

# Astronomy News

Case Western Reserve University Department of Astronomy

2014

## Dwarf Galaxies *Clues to Galaxy Formation*



*Dwarf galaxies: spheroidal (left), irregular (middle), and blue compact dwarf (right)*

Low mass dwarf galaxies, the most common and unassuming type of galaxy in the universe, may in fact hold the clues that help astronomers unlock the mystery of galaxy formation and evolution. Dwarf galaxies come in a variety of types (see figure above): smooth spheroidal dwarfs containing mostly old stars, gas-rich dwarf irregulars which are forming new stars, and “blue compact dwarfs” (BCDs) which are going through an intense and spatially concentrated burst of star formation. Postdoctoral researcher **Federico Lelli** has studied the structure and dynamics of BCDs, and investigated their relation to the other types of dwarfs.

The key to the evolution of these dwarf galaxies may lie in their interstellar medium, which contains the cold hydrogen gas out of which new stars form. Irregulars and BCDs, indeed, are gas-rich, while spheroidals are generally gas-poor. Since the main difference between spheroidals, irregulars, and BCDs is their

ability to form new stars, these three different types of objects may represent different evolutionary phases during the life of a dwarf galaxy. For example, if an irregular or a BCD runs out of cold gas to fuel star formation, it would probably evolve into a spheroidal. On the other hand, a spheroidal may capture fresh gas from the intergalactic environment and start to form new stars, turning into an irregular or a BCD. Given that the unusually high star formation rates of BCDs cannot be sustained for long periods, these types of dwarfs must necessarily evolve into another type of galaxy in a relatively short



*Federico Lelli*

time. However, the evolutionary path followed by dwarf galaxies are still poorly understood and debated among astronomers.

Lelli is using the three largest radio interferometers in the world —the American Very Large Array (VLA), the Dutch Westerbork Synthesis Radio Telescope (WSRT), and the Australia Telescope Compact Array (ATCA) — to study the distribution and kinematics of the neutral hydrogen in galaxies. Lelli has found that the distribution of gas in the outer regions of BCDs is often asymmetric, characterized by long filaments or anomalous extensions. This suggests that the intense star-

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# Dwarf Galaxies *Clues to Galaxy Formation*

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formation activity in BCDs has been triggered by some external mechanisms, which have perturbed the distribution of gas in the outer parts. Possibilities include interactions with other nearby dwarfs or the captures of gas from the intergalactic environment. Lelli has also shown that the kinematics of BCDs are markedly different from those of typical irregulars. BCDs rotate very fast in their inner regions, indicating that they have a high central concentration of mass (luminous and/or dark), which is quite unusual for a dwarf galaxy. Because of this, BCDs cannot simply evolve into typical irregular or spheroidal galaxies at the end of the intense star-formation activity. However, Lelli has also identified two new classes of dwarfs: "compact irregulars" and "rotating spheroidals", which have dynamical properties similar to BCDs. These types of galaxies are most likely the evolutionary descendants of BCDs at the end of their intense star-formation activity.

Meanwhile, fellow postdoctoral researcher **Marcel Pawlowski** is using the distribution and kinematics of dwarf galaxies to study galaxy formation on larger scales. According to our best current models of galaxy formation, these dwarfs form early in the universe's history, and are fundamental building blocks for forming bigger galaxies through collisions and mergers.



As massive galaxies grow, they can accrete more and more dwarfs, which, at least for a while, can remain intact and orbit their hosts as satellite galaxies. Under this hierarchical accretion model for galaxy formation, these dwarf galaxies should be accreted randomly, and show no preferential distribution or sense of motion around their host galaxy. By comparing the expected satellite distribution with those observed around host galaxies, Marcel Pawlowski has been testing our cosmological models of galaxy formation and evolution.

