## TABLE OF CONTENTS

**EDUCATION & OUTREACH**
- Department of Astronomy
- Center for Astronomy Education (CAE)
- Astronomy Camp
- Mt. Lemmon SkyCenter

**INTERDISCIPLINARY**
- Theoretical Astrophysics
- Center for Astrobiology

**OPTICAL / INFRARED TELESCOPES**
- Catalina Telescopes (Mt. Lemmon)
- Kitt Peak Telescopes
- MMT Observatory
- Magellan Telescopes
- Large Binocular Telescope (LBT)

**NEXT GENERATION TELESCOPES**
- Giant Magellan Telescope (GMT)
- Large Synoptic Survey Telescope (LSST)

**RADIO TELESCOPES**
- Arizona Radio Observatory (ARO)

**LABORATORIES**
- Astrochemistry/Spectroscopy Laboratory
- Steward Observatory Radio Astronomy Laboratory (SORAL)
- Steward Observatory Mirror Laboratory (SOML)
- Imaging Technology Laboratory (ITL)
- Center for Astronomical Adaptive Optics (CAAO)
- Infrared Detector Laboratory

**SPACE-BASED ASTRONOMY**
- Near Infrared Camera and Multi-Object Spectrometer (NICMOS)
- Spitzer Space Telescope - Multiband Imaging Photometer (MIPS)
- NIRCam: Near-Infrared Camera and Wavefront Sensor for the James Webb Space Telescope

**FACULTY**
- Teaching, Research, & Joint Appointments
- Post-doctoral Fellows & Adjunct Faculty
The University of Arizona’s (UA) Department of Astronomy currently has 42 Ph.D. students, making it the largest graduate program in astronomy in the country. The program is extremely high quality, with admission of approximately eight to ten students per year from among 120-130 applicants. Incoming astronomy graduate students have the highest mean GRE scores among over 100 graduate programs on campus. We compete with Caltech, Harvard, UC Santa Cruz, UC Berkeley, and Chicago for the best students in the country. The graduate program is diverse, with 33% women (compared to the national average of 30%) and 26% international. Two-thirds of the graduating Ph.D. students secure permanent astronomy positions in academia, government, or other research institutes.

According to statistics from the American Institute of Physics, the UA Department of Astronomy runs the largest undergraduate majors program in the country. In 2010, eleven students graduated, and the best of these were accepted in the Ph.D. programs at Caltech, UC Berkeley, Harvard, and Chicago, which are in the top echelon of astronomy departments nationwide. Over two-thirds of the undergraduate majors have formal research experience, drawing on the expertise of about 35 faculty members in theory, observation, and instrumentation. The undergraduate program also has excellent gender equity, with 33% women, well above the national average in physics. Many of our students have double majors in physics and astronomy.

General Education courses in Astronomy are taken by one out of four UA students, taught by Department of Astronomy faculty. Despite their major commitments to research, astronomy faculty members teach these courses in person. In 2010-11, UA astronomers taught 3,200 students in Tier One and Tier Two General Education which is the largest number of students taught by any UA College of Science department. Faculty members in the department have been innovative in the use of preceptors, classroom response devices, and instructional technology.

Since 1922, our continuing education and public outreach programs have included the Steward Observatory Public Evening Lectures. The department also houses the Center for Astronomy Education (CAE), the largest college-level astronomy education research group in the nation, and the internationally renowned Astronomy Camp.
The Center for Astronomy Education (CAE), lead by Prof. Edward Prather and Education Specialist Gina Brissenden, is devoted to improving teaching and learning in Astro 101 by conducting fundamental research on student beliefs and reasoning difficulties related to astronomy, and instructor implementation difficulties related to teaching astronomy. The center uses the research results to inform the development of research-validated curriculum and assessment materials for use in the Astro 101 classroom. These research-validated curricula and assessment materials frame the CAE Teaching Excellence Workshops for Astro 101 instructors. The goal of these professional development workshops is to increase the pedagogical content knowledge of Astro 101 instructors and improve implementation of these curricula and assessment materials.

To create sustainability and broaden the national impact and scope of the work, CAE developed the NSF-funded Collaboration of Astronomy Teaching Scholars (CATS) Program together with other leaders in astronomy education and research: Chris Impey, UA; Kevin Lee, U. of Nebraska; and Doug Duncan, U. of Colorado). The primary goals of CATS are to:
1) Increase the number of Astro 101 instructors conducting fundamental research in astronomy education.
2) Increase the amount of research-validated curriculum and assessment instruments available for use in Astro 101.
3) Increase the number of instructors prepared to develop and conduct their own CAE Teaching Excellence Workshops.

Astronomy Camp
http://www.astronomycamp.org/

Astronomy Camp is an internationally known science education program held since 1988 at the Catalina Observatories on Mt. Lemmon. Created by astronomer Don McCarthy and sponsored in part by the UA Alumni Association, the Camp engages an international audience of teenagers, adults, educators, and school groups in research-based science education using telescopes as large as 1.5 meters. Begun as a service to the public, the Camp has grown steadily and benefits the UA by providing major external funding (research and education), undergraduate and graduate recruitment (National Merit, Intel Science Search), student funding (salaries, fellowships), postdoctoral education grants, etc.

The Camp is financially self-sufficient and supports an internal scholarship program. Contributions from several generous donors help support the site and are funding the development of the Mt. Lemmon SkyCenter to expand the present activities in a multi-disciplinary approach.

Astronomy Camp is the primary focus of NASA’s James Webb Space Telescope NIRCam outreach to all 317 Councils of the Girl Scouts of the USA and has led to major improvements in the Girl Scouts national astronomy curriculum.
The Cosmic Web arises from gravitational amplification of tiny mass fluctuations soon after the Big Bang, resulting in a magnificent network of filaments on scales of millions of light years. Galaxies and galaxy clusters like the Milky Way form at the nodes of these filaments. This image shows a simulation of the Cosmic Web color-coded by temperature. Arizona theorists use super-computer simulations to investigate how to detect and characterize this Cosmic Web using the world’s most advanced telescopes.

