Searching for binary systems among RR Lyrae variables

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Abstract of Scientific Justification (will be made publicly available for accepted proposals):

I propose photometric imaging of three globular clusters—M5, M10, and M12—using the KPNO 4-m CCD Mosaic Imager to continue the study of what is currently understood to be an unusual scarcity of RR Lyrae (RRL) variable stars’ involvement in binary systems. Despite their importance to finding distances to clusters, very few RRLs are known to reside in binary systems. This approach searches for evidence of the light-travel time effect in “observed minus calculated” (O-C) diagrams. Analysis of RR Lyrae variables in the above clusters is expected to reveal an initial sample of binary candidates for further examination as part of an ongoing study.

Summary of observing runs requested for this project

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This part of the ongoing project would observe the RR Lyrae populations of the bright, nearby globular clusters M5, M12, and M10 over two nights.
This project explores whether RR Lyrae variable stars are truly as rare in binary systems as they appear to be. As of 2014, there were only two confirmed cases of binary systems with an RR Lyrae component, despite binary systems being thought to contain roughly half of all stars (Guggenberger & Steixner 2014). A more recent study found 20 new firm candidates for RRLs in binary systems (Hajdu et al. 2015), which describes the discovery as an increase by nearly 2000% in expected RRLs from analysis of the Optical Gravitational Lensing Experiment III (OGLE-III) data, collected 2001-2009 by the University of Warsaw. The detection of more RRLs in binary systems would not only dissolve concern over what might make RRLs in particular so disproportionately absent from such systems as compared to other non-variable stars, but it would also immensely aide in the study of the physical attributes of RRLs at large (Catelan 1992), especially their masses.

Currently most of the information available regarding RRL masses comes from the “Petersen diagram” (Petersen 1973) (see Fig. 1) of double-mode RRL stars (RRd). RRd stars pulsate simultaneously in the radial fundamental overtone and the radial first overtone modes (Hadju et. al 2015), and their distribution in the Petersen (period ratio vs. period) diagram is supposed to be a strong function of the mass of the pulsating star, in addition to other parameters, such as metallicity. If the orbital parameters are determinable, though, the involvement of an RRL in a binary system offers a nearly miraculous resolution to the problem of determining its mass, which is crucial to constraining the other physical parameters on which the star’s precise period values of pulsation depend, such as luminosity, effective temperature, and metallicity (Molnár et al. 2015)—and of course, these are the features that make RRLs so useful for determining distances. This method has proven effective for establishing the physical properties, including mass, of Cepheid variables (Pietrzyński et al. 2010), which are relatively common in binary systems. Established RR Lyrae variables themselves are among the most important distance indicators to open and globular clusters via their famous period-luminosity relationships (Prša et al. 2008), so fully resolved variable stars with better mass estimates in turn result in better distances to the stars’ clusters.

After collecting the B and V images, we can determine candidacy for involvement in a binary system by examining the lightcurves of stars identified as RRab Lyr variables, subtract an empirical model of the pulsation lightcurve, and search for periodic variation in the residuals (Richard 2011). So, if we succeed in finding more RR Lyrae variables in binary systems, this offers a much easier and more accurate derivation of those RR Lyraes’ masses, helping to resolve their lightcurves and further constrain their physical parameters.
References


Figures

Figure 1. Petersen diagram (ratio of shorter to longer period vs. log of longer period) for classical Cepheids (left) and RR Lyrae stars (right) with various classes of multi-mode pulsators plotted with different symbols (Smolec et al. 2017).
Figure 2. O-C diagrams of RRL binary candidates. The O-C points (filled circles are OGLE-III data, empty circles are OGLE-IV data) are fitted with the sum of a linear period change (dashed line), and the binary orbit (dot-dashed line, shifted downwards for clarity). For each star, the OGLE ID, pulsation period, and orbital period are given on top of the upper x-axis (Hadju et al. 2015).
Technical Description of Observations

The KPNO 4m Mosaic 1.1 imager has a large field of view (35.4') and high resolution (0.26"/pixel), which allows accurate photometry across multiple bands even in a crowded field, which is crucial to this project since the stars of interest are not only in clusters, but also likely to be in binary systems. The stars in the image absolutely must be distinguishable from one another, requiring a high resolution, but the image must also contain the entire cluster, requiring a wide field of view. Since the M5 cluster has an angular size of about 17.4 arcminutes, it fits well within the Mosaic 1.1 imager's 35.4-arcminute field of view. The M10 and M12 clusters fit easily as well, with angular sizes of 15.1 arcminutes and 14.5 arcminutes, respectively.

The observations should ideally occur in June, when M5, M10 and M12 (15h 18m, 16h 57m, and 16h 47m, respectively) are all most visible in the night sky (Goldsbury et al. 2010). Given M5's, M10's, and M12's apparent magnitudes of about 6.7, 6.6, and 7.7 mags respectively (NED), the expected parameters entered into the exposure time calculator for KPNO's Mosaic imager (seeing of about 1.1, and an airmass around 1.5, 300-second integrations on a full moon) return signal-to-noise ratios of about 30,000-170,000 for five-minute exposures and 19,000-98,000 for two-minute exposures (again, seeing of 1.1, airmass 1.5, now 120-second integrations on a full moon). While a dimmer moon phase would improve the signal-to-noise, the “full” phase was selected because the signal-to-noise ratios are high enough that this project does not suffer even when the moon is full, making use of nights that would otherwise be useless to more background-sensitive projects.

Each of the three clusters would have at least a two- and a five-minute image (in each filter, to assist with bolometric magnitudes) collected between once and four times an hour in order to avoid uniform timing of exposures while still exposing frequently enough to capture the periodicity of the light fluctuations of each RRL star.

A sample of the objects to be observed includes the binary candidates established by Hadju et al. in 2015, some of which are listed below, along with the likely orbital period of the star with its binary companion as well as the duration of each candidate’s periastron approach.

Table 1. Fitted and derived parameters of a few RRL binary candidates

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<th>OGLE ID</th>
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Beyond Sigma: Exploring the Relations between Supermassive Black Hole Mass and The Properties of the Galactic Bulge

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Abstract Supermassive black holes have proven to be a universal feature of elliptical and bulged galaxies. The strength of the $M_{BH} - \sigma_*$ relation, an observed correlation between the mass of the supermassive black hole and the velocity dispersion of stars in the galactic bulge, suggests a deeper link between the formation histories of supermassive black holes and their host galaxies. Exploring the relationships between supermassive black hole mass and other dynamical and photometric properties of the host galaxy may yield additional insight into the relationship between black hole and galaxy.

We propose imaging of elliptical, classically bulged, and pseudobulged galaxies in the B,V,R filters for a complete sample of 80 galaxies. Combining our optical photometry with velocity dispersion data, and K-band infrared data from the Two Micron All Sky Survey, we will investigate the correlations between virial bulge mass ($M_v$), stellar bulge mass ($M_*$), bulge Sersic index ($n_b$), bulge central surface brightness ($\mu_0$), bulge exponential scale length ($r_\alpha$), and the supermassive black hole mass ($M_{BH}$) derived from the velocity dispersion data. We are requesting four nights on the 4m PF CCD Imager to reach a limiting surface brightness $\mu \sim 25$ mag/sec$^2$ with a $S/N = 30$ for each galaxy.

Table 1: Summary of observing runs requested for this project

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1 Scientific Justification

Ever since the discovery that a central black hole lies at the center of the Milky Way Galaxy, there has been great research studying the inner regions of galaxies beyond the Milky Way with the aims of determining whether or not central black holes are unique to the Milky Way or are truly a common feature of massive galaxies. It is now the consensus that a central black hole lurks at the center of most, if not all, massive galaxies. These central black holes can reach masses on the order of $10^6 - 10^9 M_\odot$, earning them the title "Supermassive Black holes (SMBH)" in order to distinguish them from their lower mass counterparts that often form from the remnants of stellar collapses.

Techniques to measure the SMBH mass come in direct and indirect forms. Direct methods of measurement, such as reverberation mapping, measure SMBH mass by studying the gravitational influence of the black hole on the dynamics of stars and gas in the broad-emission line region (Peterson & Horne 2004). An indirect technique for measuring SMBH mass relies on using established empirical correlations, such as the relation between SMBH mass and B-band bulge luminosity (Kormendy & Richstone 1995; Magorrian et al. 1998).

Due to observational biases and systematic errors such as gas extinction in the $M_{BH} - L_{Bul}$ relation, the $M - \sigma_*$ relation is now used more often to gauge the black hole mass of galaxies. The $M - \sigma_*$ relation is a positive correlation between the mass of the supermassive black hole with the stellar velocity dispersion of stars in the galactic bulge (Ferrarese & Merritt 2000). The relation has demonstrated remarkably low scatter, robustness in quiescent and active galaxies, and in galaxy type (Ferrarese & Merritt 2000; Nelson 2000; Batcheldor 2008). The strength of this relation hints that the formations of supermassive black holes and their host galaxies may be intimately linked. To gain additional insight into how intertwined the supermassive black hole and its host galaxy actually are will require further observation that attempts to relate $M_{BH}$ to a variety of properties of the host galaxy.

Armed with K-band infrared data from the Two Micron All Sky Survey, and stellar velocity dispersion data for a sample of elliptical and bulged spiral galaxies, we will use B,V,R imaging from the 4m: PF CCD Mosaic Imager to gather an array of dynamical and photometric properties of a sample of elliptical, bulge, and pseudobulge galaxies, and then we will investigate how
well these properties correlate with supermassive black hole mass.

The dynamical properties of the host galaxy, in addition to $\sigma_*$, will include bulge virial mass ($M_v$), and bulge stellar mass ($M_*$). We will estimate the stellar mass of the bulge from the mass-to-light ratio equation used in Hu (2009), which utilizes the bulge’s K-band infrared luminosity and the bulge’s $B-V$ color, $\log(M_*/L_K) = 0.135(B-V) - 0.356$. We will find our estimate of the virial mass $M_v$ from $\sigma_*$ in the galactic bulge. With these mass estimates, we will be able to correlate supermassive black hole mass with the virial and stellar masses of the their host bulge, and compare the strength of the relation with previous attempts done in the past (Kormendy & Richstone 1995; Marconi & Hunt 2003; Hu 2009).

Building off the work of Erwin et al (2002), we will investigate the relationship between the supermassive black hole and the global structure of ellipticals and bulges in the R-band. The photometric properties of the host galaxy include its Sersic index ($n$), central surface brightness ($\mu_0$), and bulge exponential scale length ($r_e$). The light profiles of ellipticals will be modeled using a Sersic $r^{1/n}$ profile, which will yield fitted values of the Sersic index $n$, $\mu_0$, and $r_e$. For bulged galaxies, we will use the modified Sersic profile that models the light profile by an $r^{1/n_b}$ profile plus an additional exponential term that models the surrounding disk (Erwin et al 2002; Fisher & Drory 2008). This will yield a Sersic index $n_b$, an central bulge central brightness, and effective scale length for the bulge. The possible links between supermassive black hole mass and photometric properties have been investigated before, with Erwin et al (2002) finding a tight relationship with bulge sersic index in 30 elliptical and bulge galaxies, and Graham et al (2001) finding a link with bulge light concentration $C_{r_e}$ in 21 galaxies. The reliability of this relation is disputed by Beifiori et al (2012), who show that photometric properties such as $n_b$, $\mu_0$, and $r_e$ are poor tracers of $M_BH$ mass on a much larger sample of galaxies ($\sim 140$). With our R-band imaging, we will probe the relation between $M_BH$ and the photometric properties of the host galaxy with a large and diverse sample of galaxies, hopefully putting a more definitive stance on the status of the $M_BH - n_b$ relation.

The establishment of a correlation between sersic index $n_b$ and $M_BH$ would also have great practical benefit for the study of supermassive black holes because it could potentially allow researchers to get a reliable estimate of $M_BH$ from the galaxy’s photometric properties, which is often less arduous than trying to acquire accurate stellar velocity dispersion measurements in the galactic bulge, especially at high-redshift.
Figure 1: The bottom graph displays the $M_{BH} - \sigma_*$ relation for 21 elliptical and bulge galaxies studied by Erwin et al (2002). Above we see the correlation they find between $M_{BH}$ and Sersic index $n$ from photometry done in the R-band. The dark circles and open circles represent elliptical and bulge galaxies respectively.

References


2 Technological Description of Observations

To thoroughly address the question surrounding the relation between $M_{BH}$ and the chosen dynamic and photometric properties of the host galaxy, we require a large enough sample of galaxies of diverse morphology. The 80 galaxies proposed for our sample have morphological bulge classifications ranging from elliptical, classically bulged, and pseudobulged galaxies. Classically bulged galaxies have morphology similar to elliptical galaxies in their inner regions, while pseudobulged galaxies share many common spiral features, such as the presence of bar-like structures and kinematics dominated by rotation (Fisher & Drory 2008). For the purposes of our survey, we will classify galaxies in our sample as classically bulged or pseudobulged based on the bimodal distribution of bulge sersic index $n_b$ found by Fisher and Drory (2008), where pseudobulges have $n_b \leq 2$ and classical bulges $n_b \geq 2$. $M_{BH}$ used for each galaxy will be the mass derived from the $M_{BH} - \sigma_r$ relation. The low-scatter of the relation, and the durability of the relation regardless of galaxy core activity and morphology allows us to make confident estimates for $M_{BH}$ used for comparison in our survey.

We seek to image each galaxy down to a limiting surface brightness of $\mu \sim 25$ mag sec$^2$ in the B,V,and R filters to a S/N $\sim 30$ to get high quality photometry on the bulge structure of the galaxy and its surrounding disk. A higher S/N in B and V will also give us lower scatter in our color term, which is important in calculating a precise estimate for $M_\ast$.

Both the 4m PF CCD Mosaic Imager and the 0.9m HDI Imaging Camera allow us to reach our limiting surface brightness in short order, but only the 4m PF CCD Mosaic Imager allows us to image down to our limiting surface brightness, and maintain our desired S/N of 30. Using the 4m Mosaic Imager, we get exposure times of 100 sec, 117 sec, and 213 sec for B,V, and R respectively when the moon is at half moon for a single galaxy. For a sample of 80 galaxies, this amounts to more than 9 hours of total exposure time. If we include an additional 10 minutes per galaxy in order to calibrate the data, collect zeropoints, and move the telescope to view each object, then we reach a total time of approximately 23 hours of observation time. For this, we are requesting four nights of observation to collect our whole sample of targets, and properly calibrate our galaxy imaging. Due to the abundance of elliptical, classically bulged, and pseudobulged galaxies that are visible year round, there are no restraints on our sample from declination or right ascension, so our observations are not limited by time of year.
Color Magnitude Diagram and Stellar Properties of Leo T

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**Abstract of Scientific Justification:**

I propose deep imaging of the dwarf satellite galaxy Leo T to study its stellar population and create a color magnitude diagram (CMD) from the results. Leo T is a fascinating dwarf satellite galaxy in that it is in a transitional stage between dwarf irregulars and dwarf spheroidals; it contains neutral hydrogen gas and has recent star formation, but is extremely small and faint, being the faintest known galaxy with active star formation. With the use of the Kitt Peak 4.0-meter telescope I plan to apply isochrone fitting to the CMD to retrieve stellar properties of Leo T, such as the age and metallicity of its population, star-formation history, and recent star-formation rate.

