STAR FORMATION HISTORIES OF NEARBY GALAXIES AND THE CONNECTION TO HIGH REDSHIFT

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Abstract

It is an obvious statement that all the galaxies we see today in and around our Local Group have been forming and evolving for a significant fraction of the age of the Universe. It is not a great leap of logic to further state that the manner in which they have formed and evolved must be fairly representative of these processes in general. Unless of course we would like to assume that our local region of space is in some way peculiar for which there is no evidence. In other words, if we are able to determine accurate star formation histories for the nearby galaxies back to the ages of the oldest globular clusters then we will also obtain a representative picture of how galaxies have evolved from the earliest times, and predict what nearby galaxies looked like at intermediate and high redshifts.

Deep, precision, multi-colour photometry of resolved stellar populations in external galaxies can uniquely determine the star formation histories of nearby galaxies going back many Gyrs. Hubble Space Telescope and high quality ground based imaging have recently resulted in dramatic Colour-Magnitude Diagrams of the faint old resolved stellar populations in nearby galaxies. Although data deep enough to unambiguously trace back to the very oldest populations does not yet exist (except for a few small dSphs in the Galaxy Halo), these preliminary studies make the potential for deeper data for a range of galaxy types look very exciting. For example, recent results on the very low metallicity dwarf irregular galaxy Leo A suggests we have found a predominantly, if not entirely, young galaxy, less than 2 Gyr old, in the Local Group. Nearby faint star CMDs thus provide an important and independent method to confirm the high redshift galaxy survey predictions of galactic evolution.
1 Colour-Magnitude Diagram Analysis

Stellar evolution theory provides a number of clear predictions, based on relatively well understood physics, of features expected in Colour-Magnitude Diagrams (CMD) for different age and metallicity stellar populations (see Figure 1). There are a number of clear indicators of varying star formation rates ($sfr$) at different times which can be combined to obtain a very accurate picture of the entire star formation history (SFH) of a galaxy.

1.1 Main Sequence Turnoffs (MSTOs)

If we can obtain deep enough exposures of the resolved stellar populations in nearby galaxies we can obtain the unambiguous age information that comes from the luminosity of MSTOs. Along the Main Sequence (MS) itself different age populations overlie each other completely making the interpretation of the MS luminosity function complex, especially for older populations. However the MSTOs do not overlap each other like this and hence provide the most direct, accurate information about the SFH of a galaxy. MSTOs can clearly distinguish between bursting star formation and quiescent star formation, e.g. [16]. The age resolution that is possible does vary, becoming coarser going back in time. Our ability to disentangle the variations in $sfr$ depends upon the the intensity of the past variations and how long ago they occurred and which filters are used for observation. For ages less than about 1.5 Gyr it is possible to have detailed resolution on the $10^{-150}$ Myr time scales. As can be seen in Figure 1, the ages begin to crowd together for older populations. Beyond about 8 Gyr ago the age resolution with optimum data is on the scale of roughly a Gyr. This of course means that a very short high intensity burst of star formation in this period will be “spread out” over a Gyr time period and so seem less intense and longer lasting. As will be described in the following sections, however, there are other indicators in a CMD which help to narrow down the range of possible SFHs.

![Figure 1: Isochrones for a single metallicity (Z=0.001) and a range of ages, as marked in Gyr [2] at the MSTOs. Isochrones were designed for single age globular cluster populations and are best avoided in the interpretation of composite populations, which can best be modeled using Monte-Carlo techniques (e.g. [27]).](image)

1.2 The Core-Helium Burning Blue Loop Stars (BLs)

Stars of certain metallicity and mass go on, what are elegantly refered to as, “Blue Loop Excursions” after they ignite He in their core. Stars in the BL phase are several magnitudes brighter than when on the MS. They thus provide a more luminous opportunity to accurately determine the age and metallicity of the young stellar population (in the range, $\lesssim 1$ Gyr old) in nearby low metallicity galaxies [5, 6, 7]. The shape and mass at which these “loops” are seen
in a CMD are a strong function of metallicity and age, and the luminosity of a BL star is fixed for a given age. Subsequent generations of BL stars do not overlie each other as they do on the MS. The lower the metallicity of the galaxy the older will be the oldest BLs and the further back in time an accurate SFH can easily be determined. BL stars are brighter than MS stars of the same mass, often by more than a magnitude.