Figure 4. This graphic illustrates the cosmic growth of structure over the 13.8 billion year history of the Universe (from right to left), beginning in a smooth, dark state, then galaxies begin forming within the Cosmic Web. Cosmic “high noon” occurs around 10 billion years ago, when star formation was most vigorous. At all epochs, most of the visible matter in the Universe hides in the vast intergalactic medium, detectable only through its absorption signatures on background quasars. Theorists at Arizona use high-performance computers to study the evolution of the Universe, attempting to assemble a complete cosmic history of the visible and invisible (i.e. dark matter & dark energy) from the Big Bang until today. Both image simulations by Benjamin. D. Oppenheimer & Romeel Davé.

Theoretical Astrophysics
http://www.astrophysics.arizona.edu/

Steward Observatory houses a vibrant and active theoretical astrophysics group. The group includes six faculty members, a prize theory and other postdoctoral fellows, graduate students, and undergraduates. It boasts leading experts in the theory of supernovae, cosmology, black hole accretion disks, galaxy formation, active galactic nuclei, interstellar and intergalactic gas. Astrophysics is becoming an increasingly computationally-driven field, with Arizona at the forefront of modern astrophysical simulations. The theory group specializes in hydrodynamics including radiative transfer and magnetic fields, cosmological growth of structure, stellar interiors and explosions, and astrophysical visualizations. Both Steward and the University of Arizona have supercomputing facilities that are actively used by theory group members. The theory group is highly integrated with the large multi-wavelength observational community at Steward, with numerous joint collaborations and projects fostering a uniquely interactive intellectual atmosphere. At Arizona, we strongly believe that progress on the most important questions in astronomy is optimally attained through a concerted effort on both observational and theoretical fronts.

Steward Observatory is also part of the Arizona Theoretical Astrophysics Program (TAP), which includes over 20 faculty members spread over the Astronomy, Physics, and Planetary Sciences departments, making Arizona’s one of the largest astrophysics theory communities in the country. TAP runs colloquia, a visitors program for distinguished scholars, international conferences, a graduate student research prize, and a small grants program.

Figure 5. The Cosmic Web arises from gravitational amplification of tiny mass fluctuations soon after the Big Bang, resulting in a magnificent network of filaments on scales of millions of light years. Galaxies and galaxy clusters like the Milky Way form at the nodes of these filaments. This image shows a simulation of the Cosmic Web color-coded by temperature. Arizona theorists use super-computer simulations to investigate how to detect and characterize this Cosmic Web using the world’s most advanced telescopes.
By its very nature, astrobiology is interdisciplinary science spanning astronomy, biology, chemistry, geology, and physics. Its goal is to answer fundamental questions about the origins of life, such as: How did terrestrial life arise and evolve? Is there life elsewhere in the Universe? What is the future of life on Earth, on other planets in the solar system, and on some of the many exoplanets?

These exciting bold questions require a multidisciplinary approach. To meet this challenge, in 2003 the University of Arizona established the Center for Astrobiology. The goal of the Center is to develop an active and strong interdisciplinary community of researchers capable of launching new research programs that address fundamental but often complex problems in astrobiology.

The Center is pursuing a broad interdisciplinary effort within astronomy, chemistry and the biological, geological, physics, and planetary sciences to produce a greater understanding of the origin and evolution of life on Earth, in the Solar System, and on exoplanets.

The Center coordinates multiple forums to foster interdisciplinary collaborations and education. These programs include a monthly Astrobiology Lecture Series by a high-profile speaker, a weekly Astrobiology/Exoplanets Journal Club, advanced workshops, and an undergraduate and graduate minor in astrobiology.

In 2011 the undergraduate and graduate minors in astrobiology were established. Students majoring in astronomy, biosciences, chemistry, geosciences, physics, and/or planetary sciences can complement their traditional curriculum of study with core interdisciplinary courses in astrobiology. While students continue to enroll in traditional academic departments, increasingly interdisciplinary research is the key to successful scientific careers.

**Figure 7.** Astrobiology involves diverse environments to understand the distribution and origin of life. Examples shown below, clockwise from upper left are: Europa’s subsurface ocean is a key astrobiology target; Antarctica enables studies of extremophiles in dry cold environments; the volvox cells form spherical colonies and may represent an intermediate step between single- and multicellular life; research in the Arizona Meteor Crater provides clues about impacts and mass extinctions.
Catalina Telescopes on Mt. Lemmon
http://www.as.arizona.edu/telescopes/telescopes.html

The UA observing facilities in the Catalina Mountains include 1.5-m and smaller telescopes on Mt. Bigelow (elevation 2509 m) and Mt. Lemmon (2793 m), plus additional facilities operated under site maintenance contracts for universities and laboratories outside Arizona.

Steward Telescopes on Kitt Peak
http://www.as.arizona.edu/telescopes/telescopes.html

The pre-eminence of astronomy-related research and development in and around Tucson owes its history in large part to the role the UA played in enabling the establishment of the first national observing facility for optical/infrared astronomy on Kitt Peak (elevation 2096 m) in the 1960’s and 70’s. Since that time, the UA’s presence on Kitt Peak has been highlighted by the extremely productive 2.3-m Bok telescope, as well as smaller facilities whose scientific accomplishments include the identification of the optical pulsar at the center of the Crab Nebula supernova remnant. The Bok telescope, named after famous Milky Way astronomer and former department head Prof. Bart Bok, is still the largest optical telescope wholly owned by the state of Arizona. As such, it can be equipped with a wide variety of state-of-the-art instrumentation and time is awarded on a competitive basis to fulfill the varied requirements of faculty and graduate student research programs at Arizona’s three state universities. Like those in the Catalinas, the Kitt Peak telescopes of more modest aperture are dedicated to targeted research programs under long-term grants, such as the Spacewatch survey to search for near-earth asteroids, comets, and Trans-Neptunian objects, operated by the UA’s Department of Planetary Sciences. There are two Spacewatch telescopes: 0.9-m and 1.8-m reflectors.