Previous research on this galaxy has had shorter exposure times, leading to large photometric error in regions such as the top of the main sequence and red clump. To reduce these errors, I am requesting up to 4 nights on the telescope to resolve stars up to a magnitude of 25 with a signal-to-noise ratio (S/N) of 25. These reduced errors will provide more accurate measurements of the stellar properties of Leo T, which can then be extrapolated to reveal information on the evolution of similar galaxies in the Local Group that have low interaction with their larger host galaxies.

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**Summary of Observing Runs Requested for his Project:**

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*A fourth night would be required in March due to less time each night with dark skies at an airmass of less than 1.5. This will be further explained in Technical Description of Observations.
Scientific Justification:

Dwarf satellite galaxies are small galaxies that are gravitationally attached to a larger host galaxy. They are extremely faint, with metal abundances commonly well below [Fe/H] = -1 (Simon & Geha 2007). Some of the dwarf satellites are dwarf spheroidals, which are very metal poor and faint even with among other dwarf galaxies; in fact, they only started being discovered since the turn of the new millenia with recent deep imaging surveys of the night sky, such as the Sloan Digital Sky Survey (SDSS) (Simon & Geha 2007). Many of these galaxies are devoid of gas, being fossils from the era of reionization or casualties of strong gravitational interactions with the Milky Way. Despite the overall lack of recent evolutionary activity in many of these galaxies, they act as indicators of how stars and galaxies formed in the early Universe.

One distinct dwarf satellite worth looking at is Leo T. Leo T (shown in Fig. 1) was discovered by SDSS in 2006 and sits 420 kpc away from the Milky Way (Weisz et al 2012). Leo T is an interesting dwarf satellite galaxy in that it has characteristics in common with galaxies that are very different than one another. Like other ultra faint dwarf galaxies, it is relatively metal poor with a metallicity of [Fe/H] ~ -1.7 and is dark matter dominated with a mass-to-light ratio of 138 M\textsubscript{sun}/L\textsubscript{sun} (de Jong et al 2008; Simon & Geha 2007). With this amount of dark matter domination and an overall metallicity this poor, one would expect Leo T to be another standard dwarf spheroidal galaxy - effectively devoid of hydrogen gas and little or no chance of having any meaningful star formation. This assumption would be incorrect; despite its size and overall brightness, Leo T appears to have large amounts of hydrogen gas and noticeable recent star-formation history, even going to as recently as several hundred million years ago (de Jong et al 2008). As the T in its name would suggest, Leo T is a transitional type object - it is in between a dwarf spheroidal and a dwarf irregular, sharing qualities from both without properly fitting into either classification (Clementini et al 2012). Galaxies like this are intriguing because they allow us further insight into how smaller galaxies form and evolve. Leo T’s distance from the Milky Way could play a part as to why it still has as much gas as it does; its unique classification and unique location can give us more information on the evolution, star formation history, and stellar properties of galaxies this size. Given the fact that Leo T is still undergoing stellar formation, the information that can be gained covers a broader range of time than is normally seen from galaxies of this scale.

Most of these properties can be determined from getting a color magnitude diagram and applying isochronal fitting to the results. An example of the results I am trying to find can be found in Fig. 2, a CMD of Leo T from de Jong et al 2008 taken with the Large Binocular Telescope. A robust method of analyzing data from a CMD is using a Hess diagram, which takes the color-magnitude diagram of stars in a galaxy or cluster and overlays isochrones of varying age and metallicity
(Bonatto et al 2015). The purpose of overlaying the isochrones is to find the lines that fit best with the populations in the CMD by checking which lines intersect with the dense regions of the CMD. Finding fitting isochrones helps give more accurate age and metallicity estimations for different populations in a galaxy, presenting a clearer history of star formation and evolution. Isochrones for Leo T can be seen in the middle graph of Fig. 2 - the dashed lines represent isochrones for 400 Myr and 650 Myr, while the solid line represents an isochrone for 10 Gyr, with each line having a metallicity of [Fe/H] = -1.7 (de Jong et al 2008).

The CMD in Fig. 2 was taken with four 5 minute exposures in both g and r - this translates to an error in the red clump of (g-r)=0.1 and an error in the upper main sequence of approximately 0.3. My observations will be focusing on getting a clear enough signal to closely observe the red clump, red giant branch, and brightest point of the main sequence of Leo T with an altogether lower error in V and I - this will require a much longer exposure time of approximately 16 hours when accounting for overhead in between exposures. The longer exposure time will potentially reduce the error in the upper main sequence caused by the low population of stars in that region of the CMD (de Jong et al 2008). This overall reduction in error will allow for more precise measurements of the distance of Leo T, the age and metallicity of its stellar population, its star formation history, and its very recent (less than 100Myr) star formation rate. This information will be valuable in multiple facets of future research; a clearer distance relation from a more accurate red clump color reading can provide constraints to the distance a galaxy of this mass can be away from a Milky Way sized galaxy while still being able to retain gas. The metallicity and star-formation history will give information regarding how the galaxy formed - this includes identifying the times large star-forming epochs occurred and determining whether or not the galaxy had a significant infall/outflow of gas over any point in its life. Lastly, the ages of stars and recent star formation rate will help to determine the fraction of percentage of young stars in the galaxy as well as help with models that predict the future of galaxies with similar parameters. In short, a deeper analysis of Leo T will help determine how dwarf galaxies in the Local Group form and evolve when not interrupted by interaction with larger host galaxies.
Figures & References:

Fig 1: 6.5’ x 6.5’ image of Leo T taken by the Isaac Newton Telescope, focused on the galactic center. It is oriented such that the northeastern region is located in the top left of the photo. The galaxy is noticeably blue due to its low metallicity and recent star formation history (Irwin et al 2007).
Fig. 2: Color magnitude diagram of Leo T taken with the Large Binocular Telescope, taken in g and r. The left image shows the features of the galaxy, such as the red clump, blue loop, and red giant branch. The very blue (g-r<0) region in the bottom left corresponds to young bright stars on the main sequence. The middle image shows isochrone fitting corresponding to various ages and metallicities. The right image is a CMD of stars within a 6’ radius from the center of Leo T to compare the relative brightness of the galaxy to, along with photometric error bars on the right (de Jong et al 2008).


Technical Description of Observations:
Leo T is a very faint, very small galaxy. It has an absolute magnitude of $M_V = -8.0$ and a half light radius of approximately 120 pc or 0.99’ (de Jong et al 2008). It is 420 kpc away from the Milky Way, making it the most distant Milky Way satellite (Weisz et al 2012). This project will require the Kitt Peak National Observatory 4.0-meter telescope to meet the signal clarity requirements. The low brightness of this galaxy means that the WIYN 0.9-meter would not be able to properly resolve the stars of Leo T in the allotted time. Due to the nature of ground based telescopes and the signal clarity I am planning to achieve, this project will primarily be focusing on the brighter sections of the CMD such as the red clump and the red giant branch.

Exposures will be done in V and I. Exposures in B and V were initially considered due to the shorter needed exposure time in B compared to I; however it will ultimately be best to work in I as the I filter is not particularly affected by bright background sky. Observations will be done to resolve individual stars with magnitudes up to 25 with a signal-to-noise ratio of $S/N > 25$; this magnitude corresponds roughly with the brightest population of the main sequence. With a signal of this clarity, V-I color will have an error of ±0.04mag and will be able to have statistically meaningful results for smaller portions of the CMD, such as the red clump seen in de Jong et al 2008.

These above parameters will require exposure times of 91.26 minutes and 697.33 minutes in V and I, respectively. Due to the long lengths needed in exposure time, they will be broken up into 20 minute exposure cycles - therefore, there will be 5 exposure cycles in V and 35 exposures in I. Breaking the exposures up into 20 minutes sections additionally allows for dithering to help account for errors in the flat field, such as cosmic-rays or bad pixels. If 4 minutes of adjustments for dithering and other general preparations is accounted for with each exposure cycle, the exposures will take 16 hours altogether.

With a right ascension and declination of 09h 34m 53.5s and +17° 03’ 04”, Leo T is best visible during the early part of the year (de Jong et al 2008). There are new moons on January 16th, February 15th, and March 16th 2018, with each having a peak airmass of 1.12, 1.04, and 1.20 respectively. Because of the relative faintness of the galaxy along with the time needed for exposures, a lunar phase below 4 is required. Observations during February would provide the best possible environment for observations, however both January and March would fit comfortably within the realm of acceptable observing conditions with the given parameters. However, a fourth night in March would be necessary to provide enough time where both dark skies and an airmass below 1.5 are present; in both January and February conditions are acceptable for longer periods each night, meaning observations can be completed within three nights. Given the 16 hour time requirement, this selection of nights allows observations to take place at least an hour after sundown and before sunrise, ensuring dark skies.
Variable Star Classification within the Globular Clusters of Coma Berenices

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Abstract of Scientific Justification:
I propose imaging of globular clusters NGC 5024 and NGC 5053. The primary goal of this imaging would be the identification of variable stars within these globular clusters. These variables would be short period variables which we can fully observe multiple periods within our observing runs. This identification will be done machine learning algorithm developed prior for classification of stars in the Large Synoptic Survey Telescope (LSST). While this algorithm has already been trained with data from the Palomar Transient Factory (PTF), I seek to apply it in real-world use cases which we would like to know how applicable to classification outside of large survey samples. In doing this, I will compare the algorithm to variable finding methods such as ISIS (Alard 2000, Conroy et al. 2012). Furthermore, with this collection of variables, I hope to study the structure of the GC’s in question. Using distance metrics determined for the variables, I wish to trace out the GC. It has been shown that the population of RR Lyrae stars craft an empirical boundary within NGC 5024. I hope to extend this trend with other variable populations found with the algorithm. I am requesting two 7 dark night runs on the 2.1m separated by period of 7 days to increase the possible types of variables which could be detected.

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Scheduling Constraints and non-usable dates
There are no such dates.
Scientific Justification:

Variable stars are a key rung in the cosmological distance ladder. By measuring their periods and amplitudes we are able to precisely calculate distances to the populations in which they live. This allows for other measurements to be calibrated to extend the range at which we can quote distances. A main goal of LSST is the discovery of new variable stars as well as more data for known variables. It will do this over the course of a 10 year survey (Ivezić et al. 2008). This survey will generate massive amounts of data to comb through, using modern data mining techniques will allow for quicker classification of sources enabling science to be done sooner on said sources. To accomplish the goal of data mining, I previously developed a machine learning algorithm using sources from PTF and classifications made by citizen scientists on a Zooniverse project. This algorithm localizes variables within a multidimensional space of features determined from the phased light curves to determine the variable type. With this algorithm I can quickly pick out a specific type of variable from the survey database and proceed to use it for other interesting science.

A similar approach to variable star location is ISIS which makes use of image subtraction and convolution to detect variables (Alard 2000). While this method works well for identification, another step is required in the actual classification of the sources in question. Additionally, the method itself gives does little to measure other features of the source. With these extra measures, we can more accurately classify variables and possibly draw better lines between types.

With these observing runs, I hope to determine if the machine learning algorithm is applicable to studies which are less extensive as LSST’s survey. I hope to find that the compute cost/time of this algorithm is not significantly higher than would be helpful for imaging say GCs or other small populations. If it is the case that using this tool does not hinder the speed at which further analysis is done then the tool could be packaged to allow for its use by the greater community. As an additional side note, the opportunity for the public to see the direct impact of the classifications done on Zooniverse may act to increase the willingness of public spending on astronomy.

In addition to testing the algorithm in real-time, I seek to map the GCs in question. The segregation of RR Lyrae types along the horizontal branch has been found in NGC 6229 (Ferro et al. 2015), NGC 5024 (Ferro et al. 2011) and NGC 4590 (Kains et al. 2015). This hints at the possibility of a stellar distribution throughout clusters. I want to use the precise measurements of distance to try a create a 3D image of what NGC 5024 and NGC 5053 appear as. Additionally, I may be able to detect structure within the cluster by showing where clumps of variables live. With this information, an understanding of the formation history of the cluster may be possible.

Conroy, K. E., 2012, JSARA, 5, 34
Experimental Design:

NGC 5024 is a globular cluster with apparent magnitude of 8.33 in V and a size of 13.0’ also in V. Similarly, NGC 5053 has an apparent magnitude of 9.96 and size of 10.5’. Both clusters exist as part of the Coma Berenices constellation, at a distance of 17.4 kpc. These objects offer a good environment in which to study well documented variables as well as identifying new ones. The 2.1m telescope is ideally suited for this program as it allows for capture of the majority of the cluster in one image but the CCD will not become saturated in too short a time. I will take short exposures on the order of a minute or two to trace out the variations of sources. While a slightly large field of view would be appreciated in order to collect the entirety of both clusters in one image, I face the problem of collecting too much light from outside of the cluster and thus disturbing classification. The time of year was chosen to allow for maximum dark sky throughout the night giving more time to take data across the period of the source.

Figure 1: A condensed version of the feature space generated by PTF sources. While this only includes 5 features, the full space includes greater than 70. Using the classifications from Zooniverse, a machine learning algorithm localized variable types to regions of this space. Shown in yellow is an example of where an RR Lyrae might live.
Determining M53 Distance Modulus with RR Lyrae Stars

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Abstract of Scientific Justification

I propose using the WIYN 0.9m telescope to tightly constrain the distance modulus of the globular cluster M53. A precise distance modulus will enable further investigations into the early history of the Milky Way and the environment of the outer halo, as well as allowing for direct physical comparisons between various globular clusters. Using established models for RR Lyrae oscillations, the absolute magnitude of each variable star can be estimated from its period and color, combining to give a distance modulus to M53 as a whole. To quantify a precise distance modulus to M53, I request three nights of observation time, one separated from the others by at least a month, on the WIYN 0.9-meter telescope. Taking V and R images of M53 through the three nights will tightly quantify the colors and oscillation periods of M53’s RR Lyrae stars. The WIYN 0.9m telescope facilitates these investigations by allowing for continuous exposures with high S/N ratios.

Summary of Observing Runs Requested

<table>
<thead>
<tr>
<th>Run</th>
<th>Telescope</th>
<th>Instrument</th>
<th>Nights</th>
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<td>HDI Imager</td>
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<td>N/a</td>
<td>Apr-May</td>
</tr>
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</table>
Scientific Justification

Globular clusters are among the oldest structures orbiting any particular galaxy, and their properties have historically been used to constrain a wide variety of theories. Many of the investigations enabled by globular studies are supported by the old, uniform stellar populations therein. The distant orbits of remote clusters like M53 prevent interactions that might stir up star formation and diversify stellar populations. Furthermore, the shared age and metallicity of the stars in a globular cluster ensure that the Hertzsprung-Russel diagram of a particular cluster has a well-defined main sequence turn-off, a useful measure of the age of a population.

The ages of stellar populations in globular clusters have historically limited the age of the universe; the universe cannot be younger than the oldest observable star, and globular clusters present a prime target for age estimates. The diversity of local stellar populations created mixed throughout the galactic disk limits the usefulness of local estimates on maximum stellar age. Globular clusters, alternatively, have low star formation rates and homogenous metallicity, and do not mix their stars with other populations (Muratov & Gnedin 2010). These simplifications have made globular clusters a choice observational restriction on the age of the universe.

