OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

Probing the Upper Initial Mass Function in Nearby Dwarf Galaxies

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Abstract of Scientific Justification

We are proposing 3 nights using the MMT Blue Channel spectrograph to obtain optical spectra of stellar clusters in 18 nearby dwarf galaxies. Dwarf galaxies are sensitive laboratories for testing theories of star formation, and for investigating possible variations of the stellar Initial Mass Function. Establishing whether the IMF, in particular the upper end of the IMF (uIMF), is invariant or dependent upon the conditions of star formation is key for interpreting the vast majority of observations on galaxy evolution, and for understanding cosmic reionization. The combination of the wavelength coverage of the 300 l/mm grating and the robustness of stochastic stellar synthesis models will allow precise age and mass determinations of the roughly 70 stellar clusters in this sample. These data will be essential to providing a definitive test of recent claims that the uIMF in dwarfs may be at variance with that of massive galaxies.

Summary of observing runs requested for this project

								Scheduling		Sharing	
Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Optimal	Acceptable	Poss.	Adv.
1	MMT	f/9	Bluechannel			3	dark	Apr	March–May	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: None

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	UGCA292	12:38:40.0	+32:46:01	Clusters
2	UGC8024	12:54:05.3	+27:08:59	Clusters
3	UGC8215	13:08:03.6	+46:49:41	Clusters
4	UGC8760	13:50:50.6	+38:01:09	Clusters
5	UGC8833	13:54:48.7	+35:50:15	Clusters
6	UGC9128	14:15:56.5	+23:03:19	Clusters
7	UGC9240	14:24:43.4	+44:31:33	Clusters
8	UGC8091	12:58:40.5	+14:13:02	Clusters
9	CGCG-269-049	12:15:46.6	+52:23:14	Clusters
10	UGC8651	13:39:53.7	+40:44:25	Clusters
11	NGC4163	12:12:09.1	+36:10:09	Clusters
12	UGC8638	13:39:18.8	+24:46:31	Clusters
13	NGC3741	11:36:06.1	+45:17:08	Clusters
14	UGC6817	11:50:53.0	+38:52:51	Clusters
15	UGC7577	12:27:41.9	+43:29:39	Clusters
16	UGC6541	11:33:29.1	+49:14:17	Clusters
17	UGC7605	12:28:38.5	+35:43:00	Clusters
18	NGC4190	12:13:44.2	+36:37:53	Clusters

Approval for Instrument Use from PI: N/A

Graduate students *(provide the following information for* ***each*** *student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on* ***all*** *submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

The blueprint of how stars are formed, better known as the stellar initial mass function (IMF), is one of the most essential quantities in astronomy, yet its functional form and universality is still under much debate. In the local Universe, low–mass, gas–rich, star-forming dwarf ($M_{*} \lesssim 10^8 M_\odot$) galaxies show a deficiency of up to an order of magnitude in the ionizing photon rate per unit UV or optical luminosity relative to their higher mass and star formation rate (SFR) counterparts (e.g., Hoverstern & Glazebrook 2008, Meurer et al. 2009, Lee et al. 2009). One proposed scenario to explain underluminous Hα suggests that low–SFR galaxies only form low–mass clusters, which are systematically deficient in high–mass, ionizing stars (Weidner, Kroupa & Bonnell 2010), thus mimicking the effects of a variable uIMF. Unlike the outer disk regions of high/medium–SFR galaxies (Koda et al. 2012), dwarf galaxies represent overall isolated systems where we can uniquely test possible global variations of the upper end of the stellar IMF (uIMF). By measuring the relative ionizing photon rate per unit cluster mass as a function of cluster mass for the dwarf galaxy cluster populations this scenario can be tested. We are proposing MMT Blue Channel observations of 18 nearby (< 5 Mpc) dwarf galaxies (see Figure 1 for some examples) to obtain long-slit spectra of stellar clusters in order to determine whether the uIMF in dwarf galaxies is systematically depleted of the most massive stars relative to more massive galaxies.