Because of their high altitude and the personal interest of Gerard Kuiper (founder of the UA Lunar and Planetary Laboratory), the Mt. Lemmon telescopes were central in the early development of infrared astronomy under Kuiper, Harold Johnson, and Frank Low. The outstanding optical quality of the Mt. Bigelow reflector, built under Kuiper’s leadership, has provided some of the most exquisite images of Saturn and of the Moon ever taken by ground-based telescopes. Today, the availability of large amounts of time on this telescope allows programs to monitor variable sources, covering a range of possibilities from very low luminosity white dwarfs to supernovae. The telescope is ideal for tracking fast-moving near-Earth objects (NEOs). The Catalina telescopes provide learning opportunities for undergraduate and graduate student research and are the keystones of an emerging public and teacher outreach network. These programs, as part of the Mt. Lemmon Sky Center, are dedicated to advancing the role of the UA in science education activities in and beyond the Tucson area. (See the Astronomy Camp section of this document.)
The 6.5-m telescope of MMT Observatory (formerly the Multiple-Mirror Telescope) on Mt. Hopkins (2607 m) was constructed in the 1970’s as a cooperative project between the University of Arizona and the Smithsonian Institution. Currently under direction of Dr. Grant Williams, this telescope pioneered several features of modern large-telescope design, including multiple objective mirrors, a short overall length, an alt-azimuth mount, and a co-rotating enclosure. In addition to producing high-quality optical spectroscopy and infrared (IR) images, the six 1.8-m primary mirrors enabled important interferometric tests that led to the observatory’s forefront adaptive optics research, nulling interferometry, and development effort aimed at virtually eliminating the optical effects of our turbulent atmosphere in the near-IR.

During 1998-2000, the MMT was converted to a single 6.5-m mirror that has served as an essential stepping stone toward the development of two 8.4-m diameter spin-cast borosilicate mirrors now operating as the Large Binocular Telescope (LBT) and for those planned for the Giant Magellan Telescope (GMT). At the MMT, techniques were developed to control mirror temperature, figure measurement and correction, secondary mirror handling, and *in situ* primary mirror aluminization. Many of these techniques have been incorporated in the twin 6.5-m Magellan telescopes and the LBT. The present aperture of the MMT offers twice the collecting area of the original telescope and provides a much cleaner IR pupil to make best use of the high, clear, dry site. Several powerful instruments constructed by both partner institutions exploit the large collecting area, a one-degree field of view, and technological developments of semiconductor detector arrays to yield a set of research tools that are competitive with the largest telescopes in the world. Adaptive optics continues to be emphasized at the MMT for reducing sky background and obtaining near diffraction-limited images that are essential for studies of the formation and content of galaxies at high redshift, the extragalactic distance scale, star formation in dense molecular clouds, and in searches for extrasolar planetary systems.

The Magellan Telescopes at Las Campanas (2380 m) in Chile (580 km north of Santiago) are two separate 6.5-m state-of-the-art optical telescopes on alt-azimuth mountings. These telescopes are operated in collaboration with the Carnegie Institution for Science, Harvard University, MIT, and the University of Michigan, and the University of Arizona. UA’s 10% share of the facility provides valuable access to the southern sky, including such unique targets as the Galactic Center and the Large Magellanic Clouds. The site is known for its excellent seeing and clear weather. The instrumentation includes a wide-field optical spectrograph used to probe the most distant reaches of the universe, a high-resolution spectrograph to search for exoplanets, and a rapid-deployment imaging camera intended to monitor variable and serendipitous events. The success of the telescope’s optical design

http://www.as.arizona.edu
and construction has led to more ambitious plans for the Giant Magellan Telescope.

The suite of instruments makes Magellan competitive with even larger telescopes. One of the key instruments available at Magellan is the Inamori Magellan Areal Camera and Spectrograph (IMACS), which enables simultaneous observations of hundreds of objects in the standard mode and thousands of objects in a special mode conceived and designed by UA and MIT astronomers. In this latter mode, it is the most efficient instrument in the world for measuring spectroscopic redshifts of faint objects. The Low Dispersion Survey Spectrograph (LDSS-3) has been updated to work in the red portion of the optical spectrum and is now more efficient than the Echelette Spectrograph and Imager at the Keck telescopes for measuring the internal motions kinematics of faint galaxies.

Large Binocular Telescope (LBT)
http://www.lbto.org/

The LBT, located on Mt. Graham (3200 m), near Safford, Arizona, is the major telescope development for the University of Arizona (with Arizona State University and Northern Arizona University) and its partners in Italy (13 observatories under the National Institute for Astrophysics) and Germany with the LBT Gesellschaft, a consortium of five research institutions, and within the USA (Ohio State University and the Research Corp.). Partners associated with the Research Corp. include the University of Virginia, the University of Minnesota, and Notre Dame University.

With its two 8.4-m primary mirrors (each with focal ratios of f/1.14) on an alt-azimuth mount, the LBT has the light-collecting power equivalent to an 11.8-m telescope and the spatial resolution of a 22.8-m aperture. With its adaptive secondary mirrors and beam-combining optics, the LBT may be viewed as the first of the next generation of extremely large telescopes. The LBT has five focal stations where instruments are mounted permanently, enabling observers to switch instruments on a time scale of 15 minutes. Instruments now in operation include two wide-field prime-focus cameras, a Gregorian focus optical spectrometer, and near-infrared imager/spectrograph. In 2012 two separate interferometers will be installed using adaptive optics in the mid- and near-infrared regions providing angular resolution of ~ 0.01 arc sec.

The LBT’s unique spatial resolution capabilities on faint objects make it an ideal instrument for studying problems as diverse as exoplanets, zodiacal disks around nearby stars, and newly forming galaxies in the early universe.