Besides cosmological limiting, the old stellar populations and distant orbits of globular clusters allows for inquiries into the early history of galactic environments. Globular clusters are thought to have formed early in cosmologic time, and their old stellar populations and low star formation rates have effectively preserved information on the history of the formation of their host galaxy. Detailing distant clusters like M53 therefore enables further research into galaxy formation and the early galactic environment.

A remote globular cluster like M53 presents a unique target for investigating early properties like the metallicity of the proto-galaxy or gas accretion with respect to cosmological effects (Keller et al. 2012). Characterizing its distance modulus allows converting measurements from observational (angular size, magnitudes) to physical (absolute size, luminosity). This conversion enables the previously mentioned examinations of the early galactic environment and the globular population as a whole.

Absolute comparisons of metallicities or stellar populations between globular clusters are impeded by the wide dispersion of globular clusters around the Milky Way galaxy; distances range from a few kiloparsecs to over a hundred kiloparsecs (Laevens et al. 2014). Studies of globular clusters dealing with extrinsic properties such as luminosity or size depend on having tightly constrained distances to each globular cluster.

M53, as one of the more distant Messier-listed globular clusters of the Milky Way, has a historically uncertain distance. Various methods for determining distance to M53 give widely varied results. Though pulsar measurements (Hessels et al. 2007) have yielded a distance modulus of 16.3 magnitudes, analysis of gas clouds (McMonigal et al. 2016) gave a distance modulus of 24.6. This wide range indicates at least an order of magnitude of uncertainty in the distance to M53. By applying well-characterized RR Lyrae models to variable stars in M53, the distance to M53 can be more tightly limited, perhaps excluding some possibly erroneous earlier measures.
RR Lyrae stars are a family of variable stars, a common tool for finding distances to populations whose age makes the appearance of a Cepheid variable unlikely. RR Lyrae stars are evolved A- or F-class stars of about half a solar mass. Their luminosity oscillates with periods between 10 and 30 hours. The absolute magnitude of an RR Lyrae depends on its oscillation period and color, as in Figure 1 (Caceres & Catelan 2009). Detailed V and R luminosity trends for each star can be obtained by comparing numerous short exposures of M53, and enable use of the tight color-period-magnitude relation in the redder wavelengths. There are three main families of RR Lyrae stars (RRab, RRc, RRd), which display distinct luminosity trends and can be easily distinguished; stars that cannot be sorted should be excluded from analysis.

An old stellar population like M53 has enough RR Lyrae stars to provide tight constraints on distance modulus; each star contributes a measure of the distance modulus, so considering all stars together gives a distance to M53. Previous searches have yielded between 40 and 50 RR Lyrae variables in M53 according to the SIMBAD object database, meaning that the overall distance modulus from this research will hopefully be based on at least 40 independent measurements.

Figure 2 shows several example RR Lyrae luminosity curves in the B, V and I filters from Clementini et al. (2002). Because the different magnitudes of each star oscillate in phase and with similar waveforms, it is possible to determine the average V-R color of each star by matching V and R luminosity trends of a particular star and fitting to a theoretical model. The three distinct luminosity trends in Figure B are characteristic of the three subtypes of RR Lyrae stars. As long as RR Lyrae variables can be sorted into the families reliably, oscillation periods can be found from fitting well-characterized functions to observed trends.

The dependence of absolute magnitude on period for RR Lyrae variables necessitates continuous exposures. To constrain the period of each star, exposures of M53 must be collected repeatedly over an extended period. High S/N is desirable to resolve the occasional sharp drops in luminosity of RRA variables and to discriminate between RRb and RRcd variables.

The absolute magnitude of an RR Lyrae star is also dependent on average color. This color dependence includes metallicity effects; because RR Lyrae stars occupy a tightly limited region of the evolutionary timeline of a star, accounting for color removes the confounding effects of metallicity. Collecting V and R exposures over two observational runs allows for finding the average V and R magnitudes, and thus the average (V-R) color, of each variable star.

The proposed observing plan uses two observing runs to determine the period of each RR Lyrae star with high accuracy and precision. A primary two-night run in February or March will observe the variables of M53 in the R filter, while a second one-night run around April in the V band gives luminosity curves that can be matched to the primary curves, determining the period of any variables in M53 besides finding the average (V-R) color. RR Lyrae stars generally have a period of between 12 and 24 hours (Jurcsik et al. 2017); the observing plan allows for various sections of a luminosity trend to first be fitted, then constrained over the course of the two runs.
Figure 1: Color-Magnitude plot for a population of RR Lyrae stars, using SDSS filters without (top) and with (bottom) color corrections. From Caceres & Catelan (2009).

Figure 2: Example RR Lyrae luminosity trends for three archetypes (from top to bottom, RRab, RRc, RRd). From Clementini et al. (2002).
Observations

M53 is a distant globular cluster in Coma Berenices. Despite its relative remoteness compared to other Milky Way globular clusters, M53 is an intrinsically bright object, with a total V apparent magnitude of 7.8 (Dalessandro et al. 2012). Distance modulus measures for M53 vary from 16 to over 24, though most results indicate a value between 16 and 18. To err on the side of caution, a distance modulus of 20 is assumed to be the upper bound on the distance modulus to M53; if M53 is more distant than this, observations will have a smaller S/N and less statistical significance.

The WIYN 0.9m telescope allows for continuous exposures of M53 with high S/N in a variety of conditions. Appearing as a uniform sphere of diameter approximately 20 arcminutes, M53 is well-suited for the WIYN 0.9m telescope with a field of view of 29.2 arcminutes, and can be imaged continuously in its entirety. By these measures, the WIYN 0.9m telescope is ideal for probing RR Lyrae stars in M53.

RR Lyrae stars have an absolute V magnitude of around 0.75, and (V-R) color of approximately -0.5 (Jurcsik et al. 2017). Taking the conservative estimate for the distance modulus of M53 of 20 magnitudes, a hypothetical RR Lyrae star in M53 has $M_V = 20.75$ and $M_R = 20.25$. This star is probably significantly dimmer than in reality, but are used as limits for evaluating observing prospects.

Varying by 0.5 to 1 magnitude over a period in the V and R filters, a magnitude resolution of 0.03 is desirable to determine average colors and apparent magnitudes as well as periods for RR Lyrae stars in M53. A S/N ratio of at least 30 is appropriate to gain this magnitude resolution. Using the WIYN exposure time calculator, exposures of 15 minutes are sufficient to achieve this S/N in both the V and R filters. 15 minute exposures allow for high time resolution to effectively determine periods of variable stars; these short exposures still allow for high S/N measurements with sub-optimal viewing conditions.

The two observing runs are separated temporally to give a long baseline for constraining the period of each variable, and are also divided by filter to find an accurate measure of average colors. The first run, exposing only with the R filter, yields at least two five-hour spans with M53 above 1.5 airmasses. M53 will be observed as much as possible, with exposures lacking appropriate S/N ratios disregarded. A month later, another night-long run using the V filter both constrains the period measures of each variable and measures each (V-R) color. Because the V and R magnitudes of RR Lyrae stars oscillate in sync, interspersing different filter exposures is not necessary for this investigation.

Because of the extended schedule of the exposures to be collected and the variability in sky brightness over the course of a night, the sky brightness profile of M53 needs to be continuously updated in each exposure. Fortunately, M53 contains five well-characterized blue straggler stars, according to the SIMBAD object database. These star can characterize background contributions in the V and R filters. Each of these stars will be imaged alongside the RR Lyraes during the observation program.
References


Additional Sources

Signal-to-Noise estimates were found with the WIYN Exposure Time Calculator at http://spiff.rit.edu/richmond/wiyn/technotes/signal_wiyn09.shtml

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.
NOAO Observing Proposal

Date: November 14, 2017

Category: Resolved Galaxies

Measure the distance of M101 using a TRGB method

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Department of Astronomy, 10900 Euclid Ave, Cleveland, OH 44106 USA
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CoI: Chris Mihos  Status: P
Affil.: Case Western Reserve University
CoI: Paul Harding  Status: P
Affil.: Case Western Reserve University

Abstract of Scientific Justification (will be made publicly available for accepted proposals):

We propose deep imaging to measure the distances of two nearby galaxies M96 and M66 using the tip of red giant branch (TRGB) method. The TRGB is a highly accurate distance indicator since the absolute $I$ band magnitude at the tip shows only a very slightly dependence on age and metallicity. This provides us a standard ruler to calibrate the peak luminosity of Type Ia Supernovae (SNe Ia), the latter has been treated as a standard cosmological ruler to explore the extragalactic astronomy and cosmology. More importantly, SNe Ia can be used to calibrate the Hubble constant, which is a fundamental step to investigate the expansion history of the universe and yet whose value is still controversial.

Although some galaxies have been used to do the calibration, we want to extend and confirm them with higher accuracy. M101 hosts a SNe Ia 2011fe and its distance has been measured. But the estimates of distances by different group vary in a large range with relatively large uncertainty. This observation will allow us to determine a better estimate.
## Summary of observing runs requested for this project

<table>
<thead>
<tr>
<th>Run</th>
<th>Telescope</th>
<th>Instrument</th>
<th>No. Nights</th>
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Scheduling constraints and non-usable dates (*up to six lines*).
Using the Tip of the Red Giant Branch (TRGB) method to measure distance of galaxies has been dramatically attractive because of its remarkably high accuracy. Although the Cepheid period-luminosity relation also provides an accurate measurement, it is only restricted to Population I systems and late-type galaxies. On the contrary, TRGB can be applied to all morphological types of galaxies as long as an old stellar population is present. Thus, the TRGB can be used to calibrate the Type Ia Supernovae (SNe Ia), a powerful tool to measure distances at high redshift where common distance indicators become invalid. Given its high and constant peak luminosity, SNe Ia has served as an excellent standard candle to investigate the expansion history of our universe. Once calibrated accurately, SNe Ia can then be used to more accurately determine Hubble constant ($H_0$), one of the six fundamental cosmological constants.

Indeed, the expansion of the universe was right established by SNe Ia and so the expansion rate, $H_0$. $H_0$ plays a fundamental role in extragalactic astronomy and cosmology since it is the key to determining many other important quantities such as the age and the mass density of the universe. Hence, its accurate determination is of great interests.

Despite the tremendous work has been conducted, its accurate value is still controversial. WMAP and Planck groups analyzed the cosmic microwave background radiation (CMB) with a flat $\Lambda$CDM cosmology and obtained values of $H_0$ with remarkably small uncertainties, $H_0 = 69.3 \pm 0.8$ km s$^{-1}$ Mpc$^{-1}$ (Bennett et al. 2013) and $H_0 = 66.93 \pm 0.62$ km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration et al. 2016), respectively. Similarly, the analysis of the baryon acoustic oscillation (BAO) yielded a comparable value, $H_0 = 67.3 \pm 1.1$ km s$^{-1}$ Mpc$^{-1}$ (Aubourg et al. 2015). However, the Cepheid calibrated SNe Ia gives out a much larger value, $H_0 = 73.24 \pm 1.74$ km s$^{-1}$ Mpc$^{-1}$ (Riess et al. 2016). SNe Ia is a direct cosmic distance ladder while CMBR and BAO are inverse cosmic distance ladder. The discrepancy of the value of $H_0$ determined by these two kinds of ladders has been one of the critical issues in modern cosmology. By measuring the accurate peak luminosity of SNe Ia based on the TRGB method, we aim to improve the accuracy of the measurement of $H_0$.

The high accuracy of the TRGB method as a distance indicator has a clear physical basis. The tip of RGB corresponds to the helium ignition in the degenerate He core of sun-like stars. Its luminosity depends on the He core mass while it shows very little dependence on the age larger than a few Gyr. At a fixed metallicity ($Z$ between 0.0001 and 0.02), its bolometric luminosity varies by less than 0.05 mag when age varies from 10 to 20 Gyr. Furthermore, the theoretical and observational $I$ magnitude of TRGB stars in globular clusters is constant within 0.1 mag while the corresponding $V$ magnitude varies by 1.3 mag in the metallicity range of $-2.2 < [\text{Fe/H}] < -0.7$. The observed $I$ band magnitude hence is an ideal distance indicator. When the metallicity is calibrated over some range, the accuracy of the distance measurement can be even higher.

Bellazzini et al. (2001) calibrated the relation between $(V-I)$ color and metallicity $[\text{Fe/H}]$, which was then combined with the relation between $(V-I)$ color and absolute $I$ magnitude.
by Rizzi et al. (2007) to derive the dependence of absolute $I$ magnitude on $(V - I)$ color,

$$M_{I,\text{TRGB}} = -4.05(\pm 0.02) + 0.217(\pm 0.01) [(V - I)_0 - 1.6].$$  \hspace{1cm} (1)

Thus, once $(V - I)$ color of the TRGB stars is measured, an accurate absolute $I$ band magnitude can be obtained. In order to get distance modulus, one needs to measure both $(V - I)$ color and apparent $I$ magnitude.

The TRGB method requires to select resolved old red giants and hence an outer region is usually a good choice which can avoid young spiral arms. By plotting the color magnitude diagram (CMD) of the resolved stars, rough ranges of color and apparent magnitude can be determined (e.g. see Figure 1). Red giants within the ranges will be selected to measure the $(V - I)$ color and the apparent $I$ band magnitude of the TRGB. The tip marks the brightest point of the red giant branch while there are indeed some foreground stars and AGB stars experiencing the TP phase brighter than it (still see Figure 1). To extract the apparent magnitude, notice that there is a sharp discontinuity in this branch in the HR diagram, which then causes a steep drop in the luminosity function and hence a peak in its first derivative. Cioni et al. (2000), therefore, proposed using these two signals to pick up the tip. Figure 2 shows the big drop in luminosity function $N(I)$ and the peak of the edge-detection response function $E(I) (= N(I + \sigma_I) - N(I - \sigma_I))$ occur at $I = 26.2$. The $(V - I)$ color then can be estimated as the median value of the selected red giants at the measured $I$ magnitude in the CMD. With both the $(V - I)$ color and the $I$ band magnitude, a TRGB distance is measured.

By measuring TRGB distance to some galaxies hosting some SNe Ia, one can calibrate the absolute magnitude of the SNe Ia with its measured apparent magnitude and hence the Hubble constant. Reindl et al. (2005) derived and calibrated the relation between Hubble constant and the absolute magnitude of SNe Ia assuming a flat universe with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$,

$$\log H_0 = 0.2M_\lambda + C_\lambda + 5,$$  \hspace{1cm} (2)

where $\lambda$ denotes $B$, $V$, or $I$, and $C_\lambda$ is the intercept listed in Table 8 in Reindl et al. (2005) for different SNe Ia samples. With this relation, a more accurate Hubble constant can be derived.

Some galaxies have been used to calibrate SNe Ia and hence Hubble constant over the past years, such as NGC 3021, NGC 3370, and NGC 1309 (Jang & Lee 2017). We propose to continue and expand this work by observing a nearby bright spiral galaxy, M101 hosting SNe Ia 2011fe. Although its distance has been measured by both Cepheids and TRGB methods, the estimates of distances varies in a large range, $(m - M)_0 = 29.04 - 29.71$ (Shappee & Stanek 2011, Vinko et al. 2012, Matheson et al. 2012). Even using the same method, the estimated distance can still differ quite significantly. And yet, their estimated errors are relatively large. Given that M101 is nearby ($\sim 7\text{ Mpc}$), ground based telescope has high enough resolution to resolve individual stars. Given the high accuracy of KPNO, we can get a more accurate estimate of the distance for M101 and so calibrate SNe Ia and Hubble constant more accurately.
Figure 1: The CMDs of galaxies M66 (left) and M96 (right) taken from Lee and Jang (2013). The red boxes denote the boundary of the red giants used for distance determination. Blue arrows indicate the magnitudes of the TRGB.

