Results of Prior NSF Support: LSB Galaxies

The PI has held two significant NSF Grants in the recent past. One is related to Curriculum Development and the development of electronic tools and simulations: viewed at http://homework.uoregon.edu/demo; http://www.mtsu.edu/itconf/proceedings/09/itf.pdf. However, that development effort is not very relevant to this particular research based proposal and so we will describe the results of NSF sponsored research on the properties of Low Surface Brightness (LSB) galaxies. The existence of LSB galaxies and their likely large space density (at all galactic mass scales) clearly shows the severity of observational selection effects. Simply put, the degree of surface brightness bias that exists in the standard detection and cataloging of galaxies has been greatly underestimated. This has been strongly confirmed by the analysis of the SDSS which has returned many more examples of LSB galaxies (see Kniazev etal 2004; Bomans and Rosenbaum 2007) indicating that, in the words of Bomans and Rosenbaum, "*there are two branches of galaxy evolution*". In the following I will briefly summarize the highlights of the research on LSB galaxies:

- Over the period 1995-2004 this research has resulted in at least 25 peer reviewed publications as well as a few popular articles. This research was also the direct basis for at least 6 Ph.D. students: S. McGaugh, K. O'Neil, D. Sprayberry, T. Pickering, W. de Blok and J. Helmboldt.

- It is safe to now say that LSB galaxies represent a legitimate sector of the galaxy population and research on these enigmatic objects has now become part of mainstream extragalactic astronomy. **This was not the case prior to the NSF funded research so in that sense the impact of this work on the community was relatively large.**

- LSB galaxies have, as a class, shown to be relatively unevolved systems compared to more normal galaxies of similar mass. Their overall gas contents are higher than other systems, their mean ages appear to be younger, their metal abundances are low, their current star formation rates per unit mass are considerably lower, and their dust and molecular gas contents appear to be deficient. Yet, these systems have managed to produce the same number of stars over a Hubble time as more normal spirals of the same mass. This is quite curious. The nature of star formation in LSB galaxies therefore remains elusive as it's unclear whether star formation is stimulated by a sparse population of molecular clouds in these systems or is it occurring in the more plentiful diffuse atomic H I medium.

- LSB galaxies have very interesting dynamical properties. Rotation curves that are fit with standard dark matter halos invariably result in baryonic mass fractions of LSB disks that are 5-10 times lower than galaxies of higher surface brightness. Thus they appear to be considerably more dark matter dominated at all radii. This potentially makes them physically different objects than disk galaxies that define the Hubble sequence. On the other hand, LSB disks occupy the same locus of points on the Tully-Fisher diagram as normal galaxies which is manifestly impossible if their baryonic mass fractions are systematically lower because this results in systematically lower dynamical mass-to-baryonic light ratios. LSBs should therefore define a different TF relation. A possible resolution to this dilemma invokes Modified Newtonian Dynamics as an explanation for their rotation curves. MOND indeed fits all the LSB rotation curve data extremely well. There may well be something very interesting going on here.

- A family of very large LSB disks (e.g. Malin 1 like) has been discovered and characterized. These objects are extremely enigmatic structures and seem to violate most of the standard rules for star formation and evolution of disk galaxies. Some of them are the most massive galaxies ever discovered and the most recent aspect of this project (e.g. O'Neill etal 2004) has now tripled the numbers of these objects.

- While the space density of LSB galaxies is still difficult to accurately determine (because of very strong selection effects against their detection) application of reasonable selection functions to go from observed space density to intrinsic space density produces the plausible scenario that most of the missing baryons are contained in LSB disks galaxies of baryonic mass approximately 10^{10} – 10^{11} solar masses.

In sum, the NSF funded study of the properties of LSB galaxies has been a highly productive area of investigation and has helped upon up a new window of inquiry in extragalactic astronomy. The field has been the basis of several Ph. D theses. The overall research in this field has elevated LSB galaxies from idiosyncratic individual objects to a major component of the extragalactic background. No theory of galaxy evolution can therefore be complete unless it includes these objects. The same set of strong biases that apply to galaxy selection may well apply to the selection of extragalactic supernova and so this current proposal represents a nice **complement** to the expertise gained under the previous proposal.

A Systematic Study of Supernova Environments in Nearby Galaxies

Background, Motivation and Purpose

There is a pressing need in cosmology to better understand the physical nature of supernovae Ia (SNe Ia). These bright stellar explosions, used as cosmological distance markers, have the potential to uncover the nature of dark energy, and potential the equation of state of the Universe (the *w* parameter – see Bothun etal 2008) as they can be detected and measured at significant cosmological distances. To be reliable cosmological probes, SNe Ia have to pass two important tests: **a) that there is no evolution in the explosion physics that produces the event and b) that their peak luminosity is independent of the host galaxy environment in which the explosion occurs**. Neither of these conditions has yet to be reliably established. To further explore these issues, especially point b, we have already initiated a large scale study of SN demography which has formed the basis for the doctoral dissertation of **Elsa Johnson**. That dissertation is nearing completion and it has become clear that we are just starting to scratch the surface of the richness of this data set.