The IMF can be measured nearby in the Milky Way, Large Magellanic Cloud (LMC), and Small Magellanic Cloud (SMC) by counting the individual stars in clusters young enough ($\leq$ 3-5 Myr) that the most massive stars still remain (Sirianni et al. 2000, Sabbi et al. 2008, Anderson et al. 2009). Unfortunately past $\sim$ 50 kpc, resolution becomes problematic even with the *Hubble Space Telescope* (HST), and mass segregation may cause the more massive stars to sink towards the center of the cluster, where it will be harder to distinguish individual stars, while at the same time low mass stars are generally harder to count, due to the inability to easily detect smaller, fainter stars (Ascenso et al. 2009, Maíz-Apellániz 2008). The use of individual star counts is not necessary to constrain the upper end of the IMF, as we have demonstrated in Calzetti et al. (2010) and Andrews et al. (2013, 2014). Instead, we measure Q(H^0), the hydrogen ionizing photon rate, from the young, coeval stellar clusters which is equivalent to measuring the number of massive stars. Variations in the uIMF can have far–reaching impact on our ability to determine the star formation rates (SFRs) of unresolved galaxies, especially when using tracers of ionizing stars (e.g., Hα).

Compact star clusters are ideal sites for uIMF measurements (Massey 2003), as they represent a non–negligible ($\approx$10% or larger) fraction of star formation (Silva–Villa & Larsen 2011), and their massive star populations are, in first approximation, coeval. We will derive masses and ionizing photon rates for all **young** compact clusters within a sample of 18 nearby ($\leq$5 Mpc) dwarf galaxies that span SFRs (0.001–0.013 $M_\odot$/yr), metallicities (median$\sim$0.12 $Z_\odot$), and SFIs (0.0002–0.003 $M_\odot$/yr/kpc^2.) In addition to the rapid evolution of massive stars, observing clusters at young ages is necessary to get a full census of the stellar population as up to 80% of stellar clusters experience early mass loss and do not survive longer than 10 Myr (Lada & Lada 2003, ”infant mortality”). Using the optical spectra obtained at the MMT we will derive cluster luminosities, and the extinction–corrected (from Hα/Hβ) ionizing photon rate. The stellar spectra of the clusters will then be compared to stochastic SLUG (da Silva et al. 2012, Stochastically Lighting Up Galaxies) models to obtain ages and masses. The SLUG models create stellar clusters of any size, metallicity, and IMF and populate them via Monte Carlo methods (Figure 2.) Commonly used deterministic models (such as Starburst 99; Leitherer et al. 1999) assume a fully sampled stellar initial mass function, which for smaller mass clusters ($< 10^4 M_\odot$) could lead to the inclusion of unphysical fractions of stars. Stochastic models are important, especially at the low cluster mass end since as cluster size decreases, the influence of the massive star or stars in the cluster becomes much more prominent. The use of stochastic models here will provide us more robust analysis, especially in those clusters which may be dominated by just one massive ionizing source.

In a $M(max)_* - M_{cl}$ relation of Weidner et al. (2010), the summation of the total ionizing flux from the small clusters divided by the total cluster mass should be much lower than the ionizing flux from a single large cluster divided by its mass and as cluster mass decreases there is a deviation from the ratio of ionizing photons to mass expected by a universal IMF (Figure 2, dashed-dotted line). Whereas in an universal IMF scenario this summed ratio would be consistent with that of a single large cluster. The MMT spectra proposed here will not only allow us to determine luminosities, ages, and masses of the clusters, but we can also obtain accurate extinction corrections using the Hγ, Hβ, and Hα if the emission lines are present - as they most likely will be for the youngest clusters. Stellar and ionized gas components need to be corrected independently for the effects of dust extinction, because of the well–known differential attenuation present in the two, as shown for galaxies across a wide range of properties (e.g., Calzetti et al. 2000, Kreckel et al. 2013.) If in the event the HII region is too faint or possibly too extended to be measured within the slit, Hα and Hβ imaging exists for many if not all of the galaxies. The existence of other emission lines will also make it possible for us to obtain cluster-specific metallicities (in comparison with the galaxy-wide metallicity) to obtain even more accurate ages and masses as discussed below.