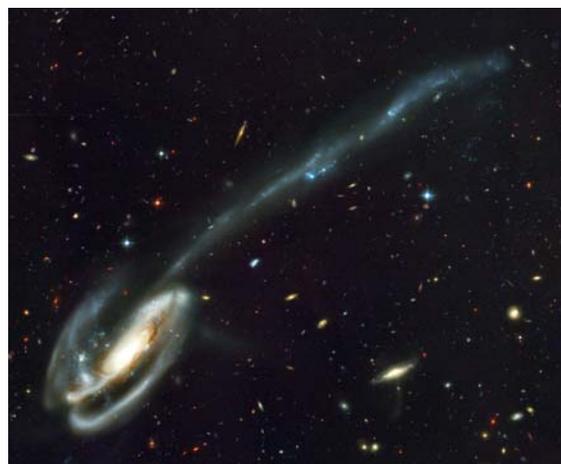
The first comparisons have been performed on the distribution of the satellite galaxies of the Milky Way, which were the easiest to discover initially. The result was surprising. Pawlowski's work has made it more and more clear that the satellites of the Milky Way are behaving almost opposite to our expectation. Instead of swarming around our cosmic home in a near-random fashion, they are distributed and orbit in a common, highly flattened structure, which Pawlowski named the 'Vast

Polar Structure' (VPOS) of the Milky Way. Less than one out of several thousand galaxies should contain such an extreme satellite distribution.

However, in recent years additional systems of aligned satellites have been discovered. Most notably, about half the satellites of our neighboring Andromeda galaxy lie in an extremely narrow plane. So the flattened plane of Milky Way satellites is not just a statistical outlier of a more random distribution — satellite alignments are a reality. And they require an explanation.

One possible scenario involves a second formation scenario for dwarf galaxies. Instead of forming early in the Universe as the fundamental building blocks of larger galaxies, dwarf galaxies can also form from the debris of colliding disk galaxies. Along the tidal tails expelled in such collisions groups of new, second-generation tidal dwarf galaxies can form. Because these share similar positions and velocities, they naturally result in correlations reminiscent of the observed satellite planes. In addition to potentially solving the problem of correlated satellite galaxies, these tidal dwarf galaxies have other unique properties — in particular, they should be the only galaxies free of dark matter.

Whether dwarf satellites reside in primordial dark matter halos or are instead formed as tidal debris is a critical test of our cosmic paradigm. Over the next several years, with the support of a new \$300,000 research grant to Professor **Stacy McGaugh** from the Templeton Foundation, Pawlowski and Lelli will work with McGaugh to test the predictions of this collision-induced galaxy formation model. Ironically, observing that tidal dwarfs are indeed free of dark matter would be one of the strongest confirmations of the existence of dark matter, as it would confirm the dynamical filtering that segregates dark and luminous matter in tidal interactions. If instead these dwarfs persist in showing mass discrepancies, one may question the law of gravity. If modified gravity rather than dark matter is at the root of the problem, the apparent need for dark matter will persist even after tides should have stripped it away.



*The bright blue knots in the tail of the interacting galaxy Arp 118 may represent dwarf galaxies in formation (STScI)*

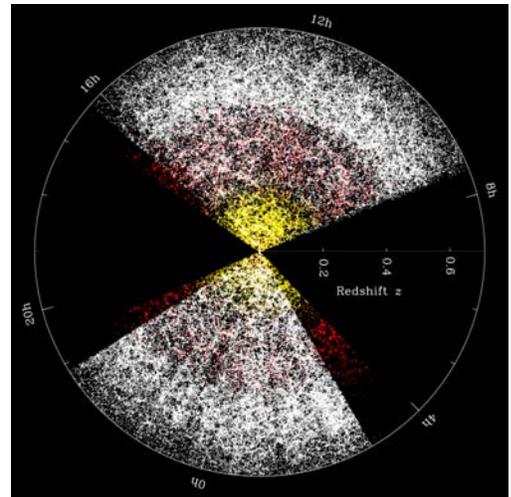
# Research Notes

## Clustering of Bright Galaxies in the Universe

The nearly completed SDSS-III BOSS survey is measuring three-dimensional positions of more than a million luminous galaxies to great depths over a quarter of the sky. As can be seen in the image, the new BOSS galaxies probe a much larger volume of the Universe compared to earlier SDSS data, making it the largest galaxy redshift survey to date, and allowing for detailed studies of the spatial distribution of these massive galaxies.

Professor **Idit Zehavi** and her collaborators at the University of Utah, including recent postdoc **Hong Guo**, have comprehensively studied the clustering properties of galaxies in this new survey, and their dependence on the galaxy's color, luminosity and redshift. They have developed a novel method to accurately measure the 3D galaxy clustering on smaller scales than was possible before, allowing for new inferences on the distribution of galaxies in their host dark matter halos. Such studies help characterize the large-scale structure in the Universe, and improve our understanding of the relation between galaxies and dark matter and the complex picture of galaxy formation.

