Thesis Proposal

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Gas-rich Dwarf Galaxies:

Evolution and Chemistry in the Local Universe

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Contents

List of Abbreviations

AAO	Anglo-Australian Observatory
BCD	Blue Compact Dwarf (galaxy)
CMD	Colour Magnitude Diagram
GRiD	Gas-Rich Dwarf (galaxy sample)
HIPASS	HI Parkes All-sky Survey
HST	Hubble Space Telescope
IGM	Intergalactic Medium
IRSF	Infrared Survey Facility
ISM	Interstellar Medium
LVHIS	The Local Volume HI Survey
NAOJ	National Astronomical Observatory of Japan
NED	NASA/IPAC Extragalactic Database
SAAO	South African Astronomical Observatory
SAO/ADS	Smithsonian Astrophysical Observatory/NASA Astrophysics Data System
SBBN	Standard Big Bang Nucleosynthesis (model)
SDSS	Sloan Digital Sky Survey
SFR	Star Formation Rate
SINGG	Survey for Ionization in Neutral-Gas Galaxies
SMC	Small Magellanic Cloud
SSO	Siding Spring Observatory
WiFeS	Wide Field Spectrograph
XMD	extremely metal deficient

Preamble

Ye realms, yet unreveal'd to human sight,
Ye gods who rule the regions of the night,
Ye gliding ghosts permit me to relate
The mystic wonders of your silent state.
– *Dryden*

You meaner beauties of the night,
That poorly satisfy our eyes
More by your number than your light,
You common people of the skies;
What are you when the moon shall rise?
– *Sir Henry Wootton (17th C)*

Astronomy is perhaps the science whose discoveries owe least to chance, in which human understanding appears in its whole magnitude, and through which man can best learn how small he is. – *G C Lichtenberg ca. 1765*

And o'er the swelling vault–the glowing sky,
The new-born stars hung out their lamps on high

– *Ode To Music, James G. Percival 19thC*

A man's reach should exceed his grasp – or what's heaven for?
– *Browning*

Supervisory Panel

Chairman: Professor Michael Dopita, RSAA, ANU
Supervisor (joint): Dr Helmut Jerjen, RSAA, ANU
Co-supervisor: Dr Lisa Kewley, Institute for Astronomy, University of Hawaii
Adviser: Dr Chiaki Kobayashi, RSAA, ANU
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1 Background

- Metallicity, the abundance of elements heavier than Helium, is an important parameter that controls many aspects of the formation and evolution of stars and galaxies (Kunth & Östlin, 2000). Observations show that larger galaxies have higher metallicities than smaller galaxies, the so-called "mass-metallicity relation".
- The mass-metallicity relation has been well studied for higher mass galaxies, but low luminosity objects have received much less attention (Tremonti et al. (2004); Lee et al. (2006)).
- There has so far been no complete or systematic study of the metallicity distribution in low mass isolated gas rich dwarf galaxies in the Local Volume (D $<$ 15 Mpc).
- Likewise, their baryonic content has not been systematically determined.
- Existing optical surveys of dwarf galaxies comprise a heterogeneous sample with the attendant Malmquist bias (emphasising optically bright objects far away, dim objects nearby).
- For example, surveys of blue compact dwarf (BCD) galaxies such as Izotov & Thuan (1999) and Izotov et al. (2006). have selected samples based on optical characteristics (eg the Byurakan surveys and Sloan SDSS data releases).
- The Survey of Ionization in Neutral Gas Galaxies (SINGG) is an H-α survey of galaxies detected in 21cm neutral atomic hydrogen with the Parkes HIPASS survey (Meyer et al., 2004). It includes many low surface brightness, low luminosity galaxies (Meurer et al., 2006).
- SINGG for the first time provides a substantially complete sample of gas-rich galaxies, which at the 95-99% level is established to a distance of $\sim$15Mpc, ie Virgo Cluster distance (Meurer et al., 2006; Zwaan et al., 2004).
- SINGG provides R band and H-α photometry and (from HIPASS) HI masses which permit a census of stellar and gas content.
- Low-mass isolated gas-rich dwarf galaxies have been selected from SINGG as a basis for the present work (see §4.1).
- If these galaxies are self-enriched, a determination of metallicities should enable effective chemical yields to be determined.
- Velocity widths in the HI profiles from the HIPASS survey, or additional image synthesis observations of the HI distributions, can be used to estimate the dark matter content of these galaxies.

2 Proposal

I propose to use the WiFeS spectrograph on the SSO 2.3m telescope to measure nebular chemical abundances in isolated gas-rich dwarf galaxies in the Local Volume.

I intend to use objects selected from the SINGG survey (see §4.1), referred to here as the "Gas Rich Dwarf" sample or GRiD. SINGG (and therefore GRiD) is derived from the HIPASS survey of neutral hydrogen 21cm emissions in the southern sky (Meurer et al., 2006; Meyer et al., 2004). The completeness of HIPASS, and thus of SINGG and GRiD, as a source of gas-rich galaxies in the Local Volume, is well established, and minimises Malmquist bias problems which plague optical methods of sampling gas-containing dwarf galaxies (Meurer et al., 2006). The GRiD sample will be refined as work progresses, but initially comprises $\sim$60 objects and provides an ideal and substantially complete sample for this analysis in the Local Volume.

The primary purpose of this work is to understand better the mass/metallicty relation for these objects, which is not well established at the low-mass end (Lee et al., 2006), and to see if there is evidence of a nebular metallicity floor. The galaxy sample provides several candidates which will allow us to explore the mass-metallicity relation at the low mass end of the scale (see §3.1).

My measurements will help improve the calibration of nebular metallicity scales by comparing direct and strong line nebular abundance methods, using state of the art diagnostic toolboxes (Mappings III) and spectral synthesis code (Starburst 99) .

As the WiFes spectrograph allows one to identify individual ionised regions within the target galaxies, I will measure the chemical abundances of individual gas clouds, and investigate whether it is possible to measure their radial velocities and velocity dispersions.

Using appropriate targets I will also explore the effect of isolation on metallicity for small galaxies, using and extending methods identified by Warren et al. (2007). I will also investigate the effect of the gas mass to light ratio on metallicity, following on from the work of Warren et al. (2006).

In addition to the proposed measurements using WiFeS, as time and opportunity permit, I propose to observe some of the target galaxies using larger instruments in Australia and overseas, to measure: (i) stellar metallicities from spectra of A-supergiant stars; (ii) infrared luminosities; and (iii) colour-magnitude diagrams in selected targets. Use/acquisition of HST imaging and colour magnitude diagrams for these targets will be necessary. Together with additional measurements of the target galaxies in the near IR, these measurements will provide accurate information on the existence and size of old stellar populations, and reliable estimates of the baryonic mass of the sample galaxies.

I propose to use existing 21cm radio observations of the target galaxies (eg the LVHIS survey) to measure their rotational characteristics, and if feasible, to extend these measurements. This data will allow measurement of the dark matter content of the galaxies.

