Research Program: Current Work and Future Directions

Since arriving at MSU four years ago, I have established a well-funded and productive research group, currently comprised of three postdocs, two graduate students, and numerous undergraduate researchers. I won a Packard Fellowship (the first to an MSU faculty member in 20 years) and obtained grants as PI from the NSF and NASA. I have published 89 refereed papers since coming to MSU (44 in the last two years), including 8 as first author. I am also the most productive current user of the SOAR 4-m telescope, with 21 papers published over the last three years. My work uses novel observational strategies spanning the electromagnetic spectrum to tackle astrophysical problems in the local universe, with an emphasis on understanding the formation and evolution of black holes and neutron stars. Here I summarize my principal research efforts since coming to MSU and my expected future directions over the next few years. I also give citations to my own recent papers, when relevant.

Compact Objects in Globular Clusters: I am leading an international collaboration that has revealed a new, unexpected population of black holes in some of the densest environments in the local Universe, with profound implications for how we discover black holes and for sources of gravitational waves. My black hole hunting grounds are globular star clusters—dense, gravitationally bound systems with typical masses $\sim 10^5$–10^6 solar masses ($M_\odot$) and ages nearly as old as the Universe itself. Globular clusters are unique environments for the study of compact objects that are the endpoints of massive stars: neutron stars and black holes.

The Problem: Except for the small subset of neutron stars observable as radio pulsars, these compact objects are challenging to study when in isolation. However, when they are located in a binary system with another star, they can become observable as X-ray binaries as matter from the secondary star flows toward the compact object and forms a hot accretion disk. This disk can be studied at optical and X-ray wavelengths, and emission from jets associated with the accretion flow are visible at radio wavelengths.

While globular clusters make up only $\sim 0.1\%$ of the stellar mass in the Milky Way, about $\sim 10\%$ of known X-ray binaries are located in globular clusters, showing that the formation of X-ray binaries is enormously enhanced in clusters. The reason is dynamical formation of binaries in globular clusters—outside of clusters, stars rarely interact with one another, and the only X-ray binaries are primordial, in which the progenitor star of the neutron star or black hole was born in a close binary. But inside a cluster, due to the high central stellar densities, compact objects can obtain new companions through gravitational interaction, thus creating new X-ray binaries.

In the Milky Way field, significant populations of neutron star and black hole X-ray binaries are both known, consistent with the expectation that stars with initial masses between ~ 8 and $25 M_\odot$ should mostly produce neutron stars, while those with initial masses above $25 M_\odot$ should mostly end their lives as black holes. However, all of the brighter X-ray binaries in globular clusters have been observed to have neutron star primaries rather than black holes (determined through periodic X-ray bursts that occur on the surfaces of accreting neutron stars, due to the accumulation of matter and resulting thermonuclear runaways).

This observed lack of black hole X-ray binaries in globular clusters was explained as follows: since the black holes are much more massive than the typical cluster stars, the black holes will tend to sink toward the cluster center. There they will form a subcluster that is dynamically segregated from the rest of the globular cluster and unstable to runaway collapse. During this collapse, many black hole–black hole binaries will be formed, and interactions between the binaries will eject practically all black holes, leaving behind at most one black hole (or black hole–black hole binary) at the present day.

Among the less luminous X-ray binaries, it is very difficult to separate those with neutron stars from those with black holes on the basis of X-ray observations alone (at low accretion rates, the neutron stars undergo bursts infrequently), but it had been assumed for decades that these too were mostly neutron stars, with no black holes. However, radio continuum observations offer a plausible way to distinguish between these objects. Black holes accreting at relatively low rates universally show radio continuum emission from compact jets glowing through synchrotron radiation, and this radio emission is correlated with the X-ray emission. Some neutron stars also show radio emission, but at a fixed level of X-ray emission, the radio emission from neutron stars is orders of magnitude below that of black holes. Thus, a a comparison of X-ray and radio luminosities offers a useful way to distinguish between the two types of objects.