Most recently, Zehavi and colleagues have been analyzing BOSS measurements of so-called redshift-space distortions, a distinct anisotropy pattern in the clustering of galaxies due to their local motions. One intriguing new result that have come from modeling the redshift-space distortions of these massive galaxies is that the galaxy motions differ from those of the underlying dark matter and that the central galaxies are not at rest with respect to their host halos. This provides further insight on how galaxies form and merge within the halos and can potentially impact varied galaxy formation and cosmological studies.

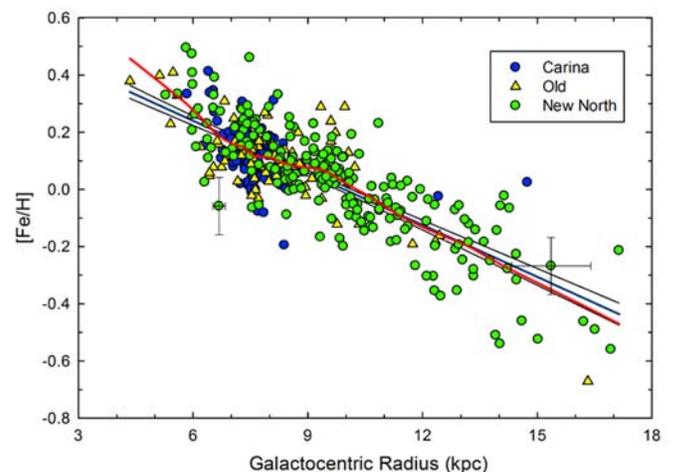


*The distribution of BOSS galaxies (in white) in a slice from the survey, relative to previous SDSS data (main sample galaxies in yellow and luminous galaxies in red).*

## Stellar Abundances in the Milky Way

The study of galactic evolution comprises a cornerstone of research in the CWRU Department of Astronomy. While one often thinks of the assembly of both luminous and dark mass as the emphasis in galaxy evolution, there is another equally important aspect. This is the subject of chemical evolution in galaxies; i.e., the building of the chemical elements. The chemical composition of stars is the research focus of Professor **Earle Luck**. His work related to galactic chemical evolution has focused on the end point of chemical evolution in the Milky Way; that is, the current abundances of the chemical elements in the Galaxy, and their spatial distribution. The importance of these studies is that they provide boundary conditions that models of chemical evolution must satisfy.

The question of how one determines the current status of abundances in the Galaxy leads to a consideration of possible probes. A probe must have a reliable distance estimate, be capable of being observed at distances of 10 kiloparsecs or more, be amenable to abundance analysis, and have an age limited to a fraction of a gigayear. These requirements eliminate most stellar candidates except for Cepheid variables. Cepheids are young massive stars, are primary distance indicators, and yield reliable abundances for many elements.



*The gradient in [Fe/H] for 398 Cepheid variables. The blue line is a simple least squares fit to the entire dataset which yields a gradient  $d[Fe/H]/dR_G = -0.062 \text{ dex kpc}^{-1}$ .*

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Over the past fifteen years, Professor Luck has assembled a database of high-resolution high signal-to-noise Cepheid spectra that encompasses about 75% of the known galactic Cepheids. With help from primary collaborators **Sergei Andrievsky** (Odessa National University) and **David L. Lambert**, (University of Texas); these data have been used to derive 1- and 2-d maps of chemical composition in the “local” area of the Milky Way. The galactocentric radial distribution (a 1-d map) shows that elements as typified by iron show a decreasing abundance from a galactocentric radius of about 3 kpc out to the outer radius of the Galaxy at about 16 to 18 kpc. The 2-d maps show that at any particular radius from the galactic center, the stars show no variation in abundance as a function of azimuth. Additionally, there is essentially no variation from element to element in the derived gradients. These results place strong constraints on element production and subsequent mixing in the interstellar medium. The future of such studies awaits better distances. Hopefully the wait will not be prolonged as the GAIA satellite, recently launched and now beginning commissioning operations, should satisfy this need.

