultimately a thesis defense. The program will be overseen by a three-member Executive Committee, supported by a Graduate Advisory Committee, a Committee on Admissions and Recruitment, and a Comprehensive Exam Committee.

## Section 1. Introduction

1) Aims and objectives of the program

The objectives of the proposed graduate program are to provide graduate training leading to a Ph.D. degree in Astronomy and to promote teaching and research in the field of Astronomy by students and faculty at the University of California, Riverside. Astronomy has long been a foundational field of basic research at institutions of higher learning, national and international government agencies, and private foundations. Astronomy attracts top-level national and international students, and is one of the key channels through which the excitement of science is shared with the public. The proposed program will capitalize on the considerable growth in Astronomy at UC Riverside over the past decade, particularly in the areas of Extragalactic Astronomy and Cosmology, and the system-wide investment in world-class telescope facilities made by the University of California. The degree program will also allow UC Riverside to be formally recognized as a world-leading center of Astronomy research and education.

2) Historical development of the field

The modern era of astronomy can be traced back to the 1600s, a century in which Galileo first observed the night sky through a telescope and Newton provided a theory of gravity that described the motions of celestial objects. California emerged as an epicenter of astronomy by the late 1800s and early 1900s thanks to the favorable observing conditions that drew construction of the world's largest telescopes to sites like Mt. Hamilton, Mt. Wilson, and Mt. Palomar. Edwin Hubble, for example, famously used the 100 inch telescope on Mt. Wilson to discover that the Universe was expanding, setting the stage for modern Big Bang cosmology.

The University of California has been a world leader in astronomical research for over a century. Lick Observatory began operations in 1888 as part of the University of California and was home of the world's largest telescope at the time, the 36-inch Great Refractor (which notably found the first moon around Jupiter that was not one of the four seen by Galileo). In 1988, the University of California Observatories (UCO) was established as a founding member of the Keck telescope project. As a Multi-campus Research Unit (MRU), UCO supports astronomy research and education across the UC system by facilitating access to world-class observing facilities, including Lick and Keck, fostering new technology development, and promoting collaboration between UC campuses. The twin 10-meter Keck telescopes remain the largest optical telescopes in the world, and are at the forefront of astronomical research on topics from extrasolar planets to black holes to the most distant galaxies. UCOP's annual contributions to UCO and Keck (roughly $14M/year in total) represent some of the largest institutional commitments to research facilities by the University of California. The University of California is also a major partner in the $2.4B Thirty Meter Telescope project, continuing its commitment to excellence in astronomy and astrophysics far into the future.

The Astronomy group at UC Riverside has grown rapidly over the past decade. Starting from a single astronomer in 2005, there are now ten astronomers within the Department of Physics and Astronomy. The core research strengths of the group include cosmology, galaxy evolution, black holes, the intergalactic medium, and astrophysical data science. Six other faculty in Physics and Astronomy work on related fields, including astroparticle physics, dark matter theories, and gravitational waves. In addition, two faculty in Earth and Planetary Sciences work on observations of extrasolar planets. The

number of graduate students studying Astronomy has grown along with the Astronomy faculty, and is currently 32 within the Department of Physics and Astronomy.

3) Timetable for development of the program

Upon approval of the Program, an Astronomy Graduate Advisor will be appointed by the Dean of the Graduate Division and the program's standing committees will be constituted as described in Section 8 below. The program will be advertised on the Department of Physics and Astronomy website, and through the channels described in the "Contributions to diversity" section below. Admissions will commence thereafter. We anticipate a graduate admission rate of 5–7 students per year. Assuming a typical time to graduation of 5–6 years, we expect the Program to grow to approximately 30–35 students, consistent with our current enrollment of Physics Ph.D. students who are pursuing research in Astronomy. Additional faculty recruitment may lead to further growth. For the first several years, the grad students recruited into the Astronomy Ph.D. program will overlap with students already pursuing Astronomy research topics within the Physics Ph.D. program.

4) Relation of the proposed program to existing programs on campus and to the Campus Academic Plan

The Astronomy degree program will directly complement the Physics degree program offered by the UCR Department of Physics and Astronomy. Graduate students pursuing Astronomy and Astrophysics research at UCR are currently enrolled in the Physics Ph.D. program and follow an "Astrophysics Track" that includes a small number (3) of Astronomy courses. The Astronomy students are selected for admission primarily by the Astronomy faculty, but they mainly follow the traditional Physics curriculum in terms of their classes and comprehensive exam. Although modern Astronomy is rooted in traditional Physics, it requires specialized training in both astrophysical theory and applied techniques in observation and computation. This proposal will establish an Astronomy Ph.D. with coursework and evaluations focused on the foundational topics in astrophysical theory and observational/computational techniques described in Section 2. The total number of graduate students (Astronomy plus Physics) in the Department is expected to remain similar to the current number of Physics students, and will continue to increase along with the growing faculty. The quality of the Astronomy students, however, is expected to significantly increase over time as we are able to attract more competitive students with a dedicated degree program.

The proposed Astronomy Ph.D. is expected to fully replace the current Astrophysics Track, at least initially. Once the Astronomy Ph.D. is underway the Department will put the Astrophysics Track "on hold" by adding appropriate language to the UCR General Catalog. The Department will then assess whether the Astrophysics Track within the Physics Ph.D. should be offered and in what form. The Astrophysics Track may be useful for students who are interested in pursuing astronomy-related research (e.g., in gravitational waves or astro-particle physics) via a more traditional Physics approach, although this will need to be balanced against the administrative burden related admissions, course offerings, comprehensive exams, etc. associated with offering an Astrophysics Track within the Ph.D. program in addition to the Astronomy Ph.D. A comparison between the course requirements for the Astrophysics Track and Astronomy Ph.D. is given in Appendix C.

In terms of promoting distinctive, transformative research and scholarship, the goals of this program are well aligned with UCR's strategic plan. A dedicated Astronomy Ph.D. program will help bring top-ranked students and faculty to UCR, supporting world-class research programs that attract extramural funding

from the National Science Foundation, NASA, and other public and private institutions. The program will also vigorously support UCR's goals of diversity, equity and inclusion (see next section).

5) Contributions to diversity

Creating a Ph.D. program that is welcoming to individuals who bring a broad range of experiences and skills is essential for supporting our goals of education and research excellence. Enabling students of all backgrounds to thrive is therefore a core goal of this proposal. As part of this, we recognizes that many students face adversity from a wide range of factors including, but not limited to, issues of health, poverty, non-traditional paths, and systemic gender and racial discrimination.