Figure 13. 8.4-m primary mirrors and prime-focus cameras of LBT. Note observer between mirrors. Photo by Wiphu Rujopakarn.

Figure 14. LBT image of spiral galaxy NGC 6946 taken with the Large Binocular Camera. Image by V. Testa and C. DeSantis.
The GMT optical system will consist of seven 8.4-m mirrors (six off-axis plus one central element) configured as the equivalent of a 25-m f/0.7 single primary. It provide collecting area equivalent to a single 21.5-m telescope and resolution corresponding to 25-m aperture. Like the Large Binocular Telescope, the GMT will be equipped with adaptive secondaries, but in this case, seven mirrors segmented like the primary aperture.

The GMT project is a collaboration of Carnegie Institution for Science, Harvard University, Arizona, Smithsonian Institution, Texas A&M, University of Texas at Austin, Australian National University, Australian Astronomy Ltd., the Korean Astrophysics and Space Science Institute (KASI), and the University of Chicago.

The GMT project represents the outgrowth of the very successful Magellan telescopes and a recommendation by the National Academy of Sciences to build a significantly larger ground-based optical/infrared telescope.

In February 2006, GMT conducted a conceptual design review, which resulted in a very positive evaluation from the international review team. Much of the GMT design was produced at the Steward Observatory and the UA College of Optical Sciences. Participation in the project is a key to the future of both the Steward Observatory Mirror Laboratory and Arizona Astronomy.

In 1997, Prof. Roger Angel at Steward Observatory embarked upon the design of a system that could survey the entire night sky in four or five nights and to 25th magnitude. This design will enable for a wide variety of science, and the concept rapidly gained community support. Since its inception, plans developed into a detailed design for the LSST, a project that has been endorsed by three review panels of the National Academy of Sciences. The LSST was ranked the top priority among plans for new ground-based telescopes by the National Academy’s 2010 Decadal Survey for Astronomy and Astrophysics.

The 23-ton LSST mirror was spun cast in March 2009. The grinding phase of the primary/tertiary mirror has been completed and polishing is now well under way at the Mirror Lab. With its three-mirror optical system, the LSST will have an 8.4-m aperture with a field of view of 9.6 sq. deg. or 49 times bigger than that of the Full Moon.

Each image will be recorded by a 3.2 Gigapixel camera, the largest ever built, to be supplied by a Department of Energy team lead by the Stanford Linear Accelerator Center. Some 30 Terabytes of data will be recorded each night. The LSST data will be processed in real time, tracking changes in more than five billion sources and discovering thousands more each night. The LSST will be an open-data project; i.e., all data will be on-line, freely accessible to the public.
The Arizona Radio Observatory continues its program in millimeter and submillimeter radio astronomy with a goal of understanding the processes of star formation, the evolution of the chemical composition of galaxies, and the influence of cosmic events leading to the origins of life. Under the direction of Prof. Lucy Ziurys, the ARO group offers observational support and state-of-the-art instrumentation for researchers at its two world-class radio telescopes. Group members are performing ground-breaking research in astrochemistry and astrobiology. In support of this work, the group is developing and applying advanced instrumentation, such as the first detector systems from the ALMA (Atacama Large Millimeter Array) Project, which is the upcoming international flagship radio telescope.

ARO facilities include the 10-m Heinrich Hertz Submillimeter Telescope (SMT) on Mt. Graham. Complemented by its elevation (3175 m), the high surface accuracy of the 10-m antenna, is arguably the best sub-mm telescope in the world observing at wavelengths shorter than 1 mm (300 GHz). Since 2001, Steward Observatory has been operating the Kitt Peak 12-m telescope (formerly run by the National Radio Astronomy Observatory). The 12-m antenna provides observational capabilities primarily at wavelengths of 2-3 mm (150-100 GHz) and is the only facility worldwide that provides access to the longer wavelengths in the 3-mm atmospheric window.

The focus of both research and instrumentation development involves heterodyne astronomy and spectroscopy. Collaborations outside ARO include other organizations, as well as departments within the University of Arizona and the Steward Observatory Radio Astronomy Lab (SORAL). UA departments involved in research at the ARO include Chemistry, Electrical and Computer Engineering, Optical Sciences, Planetary Sciences, and Biology.

Astrochemistry/Spectroscopy Laboratory
http://astrochemistry.as.arizona.edu

Astrochemistry is the study of the molecular composition of the interstellar medium. In interstellar space, molecules are primarily identified by measuring their rotational spectra using millimeter and sub-millimeter telescopes, such as those of the ARO. Key to this endeavor are laboratory measurements of rest frequencies that serve as a finding list, enabling observers to identify such molecules. Led by Prof. Lucy Ziurys, the Laboratory has developed spectrometer systems that enable the measurement of the pure rotational spectra of potential interstellar molecules over seven octaves in frequency.
range 400–800 GHz. Of particular interest are free radicals and molecular ions that must be produced in situ using non-standard chemical methods involving electrical discharges, laser ablation, supersonic expansions, Broida-type ovens, and exotic precursors.

Four spectrometers, designed and built in the lab, are currently in operation there: two direct-absorption systems working at mm and sub-mm wavelengths, a velocity-modulation spectrometer for selective detection of molecular ions, and a pulsed Fourier transform microwave (FTMW) spectrometer, which incorporates a YAG laser to ablate materials for molecular production. Thus far, rotational spectra of over 100 molecules have been acquired with these instruments including many unstable molecules and molecular ions that have never before been seen in a laboratory setting.