For accurate age determination, blue wavelengths are absolutely necessary to break degeneracies particularly in the youngest clusters. The 300 l/mm grating on the Blue Channel will allow us to get as far blue-ward as 3200 Å. Therefore we will encompass the Balmer jump, the depth of which is extremely sensitive to age. This wavelength range also has the added benefit of providing us with the [O II] λ3727 emission line, which combined with Hβ and [O III] $\lambda\lambda$ 4959,5007 can provide a measure of 12 + log(O/H). Therefore we can internally calibrate the gas-phase metallicity using the nebular oxygen abundance for each individual cluster. The use of long-slit is preferred to MOS to allow for observation of the stellar cluster and the nebular emission surround it and due to the plethora of fields and paucity of targets per field. Each galaxy only has between 2-6 young, bright clusters with noticeable hydrogen emission (see Figure 1.) By utilizing the long slit-length and the slit position angle (PA) we can position the slit in a way to get at least two clusters at a time. This means that for any one galaxy we would only need to use three pointings with the appropriate PA to obtain spectra of the total young cluster population.

As demonstrated in Andrews et al. (2013, 2014), we have utilized a reduced χ^2 fitting technique for the SLUG and the cluster photometry to determine the age, mass, and extinction of each cluster. We will employ the same procedure here, comparing the cluster spectrum to models spanning a complete reddening range appropriate for each cluster. By using spectra, as apposed to 5 or 7 band photometry, we will be able to get more accurate fits. SLUG will even allow us to output cluster SEDs with the same resolution (6 Å) as the MMT spectra. The masses will then be able to be combined with the ionizing photon rate, normalized to a common metallicity, and combined into a mass bin similar to that shown in Figure 2. The low SFRs of these dwarf galaxies should allow us to probe further down into the low mass regime where the discrepancy between universal and cluster-mass dependent IMF is the most severe. The large galaxy sample size guarantees large number statistics ($\sim$ 70 clusters) in order to average out stochastic variations in the IMF sampling that any one given star cluster will suffer from, and for which would be problematic if only observing one or two galaxies that may only have 4-5 clusters.

The observations proposed here will shed light onto whether the uIMF in dwarf galaxies is systematically depleted of the most massive stars relative to more massive galaxies. By combining constraints from the ensemble–average $\langle Q_0 \rangle / \langle M_{cl} \rangle$ normalized for metallicity we will be able to discriminate between an universal uIMF and a massive–star/cluster mass trend for the uIMF (e.g., Weidner et al. 2010).

REFERENCES

Anderson, J. et al. 2009, ApJ, 697, L58
Andrews, J.E., et al. 2013, ApJ, 767, 51
Andrews, J.E., et al. 2014, ApJ, 793, 4
Ascenso, J. et al. 2009, A&A, 495, 147
Calzettie, D. et al. 2000, ApJ, 533, 682
Calzetti, D. et al. 2010, ApJ, 719, L158
da Silva et al., 2012, ApJ, 745, 145
Hoverstern & Glazebrook 2008, ApJ 675, 163
Koda et al. 2012, ApJ, 749, 20
Lada, C.J., & Lada, E.A. 2003, ARA&A, 41, 57
Lee et al. 2009, ApJ, 706, 599
Leitherer, C., et al. 1999, ApJS, 123, 3
Maíz-Apellániz et al. 2004, ApJL, 615, 113
Massey 2003, ARAA, 41, 15
Meurer et al. 2009, ApJ, 695, 765
Sabbi et al. 2008, AJ, 135, 173
Silva-Villa & Larsen 2011, A&A, 529, A25
Sirianni, M. et al. 2000, ApJ, 533, 203
Weidner et al. 2010, MNRAS, 401, 275