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## Undergraduate Student Highlight: Sean Linden



Sean Linden

Starting in the summer of 2013, I began working with Professor **Chris Mihos** to model interacting galaxies and study the effects that different mass-ratios and orbital kinematics have on the evolution of these systems. This work transformed into my senior capstone, which focused on modeling M101’s interaction history and using that model to make predictions for the galaxy’s long-term evolution.

M101 is of particular interest because although it is a beautiful Sc galaxy with a very small central bulge, in neutral hydrogen (HI) the galaxy is remarkably lopsided in both its inner and outer disk. Recent deep imaging of M101 by Professor Mihos and his collaborators have identified two new optical features in the outer regions of the galaxy. One in particular, the NE Plume, has a B-V color that is indicative of recent star-formation, when compared to the integrated color of the entire disk. One of the questions we wanted to answer was whether or not this recent star-formation was caused by a tidal interaction with one of M101’s companions, either NGC 5477 (a small

satellite galaxy orbiting M101) or NGC 5474 (a larger but more distant companion galaxy). We also wanted to see how these encounters may be shaping the future evolution of M101’s disk.

To do this we needed an accurate dynamical model of M101 and its companions. Using N-body simulations, we were able to show that the satellite companion NGC 5477 was too low in mass to have produced the lopsidedness we see in M101, but that a more distant fly-by interaction with the more massive NGC 5474 could. From there we iterated on the initial conditions of the fly-by orbit in order to best match the velocity profile of M101, the physical separation of M101 and NGC 5474 and the projected location of NGC 5474 on the sky.

Our best-fit model showed us that the interaction between M101 and NGC 5474 was fairly retrograde, and that NGC 5474 likely passed through M101’s disk at a distance of 5 kiloparsecs approximately 250 million years ago. The timescale of our best-fit model also suggests that the recent star formation in NE plume is a direct result of the tidal interaction with NGC5474. This work was complemented by a trip out to Case Western’s Burrell Schmidt Telescope where Professor Mihos, CWRU astronomy grad student **Aaron Watkins**, and I took narrow band H $\alpha$  mages of M101 for Aaron’s PhD thesis studying the faint outskirts of near-by galaxies. —Sean

*Sean heads off this fall to start graduate studies in the astronomy department at the University of Virginia.*

## We want to hear from you!

Let us know about your job changes, awards, honors and life events. Please email your news and contact information updates to [dept@astronomy.case.edu](mailto:dept@astronomy.case.edu).

# Graduate Student Highlight: Jay Franck

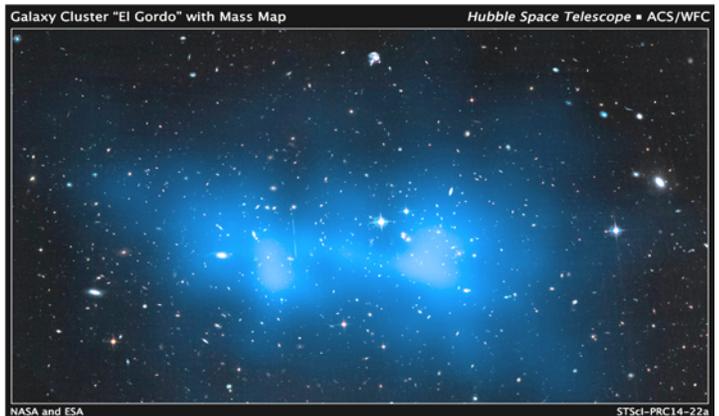


Like many astronomers, I am fascinated by the “big picture” questions. We have an advantage over other scientific disciplines that are limited to the current epoch to address fundamental questions on natural phenomena. Astronomy utilizes the finite speed of light to study the cosmos as it existed in the past; the farther away you look, the longer back in time you see.

Professor **Stacy McGaugh** offered to work with me on a project to identify distant clusters of galaxies, a rapidly growing field. These galaxy structures are so distant, we observe them as they were 10 billion years ago, when the Universe was a mere 4 billion years old. This is a snapshot into the time period in which galaxy clusters are assembling themselves, and this stage of development enables us to piece together how galaxies and groups of galaxies form and change over time. I am also interested in how massive these groups are, as our current understanding of cosmology dictates how rapidly clusters can grow.