UC Riverside is one of the most diverse research universities in the country (in fact, the number 1 university for Hispanic enrollment among selective universities, according to the Urban Institute, and the number 1 university in the United States for social mobility, according to U.S. News & World Report), with a high percentage of low-income and/or ethnic minority students who are traditionally underrepresented in Physics and Astronomy. This degree program will support UCR's efforts to jointly increase equity, inclusion, and academic excellence by the following:

- Reaching a broad and diverse applicant pool
    - In order to promote a diverse graduate student body, advertising and recruitment for the Program will be conducted through a variety of organizations. These will include the CSU system via Calbridge, the American Physical Society Bridge Program (of which UCR is a member), the Conferences in Undergraduate Women in Physics (CUWiP), the Society of the Advancement of Chicanos/Hispanics (SACNAS), and the National Society of Black Physicists (NSBP).
- Employing holistic graduate admissions procedures
    - We will consider a broad range of information beyond GPA that may indicate the potential for success in the Ph.D. program.
    - We will consider and value the perseverance of students in overcoming any disadvantages.
    - Students taking non-traditional paths towards graduate programs will be equally valued.
    - Ethnic and gender disparities in standardized testing will be recognized, and a breadth of other data related to a student's capabilities and potential will be considered.
    - Short-listed candidates will be interviewed to get a fuller picture of the candidates than can be gained from metrics such as GPA and GRE scores alone.
    - The importance of diverse graduate students in mentoring and teaching our diverse undergraduates will be recognized.
- Continuing to mentor our diverse UCR undergraduates in research through our NSF- and NASA-funded research programs.
- Continuing local outreach, especially to communities that are underserved and under-represented in Astronomy and Astrophysics (such as bilingual events, Cosmic Thursdays, outreach to School for the Deaf)
- Continuing and expanding partnerships with California community colleges and CSUs for summer research internships and graduate recruitment (for example, the existing FIELDS and Cal-Bridge partnerships)
- Including students on certain committees, such as a climate committee, to help ensure that the concerns and disparities burdening our students are heard and acted upon

- Recruiting and hiring professors who are diverse and will help promote equity in the sciences, consistent with the policies of UCR and the Department of Physics and Astronomy

6) Interrelationship of the program with other University of California institutions

Astronomy is one of the most vibrant fields of research and instruction in the UC system, with nine campuses enrolling students pursuing Astronomy and/or Astrophysics studies at the graduate level. As summarized in the table below, the host department and structure of the degree programs vary by campus. Among the other UC campuses, four (Berkeley, Los Angeles, Santa Cruz, and San Diego) currently offer degrees in Astronomy or Astrophysics. Two (Santa Barabra and Irvine) offer degrees in Physics with an Astrophysics Emphasis or Concentration. A further two (Davis and Merced) offer degrees in Physics only.

All of the UC programs supporting graduate Astronomy or Astrophysics studies have their own emphasis based on faculty interests and campus resources. These programs are complementary to one another and together form a broad base of academic excellence in Astronomy within the UC system. Riverside offers one of the world's leading programs in observational and theoretical Extragalactic Astronomy and Cosmology, as well as Astrophysical Data Science. A strong Astronomy/Astrophysics graduate program across the entire UC system promotes cooperation and collaboration among campuses, and supports UC's investment in observational facilities such as Lick Observatory, the Keck telescopes, and the Thirty Meter Telescope.

Table 1. Graduate Programs for Astronomy Students at UC Campuses

| Campus | Department | Degree |
|---|---|---|
| **Berkeley** | Astronomy | Astrophysics |
| **Davis** | Physics & Astronomy | Physics |
| **Irvine** | Physics & Astronomy | Physics with with Concentration in Astronomy and Astrophysics |
| **Los Angeles** | Physics & Astronomy | Astronomy |
| **Merced** | Physics | Physics |
| **Riverside** | Physics & Astronomy | Physics with Astrophysics Track (Current) → Astronomy (Proposed) |
| **San Diego** | Physics | Astronomy |
| **Santa Barbara** | Physics | Physics with Astrophysics Emphasis |
| **Santa Cruz** | Astronomy & Astrophysics | Astronomy |

7) Department or group which will administer the program

The Program will be administered by the Department of Physics and Astronomy. Details of the program administration are given in Section 8.

8) Plan for evaluation of the program

In the first two years, the participating faculty will self-evaluate the Program prior to the normal third-year review to be conducted by the Graduate Council that is required for all new graduate programs at UC Riverside. Thereafter, the program will be evaluated by an external team of experts every 6–7 years, as is the standard practice of the Graduate Division at UC Riverside. Success overall will be gauged by the ability of the program to recruit, train and graduate high-caliber students.

## Section 2. Program

1) Undergraduate preparation for admission

Students entering the program should have completed a Bachelor's (B.S. or B.A.) or Master's degree (M.S.) in Physics, Astrophysics, Astronomy, or a closely related field from an accredited 4-year college or university. This degree must represent the completion of a program that meets the standards established by the Graduate Division at the University of California, Riverside. Qualified applicants are expected to have a junior/senior GPA of 3.25 or higher.

International applicants are required to take the TOEFL examination as part of the pre-qualification process for admission and financial support. The scores should be submitted directly from ETS and should have a test date no older than two years from the intended date of enrollment at UCR. Qualified applicants should have a minimum score of either 550 from the paper-based test or 80 from the internet-based test (IBT). Ranges 540-550 / 75-80 may also be considered.

2) Foreign language competency

None required.

3) Program of study

3a) Specific fields of emphasis:

Research in Astronomy at UCR spans a wide range of topics in theory and observation including star formation and evolution, galaxy formation and evolution, plasma astrophysics, computational astrophysics, the interstellar and intergalactic medium, galactic dynamics, nuclear and particle astrophysics, large scale structure, dark matter, dark energy, and cosmology.

3b) Plans:

Doctor's A (5-member committee, mandatory oral defense)

3c) Unit requirements.

Unit requirements for completion of a Ph.D. degree encompass a total of at least 9 lecture courses (36 units), including 7 Core courses and at least 2 Elective courses. Students must complete all 7 Core courses plus two quarters of Directed Research during their first year, prior to the comprehensive exam. The comprehensive exam will be administered during the summer after the student's first year in the graduate program (see Section 5 below).

3d) Required and recommended courses

Core: Students must take all of the following during their first academic year.

