EXTREME DUST HEATING IN OPTICALLY STAR-FORMING GALAXIES

by

Jessica O'Connor A Dissertation Submitted to the Graduate Faculty of George Mason University In Partial fulfillment of The Requirements for the Degree of Doctor of Philosophy Physics

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By

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Abstract

EXTREME DUST HEATING IN OPTICALLY STAR-FORMING GALAXIES

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A complete census of supermassive black holes in the local universe is important, especially in low mass ($<10^{10}M_{\odot}$) galaxies. It provides observational constraints on the black hole occupation fractions of low mass galaxies and broadens our understanding of the coevolution of active galactic nuclei (AGN) and their host galaxies. Infrared selection criteria including [3.4]-[4.6] μ m (W1-W2) color provides a useful method for detecting obscured AGN which may be missed in X-ray or optical surveys. Recent work has found that not only are there more AGN in low mass galaxies than would be predicted using optical selection criteria, but that the fraction of high W1-W2 (>0.5) galaxies is actually highest in the lowest mass galaxies. This could be evidence of a significant population of obscured AGN in low mass galaxies, but it is still unclear whether the dust heating that causes high W1-W2 color can only be caused by AGN or if stars alone are sufficient. This dissertation is a study of the demographics of high W1-W2 galaxies in the local universe and the AGN or star-forming nature of their nuclear activity.

First, the number density of z < 0.1 galaxies with W1-W2>0.3, 0.5 and 0.8 are calculated as a function of r-band luminosity and stellar mass. Not only does the number density of high W1-W2 galaxies rise toward the lowest host mass regime in stark contrast to the mass distribution of optical AGN, but the red WISE population displays a bimodality in its luminosity and stellar mass functions. They are a combination of a high mass optical AGN and a low mass optically star-forming component. One optically normal, IR-red (W1-W2>1) galaxy (SDSS J1224+5555) was included in a pilot study of bulgeless, high W1-W2 galaxies which found that its X-ray flux is much lower than would be expected if it hosted an AGN. Decomposing its photometry with multiwavelength spectral energy distribution (SED) modeling revealed that it is impossible to reproduce the galaxy's mid-infrared fluxes without a substantial contribution from an obscured AGN. Lastly, the SED modeling strategy is extended to the low mass, W1-W2>0.8 galaxy sample. The ultraviolet through far-infrared SEDs of low mass, high W1-W2 galaxies can be explained by young stars with associated dust heating without the need to include an AGN. However the photometry of some optical AGNs in the test sample can also be fit with the same star and dust templates. While the emission of low mass, red W1-W2 galaxies is consistent with young stars and stellar dust heating, AGN activity cannot be conclusively ruled out. Deep and/or high energy X-ray observations or mid-infrared spectra of dwarf galaxies with high W1-W2 color are needed in order to determine whether these galaxies contain obscured AGN or their dust heating comes from stars alone.

Chapter 1: Introduction

Active galactic nuclei, or AGN as they will be referred to for the rest of this work, are black holes inhabiting the centers of galaxies that are currently accreting matter. This accretion of material leads to energy being emitted from the area outside of the event horizon of the black hole at frequencies across the electromagnetic spectrum from radio and gamma ray jets to ultraviolet and optical emission lines and infrared radiation from heated dust (Urry & Padovani, 1995, and references therein). One of the reasons that active galactic nuclei are important in the field of astronomy is because of the link between the growth of a host galaxy and that of its black hole. This has been observed in the relations between the mass of a galaxy's black hole and the velocity dispersion and luminosity of the stars within the black hole's sphere of influence (Gebhardt et al., 2000; Marconi & Hunt, 2003; Merritt & Ferrarese, 2001). This implies that the AGN and host galaxy evolve in a co-dependent way.

The majority of AGN have been observed to reside in massive host galaxies ($M_* > 10^{10}$ M_{\odot}) (Kauffmann et al., 2003a; Xue et al., 2010). In recent years AGNs have been found in a handful of galaxies with host masses as low as a few times $10^8 M_{\odot}$ (Barth et al., 2004; Dong et al., 2007; Ghosh et al., 2008; Greene & Ho, 2007; Ho et al., 2012; Izotov & Thuan, 2008; Jiang et al., 2011; Maksym et al., 2014; Moran et al., 2014; Reines et al., 2013, 2014, 2011; Schramm et al., 2013; Secrest et al., 2015; Yuan et al., 2014). Satyapal et al. (2014) even found *WISE*-selected candidate AGN with masses as low as $10^6 M_{\odot}$, but it is possible that the infrared emission seen in these galaxies could come from dust heated by stars. If these galaxies are in fact AGN, this means that most active galaxies are actually low mass sources which is the opposite result from that which would be obtained using optical selection criteria (Kauffmann et al., 2003a).

With improved demographics for the population of AGN in low mass galaxies, it may

be possible to uncover their black hole occupation fraction. The occupation fraction is the fraction of galaxies of a given mass that have a central black hole. Observing the occupation fraction of low mass galaxies in the local universe is important because while seed black hole models are mostly meant to model the universe's first black holes, the galaxies that contain them are too far away to actually observe. Thus astronomers must use local analogs. Low mass galaxies work well for this purpose because they are unlikely to have grown or obtained multiple supermassive black holes through mergers with other systems. There are currently two leading hypotheses for the formation of seed black holes: through collapse of material following the death of the universe's first stars or direct collapse of gas into a black hole (van Wassenhove et al., 2010; Volonteri, 2012; Volonteri et al., 2010). Because these two models predict different black hole occupation fractions in the lowest mass galaxies, collecting observational measurements of this quantity is essential for distinguishing which of these models is true and better understanding the universe's first black holes.

Unfortunately this is difficult to accomplish as black holes are not directly observable. In order to be seen, a black hole must almost always be in its "active", accreting state. So by finding AGN in low mass galaxies, we can put lower limits on the fraction of low mass hosts with black holes.

But even though AGN are easier to see than inactive black holes, there are still sometimes obstacles to their detection. Obscuration of the AGN by dust either in the obscuring torus or in the intervening interstellar medium (ISM) in the galaxy may hide the optical emission lines used to select AGN (Baldwin et al., 1981; Kauffmann et al., 2003a; Kewley et al., 2001, 2006) or even block the X-ray emission in the energy range observable with X-ray telescopes (Assef et al., 2015; Lansbury et al., 2014, 2015; Stern et al., 2014). X-ray observations of dwarf galaxies are currently available for few of these objects because they have not been targeted. Emission from the host galaxy may lower the effectiveness of selecting AGN using optical emission lines in cases where the galaxy's contribution to the emission line flux is greater than that of the AGN (Kauffmann et al., 2003a). Infrared AGN selection techniques are also vulnerable to bias because some types of stars can cause dust heating that mimics the energy spectrum of an AGN (Faherty et al., 2014; Kirkpatrick et al., 2011; Nikutta et al., 2014).

The issue of obscuration has been dealt with in multiple ways. Low energy (<10 keV) Xrays and optical emission lines are most useful for finding AGN with low levels of obscuration because the AGN is readily observable. But obscuration may hide optical emission lines or suppress the low energy X-ray flux from AGN by more than a factor of 10 (Brightman & Nandra, 2011). In this case, observations at other wavelengths may be more helpful. Higher energy X-rays reflected off of the obscuring material around the black hole are less attenuated in the case of heavily obscured AGN and have already been used to observe several heavily obscured AGN which would likely be missed by other selection techniques (Annuar et al., 2015; Lansbury et al., 2015; Madsen et al., 2015; Ricci et al., 2016; Ursini et al., 2015). Infrared colors selecting for dust heated by the AGN are also useful for finding heavily obscured objects because the dust becomes an asset instead of a disadvantage (Donley et al., 2012; Jarrett et al., 2011; Lacy et al., 2004; Mateos et al., 2012; Sartori et al., 2015; Stern et al., 2005, 2012). Decomposition of a galaxy's emission across a broad wavelength range has also been used as a way to solve both the issues of host contamination and obscuration by disentangling the contributions of the AGN and its host galaxy to the source's observed flux across a wide energy range by modeling the total flux as a linear combination of known template spectra (Assef et al., 2010, 2013; Berta et al., 2013; Brown et al., 2014; Hainline et al., 2014; Lansbury et al., 2014, 2015; Mullaney et al., 2011; Polletta et al., 2007).

This dissertation uses infrared selection criteria of AGN in order to first understand the number density as a function of mass and luminosity of galaxies in the local universe which would be selected as AGN on the basis of infrared colors. SED modeling is then used to determine whether the dust heating that causes these infrared colors is primarily driven by AGN activity or unusually hot stars. Chapter 2 deals with the demographics of high W1-W2 galaxies in the local universe (z < 0.1). Chapter 3 studies the galaxy SDSS J1224+5555. This galaxy is part of a pilot study of optically normal, bulgeless sources with high W1-W2 color (W1-W2>1 for this galaxy) with the X-ray telescope XMM-Newton. Its X-ray luminosity is lower than would be expected for an AGN. SED modeling is used to distinguish whether this is due to a lack of an AGN or obscuration. Chapter 4 uses an SED modeling strategy which keeps track of the luminosity of starlight absorbed by dust and re-emitted in the infrared in order to discern whether or not the heated dust emission of low mass, high W1-W2 galaxies can be explained by dust heating by stars or if an AGN is necessary.

Chapter 2: Luminosity and Stellar Mass Functions of Red W1-W2 Galaxies

2.1 Introduction

Infrared (IR) colours of galaxies observed by the *Wide-Field Infrared Survey Explorer* (WISE) provide a probe of hot dust emission (Donley et al., 2012; Jarrett et al., 2011; Mateos et al., 2012; Stern et al., 2012). Active galactic nuclei (AGN) activity and star formation are the dominant processes that heat the dust and thus galaxies with very red [3.4]-[4.6] (W1 - W2) colours provide a probe of the most extreme interstellar medium environments. The luminosity and mass functions of galaxies with red W1 - W2 colours measure the prevalence of these extreme environments in the local universe.

AGNs have a hard radiation field that, in dusty systems, is absorbed and re-radiated in the infrared. The spectral energy distributions (SEDs) of AGNs are predicted to display power law slopes ($f_{\nu} \propto \nu^{\alpha}$ with $\alpha < -0.5$) (Alonso-Herrero et al., 2006) in the infrared producing red colours in W1 - W2 (or equivalently the [3.6] - [4.5] Spitzer bands; Assef et al., 2010; Polletta et al., 2007; Richards et al., 2006). Observationally Yan et al. (2013) have shown that QSOs and some Seyfert galaxies selected from the *Sloan Digital Sky Survey* (SDSS) have redder W1 - W2 colours than star-forming galaxies. Jarrett et al. (2011), Stern et al. (2012), and Mateos et al. (2012) have created AGN selection criteria based primarily on a galaxy's W1 - W2 colour, though Jarrett et al. (2011) and Mateos et al. (2012) also make use of W2 - W3 ([4.6] - [12]) colour in their diagnostics. For W1 - W2 > 0.8, 95% of the galaxies in the COSMOS field are AGNs (Stern et al., 2012). This selection technique is particularly sensitive to heavily obscured or Compton-Thick AGN, which may not be visible in optical or X-ray wavelengths (Assef et al., 2013; Goulding et al., 2011; Mateos et al., 2013; Rovilos et al., 2014; Stern et al., 2014).

While the aforementioned work shows that AGNs can have extreme MIR colours, extreme star formation may also heat the dust in galaxies and lead to excess emission in the longer wavlelengths of *WISE* (Charmandaris et al., 2008; Ranalli et al., 2003; Schaerer & de Koter, 1997). Longer mid-infrared wavelengths such as MIPS $24\mu m$ (Kennicutt, 1998), W3 ($12\mu m$) and W4 ($22\mu m$) (Jarrett et al., 2013; Lee et al., 2013), and IRAC 4 ($8\mu m$) (Bendo et al., 2008; Calzetti et al., 2007) are used for measurments of star formation rates for this reason.

Recently Satyapal et al. (2014) found that the fraction of galaxies in the local universe with extreme mid-infrared colours is higher in low mass galaxies than at high stellar masses. It is unclear why the number of red low mass galaxies is so large and whether the dominant cause of their dust heating is extreme star formation or AGN activity. We examine the number density of these systems and their contribution to the overall galaxy population and properties from the optical spectra which may explain the nature of their nuclear activity. Throughout this paper we will use $H_0=70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m=0.3$ and $\Omega_{\Lambda}=0.7$.

2.2 Sample Selection

Our galaxy sample is selected from the Sloan Digital Sky Survey (SDSS) data release 7 (DR7) catalogue (Abazajian et al., 2009) and includes all spectroscopic objects in the Legacy area with SpecPhoto.specClass=2 (Galaxies) or SpecPhoto.specClass=3 (QSOs), 0.005 $\leq z \leq 0.1$ and the Petrosian *r*-band magnitude, corrected for Galactic extinction (Schlegel et al., 1998), $14.0 \leq r \leq 17.77$. The SDSS Legacy Survey is a spectroscopic and photometric optical survey covering over 8000 deg⁻² on the sky. The faint magnitude limit, *r*=17.77, represents the completeness limit of the DR7 spectroscopic sample (Strauss et al., 2002). On the other hand, galaxies with r < 14 may have unreliable photometry due to shredding (Strauss et al., 2002). The resulting sample contains $\approx 315,000$ galaxies.