To identify these potential clusters, we first look for very distant quasars, which are galaxies that host a supermassive black hole and output incredible amounts of energy in the form of radio waves. These host galaxies are typically massive and are usually surrounded by a number of smaller galaxies, and so we use them as sign-posts for early clusters. We then image the regions surrounding these quasars using near-infrared light, as light emitted by these galaxies in the optical (i.e. what you can see with your eye) is redshifted into the infrared by the expanding universe during its long travel time.

These images can provide some indication of a potential cluster if you observe more galaxies surrounding the quasar than you would if you pointed your telescope at a random spot. However, more observations are needed to establish if these are truly structures or just chance projections on the sky. In August I went to the Combined Array for Research in Millimeter-wave Astronomy (CARMA) to confirm if the galaxies I am analyzing are in clusters, and if they are, how massive are these groups. As the number of confirmed distant clusters increases, they provide clues as to the amount of dark energy and dark matter that constitute our Universe, as well as the processes that form the structure we see. —Jay



*Hubble Space Telescope image of an extremely massive cluster at a redshift of  $z=0.9$  (Menanteau et al. 2012), nicknamed 'El Gordo' because of its large size for its age.*

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## Summer Research Students

Each summer many of our undergraduate astronomy students work with faculty sponsors on a variety of research projects.

**Andrew Loach** (2016) worked with Chris Mihos searching for variable stars and transient objects in a decade's worth of imaging from CWRU's Burrell Schmidt telescope.

**Grace Olivier** (2016) won a university research award to work with Heather Morrison using Sloan Digital Sky Survey photometry to infer the age of the Galaxy's thick disk.

**Greg Tobar** (2016) worked with Earle Luck to develop an improved method for determining spectral line strengths in dwarf stars, using a combination of theoretical modeling and observational data.

**Kate Bush** (2017) traveled to Kitt Peak with Paul Harding to work on upgrades to the Burrell Schmidt and take photometric data to identify metal poor red giant stars in the Kepler field.

# Frontiers of Astronomy Lecture Series

Since the 1920's, CWRU Astronomy has sponsored the Frontiers of Astronomy public lecture series. These free talks are presented at the Cleveland Museum of Natural History; the Cleveland Astronomical Society and the Cleveland Museum of Natural History are co-sponsors, along with the support of the Arthur S. Holden, Sr. Endowment.

If you are in the Cleveland area, please join us for these free public lectures — last year we had more than 1,800 people in attendance! See the schedule below and check out our website [astronomy.case.edu](http://astronomy.case.edu) for more information.



*Cleveland Museum of Natural History*

Oct 16, 2014	Edo Berger (Harvard)	Gamma-Ray Bursts: The Biggest Explosions Since the Big Bang
Nov 13, 2014	Sarah Ballard (Washington)	Directions to the Nearest Alien Earth-Like Planet
Dec 11, 2014	Joshua Frieman (Fermilab)	Probing the Dark Universe
Mar 5, 2015	Volker Bromm (Texas)	Stars and Galaxies at the Dawn of Time
Apr 16, 2015	Allison Sills (McMaster)	Stellar Mergers and Interactions: Yes, Virginia, Stars Do Collide

## Chair's Space



*Professor Chris Mihos*

“Strategic Planning” — so often those words strike dread into the hearts of the academic community. Visions immediately spring to mind of endless meetings, bureaucratic doubletalk, and long-winded reports destined to collect dust. But done properly, the planning process can be a useful one, helping to shape both ambitious goals and realistic expectations. In some ways, a strategic plan is like a research proposal: it helps clarify the important issues and gives a touchstone to help guide your actions when the barrage of everyday demands threatens to crowd out the “big picture” efforts.

This fall, we will begin updating our strategic plan for the future of CWRU Astronomy. Looking back on our previous plans, they had many successes. We wanted to grow the department, and we did, bringing two new faculty members over the past several years. We wanted to grow the graduate program, and again we did: from one student in 2005 to six students last year. Of course, not every

goal has been met: while the Burrell Schmidt continues to be our workhorse telescope, a major challenge continues to be our need for access to larger telescopes with a wider variety of instrumentation.