PHYS 211A – Radiative Processes in Astrophysics
PHYS 213 – Astrophysics of the Interstellar Medium
PHYS 214 – Techniques of Observational Astrophysics
PHYS 215 – Dynamics & Evolution of Galaxies
PHYS 217 – Stellar Structure & Evolution
PHYS 219 – Cosmology & Galaxy Formation
PHYS 2xx – Computational Astrophysics [New Course Under Development]
PHYS 401 – Professional Development in Physics and Astronomy

First-year students will also take two quarters of Directed Research (PHYS 297), starting in the Winter quarter. The advisor for this research will be chosen by the start of the Winter quarter.

Electives: Students must take a minimum of two (2) of the following:

PHYS 203 – Statistical Astronomy
PHYS 204 – Advanced Galaxy Formation and Cosmology
PHYS 208 – General Relativity
PHYS 211B – Astrophysical Fluid Dynamics
PHYS 216 – Star Formation
PHYS 218 – Fundamentals of Astrophysics
PHYS 226 – Cosmology (Advanced Topics)
PHYS 227 – Particle Astrophysics
PHYS 229 – Theory of Dark Matter Halos and Galaxies
PHYS 247 – Introduction to Applied Data Science
PHYS 261 – Special Topics in Astrophysics

Other courses, including those outside the Department, may also count as electives with the approval of the Astronomy Advisory Committee.

The Core courses and Directed Research courses listed above will be offered annually. Elective courses will be offered every 2-3 years based on demand. Students must pass each course with a grade of B- or better, and must maintain an average for all courses of B or better, to remain in good standing in the program.

3e) Description of Master's capstone element

There is no separate Master's program associated with this program; however, a Master's degree is available under special circumstances when the work leading to the Ph.D. degree cannot be completed. If a student is unable to complete the full degree requirements, or decides to leave the program without a Ph.D. degree, they may be eligible for a terminal Master's Degree in Astronomy. In order to receive this degree, students must complete the core courses, directed research, and professional development requirements described in the Ph.D. program in addition to meeting the minimum requirements for a master's degree outlined in the Graduate Studies section of the general catalog. Students may either

complete the Plan I Thesis on a topic to be chosen in consultation with a faculty supervisor, or a Plan II which requires satisfactory performance on the Comprehensive Examination. Whether the Master's option is appropriate will be decided by the Astronomy Graduate Advisory Committee.

3f) Licensing and Certification Requirements

There are no licensing or certification requirements associated with this program.

4) Comprehensive Exam

Ph.D. students must pass a comprehensive exam. The exam will have two parts administered in the summer of the student's first year in the program. The first part will consist of an oral report on the research undertaken during the two graded research classes taken in the first year. The oral report will be approximately 20 minutes in length and will focus on the background, motivation, and methods of the research study. (By comparison, the Candidacy Exam will focus more on preliminary results and plans for future work that will lead to a thesis, as described below.) The oral presentation will be followed by a question and answer session with a faculty committee on topics related to the student's research. The second part of the comprehensive exam will be a four-hour written test on topics in Astronomy related to the Core courses listed above.

The oral and written parts of the comprehensive exam will be weighted equally. Based on the student's overall performance on the comprehensive exams, the department will recommend a pass at the Ph.D. level, a pass at the M.A./M.S. level, or a fail. The oral and written parts of the exam may each be repeated once by the end of the fall quarter of the second year if the initial performance was unsatisfactory.

5) Ph.D. Qualifying (Candidacy) Exam

Ph.D. students must complete an oral qualifying exam in the general area of the student's proposed dissertation research. This exam will consist of a closed oral presentation roughly 40 minutes in length, followed by an oral examination session with the student's exam committee. The oral presentation should provide background and motivation for the dissertation research, preliminary results from this research, and a clear plan for completion of the thesis including a timeline for the acquisition of data (if relevant), analysis, other key milestones, and papers to be submitted to journals. The exam committee will be composed of the student's research advisor, at least two other departmental faculty, and one faculty member from outside the department. The exam must be taken before the end of the student's third year in the program. Students who fail the qualifying exam in their first attempt may, at the discretion of the committee, be permitted to take it a second time. Only two attempts are allowed. If a student fails the exam and a second attempt is granted, the exam committee will provide specific guidelines for changes and improvements.

After passing this exam and advancing to candidacy, students will provide yearly updates on their progress to the thesis committee. The thesis committee will be comprised of the student's research advisor and at least two other departmental faculty, typically those who have served on the student's candidacy committee.

6) Doctoral dissertation

Doctoral candidates must complete a satisfactory written thesis that presents a review of existing knowledge relevant to the candidate's original research, an outline of specific problems addressed by the candidate's work, and a detailed description of the strategies, analysis techniques and results of the candidate's original research. The requirements for the doctoral thesis will be consistent with the rest of the Physics and Astronomy department. The research must be of sufficiently high quality to constitute a contribution to knowledge in the subject area. The written thesis should meet the standards of top-ranked peer-reviewed journals in the candidate's field. The thesis will be reviewed by the candidate's thesis committee, which will normally be the same as the Qualifying Exam committee. A draft of the final written thesis must be submitted to the thesis committee no less than three (3) weeks prior to the oral defense date.

7) Final exam (defense)

Doctoral candidates must perform satisfactorily in a final oral defense of their thesis before the candidate's thesis committee. This defense is normally expected to occur before the end of the student's sixth year. The oral defense will consist of a public presentation by the candidate of roughly one hour in length, followed by a closed-door examination period with the committee. The oral presentation will provide an overview of the candidate's original research, including background, goals, analysis techniques, and the main results and conclusions from the candidate's original research.

If changes or corrections to the written thesis are mandated by the thesis committee, they must be completed before the final submission of thesis materials to the Graduate Division. If the committee unanimously declines to pass a candidate following the defense, the committee will be charged to develop either a remediation or a terminal degree plan. Either plan must detail the specific deficiencies of the thesis, and in the case of remediation, what specific steps must be undertaken within a reasonable time, not exceeding one year, to submit a revised written thesis and conduct a second oral defense.

8) Explanation of special requirements

There are no requirements over and above Graduate Division minimum requirements.

9) Relationship of master's and doctor's programs

There is no separate Master's program associated with this program; however, a Master's degree is available under special circumstances when the work leading to the Ph.D. degree cannot be completed. If a student is unable to complete the full degree requirements, or decides to leave the program without a Ph.D. degree, they may be eligible for a terminal Master's Degree in Astronomy. In order to receive this degree, students must complete the core courses, directed research, and professional development requirements described in the Ph.D. program in addition to meeting the minimum requirements for a master's degree outlined in the Graduate Studies section of the general catalog. Students may either complete the Plan I Thesis on a topic to be chosen in consultation with a faculty supervisor, or a Plan II which requires satisfactory performance on the Comprehensive Examination. Whether the Master's option is appropriate will be decided by the Astronomy Graduate Advisory Committee.