The SDSS sample was matched, within 3", with galaxies in the AllWISE Catalogue

(Cutri et al., 2013; Mainzer et al., 2011; Wright et al., 2010)¹ that have S/N > 5.0 at 3.4 μm (W1) and 4.6 μm (W2). The angular resolution of WISE is approximately 6" in the W1 and W2 bands. Out of the SDSS galaxies with WISE matches (315251 galaxies or 99.7% of the SDSS sample), 6837 (2.2%) have two WISE matches and 67 (0.002%) have 3 WISE matches. In the infrared and optical images, these multiple matches appear to be single galaxies that WISE identifies two or three times, generally with the WISE position straddling the centre of the galaxy although it is not clear why in these limited cases WISE separated the galaxies into two or three infrared sources. For these systems the photometry for the source closest to the SDSS spectrum was used. Only 0.8% of galaxies with W1 -W2 > 0.3 have multiple WISE sources where the closest source to the SDSS spectrum is not also the brightest. For galaxies which are resolved in WISE, it is possible that the W1 - W2 colour of the galaxy's profile magnitudes results not from the actual difference in the total flux emitted in the W1 and W2 bands, but from an underestimation of flux in the W1 band. Thus in the case of resolved sources (w1rchi2 > 2), we use 11" aperture photometry in the W1 and W2 bands instead of the profile magnitudes. 1.4% of randomly selected positions within the SDSS footprint (for a selection of 4400 sources) have a match in the ALLWISE catalog within 3" that has W1 and W2 S/N ≥ 5.0 so almost all of the matches are expected to be legitimate.

Stellar masses for the galaxies were obtained from the NYU-VAGC (Blanton et al., 2005a; Blanton & Roweis, 2007)² which were derived from principal component analysis fits to stellar templates. Emission line fluxes used to calculate star formation rates (Brinchmann et al., 2004) and metallicities (Tremonti et al., 2004) were obtained from the MPA-JHU catalogue³. This catalogue contains line fluxes corrected for stellar absorption using the Bruzual & Charlot (2003) stellar population templates.

¹http://irsa.ipac.caltech.edu/Missions/wise.html

²http://sdss.physics.nyu.edu/vagc/

³http://home.strw.leidenuniv.nl/ jarle/SDSS/

2.3 Methods

We compute the luminosity and stellar mass functions for the galaxies in our sample using the $1/V_{Max}$ (Schmidt, 1968) method and a modified form of the stepwise maximum likelihood method (SWML; Efstathiou et al., 1988) which are not susceptible to the same biases and therefore provide a check on the results.

The $1/V_{Max}$ method is used to calculate the number of galaxies per luminosity, absolute magnitude, or stellar mass bin weighted according to the volume in which each galaxy could have been detected. For each galaxy in the sample there are both a minimum and a maximum distance at which it would be included in the V_{max} volume. The lower bound to the distance is the larger value of 21 Mpc (defined by the z=0.005 minimum redshift for the sample) or the minimum distance at which the galaxy would be included in the sample based on the bright limit r > 14.0 for galaxies in the sample. The maximum comoving distance is 418 Mpc (defined by the redshift limit of the sample z=0.1) or the maximum distance based on the faint limit, r < 17.77 for galaxies in the sample.

The $1/V_{Max}$ method has the advantage of being a relatively simple calculation with built-in normalization, but it relies on the assumption that galaxies are distributed homogeneously throughout the survey volume. The value of $\langle \frac{V}{V_{Max}} \rangle$ for this sample is 0.4877±0.0005 where a value of 0.5 indicates an evenly distributed sample. The CfA Great Wall (Geller & Huchra, 1989) and the Coma Cluster (Harrison et al., 2010) contribute to an excess of galaxies at 0.02 $\langle z \rangle$ 0.04 while the SDSS Great Wall (Gott et al., 2005) is responsible for an excess near z≈0.08. To mitigate the impact of large-scale seen in Figure 2.1 structure on the number density the $1/V_{Max}$ values have been corrected by a factor of n, the number of galaxies in the SDSS sample that are within a given redshift range divided by the number of galaxies expected to fall in that range if they are distributed according to the Blanton et al. (2005b) *r*-band luminosity function.



Figure 2.1: The cumulative number of galaxies as a function of redshift in this sample (solid histogram). The dashed line shows the cumulative number of galaxies expected as a function of redshift assuming the SDSS DR2 luminosity function (Blanton et al., 2005b).

2.3.1 Modified Stepwise Maximum Likelihood Method

The stepwise maximum likelihood method (SWML) (Efstathiou et al., 1988) for measuring the luminosity and mass functions of galaxies has the advantage of being insensitive to cosmic variance within the survey volume. For the purposes of this work we modify the standard SWML technique to account for a galaxy selection (W1-W2 colour) that does not affect the detectability of the galaxy.

In the standard formulation of the SWML method, the number density of galaxies in a given bin of luminosity (or absolute magnitude or stellar mass) is given by:

$$\phi_k = N_k \left[\sum_{i=1}^{N_{gal}} \frac{H_{ki} \Delta M_k}{\sum_{n=1}^{N_M} \phi_n \Delta M_k H_{ni}} \right]^{-1}$$
(2.1)

We derive a normalization for the SWML points by assuming that the total galaxy density within the luminosity range sampled will match that calculated using the $1/V_{Max}$ method. N_k is the number of galaxies in magnitude bin k, H_{ki} is the fraction of bin k in which galaxy i is detectable, N_{gal} and N_M are the number of galaxies in the sample and number of absolute magnitude bins, respectively. Equation 2.1 is iterated upon until all ϕ_k values change by less than 1% between successive iterations. Equation 2.2 shows the comparable expression for the mass function (Loveday, 2000). In this case the expression is two-dimensional. N_{jk} is the number of galaxies in absolute magnitude bin j and stellar mass bin k and H_{ji} and H_{ki} are the fraction of magnitude bin j and stellar mass bin k in which galaxy i could have been detected.

$$\phi_{jk} = N_{jk} \left[\sum_{i=1}^{N_{gal}} \frac{H_{ji} H_{ki} \Delta M_j \Delta M_{*k}}{\sum_{m=1}^{N_M} \sum_{n=1}^{N_{M_*}} \phi_{mn} H_{mi} H_{ni} \Delta M_m \Delta M_{*n}} \right]^{-1}$$
(2.2)

Because the only limiting quantity is the r-band apparent magnitude, Equation 2.2 can be simplified by assuming that if galaxy i is detectable in magnitude bin j $(H_{ji} > 0)$ then $H_{ki} = 1:$

$$\phi_{jk} = N_{jk} \left[\sum_{i=1}^{N_{gal}} \frac{H_{ji} \Delta M_j \Delta M_{*k}}{\sum_{m=1}^{N_M} \sum_{n=1}^{N_{M_*}} \phi_{mn} H_{mi} \Delta M_m \Delta M_{*n}} \right]^{-1}$$
(2.3)

Equation 2.3 is then summed over magnitude bins j in order to calculate values of ϕ_k (Loveday, 2000).

 $\phi_{k,x}$ is the number density of galaxies in a given stellar mass or magnitude bin k and W1-W2 colour bin x. This number density is determined by multiplying the number density of the full sample by the probability of a galaxy in bin k falling in colour range x:

$$\phi_{k,x} = \phi_k \frac{N_{k,x}}{N_k} \tag{2.4}$$

The 1-sigma uncertainties for the full sample are calculated from the information matrix (Efstathiou et al., 1988). The inverse of this matrix contains the variance in ϕ_k . Uncertainties for subsamples are calculated by adding the uncertainties in ϕ_k in quaderature with the uncertainties from Equation 2.4.

2.4 Results

Figures 2.2 and 2.3 show the luminosity and stellar mass functions for galaxies in our sample (black circles) as well as for subsamples with infrared colours W1 - W2 ≥ 0.3 (blue stars), W1 - W2 ≥ 0.5 (green triangles) and W1 - W2 ≥ 0.8 (red squares). In order to distinguish values determined using the $1/V_{Max}$ method (filled points, solid lines) from those determines using the SWML method (open points, dotted lines), the SWML points have all been multiplied by 1.5. Without this artificial separation, the results of the two methods lie on top of one another. Solid lines represent the best fit Schechter functions to the $1/V_{Max}$ points. The details of the functions will be discussed later in this section. The $1/V_{Max}$ and SWML methods yield luminosity and stellar mass functions with similar



Figure 2.2: The number density of galaxies in our full sample (black circles) and W1 - W2 colour subsamples (W1 - W2 ≥ 0.3 , blue stars; W1 - W2 ≥ 0.5 , green triangles; W1 - W2 ≥ 0.8 , red squares) as a function of *r*-band absolute magnitude. The figure shows values calculated using the $1/V_{Max}$ (filled points) and the SWML (open points). SWML values and errors are multiplied by 1.5 in order to differentiate them from the $1/V_{Max}$ points. The plot includes results from Montero-Dorta & Prada (2009) (yellow inverted triangles) for comparison. Lines indicate the best fit Schechter functions. The dashed line at M_r =-16.5 is where surface brightness effects become important.

shapes indicating that the structure is not due to cosmic variance within the survey volume.

The $1/V_{Max}$ and SWML functions are in good agreement with the yellow points in Figure 2.2 which show the SDSS DR6 *r*-band luminosity function from Montero-Dorta & Prada (2009). Figure 2.3 shows the total stellar mass function (black) plotted alongside the mass function results from Baldry et al. (2012) (yellow). The downturn at the low mass end of the stellar mass function is due to surface brightness incompleteness in the SDSS sample and is also seen in Baldry et al. (2008) and Baldry et al. (2012). Due to this incompleteness, all points below $\log(M/M_{\odot})=8$ and $M_r=-16.5$ (dashed lines in Figures 2.2



Figure 2.3: The number density of galaxies in our sample and W1 - W2 colour subsamples as a function of stellar mass. Filled points calculated using the $1/V_{Max}$ method and open points are calculated using our modified SWML method. SWML points and errors are shown here multiplied by 1.5 so that they may be more easily differentiable from the $1/V_{Max}$ points. Black circles were calculated using the full galaxy sample while the blue stars only include galaxies with W1 - W2 ≥ 0.3 , green triangles only include galaxies with W1 - W2 ≥ 0.5 and red squares only include galaxies with W1 - W2 ≥ 0.8 . Solid lines are Baldry et al. (2012)-form Schechter functions fit to the $1/V_{Max}$ points above the surface brightness incompleteness line. The dashed line at 10^8 M_{\odot} signifies the point below which the mass function is incomplete (See Section 2.4). Dotted lines are our best fit Schecter functions multiplied by 1.5 so that their normalization is comparable to that of the SWML points. This figure also contains the data points and best fit Schecter function from Baldry et al. (2012) as yellow inverted triangles.

and 2.3) are treated as lower limits and not used to determine the Schechter function fits.

Schecter functions with two characteristic number densities (ϕ_1^*, ϕ_2^*) , one characteristic magnitude or stellar mass (M^*) and two power law slopes (α_1, α_2) were fit to the points brighter than the surface brightness incompleteness limit. This double Schecter form is the same one used in Blanton et al. (2005b) and Baldry et al. (2012). Parameters of the best fit functions are listed in Tables 2.1 and 2.2.

The Schecter functions for galaxies with W1 - W2 ≥ 0.3 , 0.5, and 0.8 have two components such that the luminosity functions "dip" at intermediate luminosities. This dip can be seen in Figure 2.2 and in the values for α_1 (the power law slope of the high luminosity population) $\alpha_1=0.463$, $\alpha_1=0.473$ and $\alpha_1=0.217$ (Table 2.1). This slope is in the opposite direction of the one measured for the full sample, $\alpha_1=-0.244$. The mass functions in Figure 2.3 and Table 2.2 show a similar pattern. For the full stellar mass function, $\alpha_1=-0.557$ indicating a smooth transition between the high and low mass galaxy populations. However, the values of α_1 for W1 - W2 ≥ 0.3 , 0.5 and 0.8 are much higher ($\alpha_1=-0.137$, 0.423, 0.479). This is evident as a decrease in the number density from the high to intermediate stellar mass population of red galaxies in Figure 2.3.

In addition to this dip, the power law slopes of the red low mass/low luminosity galaxies are much steeper than those of the total stellar mass and luminosity functions. For the total stellar mass function, α_2 =-1.524. This becomes steeper (more negative) for redder galaxy populations. The values of α_2 decrease from -1.804 at W1 - W2 ≥ 0.3 to -1.892 at W1 - W2 ≥ 0.5 and -1.487 for galaxies with W1 - W2 ≥ 0.8 . The faint end slopes of the luminosity functions display a similar trend with values decreasing from α_2 =-1.438 for the full sample to α_2 =-1.973 for galaxies with W1-W2 ≥ 0.8 .

The functional forms of the galaxy luminosity and stellar mass functions are bimodal for W1 - W2 \geq 0.3. The low mass components come close to dominating by number density. Galaxies with M_r > -18 comprise 46.7% of the total number density (comparing to galaxies with -24 < M_r < -16.5). For galaxies with W1 - W2 \geq 0.5 almost 52% of galaxies have M_r > -18. However, red galaxies do not make up a large fraction of the total number

density. Galaxies with W1 - W2 ≥ 0.3 , 0.5 and 0.8 only account for 5.6, 0.7 and 0.2% of the number density of galaxies. Low mass galaxies (log(M/M_{\odot}) <9) make up 69.4% of galaxies (8 <log(M/M_{\odot}) < 12) with W1 - W2 \geq 0.3, 62.9% with W1 - W2 \geq 0.5 and 29.9% with W1 - W2 \geq 0.8.