The Steward Observatory Radio Astronomy Lab (SORAL), founded by Prof. Chris Walker, is a world leader in developing leading-edge, submillimeter-wave receiver systems. SORAL constructed the world’s first 810- and 345-GHz heterodyne array receivers and has recently built several TeraHertz (THz) receivers for radio astronomy. These instruments are multi-institutional efforts, with key components coming from JPL, several universities, and a number of industrial partners. Equipment developed by SORAL has served as primary facility instruments at the Heinrich Hertz Telescope (Mt. Graham) and the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) at the South Pole for over a decade. An automated observatory called the High Elevation Antarctic THz Telescope (HEAT), has been recently built and deployed in Antarctica by SORAL scientist Dr. Craig Kulesa (PI). SORAL also leads in the development of the Stratospheric TeraHertz Observatory. The team is also employing laser micro-machining techniques to fabricate the first integrated THz array receivers.

The Steward Observatory Mirror Laboratory (SOML), located under the east section of the UA football stadium, is a unique facility for fabricating large mirrors (up to 8.4-m diameter) for ground-based telescopes. The brainchild of Prof. Roger Angel, SOML produces spun-cast mirror blanks made of Ohara E6 borosilicate glass and light weight honeycomb technology that are finished optically to tolerances of ±15 to 25 nm with a unique, stressed-lap polishing systems. The completed mirrors are integrated and tested in telescope support systems before they are shipped to the observatory sites.
The SOML mirrors combine low thermal inertia, short focal length, and high mechanical rigidity. The SOML has successfully produced optics with superb performance at relatively low cost for numerous telescopes, including three 3.5-m telescopes (ARC, WIYN, and SOR), the 6.5-m Multiple-Mirror Telescope conversion, the two 6.5-m Magellan telescopes, and most recently, the two 8.4-m mirrors for the Large Binocular Telescope (LBT). The SOML has produced a 6.5-m collimator for the Lockheed Martin Company.

SOML is completing the polishing of the first 8.4-m off-axis segment of a paraboloid for the Giant Magellan Telescope (GMT). Work is under way to cast the second 8.4-m mirror for GMT. Six more 8.4-m mirrors are planned for the GMT project. Polishing is in progress on the combined primary/tertiary 8.4-m/5.2-m mirrors for the Large Synoptic Survey Telescope (LSST) that will be located on Cerro Pachon, Chile. Additionally, a 6.5-m mirror has been cast for an international observatory located on Sierra San Pedro Mártir in Baja California, Mexico.

The SOML has also pioneered the concept of adaptive secondary mirrors (with Italian partners in the LBT), novel optical test methods (such as holographic test plates for convex surfaces), and concepts for light-weight space optics. SOML faculty and staff collaborate with members of the UA College of Optical Sciences. SOML operates without any state funding.

The UA’s Imaging Technology Laboratory (ITL) is dedicated to developing state of the art detectors for the worldwide scientific and industrial imaging communities. ITL has been a research group within Steward Observatory under the direction of Dr. Michael Lesser since 1990 that is entirely dedicated to imaging technology research. The core focus, to enhance detector quantum efficiency, has led to several technology transfers to industry. ITL is internationally recognized as the leader in blue- and UV-optimized Charge-Coupled Devices (CCDs) and CMOS imagers. With both undergraduate and graduate students, ITL staff have developed new techniques for scientific CCD processing, including anti-reflection coatings, mosaic and large format imager packaging methods, silicon thinning methods, and backside charging thin film technologies. The UA receives scientific and industrial grants and contracts to provide optimized imaging detectors and technologies that are incorporated into camera systems all over the world. Several thousand devices have been processed over the past 21 years. The facility is located in a leased building about one mile from campus.
The Center for Astronomical Adaptive Optics (CAAO) has the goal of compensating for atmospheric turbulence in real time so that large ground-based telescopes can acquire diffraction-limited images that are even sharper than those from the Hubble Space Telescope. Prof. Phil Hinz leads CAAO which was established in 1994 with the goal of developing advanced adaptive optics techniques for the MMT and LBT. A major goal has been to integrate adaptive-wavefront corrections directly into deformable secondary mirrors in these telescopes. This strategy gives high angular resolution in the infrared.

The MMT and LBT adaptive optics (AO) systems are now beginning to acquire images of extrasolar planets. CAAO has put into operation the first tomographic adaptive optics system with multiple laser guide stars, which are key to increasing the size of the corrected field of view for ground-based telescopes, and to making AO corrections of faint objects with the LBT and Giant Magellan Telescope. An AO secondary will soon be commissioned on one of the Magellan 6.5-m telescopes at Las Campanas. Special optics required for space telescopes to make very high contrast optical images of extrasolar planets are also being developed.

In recent years, astronomers have seen a phenomenal increase in infrared observing capabilities. Much of this gain has come from advances in detector technology, where sensor arrays have grown in size and increased in quantum efficiency. Unlike the situation at optical and near-infrared wavelengths, astronomers working at far infrared wavelengths (λ > 30μ) have not had the benefit of extensive detector development for commercial or military applications. Detector advances have been made through close collaboration between astronomers and physicists.

Under the leadership and teamwork of Profs. Marcia Rieke and George Rieke, the Infrared Detector Laboratory has played an important role in virtually all of the space-based infrared astronomy missions. Starting with the Infrared Astronomical Satellite (IRAS) launched in 1983, the laboratory has contributed key technologies to various missions. The focal plane arrays for the Spacelab II Infrared Telescope that flew on the Space Shuttle, as well as detectors for the Short Wavelength Spectrometer on the European Infrared Space Observatory, were developed at Steward Observatory. The Infrared Detector Lab also tested the NICMOS flight arrays prior to their being integrated into the Hubble Space Telescope. The largest far-infrared detector array ever produced was built in the Infrared Detector Laboratory as part of the Multiband Imaging Photometer (MIPS) on the Spitzer Space Telescope. Consisting of an array of 1024 pixels operating at λ = 70μ, this detector enabled true imaging for the first time at such long wavelengths. An even more exotic array, also built for MIPS, consists of detectors where the individual detector crystals are mechanically stressed to give an efficient response at 160μ. Both far-infrared arrays, currently in orbit around the Sun, are producing a wealth of data. The current principal project of the Infrared Detector Laboratory is the packaging of the detector arrays for the NIRCam instrument on the 6.5-m James Webb Space Telescope. These detector arrays will be the largest ever flown on a space mission.