1.3 The Red Giant Branch (RGB)

The RGB is a very bright evolved phase of stellar evolution, where the star is burning H in a shell around its He core. For a given metallicity the RGB red and blue limits are given by the young and old limits (respectively) of the stars populating it (for ages \( \gtrsim 1 \) Gyr). As a stellar population ages the RGB moves to the red, for constant metallicity, the blue edge is determined by the age of the oldest stars. However increasing the metallicity of a stellar population will also produce exactly the same effect as aging, and also makes the RGB redder. This is the (in)famous age-metallicity degeneracy problem. The result is that if there is metallicity evolution within a galaxy, it impossible to uniquely disentangle effects due to age and metallicity on the basis of the optical colours of the RGB alone.

![Figure 2: In the top panel are plotted the results of Caputo, Castellani & Degl’Innocenti [3] for the variation in the extent in M\(_V\) magnitude of a RC with age, for a metallicity of Z=0.0004. We plot the magnitude of the upper and lower edge of the RC versus age, in Gyr. We can thus clearly see that this extent is strong function of the age of the stellar population. Also plotted is M\(_V\) of the zero age HB against age. In the bottom panel are plotted the results of running a series of Monte-Carlo simulations [27] using stellar evolution models at Z=0.0004 [12] and counting the number of RC and RGB stars in the same part of the diagram, and thus we determine the expected ratio of RC/RGB stars versus age.](image)

1.4 The Red Clump/Horizontal Branch (RC/HB)

Red Clump (RC) stars and their lower mass cousins, Horizontal Branch (HB) stars are core helium-burning stars, and their luminosity varies depending upon age, metallicity and mass loss [3]. The extent in luminosity of the RC can be used to estimate the age of the population that produced it [3], as shown in the upper panel of Figure 2. This age measure is independent of absolute magnitude and hence distance, and indeed these properties can be used to determine an accurate distance measure on the basis of the RC [4].

The classical RC and RGB appear in a population at about the same time (\( \sim 0.9–1.5 \) Gyr, depending on model details), where the RGB are the progenitors of the RC stars. The lifetime of a star on the RGB, \( t_{\text{RGB}} \), is a strongly decreasing function of \( M_{\text{star}} \), but the lifetime in the RC, \( t_{\text{RC}} \) is roughly constant. Hence the ratio, \( t_{\text{RC}} / t_{\text{RGB}} \), is a decreasing function of the age of the dominant stellar population in a galaxy, and the ratio of the numbers of stars in the RC, and the HB to the number of RGB is sensitive to the SFH of the galaxy [23, 15]. Thus, the
higher the ratio, \( N(\text{RC})/N(\text{RGB}) \), the younger the dominant stellar population in a galaxy, as shown in the lower panel of Figure 2.

The presence of a large HB population on the other hand (high \( N(\text{HB})/N(\text{RGB}) \) or even \( N(\text{HB})/N(\text{MS}) \), is caused by a predominantly much older (>10 Gyr) stellar population in a galaxy. The HB is the brightest indicator of very lowest mass (hence oldest) stellar populations in a galaxy.

1.5 The Extended Asymptotic Giant Branch (EAGB)

The temperature and colour of the EAGB stars in a galaxy are determined by the age and metallicity of the population they represent (see Figure 3). However there remain a number of uncertainties in the comparison between the models and the data \([14, 18]\). It is very important that more work is done to enable a better calibration of these very bright indicators of past star formation events. In Figure 3 theoretical EAGB isochrones \([2]\) are overlaid on the HST CMD of a post-starburst BCD galaxy and we can see that a large population of EAGB stars is a bright indicator of a past high sfr, and the luminosity spread depends upon metallicity and the age of the sfr.

1.6 Distance, Extinction & Metallicity

The accurate interpretation of the indicators described above depends critically upon having reliable estimates for the distance, the extinction and the metallicity of a galaxy. Ideally we would also like to know if the extinction is patchy and on what scale, and what has been the evolution of the metallicity of the stellar population with time.

The basic properties of distance, extinction and metallicity can be determined independently to the CMD, and they must be consistent with the findings in a CMD. These three basic parameters, in conjunction with observational errors and incompleteness make the most significant impact on the properties of the CMD and hence the final SFH model \([27]\). There are a number of difficulties in accurately determining these basic properties but they can be resolved with careful observation and analysis techniques.