Currently there is a significant question of how well these the luminosity of SNe Ia can be calibrated and measured with various forms of template fitting. Extant data indicate that a substantial dispersion exists in the derived peak brightness of the explosions that no amount of correction/template fitting seems to eradicate. This dispersion may well originate from sampling problems coupled with a lack of understanding the supernova Ia (SN Ia) progenitor and the properties of its host stellar population. As the discovery of SNe Ia increases, the taxonomy of the subtypes grows. This is troubling because of the nontrivial fraction of "*over luminous*" SNe Ia discovered in nearby galaxies that resemble "normal" SNe Ia. The questions arise:

- How do we distinguish between these objects and normal SNe Ia at far cosmological distances?
- How do we know if we observing a random sample of normal SNe and not a subset of abnormally bright (or faint) SNe Ia at these distances?
- How does this affect the outcome of our understanding of dark energy?

This proposed study will explore the validity of SNe Ia as good distance indicators by examining regions of nearby galaxies that have hosted an SN Ia in the last 50 years. Our effort will mostly focus on measuring the optical and near IR colors of the local region in which the SN event occurred in the host galaxy. This is accomplished by combining SDSS imaging and 2MASS imaging, together with additional imaging using the University of Oregon 1-m telescope locate at Pine Mountain Observatory. The goal is to measure the underlying stellar population metallicity, age, and reddening in as large of sample as possible. We realize, of course, that measurements of underlying stellar population metallicty and age are somewhat complicated by the likely possibility that the actual SNe Ia progenitor (white dwarf) has drifted significantly away from its parent stellar population of formation (but this would not be the case for Type II SN). However, we expect most of this drift to occur azimuthally and not in the radial dimension. Hence, we are also measuring the azimuthal colors in a ring of width approximately 2-3 kpc for host galaxies (the resolution limit is set by the 2Mass resolution scale). This provides good insight into the average stellar age and metallicty at that galactocentric radius which has hosted the SN event. In addition, the local measurements contain direct information on reddening and one of our preliminary results (see Figure 1 below) is the discovery that SN indeed occur in a wide range of reddening environments. Our proposed multi-color analysis is also motivated by the work of Prieto etal 2005 who show that when multi-color broadband data is used to better estimate the host galaxy extinction, a significantly lower scatter is produced in the Hubble diagram based on SN Ia peak brightness. Most importantly, our project will further quantitatively establish the overall nature of galaxies that host nearby SN. To quote from Benjamin etal (2003), based on an HST imaging study of a sample of 18 high red shift SN host galaxies:

> ***These similarities support the current practice of extrapolating the properties of the nearby population of SN host galaxies to those at high red shift.***

It is the overall intent and focus of this project to thoroughly investigate the validity of this current practice by performing a comprehensive statistical analysis of the properties of the entire low red shift (**z < 0.1**) sample of historical extragalactic supernova.

SNe Ia Luminosities: Normal, Over, or Sub Luminous?

Clearly the current use of SN (Ia) as cosmological probes (e.g. Tonry etal 2003; Stogler etal 2004; Kowalski etal 2008; Wood-Vasey etal 2007) motivates a more intense scrutiny of the properties of nearby SN and their environments. Any attempt to use the properties of nearby SN as a calibration template for the properties of distant SN requires some kind of test or certification that the physics of SN formation has not evolved over cosmic time and that the galactic environment which produce SN has also not strongly evolved. In order to perform this certification, it is necessary to thoroughly characterize the environments of local SN for which we can study that environment in more detail. In particular, assessing the true variance in the properties of SN hosts and the SN producing environments within those hosts is essential in understanding the probability of selecting a similar environment in any survey of distant galaxies.

In recent years, the concept of SN conforming to a standard candle has become ambiguous in the light of increasing data on actual SN. In its simplest form, SNe Ia are thought to be a standard candle because of universal explosion physics. Specifically, SNe Ia are a special type of stellar explosion consisting of a carbon-oxygen white dwarf star and a companion star that is either another white dwarf or a large, evolved helium burning star. Theory dictates that once the white dwarf accretes enough material from its companion to reach a critical mass of roughly 1.4 times the mass of the sun, it will explode. Because white dwarfs must reach this same critical mass before detonating, it follows that the explosion must consistently reach the same peak brightness. However, Phillips (1993) showed through independent measuring techniques to nearby host galaxies of SNe Ia that dispersion exists in the SN Ia peak brightness. He also noted that the intrinsic brightness appears to be a function of how fast the supernova fades over time. The faster the decay in brightness, the dimmer the supernova and conversely, the longer it takes for the supernova to fade, the more luminous the object. Phillips empirically derived a relationship between the shape of the light curve and the intrinsic peak SN brightness, rendering these objects as “calibrate-able” standard candles. Better fitting methods to the data have since replaced his original technique (e.g. Hamuy et al. 1996, Wang 2006, Guy et al. 2007, Jha et al. 2007, Bailey et al. 2009) taking into consideration factors such as the extinction effects of dust from the host galaxy. As much as these methods have improved SN Ia as distance markers, the dispersion is has placed a limit on the precision of measuring cosmological quantities (Howell et al. 2009b). The cause of the variation is likely due to an entanglement of properties of the supernova such as the metal abundance of the white dwarf, the companion type, the age of the progenitor and the explosion mechanism. For example, Howell et al. (2009a) demonstrated that simulations of metal rich progenitors produced dimmer explosions and metallicity of the SN producing environment is one of the things we plan to measure.