This work should contribute to an improved understanding of the dynamics and evolution of a range of dwarf galaxy types in the Local Volume.

3 Science case

3.1 Mass-metallicity relation

"Stellar mass and metallicity are two of the most fundamental physical properties of galaxies. Both are metrics of the galaxy evolution process, the former reflecting the amount of gas processed into stars, and the latter reflecting the gas reprocessed by stars and any exchange of gas between the galaxy and its environment. Understanding how these quantities evolve with time and in relation to one another is central to understanding the physical processes that govern the efficiency and timing of star formation in galaxies" (Tremonti et al., 2004).

The mass-metallicity relation is based on the on the observation that larger galaxies are more chemically enriched than smaller ones. Reasons suggested for this are: more active star formation in larger galaxies; more efficient retention by larger galaxies of chemical enrichment debris from supernovas; and greater impact of pristine gas inflows from the IGM on smaller galaxies. Because the mass is more difficult to measure than the stellar luminosity, to which it is related, the latter has often been used as a proxy (Tremonti et al., 2004). NIR luminosity is considered to be a better proxy than the blue luminosities commonly used (Saviane et al., 2008).

Studies of the mass- or luminosity-metallicity relation have tended in the past to be confined to larger (more luminous) galaxies than the dwarf Irregular galaxies proposed in this work.

Tremonti et al. (2004) used the Sloan Survey to measure the mass-metallicity relation for 53,000 galaxies. Figure 1 (figure 5(2) from that paper) shows their results. The data only extend to a minimum stellar luminosity of M_g = -14 and a metallicity of 12+log(O/H) = 8.0. Neither of these explores the realm of lower luminosity lower metallicity dwarf galaxies.

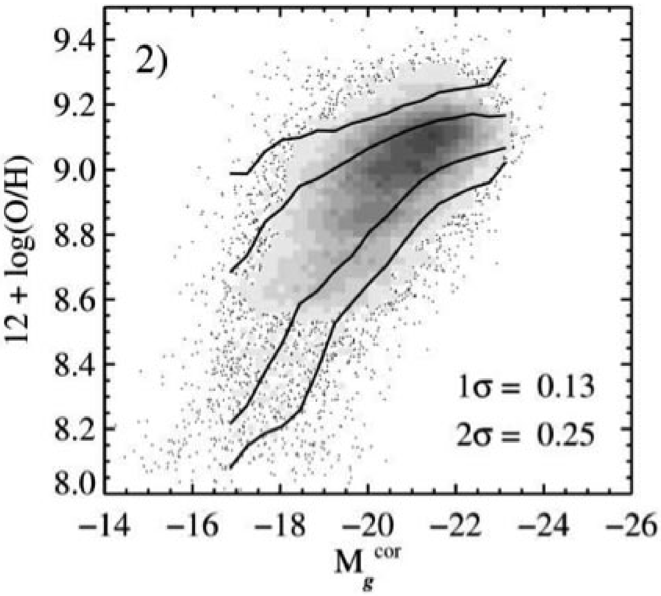

Figure 1: Nebular oxygen abundances vs corrected M_g from Tremonti et al. (2004)

Lee et al. (2006) explored the luminosity-metallicity relation for gas rich galaxies (to M_B = -13) for 2.5 orders of magnitude lower in mass than Tremonti et al. (2004), but with few data points below M_B = -14. Figure 2 (figure 5a from that paper) shows their results.

The conclusion that the luminosity-metallicity relation shows a linear trend down to low luminosities depends on a single point. Without that point, the conclusion could change from a linear fit to a metallicity floor at 12+log(O/H) = 7.6. With both points, there is a large spread. In their analysis

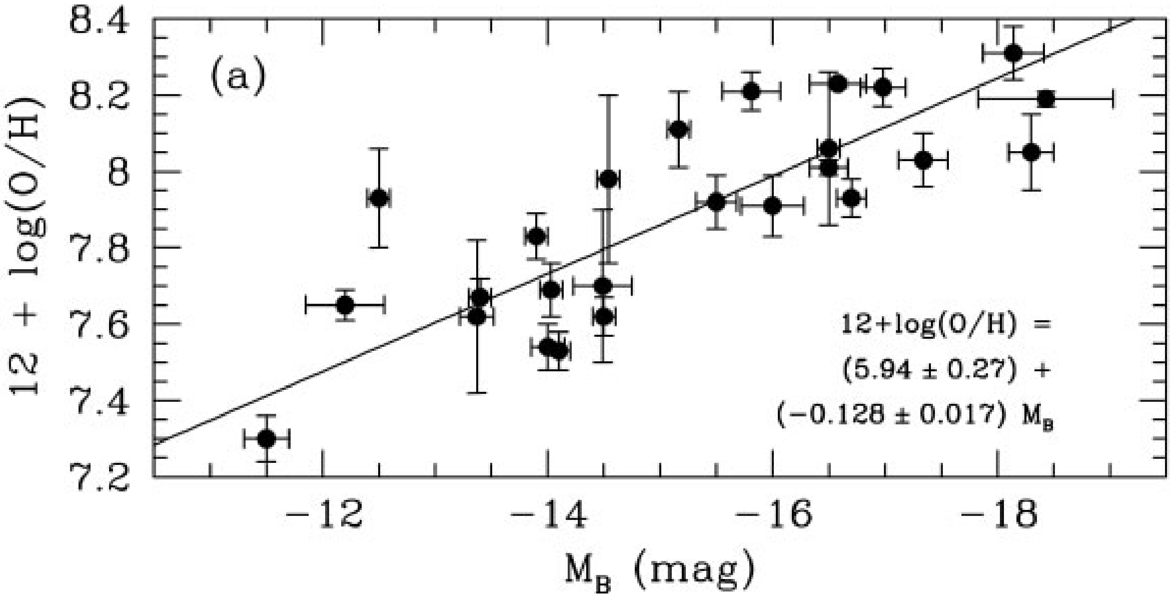

Figure 2: Nebular oxygen abundances vs M$_B$ from Lee et al. (2006)

using 4.5μ magnitudes the linear fit is better, but again depends on one data point, and the data at the low luminosity-metallicity end are very scarce. In this work I propose to measure metallicity and luminosity (and mass) for several additional galaxies to fill in the area below M$_B$ = -14.0, and clarify wither the linear fit continues, or whether there is a floor (see also §3.4 below). The GRiD sample includes 14 dwarf galaxies with M$_R$ < -14 measured by the SINGG survey. Using the R-band magnitude is preferable to using the B-band magnitude, as it is less affected by young star formation areas or by interstellar extinction (eg Garnett (2002); Tremonti et al. (2004)).