10) Special preparation for careers in teaching

Students will receive supervised teaching experience while fulfilling a requirement to serve as a Teaching Assistant (TA) for at least one (1) quarter.

11) Sample Ph.D. program

Students enrolled in the proposed program will be expected to complete the curriculum outlined below in their first two years. The first year includes 7 Core courses and 2 courses of Directed Research. Students will work with their research advisor to choose elective courses to be taken during their second year.

Table 2. Sample Program for the First Two Years

| | **Fall** | **Winter** | **Spring** |
|---|---|---|---|
| **Year 1** | Techniques of Observational Astrophysics PHYS 214 | Cosmology & Galaxy Formation PHYS 219 | Stellar Structure & Evolution PHYS 217 |
| | Computational Astrophysics [New Course] | Radiative Processes in Astrophysics PHYS 211A | Dynamics & Evolution of Galaxies PHYS 215 |
| | Astrophysics of the Interstellar Medium PHYS 213 | Directed Research PHYS 297 | Directed Research PHYS 297 |
| | | Professional Development in Physics and Astronomy PHYS 401 | |
| **Year 2** | Elective 1 | Elective 2 | Directed Research PHYS 297 |
| | Directed Research PHYS 297 | Directed Research PHYS 297 | |

13) Normative time from matriculation to degree

If the student is full-time with no deficiencies, the normative length of time pre-candidacy (before the Qualifying Exam) is not more than three (3) years. The normative time between Candidacy and Defense/Ph.D. completion is three (3) years. Overall, the normative time from enrollment in the program to Ph.D. degree is expected to be six (6) years.

## Section 3. Projected Need

1) Student demand for the program

In the last five years (2016-2020), the Department of Physics and Astronomy at UCR has received, on average, 300 applications for Ph.D. admission. Roughly half of the applicants indicate that they wish to pursue research in Astronomy and Astrophysics. In the Fall of 2020, 22% of the astro applicants were in-state, 49% were out-of-state, and the rest were international. The current graduate enrollment in the department is 129, with almost half (48.8%) being international students.

2) Opportunities for placement of graduates

According to the U.S. Bureau of Labor Statistics (https://www.bls.gov/oes/current/oes192011.htm) , the overall employment for physicists and astronomers is projected to grow by 7% from 2019 to 2029, faster than the average for all occupations. Astronomy and Astrophysics Ph.D. graduates are primarily employed by 1) universities (38%), 2) federal government supported institutions, such as NASA, the National Science Foundation's NOIRLab, the United States Naval Observatory, and the Space Telescope Science Institute (22%), 3) education, public outreach, and private companies, particularly in data science (40%). California is the state with the highest employment level for Astronomy and Astrophysics Ph.D.s, with median annual wages of $164,130. According to the American Astronomical Society (https://aas.org/careers/career-in-astronomy), in recent years, the number of Ph.D.s conferred annually in North America has averaged about 125 while the number of job openings has been around 150.

Astronomy graduate programs in the University of California have been highly successful in placement records, with an average of 5 Ph.D. awarded each year with direct employment. For instance, at UC Berkeley between 2016-2018, over 50% of the Ph.D. recipients were granted prize fellowships, with 20% of the Ph.D. recipients receiving the top-wide national fellowships (e.g., Hubble Fellowship).

The Department of Physics and Astronomy at UCR currently awards 3-5 Ph.D. degrees per year in Physics within the "Astrophysics Track.". The Astrophysics Track is relatively new, and has only been graduating students since 2012. In these last 8 years, 25 Ph.D.s have been awarded to students taking the Astrophysics Track. Twenty four of them obtained employment immediately after graduation: 21% received prize fellowships, 42% other postdoctoral positions, 16% went into college teaching positions, and 21% went into industry in data science. Of the 11 graduates who now hold permanent positions, 2 have tenure-track positions in universities, 3 are staff researchers in government-supported institutions, and 6 have leadership positions in data science industries (e.g., Lead Data Scientist, Senior Data Scientist, Senior Manager and Architect of AI, etc.)

3) Importance to the discipline

An Astronomy Ph.D. program at UC Riverside will provide rigorous training to students who will go on to lead research programs at universities, astronomical observatories, national labs, and private research institutions. It will leverage the unique faculty expertise and resources at UCR to promote world-class research and education, as well as support the broader mission of excellence in Astronomy across the University of California.

4) Ways in which the program will meet the needs of society

Astronomy is one of the oldest sciences and it has been part of every culture's history and roots. Besides inspiring humanity, Astronomy and Astrophysics have driven contributions to science and

knowledge throughout history. Moreover, scientific and technological development in Astronomy have resulted in technological advances such as mobile phones, communication satellites, Global Positioning Systems, solar panels, and Magnetic Resonance Imaging scanners.

5) Relationship of the program to research and/or professional interests of the faculty

Ten faculty members in the Department of Physics and Astronomy currently engage in Astronomy research, particularly in the areas of galaxy formation and evolution, cosmology, supermassive black holes, galaxy clusters, and circum- and intergalactic medium. These 10 faculty are listed in Section 4. Four additional faculty members (Cui, Tanedo, Wudka, Yu) work in particle theory and engage in research that explores the overlap of theoretical particle physics, astronomy, and cosmology. One other faculty member (Ellison) conducts research in experimental particle physics cosmology, and two more (Nobel Laureate Barish and Richardson, who will start Fall 2021) work in gravitational waves, an area that is closely related to the study of supermassive black holes and cosmology.

6) Program differentiation

The Department of Physics at UCR started building an astronomy research program in 2005 with the hire of the first observational astronomer. Almost from the beginning, it was decided that UCR would distinguish itself from other UC campuses by focusing its efforts in the rising area of galaxy evolution. This area has natural connections to other subdisciplines in the department (such as particle physics theory) and is ideally suited to take full advantage of the world-class UC astronomy facilities (Keck and Lick Observatories). We are currently the UC campus with the highest concentration of faculty doing research in this area.