Increasing the S/N selection threshold from 5.0 to 10.0 in the W1 and W2 bands for inclusion in our galaxy sample results in a decrease in the number density of galaxies at low masses and luminosities but due to the compact nature of the red WISE sources (discussed further in Section 5.1) this mainly affects the samples with W1 - W2 < 0.5. In addition, using the IRAF task ELLIPSE to calculate the photometry for 60 galaxies spanning a range of W1-W2 colour, S/N and angular size and comparing them to the values in the ALLWISE catalogue shows no significant trends in the catalogue colours as a function of any of these properties. The average offset between the W1-W2 colours from the AllWISE catalogue and the IRAF photometry is 0.005 mag. In short, there is no evidence that the red colours of these galaxies are artifacts of poor photometry.

2.4.1 Optical Nuclear Activity Classification

The classifications of galaxies in Figure 2.4 are based on optical emission line ratios with divisions between star-forming, composite, and AGN regions from Kewley et al. (2001) and Kauffmann et al. (2003a). The AGN classification includes both broad and narrow line systems. Galaxies are unclassified if they have S/N<3 for the H α , H β , [O III 5007] or [N II 6584] lines. As in Figure 2.3, points below $10^8 M_{\odot}$ are effected by surface brightness incompleteness and are, therefore, lower limits.

Figure 2.4 shows that optically classified AGNs are found almost exclusively at high stellar masses, in agreement with Kauffmann et al. (2003a). However, the majority of high stellar mass galaxies are optically unclassified because they lack strong emission lines. Similarly, nearly all massive galaxies with W1-W2 > 0.5 and W1 - W2 > 0.8 are strongly dominated by AGNs in agreement with both the optically selected AGN samples of Kauffmann et al. (2003a) and the X-ray and IR-selected samples of Xue et al. (2010). The fraction



Figure 2.4: The $1/V_{Max}$ stellar mass function points for the full sample (top left), W1 - W2 ≥ 0.3 (top right), W1 - W2 ≥ 0.5 (bottom left) and W1 - W2 ≥ 0.8 (bottom right). The total stellar mass function in each colour range is shown as black circles. Optical AGNs (broad and narrow line) are shown as red squares, composite galaxies as green triangles, star-forming galaxies as blue stars and unclassified galaxies as yellow inverted triangles. The vertical dashed line is the limit below which the stellar mass function becomes uncertain due to incompleteness.

of optically classified AGNs drops rapidly towards lower masses. For all infrared colours, the optical emission lines of low mass galaxies are dominated by star formation, consistent with the optical emission line studies of Kewley et al. (2006).

2.4.2 The Impact of Metallicity and Specific Star Formation Rates on Galaxy Colour

Figure 2.5 shows the average specific star formation rates (sSFRs), Sérsic indices (n) and metallicities for galaxies with W1 - W2 < 0.3 in bins of stellar mass (black points). Note that the black points in each panel are the same. The red points show the average sSFRs, Sérsic

indices and metallicities for galaxies with W1 - W2 ≥ 0.3 (left), W1 - W2 ≥ 0.5 (middle), and W1 - W2 ≥ 0.8 (right). Specific star formation rates and metallicities are drawn from the MPA-JHU catalogue (Brinchmann et al., 2004; Tremonti et al., 2004). Sérsic indices come from Table 3 of Simard et al. (2011). The sSFRs are only included for galaxies with S/N ≥ 3 in H α and metallicities are only included for galaxies with S/N ≥ 3 in H α , H β , [O III 5007] and [O III 3727]. The values for each galaxy are weighted by $1/V_{Max}$ to account for its detectability. The errors are the standard deviation in the bin divided by the square root of the number of galaxies. It should be noted that the sSFRs in low mass galaxies may be susceptible to bias due to their low masses even if there is relatively little star formation. There is also a possibility that AGN activity may falsely bolster the star formation rates of these galaxies, though the positions of low mass galaxies on the BPT diagram imply little optical input from the AGNs (if present) to the H α emission line fluxes.

Figure 2.5 indicates that galaxies with red colours in the infrared follow a similar trend in metallicity to those with bluer colours with lower mass galaxies exhibiting lower metallicities. There is some evidence for lower metallicities for the lowest mass, reddest galaxies but it is only a $3.2-\sigma$ effect.

2.5 Discussion

2.5.1 Galaxy Populations as a Function of Mass

The change in slope between high and low mass galaxies in the mass and luminosity functions of red galaxies points to two separate populations of red galaxies. By mass these populations are well aligned with the red sequence (massive galaxies) and the blue cloud (low mass galaxies) as demonstrated by Blanton et al. (2005b) and Baldry et al. (2008). Morphologically the massive red galaxies have larger average Sérsic indices than the lower mass systems, but the scatter is large within individual stellar mass bins.

Starburst galaxies and AGN can both redden galaxy colours such that W1 - W2 > 0.5 (Jarrett et al., 2011; Wright et al., 2010). Most (85.4%) high mass ($M/M_{\odot} > 10^{10}$) red



Figure 2.5: From top to bottom, the average specific star formation rates, Sérsic indices and metallicities of sample galaxies as functions of stellar mass and WISE colour. Black circles are the values calculated using only galaxies with W1-W2<0.3 while red triangles are calculated using galaxies with W1-W2 \geq 0.3 (left), W1-W2 \geq 0.5 (middle) and W1-W2 \geq 0.8 (right). All averages are weighted using the inverse of each galaxy's V_{Max} value.

(W1 - W2 > 0.5) galaxies are optically classified as AGN or composites while 85.8% of low mass ($10^8 < M/M_{\odot} < 10^9$) red galaxies are optically classified as star-forming systems. The differences in optical classifications of red galaxies as a function of stellar mass indicates that different mechanisms may be responsible for heating the dust (only ~ 13% of low mass galaxies are unclassified due to low S/N emission lines so this is not the reason for the difference).

The difference in the optical spectral properties of the high and low mass end of the red galaxy population can be interpreted in several different ways: (1) The dust heating that produces the red colours is powered by different physical processes in high and low mass galaxies – AGNs at the high mass end and star formation at the low mass end; (2) the same AGNs are responsible for the dust heating over the full mass spectrum of galaxies but the AGNs are not optically visible in low mass systems due to the dusty environments; or (3) while AGNs are largely responsible for the dust heating in massive systems AGNs and/or star formation can contribute for low mass galaxies.

For the following discussion, red galaxies refers to systems with W1-W2 > 0.5. This colour cut defines the AGN region in Stern et al. (2012) and Jarrett et al. (2011) and provides better statistics than a colour cut of W1-W2 > 0.8.

2.5.2 Star Formation as a Driver of Dust Heating in Red Galaxies?

The simplest explanation for the differences in the optical emission line properties of high and low mass red galaxies is a difference in the physical process responsible for heating the dust. For low mass red galaxies the most likely heating mechanism is star formation.

Figure 2.5 shows that low mass red galaxies have higher sSFRs than their bluer counterparts while high mass red and blue galaxies have comparable sSFRs. However, there are known correlations between star formation and AGN activity so a correlation between star formation and red colours does not rule out AGNs as a power source (Lutz et al., 2008; Netzer, 2009; Netzer et al., 2007; Rosario et al., 2012; Woo et al., 2012, e.g.).

One important note on stars being responsible for the red colours is that it must be

the heating by young stars rather than the galaxies being red due to the stellar colours themselves because stars rarely get this red. Chen et al. (2014) observed dust-free stars in the Milky Way and found that their colours rarely exceed W1 - W2 = 0.25. Faherty et al. (2014) and Nikutta et al. (2014) provide a handful of exceptions to this rule, but the classes of stars that they observe (Wolf-Rayet and PAGB stars) are both rare and unlikely to dominate the colour of an entire galaxy. Similarly, T dwarfs and later-type stars may have W1 - W2 as high as 4.2 but are too dim to dominate the light of a galaxy (Kirkpatrick et al., 2011). Though the fraction of infrared light contribution may vary significantly from one galaxy to another, Thermally Pulsating Asymptotic Giant Branch (TP-AGB) stars' emission peaks in in the 3-4 μ m range and has much redder than average [3.6]-[4.5] colour (Gerke & Kochanek, 2013; Meidt et al., 2012; Melbourne & Boyer, 2013; Villaume et al., 2015).

While stars themselves make a negligible contribution to these red colours, Calzetti et al. (2010); Kennicutt (1998) have shown that young, hot stars can contribute significantly to dust heating through the reprocessing of UV radiation. It has also been noted that redder colours from star formation might be expected in low mass galaxies due to their lower average metallicities (Hunt et al., 2010). These lower metallicity stars produce a harder radiation field (Kewley et al., 2004; Lee et al., 2004; Moustakas et al., 2006) due to a combination of decreased mass-loss rates, higher Hayashi limits and a lack of line blanketing seen in higher metallicity stars (Levesque et al., 2010) and thus additional dust heating. However, Figure 2.5 shows that the metallicity of the red and blue low mass galaxies is similar so the harder radiation field in low metallicity systems is unlikely to be a key factor in which dwarf galaxies exhibit red colours.

If dust heating by star formation drives the red infrared colours, galaxies with strong, concentrated star formation (e.g., blue compact dwarf galaxies, BCDs) may be more likely to have red galaxy-wide colours. To examine this possibility, we identify the 599 galaxies in this sample classified as BCDs using the criteria of Sánchez Almeida et al. (2008). Galaxies that are identified as BCDs are more likely to also have red W1 - W2 colors. There is a

5.2 σ difference between the fraction of BCDs and all sample galaxies with W1 - W2 > 0.5 and a 2.5 σ difference for galaxies with W1 - W2 > 0.8. Corroborating the idea that star formation is important in driving the red colours of BCDs, those with W1 - W2 \geq 0.8 all have W2 - W3 > 4 and only 19% (7/37) with W1 - W1 \geq 0.5 have W2 - W3 \leq 4. 15.0% and 12.8% of galaxies with W1 - W2 > 0.5 and W1 - W2 > 0.8 in the full sample also have W2 - W3 > 4 (5.7 and 72.7 σ difference, respectively). High W2 - W3 colour is more likely to come from star formation than AGN activity because the colour comes from enhanced PAH features in the W3 band (Jarrett et al., 2013).

Given that only a small fraction of BCDs show high W1 - W2 colours (Griffith et al., 2011; Izotov et al., 2011, 2014a), concentrated star formation is clearly not a sufficient condition for making low mass galaxies red. It is also possible that the red colours in these BCDs are actually powered by AGN. The spectra of 5 BCDs (out of 12) show [Ne v 3426] emission. 3 of these also show [Fe v 4227] emission (Izotov et al., 2004, 2012; Thuan & Izotov, 2005). Both of these high ionization lines are often associated with AGN activity and 4 out of 5 BCDs with [Ne v 3426] emission and all with [Fe v 4227] emission have W1 - W2 > 0.5 (Izotov et al., 2012).

A more detailed study of dust heating by star formation and its contribution to red colours is needed, but it is beyond the scope of this work.

2.5.3 AGN as the Driver of Dust Heating in Red Galaxies?

Most (85.2%) massive $(10^{10} < M/M_{\odot} < 10^{12})$ red (W1 - W2 ≥ 0.8) galaxies in this sample are optical AGN or composites. However a growing number of AGNs have been identified in low mass galaxies (Barth et al., 2004; Dong et al., 2007; Ghosh et al., 2008; Greene & Ho, 2007; Ho et al., 2012; Izotov & Thuan, 2008; Jiang et al., 2011; Maksym et al., 2014; Moran et al., 2014; Reines & Deller, 2012; Satyapal et al., 2014; Schramm et al., 2013; Yuan et al., 2014) including He2-10 $(1.4 \times 10^9 M_{\odot})$ (Reines & Deller, 2012; Reines et al., 2011; Whalen et al., 2015), Mrk 709S $(2.5 \times 10^9 M_{\odot})$ (Reines et al., 2014) and SDSS J1329+3234 $(2 \times 10^8 M_{\odot})$ (Secrest et al., 2015). Reines et al. (2013) has found 151 optical AGNs in galaxies with $10^{8.5} < M/M_{\odot} < 10^{9.5}$, 0.6% of galaxies in this mass range. This fraction of low mass galaxies is similar to the 0.3% of galaxies with W1 - W2 > 0.8. However, only 2 out of 15 (13%) low mass BLAGN in Reines et al. (2013) have W1 - W2 \ge 0.5 (1 with W1 - W2 \ge 0.8). Inversely 11 out of 136 (8%) low mass AGNs identified with BPT line ratios have W1 - W2 \ge 0.5 (8 have W1 - W2 \ge 0.8) so even if the galaxies with red WISE colours are AGNs, they are generally not the same ones that are optically classified as AGNs.

If AGNs are important for the dust heating in these low mass galaxies, almost all of them would have to be deeply embedded in dust despite these systems generally being thought to have very little dust (Cook et al., 2014; Draine et al., 2007). Akylas et al. (2012) find that 5 - 50% of AGN could be Compton-thick and still be consistent with the X-ray background, a lower percentage of the overall galaxy population than is contributed by low mass optically star-forming galaxies with W1 - W2 ≥ 0.5 (85%).