On the same scale as figure 2, the two record-holding low metallicity BCD galaxies, 1Zw18 and SBS0335-052 would be at/below the x-axis, at [-16.0, 7.2] and [-14.0, 7.0]. In a study of 50 BCD galaxies, Hopkins et al. (2002) noted that these two galaxies are exceptions, being brighter than expected for their metallicity than 50 other BCDs studied. This may be due to a high SFR (star formation rate). The galaxies in figure 2 from Lee et al. (2006) were normal nearby dwarf irregular galaxies similar to the majority of galaxies in the GRiD sample.

3.2 Evolutionary processes

Theory predicts that chemical abundances rise as newly-collapsing galaxies evolve and undergo generations of star formation. The spread of abundances should narrow with time as the interstellar gas becomes either internally mixed. At the same time it is being diluted with infalling chemically pristine gas and depleted by starburst-driven galactic-scale outflows (eg Kobayashi et al. (2007)). Thus, the chemical abundance in galaxies is inextricably linked to star formation and galaxy growth, providing a fundamental fossil record of the generations of cosmic star formation, mass accretion, and mass-loss in galaxies.

Ricotti & Gnedin (2005) and Ricotti et al. (2008) have shown by comparing detailed modelling and observations of Local Group dwarf galaxies that they may form in three ways: as “true fossils” from the ionisation era; by forming most of their stars later, as “survivors” from the re-ionisation era; or as a combination of the two, as “polluted fossils”. The old stellar populations in the GRiD objects should provide information on these alternative evolutionary processes, despite time resolution uncertainties making accurate dating difficult.

Due to their low luminosities and small sizes, the classification of dwarf galaxies is not simple (Cellone & Buzzoni, 2007). The GRiD sample (see definition at §4.1) includes a diverse collection of dwarf galaxies which have been listed in NED under the following categories: dIrr, Irr, dIm, Im, dIn, In, dS0, IBm, IB(s)m:pec, Im:pec, IB(s)m, IBa(s)m:pec, IB(s)m:sp, S, S?, S/I, Sdm, Sm:sp, SBd, SB(s)m and BCD, illustrating both the complexity and variability of the classification system and the diversity of dwarf galaxy types in the sample.

Studying the nebular and stellar make up of the dwarf galaxies in the Local Volume will contribute to understanding the evolution of dwarf galaxies, and thereby, galaxies in the Universe at large.

3.3 Self-enrichment

The formation of massive stars, leading to Wolf-Rayet stars, type II supernovae and, later, AGB stars with strong stellar winds, leads to the chemical enrichment of remaining gas clouds. Thus the metallicity of a cloud will indicate both the original composition of the IGM from which the gas formed into a dwarf galaxy, and the degree of enrichment that has occurred since the commencement of star formation. If one is able to study stellar metallicities, enrichment by type II supernovae will generate high a α/Fe ratio, whereas a low α/Fe ratio will indicate the presence of later type Ia supernovae.

The presence (or absence) of one or more older populations will show the extent of likely self enrichment since the galaxy first started star formation. The absence of substantial evolved populations in a star-forming galaxy will indicate a near pristine source gas for current star formation.

Sutherland (pers. comm., 2009) has shown that supernovae exploding in a low baryonic-mass gas-rich galaxy will not necessarily blow out the remaining gas, and thereby terminate star formation, nor will the chemical enrichment from the supernova be efficiently retained in that gas. Assuming a fractal distribution of mass in gas clouds, rather than the usually assumed smooth distribution, energy and high velocity outflows may preferentially escape into the IGM through the low-density ‘portals’ in the gas cloud, thereby removing the energy from the gas cloud which might otherwise disperse it into the IGM; and the chemically enriched debris from the supernova will escape and not be retained efficiently in the cloud. It is generally assumed (Gilmore & Wyse, 1991) that the existence of gas-rich dwarf galaxies after a Hubble time means that episodes of star formation in them have only been in a few, infrequent bursts, in order for the gas in the galaxy to remain to the present. Sutherland’s hypothesis suggests that star formation episodes could be more frequent than previously supposed, without completely removing the gas from the dwarf galaxy. Measurement of the evolved stellar populations may provide data on this.

Another implication of the Sutherland model may explain why small dwarf galaxies are dark matter dominated. If one supposes that they start out with a baryonic to dark matter ratio typical of larger galaxies, and that star formation began early, assuming a uniform gas distribution might lead one to conclude that all gas would have been removed from the galaxy early in its history, leaving a galaxy with very few stars and no gas, which is unlikely to be detected. If a non-uniform mass distribution in the gas cloud is assumed, Sutherland’s model suggests that gas dispersal could be considerably less efficient, thereby leaving some gas from which to form stellar populations at later times. Depending on the inhomogeneity of the initial gas, some or even most, but not all, the gas might have been dispersed into the IGM, thereby leaving a low baryonic to dark matter ratio, as observed. Observing a correlation between the baryonic to dark matter ratio and the complexity of older stellar populations may provide data on this.

Thus studies of the nebular metallicity, the stellar population history, stellar metallicities and the total (baryonic + dark) mass of small galaxies could provide valuable information on the evolution of the galaxy, and important input into theoretical models of enrichment of the IGM throughout cosmic time.

3.4 Chemical yield

Understanding the chemical yield is important when considering the mass/metallicity relation of galaxies. The metallicity (initially assumed to be near-pristine) is affected by the chemical enrichment generated by star formation, as well as by gas outflow and infall. For the closed box model, where there are no in/outflows, the metallicity Z can be expressed in terms of the true yield y, the total mass M and the gas mass g (Garnett, 2002) as:

$$Z = y\ \ln(\frac{M}{g}) \tag{1}$$

Expressing the gas mass fraction as μ, the effective yield y_{eff} may be expressed in terms of the observed metallicity and gas fraction as:

$$y_{eff} = \frac{Z_{obs}}{\ln(\mu^{-1})} \tag{2}$$

which is a quantity that may be derived from the observed metallicity and gas fraction.

For small galaxies the closed box model breaks down, so there may be outflows of chemically enriched gas that will reduce the effective yield. Understanding how the effective yield for the GRiD sample galaxies varies with total mass will provide information on the efficiency with which these galaxies retain supernova and stellar wind outflows.

3.5 Metallicity floor

The metallicity floor may be defined as the lowest level of metallicity found in the IGM, after the initial starburst of Population III stars in the early Universe. Such a floor may result from pollution of an otherwise pristine cool or cold ISM by heavy elements ejected into the hot inter-galactic medium by outflows from massive galaxies. Such outflows can arise in either starbursts which input more energy to the ISM than can be radiated away, or as a phase of evolution in which an active nucleus blows sufficiently powerful relativistic jets to unbind the ISM. Either way, a floor constrains parameters of mass ejection and galactic winds occurring at the epoch of massive galaxy formation.