The proposed Astronomy Ph.D. at UCR will distinguish itself from other Astronomy and Astrophysics programs in California by the large range of opportunities that will be available to students for research in the area of galaxy evolution and cosmology. Ph.D. students will also have a faster path to research by the requirement of two research classes in their first year and the inclusion of their initial research projects in the comprehensive exam. UCR also has unique strengths in Astrophysical Data Science, with connections to UCR's Data Science Center, Visualization Lab, and online Master's Program in Data Science. Astrophysical Data Science at UCR is currently supported by a NASA grant for $4.5M, which has trained 400 students at different levels over five years. UCR also offers unique opportunities for students to collaborate with colleagues at other southern California institutions, including a UCR/Carnegie Graduate Student Fellowship at the Carnegie Observatories in Pasadena. In addition to its academic program, UCR maintains a dedicated astronomy outreach program serving roughly 6000 elementary-to-high school students per year in the Inland Empire, with high levels of graduate student involvement.

Finally, students wishing to pursue non-academic careers after obtaining their Ph.D.s will have access to unique programs at UCR that prepare them for such careers, such as the Science to Policy Graduate Certificate Program (https://sciencetopolicy.ucr.edu/), the University Teaching Certificate (https://gsrc.ucr.edu/certificate-programs/university-teaching-certificate), and the different programs offered by the Data Science Center (https://datascience.ucr.edu/).

## Section 4. Faculty

The participating faculty in the proposed Astronomy program are all from within the Department of Physics and Astronomy. Further information on the faculty is given in their CV's, which are attached as Appendix D.

Table 3. Participating Faculty

| Name | Rank | Degree | Expertise/Qualifications |
|---|---|---|---|
| George Becker | Associate | Ph.D. Astrophysics<br>Caltech, 2006 | Reionization and Intergalactic Medium |
| Simeon Bird | Assistant | Ph.D. Astronomy<br>Cambridge 2012 | Dark Matter, Intergalactic Medium, Structure formation and Numerical Simulations |
| Gabriela Canalizo | Full | Ph.D. Astronomy<br>U. of Hawaii, 2000 | Galaxy Dynamics and Evolution, Active Galactic Nuclei |
| Anson D'Aloisio | Assistant | Ph.D. Physics<br>Yale, 2011 | Theoretical Cosmology, Reionization, Intergalactic Medium |
| Fred Hamann | Full | Ph.D. Astronomy<br>SUNY Stonybrook, 1987 | Active Galactic Nuclei, Galactic Winds |
| Bahram Mobasher | Full | Ph.D. Physics<br>Durham, 1988 | Galaxy Formation and Evolution, Cosmology |
| Naveen Reddy | Associate | Ph.D. Astrophysics<br>Caltech, 2006 | Galaxy Formation and Evolution, Reionization, Circum-galactic Medium |
| Laura Sales | Associate | Ph.D. Astrophysics<br>Cordoba, 2007 | Numerical Simulations, Radiative Transfer, Theoretical Astrophysics |
| Brian Siana | Associate | Ph.D. Physics<br>UC San Diego, 2005 | Galaxy Formation and Evolution, Quasars |
| Gillian Wilson | Full | Ph.D. Physics<br>Durham, 1996 | Galaxy Formation and Evolution, Cosmology, Structure Formation |

The following faculty members in the Department of Physics and Astronomy work on closely related fields:

<u>UCR Particle Theory Group</u> (Theoretical Particle Physics and Astrophysics, Dark Matter)
Yanou Cui (Assistant)
Flip Tanedo (Assistant)
José Wudka (Full)
Haibo Yu (Associate)

<u>Experimental Particle Physics Cosmology</u>
John Ellison (Full)

Gravitational Waves
Barry Barish (Distinguished, Nobel Laureate)
Jonathan Richardson (Assistant, starting Fall 2021)

## Section 5. Courses

The following courses are included as either Core or Elective courses (see Section 3d). Catalog descriptions of the above courses are provided in Appendix A. All courses are currently offered (some in alternate years), and all are currently staffed.

PHYS 203 – Statistical Astronomy
PHYS 204 – Advanced Galaxy Formation and Cosmology
PHYS 208 – General Relativity
PHYS 211A – Radiative Processes in Astrophysics
PHYS 211B – Astrophysical Fluid Dynamics
PHYS 213 – Astrophysics of the Interstellar Medium
PHYS 214 – Techniques of Observational Astrophysics
PHYS 215 – Dynamics & Evolution of Galaxies
PHYS 216 – Star Formation
PHYS 217 – Stellar Structure & Evolution
PHYS 218 – Fundamentals of Astrophysics
PHYS 219 – Cosmology & Galaxy Formation
PHYS 226 – Cosmology (Advanced Topics)
PHYS 227 – Particle Astrophysics
PHYS 229 – Theory of Dark Matter Halos and Galaxies
PHYS 247 – Introduction to Applied Data Science
PHYS 261 – Special Topics in Astrophysics
PHYS 401 – Professional Development for Physics and Astronomy

In addition to the above, a new course in Computational Astrophysics will be created. A syllabus for this course is included in Appendix B. Further new elective courses can be added upon approval of the Astronomy Executive Committee, as described in Section 8.

The Astronomy faculty currently teach eight Astronomy/Astrophysics graduate courses in a typical year. This includes four courses that are currently offered to Physics Ph.D. students pursuing a specialization in Astrophysics, along with four elective courses. As outlined in Section 3, the Astronomy Ph.D. program will include seven Core and two Elective courses for a total of nine Astronomy graduate courses. This moderate increase is manageable within the overall teaching load of the Department of Physics and Astronomy.

## Section 6. Resource Requirements

1) FTE faculty:

No additional faculty positions are sought, although new or replacement positions awarded to the department can be utilized to expand the program. Administrative support will be provided by the Department of Physics and Astronomy and the Graduate Student Affairs Center of CNAS.

2) Library acquisition:

The UC Riverside library system, in particular the Science Library, currently subscribes to all the major journals relevant to Astronomy, and also purchases the important reference books in the field. No increase in demand for new acquisitions is anticipated.

3) Computing costs:

No increases in computing costs are anticipated. Personal computer facilities are available in the offices of all the participating faculty, providing access to the Internet. The computer facilities of the Science Library are also available to students and participating faculty of the program. More advanced computing capabilities are available in the laboratories of several of the participating faculty, who also have access to off-campus supercomputing facilities as needed.

4) Equipment:

No new equipment is required to implement the proposed program.

5) Space and other capital facilities:

The current faculty office and graduate student space in Pierce Hall and the Physics building is sufficient to meet the demands of the new program. The number of graduate students entering the new Astronomy Degree program will be similar to the enrollment of Physics students pursuing astrophysical research in previous years, and we do not anticipate an increase in graduate student enrollment under the new degree program.

6) Other operating costs:

No other operating costs are required for the new degree program.