We have also examined the 2MASS (Skrutskie et al., 2006) colours of our sample galaxies. Only 1.6% of the full sample has J - $K_s > 2$, which is typical of QSOs (Hutchings et al., 2003; Warren et al., 2000) and only 168, 41 and 10 galaxies with W1 - W2 ≥ 0.3 , 0.5 and 0.8 were matched with a 2MASS source in the AllWISE catalog. Three galaxies with 0.3 < W1 - W2 < 0.5 have J - $K_s > 2$, which is consistent with the 2.7±1.6 sources expected in this category. None of the galaxies with W1 - W2 > 0.5 have red 2MASS colours, but this is also statistically consistent with the 1.6% found in the full sample.

Additional observations are needed to confirm the AGN nature of low mass red W1 -W2 galaxies. X-ray observations with facilities such as *Chandra* and *XMM-Newton* have proven effective in uncovering AGN in low mass galaxies (Reines et al., 2013, 2011; Secrest et al., 2015), though as evidenced by the lack of optical emission line visibility, obscuration may be an issue. At z=0, the hard X-ray (2-10 keV) emission of an AGN with $N_H=10^{24}$ cm⁻² is suppressed by more than a factor of 10 (Brightman & Nandra, 2011). Fortunately, the higher energy (10-195 keV) emission is reduced by a factor of less than 2 (Brightman & Nandra, 2011). *NuSTAR* (Harrison et al., 2013) is capable of explaining this higher energy (3-79 keV) range and has already observed several obscured and/or low luminosity AGN (Annuar et al., 2015; Lansbury et al., 2014, 2015; Madsen et al., 2015; Ricci et al., 2016; Ursini et al., 2015).

The launch of the James Webb Space Telescope (Gardner et al., 2006) in 2018 will bring about the opportunity to observe the infrared spectra of low mass IR-red galaxies. Though the wavelength range of JWST's NIRspec and MIRI instruments (0.6-28 μ m) is shorter than that of IRS (5-38 μ m), it will still be capable of observing spectral features such as the 6.2 μ m and 11.3 μ m PAH features and high ionization lines like [NeV 14.32 μ m] and [OIV 25.89 μ m] used in AGN diagnostics developed for galaxies observed with IRS (Gruppioni et al., 2016; Hernán-Caballero & Hatziminaoglou, 2011; Magdis et al., 2013; Spoon et al., 2007; Tommasin et al., 2010).

2.5.4 Implications for Seed Black Hole Models

Two models currently exist for the origin of supermassive black hole seeds at the centres of galaxies: (1) the creation of a seed through the death of a population III star and (2) the direct collapse of a massive gas cloud Volonteri (2012, and references therein). The fraction of very low mass galaxies with central black holes (occupation fraction) can provide a test of these models, but in practice measuring the occupation fraction in low mass galaxies is difficult to do (Miller et al., 2015).

van Wassenhove et al. (2010) use these two mechanisms to seed satellites in Milky Way type haloes. The result of the van Wassenhove et al. (2010) study is that the occupation fraction is significantly lower for massive seeds than it is for the population III seeds. To compare with these models which determine the occupation fraction as a function of velocity dispersion, V-band luminosities are derived from the r-band luminosity and g - r colour according to the transformations of Jester et al. (2005) and from those values velocity dispersion is derived using the V- σ relation in van Wassenhove et al. (2010).

For both models the occupation fraction at z = 0 is one for velocity dispersions above
$\sigma = 50 \text{ km s}^{-1}$. At velocity dispersion of $\sigma < \sim 32 \text{ km s}^{-1}$, which corresponds to $M_r = -14.4$ (just beyond the last point of the full luminosity function), the models begin to diverge with the population III seeds continuing to have an occupation fraction of one while direct collapse model seeds have an occupation fraction of 0.6. At this luminosity the fraction of optical AGN have effectively gone to zero so optical AGN would indicate either a much lower occupation fraction than predicted in either of these models or they predict a rapidly falling fraction of central black holes that are active as galaxy mass decreases.

One possible explanation for the decrease in optical AGN at lower masses is the increase in the number of AGN that are embedded in dust. Given that these are the masses at which there is a transition from early type galaxies that have small amounts of gas and dust in their ISM to late type galaxies that have significant gas and dust in their ISM, it is possible that the number of deeply embedded AGN would increase.

While it is unlikely that all low mass galaxies with red WISE colours are AGN that assumption can be used to place some constraints on the population. Galaxies with W1 - W2 ≥ 0.5 and W1 - W2 ≥ 0.8 at a luminosity of M_r ~ -14.4 comprise ~3% and ~1% of the total number density. For the population III seed models only ~3% and ~1% of the black holes would, therefore, be expected to be active in these low mass galaxies because the occupation fraction is predicted to be one. For the massive seed models ~5% and ~2% of the galaxies would be expected to be active depending on the colour above which all of the galaxies possess embedded AGN. In both cases this still predicts a much smaller active fraction than observed in more massive galaxies (Kauffmann et al., 2003a). These numbers indicate that either there is a problem with the black hole seed models or the fraction of active black holes drop with galaxy mass even if there is a substantial population of embedded AGN residing in low mass late-type galaxies. We note that mid-IR colour selection only finds AGN that dominate the bolometric luminosity of the galaxy. It is possible that there is a significant fraction of weakly accreting and optically unidentified AGNs (Satyapal et al., 2009, 2008, 2007) that would not be identified through W1 - W2 colour selection.

2.6 Summary

We have calculated the r-band luminosity and stellar mass functions of z < 0.1 galaxies from AllWISE and SDSS DR7 for the full population, galaxies with W1 - W2 ≥ 0.3 , W1 -W2 ≥ 0.5 and W1 - W2 ≥ 0.8 . We find:

- 1. Galaxies with colours redder than W1 W2 = 0.5 make up 0.6% of the galaxy population and galaxies with W1 W2 \geq 0.8 make up 0.04% of the galaxy population for galaxy masses $10^8 < M/M_{\odot} < 10^9$. These are fairly rare, but not an insignificant fraction of the galaxies in the local universe.
- 2. Massive galaxies $(M/M_{\odot} > 10^{10})$ with colours redder than W1 W2 ≥ 0.5 make up 1.0% of the galaxy population and galaxies with W1 W2 ≥ 0.8 make up 0.3% of the galaxy population in that mass range. Relative to the total galaxy population massive red galaxies are also rare in the universe.
- 3. Most (85.2%) massive $(M/M_{\odot} > 10^{10})$ galaxies with W1 W2 \geq 0.8 are optically classified as AGN or composites, in agreement with the numbers in Stern et al. (2012) and Jarrett et al. (2013) and a good indicator that these colours are a good way to select massive galaxies with dusty AGN.
- 4. The physical mechanism responsible for the red colours in low mass galaxies is less clear than it is in their higher mass counterparts. An increase in the sSFR of red, low mass galaxies may point to star formation driving the heating. However, the possibility exists that in at least some cases the red colours are indicative of dust enshrouded AGN.
- 5. Even in the unlikely case that all of the low mass red galaxies possess dust enshrouded AGN, both pop III and massive seed models indicate that the fraction of black holes that are active in low mass galaxies is significantly less than in more massive systems.

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ϕ_1^*	ϕ_2^*	M_r^*	α_1	α_2
$\rm Mpc^{-3}$	$\rm Mpc^{-3}$	mag		
$5.659 {\pm} 0.007 {\times} 10^{-3}$	$1.949{\pm}0.0.010{\times}10^{-3}$	$-20.753 {\pm} 0.0.013$	-0.244 ± 0.029	$-1.438 {\pm} 0.013$
$4.323 \pm 0.159 \times 10^{-4}$	$9.795{\pm}1.121{\times}10^{-5}$	$-19.985 {\pm} 0.035$	$0.463{\pm}0.0.078$	-1.682 ± 0.034
$7.150{\pm}0.0.362{\times}10^{-5}$	$4.929 \pm 1.422 \times 10^{-6}$	$-20.354 {\pm} 0.066$	$0.473 {\pm} 0.129$	$-1.911 {\pm} 0.0.084$
$2.385{\pm}0.154{\times}10^{-5}$	$5.782{\pm}6.766{\times}10^{-7}$	$-20.378 {\pm} 0.128$	$0.217{\pm}0.226$	$-1.973 {\pm} 0.351$
	$\begin{array}{c} \phi_1^* \\ Mpc^{-3} \\ 5.659 {\pm} 0.007 {\times} 10^{-3} \\ 4.323 {\pm} 0.159 {\times} 10^{-4} \\ 7.150 {\pm} 0.0.362 {\times} 10^{-5} \\ 2.385 {\pm} 0.154 {\times} 10^{-5} \end{array}$	$\begin{array}{c ccc} \phi_1^* & \phi_2^* & \\ Mpc^{-3} & Mpc^{-3} \\ \hline 5.659 {\pm} 0.007 {\times} 10^{-3} & 1.949 {\pm} 0.0.010 {\times} 10^{-3} \\ 4.323 {\pm} 0.159 {\times} 10^{-4} & 9.795 {\pm} 1.121 {\times} 10^{-5} \\ 7.150 {\pm} 0.0.362 {\times} 10^{-5} & 4.929 {\pm} 1.422 {\times} 10^{-6} \\ 2.385 {\pm} 0.154 {\times} 10^{-5} & 5.782 {\pm} 6.766 {\times} 10^{-7} \end{array}$	$\begin{array}{c cccc} \phi_1^* & \phi_2^* & M_r^* \\ Mpc^{-3} & Mpc^{-3} & mag \\ \hline 5.659 {\pm} 0.007 {\times} 10^{-3} & 1.949 {\pm} 0.010 {\times} 10^{-3} & -20.753 {\pm} 0.0013 \\ 4.323 {\pm} 0.159 {\times} 10^{-4} & 9.795 {\pm} 1.121 {\times} 10^{-5} & -19.985 {\pm} 0.035 \\ \hline 7.150 {\pm} 0.0.362 {\times} 10^{-5} & 4.929 {\pm} 1.422 {\times} 10^{-6} & -20.354 {\pm} 0.066 \\ 2.385 {\pm} 0.154 {\times} 10^{-5} & 5.782 {\pm} 6.766 {\times} 10^{-7} & -20.378 {\pm} 0.128 \\ \hline \end{array}$	$\begin{array}{c ccccc} \phi_1^* & \phi_2^* & M_r^* & \alpha_1 \\ Mpc^{-3} & Mpc^{-3} & mag \\ \hline 5.659 {\pm} 0.007 {\times} 10^{-3} & 1.949 {\pm} 0.010 {\times} 10^{-3} & -20.753 {\pm} 0.013 & -0.244 {\pm} 0.029 \\ 4.323 {\pm} 0.159 {\times} 10^{-4} & 9.795 {\pm} 1.121 {\times} 10^{-5} & -19.985 {\pm} 0.035 & 0.463 {\pm} 0.0.078 \\ \hline 7.150 {\pm} 0.0.362 {\times} 10^{-5} & 4.929 {\pm} 1.422 {\times} 10^{-6} & -20.354 {\pm} 0.066 & 0.473 {\pm} 0.129 \\ 2.385 {\pm} 0.154 {\times} 10^{-5} & 5.782 {\pm} 6.766 {\times} 10^{-7} & -20.378 {\pm} 0.128 & 0.217 {\pm} 0.226 \end{array}$

Table 2.1: Luminosity Function Schechter Parameters

Note. — Blanton et al. (2005b)-form Schechter functions fit to our data as described in Section 3.

 Table 2.2: Stellar Mass Function Schechter Parameters

Colour Range	ϕ_1^*	ϕ_2^*	$\log(M^*/M_{\odot})$	α_1	α_2
	${ m Mpc^{-3}}$	${ m Mpc^{-3}}$	$\log({ m M}_{\odot})$		
Total	$4.407 \pm 0.004 \times 10^{-3}$	$5.833 \pm 0.545 \times 10^{-4}$	$10.620{\pm}0.005$	$-0.557 {\pm} 0.024$	$-1.524{\pm}0.018$
$W1-W2 \ge 0.3$	$3.733{\pm}0.066{\times}10^{-4}$	$1.757 {\pm} 0.408 {\times} 10^{-5}$	$10.281 {\pm} 0.015$	$-0.137 {\pm} 0.064$	$-1.804{\pm}0.057$
$W1-W2 \ge 0.5$	$7.095 {\pm} 0.315 {\times} 10^{-5}$	$1.256{\pm}0.595{\times}10^{-6}$	$10.280 {\pm} 0.025$	$0.423 {\pm} 0.123$	$-1.892{\pm}0.124$
$W1-W2 \ge 0.8$	$2.178{\pm}0.211{\times}10^{-5}$	$5.593{\pm}7.798{ imes}10^{-7}$	$10.216{\pm}0.043$	$0.479 {\pm} 0.224$	$-1.487 {\pm} 0.397$

Note. — Baldry et al. (2012)-form Schechter functions fit to our data as described in Section 3.