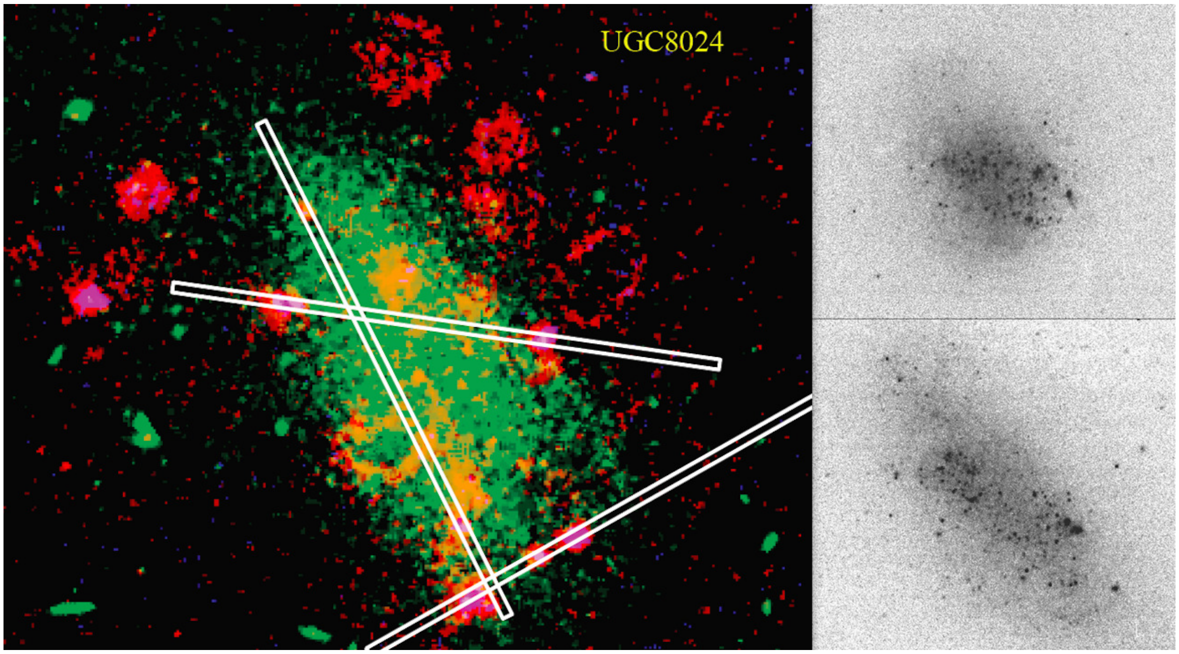

Figure 1: **Left:** KPNO 2.1m image of UGC 8024 in continuum-subtracted Hα (red), Hβ (blue) overlaid on a smoothed ACS/WFC F814W (green). The positions of the slits are illustrated by the three white boxes. **Right:** KPNO 2.1m B band images of UGC 9240 (top) and UGC 7577 (bottom), two galaxies that will be observed in this sample. All galaxies have major diameters $< 4'$.