It has been suggested that this floor is exhibited in the metallicity of extremely metal deficient (XMD) dwarf galaxies (eg Thuan (2008)). However, any ionised nebular medium will exhibit some enrichment due to local supernovae arising from the newly forming young stars within it. (That we should observe one of these galaxies after star formation has started but before the first supernova, seems improbable.) This is also suggested by the lower value for oxygen abundances (by -0.88 dex) in neutral gas compared to ionised gas contained in the same clouds (Lebouteiller & Kunth (2008), using FUSE observations).

Further, using HST observations of Lyman-forest absorbers with redshifts between $1.6 < z < 2.9$, Telfer et al. (2002) have measured the EUV absorption and demonstrated that there is a minimum oxygen metallicity in the IGM of 6.5 $<$ 12+log(O/H) $<$ 7.4 (between 1/150 and 1/20 solar, where solar is taken as 12+log(O/H) = 8.7). This suggests the reality of a metallicity floor in the IGM of galaxies at high redshift. It is consistent with metallicity values obtained from nebular emission lines in the local (D = 53 Mpc) Blue Compact Dwarf galaxy SBS 0335-052W, which has recorded a minimum value of 1/70 solar (Izotov et al., 2009).

Thus the abundances in ionised HII regions in dwarf galaxies provide an upper limit for this metallicity floor and the observations proposed will provide a measure of this upper limit for the Local Volume.

Dwarf spheroidal galaxies are also relevant to considerations of metallicity levels in the early Universe. Observations of these galaxies in the Local Group indicate very low stellar metallicity (see for example, Kalirai et al. (2009); Kirby et al. (2008b)). It is possible that the stellar populations in these objects formed very early, from near-pristine source gas. As a consequence the stellar spectra in dwarf spheroidals would not reflect any metallicity floor that may be evident in gas-rich dwarf galaxies. The situation is not clear – see for example conflicting analyses in Ricotti & Gnedin (2005) and Fenner et al. (2006) who debate whether or not dwarf spheroidals formed predominantly in the pre-reionisation era. Further, the trend in star formation versus mass shown by dwarf spheroidal galaxies in the Local group is not matched by dwarf irregular galaxies (Dolphin et al., 2005). Thus it would be useful to explore gas-rich dwarf nebular metallicities to see how the data compares with the stellar metallicities from dwarf spheroidal galaxies.

3.6 Metal-deficiency: Nature and Nurture

Most Blue Compact Dwarf galaxies (BCDs), a type known to harbour the lowest nebular abundances yet found, do contain evolved populations with ages of a least a few Gyr, implying that they are not new to star formation (eg Bekki (2008); Amorín et al. (2007); Kirby et al. (2008a)). The current H-α regions excited by the clusters of new stars they contain are just the latest results of ongoing star formation (be it continuous or episodic). However, the picture is not yet clear, and to the extent that the most metal-deficient galaxies show limited evidence of evolved stellar populations, they appear to be young (0.5-1Gyr) (Thuan, 2008).

There is evidence to suggest that dwarf galaxies that are isolated develop more slowly than similar galaxies in more crowded areas (Pustilnik (2008); Warren et al. (2007)), and therefore, to the extent that local star formation has not already chemically enriched their ISM, they should reflect – or at least provide an upper limit for – the metallicity of the IGM from which they have formed.

There is also evidence that suggests that XMDs arise from local tidal interactions within extended HI clouds (eg Bekki (2008); Ekta et al. (2008, 2009); van Zee et al. (1998); Pustilnik & Martin (2007); Corbin et al. (2006)).

Thus, dwarf galaxies that are intrinsically isolated from larger galaxies, and therefore slow to form, and which interact with close-by similarly isolated dwarf galaxies offer the best opportunity to find the most-XMD galaxies, newly formed from an unenriched IGM.

In other words, both nature and nurture are important in the evolution of these dwarf galaxies.

Further, the morphology of dwarf galaxies is somewhat blurred. For example “BCD” galaxies share many characteristics with normal dwarf Irregular galaxies, and there is considerable overlap between the categories. Vaduvescu et al. (2007) have further suggested similar evolutionary paths for dIrr and BCD galaxies.

So using a more general sample of dwarf galaxies such as GRiD provides may yield unexpectedly low metallicities, and will provide a useful comparison with the results from the already quite extensive measurements of previously-identified low-metallicity BCD objects.

3.7 Are BCDs a distinct physical type?

Blue Compact Dwarf galaxies have usually been identified by their appearance on objective prism surveys, as centrally condensed small emission line galaxies with $M_B < -17$. The term was a descriptive one. See Kunth & Östlin (2000).

Loose & Thuan (1986) postulated four different types of “BCD”. The only characteristics they share, and which warrant their descriptions as BCDs, are low luminosity (small size), compact appearance and strong emission lines on a blue continuum. This system allows single or multiple star forming regions; elliptical or irregular LSB components; and the presence or absence of an underlying older stellar population. Thus, "normal" dIrr galaxies with strong emission lines and a blue continuum could be classified as "BCDs".

More recently, Sung et al. (2002) have introduced a new classification system for BCD galaxies: isolated, post-merger, detached interacting, and merger-in-progress types. However the morphologies do not differ essentially from the earlier morphologies.

One widely accepted definition of Blue Compact Dwarf galaxies is "dwarf irregular galaxies whose optical presence is exemplified by an active region of star formation" (Sung et al., 2002). Under this much broader description, many of the GRiD sample galaxies would qualify as BCDs, returning the category to being a descriptive rather than an evolutionary or morphological one.

The extended GRiD sample of ∼80 objects includes ∼40 which could be (or have already been) classed on the basis of appearance as BCD galaxies. Indeed, some may qualify as "ultra-compact blue dwarf" galaxies, as defined by Corbin et al. (2006). The remainder are not centrally condensed. BCD objects are considered to be rare (Cellone & Buzzoni, 2007), but the number of possible BCD galaxies in the GRiD sample suggests this might be – at least in part – a selection bias effect. Measurement of the spectra of these "BCD"-like objects, together with the SINGG photometry, will clarify their nature and whether true BCDs are rare.

Measurement of the nebular metallicities and stellar populations in a range of BCD-like objects in the GRiD sample will help explore morphological and evolutionary relationships among dwarf galaxies.

3.8 Primordial Helium

^{4}He is one of four isotopes produced in addition to Hydrogen in the Big Bang, according to the standard big-bang theory of nucleosynthesis (SBBN). Measurements of the abundance of these isotopes can provide important information on the mean density of ordinary matter in the Universe as well as a test of the SBBN model (Izotov & Thuan, 2004). The primordial abundance of ^{4}He can be derived accurately from the He and H emission lines in low metallicity galaxies (Izotov et al., 2007).

As shown below in figure 7 (§4.6), the He I recombination lines have already been detected in the Pilot Study of GRiD objects. The proposed observations should therefore provide useful data on the primordial abundance of ^{4}He.