Infrared Detector Laboratory  
http://www.as.arizona.edu/research/infrared_detector_laboratory.html

Figure 22. The LBT AO imaging system, using one 8.4-m mirror, shows a 6.9-mag star (HD175658) in Lyra where ten diffraction rings are visible. The angular resolution (or point-spread function) is 0.025 arc sec (FWHM) at 1.6μ with a Strehl ratio of 85%. Image by Simone Esposito, LBTO and Arcetri Observatory.
Near Infrared Camera and Multi-Object Spectrometer (NICMOS)
http://nicmos.as.arizona.edu/

Steward Observatory provided the Near Infrared Camera and Multi-Object Spectrometer for the Hubble Space Telescope. NICMOS, installed in 1997, images at three different spatial resolutions in the wavelength range $\lambda = 0.8$ to $2.5 \mu$. It can also take low resolution slitless spectra in the same spectra range. In addition, it has the capability for polarization imaging and coronagraphic observations. NICMOS was the first HST instrument capable of observations at $\lambda > 1 \mu$. A second infrared instrument WF3-IR was recently installed on HST working at $\lambda < 1.7 \mu$. Prof. Rodger Thompson was the Principal Investigator for NICMOS and led the Instrument Definition Team with many Steward personnel as members.

NICMOS has acquired infrared images and spectra of the some of the most distant galaxies ever observed, the dust obscured nuclei of galaxies, star formation regions in our own galaxy, and candidates for extra-solar planets. The detector arrays developed for NICMOS revolutionized near-infrared astronomy and placed the UA at the forefront of this discipline. NICMOS was one of the first large research contracts within the UA that led the way for how the UA handles large projects. A mechanical cooler was added by astronauts on Space Shuttle Columbia in March 2003. NICMOS is currently waiting the restart of the mechanical cryogenic cooler.

Multiband Imaging Photometer for the Spitzer Space Telescope (MIPS)
http://mips.as.arizona.edu/mipspage/

The Spitzer Space Telescope is NASA’s primary infrared astronomy mission, along with the Chandra Observatory in x-ray, and the Hubble Space Telescope for the ultraviolet and visible light. The overall design of Spitzer is based on a concept developed by the late University of Arizona Prof. Frank Low. Subsequently Prof. George Rieke led the development of the far-infrared photometer (MIPS), one of three Spitzer instruments, and two of the initial six large science projects originated from the UA (under Profs. Michael Meyer and Robert Kennicutt, now at ETH Zurich and Cambridge University, respectively).

The MIPS required development of specialized technologies for far-infrared detector arrays, that were constructed at Steward Observatory. The flight array for the 70-\(\mu\) band was the first large format detector array ever constructed for the far-infrared. An example of its power is shown in Figure 24 which compares planetary debris produced by collisions of asteroids associated with two bright nearby stars: Vega and Fomalhaut. The Fomalhaut system is nearly edge-on and is dominated by a ring of material like the Kuiper Belt in the Solar System, but has a radius about 2.5 times larger. The Vega system is face-on, and extends to a radius five times larger. Modeling to account for the difference between the systems shows that there has probably been a huge collision in the Vega Kuiper Belt and that fine dust particles are being ejected by radiation pressure. Both stars are about 300 million years old. The dramatic behavior of the Vega system is similar to the period about 4 billion years ago when planet building was completed in the Solar System. Similar observations of other stars enable us to explore the evolution of hundreds of planetary systems.
Under the leadership of Prof. Marcia Rieke, Steward Observatory is developing a 40-Megapixel camera called NIRCam. This project is the only instrument for the JWST being developed by a university team. Her team is working with the Lockheed Martin Advanced Technology Center in Palo Alto, CA, which is responsible for instrument fabrication, and with Teledyne Imaging Sensors in Camarillo, CA, which is providing the detector arrays.

UA provides oversight and is packaging the Teledyne arrays into mosaics for flight use. The residual arrays will be available for use on ground-based telescopes such as the 6.5-m MMT and the 11.8-m Large Binocular Telescope. The team will receive an allocation of observing time that will be used to investigate the earliest light emitting aggregates in the Universe, to probe the physical processes underlying the formation of stars and planetary systems, and to characterize Jupiter-size planets around nearby stars.

**Figure 24.** Image shown at left demonstrates the power of MIPS infrared imaging system, acquired with NASA’s Spitzer Space Telescope. The two fuzzy objects are extended systems of planetary debris, surrounding the bright stars Vega and Fomalhaut, reproduced here at the same physical scale. In the course of time, over millions of years, this material collapses into a revolving protoplanetary disk and then coalesces to form planets.

**Figure 25.** CAD drawing of one NIRCam module with baffles removed to reveal the optical path. The real instrument will be approximately 1 meter in the vertical direction.