1.6.1 The Distance is the most crucial parameter for accurate analysis of a CMD, partly because it can easily be wrong by many orders of magnitude (for example the young, red supergiants can be mistaken for the RGB, if the observed CMD isn’t deep enough to confirm the identification, i.e. by detecting a RC or HB). If the distance to a galaxy is incorrect this will result in the masses of individual stars being wrongly determined, and hence the age of
the different populations will be wrong. Distances are most accurately determined by primary
distance indicators (e.g. RR Lyr or Cepheid variable stars), but there is also useful information
in the tip of the RGB [17]; the RC [1]; BLs [29]. To be sure of the distance to small faint
galaxies it is necessary to have a CMD which goes deep enough to extend below the RC/HB.

1.6.2 The Extinction , both internal to a galaxy and between us and a galaxy can affect
the accurate analysis of a CMD. If the extinction is incorrectly determined it will have the same
effect as a distance error, and hence effect the reliability of the SFH models. Local HI maps in
conjunction with Infra-Red (e.g. IRAS) 100µm maps can provide an accurate picture of how
much extinction can be expected in any given direction in the sky [13].

1.6.3 Metallicity: When a galaxy makes stars, then the detritus of this process (e.g.,
from SN explosions and stellar winds) make it unlikely that the galaxy can avoid metallicity
evolution altogether [14]. However, there is no concrete observational evidence that this is true,
although abundance ratios of different elements do give us model dependent suggestions [21].
In the disc of our Galaxy, for example, it was recently shown that, although there is a general
trend in metallicity evolution with time, the scatter is always large [3]. We do not understand
in detail how stars interact with their surrounding ISM, and thus how current star formation
feeds the metal enrichment of future generations. Looking at recent results of absorption line
studies of Zinc abundances at cosmological distances (z = 0.7 − 3.4) there is evidence for a
shallow evolution of metallicity in galaxies over this long redshift range, but there is also a large
scatter in values at any time [22]. Absorption line studies of these species provides arguably
the most reliable estimator of the metallicity of the gas in a galaxy. If suitable background
continuum sources could be found behind nearby galaxies this would dramatically improve our
understanding of how the ISM in different galaxies evolves and is affected by the proximity of
current star formation.

Accounting for metallicity evolution in a CMD is difficult. It is impossible to determine
a unique model based solely on the RGB because of age-metallicity degeneracy. However, if
metallicity evolution is neglected in a CMD model then the best model for that galaxy will
typically be younger than if metallicity evolution were included [29].
Understanding the details of metallicity evolution in galaxies is one of the most critical areas
for further study if we are to develop an accurate understanding of galaxy evolution.

2 Recent Results from HST Observations

An HST program was initiated by Skillman [26], using four orbits of telescope time per galaxy,
in three filters (effectively B, V and I), to study a sample of four nearby dwarf irregular (dI)
galaxies. The initial sample consists of: Sextans A, Pegasus, Leo A & GR 8. The results have
been dramatic and illustrate the tremendous advances possible, even with short exposures,
when crowding has been virtually illuminated [3, 6, 7, 8, 13, 26, 29].

2.1 Leo A: A Predominantly Young Galaxy within the Local Group

The unprecedented detail of the WFPC2 CMDs of the resolved stellar population of Leo A has
resulted in an improved distance determination and an accurate SFH for this extremely metal-
poor Local Group (LG) dI galaxy [29]. From the position of the RC, the BLs and the tip of the
RGB, a distance modulus, m−M=24.2±0.2, or 690 ± 60 kpc, was obtained which places Leo A
firmly within the LG. The interpretation of these features in the WFPC2 CMDs at this new
distance based upon extremely low metallicity (Z=0.0004) theoretical stellar evolution models suggests that this galaxy is predominantly young, i.e. < 2 Gyr old. A major episode of star formation 900−1500 Gyr ago can explain the RC luminosity and the ratio of N(RC)/N(RGB) stars as well as consistency with the the number of anomalous Cepheid variable stars seen in this galaxy. The presence of an older, underlying globular cluster age stellar population could not be ruled out with these data. However, using the currently available stellar evolution models, it would appear that such an older population is limited to no more than 10% of the total star formation to have occured in this galaxy. The HST CMDs and the modeling results are shown below in Figure 4.