References

Figure 2: The $I$ band luminosity functions and the edge detection responses of M66 (left) and M96 (right) taken from Lee and Jang (2013).
Observing Run Details for Run 1: KP-4m & WIYN-0.9m

**Technical Description**  
Describe the observations to be made during this observing run. Justify the specific telescope, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section below (required for queue and Gemini runs).

The nearby galaxy we are going to observe has a coordinate of RA=14h03m12.5s, Dec = +54d20m56s. Based on its coordinate, we find that M101 is visible from February to June and best observed from March to May. Its mean distance 6.872 Mpc as shown in NED. M101 is 2400 arcsec large, which can be covered neither by KP-4m nor WIYN-0.9m. However, we only need to explore a small part of it, where red giants reside. Thus, both choices meet our requirements.

Since KP-4m has a high resolution, we want to use it to do $I$ band photometry. Previous work showed that the $I$ band magnitude of M101 is around 25 mag and its $V$ band magnitude is about 26.5 mag (e.g. Shappee & Stanek 2011). To get a relatively high signal-to-noise ratio, we will not observe those stars fainter than 25.5 mag in $I$ band and 27 mag in $V$ band. We then want a signal-to-noise (S/N) of 15, which corresponds to an accuracy of 0.66 mag considering the limited observational time. This is already a high accuracy although a larger S/N is better. We estimate the seeing is 1.1 arcsec and the airmass is 1.2 (actually lower than this value), thus the exposure time is 77958 s. We then request 4 darkest nights to minimize the effect of the sky background.

For the $V$ band magnitude, since we only need to use it to calculate the $(V-I)$ color and the absolute $I$ band magnitude only very weakly depends on the color as we talked earlier, we therefore do not need it to be very accurate. Thus, we choose WIYN-0.9m to do the photometry. And still since we don’t need to get very accurate color, a high S/N is also unnecessary. With a seeing of 1.1 airmass and a $V$ magnitude of 26.5, we set a exposure time of 99999 s, corresponding to a S/N of 7.42. (I want to enter a larger exposure time but the box of the exposure time calculator does not allow any number longer than 5 digits. But this S/N seems Okay already.) We hence request 4 nights for the $V$ band photometry.

Since the exposure times we request are quite long, we will break them into several short observations with each of 20 minutes long. We will select an outer region of M101 where red giants usually reside. Therefore, when observing this region we can use part of the field to get the images of sky background by pointing our telescopes off from the object.

**Instrument Configuration**

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</table>

**Special Instrument Requirements**  
Describe briefly any special or non-standard usage of instrumentation.

NOAO observing proposal LATEX macros v3.0.
Using the Period of Cepheid Variable Stars to Measure the Distance to M81

**PI:** Sam Llaneta  
**Affil:** Case Western Reserve University  
**Email:** sbl38@case.edu

**Abstract**
We propose to use Cepheid variable stars to measure the distance to M81 to set the groundwork for an investigation of how galaxies in the M81 group fit to the Tully-Fisher relation. Cepheid variable stars are the most reliable way to measure distances to nearby galaxies, so we will take advantage of the fact that there are many Cepheids in M81 that we can observe with the KPNO 4m telescope. Cepheid variable stars exhibit a strong correlation between the oscillation period of their magnitudes and their apparent magnitudes. By measuring the periods and apparent magnitudes of Cepheids in M81, we can then measure the distance modulus to the galaxy. This will be useful in the future when we plan on examining how the galaxies in the group fit to the Tully-Fisher relation which connects the rotational velocity of a galaxy to its mass-to-light ratio. Once we have the distances to galaxies in the M81 group, we can use their apparent magnitudes to work out total luminosities, and combine that with a number of mass measurements to get mass-to-light ratios. We will then take spectroscopic data across the disks of the galaxies to get rotational velocities. Our proposal right now is a preliminary investigation to measure the distance to M81 and compare our technique using a ground based telescope to existing measurements that used data from the Hubble Space Telescope. We are requesting 2 runs of 2 nights each on the 4m telescope to reduce the uncertainty from fitting periods to the noisy measured data.

**Summary of observing runs requested for this project**

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</table>
Scientific Justification

M81 has several properties which make it of important scientific interest. It is a very luminous galaxy close to the milky way with an active galactic nucleus (AGN) (Pellegrini et al. 1999), and these properties make it a common subject for scientific study. However to effectively study the galaxy, we must be certain that our measurement of the distance to M81 is accurate. We will measure the period of Cepheid Variable stars to determine their absolute magnitude. From this we can use the apparent magnitudes, which we can measure directly, to find the distance modulus and subsequently the physical distance to M81. This will also give us a distance to the M81 group which can be used for better measurements of cosmological distance indicators.

One of the greatest challenges for extragalactic astronomy has always been getting reliable distances. While we can measure some important properties of galaxies like mass and color, our inability to measure precise distances means that we are unable to measure other important quantities like luminosity, and the properties derived from it. The difficulty of measuring extragalactic distances comes from the difficulty of using the methods we use to measure extrasolar distances outside of the Milky Way. Stellar populations, which are often used to measure distance to clusters in the Milky Way, cannot be used since because of their potential variability in other galaxies and our inability to resolve all but the the brightest stars in the nearest galaxies. Thus, the only semi-effective measures of extragalactic stellar populations are the colors and color profiles of galaxies, but these have their own uncertainties due to the fact that many different stellar population distributions can result in the same overall color when integrated over a galaxy or a region of a galaxy, so stellar populations cannot be used to estimate the absolute magnitude of a galaxy to find a distance. Another semi-effective measure of distance is the redshift of a galaxy which can be measured through the shift of emission lines in a galaxy spectra. However these distances have large uncertainties due to the large peculiar velocities of galaxies and the uncertainty in the value for the Hubble constant, so they are often only used for rough relative distances. The only other reliable measure of distance is type 1a novae which have a strong correlation between decay time and peak luminosity (Phillips 1993, Hamuy 1996), but these events are relatively rare, and cannot be guaranteed to occur in a given galaxy.

The most reliable and useful method to measure distances to nearby galaxies is through measuring the period of Cepheid variable stars. Cepheids massive and bright stars (Turner 1994) which are in fact so bright that we can resolve extragalactic Cepheids from ground based telescopes on earth (Gerke et al. 2011). This on its own is not very useful for determining distance, as Cepheids span several magnitudes of brightness as a population of stars. However Cepheids vary in brightness on a timescale of days, and this variation is observable from Earth (Gerke et al. 2011). Cepheid magnitudes oscillate with a well defined specific frequency, and an example of this oscillation is illustrated in Figure 1 (Freedman et al. 1994). This oscillation is important because it is is tied to the properties of the star including its absolute magnitude. The log of the period specifically tightly correlates with the absolute magnitude of the star (Udalski et al. 1999, Soszyński et al. 2008) which is useful for our purposes since we can observe the period of bright Cepheids in M81 using ground based telescopes to measure the absolute magnitudes of those stars which will allow us to measure the distance. This relationship is between the period
and the V-band absolute magnitude of the star, which we will use for our observations, is given by

\[ M_V = -2.43[\log P - 1] - 4.05 \]  

(Benedict et al. 2007)

where \( M_V \) is the V-band absolute magnitude and \( P \) is the period of the magnitude oscillation in days. While this period can be difficult to measure accurately given the limited time we will have at Kitt Peak, we will compensate by having two observing runs. By waiting between the two observing runs, we can greatly reduce the uncertainties in our measurement of the periods of the stars due to fitting. This is because small variations in the period of an oscillatory behavior like that exhibited by Cepheid magnitudes will lead to large distances between features in the oscillation pattern at much later time, so by observing at later time we can reduce the uncertainties that come from fitting to noisy data.

We will use our observed periods of Cepheid variable stars to measure the distance to M81 and compare it so existing measurements from measured using data from Cepheids and supernovae in the galaxy. Once we have the absolute magnitudes of Cepheids in M81, we can use our observed apparent magnitudes to get a distance modulus and physical distance to M81 and subsequently a distance for its group. For this observing run, we want to test this method for obtaining distances, and in a later project we will ultimately get distances to Cepheids in other galaxies in the M81 group in order to analyze how the galaxies in the group fit to the Tully-Fisher relation.

The Tully-Fisher relation is an empirical linear relationship between the log of the rotation of a spiral galaxy and the log its mass-to-light ratio (Tully et al. 1977). The rotation of a spiral galaxy can be measured by the difference in redshift of spectral lines showing the velocity gradient across the galaxy's disk. The resulting velocity curve of the galaxy will flatten out to two different values at opposite ends of the galaxy, and we can measure the difference between these values to find how fast the galaxy is rotating (Bell et al. 2001). The mass-to-light ratio is harder to determine because it requires us to know the galaxy’s luminosity. While we can easily measure total apparent magnitudes of galaxies, we need to know the distance a galaxy to find its total absolute magnitude which we can use to find its total luminosity, and using one of a number of methods, we can get masses to find the total mass-to-light ratio of the galaxy. Once we do this for nearby galaxies, like those in the the M81 group we can fit a line to the data of the galaxies we have reliable distances to, and use the values for the that fit line to work backwards to find luminosities of galaxies with measured masses. We can then measure apparent magnitudes to measure a distance with some uncertainty due to scatter around the fit line. This all relies on finding reliable distances to nearby galaxies in order to get accurate mass-to-light ratios for the fit. Several galaxies in the M81 group are good candidates to get measurements in the the future for this since they are oriented in a way that allows us to measure their rotational velocity and total apparent magnitude. M81, NGC 2366, NGC 2976, and NGC 4236 are all oriented neither face nor disk on meaning the rotational velocities of their disks have a radial component with respect to the Earth we can measure through redshift and the light from these galaxies is not largely obscured by the dist in their disks. We want to measure a distance M81 and later to these other galaxies and take spectra of their disks to investigate how they fit to the Tully-Fisher relation and better constrain the fit of this relationship.
Technical Description

We will focus on Cepheids in M81 with apparent V-magnitudes brighter than 22 mag. There are several examples used by Gerke et al. 2011 in a similar analysis using Hubble data. M31 has an angular size on the sky of 26.8 by 14.1 arcmin (de Vaucouleurs et al 1991), so it will easily fit in the field of view of the 35.4 by 35.4 arcmin CCD. This allows us to measure all the stars of interest in M81 simultaneously, so we can get a fairly large sample constrained only by what observing time is necessary to reach our desired signal-to-noise ratio for a given magnitude star. Thus we will set our lower magnitude limit at 22 mag which still leaves us with many observable Cepheids in M81. Some examples of stars that we will observe are:

<table>
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<tr>
<td>M81C 095621.72+690357.3</td>
<td>21.64</td>
</tr>
<tr>
<td>M81C 095611.68+685932.2</td>
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</tr>
<tr>
<td>M81C 095621.16+690557.1</td>
<td>21.69</td>
</tr>
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</table>

(Gerke et al. 2011)

Time constraints mean that we will have to focus on stars brighter than 22 magnitudes to get our desired signal-to-noise ratio of 250. Using a magnitude 22 star during a new moon, a typical seeing of 1.1, and a conservative airmass of 1.4, arcsec we will need to get an exposure of $3589.56^1$ seconds or about an hour to get our desired signal-to-noise ratio. To be sure that we are achieving a signal-to-noise ratio of 250 we will take three 20 minute exposures and combine those images to get an each measurement. Each night we will observe every other hour that M81 is above 1.5 airmasses to get a good sampling, and during the off hours we will focus on the standard calibrations necessary to ensure that we are getting reliable and accurate data like flat-fielding or observing standard stars. The time scale of Cepheid oscillations are on the time scale of days so this should give us a good sampling of the period when measured over two nights.

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^1 This time was calculated using the NOAO exposure time calculator found at https://www.noao.edu/scope/ccdtime/
Figures

Figure 1. Example plot of the V-magnitude oscillation of a Cepheid variable star. (Freedman et al. 1994)

Figure 2. Period W-band luminosity relation for Cepheid variable stars. (Soszyński et al. 2008)

Figure 3. Example plot of the Tully-Fisher relation. (Bell et al. 2001)

References

de Vaucouleurs, G., de Vaucouleurs, A., Corwin Jr., et al. 1991, RC3
The Exploration of Numerous White Dwarfs in M67

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Abstract: I propose deep imaging of the nearby open cluster M67 to obtain accurate luminosities of a large number of white dwarfs, with emphasis on those at fainter magnitudes. This cluster is unique in that it is one of few relatively old open clusters that are close enough to observe white dwarfs. White dwarfs can be used as a method for determining the age of a stellar population and gaining insights into the evolution of the galactic disk. Open clusters are particularly useful in this regard because they give a population at a constant age. Selection bias leaves many questions about the properties and abundances of cooler white dwarfs, which is particularly important because the coolest white dwarf is used to determine age. Studying these older stars can allow further constraints to the relationships between luminosity, age, and progenitor stars. Previous studies of M67 have observed many white dwarfs, but it is estimated that only 40% have been observationally accounted for and there may be as many as ~600 within the cluster. Many of the white dwarfs that have not yet been observed are suspected to be the cooler white dwarfs, which are not as well constrained, and such white dwarfs also have more diverse and less understood properties. I request two nights of dark time on the Kitt Peak 4m Mosaic Imager to observe the large population of cool, white dwarfs in M67 to constrain their relationship with luminosity, age, and evolution. This will allow us to reach $M_V = 25.5$ as the limiting magnitude for white dwarf stars in the open cluster.

<table>
<thead>
<tr>
<th>Run</th>
<th>Instrument</th>
<th>No. Nights</th>
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<td>Dec-Mar</td>
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</table>
Scientific Justification: Open clusters can serve as indicators of the evolution and structure of the galactic disk. For this purpose, the older open clusters are of particular interest. These clusters contain population I stars and are inherently rare in comparison to younger open clusters (Fiel 1995; Soderblom 2010). The evolution of the galactic disk can be seen as the aggregation of many open clusters, which each show a population of stars of similar age and metallicity. The older open clusters have significantly different properties than the younger; they typically have a greater and more concentrated population, which is evident in their survival of interactions that destroy many younger open clusters (Fiel 1995). M67 is no exception to these properties and is relatively close. The proximity allows fainter objects, such as white dwarfs, to be observable and allows for little extinction or reddening (Dinescu et al. 1995).

Photometric data yields information on the age of open clusters. There are two main techniques for determining the ages of stellar populations: one using main sequence evolution theory (isochrone fitting) and the other using white dwarf cooling theory (Jeffery et al. 2007). The ages derived from these different methods can yield significantly different results (Soderblom 2010) and the results are independent of one another (Richer et al. 1998). The main sequence turn off (MSTO) method is most reliable for the galactic halo and globular clusters, while measuring the white dwarf cooling ages is most reliable for the disk (Jeffery et al. 2007). The MSTO method compares theoretical isochrones at fixed metallicity to the color magnitude diagram of a cluster in order to find the matching turnoff at the main sequence, subgiant, and giant branches (Dinescu et al. 1995). MSTO studies of M67 have concluded an age of 4.0 ± 0.5 Gyr, with most of the uncertainty in the reddening (Dinescu et al. 1995, Richer et al. 1998). Some of these earlier studies, such as Dinescu et al. (1995), have a limiting magnitude of $M_v = 20$. It should be noted that the MSTO method is exacerbated by the presence of binaries (Soderblom 2010), which are relatively common in older clusters such as M67, with estimates of 38% (Fiel 1995) and 50% binaries in M67 (Richer et al. 1998).