**Figure 26.** Artist’s conceptual drawing of JWST showing a planetary system in formation in background. NIRCam will be mounted in the structure attached to the back of the 6.5-m primary mirror. JWST illustration courtesy Northrop Grumman. Courtesy of © David A. Hardy, www.astroart.org/PPARC.
<table>
<thead>
<tr>
<th>Name</th>
<th>Degree, Institution, Year</th>
<th>Title</th>
<th>Research Interests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apai, Daniel</td>
<td>Ph.D. Heidelberg 2004</td>
<td>Assistant Professor</td>
<td>Exoplanets, exoplanetary atmospheres, planet formation.</td>
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<td>Arnett, David</td>
<td>Ph.D. Yale 1965</td>
<td>Regents Professor</td>
<td>Nuclear astrophysics, stellar and galactic evolution.</td>
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<tr>
<td>Bechtold, Jill</td>
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<td>Professor</td>
<td>Cosmology, intergalactic medium, instrumentation, extragalactic astronomy, active galactic nuclei, quasars.</td>
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<tr>
<td>Bieging, John H.</td>
<td>Ph.D. Caltech 1974</td>
<td>Professor</td>
<td>Interstellar medium, galactic astronomy, star formation.</td>
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<tr>
<td>Brown, Robert</td>
<td>Ph.D. Hawaii 1982</td>
<td>Professor</td>
<td>Kuiper Belt objects, brown dwarfs, exoplanets, infrared instrumentation.</td>
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<td>Cocke, William J.</td>
<td>Ph.D. Cornell 1964</td>
<td>Professor Emeritus</td>
<td>Relativity, probability, theoretical astrophysics.</td>
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<tr>
<td>Davé, Romeel</td>
<td>Ph.D. UC Santa Cruz 1998</td>
<td>Associate Professor</td>
<td>Theoretical astrophysics, extragalactic astronomy, intergalactic medium, cosmology, numerical hydrodynamics.</td>
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<td>Eisner, Joshua</td>
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<td>Fan, Xiaohui</td>
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<td>Guyon, Olivier</td>
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<td>Melia, Fulvio</td>
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<td>Galactic center, relativistic jets, active galactic nuclei, accretion-disk coronae, cataclysmic variables.</td>
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<td>Pinto, Philip</td>
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<td>Theoretical astrophysics, radiative transfer, supernovae, cosmic distance scale.</td>
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<td>Poss, Richard</td>
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<td>Associate Professor</td>
<td>History of astronomy, astronomy and the arts.</td>
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<td>Prather, Edward</td>
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<td>Robertson, Brant</td>
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<td>Sarcevic, Ina</td>
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<td>Ph.D. Arizona, 1988</td>
<td>Professor</td>
<td>Optical design, fabrication, and testing, optical design of astronomical instrumentation.</td>
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<td>Shirley, Yancy</td>
<td>Ph.D. Texas 2002</td>
<td>Assistant Professor</td>
<td>Galactic astronomy, star formation, extra-galactic astronomy, astrochemistry, astrobiology.</td>
</tr>
</tbody>
</table>
Smith, Nathan: Ph.D. Minnesota, 2002: Assistant Professor. Evolution of massive stars, supernovae and eruptive transients, star forming regions, interstellar medium, circumstellar material.

Strittmatter, Peter, Ph.D. Cambridge 1966: Regents Professor, Director of Steward Observatory. Theoretical astrophysics, extragalactic astronomy, cosmology, active galactic nuclei, instrumentation, astronomy education.

Thompson, Rodger, Ph.D. MIT 1970: Professor. Extragalactic astronomy and cosmology, galactic astronomy and star formation, infrared astronomy, Instrumentation.

Tifft, William G., Ph.D. Caltech 1958, Professor Emeritus. Space astronomy, galaxies.


Zabludoff, Ann, Ph.D. Harvard 1993: Professor. Dependency of galaxy evolution on environment, type, mass, and merger history, structure and evolution of galaxy clusters and groups.


Research Faculty


Green, Richard F. Ph.D. Caltech 1977: Astronomer, Director of LBT. Extragalactic astronomy and cosmology, instrumentation.


Hill, John, Ph.D. Arizona 1984: Astronomer. Large telescope design, optical fabrication, instrumentation


Halfen, DeWayne, Ph.D. Arizona 2006: Assistant Astronomer. Astrochemistry, laboratory astrophysics, galactic astronomy, radio astronomy star formation


Hill, John, Ph.D. Arizona 1984: Astronomer. Large telescope design, optical fabrication, instrumentation


Hubeny, Ivan, Ph.D. Charles University (Prague), 1977: Senior Research Scientist. Galactic astronomy, star formation, planetary astronomy, theoretical astrophysics, supernovae, brown dwarfs, exoplanets, white dwarfs, active galactic nuclei, astrobiology.


http://www.as.arizona.edu
Lesser, Michael P., Ph.D. 1988, Senior Research Scientist: Director of Imaging Technology Laboratory. CCD Development, Instrumentation.

Martín, Hubert (Buddy), Ph.D. Cambridge 1983: Research Faculty. Instrumentation, optical design and testing.


Misselt, Karl, Ph.D. Louisiana State, Associate Staff Scientist. Galactic Astronomy and Star Formation

Morrison, Jane, Ph.D. 1995, Florida: Associate Staff Scientist. Extragalactic astronomy and cosmology.


Peters, Bill Ph.D. Texas at Austin, 1973: Staff Scientist. Radio astronomy, star formation, interstellar medium

Schneider, Glenn, Ph.D., Florida (Gainesville), 1985: Astronomer. Galactic astronomy, infrared astronomy, exoplanets, brown dwarfs, star formation, instrumentation

Smith, Paul, Ph.D. New Mexico, 1986: Associate Astronomer. Extragalactic astronomy and cosmology, polarimetry, active galactic nuclei

Stansberry, John, Ph.D. Arizona, 1994: Associate Astronomer. Galactic astronomy, Star and Planet Formation, Instrumentation

Su, Kate, Ph.D., Calgary, 2000: Assistant Astronomer. Planetary astronomy, galactic astronomy, star formation


Wehinger, Peter, Ph.D. Case Western Reserve, 1966: Staff Astronomer, Development Officer. Comets, spectroscopy and imaging of quasar host galaxies, instrumentation.


Williams, Grant, Ph.D. Clemson, 2000: Astronomer, Director of MMT Observatory. Massive stars, supernovae, gamma-ray bursts, instrumentation, polarimetry.

Wilmer, Christopher, Ph.D. CNPq Observatório Nacional (Rio de Janeiro), 1990: Assistant Astronomer. Extragalactic astronomy and cosmology, infrared astronomy.

Joint Appointments


Fang, Li-Zhi, Diploma. Peking, 1956: Professor of Physics. Cosmology clustering at high redshift.


Post-Doctoral Fellows

Abate, Alexandra, Ph.D., University College London, 2008: Cosmology (Mentor: Elliot Cheu).