As we start this new planning process, several guiding principles will be critically important. First, we must continue giving our students an excellent education, not just in astronomy, but in the broader arena of critical thinking and technical problem solving. Not all our students will go on to be research astronomers — indeed, many won't. Some will go into related technical fields such as data science or information technology, some into science outreach and education, and others will go in entirely new directions unrelated to science and technology. Our curriculum and mentoring must prepare our students for the diverse paths they will walk.

Second, our plan must also recognize that astronomy research is changing fast. The era of big data and large research collaborations is upon us, and we must look for opportunities to partner with other universities and institutions on research resources. At the same time, astronomy has a rich history of individual creativity and contribution that has led many of us into this field; we want to preserve that aspect of our research program.

And finally, our plan must recognize growing financial constraints. Without sacrificing our ambitions, we must also make a plan that we can execute. It's a complicated mixture of aspiration, responsibility, and reality. As we take on this planning process, we welcome your thoughts and suggestions on how we can keep CWRU Astronomy at the forefront of scientific research and education. — **Chris**

# Alumni Updates

**Bob McMillan (BS 1972)** went on to get his PhD at the University of Texas at Austin in 1977. Since 1980 he has been chasing asteroids that might hit the Earth. He is the Principal Investigator of the Spacewatch Project that uses telescopes on Kitt Peak to search for asteroids and update knowledge of their orbits using astrometry with CCD imaging detectors. Bob deeply appreciates the solid education he got at Case and uses the skills in observing, scientific writing, spherical trigonometry, and celestial mechanics he learned from Profs. Pesch, Stephenson, and McCuskey. Integrity, diligence, precision, and dedication were taught at the Warner and Swasey Observatory to both undergrads and graduate students, who often attended the same upper-division astronomy classes. McCuskey's watchwords that success "depends on the constant application of pressure" applied much to the agony of students at Case, but has stood Bob in good stead for 35 years in the competition for soft money.



*Bob McMillan*

Bob has been happily married since 1980 to Gloria, an artist and writer in Tucson, and has a son who now works in an architectural firm in Los Angeles.



*Amanda Kepley*

**Amanda Kepley (BS 2002)** loves big telescopes and messy galaxies. She is currently an NRAO postdoctoral fellow at the Green Bank Telescope, the world's largest, fully-steerable radio telescope. Starting fall 2014, she will contribute to early science commissioning for ALMA, the world's most sensitive millimeter/submillimeter telescope, as a postdoctoral fellow at the North American ALMA Science Center. Her research investigates how stars form in galaxies that have lower masses, lower metallicities, and much higher star formation rates than found in spiral galaxies like the Milky Way. Her recent work showcasing the deepest map ever of the star-forming gas in the nearby galaxy M82 was published earlier this year in *Astrophysical Journal Letters* and featured in an NRAO press release.

## The Whirlpool Revealed

As part of his PhD thesis studying the faint outskirts of nearby galaxies, CWRU Astronomy graduate student **Aaron Watkins** has used the Burrell Schmidt to produce an extremely deep image of M51, the Whirlpool Galaxy. With a limiting surface brightness of  $\mu_B \sim 30$  mags/arcsec<sup>2</sup> (nearly 1000x fainter than the dark night sky), this image traces the faint tidal features around the galaxy out to a distance of 20 arc minutes, or nearly 50 kiloparsecs in length. These tidal tails were formed during the collision of the galaxy pair several hundred million years ago. Working with collaborators **Chris Mihos** and **Paul Harding**, Watkins is using the morphology and colors of the tidal features to help constrain evolutionary models of the M51 system.



*Watkins, Mihos, and Harding 2014*

# Halloween Pumpkin Carving!



Halloween brings our annual Astronomy Department pumpkin carving event. For Halloween 2013, we had carvings of the giant Virgo elliptical galaxy M87, the International Space Station, outer space aliens, Star Trek logos, and a pair of pumpkins battling it out between Cold Dark Matter and modified gravity theories.

Inspired by Professor **Stacy McGaugh's** new course on dark matter, our students even managed to carve up a pumpkin (right) illustrating the difference between flat galaxy rotation curves and those expected from normal Newtonian gravity without dark matter. Scary, indeed!



## Support the Department of Astronomy

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Sean Parker Photography

*Moonset at the Burrell Schmidt (courtesy Sean Parker)*