It is also now accepted that there are at least two distinct types of progenitor that come from an old and young stellar populations (see review in Mannucci 2009) . An early foray into this idea that the underlying stellar population of the progenitor may be important can be found in von Hippel etal (1997) who suggested that, since progenitors of SN Ia are white dwarfs in binary systems, then there may be a dependence of SN Ia peak luminosity on the white dwarf mass function (WDMF) of the host galaxy and that the WDMF is a function of the mean age of the galaxy. Indeed, it is well established (see Hamuy etal 1996) that among SN Ia, those that occur in E/S0 hosts are 0.3 mag fainter than those that occur in spiral hosts. The essential difference between an E/S0 galaxy and a spiral galaxy lies in the mean age of the stellar population (E/S0 being significantly older). The wdmf models of von Hippel etal correctly predict this observed difference. If the SN Ia formation mechanism is related to binary mergers and if the binary population depends upon host galaxy type as well as the range of local environments within that galaxy (a plausible scenario– Ruiz-Lapuente etal 2004), then there may well be important evolutionary corrections to SN Ia luminosity since **local galactic environments do evolve.** Such evolutionary corrections need to be properly accounted for in calibrating the SN Ia luminosity scale. Other groups (e.g. Umeda etal 1999; Reindl etal 2005) offer different explanations for this observed 0.3 mag difference. However, the origin of the difference, at this point, is not important. What matters is that the difference exists and that 0.3 mag of dimming is an appreciable fraction of any cosmological signal that the dimming of distant SN might be providing. These results point to two potential problems which need substantially more data analysis to resolve:

1. **Is there any statistical evolutionary correction to SN Ia peak luminosity that is based on the mean age of the stellar population in the host galaxy**.

2. **Is there any dependence of SN Ia peak luminosity on other host galaxy properties which is significant enough to require knowledge of these properties for galaxies at high redshift?**

The fact that both of these questions can be raised should be regarded as evidence that we should not be so secure in our assumptions that we can analyze the peak brightness of distant SN without any knowledge of the properties of the host galaxy. In addition, the potential role of dust extinction remains ambiguous (see Blondin et al. 2009, Chornock et al. 2008). Dust has a dual effect of reddening colors and dimming the luminosity. Dust is handled by either 1) assuming that after several days, the supernova light will decay in a specific way in all filters and any deviation from this is dust (Wang et al. 2006). 2) Estimating the amount of dust by examining the host galaxy spectra (Guy et al. 2007). The first technique lies on the unfounded assumption that all SNe Ia must behave the same. The second technique is more robust; however, it fails to consider what happens to the local environment once the supernova explodes.

Amid such variation there are also subtypes of SNe Ia, specifically over and under luminous types that do not work with the usual empirical fitting techniques and therefore, bu definition, become anomalous. There are considerable concerns to distinguishing these types at vast distances, particularly over luminous SNe Ia. After 2-5 days past peak brightness the spectra of over luminous SNe Ia resemble that of normal SNe Ia (Foley et al. 2009). Gathering spectra for a supernova doesn’t always occur immediately after discovery due to telescope scheduling. Studies show that these over luminous types can consist of ~20% of the nearby (Li et al. 2001) and intermediate distance (Foley et al. 2009) sample, an amount significant enough to cause inconsistent results. This is another area where analysis of a larger sample, along with proper identification of selection effects will return a more secure calibration of the SN luminosity scale.

In addition, recent years have seen an increase in theoretical activity aimed at explaining over and under luminous supernova. In particular, Fink etal (2007) have revived and revised earlier (e.g. Woosley and Weaver 1994; Arnett 1997) work on sub-Chandrasekhar mass explosions to more rigorously characterize the case where slow helium burning can allow for a dynamical helium shell (flash) explosion before the Chandrasekhar mass limit is reached. The difference between this mechanism and the standard C deflagration mechanism is just the material accretion rate onto the white dwarf. It is reasonable to presume that accretion rate a) depends upon the environment and b) can vary by orders of magnitude. In addition, Bildsten etal 2007, show how accretion of helium onto a carbon/oxygen white dwarf can produce flashes that would result in the appearance of an under luminous SNe Ia The likely variance in the accretion rate should then naturally produce some sub-Chandrasekhar mass progenitors and the comprehensive study of Stritzinger etal 2006 seems to confirm this. That work also strongly counters the sentiment of Benjamin etal (2003) by stating

> ***In order to explain a factor of ten range in the observed bolometric luminosity, more detailed modeling of the explosion mechanism is required.***

Hence, there is every reason to believe that sub-luminous SN Ia are going to be included in any selected sample and it thus seems imperative to determine, in the nearby sample, whether or not the presence of sub-luminous SNe Ia correlates with any environmental variable within the host galaxy. Indeed, low accretion rate white dwarf systems might take significantly longer to "flash" than high accretion rate objects**. Thus, as a function of time (redshift) the ratio of He-flash SN Ia (e.g. sub-luminous) to normal (e.g. C deflagration) may well increase**. The accretion rate likely depends on the separation between the white dwarf and the binary star. If this characteristic separation is a function of galactocentric radius (more widely separated binaries in regions of lower stellar density at larger radii) then sub-luminous SNe Ia may be preferentially found in galactic outskirts. Indeed, preliminary analysis of our already gathered sample (see more below) shows that under luminous SNe Ia have twice as high of probability of originating outside the visible radius of the host galaxy compared to SNe Ia of more normal luminosity. It is these kinds of host galaxy inspection studies and subsequently derived statistics that are important to gather for as large as possible sample of nearby galaxies in order to truly reveal the range of SN/host galaxy properties and configurations that exist in Nature.