Figure 4: Here we show the results for the analysis of the HST/WFPC2 data [29]. In a. is the V−I, I HST CMD for Leo A, 1 orbit exposure time per filter. In b. is the B−V, V HST CMD for Leo A, 2 orbits in B (F439W). In c. is the best match Monte-Carlo simulation model (in V−I, I) found for these data convolved with the theoretical measurement error distribution [28], and in d. is the SFH that created the model CMD which best matches these data. See Tolstoy et al. [29] for more details.

2.2 Pegasus: A Not so Young Galaxy?

The resolved stellar population of the Pegasus dI galaxy reveals quite a different SFH to Leo A [13]. A young (< 0.5 Gyr), and weak MS stellar component is also present. In Pegasus however,
the distinctive BLs are not visible in the data. This may be due to spatial variations in the internal extinction properties of Pegasus which effectively smear out this feature which would already be weak in a galaxy with such a small young population. The colours of the MS also suggest an unexpectedly large foreground extinction of $A_V = 0.47$ mag. The width in colour of the RGB implies a range of stellar ages and/or metallicities. A small number of EAGB stars are found beyond the RGB tip and in WIYN ground based imaging and near the faint limits of the HST data is a populous RC. Fitting a self-consistent stellar population model based on the $Z=0.001$ Geneva stellar evolution tracks yielded a revised distance of 760 kpc. The numbers of MS and BL stars require that the sfr was higher in the recent past, by a factor of $\sim 10$ about 2 Gyr ago, assuming no metallicity evolution. Unique results cannot be obtained for the SFH over longer time baselines without better information on stellar metallicities and deeper photometry. Even at its peak of star forming activity, Pegasus most likely remained relatively dim with $M_V \sim -14$. The HST CMDs and the modeling results for Pegasus are shown in Figure 5 below.

Figure 5: Here we show the results for the analysis of the HST/WFPC2 data. In a. is the $V-I$, $I$ HST CMD for Pegasus, 1 orbit exposure time per filter. In b. is the $B-V$, $V$ HST CMD for Pegasus, 2 orbits in $B$ (F439W). In c. is the best match Monte-Carlo simulation model, in $V-I$, $I$, found for these data (excluding the RC) and convolved with the theoretical measurement error distribution, and in d. is the SFH that created the model CMD which best matches the data. See Gallagher et al. for more details.
2.3 Sextans A & GR 8: Detailed Star Formation Patterns

Sextans A and GR 8 are the furthest away in the Skillman sample (at 1.4 and 1.6 Mpc respectively) and so these data do not allow us to consider SFHs beyond \( \sim 800 \) Myr ago, however they do provide detailed information about how star formation has varied spatially across these small galaxies on time scales \(<1\) Gyr using the MS and BL stars. There is insufficient information to obtain unique information from the RGB about the older populations from these data. The Dohm-Palmer contribution to this volume [5] discusses these results in detail, and see [6, 7, 8].

2.4 VII Zw 403: A Post-Starburst Blue Compact Dwarf Galaxy

Another interesting new result from HST comes from a study of the nearest by Blue Compact Dwarf (BCD) Galaxy, VII Zw 403 by Lynds et al. [18]. The \((V-I, M_V)\) HST CMD is shown in Figure 3. Another study of the same HST observations of VII Zw 403 is presented by Schulte-Ladbeck, in this volume. This galaxy is at a distance of \(\sim 5\) Mpc, and thus it of similar resolution to ground based observations of nearby dI type galaxies, such as NGC 6822 [14]. The similarity between Figure 3 and the ground-based CMD of NGC 6822 of Gallart et al. [14] is quite startling. Clearly this is a similarity which needs further study. NGC 6822 is also close enough to calibrate the EAGB versus SFH via the detection of older MSTOs.

3 The Connection to High Redshift

Star-forming, dI galaxies represent the largest fraction by number of galaxies in the LG, and it is clear from deep imaging surveys that this number count dominance appears to increase throughout the Universe with lookback time [11]. The large numbers of “Faint Blue Galaxies” (FBG) found in deep imaging-redshift surveys appear to be predominantly intermediate redshift \((z < 1, or a look-back time out to roughly half a Hubble time), intrinsically small late type galaxies, undergoing strong bursts of star formation [1]. Thus we can assume that the dIs we see in the LG (e.g. Leo A, Pegasus, Sextans A, etc.) are a cosmologically important population of galaxies which can be used to trace the evolutionary changes in the sfr of the Universe with redshift. The “Madau-diagram” [19] uses the results of redshift surveys to plot the SFH of the Universe against redshift. It predicts that most of the stars that have formed in the Universe have done so at redshifts, \(z \sim 1 - 2\). If it is correct, then the MSTOs from the most active period of star formation in the Universe will be easily visible as \(7-9\) Gyr old MSTOs in the galaxies of the LG [23]. Determining accurate SFHs for all the galaxies in the local Universe using CMD analysis provides an alternate route to and thus check upon the Madau-diagram.