My Solution: The recently upgraded Very Large Array (VLA) now has sufficient sensitivity to detect even faint black holes in Milky Way globular clusters through radio continuum observations. Toward the end of my postdoctoral fellowship, I initiated a pilot program with the VLA to use radio data to study compact objects in a small sample of globular clusters ([redacted] In one of these sample clusters, M22, I discovered two radio sources with properties consistent with being accreting black holes. Soon after my arrival at MSU, I published this result in Nature ([redacted]

After this success with the VLA pilot program, I had a Large Program with the VLA approved as PI to perform a systematic radio continuum survey of 28 globular clusters. I also wrote a successful proposal with collaborator [redacted] to observe southern clusters not visible to the VLA with the Australian Telescope Compact Array, giving a total sample of 50 clusters. All of the data for this program have now been taken. The reduction and analysis is being led by my graduate student [redacted]; this program will form the core of her Ph.D thesis. She has found at least 14 additional candidate black holes in our sample, and is close to submission of her first paper on a candidate in the cluster M10. In addition, we have already published black hole candidates in the clusters M62 ([redacted] and 47 Tuc [redacted]

Significance: My team's discoveries have prompted theorists to revisit their models of black holes in dense stellar clusters, and using the most recent simulations, several groups now argue that significant numbers of black holes ($\sim$10 to hundreds per cluster) can be retained until the present day. My discovery that at least some globular clusters *do* contain black holes has wide implications:

- It is now clear that globular clusters are important hunting grounds for stellar-mass black holes;
- Dynamical interactions in globular clusters can lead to the formation of black hole–black hole binaries observable as gravitational wave sources. One or both of the black hole–black hole binaries detected in the last year by Advanced LIGO may have formed in globular clusters;
- Black holes in globular clusters offer good tests of the physics of low-luminosity accretion;
- Globular clusters likely offer a less biased view of the black hole mass function than the field.

Future: This work was the basis of the five-year Packard Fellowship that I was awarded last year, and which will support my group's work in this area in the coming years. In 2013 I was awarded an

NSF grant as PI to support this radio survey, and have also been awarded NASA funds associated with the X-ray followup of candidate black holes discovered in some clusters. Given the central relevance of this work to gravitational wave sources, I expect here to be expansive scientific and funding opportunities associated with this survey and its follow-up work.

Galactic Compact Binaries as γ-ray Sources: With MSU's guaranteed access to the SOAR telescope, I am discovering new compact objects and characterizing their formation and evolution.

The Problem: A significant number of the GeV γ-ray sources newly discovered by the *Fermi* mission cannot be easily classified into a standard source class with the available data. The vast majority of these unidentified *Fermi* sources are likely to be either active galactic nuclei (if extragalactic) or non-accreting millisecond pulsars (if Galactic), but it is possible that entirely new classes of γ-ray sources exist. For example, *Fermi* recently discovered that most classical novae—thermonuclear runaways on the surfaces of white dwarfs—produce γ-rays through internal shocks in the nova explosion. Even among the known source class of millisecond pulsars, the discovery of new systems can address key unsolved questions, such as the maximum mass of neutron stars.

My Solution: I am leading a program of optical spectroscopic follow-up of southern unidentified *Fermi* sources as my central science using the SOAR telescope. In many cases, the candidate counterparts are identified as variable stars, so this program can be viewed as doing precursor science for the Large Synoptic Survey Telescope.

While many objects we have observed are distant active galactic nuclei as expected, we have also discovered a number of less-common sources. For example, we have found a novel class of millisecond pulsar binaries with giant companions, predicted to exist by theories of millisecond pulsar formation but never before observed. The first of these, 1FGL J1417.7–4407 ([redacted] is included as a preprint in this packet, and we have identified two other members of this new class.

The most recent discovery from this SOAR program is of a γ-ray bright eclipsing low-mass X-ray binary ([redacted] Few low-mass X-ray binaries show total eclipses (which allow a determination of the inclination and thus precise component masses), but remarkably, this system also shows a γ-ray eclipse—the first observed in a low-mass X-ray binary. Further study of this system holds promise for determining the unknown origin of the γ-rays in accreting low-mass binaries.

Significance and Future Directions: This program continues to be productive, with the discovery of both new binaries and spectroscopic follow-up of known binaries with scant data. This observing program is well-matched to SOAR's capabilities and, as noted above, is a clear precursor for science with the Large Synoptic Survey Telescope. I have already obtained grant support from both NASA's *Fermi* Guest Investigator Program and *Chandra* for this program. I expect it to be scientifically fruitful going forward, with opportunities for both serendipitous discoveries and continued funding.