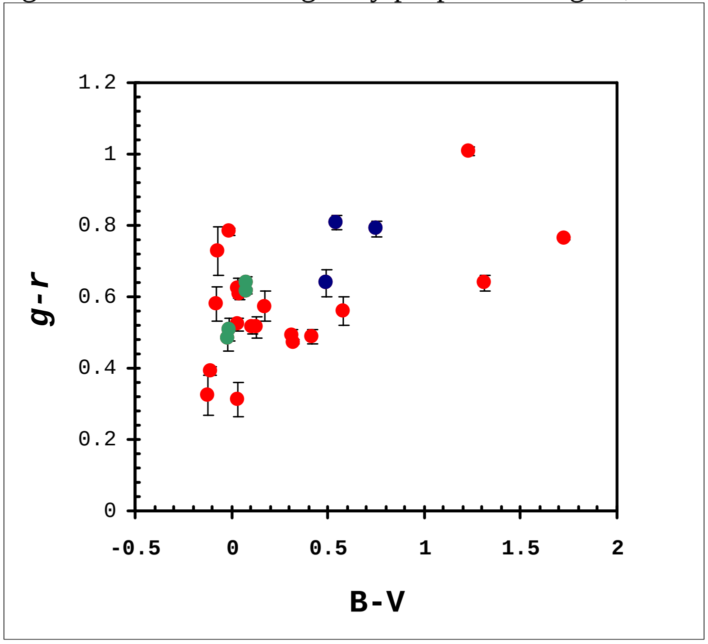
At the other end of the scale, the Supernova Legacy Survey has found several examples of significantly over luminous SNe Ia. Interesting, most of these appear to come from underlying stellar populations that are relatively young. The Graham etal (2008) analysis of the Legacy Survey results has shown that "*… correlations exist between SN Ia rates, properties, and host galaxy star-formation rates (SFRs*)". This again indicates a dependence of SN properties on host galaxy/environmental properties. Modeling by Hillebrandt etal 2007 suggest that over luminous SNe Ia can be produced by certain kinds of mergers between massive white dwarfs (which once again, invokes the **WDMF** as an important player in determining SN type) and/or possible off center explosions of Chandrasekhar mass white dwarfs. Hence, with regard to the SNe Ia luminosity scale we have clearly arrived at the following situation:

- Observed SNe Ia have a factor of 10 range in their bolometric luminosity

- Observed SNe Ia can be sub-luminous with respect to the template fitting procedure

- Observed SNe Ia can be over-luminous with a likely dependence on the mean age of the stellar population (as predicted in von Hippel etal 1997).

These recent results (theoretical and observational) serve very much to cloud the issue of “calibrated standard candle” and requires a more in depth exploration of the connection between produced SN state and underlying environmental/host galaxy properties. Again, that is the chief aim of this proposal to perform this exact exploration. An initial result from our analysis so far is shown below on two existing SN samples. In this analysis we relate the observed color of the SNe Ia at peak luminosity to the stellar environment colors from the SDSS. The data are plotted in Figure 1 where red are “normal Ia”, green are 91T type (over luminous) events and blue are 91bg (sub-luminous The very wide range in observed B-V colors suggests that extinction by dust is important and to first order, redder observed SN come from redder observed underlying stellar populations. More formally, dividing the SNe Ia peak color at B-V = 0.25 shows a difference of about 0.15 mag in underlying (g-r) color between those two samples. This result is quite relevant to the general observation that distant SN (presumably Ia) have significantly bluer colors than nearby SN. Indeed, the very Benjamin etal (2003) paper that claims its okay to extrapolate the properties of nearby SN to a more distant population, also reveals, in their small sample of 18 hosts, a significant correlation between the observed V-R color (of the host galaxy) and distance residual with respect to some cosmological fit. Hence, obtaining independent evidence of reddening (or lack thereof) in the SN producing environment of the host galaxy seems important. Ground based data, such as SDSS can test this for only nearby galaxies, but some intermediate redshift SN with HST imaging data can extend that test to higher redshift hosts.



Snapshot of the current SN Demography Sample

Our sample includes all SN that occurred as of April 2008 and which have known redshifts of z < 0.1. The features of this sample are the following:

- 2595 SN events which occurred in 2346 unique host galaxies with measured diameters
- 169 Multiple SN host galaxies which have produced approximate 400 SN events – this sub sample (e.g. NGC 6946 has had 8 SN events) makes for a rich exploration of the galactic environment of SN.

- 2006 SN have redshifts < 0.033 (equivalent to the approximate “completeness” level of the RC3 catalog)
- 1056 SN have redshifts < 5,000 km/s and this includes 292 SNe Ia (of all subtypes)

It is interesting to notice a couple of statistical outcomes on detection efficiency using the sample described above:

- In the combined UGC and Zwicky catalogs (which include most all RC3) galaxies, there are approximately 15,000 known galaxies with redshifts. Therefore we have detected a SN event in about 30% of that sample.