Chapter 3: SED Fitting and the AGN Nature of SDSS J1224+5555

3.1 Introduction

Optical AGN are rare in low mass ($<10^{10} M_{\odot}$) galaxies (Kauffmann et al., 2003a; Reines et al., 2013). However a number of AGN have recently been detected in host galaxies with stellar masses down to $10^8 M_{\odot}$ using optical (Barth et al., 2004; Dong et al., 2007; Ghosh et al., 2008; Greene & Ho, 2007; Ho et al., 2012; Izotov & Thuan, 2008; Jiang et al., 2011; Maksym et al., 2014; Moran et al., 2014; Reines et al., 2013; Yuan et al., 2014), X-ray (Ghosh et al., 2008; Reines et al., 2014, 2011; Schramm et al., 2013; Secrest et al., 2015; Yuan et al., 2014) and/or radio (Reines et al., 2011) observations. In addition, Satyapal et al. (2014) found a significant population of galaxies with high W1-W2 colors in hosts down to $10^6 M_{\odot}$. High W1-W2 color has been shown to be an indicator of AGN activity in higher mass galaxies as predicted by the color tracks of AGN templates (Jarrett et al., 2011), and observed WISE color space of optically (Yan et al., 2013), infrared (IRAC, see Lacy et al. (2004)) (Stern et al., 2012) and X-ray (Mateos et al., 2012) selected AGN. As shown in Chapter 2, red WISE galaxies constitute a greater percentage of optically normal, low mass galaxies than their higher mass, optical AGN counterparts. It is not clear whether these low mass red WISE galaxies contain AGN. It is possible that the dust heating that the high mid-infrared colors are indicative of could be caused by star formation (Smith & Hancock, 2009). There are compelling arugments both for strong star formation and AGN activity in these galaxies (see Chapter 2). Thus W1-W2 color alone, while indicative of powerful dust heating often seen in AGN, is not proof that these optically normal, IR-red galaxies are AGN hosts. X-ray observations of high W1-W2 galaxies offer a less ambiguous way to discern the presence or abscence of AGN activity in these sources (Ghosh et al., 2008; Reines et al., 2014, 2011; Schramm et al., 2013; Secrest et al., 2015; Yuan et al., 2014).

3.2 Observations

In Satyapal et al. (2014), the authors found a sample of bulgeless galaxies which have W1-W2 colors characteristic of AGN despite lacking optical evidence of AGN activity. As seen in Ghosh et al. (2008), Reines et al. (2011), Schramm et al. (2013), Reines et al. (2014) and Yuan et al. (2014), X-ray data is useful for finding AGN in low mass galaxies. For four of the galaxies from the Satyapal et al. (2014) sample, follow up observations were obtained in the form of a pilot study on XMM-Newton as part of GO proposal 072190. One of the targets, which in addition to being bulgeless is low mass (log(M/M_☉)=8.3), was shown to be an AGN host in Secrest et al. (2015). SDSS J1329+3234 has a hard X-ray luminosity more than two orders of magnitude greater than the expected contribution of X-ray binaries given its star formation rate (Lehmer et al., 2010; Secrest et al., 2015). But the target of this project, SDSS J1224+5555, is more ambiguous. It has an X-ray luminosity of $L_{2-10keV}=(1.1\pm0.4)\times10^{40}$ erg s⁻¹ which is consistent with XRB given its 60 μ m SFR of 5 M_{\odot} yr⁻¹. This means that either the galaxy lacks an AGN or that it is heavily absorbed.

A near-infrared spectrum of SDSS J1224+5555 was taken on the Large Binocular Telescope (LBT) to look for observing the broad emission lines that would be expected in an AGN including Paschen α (1.875 μ m) and Brackett γ (2.166 μ m) (Murphy et al., 1999; Veilleux et al., 1997). Though the nuclear spectrum does contain clear Pa α emission, there does not appear to be a broad component and Br γ is not detected at all. Fortunately we can use the hydrogen recombination lines in order to calculate the amount of obscuration in the nuclear region. With an H α flux of 7.74±0.08×10⁻¹⁵ erg s⁻¹ cm⁻² (Brinchmann et al., 2004) and a Pa α flux of 7.74^{+0.20}_{-3.57}×10⁻¹⁶ erg s⁻¹ cm⁻² we can use Equation 3.1 to calculate E(B-V).

$$\frac{F_{obs}(H\alpha)}{F_{obs}(Pa\alpha)} = \frac{F_{int}(H\alpha)}{F_{int}(Pa\alpha)} 10^{-0.4(k(H\alpha)-k(Pa\alpha))E(B-V)}$$
(3.1)

This calculation assumes that the intrinsic ratio (in the case of no obscuration) of the H α flux to Pa α flux is 7.82 for case B recombination and 12+log(O/H) > 8.35 (Osterbrock & Ferland, 2006) and difference in the extinction curves between the wavelengths of H α and Pa α (k(H α)-k(Pa α)) is 2.08 (Fitzpatrick, 1986). Assuming a Milky Way extinction curve with R_V=3.1 this leads to E(B-V)=1.255 and A_V=3.89. Furthermore this A_V is only an upper limit as there is likely additional ionized gas outside of the SDSS spectroscopic fiber, meaning the F_{obs}(H α)/F_{obs}(Pa α) used in Equation 3.1 is likely an underestimate of the flux contained within the larger LBT aperture.

One other option to explore is spectral energy distribution (SED) modeling. This compares the multiwavelength photometry of a galaxy against a set of templates so that inferences can be made about the host galaxy's properties. This project will focus on decomposing the SED of SDSS J1224+5555 using a set of templates created from the median SEDs of elliptical, spiral and irregular galaxies and AGN hosts (Assef et al., 2010) templates described in Section 3.3.

3.3 The Assef Templates

The Assef et al. (2010) templates contain low resolution wavelength coverage from 0.03 to 30 μ m. This extends from the far-ultraviolet through the mid-infrared, including the GALEX, SDSS, 2MASS, IRAC, WISE and first two IRAS bands. The set of four templates contains three galaxy models made from the median SEDs of elliptical (E), spiral (Sbc), irregular galaxies (Im) and Type 1 (unobscured) quasars (AGN). It is assumed that any galaxy can be modeled using a linear combination of these four templates with normalization and extinction of each component as free variables.

The three galaxy templates are based on elliptical, spiral and irregular SEDs from

Coleman et al. (1980) with wavelength coverage expanded further into the ultraviolet and infrared using stellar population synthesis from Bruzual & Charlot (2003). Since the Sbc and Im templates contain active star formation, PAH emission was added to their infrared SEDs using spectra from the star forming galaxies NGC 4429 and M82 (Devriendt et al., 1999). The AGN template is based on the average Type 1 quasar from Richards et al. (2006) with an additional variable reddening component. This is combines an SMC reddening curve at wavelengths $\lambda < 0.33 \ \mu m$ (Gordon & Clayton, 1998) and Galactic reddening at longer wavelengths (Cardelli et al., 1989), assuming $R_V=3.1$ in both cases. Figures 3.1 and 3.2 show the spectral shapes of each of the four templates with varying levels of extinction. Unlike Assef et al. (2010) and most other papers that have used this method of SED decomposition (Assef et al., 2010, 2013, 2015; Hainline et al., 2014; Lansbury et al., 2014, 2015), here variable reddening is also included in the galaxy templates in some versions of the fit as opposed to only including variable extinction in the AGN template. Extinction depresses the emission at the high energies (ultraviolet and optical) while leaving longer wavelengths mostly unaffected except in cases of very high attenuation. All templates (before extinction is added) are normalized to D=10 pc and $L_{0.03-30\mu m}=10^{10} L_{\odot}$.

3.3.1 Pros and Cons of Assef Templates As Tools For SED Decomposition

The main advantages of the Assef et al. (2010) templates come from their simplicity. With only four templates and a minimum of free parameters, it is easy to decompose the SED of a galaxy using a simple chi-squared minimization procedure. This means it can fairly easily be applied to large samples of galaxies. Furthermore, the method only requires an observed galaxy to have photometry and not spectroscopy which can be more time consuming to obtain. The Assef et al. (2010) templates include AGN in the fitting and can be used for the calculation of photometric redshifts.

However decomposing SEDs using the (Assef et al., 2010) templates also has several drawbacks. First, the galaxy templates are based on the median SEDs of broad classes of galaxies. They contain an unknown amount of internal reddening and may lack the



Figure 3.1: Flux versus wavelength of AGN and E templates from Assef et al. (2010). Line colors represent different levels of extinction to the templates.



Figure 3.2: Flux versus wavelength of Sbc and Im templates from Assef et al. (2010). Line colors represent different levels of extinction to the templates.

flexibility necessary to model galaxies with nonstandard features such as unusually high star formation rates or PAH features not captured in the Devriendt et al. (1999) templates. Thus galaxies with SEDs that don't fall near these median values may end up with poor quality fits. The lack of adjustable parameters in the model, while expediting the fitting process, means that it is impossible to extract specific information about the host galaxy from the fit such as mass, metallicity or star formation rate. There is no energy balance or radiative transfer included in the reddening of the templates as this would have the potential to make the fitting process prohibitively computationally intensive. This means that light absorbed in the ultraviolet or optical range by dust does not coincide with increased blackbody emission in the infrared.

3.4 SED Fits of SDSS J1224+5555

The spectral energy distribution of J1224+5555 was modeled as a linear combination of the four Assef et al. (2010) templates described in Section 3.3 with variable normalization and extinction included for each component. The best fit was obtained using an IDL routine using the function mpfitfun.pro¹. This uses a Levenberg-Marquardt least squares minimization procedure to vary the function's free parameters until it converges at the lowest χ^2 value. As these templates only extend between 0.03 and 30 microns, it is not possible to include the XMM or IRAS 60 μ m photometry.

3.4.1 Tests of the Fitting Procedure

As a sanity check, SED fits in Hainline et al. (2014) which also used the Assef et al. (2010) templates to decompose the spectra of WISE quasars were reproduced. The left panel of Figure 3.3 shows an example reproduction of Hainline et al. (2014)'s fit of SDSS J160903.75-000426.2 using the normalization constants and AGN extinction from Table 3 of that paper. When taking into account that the fitting routine of that paper includes only three free parameters (Sbc and AGN normalization and AGN extinction), the program used

 $^{^{1}} http://hesperia.gsfc.nasa.gov/ssw/gen/idl/fitting/mpfit/mpfitfun.pro$



Figure 3.3: Flux versus wavelength for the fit of the galaxy J160903.75-000426.2 from Hainline et al. (2014). Green points are the observed SDSS u, g, r, i, z and WISE W1, W2, W3 photometry. Black points are model photometry. Line color represents the flux of the Sbc (blue) and AGN (red) templates as well as the combined flux (black). Left panel: Template combination using normalization constants (given in the legend) from Table 3 of Hainline et al. (2014). Right panel: Template combination using best fit constants obtained with mpfitfun.pro.

here also results in the same χ^2 value. Running the photometry through mpfitfun (right panel of Figure 3.3) results in a very similar fit to that in the Hainline et al. (2014) paper but with a slightly lower χ^2 .

3.4.2 Parameter Space Exploration

While the Levenberg-Marquardt least squares method is useful for curve fitting, there is a possibility of the algorithm getting stuck in local rather than global minima if the initial guess for the free parameters is too far off from the correct value. To find all minima in the SED fit's χ^2 value, we created 100,000 randomly generated model spectra from the Assef et al. (2010) base templates spanning from 10^{-18} to 10^{-13} in normalization and 0 to 100 in A_V for all templates. Figure 3.4 shows that there are up to two minima depending on the combination of parameters. The first minimum is mainly a combination of the Im and AGN templates (χ^2 =470) with negligible contributions from the E and Sbc spectra. The second minimum is a combination of the E, Im and AGN templates (χ^2 =333) with only a small Sbc contribution. While the galaxy template combinations of these two minima differ substantially, the AGN normalization is only 7% higher in the second minimum than the first. AGN extinction is 0.34 mag (46%) greater in the second minimum than in the first. Plugging the parameters from both of the local minima from Section 3.4.2 into the least squares minimization routine results in the same best-fit model shown in Figure 3.5. This confirms that the program has found the global minimum and best fit parameters.

3.4.3 Best Fit Templates

A substantial contribution from the AGN is necessary in order to match J1224+5555's photometry, especially in the mid-infrared. The AGN accounts for 83% of the galaxy's luminosity (before A_V) in the 0.1-30 μ m range.

In contrast, the best fit SED that can be constructed using only the galaxy (E, Sbc and Im) templates in Figure 3.6 has $\chi^2 > 1000$ and has much lower W2, W3 and W4 fluxes than those observed in the galaxy.

3.5 Discussion

The results of Section 3.4 have demonstrated that the best fit SED of SDSS J1224+5555 using the Assef et al. (2010) templates has a substantial contribution from an obscured AGN. As shown by the existence of 2 minima in Section 3.4.2, there is some degeneracy in the combination of galaxy templates. The fit, particularly in terms of AGN contribution, could be improved by expanding the wavelength coverage of the Assef et al. (2010) templates so



Figure 3.4: The top panels show the minimum χ^2 values for the randomly generated fits to J1224+5555 as a function of AGN normalization (panel a), Im normalization (panel b), E normalization (panel c), Sbc normalization (panel d), AGN template extinction (panel e), Im template extinction (panel f), E template extinction (panel g) and Sbc template extinction (panel h). Red lines show the best fit values obtained with mpfitfun. There was no significant contribution from the Sbc template in the best fit model.



Figure 3.5: Best fit SED OF J1224+5555 derived using least squares minimization. A combination of the E and Im templates with low extinction dominates the optical and near infrared while the mid-infrared has a substantial contribution from the obscured AGN template.