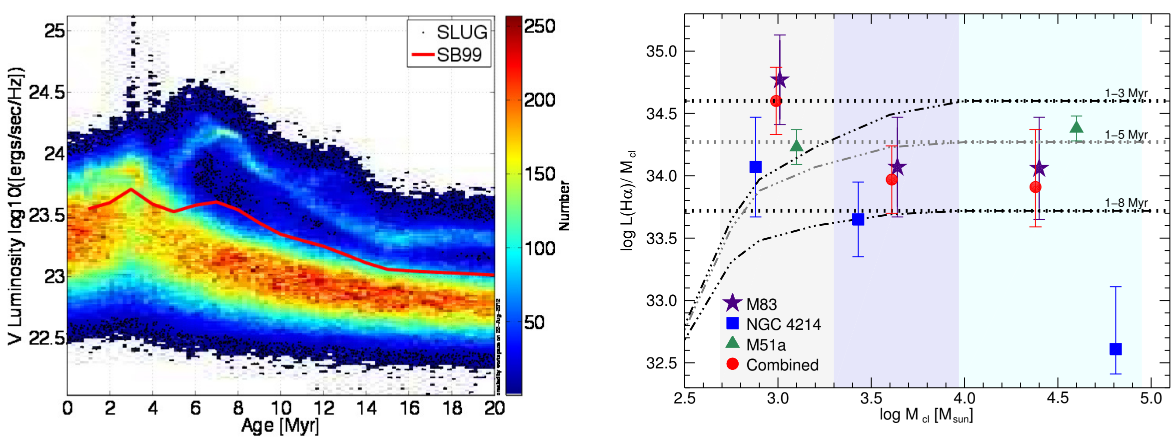

Figure 2: **Right:** Comparison V magnitudes of deterministic models (Starburst99, red line) with 1×10^3 $M_\odot$ SLUG models. The scatter from the stochastic models will also create a scatter of cluster mass not allowed in SB99 (Andrews et al 2013). **Left:** Location of $L_{H\alpha}$ /M_{cl} for mass bins in M83, NGC 4214 (Andrews et al. 2013), M51 (Calzetti et al. 2010) and combined bins for M83 and NGC 4214 for clusters < 8 Myr. All galaxies have been normalized to the metallically of M83 (Z = 1 $Z_\odot$). Dotted lines are the expected $L_{H\alpha}$ /M_{cl} for an universal IMF for various age ranges while the dash-dotted line is for a cluster–mass–dependent upper mass limit (Weidner et al. 2003, Weidner et al. 2010) where the most massive star in a cluster is determined by cluster mass. Each shaded region indicates the mass range for each mass bin (500-2000 M_{cl}, 2000-9000 M_{cl}, and 9000+ M_{cl}).

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

We plan to use the Blue Channel on MMT to obtain low resolution spectra of stellar clusters in nearby dwarf galaxies. The stellar spectra can then be compared to the stellar synthesis models to determine accurate ages and masses as described above. If in the event the resolution is too coarse for direct detection of the Balmer absorption under the emission lines, we plan to use an iterative process that models both the stellar continuum (SLUG) and the nebular emission lines (Cloudy) in order to obtain absorption-corrected nebular lines and the nebular continuum.

Because the bluest wavelengths are needed to break degeneracies in ages, particularly in the young clusters in which we are interested here, we will use the 300 l/mm grating centered at 5950 Å. This should allow us coverage from 3315 - 8500 Å. This wavelength coverage will also include Hγ, Hβ, and Hα nebular emission lines, needed for extinction correction, as well as various oxygen lines which are important for metallicty measurements. Due to the extended nature of the clusters we will also use the $2''$ wide slit, with $180''$ length. The length will allow us to cover two clusters at a time in the galaxy (as seen in Figure 1) as well as extended nebular emission from the clusters that lie along the slit. We will then change the slit position angle to line up another two clusters on the slit. This will allow us to cover at least 6 clusters, the average number of bright, young clusters in each galaxy, with only three pointings. Each galaxy has numerous ground-based and HST images which will provide us accurate photometric identification of clusters and the appropriate PA needed for optimum cluster observations.

The sample here all cover an RA range between 12 -15 hours, making them ideal targets for the month of April, although most times during the semester will be doable, with March and May being desirable to any months earlier or later. Due to the need for the bluer wavelengths we do request dark to gray nights if at all possible.

Typical cluster magnitudes range between 18-20th magnitude. Taking into account the $2''$ slit width, we estimate that 3 x 400s exposures for each pointing will create a decent S/N. This means that on average 1 hr will be needed for each galaxy to obtain spectra of up to 6 clusters. With this in mind, we believe that we will need 3 nights to complete the program. This should allow us to complete 6 galaxies, along with standards and overheads, each night, for a total of 18 galaxies.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

This is the first time proposing time for this program. We estimate that it will take one night to do 6 galaxies plus standards, so a total of 3 nights to complete the whole sample. The nights do not need to be consecutive.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

I am a new employee of UofA and this will be my first time submitting a proposal. I am CoI on N. Smith's current 2014B Aztec proposal (program S48), and have experience observing on MMT.