Recent detailed CMDs of several nearby galaxies and self-consistent grids of theoretical stellar evolution models have transformed our understanding of galactic SFHs. Both of the dIs we have looked at, and for which we detected a RC, (Leo A and Pegasus) agree that the sfr was higher in the past, although the peak in the sfr has occurred at relatively recent times as defined by Madau-diagram (the peaks occur at \(z=0.1-0.2\), within the first bin). The Mateo review of all LG dwarf galaxies [20] and studies of M31 and our Galaxy [23], on the other hand, suggest that the LG had its most significant peak in star formation >10 Gyr ago (i.e at \(z > 3\)), the epoch of halo formation. Many galaxies contain large numbers of RR Lyr variables (or HB) and/or globular clusters which can only come from a significant older population. It is possible that dI galaxies have quite different SFHs to the more massive galaxies. Thus although the small dI galaxies in the LG have been having short, often intense, bursts of star formation in comparatively recent times this is not representative of the majority of the star formation in
Figure 6 summarises what can currently be said about the SFH of the LG and how this compares with the Madau et al. [19] and Shanks et al. [25] redshift survey predictions. We have not included the dominant large galaxies in the LG, the Galaxy and M 31, but the SFH of the combined dwarfs is broadly consistent with what is known about the SFH of these large systems. They have, as far as we can tell, had a global sfr that has been gradually but steadily declining since their (presumed) formation epoch \( >10 \) Gyr ago. There is currently no evidence for a particular peak in sfr around \( 7-9 \) Gyr ago or any other time, as predicted by the Madau-diagram for either large galaxies or dwarfs. Perhaps if dIs are singled out a population with a star formation peak in the Madau-diagram range can be found. But at present the statistics are too limited. This is a question that would be very useful to study again with HST data and modern CMD analysis techniques. There is clearly a total mismatch between the SFH of

the LG. dIs represent a small fraction of the total star formation in the LG. However direct observations of the details of the oldest star forming episodes in any galaxy are limited at best. There are only a few cases for which we have observations which can tell us not only when the dominant epoch of star formation has been in a galaxy, but also how intense this was. This is an area where advanced CMD analysis techniques have been developed [28] and telescopes with sufficient image quality exist and the required deep, high quality imaging are observations are waiting to be made.

Figure 6: In the upper panel is a rough summation of the sfrs of the LG dwarf galaxies with time (data taken from Mateo [20]) to obtain the integrated SFH of all the LG dwarfs. The redshifts corresponding to lookback times (for \( H_0 = 50, \) \( q_0 = 0.5 \)). In the middle panel, a wild extrapolation is made; the assumption that the integrated SFH of the LG dwarfs in the upper panel is representative of the Universe as a whole. The resulting star formation density of the LG versus redshift is plotted using the same scheme as Madau et al. and Shanks et al. [25], and these two models are also plotted and the LG curve is arbitrarily, and with a very high degree of uncertainty, normalised to the other two models. In the lowest panel the The LG dwarf sfr as a fraction of the total star formation integrated over all time is plotted versus redshift, and the Madau curve is also replotted in this form, for the volume of the LG. This highlights the totally different distribution of star formation with redshift found from galaxy redshift surveys and what we appear to observe in the stellar population of the LG.
the LG and the results from the redshifts surveys. This might hint at serious incompleteness problems in high redshift galaxy surveys, which appear to miss passively evolving systems in favour of small bursting systems.

The recent HST CMD results give much cause for optimism that we can hope to sort out in detail the SFH of all the different types of galaxies within in the LG if only HST would point at them occasionally. There is also great potential for ground based imaging using high quality imaging telescopes with large collecting areas, such as VLT is clearly going to be.

Acknowledgments: I thank Jay Gallagher, Mario Mateo, Piero Rosati, Evan Skillman and Alvio Renzini for useful conversations.

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