3.9 Measurement of target isolation

As noted above, there is evidence to suggest that isolated dwarf galaxies have lower metallicities than similar objects in locally or globally dense regions (Pustilnik (2008); Warren et al. (2007)). It would be useful and instructive to confirm this in the proposed work by measuring isolation versus metallicity. This would be relatively straight forward to calculate using the Karachentsev & Markarov Tidal Index and Peebles' two point angular autocorrelation nearest neighbour measure (Karachentsev & Makarov (1999); Peebles (2001); Peebles (1980); Warren et al. (2007)).

3.10 Internal dynamics

As is evident from the Pilot Study (§4.6), WiFeS easily spatially resolves the ionised regions which constitute the target galaxies. As the bright nebular emission lines are very narrow, it may be possible to measure the radial velocity variations of the individual ionised regions within galaxies. For targets with the best signal to noise ratios, using WiFeS at a resolution of 7000, it will also be interesting to find out if the regions display any measurable variation in internal velocity dispersion.

3.11 Gas fraction vs. luminosity

Galaxies with low luminosities but high neutral hydrogen mass to luminosity ('mass to light') ratios are likely to have evolved more slowly than galaxies with higher luminosities and thus larger stellar populations. Warren et al. (2006) have explored high HI mass to light ratio in galaxies selected from the HIPASS catalog, using carefully measured B-band magnitudes. The same analysis could readily be undertaken for the GRiD sample using R-band data – which are available, and preferable to using B-band data, as noted in §3.1.

The absolute R-band luminosities can be obtained from the SINGG data, and neutral hydrogen masses and recession velocities from the HIPASS catalog. If we select a subset of targets from GRiD that have high mass-to-light ratios, the metallicities of these targets can be measured to explore the extent to which a high HI mass to light ratio selects for low metallicity galaxies. Figure 3 plots the HI-mass-to-light ratio vs. R-band absolute magnitude for 69 objects in the extended GRiD sample.

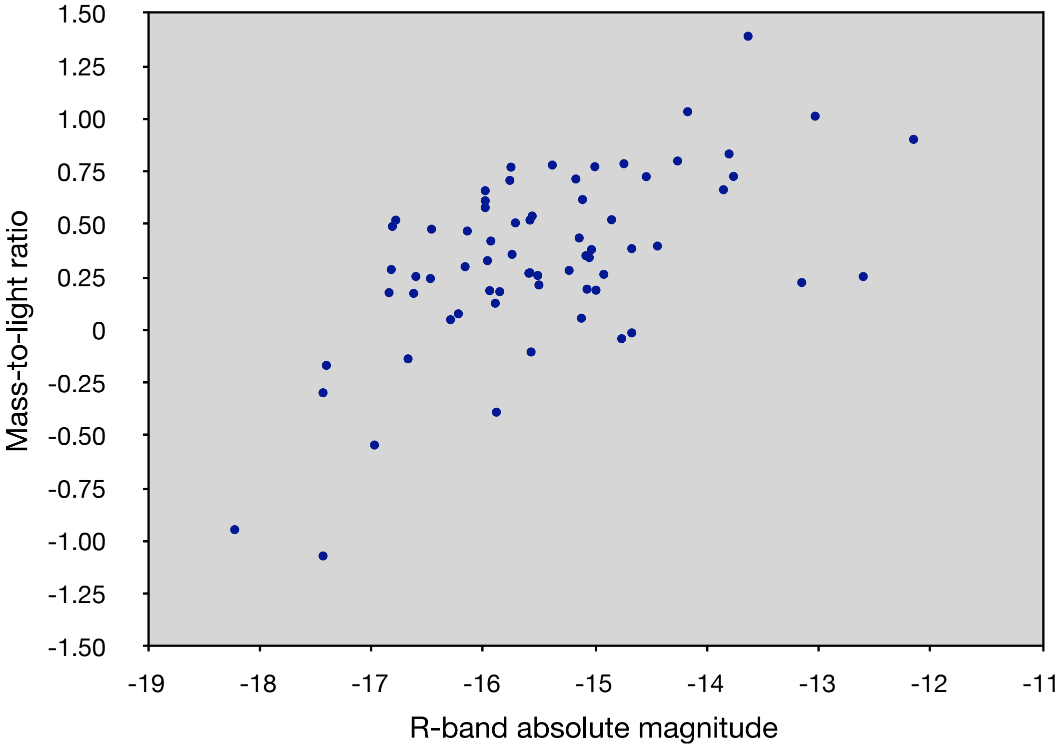

Figure 3: HI Mass to Light ratio vs. absolute magnitude for 69 GRiD galaxies

The graph shows a clear trend with less luminous galaxies having higher HI mass to light ratios. The spread in data points may be due in part to the use of recession velocities rather than more accurate distance measures such as D_{trgb}, which are available for some of the closer objects.

4 Observations

4.1 Target selection from SINGG – the GRiD sample

Data for the 468 galaxies in the SINGG survey have been examined to find suitable gas rich dwarf galaxies for study in this work. Sixty-one targets have been selected on the basis of:

- distance between 350 and 1600 km/s heliocentric velocity
- low mass: neutral gas mass (log(M_{HI})) less than 8.70 solar ($\lesssim$ SMC which has an HI mass of 8.62 solar (Stavely-Smith et al., 1998))
- low brightness: $M_R < -16$
- optical confirmation using R-band and H-α images of the absence of any suggestion of spiral structure
- apparent isolation as measured by no immediate larger neighbours

The last of these criteria will be refined (and the GRiD sample revised) using quantitative measures of isolation described in §3.8. An additional 18 (somewhat more luminous: $M_R \leq -18$) possible BCD galaxy targets have been included in the extended sample, as BCD galaxies tend to exhibit low metallicity but due to strong star formation are more luminous than otherwise similar dwarf irregular galaxies (as noted in §3.1).

4.2 Use of the ANU 2.3m telescope and WiFeS

For my thesis I propose to:

- measure with WiFeS the nebular abundances in the GRiD sample of dwarf galaxies
- determine the mass-metallicity relation for these galaxies;
- investigate whether there is evidence for a metallicity floor in the sample galaxies;
- investigate the effect of isolation on metallicity;
- derive the chemical yields;
- re-examine the primordial He abundance;
- explore the effect of the gas mass to light ratio on metallicity;
- to the extent possible, undertake additional measurements in the optical, infrared and radio to explore the chemical abundances, mass and dynamics of the target objects.

The brightness distribution of HII regions in the sample varies by at least a factor of 1000: the typical range is between 10^{-16} and 10^{-13} erg/sec/cm^2/square arc second. In some regions, faint lines such as [OIII] 4363Å can be readily measured, permitting direct metallicity measurement, while in others the emissions are faint and only the Strong Line techniques can be used to measure metallicity.

Nod and shuffle observations totalling $\sim$2 hours per object are the minimum needed. Assuming early results warrant observing the complete (extended) sample of $\sim$80 objects, this implies a minimum total telescope time of ∼16 clear nights. To permit adequate signal to noise in the fainter targets, the minimum observing time required is ∼24 clear nights spaced throughout the year.