Ammons, S. Mark, Ph.D. UC Santa Cruz, 2009: Active galactic nuclei, adaptive optics (Jill Bechtold).


Buenzli, Esther, Ph.D. Institute of Astronomy, ETH Zurich, 2011: Exoplanet and brown dwarf atmospheres (Daniel Apai).

Christiansen, Charlotte, (Bessey Fellow), Ph.D. Univ. Washington, Seattle, 2010: Star formation (Romeel Davé).

Clément, Benjamin, Ph.D. Université de Provence, Marseille, 2011: High redshift galaxies z >6, lensing of galaxy clusters (Eiichi Egami).

Flaherty, Kevin, Ph.D. Arizona, 2011: Circumstellar gas and dust in young stars (George Rieke).

Guver, Tolga, Ph.D. Istanbul Univ., Turkey, 2008: Physics of neutron stars (Feryal Özel).

Haines, Christopher, Ph.D. Univ. Central Lancashire, U.K. 2001: Galaxy evolution from infrared space surveys (Eiichi Egami).


Mauerhan, Jon, Ph.D. UCLA 2008: Evolution of massive stars (Nathan Smith).

McGreer, Ian, Ph.D. Columbia, 2009: High redshift quasars (Xiaohui Fan).

Metchnik, Marc, Ph.D. Arizona, 2009: N-body simulations (Philip Pinto).
Milne, Peter, Ph.D. Clemson, 1998: Galactic astronomy, star formation, gamma-ray bursters (Grant Williams).

Morzinski, Katie, (Sagan Fellow), Ph.D. UC Santa Cruz, 2011: Adaptive optics (Laird Close).

Narayanan, Desika, (Bok Fellow), Ph.D. Arizona 2007: Molecular clouds, star formation (Chris Walker).

Peirera, Marie, Ph.D. Columbia 2009: Galaxy formation (Eiichi Egami)

Rawle, Timothy, Ph.D. Durham 2009: Extragalactic astronomy, cosmology (Eiichi Egami)

Rex, Marie, Ph.D. Pennsylvania 2007, 08?: Submillimeter star formation (Eiichi Egami)

Skemer, Andrew, Ph.D. Arizona 2011: Imaging exoplanets (Phil Hinz)

Adjunct Faculty


Christopher Corbally, S.J., Ph.D. Toronto, 1983: Vatican Observatory, Associate Professor/ Associate Astronomer. Stellar spectroscopy, stellar classification.


Duschl, Wolfgang, Ph.D. Munich, 1985, Professor Institute for Theoretical Physics and Astrophysics, University of Kiel, Professor/Astronomer. Accretion disks, active galactic nuclei.

Funes, José, S.J., Ph.D. Padua, 2000: Director, Vatican Observatory, Assistant Astronomer. Extragalactic astronomy, active galactic nuclei.


Goldsmith, Paul, Ph.D. UC Berkeley 1975: Jet Propulsion Laboratory, Professor. Giant molecular clouds, star formation.


Neugebauer, Gerald, Ph.D. Caltech, 1960: Caltech, Professor Emeritus. Infrared astronomy, IR surveys.


Najita, Joan, Ph.D UC Berkeley 1993: NOAO, Associate Astronomer. Star and planet formation, substellar objects, wide-field surveys.

Stephen Pompea, Ph.D. Arizona, 1989: NOAO, Associate Professor. Education and public outreach.


Steinmetz, Matthias, Ph.D. Technical University Munich, 1993: Leibnitz Institute for Astrophysics Potsdam, Professor/ Astronomer. Extragalactic astrophysics, cosmology.


Stoeger, William, S.J., Ph.D. Cambridge, 1979: Vatican Observatory, Associate Professor/Associate Astronomer. Accretion disks, active galactic nuclei, cosmology.

Vestergaard, Marianne, Ph.D. Copenhagen, 1999: Dark Cosmology Centre, Niels Bohr Institute, Associate Professor. Quasars, active galactic nuclei, accretion disks.


Windhorst, Rogier, Ph.D. Leiden, 1984: Arizona State University, Regents Professor. Cosmology, galaxy formation, cosmic dark ages, instrumentation.
Steward Observatory is the research arm of the Astronomy Department at the University of Arizona (UA). With Andrew Ellicott Douglass as the first director, the Observatory was founded in 1916 as a result of a major gift from Mrs. Lavinia Steward.

Steward Observatory telescopes are operated on several mountain sites in southern Arizona and time is available on a competitive peer-reviewed basis to scientists at the UA, Arizona State University, and Northern Arizona University. The astronomical facilities focus on research that benefits from Arizona’s dry, clear weather over wavelengths ~0.3 µ to 3 mm. Profiting from instrument development associated with ground-based observations, Steward Observatory conducts space astronomy research mainly in the mid- and far-infrared region. Steward personnel use external research facilities in other wavelength ranges as well, from x-ray to cm-wavelength radio astronomy.

The Steward Observatory Mirror Lab, located under the east section of the UA football stadium, is developing the world’s largest light-weight spun-cast mirrors for the next generation of large telescopes including the 8.4-m Large Synoptic Survey Telescope and the 25-m Giant Magellan Telescope. The Mirror Lab produced three 6.5-m mirrors: one in Arizona (MMT) and two in Chile (Magellan Project), and two 8.4-m mirrors for the Large Binocular Telescope (LBT). Three more 8.4-m mirrors are currently in production.

In 1916 Lavinia Steward provided a generous gift to build a 36-inch reflecting telescope on the University of Arizona campus. It was dedicated in 1923 and was moved to Kitt Peak in 1962 where it is still in operation today. In its place, the Ray White 21-inch reflector is housed in the same dome and is regularly used by students. Photo by Laura Forsyth.

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FRONT COVER: M57, the Ring Nebula in Lyra, acquired with the LBT and LUC-1 infrared camera at three wavelengths: 2.122, 2.15, and 2.166 µ at the bent Gregorian focus. Photo by David Thompson.