## Section 7. Graduate Student Support

Graduate students in the proposed program will be supported by a combination of sources. Support in the first year will be provided by fellowships through the Graduate Division, after which students, having selected a thesis advisor, will typically be supported as research assistants on grants awarded to their thesis advisors, individual predoctoral fellowships from federal granting agencies and private foundations, and/or teaching assistantships provided by the home department or college of their advisor. The department will work in partnership with the Graduate Division and CNAS to ensure continuous funding for all program students in good academic standing throughout their time in the proposed program. In terms of teaching assistantships, enrollment in the Astronomy Ph.D. is expected to generally replace the current enrollment of students in the Physics Ph.D. program who are engaged in Astronomy research. The total enrollment of graduate students in the Department of Physics and Astronomy is therefore expected to remain constant. Astronomy graduate students will continue to TA the

same courses that are currently served by the Physics Ph.D. students. No additional teaching assistantships will therefore be required as a result of the new program. The Astronomy admissions and Physics admissions committees will set admissions targets together to make sure TA's cover the expected needs of both programs.

## Section 8. Governance

The Astronomy program will be administered by a three-member Astronomy Graduate Executive Committee. The Executive Committee, in conjunction with the existing administration of the Department of Physics and Astronomy, will be responsible for the day-to-day operation of the program, including admissions, student advising, and monitoring students' progress through the Astronomy program.

The proposed Astronomy program will be governed by the following by-laws:

*Article I. Objective*

The proposed degree program is intended to provide focused study in Astronomy, starting with classes on several sub-topics that provide a foundation for the Ph.D. All students will be required to take a set of required "Core" classes. Elective classes can be chosen based on the interests and goals of individual students. Students will also engage in original research leading to a Doctoral Dissertation. The new degree plan will enable students to engage in research starting from their first year, with the potential for more in-depth research programs and better preparation for jobs in academia and industry.

*Article II. Organization and Administration*

The administration of the program will be vested in the Astronomy Graduate Executive Committee, made up of the Astronomy Graduate Advisor and two other Astronomy faculty members. One of the three members (normally the Astronomy Graduate Advisor) will chair the committee. The Astronomy Graduate Advisor will also chair the Astronomy Graduate Advisory Committee. Each of the other two Executive Committee members will chair one of the following committees: the Astronomy Admissions and Recruitment Committee, and the Astronomy Comprehensive Exam Committee.

*Article III. Committees*

1) Executive (3 members): The charge of the Astronomy Graduate Executive Committee is to oversee the administration of the Astronomy Degree program, including the assessment of, and changes to, the curriculum of the Astronomy degree program. Any recommended changes will be forwarded to the entire Astronomy faculty for comments, feedback, and eventual voting. Changes to the curriculum will be approved if at least 51% of the Astronomy faculty vote in favor of those changes. Curriculum change requests will then be submitted to the full faculty of the Department of Physics and Astronomy for vote and forwarding through existing channels for curriculum changes. The committee will consist of three tenured Astronomy faculty members, and will meet at least once per year, and more frequently as needed. One of the three members will serve as the chair of the Executive Committee.

2) Advisory (3 members): The charge of the Astronomy Graduate Advisory Committee is to oversee students' progress through the Astronomy degree program, and provide general guidance (e.g., on which

classes to take, clarifying requirements for graduation, etc.) to students as needed. The Advisory committee will coordinate and review Individual Developments Plans with the students. The Advisory committee may also assist students in forming their Candidacy and Dissertation Committees. The Advisory committee will be chaired by one of the members of the Executive committee, with additional members selected from the full Astronomy faculty who will serve for a term of three years.

3) Admissions and Recruitment (3+ members): The Astronomy Admissions and Recruitment Committee will be responsible for reviewing and ranking graduate school applications and organizing recruitment activities. In coordination with the Physics Graduate Admissions committee, the Astronomy Admissions Committee will send files of qualified applicants, along with supporting documentation, to the Graduate Division Dean, who will make the final decision regarding admission and Graduate Division fellowship support. The committee will also oversee the maintenance of the program website and production of advertising/recruitment materials for the program. The committee shall be chaired by one member of the Executive committee. At least two additional members of the committee will be chosen from the Astronomy faculty. The term of membership is three years.

4) Comprehensive Exam (2+ members): The Astronomy Comprehensive Exam Committee will be responsible for collating problems for the exam, proctoring, and grading of the exam. The committee will also decide on the pass/fail cutoff. The committee shall be chaired by a member of the Executive committee. The chair of the committee will solicit additional members to serve on the committee as needed, to be drawn from the Astronomy faculty and to serve for a term of three years.

*Article IV. Changes to the By-Laws*

Changes to the by-laws of the program will be considered at a meeting of the Astronomy faculty, and a subsequent in-person or e-mail vote will be held to approve or disapprove the proposed changes. In order to be considered approved, at least 51% of the Astronomy faculty must vote in favor of proposed changes to the program's by-laws.

## Section 9. Changes in Senate Regulations

No changes in Academic Senate Regulations are required.

## Optional Appendices

## Appendix A: Course Descriptions

The following are courses for the Astronomy Ph.D. that are currently included in the UCR Course Catalog:

- **PHYS 203 - Statistical Astronomy (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): PHYS 218. Introduces statistical methods needed to analyze astronomical data. Provides case examples of problems in observational astronomy and applies statistical techniques to solve them. Covers probability, correlation and association, hypothesis testing, data modelling, maximum likelihood technique, detection and surveys, sequential data, and surface distribution. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 204 - Advanced Galaxy Formation (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): PHYS 218; PHYS 219; graduate standing; or the consent of instructor. Covers topics on galaxy formation, star formation in galaxies, intergalactic medium, first generation of stars and galaxies, high redshift Universe, reionization, evolution of galaxies and stellar population, and number counts. Also covers luminosity functions, correlation functions, and clustering. Introduces new techniques and latest data sets and archives used for research. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 208 - General Relativity (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): PHYS 205; graduate standing; or consent of instructor. An introduction to general relativity. Covers tensors, covariant derivatives, the Riemann curvature tensor, and Einstein's equation. Explores the Schwartzchild and Kerr black hole metrics and wormholes. Also addresses gravitational waves and their detection. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 211A - Radiative Processes in Astrophysics (4 units, existing)** - Lecture, 3 hours; consultation, 1 hour. Prerequisite(s): PHYS 135A, PHYS 135B, PHYS 136, PHYS 156A, PHYS 156B. Radiative transfer of continuum and line radiation, Einstein coefficients, photoionization equilibria, radiation by free electrons, bremsstrahlung and synchrotron emission, Compton and inverse Compton scattering, wave propagation through magnetized plasmas, atomic and molecular structure and spectra, atomic fine structure, and molecular hyperfine lines. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 211B - Astrophysical Fluid Dynamics (4 units, existing)** - Lecture, 3; consultation, 1 hour. Prerequisite(s): PHYS 211A. Covers hydrodynamics, sound waves, turbulence, supersonic turbulence, magnetohydrodynamics, Alfven waves, extragalactic relativistic jets, supersonic jets, galactic spiral structure and density-wave theory, accretion disk theory, Balbus-Hawley instability, and stellar winds. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 213 - Astrophysics of the Interstellar Medium (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): graduate standing. An overview of the interstellar medium and relevant physical processes. Covers the structure and evolution of ionized hydrogen regions