Figure 3.6: SED of J1224+5555 with observed SDSS, 2MASS and WISE photometry in green points (photometric errors are smaller than the data points for all bands except 2MASS J, H, K_s) and photometry from the best fit linear combination of galaxy templates (E, Sbc, Im) in black. Line color represents the contribution from each individual template with Sbc in dark blue and Im in orange. Normalization constants as percentages are given next to the template name.

that the XMM or IRAS 60μ m photometry could be used as a constraint. Even in powerful AGN the IRAS 60μ m emission is thought to be dominated by dust heating from stars (Rosario et al., 2012), allowing this measurement to narrow down the possible combinations of templates. There is also an issue in the way the templates themselves were constructed-from the median SEDs of broad classes of galaxies- in which high W1-W2 sources are not likely to be well represented due to their rarity in the local universe (see Chapter 2). If the high W1-W2 color in J1224+5555 is due to unusual stellar properties rather than AGN activity, the Assef et al. (2010) templates would be unable to show that. Better measurements in the GALEX FUV and NUV bands would be useful for disentangling contributions from the galaxy templates because as seen in Figures 3.1 and 3.2, they look very different in this wavelength range. IRAC [5.8] and [8.0] micron photometry would also help because both the Im and Sbc templates display prominent PAH features here while the AGN template has a flatter power law spectrum. Unfortunately the Spitzer telescope is currently in the Warm Mission phase and is no longer taking data in these bands.

As mentioned in Section 3.3, there is an unknown level of extinction already included in the E, Sbc and Im templates and there is no energy balance or radiative transfer included in the models. Adding extinction to the templates depresses the short wavelength emission without boosting the long wavelengths which is not physically realstic, especially in cases of high obscuration.

The templates themselves are limited due to the fact that they are empirically derived from the median spectral energy distributions of broad classes of galaxies. As red W1-W2 objects are rare in the local universe (See Chapter 2), it is unlikely that they are well represented in the Assef et al. (2010) templates. There could be other unusual properties of the SEDs of red W1-W2 galaxies in addition to their hot dust emission that make them difficult to model as a linear combination of the Assef templates. Furthermore it is unclear whether or not star formation can produce W1-W2 colors in the range of J1224+5555 (W1-W2=1.1). Both of these topics are explored further in Chapter 4.

3.6 Conclusion

The red WISE, bulgeless, optically normal galaxy SDSS J1224+5555 has an X-ray luminosity much lower (>2 orders of magnitude) than expected given the (Secrest et al., 2015) relation between W2 and 2-10 keV luminosity and its observed W2 flux. This may indicate that this galaxy's red colors are the result of star formation or of a heavily obscured AGN. To distinguish between these two scenarios, I employed SED modeling using the Assef et al. (2010) templates. This method has advantages including a minimum of free parameters and small number of base templates, but may not represent the full range of possible galaxy SEDs. There is degeneracy in the templates such that multiple combinations of the E, Sbc and Im galaxy templates may be added together to produce roughly the same optical-NIR photometry observed in the galaxy.

The main result of the SED fitting is that an AGN template contribution is always necessary in order to reproduce the galaxy's observed colors in the WISE bands. This is true regardless of whether A_V is left as a free or fixed parameter in the galaxy templates. The results obtained by fitting the Assef et al. (2010) templates to SDSS J1224+5555's observed SED would seem to indicate that the galaxy does indeed host an obscured AGN.

Chapter 4: SED Fitting of Optically Star-Forming Galaxies with W1-W2 \geq 0.8

4.1 Introduction

An unusual population of galaxies has been identified in the local universe with extremely red (W1 - W2 > 0.8) colors that are thought to be indicative of AGN activity in massive galaxies (Satyapal et al., 2014; Stern et al., 2012). However these are low mass systems that lack AGN signatures in either broad or narrow optical emission lines (Sartori et al., 2015; Secrest et al., 2015; Shao et al., 2013) (see also Chapter 2). There are two possible explanations for the extreme dust heating in these galaxies: (1) they do contain AGN which are heavily obscured so as to remain optically invisible or (2) they do not contain AGN and the dust heating that results in high W1-W2 color is caused by stars alone.

One way to distinguish between the two scenarios is through the modeling of spectral energy distributions (SEDs). Though SED modeling has many uses in inferring galaxy properties, here we will concentrate on instances where the SEDs of this unusual population of optically normal high W1-W2 galaxies have been studied. For example, Shao et al. (2013) examined the SEDs of high W1-W2 galaxies of all BPT (Baldwin et al., 1981) classes of galaxies. They found that while W1-W2 color seems to be independent of stellar mass and only rises as a function of AGN activity, there is a small population of galaxies with high W1-W2 which are not optically identified as AGN. Shao et al. (2013) did not conduct a detailed analysis of these galaxies, instead suggesting that this population arises from low signal to noise emission line objects resulting in optically unidentified galaxies. However the sample of Shao et al. (2013) has a higher mass limit ($\log(M/M_{\odot}) > 9.5$) than the point where optically normal galaxies begin to dominate the number density of W1-W2>0.8 sources (Chapter 2). Izotov et al. (2014a) and Izotov et al. (2014b) did focus on the SED modeling of dwarf galaxies, some of which have W1-W2>2. By fitting three component blackbody radiation models to the infrared SEDs of these galaxies, they found that high W1-W2 color corresponds to a dust temperature of a few hundred Kelvin. Izotov et al. (2014b) also showed that the luminosity of hot dust in high W1-W2 dwarf galaxies is linked to their H β emission, implying a link between star formation and dust heating in these galaxies.

On the other hand, there are numerous examples of SED modeling providing evidence for AGN activity in high W1-W2 galaxies. Lansbury et al. (2014) used the Assef et al. (2010) templates to model the AGN components of 3 heavily obscured AGN observed in the hard X-rays with NuSTAR, 2 of which had W1-W2>0.8. Both the X-rays and the SED fits confirmed the high N_H and AGN contribution to the WISE colors of these galaxies. Hainline et al. (2014) used the (Assef et al., 2010) templates to fit a sample of 40 galaxies with W1-W2>0.8 in the Böotes Field with SALT spectra and found that an AGN component was necessary in all galaxies because of their red WISE colors, even if their optical spectra lacked signs of AGN activity. However they do note that this may be explained by star formation more extreme than that modeled by the Assef et al. (2010) templates. Stern et al. (2014) used these templates to extract the AGN components of three high redshift ($z\approx2$) galaxies including one (WISE J1814+3412) with an optically normal spectrum.

The Assef et al. (2010) templates, while useful in uncovering general properties such as AGN obscuration levels and contributions to galaxy flux as a function of wavelength, have limitations. The models rest on the assumption that any galaxy can be modeled as a combination of only four templates. These templates are created from the median spectral energy distributions of broad classes of galaxies in which high W1-W2 sources are not likely to be well represented due to their rarity in the local universe (see Chapter 2). Due to the generality of the templates, it is impossible to extract information from the fit beyond the relative luminosities and obscuration levels of each of the models. The Assef et al. (2010) templates also lack radiative transfer. Fortunately there are other sets of templates used to model the SEDs of galaxies which do not have the same sets of limitations. Here we will use the MAGPHYS code (da Cunha et al., 2008) described in Section 4.3. The code's inclusion of a longer wavelength range (0.1-1000 μ m) and use of thousands of stellar and dust templates allows for more detailed decomposition of the observed photometry of a given galaxy. While MAGPHYS does not include full radiative transfer, it does contain an energy balance between the starlight absorbed in the ultraviolet and optical ranges and the light emitted by dust and PAH molecules in the infrared. In this way, it presents an ideal method for determining whether or not the dust heating that optically normal galaxies with W1-W2>0.8 display can come from the galaxies' stars or if some other dust heating source (ie an AGN) is necessary.

This Chapter is organized as follows: Section 4.2 describes unusual properties of optically normal high W1-W2 galaxies in addition to their red MIR colors, Section 4.3 describes the MAGPHYS code and fits of three test galaxies, Section 4.4 discusses the interpretation of Sections 4.2 and 4.3's results and the conclusion is found in Section 4.5.

4.2 Properties of High W1-W2 Galaxies

4.2.1 Optical Colors

Galaxies with W1-W2 \geq 0.8 constitute a rare population in the local universe (see Chapter 2). Given that this color is used as an AGN selection criterion (Stern et al., 2012), it is unsurprising that many of these (high mass) sources are also optical AGN. However there are 90 optically normal galaxies with W1-W2>0.8 from the matched SDSS+WISE sample of Chapter 2, 26 of which have stellar masses below 10⁹ M_☉. These low mass sources with W1-W2>0.8 are of particular interest because they represent a different galaxy population than their high mass optical AGN counterparts as seen in Chapter 2. In addition to the photometry from the original SDSS+WISE sample, we have obtained GALEX AIS and MIS (*FUV* and *NUV*) (Bianchi, 2014), SDSS DR12 (*u*, *g*, *r*, *i* and *z*) (Alam et al., 2015), 2MASS (*J*, *H* and *K_s*) (Skrutskie et al., 2006), AllWISE (*W1*, *W2*, *W3* and *W4*) (Cutri

et al., 2013) and IRAS (12, 25, 60, 100μ m) (Neugebauer et al., 1984) data for the galaxies with W1-W2 \geq 0.8 as well as a comparison sample of galaxies with W1-W2<0.3. These colors (W1-W2<0.3) are in line with non-AGN host galaxies at z=0 (Assef et al., 2010) and observed W1-W2 colors of Galactic stars (Chen et al., 2014).

In the context of SED modeling, it is useful to investigate the possibility of differences in the optical colors of optically normal IR-red and IR-blue galaxies because these colors may indicate differences in stellar properties between these two classes of galaxies. Optical colors including g-r and r-i may be affected by stellar age, metallicity and obscuration levels. As seen in Figures 4.1 and 4.2, there are differences in the SEDs of W1-W2 \geq 0.8 and W1-W2<0.3 galaxies in addition to mid-infrared colors. For low mass galaxies (log(M/M_{\odot})<9), there is a large difference between the median g-r and r-i colors of those with high (W1-W2 \geq 0.8) and low (W1-W2<0.3) IR color galaxies. The bluer optical colors of low mass galaxies with W1-W2 \geq 0.8 along with their higher star formation rates and lower metallicities compared to IR-blue galaxies of the same stellar mass (see Figure 2.5) imply a link between young stars and the dust heating that creates high W1-W2 colors.

4.2.2 HI Gas Fraction

The sample of galaxies from Chapter 2 (SDSS (Abazajian et al., 2009) and WISE (Cutri et al., 2013) surveys with stellar masses, metallcities and star formation rates from the MPA-JHU catalogs (Brinchmann et al., 2004; Kauffmann et al., 2003b; Tremonti et al., 2004)) was also matched to the ALFALFA 40% catalog (Haynes et al., 2011) which contains measurements of the atomic hydrogen content of galaxies within that sample's volume (z<0.06). Approximately 3% of the Chapter 2 sample appears in the ALFALFA 40% catalog. Atomic hydrogen traces molecular hydrogen, which is used to form new stars so it is useful to investigate the relation between this quantity and high W1-W2 colors. As seen in the red line of Figure 4.3, there is a small correlation between W1-W2 color and the relative fraction of the masses of atomic hydrogen gas mass to stellar mass, albiet with a large amount of scatter. The Pearson Correlation Coefficient between these two



Figure 4.1: g-r color of galaxies with W1-W2<0.3 (black contours) and W1-W2 \ge 0.8 (red circles). Blue and green points are the median g-r colors and standard deviations of the respective colors in each dex of stellar mass.



Figure 4.2: r-i color of galaxies with W1-W2<0.3 (black contours) and W1-W2 \ge 0.8 (red circles). Blue and green points are the median r-i colors and standard deviations of the respective colors in each dex of stellar mass.



Figure 4.3: W1-W2 color versus hydrogen gas mass fraction (HI mass divided by stellar mass) for galaxies which have measurements in the SDSS DR7, AllWISE and ALFALFA 40% catalogs. Contour levels are noted in the plot. The red line is the best linear fit between W1-W2 and gas fraction.

quantities is 0.055. We can reject the null hypothesis of no correlation between W1 - W2 and $\log(M_{HI}/M_*)$ at a 95% confidence level. Galaxies with the highest gas fraction span the widest range of W1 - W2 color. Figures 4.1, 4.2 and 4.3 in addition to 2.5 provide evidence that galaxies with high W1-W2 colors are gas-rich star-forming systems. Star-formation and AGN activity may occur in the same source simultaneously, so this does not eliminate the possibility that AGN contribute to the dust heating in these systems even if they appear to be strongly star-forming (Davies et al., 2014; Kauffmann et al., 2003a; Melnick et al., 2015; Murphy et al., 1999).

4.3 MAGPHYS SED Fitting

In order to decompose the spectral energy distributions of sample galaxies, we use the MAG-PHYS code described in da Cunha et al. (2008). This code combines stellar population and infrared dust models in a way that creates self-consistent, energy-balanced model spectral energy distributions which can then be compared to the observed photometry of a galaxy in order to find the best fit.