Ultra-Compact Dwarfs: I am leading efforts to characterize this new class of galaxies and search for supermassive black holes within them (note that supermassive black holes found at the centers of galaxies have masses $\gtrsim 10^5 M_\odot$, rather than the $5-100 M_\odot$ expected for stellar-mass black holes that were discussed in the earlier section within globular clusters).

The Problem: Radial velocity studies of bright, compact objects around massive galaxies over the last $\sim$ 10–15 years have turned up a new class of stellar system. Dubbed "ultra-compact dwarf" galaxies, these are stellar systems with sizes and masses intermediate between those of globular clusters and compact ellipticals (sizes $\sim$ 10–100 pc; mass $\sim 10^6$–$10^8 M_\odot$; e.g., 2014, MNRAS, 439, 3808). The difference between star clusters and galaxies is that galaxies are formed within dark matter halos ([redacted]

While the least massive ultra-compact dwarfs, with $\sim 10^6 M_\odot$, are likely to be star clusters, the structural and chemical properties of the massive ($\gtrsim 10^7 M_\odot$) ultra-compact dwarfs suggest that many of these are the tidally stripped remnants of more massive progenitor galaxies. There is more at stake than the natural desire to understand these novel objects. If ultra-compact dwarfs are the remnants of larger galaxies, then they form a populous class that must be included in counts of halos in galaxy groups and clusters for comparisons to cosmological theory. In addition, there is evidence that ultra-compact dwarfs may contain a substantial population of supermassive black holes that can help constrain the formation of all central black holes in galaxies.

My Solution: While doing a larger study of a the globular cluster population of the massive elliptical galaxy M60, I discovered a new ultra-compact dwarf (called M60-UCD1). Through follow-up studies I found a dynamical mass of $\sim 2 \times 10^8 M_\odot$ but a size of only $\sim$ 24 pc. With these unusual properties, M60-UCD1 is the most massive ultra-compact dwarf, and is the densest galaxy known in the local universe. In the paper I led about this object ([redacted] also pointed out that there is an X-ray source at the position of M60-UCD1, consistent with the presence of an accreting supermassive black hole at the center of M60-UCD1. Since most galaxies other than low-mass dwarfs have central black holes, a supermassive black hole might be expected if M60-UCD1 is the tidally stripped remnant of a more massive galaxy.

In a follow-up paper led by my collaborator [redacted], we dynamically confirmed the existence of a supermassive black hole at the center of M60-UCD1 using adaptive optics spectroscopy ([redacted] With a measured mass of $2.2 \times 10^7 M_\odot$, it is $\sim$ 15% of the total stellar mass of the ultra-compact dwarf. This is consistent with the idea that M60-UCD1 had $\sim$ 99% of its stars tidally stripped away, but originally fell on the standard scaling relations for central black holes. This is the first supermassive black hole confirmed in an ultra-compact dwarf.

Significance: While M60-UCD1 is an extreme object, there are reasons to believe that ultra-compact dwarfs as a population frequently host supermassive black holes. It is observed that typical ultra-compact dwarfs have dynamical masses that are $\sim$ 50% larger than would be expected solely on the basis of their observed stars. This discrepancy cannot be explained with non-baryonic dark matter, but could be explained if typical ultra-compact dwarfs have supermassive black holes that are 10–15% of the mass of the galaxy—entirely consistent with the ratio observed for M60-UCD1.

The detection of supermassive black holes in ultra-compact dwarfs can provide a strong constraint on the formation of all supermasive black holes. Typical ultra-compact dwarfs likely originate in the tidal stripping of galaxies with stellar masses $\sim 1 - 20\%$ that of the Milky Way. The demographics of black holes among galaxies in this mass range are poorly constrained but have substantial implications for supermassive black hole formation and growth. If supermassive black holes start from more common, low-mass seed black holes (such as hypothesized zero-metallicity "Population III" stars), then most galaxies are expected to have central black holes. However, if the seed population is rarer, such as black holes hypothetically formed from direct collapse of giant gas clouds or runaway massive-star mergers in star clusters, then the occupation fraction among low-mass galaxies could be much lower.