associated with massive stars and supernovae. Also addresses the neutral and ionized phases of the interstellar medium, as well as cooling processes. Includes the interpretation of spectral lines. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 214 - Techniques of Observational Astrophysics (4 units, existing)** - Lecture, 2 hours; laboratory, 3 hours; written work, 3 hours. Prerequisite(s): graduate standing. An introduction to the basic tools of observational astronomy. Topics include astronomical telescopes and detectors, observing techniques, calibration, and error analysis. Students whose research is related to astronomy receive a letter grade; other students receive a letter grade or Satisfactory (S) or No Credit (NC) grade.

- **PHYS 215 - Dynamics and Evolution of Galaxies (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): graduate standing. Discusses the structure, stability, and dynamic and cosmological evolution of galaxies. Interprets observational data on galaxies within a coherent theoretical framework. Topics include potential theory, orbits, collisionless systems, and the structure and evolutionary history of galaxies. Students whose research is related to astronomy receive a letter grade. Other students receive a letter grade or Satisfactory (S) or No Credit (NC) grade.

- **PHYS 216 - Star Formation (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): graduate standing. Discusses the processes involved in the formation of stars: the initial conditions in the interstellar medium that leads to star formation and the formation of planets and planetary systems around young stars. Topics include molecular cloud formation, the properties of young stars, jets and outflows, massive stars, and cosmological star formation. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 217 - Stellar Structure and Evolution (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): graduate standing. Topics include physics of stellar structure and main sequence evolution, and energy production and transport; post-main sequence evolution through the giant stage and the formation of compact objects; supernovae, nucleosynthesis, pulsars, and the roll of accretion within the framework of stellar evolution; and the physics of white dwarfs, neutron stars, and black holes. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 218 - Fundamentals of Astrophysics (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): graduate standing or consent of instructor. Develops basic astrophysical concepts from fundamental physics. Topics include nucleosynthesis, stellar structure, evolution of stars of different masses, end-states of stars, and bremsstrahlung and synchrotron radiation. Also covers cross-sections, opacities, hydrogen atom transitions, forbidden lines, and molecular lines. Addresses the ongoing search of life in the Universe. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 219 - Cosmology and Structure Formation (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): graduate standing; or the consent of the instructor. Explores cosmology, models for the universe, galaxy formation scenarios, evolution of galaxies and stellar population, and number counts. Also covers star formation activity in the universe, cosmic background radiation, dark matter, and dark energy. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.

- **PHYS 224 - Frontiers of Physics and Astrophysics (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): graduate standing; or consent of instructor. Covers particle physics to cosmology from an experimental perspective. Includes the present status of our understanding of the physics of the universe, the major challenges, and future opportunities. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.
- **PHYS 226 - Cosmology (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour., Prerequisite(s): graduate standing; PHYS 208. Discusses advanced topics in cosmology: Friedmann models and the large-scale structure of the universe, Hubble constant and deceleration parameter, and galaxy counting and the physics of the early universe. Also covers vacuum phase transitions, inflation, baryon number generation, fluctuations, topological defects and textures, primordial nucleosynthesis, density fluctuations, dark matter candidates, and the age of the universe. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.
- **PHYS 227 - Particle Astrophysics (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour., Prerequisite(s): graduate standing; PHYS 208. Discusses advanced topics in cosmology: Friedmann models and the large-scale structure of the universe, Hubble constant and deceleration parameter, and galaxy counting and the physics of the early universe. Also covers vacuum phase transitions, inflation, baryon number generation, fluctuations, topological defects and textures, primordial nucleosynthesis, density fluctuations, dark matter candidates, and the age of the universe. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.
- **PHYS 229 - Theory of Dark Matter Halos and Galaxies (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): graduate standing; or consent of instructor. A theory-based study of the properties of dark matter halos and their connection to galaxy properties. Topics include dark matter collapse in the non-linear regime, Press-Schechter, self-similar collapse, acquisition of mass, and angular momentum. Includes the impact of dark matter properties on hosted galaxies, mergers, environmental effects, and scaling relations. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor.
- **PHYS 261 - Special Topics in Astrophysics (4 units, existing)** - Lecture, 3 hours; discussion, 1 hour. Prerequisite(s): graduate standing; or consent of instructor. Explores topics in astrophysics that emphasize recent advances. Content varies. May be taken Satisfactory (S) or No Credit (NC) with consent of instructor and graduate advisor. Course is repeatable to a maximum of 12 units.
- **PHYS 401 - Professional Development in Physics and Astronomy (2 units, existing)** - Lecture, 1 hour; discussion, 1 hour. Prerequisite(s): graduate standing or consent of instructor; Introduces students to strategies for successful graduate study and early career development. Covers research and professional ethics, scientific writing (proposals, manuscripts, and abstracts), conference presentations, effective job search skills including preparation of curriculum vitae and networking, effective oral presentations, and job interviews. Visiting experts may give lectures on various topics. Graded Satisfactory (S) or No Credit (NC).

## Appendix B: Syllabus for a new course in Computational Astrophysics

[Syllabus Link]

## Appendix C: Course Requirements for the current Physics Ph.D. Astrophysics Track and the proposed Astronomy Ph.D.

| | **Physics Ph.D. Astrophysics Track (existing)** | **Astronomy Ph.D. (proposed)** |
|---|---|---|
| **Required Courses** (to be taken in first year) | Phys 210A, 210B, 210C<br>Electromagnetic Theory<br><br>Phys 212A<br>Thermodynamics and Statistical Mechanics<br><br>Phys 205<br>Classical Mechanics<br><br>Phys 214<br>Techniques of Observational Astrophysics<br><br>Phys 218<br>Fundamentals of Astrophysics<br><br>Phys 219<br>Cosmology and Galaxy Formation<br><br>Phys 288<br>Current Research Themes in Physics<br><br>Phys 401<br>Professional Development in Physics and Astronomy | PHYS 211A<br>Radiative Processes in Astrophysics<br><br>PHYS 213<br>Astrophysics of the Interstellar Medium<br><br>PHYS 214<br>Techniques of Observational Astrophysics<br><br>PHYS 215<br>Dynamics & Evolution of Galaxies<br><br>PHYS 217<br>Stellar Structure & Evolution<br><br>PHYS 219<br>Cosmology & Galaxy Formation<br><br>PHYS 2xx<br>Computational Astrophysics<br>[New Course Under Development]<br><br>PHYS 401<br>Professional Development in Physics and Astronomy |
| **Number of Required Electives** (second year) | 3 | 2 |

## Appendix D: Comparable Degree Programs

The table below lists comparable degree programs in either Astronomy or Astrophysics.