- However, if one extrapolates those catalogs out to a volume defined by z = 0.1, there are at least ½ a million potential hosts and therefore our catalog only includes 0.5% of those potential hosts.

In addition, it is now common practice to not report to the IAU any SN which have observed magnitudes fainter than 21. While most of those presumably occur in distant galaxies, a completely unknown percentage may be sub luminous SN occurring in the z < 0.1 universe.

From that sample, two principle questions have guided the PHD thesis:

1. **Is the galactic environment that produces SN (of all types but mostly SN Ia) likely to be the same environment that produces the detected sample of SN at higher red shift?**

2. **What is the selection function that Earth based observers have used to detect the approximately 2500 nearby SN in the last 50 years?**

Providing definitive answers to these questions will a) either validate or cast doubt on the voracity of the current and standard practice of directly mapping the properties of nearby SN Ia to those that occur in more distant galaxies and thereby assuming that nothing is evolving in time and b) produce the most robust estimate for the actual SN rate in the nearby Universe. This latter aspect is important to nail down in order to determine the expected yield of distant SN as a function of red shift/survey volume as well as to provide independent confirmation that we are selecting SN in distant galaxies that have “normal” rates. In addition, even the simplest selection effect suggests that, if the production of over luminous SNe Ia is tied to the actual SN production rate in the host galaxy, then at large cosmological distances, a subset of brighter and particularly over luminous events will be detected **more often** than normal SNe Ia, thereby **not forming a random sample**.

Objectives of the Continued Investigation into SN Demography:

As stated earlier, the richness of the SN demography data set is large and with many dimensions. These many dimensions lend themselves to a significant large scale study which seems ideally suited for postdoctoral work. We emphasize that the primary goal of this work is to search for dependencies of SN type, SN Ia peak luminosity, and SN rate on the local and global properties of the host galaxy as well as the environment of that host galaxy and to assess whether or not these same conditions are likely to apply at higher redshift

The objectives of our proposed study include the following:

- What is the distribution of galactocentric radius as a function of SN type? Does this distribution show residual correlations with host galaxy luminosity, metallicity, local stellar population color, or integrated SFR?

- Is their a dependence of SN color (at maximum) on galactocentric radius or host galaxy color or luminosity? That is, do most SN (especially SN Ia) occur in a preferentially un-reddened environment - (our preliminary analysis says no).

- Is their a preferred meta-galactic environment for the production of SN or is this production more a function of the properties of the individual host?

- Is there a preferred local galactic environment (e.g. spiral arms) for the production of SN within an individual host? What is the nature of the local environments in those few galaxies which have produced multiple SN over the last 100 years (e.g. NGC 5253, M100, NGC 2841, NGC 1316, NGC 6946)?

- Is there an a priori combination of SN + Host galaxy broadband colors that strongly favor a candidate distant SN as being SN Ia?

- Is there a correlation between SN Ia peak luminosity and *any* other properties of the host galaxy?

- What is the local environment of the relatively large percentage of SN that is known to have occurred well outside the nominal optical radius of the host?

- Has a SN of any type ever occurred in a Low Surface Brightness Galaxy? (see also Howell 2009).

- What is the revised SN rate that results when Earth observer selection function is applied to various SN samples? How does that rate vary with type of SN or with host galaxy properties? Is that rate consistent with the rate that we infer from the detected distant SN?

Local Stellar Population Colors: Is Reddening a problem or not?

If SNe Ia are truly standard candles, it is crucial to understand the variability in SN Ia brightness from a physical point of view rather than relying on strictly empirical methods to correct the dispersion. A first step would be to examine the underlying stellar population of the progenitor in nearby galaxies. Prior studies (Gallagher et al. 2005, Howell et al. 2009a) have looked for correlations between SNe Ia luminosity and their host galaxy properties, such as: metallicity, average age of stellar population and dust content. The limitation of this type of analysis is that all stellar population characteristics from the entire galaxy are averaged together. Thus, it will not reveal much about the unique **local** stellar population of the SN Ia. Others have examined Hubble Space Telescope (HST) images for supernova progenitor environments (e.g, Barth A. 1996, Hendry et al. 2006) with no success for finding SNe Ia. This is a difficult analysis because only a handful of SNe Ia have occurred in galaxies close enough to have individually imaged stars. **It is the objective of this proposal to examine regions of galaxies where a supernova occurred in attempt to correlate the local parent stellar population to the peak supernova colors.** Preliminary results using Sloan Digital Sky Survey (SDSS) images processed by Elsa Johnson, revealed a significant correlation between these two properties (see figure 1).