Determining the age of a system by the white dwarf cooling time is relatively straightforward. There is no energy generated for these stars, only lost. For the brighter white dwarfs the physics is well understood, resulting in a simple relationship between the cooling time and luminosity of the white dwarf (Jeffery et al. 2007; Soderblom 2010). This basic theory follows a power law between the age and luminosity of the white dwarf, which does not fully describe the processes but has a very similar behavior (D’Antona & Mazzitelli 1990). White dwarfs can be identified in the color magnitude diagram as faint blue stars and can be confirmed with spectroscopy. The usual technique involves the coolest white dwarfs of the cluster, which causes a selection effect because the samples are biased in favor of the hotter stars. This lies in the fact that the cooler white dwarfs have lower luminosities and search volumes (Liebert 1980; Soderblom 2010). The color range of white dwarf stars extends from spectral types O to K, and they are often present in binary systems with brighter, redder companions, but identification for the luminosity function must be limited to non-binaries (Liebert 1980). The uncertainty for this method can be on the order of ~1 Gyr (Soderblom 2010), but can be much better constrained with a sample as large as M67. The fraction of stars that have evolved through different evolutionary channels can be estimated from the white dwarf population (Wiedemann 1990). The birthrate and abundance of the dwarfs can thus be linked to the evolution of their progenitor stars (Liebert 1980). The mass of these progenitor stars can be found by equating the cluster age minus the cooling age and time to the AGB tip (Wiedemann 1990). The upper limit of the mass of the progenitor star varies, depending on whether convective overshooting and other mass loss
is accounted for. The upper limit for progenitor mass is 8 M☉ with convective overshooting and 5 M☉ without. Using this reasoning, the large population of dwarfs in M67 can not only be linked to the evolution of progenitors, but can also constrain the mass loss during the transition between progenitor and dwarf (Liebert 1980).

The oldest white dwarfs provide the most insight into the early history of our galaxy, but are not as well constrained. While the hot and luminous white dwarfs are better understood, the cooler white dwarfs are complicated by a variety of mechanisms. Some of the complications linked to the age of white dwarfs are contraction resulting the release of gravitational energy, energy loss by neutrinos, energy transfer between layers, and radiative opacity (D’Antona & Mazzitelli 1990). While hot white dwarfs are easily identified in their color and spectra due to the balmer jump and hydrogen lines, these characteristics are weaker in cool white dwarfs (Hansen & Liebert 2003). The coolest white dwarfs have very strong collision induced absorption from molecular hydrogen and have convective zones (Hansen & Liebert 2003). This is one of many factors that causes the luminosity function for these cooler white dwarfs to be not as well constrained and have diverse spectral properties depending on the population (D’Antona & Mazzitelli 1990; Hansen & Liebert 2003). Identifying a large sample of cool white dwarfs, such as in M67, can help constrain these properties. Another characteristic of the cooler population of white dwarfs is that they are frequently observed to have an abundance of heavy metals (Jura & Young 2014). This is surprising for white dwarfs, because elements heavier than helium sink to the interior relatively quickly during the cooling phase. Initially it was believed that this material was accumulated from the interstellar medium, but recent evidence indicates that these heavy metals are derived from rocky planetesimals (Jura & Young 2014). Deeper imaging data in M67 to observe a number of these cooler white dwarfs can help constrain their abundance in a system of constant age and metallicity.

While the age of a stellar population is typically determined from the coolest white dwarfs, it can also be determined from the hottest members (Jeffery et al. 2007). M67’s population would also be helpful in determining this relationship between the age estimates using either the coolest or the hottest white dwarfs. Constraining this technique could eliminate the selection bias of finding the cooler white dwarfs in future studies. In addition, the overlap between the MSTO method and white dwarf cooling time is best calibrated in open clusters (Jeffery et al. 2007). High accuracy data from M67 would help to this end. Also, having accurate luminosities of the white dwarfs can provide constraints for the relationship between the final white dwarf mass and the main sequence turnoff mass (Hansen & Liebert 2003).

The proximity, age, and large population of M67 uniquely situate it so that deep imaging of the open cluster can assist in answering a number of questions. Not only does M67 have dozens of confirmed white dwarfs, but it is suspected that the number observed in shallower, previous studies fall significantly short of estimates (Richer et al. 1998). This implies that many of the missing white dwarfs may be the fainter, cooler dwarfs. Deep imaging can not only discover these stars, but can provide data that will assist in constraining and answering a number of scientific questions regarding the cooler population of white dwarfs.
Figure 1: The Sloan Digital Sky Survey Image of open cluster M67.

Figure 2: The isochrone fit and white dwarf luminosity function of M67 in Richer et al. (1998). The white dwarf luminosity function does not appear to match the data particularly well. With a deeper study, we can increase the precision and accuracy of the measurements as well as potentially detect a number of fainter white dwarfs. The Richer et al. (1998) study observes 87
white dwarfs and suggests that due to the high presence of binaries, this accounts for roughly 150 total white dwarfs. They suggest that these 150 only account for 40% of the white dwarfs expected from the isochrones and also falls short of earlier studies.

References:
Jura, M., Young, E. D., 2014, AREPS, 42, 45
Wiedemann, V. 1990, ARA&A, 28, 103

Technical Description of Observations:

Properties of M67

<table>
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<tr>
<th>Right Ascension</th>
<th>Declination</th>
<th>Diameter</th>
<th>Isochrone Derived Age</th>
<th>Total Magnitude</th>
<th>Distance</th>
<th>Distance Modulus</th>
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<td>08h51m20s</td>
<td>+11d48m43s</td>
<td>23’</td>
<td>4 Gyr</td>
<td>M_v = 6.1</td>
<td>908 pc</td>
<td>9.97 mag</td>
</tr>
</tbody>
</table>

1. Nasa Extragalactic Database (NED)
2. Richer et al.

Exposure Time and Telescope Justification

The coolest white dwarfs have an absolute magnitude as low as M_v = 16.5 (Jeffery et al. 2007). However, the population of M67 is not old enough to have a dwarf quite that faint and should be limited an absolute magnitude of M_v = 15.5. With the distance modulus this results in a limiting apparent magnitude of M_v = 25.5. We desire a deviation of no more than 0.1 magnitudes for accurate measurements of the white dwarf luminosity, which implies a S/N ~ 12. We will use the Johnson V and I bands to determine the color of the white dwarfs. On the Kitt Peak 4m Mosaic imager, at least three exposures of 20 minutes (1200 seconds) during dark time are needed to satisfy our V-band S/N requirements. As least six 20 minute exposures are needed for the R filter to satisfy the same S/N. These exposure times assume a typical seeing of 1’’ and an Airmass of X = 1.2. We assume that with several hours needed each night for flat fielding and
10 minutes for readout and setup between each image, we need a minimum of 8 hours of dark
time. The object is above airmass X=1.5 for about 6 hours in January and February, and at least 4
hours for most of December and March.

A smaller telescope would not be able to achieve the same S/N in a reasonable amount of
time, nor would more presence from the moon. The 35.4’ per side on the CCD will fit the entire
cluster in the field of view for each image.

Data Reduction

The images will need to use standard data reduction methods to account for the sky
brightness and flat fielding. The open cluster is likely too crowded for aperture photometry, so
PSF fitting will be used to get the photometry on the resulting images. The resulting color
magnitude diagram will be used to classify the white dwarfs. They will then be fitted to the
dwarf luminosity function and relevant parameters, such as the reddest and bluest dwarfs, will be
recorded.
Abstract of Scientific Justification:

We purpose imaging of galaxies in the Coma cluster to study the effect of location within the cluster on their galactic color. Investigating color in the cluster provides insight into the star formation rates within the galaxies, which yields information on the effects of gas stripping in clusters. The interstellar medium of galaxies can stripped or disturbed by ram pressure stripping and gravitational interactions with nearby galaxies. Both of these processes are heightened in clusters due to the increased density of the environment. We will study the Coma cluster to a limiting surface brightness of \( \mu_B = 27 \) mag arcsec\(^{-2} \) and \( \mu_V = 26 \) mag arcsec\(^{-2} \) in order to account for the reder color of cluster galaxies. We are requesting 2 dark nights on the KPNO 4m to complete this study.

<table>
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</tbody>
</table>
Scientific Justification

Many galactic properties, such as color, gas fraction, star formation rates, and stellar mass, are correlated to their environments (Kauffmann et al. 2004). Various studies have found distinct color differences in cluster disk galaxies compared to their field counterparts; field disk galaxies tend to be significantly bluer than disk galaxies in clusters (Pranger et al. 2017, Cantale et al. 2016). Generally speaking, galaxies in clusters tend to be redder than field galaxies, in part due to the density-morphology relation, which states that early-type galaxies like elliptical and lenticular galaxies are more commonly found in dense, cluster environments, while spiral galaxies are more prevalent in field environments (Dressler 1980). Early-type galaxies tend to have different properties than spiral galaxies, including a lack of ongoing star formation, redder color, and lower gas content. These differences in properties are reflected in the differences in galactic color in field versus cluster environments.

In dense environments, various processes remove gas from galaxies, including ram pressure stripping and gravitational interactions. Removing gas from a galaxy decreases the available material to form stars, and hence decreases star formation rates. The amount of ongoing star formation in a galaxy is closely related to the integrated color of the galaxy. Blue populations of stars are generally younger and indicate ongoing star formation, while redder populations are older and lack ongoing star formation. Hot, blue stars have shorter lifespans, which is what warrants the claim that blue populations of stars are indicative of young, star forming regions; if the population of stars appears redder, then these hot, blue stars with shorter life spans than red stars must have had time to die off. Our study will use the link between color and star formation to infer the amount of star formation in cluster galaxies.

Galactic properties, such as star formation rates, color, gas fraction, and galactic bulge fraction, are also dependent on the location of the galaxy within the cluster. von der Linden et al. (2010) found that the star formation rate of galaxies in clusters decreased with decreasing clustercentric distance; that is, the closer the galaxy is to the center, or the densest part of the cluster, the less star formation it has occurring in it. Generally speaking, the center of large clusters are more dense, indicating that galaxies should be increasingly redder. This is thought to be due to ram pressure stripping and gravitational interactions, both of which increase in more dense regions like the center of galaxy clusters.

There are two main ways for a galaxy to stop forming stars (i.e. quenching star formation); these are internal processes and environment driven processes. In examining the dependence of galactic color on cluster location, this study aims to explore the effect of the environment on quenching star formation in galaxies. There are two types of environmental processes responsible for quenching star formation, hydrodynamic interactions and gravitational interactions (Consolandi et al. 2017). Both of these processes have an effect on cluster galaxies, and will be considered in this study.

Gravitational interactions with surrounding galaxies include both mergers and tidal interactions. Moore et al. (1996) found that the effect of galaxy harassment (interactions with surrounding galaxies) was significant in driving evolution and creating dramatic features in galaxies. However, while clusters induce many gravitational interactions due solely to the amount and proximity of galaxies to one another, the galaxies are moving at relative speeds much faster than field galaxies. The strength of the interaction is related to the speed at which the interaction occurs; a galaxy which is moving slower has more time to interact with
another galaxy and induces more disruption.

A well studied hydrodynamic interaction that quenches star formation in galaxies is ram pressure stripping. Ram pressure stripping, which occurs only if the ram pressure force is greater than the gravitational force, is dependent on the properties and movement of the individual galaxy within the cluster as well as the density of the cluster (Gunn & Gott 1972). The ram pressure force pulls gas from the interstellar medium of the galaxy out of the galaxy and into the intracluster medium. In order for ram pressure to be a dominant force and pull out the gas in a galaxy, the density of the intracluster medium must be rather large compared to the size and speed of the galaxy. Figure 1 shows the dependence of ram pressure stripping on the velocity of the galaxies compared to the density of the intracluster medium where the shaded region is where ram pressure stripping is not an effective gas removing process. For denser clusters, the region in which ram pressure stripping does not induce gas stripping on galaxies is much smaller. Hence, in a large, dense cluster like the Coma cluster, we expect ram pressure stripping to be a factor in the stripping of even large spiral galaxies.

Yoshida et al. (2010) found extended ionized gas around four member galaxies of the Coma cluster presented in their study with data that fit current models for ram pressure stripping of galaxies in clusters. These galaxies are being actively changed by the cluster, changing their properties and ability to form stars. The effects of ram pressure are thought to change the star formation rates in galaxies and the galaxy’s integrated color (Kelkar et al. 2015). Therefore, the study of color as a function of radius would provide detail into the location and extent of ram pressure stripping in the Coma cluster of galaxies.

Ram pressure stripping is thought to be most effective in the central regions of galaxy clusters (Vollmer et al. 2001). This is likely due to the fact that the central region tends to be more dense, and hence the ram pressure force is larger toward the center of the cluster. The amount of time a galaxy spends in the cluster also determines the change in the galaxy due to the cluster. Jaffé et al. (2015) studied a galaxy cluster and noted that the recent infall region (outer region) contains many more blue galaxies than central regions and that a single pass through the central region can strip galaxies of enough gas so that they are no longer detected in HI. While this study will not investigate the spectroscopic properties of Coma cluster galaxies, it aims to get an understanding of the trends in amount of ongoing star formation by using galactic color as a proxy for star formation rate.

The study of color dependence on the distance from the cluster center is particularly interesting because of the differing results found in the literature for different clusters. Figure 2 shows the data from the study of the Virgo cluster by Roedinger et al. (2011), where the different colored data points are groups of different ranges of distances from the center of the cluster. This color versus color plot show no statistically significant trend in color as a function of distance from the center of the cluster (Roedinger et al. 2011). This seems to conflict the idea that ram pressure stripping is more effective in the central regions of the cluster, since stripping gas quenches star formation and hence should redden color (Vollmer et al. 2001). Likewise, von der Linden et al. (2010) found that star formation rates decrease significantly toward the center of cluster, which should indicate that color would become redder closer to cluster centers. This study’s investigation of the Coma cluster will hopefully yield another data set with which to constrain the changes in color, and star formation, on cluster galaxies.
Figure 1: Velocity of a galaxy as a function of the intracluster medium density of the galaxy cluster. The shaded region below the solid line in the region in which ram pressure does not induce any stripping on galaxies in the cluster. The other lines are indicative of how much gas stripping occurs. (Image credit: Vollmer et al. 2001)

References:
Figure 2: Plot of $r - H$ color as a function of $g - r$ color. The different colored data points correspond to different ranges of clustercentric distances. Roeding et al. argue that there is essentially no correlation between clustercentric distance in Virgo and color, although this plot does have a lot of scatter. (Image credit: Roedinger et al. 2011)
Low surface brightness galaxies have disk central surface brightnesses of $\mu_B \sim 26$ mag arcsec$^{-2}$ (Sabatini et al. 2005). We will use $B - V$ color to conduct our study, and given that cluster galaxies are generally redder than field galaxies, our $B$ band data will need to go to dimmer than $V$ data. We propose a study with a limiting surface brightness of $\mu_B = 27$ mag arcsec$^{-2}$ and $\mu_V = 26$ mag arcsec$^{-2}$. Our goal is to get an idea of the general trend of galactic properties within Coma, so while we do need to get a proper sample of galaxies in Coma, we are not as concerned about detecting the faintest such galaxies.