Thus, if black holes are common among ultra-compact dwarfs, this suggests that the occupation fraction may be high generally, favoring low-mass seeds; if black holes are uncommon, then seed formation via direct collapse or runaway merger may be more likely. The confirmation that many ultra-compact dwarfs contain supermassive black holes would have large implications for the demographics of black holes in the local universe. For instance, the number of ultra-compact dwarfs with masses $\gtrsim 10^7 M_\odot$ just around the central galaxy M87 in the Virgo Cluster exceeds the number of massive black holes detected dynamically in all of Virgo over years of effort.

Future: We have now confirmed supermassive black holes in two additional ultra-compact dwarfs, with submission of the papers expected early next year. However, it will prove difficult to obtain dynamical confirmation of black holes in most ultra-compact dwarfs due to their faintness (though it is an excellent science case for forthcoming 30-meter class telescopes in the next decade). X-ray emission alone does not prove the existence of an accreting supermassive black hole, since it may also be due to a low-mass X-ray binary with a neutron star or stellar-mass black hole primary. However, radio emission from a supermassive black hole would be much brighter than from a stellar-mass black hole, and would be detectable with the VLA to large distances. I am leading the effort to obtain radio continuum data for a sample of ultra-compact dwarfs to confirm supermassive black holes, and plan to extend the effort to normal galaxies in the mass range $\sim 10^8$ to $10^{10} M_\odot$ over the next couple of years. I will also be a central member in the effort to dynamically confirm additional supermassive black holes. These activities are supported by an NSF proposal awarded last year.

Other Topics: I am involved with other fruitful research efforts, both as a leader and collaborator, which I briefly summarize here.

Continuing research lines I began as a postdoc, I am interested in several aspects of the formation and properties of globular clusters. Recently, I have focused on projects to study self-enrichment and multiple stellar populations in globular clusters, including efforts to directly measure the spread in helium abundance ([redacted] setting strong constraints on possible mass loss from clusters, and placing limits on gas retained in young massive clusters ([redacted]

I continue to work on projects that grew out of my Ph.D. thesis work on the formation of massive galaxies, with a focus on using stellar halos and their associated globular clusters to study galaxy assembly. I am a central member of the productive SLUGGS collaboration, a large photometric and spectroscopic survey of stars and globular clusters to help understand the formation of massive galaxies [redacted] Recently my work on this survey has focused on the study of the central cluster galaxy M87, with one well-cited first-author paper published in 2011 ([redacted]); I am also leading a large follow-up paper planned for submission next year.

Future: This diversity of "near-field cosmology" projects provides a wealth of funding opportunities. I was awarded an NSF grant (as co-PI) in 2015 to study massive clusters and ultra-compact dwarfs, and there are ongoing possibilities for funding from NASA for these and related projects.

Teaching Philosophy and Methods

ISP 205: I have taught five sections of the integrated science class centered on astronomy for non-majors (ISP 205; "Visions of the Universe") since starting at Michigan State. Here I describe my philosophy and methods for the class and why I believe they are effective. My primary goal for ISP 205 is to get students to see astronomy as an *example* of how science is done, with an emphasis on its dynamic nature by frequently highlighting new advances. Because astronomy is such an active field, this is possible even in an introductory class. Since this is likely the final time many of the students will encounter science in a organized setting, I aim to ensure they have a positive and engaging experience with astronomy.

In a large lecture class it is crucial to keep students actively engaged for a substantial fraction of class without the help of substantial additional personnel (ISP 205 has a single undergraduate "teaching aide" assigned). Here are my tactics. First, I use frequent personal transmitter ("clicker") questions—typically 6 to 12 per class—which incentivizes student engagement. These are done with a standard think–pair–share format, and if I don't hear enough "chatter" after a question I verbally encourage as necessary.

Second, I design and use more substantial group activities (typically 15-20 min in length, every second class) for in-depth engagement on particular issues. These are done in groups of 3-4, often require math, and gradually ramp up in complexity as the semester advances. An example ("Sample ISP 205 In-Class Group Activity") can be seen in the next section on Teaching Innovations.