The code starts with a stellar library calculated using the Bruzual & Charlot (2003) population synthesis code with the Chabrier (2003) Galactic disk stellar disk initial mass function. Using the same star formation histories as Kauffmann et al. (2003b) and variations in metallicity (2-200%), optical depth and fraction of dust luminosity from the ambient interstellar medium (as opposed to stellar birth clouds) with probability densities matched to the observed distribution of SDSS galaxies, MAGPHYS contains a library of 50,000 stellar templates. Since the level of obscuration in each stellar template is known, the code can then calculate the luminosity of the starlight absorbed by dust. This absorbed starlight is then re-radiated in the infrared as a combination of polycyclic aromatic hydrocarbon (PAH) molecules, a warm infrared continuum, warm dust grains (30-60 K) in stellar nebulae and cold dust grains (15-25 K) in the ambient ISM. Although the relative normalization of the infrared components can be varied with their combined luminosity matched to that of the absorbed starlight, this code does not include full radiative transfer. It should be noted that the default version of MAGPHYS (da Cunha et al., 2008) only includes stars as light sources without any AGN component.

Given the observed photometry of a galaxy, MAGPHYS calculates the photometry of each model in the same bands. Then the code calculates a χ^2 goodness of fit statistic for every model and probability distributions for model parameters including stellar mass, star formation rate, optical depth, dust mass, luminosity and temperature.

4.3.1 MAGPHYS SED Fit Sample

The goal of fitting galaxies with MAGPHYS models is to see whether or not the spectral energy distributions of optically normal sources with W1-W2>0.8, which indicates AGN activity in high mass sources (Stern et al., 2012), can be explained by stellar dust heating alone without an AGN contribution. In order to achieve the goals of this project, it is necessary to test the MAGPHYS code on three galaxies. First: a low mass $(M < 10^9 M_{\odot})$ galaxy which is known to be purely star-forming with no optical or infrared evidence of AGN activity. This is both to make sure that the code produces a reasonable fit to a normal stellar population and for comparison of stellar and dust properties with the galaxy in the second category. Second: a low mass galaxy which appears to be optically normal (no broad or narrow line AGN indicators) but with W1-W2>0.8. The fit will reveal if this unusual galaxy's SED can be explained without an AGN contribution. Secondly, the fit will show any unusual properties of the galaxy such as a high star formation rate, dust content and optical depth which may explain why such a small fraction of low mass optically normal galaxies have high W1-W2 colors. Third: we must fit a galaxy with optical and infrared AGN signatures to show that the SED of this source *cannot* be fit by a template composed purely of stars and dust because the AGN dominates the galaxy's emission. Lastly, we decompose the SED of SDSS J1224+5555, the subject of Chapter 3. We have studied this galaxy in detail and fit its SED with the Assef et al. (2010) templates which indicated a significant contribution from the AGN template. By fitting this galaxy's SED again with MAGPHYS, we can see whether or not a non-stellar component is still necessary to explain its emission with a wider range of stellar populations and dust SEDs available.

4.3.2 MAGPHYS SED Fit Results

Figure 4.4 shows a low mass, optically and infrared-normal source. MAGPHYS does produce a good fit to the multiwavelength SED with well constrained likelihood distributions for dust optical depth, stellar mass and specific star formation rate. The fit indicates that the program is capable of modeling the stars and dust for this relatively normal dwarf galaxy.

The fit for an optically normal, high W1-W2 galaxy (CGCG 007-025) is shown in Figure 4.5. The galaxy's SED is consistent with stellar and dust emission without an AGN as a dust heating source. The best fit includes a stellar population with $\tau_V \approx 1$ and a very high specific star formation rate. This would imply that a young massive stellar population that is still within intact stellar birth clouds while the galaxy in Figure 4.4 has fewer and less heavily imbedded massive stars.

Figure 4.5 shows that the multiwavelength SED of a galaxy which appears to be optically normal but with W1-W2>0.8 indicative of dust heating from an AGN can also be explained as dust heating from young stars without an AGN illumination source. But in order to accurately interpret this result, it is also necessary to make sure that the SEDs of known AGN can't be modeled without an AGN template. We need to show that the SED shapes of AGN and stars are different and can be reliably separated by decomposition. Figure 4.6 shows the fit of one such AGN. The galaxy has broad H α and H β lines in its SDSS spectrum and W1-W2>0.8, giving it an unambiguous classification as an AGN. Figure 4.6 demonstrates that even though the test galaxy's emission should be dominated by the AGN and thus have an SED that differs from a pure stellar spectral energy distribution. MAGPHYS produces a model fit to the AGN that has a lower χ^2 than even the known starforming galaxy in Figure 4.4. Though the optical depth from the fit is poorly constrained and the galaxy lacks a specific star formation rate measurement in the MPA-JHU catalog, its stellar mass is consistent with its corresponding value in the NASA-Sloan Atlas¹. However this mass itself was calculated using SED fitting to a set of galaxy templates which only includes stellar inputs (Blanton & Roweis, 2007). What this means is that MAGPHYS cannot be used to distinguish star formation from AGN activity as the primary dust heating mechanism in high W1-W2 galaxies. Though there are cases in the literature of authors adding AGN components to MAGPHYS either as a power law (Brown et al., 2014) or as the Fritz et al. (2006) torus template library (Berta et al., 2013), the fact remains that

¹http://www.nsatlas.org/

MAGPHYS cannot be used to eliminate AGN as a possible source of dust heating in these galaxies. There is enough overlap in the SED shapes of galaxies with only stars and galaxies with stars and AGN, especially low luminosity AGN, that they cannot be reliably separated.

Using the MAGPHYS code, we are also able to fit the SED of SDSS J1224+5555 which was shown to have emission consistent with dust heating from an obscured AGN in Chapter 3. Figure 4.7 shows that despite this, J1224+5555 can be fit as a combination of stars and dust heated by stars without an AGN contribution. However as demonstrated by Figure 4.6 this is not proof that the galaxy does not contain an AGN. Like in Figure 4.6, J1224+5555's optical depth is poorly constrained but its stellar mass and star formation rate are consistent with the corresponding values listed in the MPA-JHU catalogs. Though the stellar mass in the MPA-JHU catalog was also calculated using an SED modeling procedure which assumes no AGN input (Kauffmann et al., 2003b), the galaxy's star formation rate was calculated using the H α line flux from the SDSS spectrum (Brinchmann et al., 2004). But if as suggested by Chapter 3, the galaxy contains an obscured AGN, its contribution to the H α line should be negligible. An infrared spectrum could reduce the ambiguity in the interpretation of J1224+5555's SED fits by discovering if the WISE bands are dominated by PAH emission as the MAGPHYS fit in Figure 4.7 suggests or if the mid-infrared is instead composed of an AGN power law like in Figure 3.5.

4.4 Discussion

As demonstrated in Section 4.3.2, the spectral energy distributions of low mass, optically normal galaxies with W1 - W2 > 0.8 may be explained as dust heating by young stars. There are instances in the literature of starbursting dwarf galaxies with red W1 - W2 colors, but neither is AGN activity ruled out. For example, SBS 0335-052E has a W1-W2 color greater than 1 and both ISO observations and infrared spectra modeled with Starburst99 that are consistent with the galaxy containing a heavily obscured ($A_V > 20$) starburst region (Engelbracht et al., 2008; Hirashita & Hunt, 2004; Houck et al., 2004; Hunt et al., 2014; Izotov et al., 2014b; Thuan et al., 1999). In addition, while the galaxy does



Figure 4.4: MAGPHYS fit of a low mass galaxy without optical or infrared AGN indicators. Pink points are observed photometry (GALEX, SDSS, 2MASS, WISE and IRAS bands). Blue and black solid lines are unattenuated stars and attenuated stars plus dust. Underneat the SED fit are likelihood distributions for the galaxy's dust optical depth, stellar mass and specific star formation rate.



Figure 4.5: MAGPHYS fit of a low mass optically normal galaxy with W1-W2>0.8. Pink points are observed photometry (GALEX, SDSS, WISE and IRAS 60 μ m). Blue and black solid lines are unattenuated stars and attenuated stars plus dust. Bottom panels show the likelihood distributions for optical depth, stellar mass and specific star formation rate.



Figure 4.6: MAGPHYS fit of a Type 1 AGN (broad H α , H β) with W1-W2>0.8. Pink points are observed photometry (GALEX, SDSS, 2MASS, WISE and IRAS 60 μ m). Blue and black solid lines are unattenuated stars and attenuated stars plus dust. Bottom panels show the likelihood distributions for optical depth, stellar mass and specific star formation rate.



Figure 4.7: MAGPHYS fit of SDSS J1224+5555 from Chapter 3. Pink points are observed photometry (SDSS, 2MASS, WISE and IRAS 60 μ m). Blue and black solid lines are unattenuated stars and attenuated stars plus dust. Bottom panels show the likelihood distributions for optical depth, stellar mass and star formation rate.

contain ULXs as observed by Chandra, SBS 0335-052E lacks X-ray evidence of an AGN, obscured or otherwise (Prestwich et al., 2013). More generally, Izotov et al. (2014a) found that while there is no solid correlation, starburst galaxies with the highest W1-W2 color also tend to have the highest H β luminosities, implying a connection between W1-W2 color and star formation. While metallicity is in general uncorrelated with W1-W2 color, the lowest metallicity galaxies known thus far (I Zw 18 and SBS 0335-052E) both have W1-W2>0.5 (Griffith et al., 2011). It has been suggested that perhaps a low metallicity environment contributes to the formation of especially massive stars and leads to an unusually hard ionizing radiation field which then heats the dust and destroys PAH molecules in dwarf starbursts in a way that looks very similar to AGN activity (Brandl et al., 2006; Griffith et al., 2011; Houck et al., 2004; Magdis et al., 2013; Shim & Chary, 2013; Smith & Hancock, 2009; Wu et al., 2007). If this were true it would explain why so many red W1-W2 dwarf galaxies also have Wolf-Rayet features in their optical spectra (Shim & Chary, 2013; Shirazi & Brinchmann, 2012). Over 50% of the Wolf-Rayet galaxies in the SDSS-derived sample of Shirazi & Brinchmann (2012) have W1 - W2 > 0.8 in AllWISE. But 69% of these galaxies also show signs of AGN activity (BPT classification is either composite or AGN) with only 57 purely optically star-forming sources with both Wolf-Ravet spectral features and W1 - $W_2 > 0.8$. This is also consistent with the enhancement in specific star formation rate found in low mass high W1-W2 galaxies in Chapter 2 and the unusually blue q-r colors and higher atomic gas fractions found in Section 4.2. Furthermore, Smith & Hancock (2009) showed that the [4.5] flux of blue compact dwarfs may be enhanced either by the nebular continuum of stars younger than 4 Myr or $Br\alpha$ emission, though they could not conclusively rule out heated dust from AGN as a contributing factor.

However, Section 4.3.2 also shows that even some optical AGN SEDs (see Figure 4.6) can be modeled as a stellar population with associated dust heating, though this is clearly not where the bulk of the emission is actually coming from. SDSS J1224+5555, the subject of Chapter 3, can also be fit with MAGPHYS (Figure 4.7) which offers an alternative explanation for its high W1-W2 color and low X-ray luminosity. Thus it may not be

possible to use SED modeling to rule out AGN activity in low mass star forming galaxies. Additional observations are needed to break the degeneracy. NuSTAR offers a particularly promising option, as it probes energies high enough that even Compton-Thick AGN will be visible. It has already unvieled several heavily obscured, low luminosity AGN (Annuar et al., 2015; Lansbury et al., 2015; Madsen et al., 2015; Ricci et al., 2016; Ursini et al., 2015). NuSTAR observations may also place limits on the X-ray luminosity of nuclear sources in starburst galaxies (Lehmer et al., 2015; Walton et al., 2015).

4.5 Conclusion

Having previously calculated the spatial density of low mass high W1-W2 galaxies in the local universe and shown through SED modeling with the Assef et al. (2010) templates that at least one optically normal IR-red source is consistent with being an obscured AGN, the question remained concerning the nature of the dust heating mechanism in the low mass red WISE sample. Section 4.2 showed that compared to blue W1-W2 galaxies (W1-W2<0.3) of the same stellar mass, low mass ($6 < \log(M/M_{\odot}) < 9$) galaxies with W1-W2>0.8 have much bluer *g*-*r* and *r*-*i* colors. This would seem to indicate active star formation but does not mean that AGN are not also present. We have also found a weak correlation between W1-W2 color and HI gas mass fraction in sample galaxies with measurements in SDSS, AllWISE and the ALFALFA 40% catalog.

Next, we attempted to discern whether or not the ultraviolet through far-infrared spectral energy distributions of the low mass red WISE population could be modeled as coming from stars and dust heated by stars without needing to invoke an AGN contribution to the mid-infrared luminosities. Section 4.3.2 showed that this is true, but still not definitive as even some optical AGN have SEDs consistent with stars.

Thus it appears that even sophisticated means of SED modeling such as MAGPHYS are incapable of distinguishing between SEDs dominated by stars and AGN. More high energy observations of dwarf galaxies with high W1-W2 are needed with instruments such as NuSTAR. The telescope has already demonstrated an ability to uncover low luminosity obscured AGN and could at the very least place an upper limit on the X-ray luminosities of galaxies in which the AGN is absent (see Section 5.1).
Chapter 5: Conclusions and Future Work

The main questions of this dissertation concerned the population and dust heating mechanisms of galaxies with high W1-W2 colors in the local universe. Chapter 2 expanded upon the results of Satyapal et al. (2014) by calculating the number density of galaxies with W1-W2 \geq 0.3, 0.5 and 0.8 as a function of optical luminosity and stellar mass. While the high mass components of the red WISE luminosity and stellar mass functions contained optical AGN indicators, these were absent in the dominant low mass population. Enhancements in specific star formation rates and lower metallicities were also observed in low mass red W1-W2 galaxies, implying a stellar rather than AGN dust heating source. But the correlation between W1-W2 color and star formation does not equal causation as AGN and starbursts grow from the same fuel source and often occur simultaneously (Trump et al., 2015, and references therein).