These preliminary results are based on the HST archive of of 18 SNe Ia regions with published peak values in either Wang et al. (2006) or Hicken et al. (2009). Of these published SNe Ia colors, about half are near enough to do analysis on just a region of the host galaxy. Additional filter imaging (particularly in ground based U) can be provided by the wide field CCD camera on the University of Oregon's Pine Mountain 1-m telescope. For instance, this has already been done for the multiple SN host galaxy NGC 6946 in which the local colors (UBVRI) of the SN progenitor region show huge variance (some of which could be patchy foreground reddening). As more data enters the HST archive there are abound to be more cases of SN hosts in which we can employ our photometric methodology to measure those local colors. In addition, with the combination of near IR colors, as provided by 2MASS, one can employ the techniques described in Bothun etal (1984) and Bothun and Gregg (1990) (see also Silva and Bothun 1998) to effectively decouple the effects of reddening, stellar population age, and stellar population metallicty from appropriate combinations of optical and IR colors. One example is provided by the use of the I-K color. If the I-K color is constant with peak B-V supernova color, then redder colors are due to dust in the progenitor populations and come from similar stellar regions of age and metal abundance. This also means that dust extinction is **not correctly accounted** for in supernova cosmology (e.g. Wang et al. 2006) which will obviously effect measurements of dark energy. If I-K color is not constant, then an intrinsic variation in stellar populations and possible progenitors does exist that will cast doubt as to whether these objects can ever achieve a low dispersion to be useful as standard candles.

Hence a major component of the proposed continued research on SN demography will involve the measurement of the optical and IR colors of local (0.5 – 2pc) environment using image data from SDSS, HST archive, 2MASS, Pine Mountain, and other surveys. The ultimate aim of this analysis is to provide a thorough assessment of the stellar population environment of the SN Ia event for as large of sample as possible. The most immediate result of this analysis would be to add data to Figure 1 and to get a better assessment of the reddening environment in which SNe Ia encounter within their spiral galaxy hosts.

Most of the published work on the issue of dust extinction and SNe Ia Peak luminosities is both incomplete and ambiguous. For instance, a study of archival HST R and I images of 22 z=0.6 SN Ia host galaxies by Farrah etal (2002) finds that a) projected distances from galaxy centers range from 3-30 kpc and b) the variation in the broad band colors is large suggesting that extinction is important and is highly variable from host to host. Furthermore, they find no evidence that high red shift detected SN Ia events preferentially occur at radii larger than 10 kpc, where extinction might be expected to be low. In contrast to this, Sullivan etal 2003 show that Hubble diagram of type Ia SN as a function of host galaxy morphology reveals no evidence for dust effects in their overall sample but instead the scatter in peak brightness correlates with morphology (and is lowest in early type galaxies). This result is consistent with an attempted direct measure of dust content of 14 z=0.5 Ia hosts by Clements etal (2005). Using the sub-mm flux to define dust content, Clements etal find little evolution in mean dust content from z =0 to z =0.5 but do note that two objects in their sample of 14 appear to have quite large dust contents. Other authors suggest, sometimes strongly, that potentially unknown and variable extinction within the host precludes the usefulness of distant SN as reliable cosmological probes. For instance Rowan-Robinson (2002) claims that dust extinction has been so seriously underestimated that the observed distribution of SN Ia peak brightness carries with it no cosmological implication. Reindl etal 2005 go so far as to state that the observed difference in brightness (e.g. 0.3 mags) between SN Ia in E/S0 hosts compared to spirals is solely a result of differential extinction between the two types of hosts as opposed to the mean age differences suggested by von Hippel etal (1997). Totani and Kobayashi (1999) show that a simple model in which the optical depth of dust is proportional to gas column density and gas metallicity yields an average B-band extinction at z =0.5 which is 0.15 mag larger than the extinction at z=0. Riello and Patat (2005) present an actual model for extinction and SNe Ia events and conclude that the total dust content of the host as well as the size of its Galactic bulge have a greater effect than the particular spiral arm geometry in that host**.** Adding to the complexity is the study by Reindl etal 2005 who claim that the extinction law for SN in distant galaxies is governed by a different extinction curve than that which holds for the Galaxy. As the form of the extinction law depends upon the distribution of grain sizes, this proposition may not be unreasonable as SN shocks have the potentially for altering the grain size distribution locally (see Contini 2004)

Clearly the issue of the amount of expected/observed reddening in the vicinity of SNe Ia events remains controversial, ambiguous and open ended. Our position is that many more data points need to be measured and put into the context provided by Figure 1. Recall that the difference between an open universe cosmology and a cosmology dominated by dark energy amounts to only 0.2 B magnitudes in SNe Ia peak luminosity at z=0.5. NASA and the Department of Energy are investing long term in the use of supernovae Ia as a method to measure the properties of dark energy and the equation of state through The Joint Dark Energy Mission (JDEM). At the cost of an estimated one billion dollars to develop this satellite, it makes sense to **critically examine and measure the issue of dust extinction in the SNe Ia environments as thoroughly as possible and this is a major thrust of our proposed continuing research.**

Micro Location of SN in Hosts and Stellar Population Mean Ages:

Another set of objectives relates to the physical location of the SN occurrence within a host galaxy. For that, we only need one good image of the host in one filter and we note that approximately 400 galaxies with historical SN have now been imaged by HST. The issue of SN location in host galaxies has received some scrutiny by others to date. Historically, the Sternberg Astronomical Institute Supernova Catalogue compiles SN photometric data in order to study SN frequency in galaxies as well as the radial distribution of SN within galaxies (see Tsvetkov etal 2004 for the latest analysis). One of their outstanding results is to document the relatively high preponderance of detected SN that occurred in galaxies at positions well outside the optical radius where the density of progenitors is rather low. The analysis of the Sternberg data also show that SN Ia tend to have a significant concentration in spiral arms (i.e. locally dusty environments), but not necessarily in H II regions where SN Ib/c or SN II are often found. We certainly plan to improve upon these results by utilizing the higher angular resolution data of the HST image archive which will more properly define the galactic environment in which the SN occurred compared to ground based images.