Abbreviations: ISM = Interstellar Medium, OIR = Optical/Infrared, GR = General Relativity

Table 4. Comparable Degree Programs

| School | NRC S-Rank | No. of Core (Required) Courses | Topics of Core Courses | No. of Required Electives | Example Elective Topics |
|---|---|---|---|---|---|
| UCR (proposed) | | 7 Core + 2 Research | Observational and computational astro, ISM, cosmology, radiative processes, stars, galaxies | 2 | Statistical astro, fluid dynamics, adv. cosmology, particle astro, dark matter, data science |
| Caltech | | 7 | Radiative processes, stars, galaxies, HE astro, ISM, cosmology, measurements & instrumentation | 0 | Optional: planetary physics, atomic and molecular processes, adv. cosmology, order of magnitude physics |
| Cornell U. | | 8 courses in 3 years | E.g., galaxies, stars, OIR/submm astronomy, fluid dynamics, planets, cosmology | Decided by special committee | GR, computational physics |
| Harvard | | 1 | radiation | 5 + 1 | Fluids, cosmology, ISM, stars, planets, GR + 1 from another dept. |
| JHU | | 5 + 2 research | Stars, ISM & fluids, radiative astro, dynamics | 0 | N/A |
| U. of Arizona | | 7 + 2-3 research | Physics of astrophysics, statistical and computation methods, cosmology, stars and planets, ISM, galaxies, instrumentation | 3 | Data science, optics, GR, radio astronomy, plasma physics |
| UC Berkeley | | 6 of 13 | Astrophysical techniques, numerical | 0 | Optional to take up to two courses |

| | | | | | |
|---|---|---|---|---|---|
| | | | techniques, ISM, radiation, dynamics, fluids, stars, computational, plasma | | outside department |
| UCLA | | 7 | Fluids, radiation 1 and 2, stars, ISM, galaxies, astro quantum | 2 | Instrumentation, high energy, astrostats, order of magnitude, solar system, exoplanets |
| UC Santa Cruz | | 6 | Radiation 1 and 2, fluids, research & teaching, stars & planets, galaxies & cosmology, observational astronomy | 2 | Statistical techniques, ISM, instrumentation, adaptive optics |

## Appendix E: Faculty CVs

[CVs Link]

## Appendix F: Feedback from Other UC Departments

This proposal was sent for comment in April 2021 to the following UC departments:

Berkeley, Department of Astronomy
Davis, Department of Physics and Astronomy
Irvine, Department of Physics & Astronomy
Los Angeles, Department of Physics and Astronomy
Merced, Department of Physics
San Diego, Department of Physics
Santa Barbara, Department of Physics
Santa Cruz, Department of Astronomy & Astrophysics

A sample of the cover letters sent to these departments is given below. We received feedback from UC Irvine. This is also given below, along with our response.

[Sample Letter]

**Department of Physics & Astronomy**
900 University Avenue
Riverside, CA 92521

April 21, 2021

Timothy Tait, Chair
Department of Physics & Astronomy
University of California, Irvine
4129H Frederick Reines Hall
Irvine, CA  92697-4575

Dear Chair Tait,

At UCR we are in the process of proposing a new graduate program leading to a Ph.D. in Astronomy. In accordance with the review policy established by the systemwide Coordinating Committee of Graduate Affairs (CCGA), I am providing you, as the Chair of an existing comparable program, with a copy of the current draft of our proposal. We would be very grateful for any feedback you may wish to offer us, so that the proposal may be made as strong as possible before submission.

As background, please understand that the format and contents of the proposal follow the required outline found in the CCGA Handbook, and that internal and external reviewers will later be asked to address the following four points when examining our final submission:

– Quality and academic rigor of the program
– Adequacy of the size and expertise of faculty to administer the program
– Adequacy of the facilities and budgets
– Applicant pool and placement prospects for the graduates

If you wish to provide feedback, we would like to receive it within four weeks of the date of this letter, since we expect to submit the proposal for campus review at that time.

Sincerely,

Kenneth N. Barish

Professor of Physics
Chair, Department of Physics and Astronomy
UC Riverside
Kenneth.Barish@ucr.edu

**Feedback from UC Irvine:**

On May 10, 2021, at 9:24 AM, Timothy Maurice Paul Tait <ttait@uci.edu> wrote:

Dear Ken,

Thank you for the opportunity to review the UCR proposal for its new graduate program in Astronomy. Although I am not an astronomer myself, I did oversee UCI's recent move to adding a Ph.D. in Physics with a concentration in Astrophysics and Astronomy to its curriculum. Your proposed program looks quite similar to the one started at UCI (which so far we are quite happy with), and I believe it will serve your Ph.D. students in Astronomy very well to prepare them for Ph.D. research and beyond. It offers a balanced and complete set of topics in Astronomy and Astrophysics. It also seems like the impact on department teaching resources will be manageable.

I could find almost nothing to complain about or suggest to improve. The only thing I flagged was that the proposed course in Computational Astrophysics might consider incorporating some sections on Machine Learning, which is increasingly an important subject both in Astronomy research and beyond. But I also note that it covers a lot of important and worthy ground in its proposed subject matter, which might explain this absence.

Best wishes
Tim

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Professor Tim Tait
Chair, Department of Physics and Astronomy
University of California, Irvine

**Response:**

Including Machine Learning in the coursework is an excellent suggestion. We considered adding a section to the Computational Astrophysics course but concluded that a proper treatment of ML would require its own course. In fact, we are currently developing a graduate course on ML techniques applied to Astronomy and hope to offer this as an elective in the near future. In the meantime, UCR offers a graduate course on ML through its Bourns College of Engineering (CS 299: Machine Learning). Our students interested in ML are encouraged to take this course, and it would be allowed as an elective for the Astronomy Ph.D. program.