Fortunately two of the optically normal, red W1-W2 sources in Chapter 2's sample were observed with XMM-Newton as part of a pilot study of red WISE bulgeless galaxies. One of these, J1329+3234, was shown to be an AGN in Secrest et al. (2015). The second, J1224+5555, contained a 3σ X-ray detection albiet at a much lower luminosity than would be expected given its W2 flux and the Secrest et al. (2015) $L_{2-10keV}$ - L_{W2} relation for AGN. Using the templates from Assef et al. (2010), I was able to show that the SED of J1224+5555 could not be satisfactorily modeled without a significant contribution from the AGN template. Though this would seem to indicate that the dust in this galaxy is heated by an obscured AGN rather than unusual stars, the Assef et al. (2010) templates rely on the assumption that any galaxy can be modeled as a combination of four templates created from the median SEDs of large, broad classes of galaxies in which high W1-W2 objects are dominated by AGN in massive galaxies, as they are in the galaxy population as a whole. To make matters worse, adding extinction, which should redden the W1 - W2 values of these templates, only supresses high energy emission without increasing the infrared emission because the models do not include radiative transfer.

Chapter 4 took advantage of the MAGPHYS (da Cunha et al., 2008) SED modeling code which not only includes a much larger variety of stellar populations and dust properties, but includes energy balance so that the infrared luminosity of the dust is determined by the amount of the ultraviolet and optical starlight absorbed by stellar birth clouds and the ambient ISM. Fitting a few sample galaxies with MAGPHYS showed that the SEDs of star-forming galaxies with red W1 - W2 colors could be fit assuming only stellar and dust emission. However, because of the large number of free parameters in these models, known AGN were also able to be fit with these purely stellar plus dust models. In order to properly determine the origin of the energy source that gives rise to the red W1 - W2 colors in these low mass galaxies more observations are required.

5.1 Future Work

One promising avenue of future exploration of the AGN nature of high W1-W2 galaxies is in the X-rays, observations of which are lacking for dwarf galaxies. There are 7 low mass ($6 < \log(M/M_{\odot}) < 8$), red WISE (W1 - W2 > 0.5), optically normal (no broad or narrow line AGN indicators) galaxies in the 0 < z < 0.003 range in the Sloan Digital Sky Survey DR12 (Alam et al., 2015) and WISE All Sky Catalog (Wright et al., 2010). The z = 0.003 upper redshift limit was chosen so that very low mass/low luminosity sources can be observed with *NuSTAR* in a reasonable amount of time. As evidenced by their lack of optical activity, if AGN are present in these sources they are either diluted by starbursts (Trump et al., 2015) or heavily obscured. This can make observation with *Chandra* or *XMM-Newton* difficult because in Compton-Thick sources, the emission at energies less than 10 keV will be suppressed by a factor of 10 (Brightman & Nandra, 2011). However the Nuclear Spectrscopic Telescope Array (*NuSTAR*) (Harrison et al., 2013) is capable of observing a higher energy range than *Chandra* or *XMM-Newton* (3-79 keV). The low mass,

Source	z	$\begin{array}{c} \log(M_{*}) \\ \log(M_{\odot}) \end{array}$	$\begin{array}{c} L_{2-10}(AGN) \\ erg \ s^{-1} \end{array}$	$\begin{array}{c} L_{2-10}(XRB) \\ \mathrm{erg} \ \mathrm{s}^{-1} \end{array}$	Exp t ks	Input N_H cm ⁻²	$\begin{array}{c} \text{XSPEC N}_H \\ \text{cm}^{-2} \end{array}$	XSPEC Γ
1	0.00288	6.155	$2.350{ imes}10^{40}$	4.632×10^{37}	20	10^{23}	$1.0128^{+1.066}_{-0.855}{\times}10^{23}$	$1.926^{+0.616}_{-0.536}$
1	0.00288	6.155	$2.350{\times}10^{40}$	$4.632{ imes}10^{37}$	20	$1.5{\times}10^{24}$	$1.47^{+0.25}_{-0.23}{\times}10^{24}$	$1.840\substack{+0.368\\-0.332}$
2	0.00087	6.022	$2.685{ imes}10^{38}$	$3.990 imes 10^{35}$	20	10^{23}	$1.090^{+30.365}_{-1.089}{\times}10^{23}$	$1.753^{+1.753}_{-2.516}$
2	0.00087	6.022	$2.685{ imes}10^{38}$	3.990×10^{35}	20	$1.5{\times}10^{24}$	$1.254^{+1.117}_{-0.910}{\times}10^{24}$	$1.314^{+1.615}_{-1.245}$
3	0.00094	6.017	1.099×10^{39}	3.721×10^{36}	100	10^{23}	$1.245^{+0.506}_{-0.451}{\times}10^{23}$	$1.916\substack{+0.259\\-0.245}$
3	0.00094	6.017	1.099×10^{39}	3.721×10^{36}	100	$1.5{\times}10^{24}$	$1.730^{+0.256}_{-0.095}{\times}10^{24}$	$2.107\substack{+0.325 \\ -0.095}$

Table 5.1: NuSTAR Observation Parameters

high W1-W2 galaxy shown in Figure 4.5 (CGCG 007-025) has already been observed by NuSTAR in November of 2015 (proposal ID 1299), though as of yet no results have been published.

In order to discern the nature of the X-ray sources in these low mass, red W1 - W2 galaxies, three measurements are needed: (1) X-ray luminosity (2 - 10 keV range), (2) Photon index (Γ) where flux $\propto E^{-\Gamma}$ (keV) and (3) hydrogen column density (N_H cm⁻²). While these quantities can be estimated from photometry, spectra are needed for robust measurements. Exposure times and model spectra were calculated using the Web PIMMS¹ and Web Spec² tools using an absorbed power law and parameters given in Table 5.1. Model spectra were created for each source using an intrinsic N_H of 10²³ cm⁻² and 1.5×10²⁴ cm⁻², spanning a range from moderate to Compton-Thick obscuration, a photon index (Γ) of 1.8 and fluxes based on the 2-10 keV luminosity of an AGN given the source's W2 luminosity and the Secrest et al. (2015) relation. Exposure times were chosen so that the photon index and hydrogen column density put into Web Spec could be recovered by the XSPEC fit to the simulated spectrum. The three highest flux sources listed in Table 5.1 would be observable in 140 ks, which is 2.2% of the 6.5 Ms available for guest observers based on the Cycle 2 Call for Proposals³.

Although this would be unexpected given their W2 luminosities, if any of these sources are observed to have X-ray luminosities above 10^{42} erg s⁻¹, that will classify them as

¹https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl

²https://heasarc.gsfc.nasa.gov/webspec/webspec.html

 $^{^{3}} https://heasarc.gsfc.nasa.gov/docs/nustar/nupropthread.html$

unambiguous AGN as the most luminous XRB are below this limit (Lehmer et al., 2010). This would have enormous implications for our understanding of AGN populations because all of these target galaxies have lower stellar masses than the low mass AGN from Secrest et al. (2015). In the $10^{39} < L_X \text{ erg s}^{-1} < 10^{42}$ range, ambiguity is introduced in the form of ultraluminous X-ray sources (ULXs). One such example of a low mass galaxy with a ULX is Haro 11. Prestwich et al. (2015) observed 2 X-ray sources (X-1 and X-2) in this compact galaxy. X-2 has $L_X \approx 10^{40} \text{ erg s}^{-1}$ and is classified as a ULX rather than an AGN on the basis of its soft X-ray spectrum ($\Gamma=2.2\pm0.4$). The fact that low mass red W1-W2 galaxies also tend to be metal poor means that they are more likely to host ULXs than their solar metallicity counterparts (Prestwich et al., 2013). The Secrets et al. (2015) relation between L_X and L_{W2} shows that AGN display a proportionality between their luminosities in these two bands while ULXs are underluminous in the X-rays compared to W2. It should be noted that while the low mass AGN SDSS J1329+3234 falls within 1σ of the luminosity relation for AGN, it is only one of two AGN below $L_X = 10^{42} \text{ erg s}^{-1}$ for which this relation was tested. Still, it should be possible to use the X-ray spectra to calculate Γ and N_H and observe signatures of Compton-Thick AGN like the 6.4 keV Fe K α line and Compton Hump at ≈ 30 keV which are only present in obscured AGN (Baloković et al., 2014; Brightman & Nandra, 2011; Iwasawa et al., 2012; Matt et al., 1996). The 6.4 keV line has an equivalent width between 0.02 and 0.5 keV in CTAGN (Ricci et al., 2016). Conversely, ULXs observed in NuSTAR often exhibit an energy cutoff at approximately 10 keV (Annuar et al., 2015).

At luminosities below 10^{40} erg s⁻¹, contributions from X-ray binaries (XRB) also become important. Using stellar masses and star formation rates from the MPA-JHU catalog (Brinchmann et al., 2004; Kauffmann et al., 2003b), the Lehmer et al. (2010) relation is used to predict the luminosity of the X-ray binaries expected to reside in the target galaxies. This should be more than two orders of magnitude lower than the X-ray luminosity of the sample galaxies predicted from the Secrest et al. (2015) relation for AGN given their W2 measurements. High/soft state XRBs may increase in luminosity by a factor of 100 in their transition from the low/hard state as seen in VII Zw 403 (Brorby et al., 2015), but this corresponds to an increase in Γ and a softer X-ray spectrum than is seen in most AGN (Remillard & McClintock, 2006). Low/hard state XRBs on the other hand may have similar photon indices to AGN but lower luminosities (Remillard & McClintock, 2006). So even if the target galaxies are observed without enough counts for a spectrum, diagnostics like Baloković et al. (2014); Brightman & Nandra (2012); Iwasawa et al. (2012) which use the count ratios in various energy ranges to discern the hardness ratio and obscuration level of a source could distinguish between an obscured AGN and a high/soft XRB. Only in the cases of truly unusual objects does it become difficult to separate these two types of X-ray sources. Haro 11's X-1 has an X-ray luminosity above 10^{41} erg s⁻¹, a very hard X-ray spectrum (Γ =1.2±0.2) (Prestwich et al., 2015) and W1 - W2 = 1.336. This could either indicate an AGN or an XRB where the accreting black hole is an intermediate mass black hole (IMBH) (M > 7600 M_☉ rather than the stellar mass black holes typically seen in these systems) or a stellar mass black hole accreting at a super-Eddington rate, though it should be emphasized that this is a very rare object. As seen in Table 5.1, the XRB luminosities of the sample galaxies are expected to be serveral orders of magnitude below this threshold.

In summary, NuSTAR should be able to detect even low luminosity, obscured AGN in this sample of nearby, low mass, optically normal, red W1-W2 galaxies. A non-detection would almost certainly mean that either these galaxies lack AGN or that they have extremely high hydrogen column densities ($N_H > 1.5 \times 10^{24} \text{ cm}^{-2}$).

When the James Webb Space Telescope (JWST) launches in 2018 it may also be possible to find hidden AGN in these galaxies by observing their mid-infrared emission lines. In the past, mid-infrared spectra taken with the *Spitzer* Infrared Spectrograph (IRS) have been used to distinguish galaxies with AGN from those dominated by starbursts through a combination of PAH and ionization line measurments. As the AGN contribution to a galaxy's mid-infrared emission increases, a harder ionizing radiation field is produced. This leads to decreased PAH equivalent widths and increasing fluxes in the high ionization lines such as [NeV] 14.32 μ m and [OIV] 25.89 μ m (Gruppioni et al., 2016; Hernán-Caballero & Hatziminaoglou, 2011; Magdis et al., 2013; Spoon et al., 2007; Tommasin et al., 2010). In addition to PAH features, the spectral range of JWST will also cover several infrared hydrogen recombination lines such as Pa α (1.875 μ m), Br α (4.051 μ m) and Br γ (2.166 μ m) which may appear broadened in an AGN. Due to the lower impact of extinction in the infrared, these lines may be affected by the AGN even if the optical H α and H β lines are dominated by star formation.

In conclusion, while this dissertation has added to our knowledge of the population of low mass, high W1-W2 galaxies and their unusual properties, it has also revealed the limits of SED modeling in distinguishing AGN hosts from galaxies with unusual stars. Additional observations of low mass, high W1-W2 galaxies with facilities such as *NuSTAR* and *JWST* are needed in order to truly constrain the AGN demographics in the low mass range.

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Biography

A native of East Longmeadow, Massachusetts, Jessica O'Connor graduated from Pioneer Valley Performing Arts Charter School in South Hadley, Massachusetts in 2006 with a concentration in Music Performance. She began playing the flute when she was 9. Though she continued to do this as a hobby and continued performing in The Wailing Banshees Celtic Folk Music group at Smith College, her academic focus switched from Music to Astronomy. (I blame Reading Rainbow, Star Trek and NOVA.) She received two Bachelors of Science in Astronomy and Physics from the University of Massachusetts in Amherst, Massachusetts in 2010 and a Masters of Science in Applied and Engineering Physics from George Mason University in Fairfax, Virginia in 2013. She is an avid fan of reading and writing science fiction and fantasy. She is also a fan of music from multiple genres including Celtic, metal, rock, classical and electronica.