Two striking examples of SN occurring at large galactocentric radius are shown below for SN 2003gd which occurred in NGC 628 (left) and SN 2000ch occurring in NGC 3432.

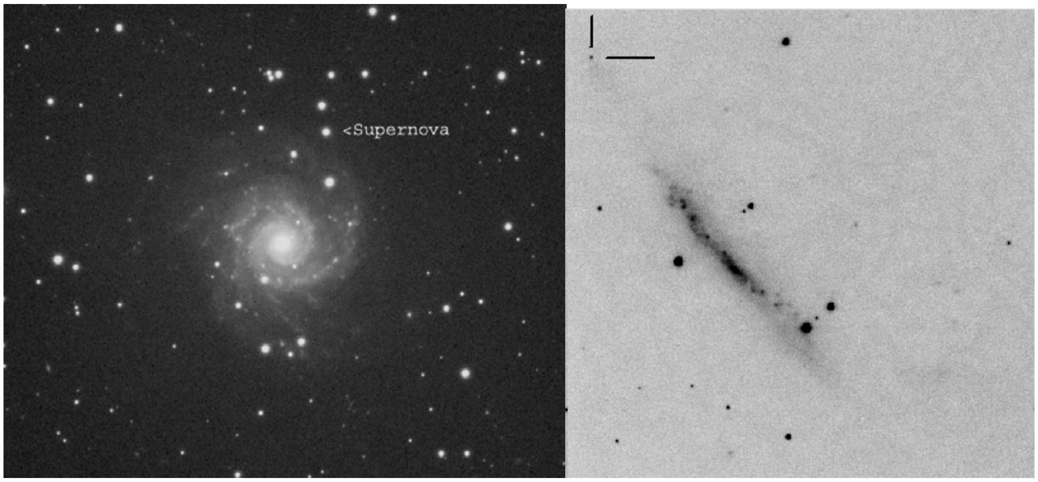


Figure 2: Examples of the occurrence of SN at large galactocentric radii

Using the broadband imaging capabilities of the Pine Mountain 32-inch telescope (described in more detail in the facilities section of this proposal), we plan to image the environments of these curious cases of distant galactocentric SN to determine mean colors and surface brightness in those regions. Indeed, the PHD level analysis of the sample has revealed that approximately **15%** of the SN sample lie outside the visible radius of the galaxy, defined as approximately 4 scale lengths of disk light. Since 4 scale lengths enclose 99% of the light in an exponential disk, then, only 1% of the stars in the host galaxy are beyond that. Thus the 15% figure is intriguing (and is not the result of any selection effect as SN can easily be detected within 1 scale length of a spiral galaxy) and requires further exploration (and is important as those regions are likely to be unreddened). The study of the micro location of the SN is important as its Peak brightness might have some dependence on this location. For instance, the study of Wang etal 1997 has produced a fairly alarming result which requires better investigation with a larger sample. That group studied the correlation between galactocentric distance and SN properties in a relatively small sample (less than 50 hosts). They find that SN which occurred at a distance of more than 7.5 kpc from the respective galactic centered showed 3-4 times smaller scatter in peak brightness than those SN which occurred closer to the center. Howell etal 2000 also performed an analysis of projected distances. They find that **photographically** discovered SN are preferentially discovered at larger galactocentric distances compared to those that have been discovered with more modern CCD imaging (this is a selection effect). They also find that SN located at large galactocentric radius are 0.3 magnitudes fainter than near the center (but they integrate all types of host galaxies together to make this determination). Importantly, Howell etal calculate the probability that any high Z sample of selected SN coming from the same parent population as defines the local sample to be less than 0.1%. To first order, this reinforces the overall concern of this proposal – namely that the SN occurring in distant hosts come from a different parent sample than the local SN. Additionally, Ivanov etal 2000 studied the properties of 62 SNe Ia as a function of radial distance from host galaxy center. They find no radial dependence of the distribution of peak brightness for E/S0 hosts but do find that spiral hosts show a larger range in the peak brightness distribution, supporting the general idea that the mean age of the stellar population is a factor that determines the overall brightness distribution**. Clearly, stellar populations at high redshift have younger mean ages than stellar populations at z=0** and so there is cause for calibration concern. Our proposed azimuthal optical and near IR colors will further address the issue of the dependence of SNe Ia Peak luminosity and mean age of the stellar population (recall that von Hippel etal 1997 predict a dependence). An earlier similar study is that of Hole etal (1996) who did V-I imaging of 50 SN host galaxies to determine the approximate mean age of the local stellar population. Their overall result was a wider variation in V-I colors associated with Type Ia events compared to Type II events. However, V-I by itself is not a good indicator of stellar population mean age (see Bothun etal 1984) and a proper analysis requires combining optical and NIR colors. Another benefit of this approach will be to further the work of Shella and Crotts (2004) who find that the use of the host galaxy B-V color in combination with the B-V or V-R color of the SN at maximum produces a relatively clean separation of types Ia from Ib, Ic and II. Their sample size was only 37 hosts so we wish to verify this separation with a much larger sample. If verified, this photometric determination of supernova type will be very helpful in correctly identifying probable distant SN Ia candidates without the need for very telescope time consuming direct spectroscopy.