Dark nights are essential to reveal the key faint diagnostic lines ([OIII] 4363Å and [HeII] 4686Å).

High excitation HeII lines may also be present in the spectra which are produced by excitation from very hot low metallicity stars (where the low stellar atmospheric blanketing allows emission of radiation $>$ 54eV). The presence of this line implies a high excitation, low metallicity environment, and its presence in two of the objects measured so far is very encouraging. Measurement of the HeI recombination lines (also present) will shed light on the primordial Helium abundance.

In some cases, what appear as HII regions may in fact be supernova remnants, in which case radiative shock theory can provide an independent measure of abundances.

Seeing: the proposed observations are insensitive to seeing, as the main HII regions are typically ∼5 arcsec across and are physically resolved. Only integrated spectra for each HII region will be required.

Additional observations to complement the WiFeS work are described in §6.

4.3 Advantages of WiFeS for this work

WiFeS is an integral field spectrograph mounted on the ANU 2.3m telescope. It is specifically designed to maximise the throughput (Dopita et al., 2007). Its field of view is relatively large – 25x38 arcsec – and this is close to the typical size of the GRiD galaxies which are the subject of this proposal. While all the measurements likely to be required for this work could be undertaken with a standard slit spectrometer, the use of WiFeS makes these observations 20-50 times more efficient. Multiple areas within an object may be investigated from a single observation, allowing abundance measurement of different nebular components within a given dwarf galaxy; and many more objects can be observed in a given time.

4.4 Implications of sample bias

Selecting a dwarf galaxy sample using neutral hydrogen emissions will detect – within the completeness limits of the HI survey – all gas-rich galaxies. The source list for GRiD, the SINGG survey, itself selected from the Parkes HIPASS neutral hydrogen survey, is therefore “blind” to the optical characteristics of the galaxies it finds (Meurer et al., 2006). In this respect it avoids any optical bias problems which arise, for example, from the star-like optical appearance of some galaxies. It may miss detecting many low-gas-content dwarf Spheroidal and dwarf Elliptical galaxies, but they are not the subject of this study.

Previous searches for low metallicity galaxies have used samples based on optical characteristics (eg Byurakan catalogs, Sloan SDSS data releases). Selections of potential low mass galaxies are thus compromised by the Malmquist bias (Butkevich et al. (2005); Malmquist (1922)). The scarcity of BCD galaxies in the source catalogs may also be a selection bias effect (§3.6, above). It may be that new knowledge will result from a dwarf galaxy sample which is largely free of optical bias.

To confirm the completeness of the current GRiD sample, it will be necessary to re-examine the HIPASS catalog for objects with the same HI mass and distance parameters used to select the GRiD sample. This will identify any additional dwarf gas-rich galaxies missed by SINGG.

4.5 Variability in enrichment

When we look at the diverse types of dwarf gas-rich galaxy, we may be observing them either at or near the peak of a star forming event, when nebular continuum and the continuum from young stars can swamp the continuum from older star populations; or later, when the HII regions have faded, and underlying older populations become more obvious.

Although earlier work on BCDs (eg Loose & Thuan (1986)) suggested that some showed no evidence of older stellar populations, more recent work has shown that evolved populations are present in all the objects studied (see Amorín et al. (2007), Kirby et al. (2008a)). This is supported by Larsen et al. (2001) who argued the case for episodic star formation in dwarf galaxies. This suggests the likelihood of differing levels of enrichment within a single dwarf galaxy, such as are found in intermediate age star clusters in the SMC (Glatt et al., 2008).

It appears reasonable for any multi-gas-cloud galaxy where there has been episodic star formation that there will be variations in the level of nebular metallicity. This is also likely to be true where there is interaction between dwarf galaxies or active star forming regions in a common HI envelope (Bekki, 2008).

Glatt et al. (2008) found stellar metallicity variation of $\sim$0.6 dex in six star clusters of similar, intermediate (6Gy), ages in the SMC. This implies the existence of earlier star formation episodes which contributed differing amounts of enrichment to the clouds from which the studied clusters grew. The variable enrichment is explained by different levels of star formation in the earlier clusters, different numbers of earlier clusters contributing to the source nebulae, and different levels of isolation of the nebulae from earlier star forming regions. We may expect the same characteristics in the stellar populations in dwarf irregular galaxies in the GRiD sample. Initial WiFeS measurements of different ionised gas clouds in HIPASS J1609-04 (figure 4), a reasonably luminous object, indicate that there may indeed be variation in abundances in different ionised regions.

Conversely, very small undisturbed dwarf galaxies ($\log(M_{HI}) < 7.8$) with few regions of star formation, of which there are a number in the GRiD sample, may well exhibit a more uniform metallicity. Integrating across multiple objects within these galaxies will help reduce signal to noise, and thus errors in derived global metallicity values.

Where multiple HII regions are present in a single galaxy we can use techniques developed by Dopita et al. (2006) to determine the age of individual HII regions independently.

The observations proposed here will explore these questions further.

4.6 Star formation duty cycle

Related to variable enrichment is the question of the extent and timing of star formation in small gas-rich dwarf galaxies – whether the star formation is occasional or episodic, as suggested by Larsen et al. (2001). The number of galaxies in the (extended) GRiD sample that appear to be undergoing strong star formation ($\sim$50%) suggests that the “duty cycle” for star formation in these galaxies may be quite short. That is, the star formation and quiescent periods may be similar. To investigate this it will be necessary first to confirm the completeness of the galaxy sample (see §4.4), as quiescent dwarf galaxies may be harder to identify, even given their neutral hydrogen signatures.

4.7 Pilot study

Using instrument commissioning time, measurements were made of three of the GRiD sample galaxies. These measurements were intended to prove the viability of the proposal, to see what the data would look like that could be expected from the instrument.

The results are impressive. Figure 4 shows a wavelength slice through the image cube of object J1604-09, at the wavelength of [OIII] 5007Å. The ionised hydrogen regions (in which the oxygen has been generated) are clearly resolved and typically 5 arc seconds across, implying a dimension of 300 pc at the distance of J1609-04, 13.5 Mpc. Total exposure for this cube was 2400 seconds (data only).