Due to the discrepancies in radial trends in the literature, we want to get color resolved to $\pm 0.1$ mag. This means, we need $\sigma_{B/V} = 0.07$, corresponding to a signal-to-noise ratio of approximately 30. Based on this signal-to-noise ratio and limiting surface brightness described above, our exposure times on the KPNO 4m telescope are on the order of approximately 10 minutes in the $V$ band and 25 minutes in the $B$ band.

With a field of view of $\sim 36 \times 36$ arcmin on the KPNO 4m, our study will take a total of 16 observations, creating a $4 \times 4$ grid of exposures to cover an approximately $2.4 \times 2.4$ degree area on the sky which contains the Coma cluster. This grid will be centered on NGC 4874, a central cD galaxy in the Coma cluster. This covers approximately the same area of the sky as shown in Briel et al. (1992).

With a total of 16 “frames”, 15 minute exposures for each frame for the $V$ band, and 25 minute exposures for each frame for the $B$ band, we require a total of 11 hours of observing time (which includes time for read-out, moving the telescope, zero frames, flat fields, and other tasks around the observatory). We are asking for two nights on the KPNO 4m to complete this amount of observing. In order to do our observing in two nights, we will need at least 5.5 hours each night with an airmass less than 1.5, which occurs only between mid February and late April.

The proposed “center” of the Coma cluster for this study is a right ascension of 12h 59m 17.8s and a declination of +27d 57m 33.3s (taken to be the coordinates of NGC 4874, the central cD galaxy, as in Hammer et al. 2010); a central distance will be calculated from the average redshift of the cluster of $z \sim 0.023$ (Hammer et al. 2010). This yields a distance of $\sim 105$ Mpc. In order to get distance from the cluster center, we will also need the distance to the individual galaxies in the cluster.

Our main source of uncertainty will be in the clustercentric distances of galaxies, due to the assumed spherical shape of clusters. The imaging data will allow us to get projected clustercentric distances as computed in the Virgo cluster in Roedinger et al. (2011). Cluster galaxies have high velocity dispersions, on the order of 1000 km/s for the Coma cluster, due to gravitational interactions. An uncertainty on the recessional speed of a galaxy on the order of 1000 km/s leads to an uncertainty of redshift of $\sim 0.003$. Hence, with Coma’s recessional velocity of $\sim 6900$ km/s, redshifts will be an unreliable measure of distance.

We will conduct our study similarly to Roedinger et al. (2011) and use the projected clustercentric distance, which will allow us to see any azimuthal symmetries in galactic color in clusters. Issues arise in that the projected central regions of the cluster will have both truly central galaxies as well as galaxies in the outer regions of the galaxy. However, conducting our study in this manner allows us to compare the Coma cluster to the study of the Virgo cluster in Roedinger et al. (2011).
We propose an analysis of the tidal dwarfs within two peculiar galaxies, Arp 105 and Arp 135, to determine whether they lie upon the baryonic Tully-Fisher relation. Tidal dwarfs form during galaxy mergers and, within the ΛCDM paradigm, do not contain cold dark matter. By discerning their position on the baryonic Tully-Fisher relation, we can therefore see whether this is in agreement with the Standard Model of Cosmology, or whether it supports an entirely different model for dark matter.

In addition to these calculations, we are planning to provide an observational comparison between tidal dwarfs and their parent galaxies, looking specifically at star formation, B-V and U-B color, and stellar population. This information could further our understanding of tidal dwarfs and where they differ from other galaxies.

We are applying for one night on the Kitt Peak 4m telescope in January-February of 2018. The 4m telescope is necessary for our project because we are interested in the U band filter, which has relatively long exposure times.
1 Scientific Justification

Tidal dwarf galaxies form in regions of over-density within the tidal tails of larger galaxies. These over-densities are often created during galaxy mergers or strong interactions in very luminous, massive spiral galaxies (Duc 1997, Bournaud et al. 2007, Bournaud 2010, Duc 2011). The tidal dwarfs themselves are kinematically decoupled from their parent galaxy and are gravitationally bound, which makes them more resilient against being torn apart by the parent galaxy (Duc 2011).

The two galaxies that we propose to observe for this project are Arp 105 and Arp 135. Arp 105 (Figure 1) is known to have two tidal dwarf galaxies within the tips of its tidal arms, and the galaxy itself formed as the collision of a spiral galaxy, NGC 3561A, and an elliptical galaxy, NGC 3561B (Duc et al. 1997). The other galaxy, Arp 135, is a strong candidate for finding more tidal dwarfs. Observations of Arp 135 from Iyer et al. (1999) indicate highly disturbed HI regions and the presence of clumps and knots in close proximities (Figure 2). With this galaxy, we would be focusing on the over-densities to examining whether they are tidal dwarfs. This would be done by my colleague using spectroscopy to determine whether the knots are gravitationally bound and rotating independently from the parent galaxy. At least a few of these knots are very likely to be tidal dwarfs, and if none of them are, it would still help us constrain the formation conditions for tidal dwarfs (Iyer et al. 1999).

During this study, we would be studying the color, star formation model, and stellar population of the tidal dwarfs in Arp 105 and Arp 135. This is of scientific interest because it would allow us to compare these properties with those of the galaxies they inhabit. We want to study whether distinct galaxies that formed from the same merger have noticeable differences in composition and evolution. Within the larger spiral galaxy, we would be finding signs of mergers in an attempt to determine more about the conditions that led to the formation of their inhabiting tidal dwarfs. This involves examining the tidal features of the parent galaxies. Such features are normally the result of large amounts of material being expelled from the galaxy’s disk due to the gravitational torques applied during mergers or interactions (Bournaud 2010).

In terms of color, we would be looking at the U-B and B-V colors of both the tidal dwarfs and the parent galaxies. The U filter lets us measure the ultraviolet light from young stars (O, B, and A) in the hotter stellar classes, which are what we are expecting to find within our objects. The point of interest is to compare the U-B color between the tidal dwarf galaxies and their parent galaxies. Since the U filter is in the range of many young stars, it can be integral in determining star formation models. The star formation rates and regions of each galaxy would help us understand how the tidal galaxy and the parent galaxy evolve differently within such a close proximity. It would also lend information on the stellar populations and ages of the stars, which we can then compare as well. In addition, we are measuring the magnitude in the B and V filters, since we will at least need the B filter for the U-B color, but also because B-V color is commonly used when discerning stellar populations for a galaxy.

The other main reason we would like to investigate these tidal dwarfs is because the data could help us determine more about the properties of dark matter. Within our Standard Model of Cosmology, dark matter is chosen to be ΛCDM, or cold dark matter. This requires the existence of another particle, one that has little to no interactions with other particles or
waves. It would, however, feel the effects of gravity. According to ΛCDM paradigm, the tidal dwarfs within a larger galaxy should lack cold dark matter because: 1) the larger galaxy’s potential well would pull most of it away, and 2) they form from the material in the disks of galaxies, where less dark matter resides anyways (Bournaud 2010, Duc 2011). We propose to test this.

During this study, we would be calculating where the tidal dwarfs in Arp 105, and potentially Arp 135, lie upon the baryonic Tully-Fisher relation (Figure 3). The baryonic Tully-Fisher relation is a relationship between the baryonic mass \( M_{\text{star}} + M_{\text{gas}} \) and the flat rotational velocity \( V_f \) of a galaxy (McGaugh 2012). The rotational velocity is being calculated based on spectroscopic observations made by my colleague, while I plan to determine the stellar mass of the tidal galaxies using the Kitt Peak 4m telescope. The stellar mass of a galaxy can be determined by converting the galaxy’s luminosity into mass by using the Mass-to-Light ratio \( Y_* \). An important step in this process will be to determine the tidal dwarf galaxies luminosities separately from those of their parent galaxies, while trying to minimize overlap. The gaseous mass of the tidal dwarfs will be calculated by my colleague by using the HI emission lines from the spectra.

Under the Standard Model of Cosmology, objects with dark matter have been constrained to lie upon the baryonic Tully-Fisher relation (Desmond 2012, McGaugh 2012). Therefore, if we find that the tidal dwarfs’ rotation are accounted for primarily by their baryonic masses, it supports the ΛCDM model and suggests that tidal dwarfs do not contain much cold dark matter. In this case, the parent galaxies would have pulled away most of the tidal dwarf galaxies’ dark matter particles. If, however, we find that the tidal dwarf galaxies still lie upon the baryonic Tully-Fisher relation, there is a larger consequence. This would be in disagreement with ΛCDM, and lend support to an alternative model of dark matter, potentially a universal law rather than a particle. Every current dark matter model has specific disagreements with observations, which makes this project scientifically significant. If we can find accurate data for the tidal dwarfs in Arp 105 and Arp 135, it could lend support to a dark matter model or even help to falsify one.

![Figure 1](image_url)

**Figure 1**
An image of Arp 105 from Duc (1997). Arrows are pointed at the two tidal dwarfs within the galaxy. The HI contour map is from Malphrus et al (1997).
Figure 2
An image of NGC 1023 (Arp 135) from Sancisi et al. (1984). It shows a map of the HI column density superimposed on a photograph of NGC 1023. Crosses mark the positions of stars as in Fig. 1.

Figure 3
A plot from McGaugh (2012) showing the baryonic Tully-Fisher relation across a range of baryonic masses. Data for galaxies with \( V_f \) measured from resolved rotation curves include the rotating cases of Trachternach et al. (2009), the data of Begum et al. (2008a) with consistent inclinations, the gas dominated galaxies compiled by Stark et al. (2009, green circles), and the star dominated galaxies compiled by McGaugh (2005b, dark gray squares).

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Iyer M. et al., 1999, AAS, 31, 1451
2 Technical Description of Observations

Over the course of a single night run, we plan to observe two galaxies, Arp 105 and Arp 135. In particular, we would be focusing on the tidal dwarfs (or over-densities in the case of Arp 135) in each galaxy. Arp 105 is at a distance of about 115 Mpc, and Arp 135 is located about 15 Mpc away. In order to observe the tidal features and tidal dwarfs in these galaxies, we calculated exposure times to reach a surface brightness of 26.5 V magnitudes per square arcsecond. Arp 105 covers approximately a 5.8 arcmin by 5.8 arcmin field (Duc et al. 1997), and based on Figure 2, Arp 135 covers a 30 arcmin by 30 arcmin field. The Kitt Peak Direct Imaging Manual cites that the 4m telescope has a field of view of 36 arcmin by 36 arcmin, which although tight for Arp 135, can view both galaxies in their entirety.

During this observing run, we would observe the galaxies in the U, B, and V bands. The U band exposure is the main reason that we are asking for time on the 4m telescope, but it is also one of the more important components of this project. In order to compare the joint history and evolution of tidal dwarfs and their parent galaxies, data in the ultraviolet range is critical. These galaxies are expected to have a number of young, hot stars that emit significant amounts of UV light. Young O, B, and A stars in the presence of gas are indicative of star formation, and from the HI maps created by Malphrus et al (1997) and Sancisi et al. (1984) for Arp 105 and Arp 135, respectively, we know that gas is present in these galaxies. Therefore, the U band provides us with invaluable data for describing and comparing these galaxies, in relation to our goals.

For this project, a Signal to Noise ratio of 10 is adequate. This corresponds to the following exposure times:

<table>
<thead>
<tr>
<th></th>
<th>U band</th>
<th>B band</th>
<th>V band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arp 105</td>
<td>7 exposures of 15 minutes</td>
<td>(4) 3 minutes</td>
<td>(4) 4 minutes</td>
</tr>
<tr>
<td>Arp 135</td>
<td>7 exposures of 15 minutes</td>
<td>(4) 3 minutes</td>
<td>(4) 4 minutes</td>
</tr>
</tbody>
</table>

Without including time for calibrations, the total exposure time is equal to nearly 5 hours of observing. Multiple dithered exposures would be taken in the B and V bands in order to increase the accuracy of the data. Assuming an additional 20% of this time would be spent on overhead (readout, setup) and calibration, this brings the time to about 6 hours.

We are requesting a night on the Kitt Peak 4m telescope between January through February of 2018. Both objects will be in the sky for multiple hours during this time and at an airmass less than 1.5. Observations can take place during a quarter moon through a new moon.
Observing Galaxy-Galaxy Interaction Effects Via Stellar Distributions In Host Galaxies

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**Abstract**

We propose imaging a sample of face-on binary interacting spiral galaxies and isolated non-interacting spiral galaxies to study the effects of galaxy interactions on the stellar distribution in spiral galaxies. The baryonic distribution in an interacting spiral binary is likely impacted by the companion galaxy in a variety of ways, including perturbation driven starbursts, disk elongation, winding, and skewing so that the interaction history is encoded in the symmetry breaking of the disk mass distribution. Tracing the mass distribution through the luminosity, we will analyze the symmetry breaking by fitting elliptic isophotes to the disk. An isophote’s ellipticity and center trace the disk elongation and skewing respectively, while the winding in direction and the center of the isophote exhibit the timescale and strength of the interaction.

Strong interaction break the symmetry of the disk, the specifics of which are encoded in the isophotes. To confirm this, we propose to target 50 face-on binary interacting spiral galaxies, focusing on pre-merger and face-on pairs so that the interaction effects may be correlated between the galaxies. In addition, we also plan to observe 5 isolated non-interacting spiral galaxies as a control to isolate properties inherent to the disk from those caused by interactions. In conjunction to this we collected measurements, for the same sample of galaxies, of the dust distribution through IR measurements taken on IRTF, Mauna Kea. By combining both data sets we will quantify the effects of interactions not just on stellar distributions, but on the total baryonic distributions in spiral galaxies. We are requesting 4 half-moon night on the 4m CCD Mosaic imager to reach $\mu_V = 27$ [mag/sq asec] in each galaxy.

**Table 1:** Summary of observing runs requested for this project

<table>
<thead>
<tr>
<th>Run</th>
<th>Telescope</th>
<th>Instrument</th>
<th>No. Nights</th>
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<th>Optimal months</th>
<th>Accept. months</th>
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</thead>
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<td>KPNO</td>
<td>4m Mosaic</td>
<td>4</td>
<td>half</td>
<td>July</td>
<td></td>
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</tbody>
</table>
Scientific Justification

The study of galaxy interactions has had an impactful history on the field of astronomy since first Lindblad (1926) conjectured galaxy collisions, Baade and Shapley joked that galaxies seem to come in pairs (Irwin 1963), and (Holmberg 1941) presented the first N-body simulation of galaxy interactions. The reason for interest is clear: the history of a galaxy’s interactions is inextricably tied to its formation history and future. Interactions may alter a galaxy’s morphology and accelerate evolutionary processes and are thus a primary driver of galaxy evolution, star formation, heavy element synthesis, and planet formation (Struck 1999).