Host Galaxy Biases

The other important calibration question relates to whether or not the peak brightness of SN Ia is dependent upon any other property of the galaxy. van den Bergh et al 2005 analyzed the morphologies of 604 recent SN hosts to find that SNe Ia occur in all Hubble types, with almost equal probability, and therefore in a variety of systems with different mean ages, metallicity and reddening environments. Evidence that SN Ia peak brightness depends upon host galaxy metallicity exists. Theoretically, Umeda etal (1999) have shown that the variation in fractional carbon abundance among the heavy elements is important in the sense that environments with low fractional carbon abundance will produce fewer bright Ia events. Those progenitors located in old stellar populations (e.g. E/S0) or in low metallicty environments will preferentially produce fainter SN Ia events. Observationally, Hamuy etal 2000 show that, for a sample of 44 SN Ia events, the brightest events occur in the least luminous galaxies. This is contrary to the theoretical expectation. However, they also find that the brightest events occur in the youngest stellar environments (consistent with the expectation of von Hippel etal 1997). This ambiguity shows the importance of dis-entangling age and metallicity effects. With the release of the 2MASS data, V-K colors are now available for hundreds of SN hosts so that, in combination with broad band UBVRI data, we can make a more reliable separation between age and metallicty to study these overall dependencies more directly. Indeed, the recent recalibration of the Cepheid distance scale, based on a re-formulation of the Galactic metal abundance correction, by Allen and Shanks

(2004) shows that for the 8 nearby SN Ia hosts with a Cepheid based distance, there is a weak correlation between SN Ia peak luminosity and metal abundance. In contrast, Gallagher etal (2004) have used integrated spectra of 57 host galaxies to study the dependence of SN Ia light curve shapes on global metallicty or star formation rate and see little strong dependence and that the range of host galaxy metallicity is normal. We consider this issue as far from resolved. Our proposed azimuthal measures of optical and IR color for hundreds of hosts will certainly shed light on this important issue.

The Recalibrated SN Rate from the Global Sample

Supernova rates are expressed in terms of SNUs where 1 SNU is equal to one supernova event every 100 years per 10^{10} blue solar luminosities of stars. To properly derive the intrinsic SN rate in the nearby Universe, the selection function for SN must be known. Extant analysis use only small and well defined samples are used to derive the rate in which the selection function is supposedly easier to derive. However, it is by no means clear that such small samples are representative. The largest sample to date for which the SN rate has been derived is that of Cappellaro etal 1999 (see also Hamuy and Pinto 1999). Those authors correct for biases against SN detection in the inner regions of galaxies and in inclined spirals to derive a z=0 SN rate of 0.16 SNU. They do not find any dependence of SN Ia rate on galaxy properties. Estimates of the SN rate at higher red shifts are prone to even larger selection effects. Pain etal 2002 derive a SN Rate at average z = 0.55 of 0.65 SNU based on 38 SN with z = 0.25 – 0.85. In deriving this rate, they assume zero evolution in the SN rate with redshift even though they end up with a rate at z = 0.55 which is 4 times higher than the z=0 rate! In addition, a recent study by Dahlen etal 2004 finds a SN Ia rate at z~1 that is 3-5 times higher than the local rate. These high rates are similar to the rate of 0.7 SNU derived for active and starburst galaxies by Richmond etal 1998 with all detected SN in that sample coming from outside the dense stellar nucleus. The strongest suggestion that host galaxy properties matter in the rate comes from Manucci etal (2005) the type Ia rate in the galaxies bluer than B-K=2.6 is about a factor of 30 larger than in galaxies with B-K>4.1; this result is certainly not consistent at all with those of van Den Bergh etal (2005). We therefore feel that SN rates remain sample dependent and biased and driven by particular sample selection functions.

To give an idea of the possible severity of the selection biases consider the following global case: For the current cosmology (h=0.7 and $\Omega_{\_M}$ =0.3), the volume out to z = 0.1 is 10^8 Mpc^3. Taking the current galaxy luminosity function and correcting it for the presence of LSB galaxies (e.g. O'Neil and Bothun 2000; O'Neil etal 2004) indicates that this volume contains approximately 2 million galaxies each capable of a 1 SNU of production (the contrast with respect to the previous estimate of ½ a million catalogued galaxies in this volume is another manifestation of the strong bias against the selection of LSB galaxies) . Over a 100 year period then, 2 million SN have occurred within this volume yet we have catalogued, at most, 2500 events (in about 2000 unique hosts). Thus our earth observer detection efficiency averaged over this time period is approximately 0.1%. Efficiency this low necessarily carries with it a very large and uncertain selection function. Moreover, the rapid rise in SN detection efficiency by the community of Earth observers in the last few years (where we now typically detect 200-300 SN per year instead of order 50) significantly complicates makes the selection function highly time dependent. For any sample, if the sample selection function is not properly accounted for or perhaps even known, then significant bias in the obtained sample will be the result.

In the PHD thesis, we have made a first cut and the global selection function used by earth observes and provide two examples below:

ELSA SIMULATIONS HERE