Third, I tie in course material to everyday experience whenever possible—e.g., how thermal vs. spectral line emission is related to incandescent and fluorescent light bulbs; train whistles and the Doppler shift; the location of the rising and setting Sun with the seasons; the role of radioactivity in their daily lives.

Fourth, I think it's critical for the instructor to always be energetic and positive.

Finally, it is important to me that all students believe that they have the opportunity to succeed in the course. I am proud that one of my previous students nominated me for the Spirit of Ability Award through the MSU Resource Center for Persons with Disability, which is for those who "create vibrant environments that welcome, fortify, and compassionately challenge each person to reach their fullest ability."

I map out a typical lecture as follows. First I show an "Astronomy Picture of the Day", a (usually) beautiful image that illustrates some aspect of astronomy, and discuss what is shown. I next take care of any necessary announcements, and then quickly summarize the material we discussed in the previous lecture. I introduce the principal topic for the day, and usually try to start with a clicker question with a surprising answer or an anecdote. When possible, group activities are done in the middle of the lecture time. Material and clicker questions are alternated through the lecture.

A sample syllabus and final exam for ISP 205 are included in this packet.

AST 825: AST 825 ("Galactic Astronomy") is a core course taken by all graduate students in astronomy. I am currently in the middle of my second time teaching this class.

AST 825 is essentially the only course in the graduate curriculum where galaxies are discussed, so the content of the course is necessarily broad. That said, the focus on the course is using the Milky Way as a specific example for understanding how galaxies form and evolve, with an emphasis on understanding and *using* modern surveys such as the Sloan Digital Sky Survey, Gaia, and eventually the Large Synoptic Survey Telescope. Whenever possible I reference course topics to recent papers in the literature to emphasize the liveliness of the topic. At the end of the course, my goal is to have the students on firm footing to enter the literature (and seminar rooms) with confidence.

The coursework consists of five problem sets and two short talks given throughout the semester. The problem sets involve a mixture of problem types: theoretical derivations, plotting and initial analysis of data, writing short computer programs, and more involved statistical inference. The central goal of the problem sets is to hone skills and critical thinking processes that students will need for their research. The talks are on topics related to the course material of the student's choosing, and are designed to get the students not only comfortable with speaking about science but also with constructing engaging and coherent explanations of ideas. As a small graduate class, I emphasize an involved and interactive classroom.

I am not teaching the course out of a textbook, and I have developed the course plan and written every lecture from scratch.

The syllabus and first problem set for AST 825 are included in this packet.

Research Student Advising: For both undergraduate and graduate students actively working on research projects, we meet once a week individually to review progress, tackle problems as they arise, and discuss progression in projects. However, my door is also open for quick discussions when I am in the office, and many other questions can be answered in the evening over email.

For graduate students, I think it is important for them to start working on research projects as soon as possible, even though a substantial amount of their initial two years are taken up with classes. I also believe that the student must affirmatively choose their own thesis project, and I offer what I consider to be the most exciting and promising projects to my students and postdocs. I am comfortable working both with students who are committed to pursuing a research career in astronomy and those who have other goals, provided mutual expectations are clear. When I begin advising a student, I explicitly state my expectations for our work together and listen to the students goals; subsequently, I check in at regular intervals to let the student know how they are progressing, give constructive criticism, and encourage them to express their own concerns about our project or their progression generally.

I encourage the involvement of undergraduates in research early in their time at MSU, and view career mentoring as an essential responsibility. I co-wrote a guide for undergraduates to getting involved in research at both MSU and for opportunities elsewhere. My first undergraduate research student at MSU, [redacted], took the initiative to conceive a project using new SOAR data (rather than the safe data already in hand), learned how to take and reduce data from the SOAR spectrograph, and wrote an excellent thesis on her measurement of the dynamical mass of the nuclear star cluster of a nearby disk galaxy (once some supporting data have been obtained, I expect this to culminate in a refereed publication). [redacted] has gone onto to astronomy graduate school at the University of Michigan. However, I am also proud of positive research experiences with students who have not continued in astronomy. For example, my undergraduate student [redacted]raduated last year and took a job in the defense industry, and told me his research experience was a central part of his application.