Galaxy interactions are used to explain the evolution of galaxies along Hubble’s “tuning fork” (M & C J A 1936). Isolated galaxies in the field form as spirals while galaxies in cluster environments may interact to form ellipticals. The general consideration has been that a binary interaction and merger has sourced ellipticals; however, simulation work done by Weil & Hernquist 1996 and Governato et al. 1996 show that multiple mergers better explain ellipticals. This disconnect between binary vs multiple galaxy interactions sourcing ellipticals shows that the specific consequences of galaxy interactions are deficiently understood (Dressler 1984). The situation is further complicated by the evidence that even isolated galaxies strongly interact with their environment (Struck 1999), making more ambiguous the effects of specific galaxy interactions. To address this, we are studying face-on binary spirals in comparison to isolated spirals to better understand the properties intrinsic to interactions and serve as a future basis of differentiation for more complex interactions. Motivating our choice of binary spirals are observations (eg. Sanders & Mirabel 1996) that small groups of galaxies show stronger interactions due to the low relative velocity of the galaxies, resulting in larger timescales over which the interaction takes place. Spiral binaries should thus show the largest effects. Specifically, we are investigating how interactions in binary spirals manifest as asymmetries in the spirals’ disks.

We will conduct our analysis on the asymmetry in the luminosity distribution by fitting elliptic isophotes, in both B and V bands, to the luminosity data. The properties of the isophotes — center, ellipticity, position angle — as well as the change in the isophotes, both radially and between bands, encodes much of the interaction information of the galaxies. Explained subsequently are the interpretations for all these properties. Moreover, we will also analyze asymmetries the mass distribution. To retrieve the mass distribution from the luminosity we apply mass-to-light ratios, which are best differentiated by color measurements in the optical bands as they are a strong function of stellar populations. Consequently we are using both the Johnson B and V filters, which are suited for measuring galaxy interactions (Wallin et al. 1990), to map the luminosity as well as color. Moreover, my collaborator, Rev. Resbo, has collected measurements in infrared bands for each galaxy in our proposed sample. Infrared band photometry is sensitive to dust and gas and will be used in conjunction with the optical data to measure not only the stellar populations composing the galaxy but all baryonic components (Kennicutt 2016).

There are expected differences between stellar and non-stellar galaxy components resulting from galaxy interactions. For instance, shock heating of the gas by dynamical friction can dramatically alter the mass distribution (Hernquist & Mihos 1995; Athanassoula 1994). We will thus use both stellar and gas / dust distributions to probe signatures of binary spiral interactions.

Altered star formation, particularly starbursts, is a hallmark of galaxy interactions
Keel 1991). Strong tidal interactions between galaxies create disk instabilities, driving rapid star formation. The starbursts contribute a large fraction of the total luminosity of the galaxy, 25 percent on average, but occasionally near 60 percent (Kennicutt 2016). Due to the luminosity, single band photometry can indicate the presence of starbursts, but is unable to distinguish between naturally bright regions and those created by the interaction. As young stellar populations are bluer than the surrounding environment, through the difference between isophotal fits in the B, V and IR we will be able to map the starburst regions (Schombert et al. 1990). Specifically, a starburst will increase the local surface brightness, resulting angular alignment of the isophotes an increase in the semi-major axis, as well as isophotal decentering. Starburst affect the B isophotes more than the V or IR, so the starbursts may be mapped using the difference between the isophotes.

Interacting galaxies live in one another’s gravity well and, depending on distance, experience a non-trivial gradient across the disk. Countered by the self-gravity of the disk, the inner regions of the spiral will be less affected than will the outskirts. In the center-of-mass frame the galaxy experiences tidal distortions which cause disk elongation towards the other galaxy. This asymmetry manifests as a change in isophotal ellipticity. By imaging both spiral galaxies in the interacting pair we will be able to correlate the galaxy interactions as well as apply coincidence detection techniques. This should allow us to isolate interactions caused by each galaxy, rather than the environment in which the pair are situated, by looking for consonance in the orientation and positioning of the isophotes in each galaxy. For instance, the disk semi-major axis should preferentially align between the galaxies. The rotation of each disk will likewise rotate the axis, but since the outskirts are more strongly affected than the center, the outskirt axis will rotate more slowly, winding the axis. Consequently, for a binary spiral pair there should be a radial winding of the position angle of the isophotes and mass distribution as the rotation of the disk is counteracted by the gravitational attraction towards the second spiral. Observing a similar winding in the second galaxy, adjusting for the relative strengths of the galaxies’ gravity, is proof positive of an interaction between the galaxies and not from the environment. A qualitative study of isophotal winding was conducted in (Kennicutt 2016; Kennicutt et al. 1987) showing a strong spiral patterns in the close galaxy pairs. Our study should provide quantitative analysis of this phenomenon. With reference to starbursts, simultaneous detection of starburst activity might help resolve the debate of possible time delays between interacting galaxies of starburst activity. (Bernloehr 1993) finds that the smaller galaxy in interacting pairs is more likely to be undergoing starburst activity and that the larger galaxy may lag in enhanced star formation by nearly 100 million years. (Telesco et al. 1988) find the opposite result when observing in the IR. By taking optical as well as IR photometry of strongly interacting systems we hope to resolve this discrepancy.

There are natural asymmetries which form in the disk without interaction progenitor events. For instance, central bars are a natural asymmetry. Using the techniques outlined in (Márquez et al. 1999) we can account for the effects of bars on isophotal symmetry (Jedrzejewski 1987). Another form of natural asymmetry is disk lopsidedness. (Zaritsky et al. 2013) shows that lopsidedness is a generic feature of spiral galaxies, though interactions may likewise drive a lopsided mass distribution. To determine whether any observed disk asymmetries are specific to interacting galaxies or properties of spirals in general, we will also take photometry data for 5 isolated non-interacting spiral galaxy. Through bootstrap methods keeping the ratio of sample to control constant we can minimize the effects of nuisance parameters on the analysis while simultaneously isolating global versus interaction specific properties.
Figure 1: This frog was uploaded via the project menu.

Figure 2: LEDA 62867 and NGC 6786, hubblesite.org/image/2289/newsrelease/2008^16.
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**Technical Description of Observations**

We propose to image a dataset of 50 face-on binary interacting spiral galaxies as well as 5 isolated non-interacting spiral galaxies. We target pre-merger interacting spirals which are distant enough from each other to retain strong spiral characteristics. Surveying the Catalogue of Isolated Galaxies, and Isolated Pairs, a subset of the SDSS by Argudo-Fernández et al. 2015, pre-merger isolated spirals are relatively rare. Exhibiting strong effects of interactions without actively merging represents a small percentage of the total interaction time. The rarity of suitable binary galaxies translates to galaxies in the sample are at distances around 100 Mpc. At these distances, the sample galaxies span a range of integrated apparent magnitudes, from around 12 to 15th magnitude in the B band.

An example pair of spiral galaxies from the data set are NGC 6786 and LEDA 62867 (Argudo-Fernández et al. 2015), shown in Figure 1. NGC 6786 and LEDA 62867 are nearly 100 Mpc away, using Hubble flow distance estimation (de Vaucouleurs et al. 1991). Each galaxy subtends over 70 arcseconds to the 25 mag/sq asec isophote and are separated by a few arcminutes. On the 4m Mosaic Imager, with 0.′′26 [pixel\(^{-1}\)], both galaxies are well resolved spatially. The total B band magnitude of NGC 6786 and LEDA 62867 is 13 and 14 mags in the B band, respectively (de Vaucouleurs et al. 1991). Like all galaxies in the sample, NGC 6786 and LEDA 62867 are Northern objects; NGC 6786 is at a RA and Dec of 19h10m53.9s, +73d24m37s. A subset of the galaxy sample is isolated non-interacting spiral galaxies, serving as a control group. An example such galaxy is NGC 2649 (Argudo-Fernández et al. 2015) shown in Figure 3. NGC 2649 is 12 magnitude in the visual bands, and located at an RA & Dec of 08h44m08.271s, +34d43m02.08s (2007SDSS6.C...0000).

As discussed, the effects of interactions manifest with increasing strength at larger galactocentric radii. Considering the time constraints imposed by observing past ~27 magnitude surface brightness compounded with the need for statistically significant results, we will take B and V photometry from ~20 up to 27 mag / sq asec, covering to approximately 5 radial scale lengths. Given the median distance to the galaxies in the sample, the 4m Mosaic Imager’s 36 arcmin field of view is capable of simultaneous imaging of both spiral galaxies as well as enough sky for calibration purposes. This is important for cross-correlation of isophotal properties of each galaxy in the pair to one another as well as comparison between galaxy pairs. While starbursts in galaxies may brighten a region by appreciably over a magnitude, other effects, discussed previously, which contribute to a galaxy’s isophotes, are much subtler. This is especially true at smaller radii. To make meaningful inferences about interaction effects using photometry only out to \(\mu_V = 27\) [mag/sq asec] we need to achieve magnitude errors ~0.1 mags, translating to a signal-to-noise of 10.

The main justification for choosing the 4m Mosaic Imager rests on the necessity to collect a statistically significant sample of galaxies out to 22nd B and V magnitudes. For a sample of 55 galaxies at relatively low surface brightness, each exposure must be relatively rapid. This has the added bonus of reducing inter-measurement sky variation. We propose to take measurements for 4 half-moon nights on July 17th-20th, 2018. The B and V band measurements will require 7.5 and 8 minutes per galaxy (pair), respectively. Splitting this into two exposures allows for “dithering” on the CCD to reduce CCD pattern effects. Allowing for 10 minutes overhead between exposures for readout and setup, each galaxy measurement in the sample requires 25 minutes, totaling 24 hours. July 17th-20th, 2018 should offer 6 hours per night of viable observation time, requiring 4 nights in total to image the whole galaxy survey.
ABSTRACT

We propose to study the Milky Way globular cluster NGC 6934 using optical broadband photometry on the Kitt Peak four-meter telescope. By constructing a $m_V$ versus $V - I$ color-magnitude diagram and fitting theoretical stellar isochrone models to the observational data, we can derive the cluster’s age and metallicity. The properties of globular clusters in the Milky Way’s halo, such as NGC 9634, can constrain models of galaxy formation and stellar evolution.

SUMMARY OF OBSERVING RUNS REQUESTED FOR THIS PROJECT

<table>
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<th>Run</th>
<th>Telescope</th>
<th>Instrument</th>
<th>No. Nights</th>
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<th>Optimal months</th>
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<td>Jul–Aug</td>
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</table>
**Scientific Justification**

Globular clusters are extremely close to simple stellar populations: stars formed at one point in time of the same chemical composition (Jimenez 1998). This makes them prime observational targets for studying stellar populations and stellar evolution. With thousands of stars densely packed within a few arcminutes, rich color-magnitude diagrams can be obtained by broadband photometry. Because the stars all have the same age and metallicity, these parameters can be found by matching theoretical stellar isochrones to globular cluster color-magnitude diagrams. This comparison can also verify the validity of theoretical models.

Age, metallicity, distance, and galactic extinction are all degenerate to some extent, affecting the color and/or luminosity of the observed stars and therefore the best fit isochrone. We can correct for galactic extinction in this direction using the estimates of Schlafly and Finkbeiner (2011). Although main sequence fitting can yield a ballpark distance, more reliable distance estimates have been obtained from variable star studies. By adopting values for distance and galactic extinction from other techniques, we can focus the isochrone fits to measure age and metallicity.

We know globular clusters must be old because their main sequence turnoff points correspond to stars with less than one solar mass (Jimenez 1998). The main sequence turnoff point on the color-magnitude diagram tells us the youngest remaining stars in the cluster, and thus the age of the cluster. Globular clusters are also generally of low metallicity, less than 1% that of solar. Though some globular clusters are found in the bulge of the Milky Way, most globular clusters in our galaxy are evenly distributed in the halo.

Possible models for halo formation include a rapid collapse of a proto-galaxy (Eggen et al 1962) and a piecemeal assembly from separate clouds of gas (Searle & Zinn 1978). The spread in the age distribution of globular clusters provides evidence for one model over the other. Harris et al (1997) suggest that the Milky Way globular cluster age distribution is strongly peaked in a 1 Gyr range, around 14 Gyr (though the absolute uncertainty in age is larger). Chaboyer et al (1996) instead find a 5 Gyr range of ages, with a relation between age and metallicity, with the oldest globular clusters being most metal-poor. Additional research is needed to pin down the absolute ages of globular clusters and definitively distinguish between these models.

In constructing the color-magnitude diagram to measure age and metallicity, there are substantial advantages to using the $V - I$ color index, rather than the typical $B - V$ color index. Since globular clusters consist of red stars which are brighter at red wavelengths than blue wavelengths, the required exposures are not as long in $I$ as they would be in $B$. The line opacity in the red and near infrared is substantially less than in the blue (Kurucz et al 1987). Theoretical isochrone models are more reliable where the continuum is less depressed and the contribution from metal absorption lines is lower (Alcaino et al 1989). Additionally,
the greater separation of the central wavelengths of $V$ and $I$ filters produces a wider color baseline. This assists in separating out stellar isochrones by age and metallicity.

The particular cluster NGC 6934 is a good candidate for observation, located in an environment with few field stars away from the center of the Milky Way (Harris & Racine 1973). Yepez et al (2017) report a distance of $(16.03 \pm 0.42)$ kpc to NGC 6934, derived from 64 RR Lyrae stars. This distance is in agreement with the publications of Hessels et al (2007) and Kaluzny et al (2001). Adopting this precise distance measurement decreases our parameter space so we can better derive the age and metallicity of the globular cluster. We will also adopt Schlafly and Finkbeiner’s extinction measurements of $A_V = 0.289$ and $A_I = 0.159$. The extinction is mild because we are looking out of the galactic plane.

NGC 9634 has galactic longitude $+52.10$ and galactic latitude $-18.89$. A distance measurement of 16 kpc places it roughly 12 kpc away from the galactic center and 5 kpc out of the galactic plane. Clearly it is not part of the Milky Way’s bulge; this location suggests that the cluster is part of the galactic halo. Deriving the age for the cluster will provide a timescale for halo formation, and also place a strong lower bound on the age of the universe. The age and metallicity measurements from this project will constrain models for the early formation of the Milky Way.

**Figures and References**

- Jimenez, R. PNAS, 95, 13 (1998)
**Figure 1.** An example color-magnitude diagram for a globular cluster, with plotted isochrones (Alcaino et al 1989).

**Figure 2.** The globular cluster NGC 6934, inverted HST image, $3.5 \times 3.5$ arcmin.
Technical Description of Observations

The globular cluster NGC 6934 is located in the constellation Delphinus, with coordinates of $\alpha = 20^h34^m11.49^s$, $\delta = +07^\circ24'14.8''$ (J2000). Thus, it is best observed from the Northern Hemisphere in late July or early August; throughout each of those months the object is below 1.5 airmasses for at least five hours during the night.

To create a useful color-magnitude diagram of the resolved stars, we must be able to discriminate color differences of 0.1; this means that any measured color must have an uncertainty less than 0.05. Therefore, the uncertainties on our measured magnitudes in $V$ and $I$ must be less than 0.025, corresponding to a S/N of 40. Using stars from the SDSS catalog as reference standards, we can obtain photometric solutions accurate to 0.025 magnitudes, without needing to observe standard stars in separate exposures.

The 4m telescope is necessary to observe the faint end of the main sequence, K7V stars, with a S/N of 40. These faint stars have absolute magnitudes of $M_V = 8.2$ and $M_I = 6.7$. Since the distance modulus for NGC 6934 is $(m - M) = 16.0$, we need to observe absolute magnitudes of 24.2 in $V$ and 22.7 in $I$. Looking through 1.2 airmasses with a typical seeing of 1.1 arcsec and a 10 day moon, a 9000 second exposure can reach S/N = 40 for a star with $m_V = 24.2$. This is best accomplished with ten exposures of 15 minutes each. Even on a dark sky, obtaining sufficient signal-to-noise ratio for such faint stars would be prohibitively expensive on a smaller class of telescope.