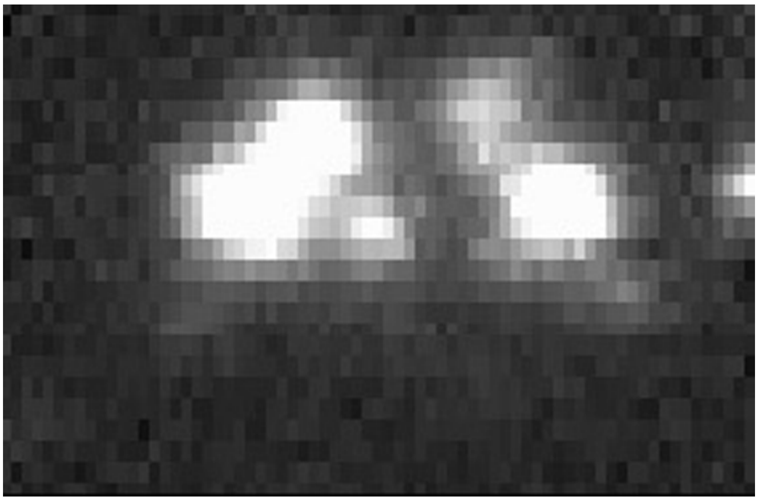

Figure 4: Image cube slice of J1609-04 at 5007 Å [OIII]

Figure 5 shows the reduced blue spectrum (R3000), in which the following emission lines are clearly detected: [OII] 3726+3729 Å (not resolved on this scale), H-γ, H-β, [OIII] 4959 & 5007Å (rest frame). The early reductions were not ideal, and I expect to reduce the noise further, but it appears unlikely that nebular [OIII] at 4363 Å is present.

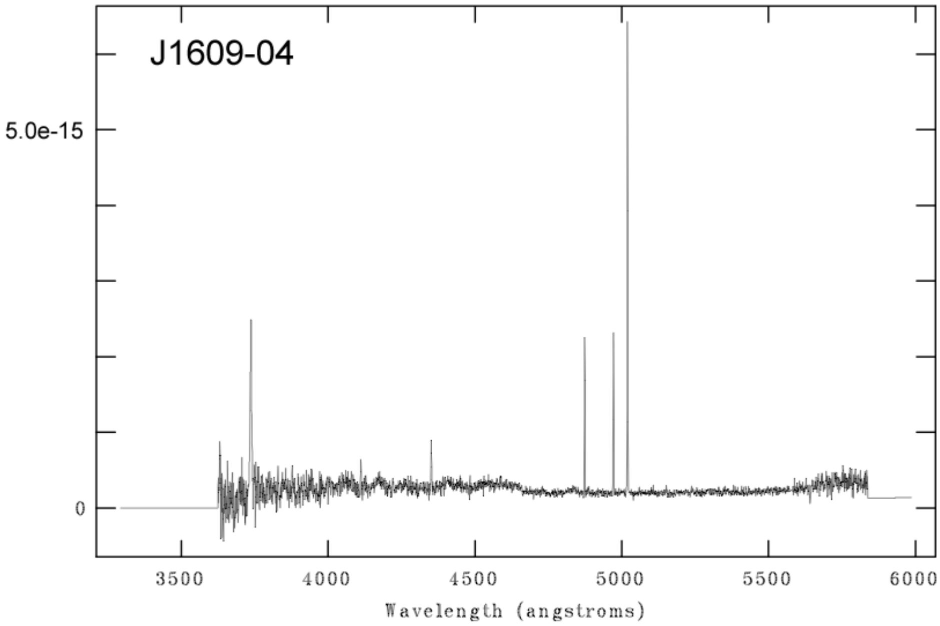

Figure 5: Reduced blue spectrum of J1609-04

Figure 6 shows the SINGG R-band and H-α image of the gas-rich dwarf galaxy J2254-26. This is a bright object at a distance of 12.3 Mpc with a neutral hydrogen mass of log(M_{HI}) = 8.57 M$\odot$. The absolute B magnitude is ∼-15.3 (R-band: -15.9). The ionised H-α region is ∼500 pc across. It is a possible Blue Compact Dwarf candidate.

Figure 6: SINGG R-band and H-α image of J2254-26 (see details above).

Figure 7 shows the (unreduced) blue spectrum (R3000) of object J2254-26. The spectrum shows several Balmer lines, [OII] and [OIII] strong lines, He I and II lines, [NeIII] 3967 and 3869Å, [ArIV] 4711Å and clear evidence of the auroral line [OIII] 4363 Å, implying low metallicity. Very preliminary analysis suggests a metallicity of less than 12+log(O/H) ∼ 7.6.

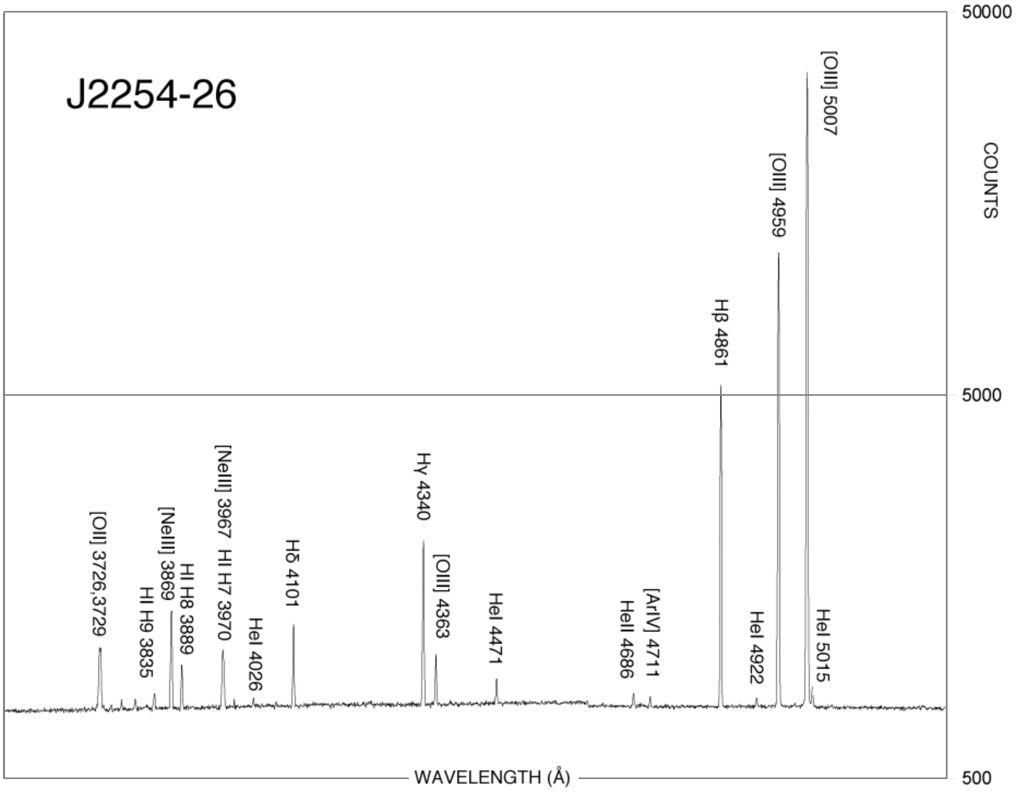

Figure 7: Spectrum of J2254-26, unreduced WiFeS blue camera output

The emission line observations show excellent S/N and suggest that the data obtained from WiFeS from the GRiD sample are likely to be outstanding.