However, we also need good photometry for the brighter stars in the cluster. Stars brighter than $m_V = 20.5$ will saturate on a 900 second exposure, so we must also take shorter exposures. A 20 second exposure will obtain the requisite S/N = 40 for stars of $m_V = 20.5$, yet stars of $m_V = 16.2$ will still saturate. The brightest red giants will have $m_V \approx 14$, so we will add a 2 second exposure as well.

In the $I$ band under the same photometric conditions, a star with $m_I = 22.7$ can be reached with a 2700 second exposure, or three exposures of 15 minutes each. We will also take short exposures in this band for the red giants.

Altogether, adding 20% extra time to account for overhead (such as setup and flat-fielding), this project requires five hours of observing time. Thus, these observations can be accomplished in a single night of grey time in July or August.
Probing the distance to M33 through Cepheid variable stars

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**Status:** S  
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**Abstract:**
I propose observations of Cepheid variable stars in the Local Group galaxy M33 in order to derive a distance measurement. Cepheid variable stars are essential standard candles in the distance ladder framework for measuring extragalactic distances. Accurate measures to nearby object serve as tests for applying the same methods to farther galaxies, and errors to nearby objects likewise propagate up the ladder. I plan to obtain accurate light curves for a large sample of Cepheids in M33 over two staggered observing runs in order to get the best possible estimation of their periods. Using the latest calibrations for the Cepheid period-luminosity relation from the literature, I will derive a distance to M33 and later incorporate additional infrared photometry to further constrain the periods of the served stars, improving the distance estimate further.

**Summary of observing runs requested for this project**

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Scientific Justification:

Without knowing the distance to astronomical objects, the amount of interesting science that can be done is significantly reduced. Currently, cosmology is an active topic in astronomy, which studies the geometry and structure of the universe primarily through tracing the distribution and clustering of galaxies. The first step to measuring the distances to distant galaxies is to accurately determine the distances to nearby objects where one can employ techniques to infer the intrinsic luminosity of stars. One such method is the use of Cepheid variable stars. I propose to measure the light curves of Cepheids in M33 in order to derive a distance measurement that can will be useful in calibrating distance measurements to more distant objects.

Obtaining accurate distances to nearby objects is essential for then measuring much farther objects based on the astronomical distance ladder (de Grijs, 2012). For the closest objects within the Milky Way, geometric parallaxes provide an absolute measurement independent of the properties of the object being observed with the weakness that it cannot be applied to very distant objects. For objects that are too far for the parallax method, standard candles are crucial to determining distances as well as calibrating empirical relations such as Tully-Fisher and the Fundamental Plane, methods for finding absolute properties of spiral galaxies and ellipticals, respectively. Standard candles are light sources whose absolute magnitudes can be determined through models or empirical relations. Of utmost importance in finding and utilizing a standard candle is reliability and accuracy. Cepheid variable stars fulfill both of these criteria and have been used to measure distances to star clusters within the Milky Way as well as in other galaxies (de Grijs, 2012). Being able to effectively use Cepheids as distance indicators in the local universe reduces the errors involved when utilizing them for more distant objects.

Cepheid variable stars are a crucial rung on the distance ladder framework for measuring extragalactic distances. Cepheid stars are former O and B stars that have evolved to reside within the instability strip. This is a region on H-R diagrams where stars vary in radius and thus luminosity in a regular, observable fashion. Cepheid variable stars are among the most luminous of variable stars and are useful in measuring distances to nearby galaxies owing to their ease of detection. They obey a period-luminosity relation (Leavitt & Pickering, 1912) which can be used to find the mean luminosity of the star by accurately constraining the period of fluctuations, allowing the star's distance to be deduced if the relation is properly calibrated (Subramanian et al. 2017). Calibration of the period-luminosity relation via the distance to the Large Magellanic Cloud (LMC) has been enhanced by the work of Pietrzyński et al. (2013).

Cepheid distance measurements are not without additional systematic effects. Observationally, reddening, crowding, and metallicity affect the observed flux and thus the derived distance measurements and introduce a scatter on the published distances for objects such as M33 (de Grijs & Bono, 2014). Properly accounting for something such as reddening for Cepheids is made more difficult because the young stars are more likely to be found in dusty star forming regions, requiring not only an estimation of the Milky Way's galactic extinction, but also the extinction within the target galaxy as well. This problem can be alleviated somewhat by shifting observations to longer wavelengths at the cost of lower amplitude variability (Subramanian et al. 2017). I will be working with a collaborator that is obtaining infrared photometry of M33 for the purposes of tightening the period-luminosity relation into the period-luminosity-color relation which gives a tighter fit to the derived intrinsic luminosity of Cepheid variables as well as being immune to extinction effects (Udalski et al. 1999).

There is some disagreement within the literature as to the effect of metallicity on the Cepheid relations and thus any distance measurements derived from them (Subramanian et al. 2017). The metallicity of the surrounding interstellar gas can be used to estimate the metallicity of any observed Cepheid, but this introduces a systematic uncertainty to any derived values from the Cepheid luminosity. The extent of the metallicity dependence has been difficult to quantify, as shown by the efforts to accurately measure the Hubble Constant by Freedman et al. (2000). Additional absolute
measurements of distances to Cepheids of various metallicities such as those proposed by Subramanian et al. (2017) via comparing the Cepheid populations in the Milky Way, LMC, and Small Magellanic Cloud are potential future solutions to this issue. For the purposes of my study, I will be utilizing radial metallicity measurements of M33 as obtained by Magrini et al. (2010) as estimates for the metallicity of observed Cepheids in order to investigate any correlations between metallicity and period.

M33 is a small spiral galaxy within the local group along with the larger M31 and Milky Way. As M33 is the second-closest spiral galaxy that can be observed for calibrating the Tully-Fisher relation, an accurate distance measurement to M33 is extremely important for finding the distance measurements to more distant spiral galaxies. The distances to galaxies outside of the local group are the tracers of modern cosmology, allowing values such as the Hubble constant, $H_0$, to be determined with ever-increasing precision as the measurements to nearby objects improve with time (Pietrzyński et al. 2013). I will utilize LMC Cepheid distances as a zero point calibration in my derivations of a distance measurement to M33.

With measurements of the light curves of several Cepheids in M33, I will be able to fit a light curve to my observations and have an estimated period from the fit. Using calibrations in the literature (Udalski et al. 1999), I will be able to set the slope of the period-luminosity relation and from the distance to the LMC, I can then derive a zero point to the relation. With the fit, I can then derive distance measurements to M33 with the periods that I measure. The period-luminosity relation by itself does have a fair amount of scatter, but by incorporating the data I obtain here with infrared observations, the derived distance measurements are expected to improve.

![Figure 1](image.png)

**Figure 1:** An example phase-folded light curve from a Cepheid in M33 from Pellerin and Macri (2011). The different colored dots are measurements taken with different telescopes. The lines are the best fits to the respective colored dots.
Figure 2: A GALEX image of M33 overlaid with the two fields being targeted in this proposal. The coordinates of the targets that will be used in this study are those found in Pellerin and Macri (2011).
Experimental Design:

For my project, I will need to observe two regions of M33 several times a night over multiple observing runs in order to obtain accurate light curves for Cepheid variable stars. From the Cepheid Survey conducted by Pellerin and Macri (2011), I consider an average Cepheid in M33 to be 22 m\text{V} in Vega magnitudes with an average amplitude of variability of 0.4 m\text{V}. In order to be able to accurately determine this variability, I am requiring a minimum signal-to-noise ratio of 27. This will allow me to accurately identify variable stars at the ±0.04 magnitude level. With stars of this brightness, an exposure time of thirty minutes will be sufficient to get over a minimum signal-to-noise ratio of 27. These preliminary calculations all assume observing during a new moon, an average airmass of 1.2, and an optimal seeing of 1 arcsec. In order to maximize Cepheid identification, I will be observing in the Johnson V filter as the amplitude of Cepheid oscillations are generally greatest in V as shown by Pellerin and Macri (2011). Observations in another filter, particularly in the infrared, would offer another verification of the period of the Cepheids. I will be working with collaborators with observation time on the Spitzer Space Telescope who will be able to get infrared observations of M33 Cepheids that are less encumbered by dust extinction.

The WIYN 0.9m telescope is large enough to image approximately half of M33 at once. The field of view is sufficient such that the sample size of Cepheids is only magnitude limited. M33 is above 1.5 airmasses for approximately 7 hours in September and 5 hours in November, leaving enough time for observing each of the two regions multiple times a night as well as standard stars in between. The project is, however extremely sensitive to the sky background and thus the moon phase as it is imperative that the photometry does not obfuscate observed Cepheid variability. As a result I am requesting the darkest possible times to extend the observations to the dimmest possible stars.

As this project requires photometry of individual stars, the resolution of the telescope is of some importance. The WIYN 0.9m does have a smaller pixel scale, meaning that a point source will lie on fewer pixels and introduces an issue with resolvability. Due to this, the observations are more dependent on favorable seeing conditions; an increase in the seeing radius would more easily cause adjacent stars to become ambiguous on the 0.9m as opposed to the 4m. This problem is dealt with by observing as many Cepheids as possible as to not lose a significant portion of the sample to crowding. Significant time afterwards will also be devoted to accurate point spread function fitting for stars affected by crowding.

By requesting two observing runs separated by around a month, I am better able to constrain the periods of the stars. Cepheid stars have periods on the order of days to tens of days, and thus a single observing run on consecutive nights runs the risk of sampling the oscillations at the same time per period, causing aliasing in the data set. In addition to aliasing, the staggered observation runs allows the period to be more accurately constrained. Slight errors in the fitted light curve from the first round of observations will show significant phase shifts from the observations in the second round if the periods are wrong. To properly account for all of these issues, I propose to spread out the observing runs over several periods of the stars to sample their light curves at various locations.

Significant time will also be spent on obtaining good calibration images such as dome flats and zeros. The accuracy of the photometry is key to getting most of the uncertainty in the derived distance calculations to be from the fitted light curves and period-luminosity relations.
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Observing Proposal

Date: 14 November 2017

Finding the period of RR Lyrae variable stars in M92 (NGC 6341)

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We propose imaging of the globular cluster M92, specifically targeting at least one of its RR Lyrae variable stars in order to discover the star(s) period. The period of an RR Lyrae star can be used to infer several properties, including general composition and distance. Knowing this information can give insight into star formation history, and the structure and formation of our galaxy.

Summary of observing runs requested for this project:

1. 2 consecutive nights in May - Jun, any moon phase
2. 2 consecutive nights in Jul - Aug, any moon phase
Scientific Justification

RR Lyrae stars are a type of variable star that form from low mass stars that have aged into the horizontal branch (Smolec et al 2017). They are slightly smaller than the sun, averaging a mass of between 0.5 - 0.8 M\(_\odot\) (Bono et al 2007). These stars have short periods due to their low mass, often one day or less. The short periods mean that they are rather faint, largely too faint to be detected outside of the Milky Way galaxy. However, given their presence in many globular clusters, they can be useful tools within the galaxy, giving us important information about distances and galactic structure.

RR Lyrae are the most common type of variable star found in globular clusters, and seem to exist within globular clusters regardless of the density, brightness, or metallicity of the cluster\(^1\) (Clement et al 2001, Shapley et al 1927). Since they are standard candles, and are relatively common within metal-poor populations of our galaxy, RR Lyrae stars are very good for finding distances to globular clusters. In fact, they are one of the primary distance indicators for Population II stars (De Principe et al 2005).

Cepheid stars, another common type of variable star, follow a period-luminosity relation which is used directly to find distances. While there have been attempts to fit a period-luminosity function based on calculations derived from the Horizontal Branch (Catelan et al 2004), RR Lyrae stars only have consistent period-luminosity functions in the near infrared, not in the visible range (De Principe et al 2005). RR Lyrae stars do follow a period-color relation within the visual bands. The period and the color are both found through observation. The stars are then compared to isochrone data on a color-magnitude diagram, which is used to find the distance to the cluster. There have been attempts to fit a period-luminosity function based on calculations derived from the Horizontal Branch (Catelan et al 2004) but we are choosing to go the more direct route.

Galactic variable stars have long been of interest to the scientific community, at the latest since Sawyer (1939) published a catalogue of known variable stars. The study of RR Lyrae stars in globular clusters in our galaxy can provide numerous insights. They are old, metal-poor stars, in fact some of the oldest in the Milky Way. It is because of this that they have long been used to gather information about the

\(^{1}\) It should be noted that, although the presence of RR Lyrae stars is not dependent on the structure or composition of the cluster they are in, the subtype of RR Lyrae star is (Oosterhoff 1939). While an important note for some studies, it has not been deemed especially relevant to this observation.
age of the galaxy, namely to establish a lower limit. They have also been used to study stellar evolution.

The distance to these stars, and the clusters that contain them, can reveal much about the structure of our galaxy, which can give information of its formation history (Clement et al 2001). Knowing more about the formation history of our own galaxy can help us infer more about the formation of other galaxies, which is important to our understanding of how the universe builds structure. Furthermore, the distances derived from RR Lyrae stars can further help calibrate the distance ladder, especially with programs such as GAIA finding parallax values for stars in many globular clusters (Bono 2003).

We will be viewing globular cluster M92, an old and metal-poor cluster. The cluster has 17 RR Lyrae variables, at least one of which does not have a well-measured period (Del Principe et al 2005, Clement et al 2001). My collaborators and I are planning to schedule times at other telescopes to find the color and metallicity of several of these variable stars. We will then be comparing our results to a Horizontal Branch synthesis. With these measurements, we will be able to figure out the distance to the cluster, as well as an approximate age and metallicity of the cluster.
Figure 1: The known periods of RR Lyrae stars in globular clusters, as compiled by Clement et al (2001). The two different plots are indicative of a division by subtype of variable star, based on metallicity. M92, a very metal-poor cluster, is an Oosterhoff II type globular cluster (Lee et al 1990).

![Figure 1](image)

Figure 2: Synthetic Horizontal Branch of M92, created by Lee et al (1990). We will be using a similar technique to analyze our data from these observation.

**References**


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Technical Description

We wish to observe globular cluster M92 with the WIYN 0.9 m telescope at Kitt Peak. We will be using the HDI imaging camera, with 4096x4112 CCD with 0.43 arcsec pixels. The cluster itself is bright, being visible with the naked eye under the right viewing conditions. It has a half light radius of 1.09' and a tidal radius of 15.07', which both fit within our field of view (29.2'x29.2'). The stars we are interested in tend to have average magnitudes of $M_v = 15.08$ (Kopacki 2001). The 0.9 m telescope gives us sufficient resolution of stars at this brightness with acceptable signal-to-noise values (greater than 10). The flat-field will be done with twilight-sky flat fielding techniques.

The observations will take place over two observing periods, each two nights long. Since the periods of RR Lyrae stars are so short, we will be taking images of our chosen star(s) every hour over the course of each night. The individual image exposure times are fairly short (20 minutes each), but we need many of them over time in order to obtain the data we require. The first two nights of observing are to establish the period and luminosity of the star(s). The next two nights, at least one month later, are to check for any long term variability the star may show. This, along with the data my collaborators and I are gathering elsewhere, will give us the information we need.