5 Analysis

5.1 Nebular metallicity data analysis

Key to this proposal is the accurate measurement of metallicity in the ionised gas clouds, through analysing the spectra recorded by WiFeS.

The data will be analysed using modern stellar atmospheric models: the state-of-the-art diagnostic “toolbox” developed over the past seven years, Mappings III (Dopita et al., 2007). Model input distributions will be used from the spectral synthesis code Starburst 99 (Leitherer et al. (1999); see also Dopita et al. (2005)).

Spectra will be analysed using strong line methods (Kewley & Dopita, 2002; Kewley & Ellison, 2008) and also by classical methods using the electron temperature (Te) from the line intensity ratio of [OIII] 4363Å and [OIII] 5007Å (Peimbert et al., 2007).

One of the GRiD sample has been shown in preliminary WiFeS measurements to lack the high-excitation [OIII] 4363Å emission. This may be typical of numbers of sample objects. For these the strong-line method must be used to measure abundances. So far, two of the three observed objects (eg Figure 7) show both high excitation lines and strong lines, allowing calibration of the latter by the former.

There are considerable discrepancies between different calibration procedures for this method (< 0.5 dex), thoroughly explored in Kewley & Ellison (2008). The data obtained from observations of the GRiD sample will therefore contribute to a more reliable calibration of the nebular abundance scale.

6 Adjunct Measurements

In addition to the WiFeS measurements of nebular abundances, other measurements of the GRiD sample will yield important information. The exact details of these observations depend on the WiFeS data. They will be undertaken on an opportunity basis, if observing time is granted on the necessary instruments.

6.1 A-supergiant measurements of stellar metallicity

Kudritzki, Bresolin and others at the University of Hawaii (and elsewhere) have developed techniques to measure the stellar metallicities and other parameters for A-supergiant stars in active star formation areas in galaxies out to about 8 Mpc, using the Keck telescopes (Kudritzki et al., 2008b,a). Stars retain the chemical imprint of the interstellar gas out of which they formed (Tolstoy, 2004).

Seven of the GRiD sample galaxies within 8 Mpc are sufficiently far north to observe from Mauna Kea. If we are able to identify suitable stars in these objects (from HST archives or other sources), measuring their metallicity would provide a valuable independent cross-check of the nebular abundance measurements, and an indictor of the evolution of the nebular metallicity.

Initial contacts have been made with the University of Hawaii concerning possible collaboration in this area. Professor Kudritzki and Dr Kewley (U of H) are proposed as members of the thesis supervisory panel, and have agreed to act in this role.

6.2 HST CMD measurements and identification of A-supergiants

To identify suitable A-supergiant candidates for the Kudritzki technique, observations using the Hubble would be valuable, if such data is not already available in the HST archives. HST observations to measure the colour magnitude diagrams of sample objects would also elucidate the star formation history (eg Makarova & Makarov (2008); Corbin et al. (2006)). The first step is to explore the HST archives for existing data. Direct observations would depend on obtaining HST time.

6.3 Infrared measurements of old stellar populations

In order to determine the mass-metallicity relation for dwarf galaxies, an accurate estimate of the stellar mass of each object is essential. Near infrared luminosities provide a better proxy for mass of than the blue luminosities commonly used (Saviane et al. (2008); Kirby et al. (2008a)). Therefore I propose to request observing time on the AAO/IRIS2 or SAAO/NAOJ/IRSF/SIRIUS infrared facilities to measure the old stellar populations in selected GRiD targets. These measurements will assist in accurate determination of the baryonic content of the targets. The population measurements will also aid in understanding the evolutionary history of these objects.

Identifying appropriate targets has yet to be undertaken, and will depend on the results of initial WiFeS observations.

6.4 Radio observations

Similarly, understanding the relationship between neutral and ionised hydrogen would yield an improved understanding of the dynamics involved in these galaxies. While the original HIPASS observations provide 21cm total flux, line widths and heliocentric velocities, they do not map the structure of the neutral hydrogen clouds in which the ionised regions are embedded. Some of this work has been undertaken for nearby objects in the LVHIS program (Koribalski, 2007). However, there would be benefit in extending this work to additional galaxies in the GRiD sample. For example, there is increasing evidence that interacting dwarf galaxies within a larger HI cloud trigger the evolution of BCD galaxies (eg Bekki (2008)). Some of the galaxies in the GRiD sample closely resemble BCDs and radio synthesis mapping of neutral hydrogen would provide valuable input to understanding these objects.

Detailed maps of the HI cloud dynamics will assist estimation of the dark matter content of the target galaxies, and will help confirm the current view that dwarf galaxies are dark-matter dominated.

This is predicated on whether the objects can be resolved with the ATCA. Again, identifying appropriate targets has yet to be undertaken, and will depend on the results of initial WiFeS observations.

7 Contingencies

The primary thrust of the thesis proposal is to measure nebular abundances in the GRiD sample, with a view to understanding better the mass-metallicity relation for small galaxies. Some measurements have already been obtained, and demonstrate that the proposed study is practicable and yields interesting results. My intention is to undertake initial observations of a subset of the GRiD sample and extend observations to the remainder if the results justify it. However, in the event these measurements are not possible in the necessary time frame (for example due to instrument failure caused by lightning strike), other work such as the proposed A-supergiant, IR and radio measurements could be expanded to achieve a satisfactory basis for the thesis.

Note on references

I have included the SAO/ADS citation bibcode keys in the references section to simplify finding papers. Each reference in the electronic version of this document is linked to its ADS web location.

8 Time line

The following notional timeline will allow completion of the work within the allocated span.

Year 1

- Orientation/reading in proposed field of study (ongoing)
- Learning to operate telescope/instrument (ongoing)
- Learning data reduction methods (ongoing)
- Exploratory observations of GRiD objects to prove feasibility
- Development of data reduction methodology (ongoing)
- Visit to IfA, Hawaii, to work with Dr Kewley and explore collaborative opportunities for Keck spectroscopy
- Selection of thesis supervisory panel
- Attend courses relevant to thesis topic
- GRiD target observations on an opportunity basis and initial TAC bid for ANU2.3 time
- Draft paper on initial observations of GRiD targets using WiFeS
- Preparation of Thesis Proposal (this document)
- Preparation of Research Progress Report
- Presentation on Thesis Proposal (December 4th)

Year 2

- Complete/submit first research papers
- GRiD target observations (ongoing)
- Initial bids for telescope time on ANU2.3, Keck, AAT/SAAO, HST, ATNF
- Adjunct observations depending on TAC outcomes
- Paper(s) on mass-metallicity measurements for smallest GRiD targets
- Mid-term report

Year 3

- GRiD target observations (ongoing)
- Bids for telescope time on ANU2.3, Keck, AAT/SAAO, HST, ATNF
- Adjunct observations depending on TAC outcomes
- Paper(s) on outcomes of observations of GRiD targets

Year 4

- Final report
- Thesis

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