

The chemical evolution of dynamically hot galaxies

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Abstract. We investigate the chemical properties of M32, the bulges of M31 and the Milky Way, and the dwarf spheroidal galaxies NGC 205, NGC 185, Sagittarius, and Fornax using previously published oxygen abundances for their planetary nebulae. Our principal result is that the mean stellar oxygen abundances for all of these galaxies correlate very well with their mean velocity dispersions. This implies that the balance between energy input from type II supernovae and the gravitational potential energy controls how far chemical evolution proceeds in bulges, ellipticals, and dwarf spheroidals. It appears that chemical evolution ceases once supernovae have injected sufficient energy that a galactic wind develops. All of the galaxies follow a single relation between oxygen abundance and luminosity, but the dwarf spheroidals have systematically higher [O/Fe] ratios than the other galaxies. Consequently, dynamically hot galaxies do not share a common star formation history nor need they share a common chemical evolution, despite attaining similar mean stellar oxygen abundances when forming similar stellar masses. The oxygen abundances support previous indications that the stars in higher luminosity ellipticals and bulges were formed on a shorter time scale than their counterparts in less luminous systems. We calibrate the Mg_2 index for dynamically hot galaxies as a function of observed age and oxygen abundance using the mean oxygen abundances from the planetary nebulae and the best age estimates available for the stars in M32 and the bulges of M31 and the Milky Way.

Key words: ISM: planetary nebulae: general – galaxies: abundances – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: ISM

1. Introduction

At the present epoch, chemical evolution has largely ceased in most dynamically hot galaxies (DHGs: ellipticals, bulges, and dwarf spheroidals). The majority of the stars in the majority of DHGs are at least several billion years old, so it is likely that

we observe most DHGs in the chemical evolution state in which they are destined to remain. The properties of DHGs, however, reflect the evolution that occurred earlier. The existence of a well-defined relation between metallicity and mass is a fundamental clue concerning the evolution of DHGs (e.g., Bender et al. 1993). The relation between the Mg_2 index and the velocity dispersion, for instance, has long been interpreted as evidence for galactic winds (e.g., Brocato et al. 1990). The velocity dispersion is a measure of the galaxy's gravitational potential, and consequently is a probe of its mass. Type II supernovae are the principal source of magnesium, so the Mg_2 index is a natural representative for the energy injected by massive stars. Larson (1974) first considered the effects of supernova-driven galactic winds upon a star-forming elliptical galaxy: As star formation proceeds, supernovae explode, and part of their energy goes into raising the internal energy of the interstellar medium. If the rate of energy input is higher than that at which it can be lost, e.g., by radiative processes, the internal energy of the interstellar medium will eventually exceed its gravitational binding energy, and the interstellar medium will flow away in a wind.

Progressing beyond this qualitative picture to a more quantitative one has been difficult. The difficulty arises largely because no easily interpretable, quantitative measure of abundances has been available for DHGs. Traditionally, investigations of the metallicities and chemical evolution of DHGs have hinged upon metallicity indicators derived from integrated light spectroscopy; the Mg_2 index is the best known (see, e.g., Worthey et al. 1994 for a definition). While the Mg_2 index is an excellent tool for ranking metallicities in DHGs, it does not directly yield an abundance, i.e., the number density of an element relative to hydrogen. Through population syntheses, it is possible to calibrate metallicity indicators in terms of the age and metallicity of the underlying stellar population (e.g., Worthey 1994; Casuso et al. 1996), but the utility of such calibrations is inevitably compromised due to the difficulty of disentangling age and metallicity in composite spectra (Worthey 1994). (By “stellar populations” we mean stars of a given age and metallicity, recognizing that the metallicities of stars in a DHG may vary considerably though their ages might not.)

Recently, CCD detectors coupled to efficient spectrographs on 4m-class telescopes have allowed direct measurements of

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Table 1. Elemental abundances^a and galactic properties for our sample of DHGs

Galaxy	N_{PNe}	mean [O/H] (dex)	max [O/H] (dex)	mean [Fe/H] (dex)	M_B (mag)	σ_m (km/s)	Mg_2 (mag)	Data Sources ^b
MW bulge	32	-0.30 ± 0.27	0.27	-0.23 ± 0.40	-19.5	125	0.25	A,F,M,N,U
M31 bulge	21	-0.26 ± 0.27	0.18		-19.6	166	0.34	B,M,P,V
M32	5	-0.61 ± 0.20	-0.43	-0.25 ± 0.30	-15.6	60	0.20	B,G,M,S,V
NGC 205	8	-0.40		-0.85 ± 0.50	-15.9	50	0.10	C,H,C,Q,W
NGC 185	4	-0.78		-1.23 ± 0.30	-14.6	25	0.08	C,K,C,T,W
Sagittarius	2	-0.93		-1.10 ± 0.30	-13	11.4		D,J,J,J
Fornax	1	-0.95		-1.34 ± 0.40	-11.7	9.6	0.067	E,L,C,R,W

^a Throughout, we use the notation $[A] = \log A - \log A_\odot$ and the Anders & Grevesse (1989) solar abundances.

^b The order of the data sources is [O/H], [Fe/H], M_B , σ_m , and Mg_2 .

Data sources: (A) Stasińska et al. 1998; (B) Richer et al. 1998; (C) Richer & McCall 1995; (D) Walsh et al. 1997; (E) Maran et al. 1984; (F) McWilliam & Rich 1994; (G) Grillmair et al. 1996; (H) Mould et al. 1984; (J) Ibata et al. 1997; (K) Lee et al. 1993; (L) Beauchamp et al. 1995; (M) McCall 1998; (N) Sellgren et al. 1990; (P) Kormendy 1988; (Q) average of Held et al. 1990, Carter & Sadler 1990, and Bender et al. 1991; (R) Mateo 1997; (S) Kormendy 1987; (T) average of Held et al. 1992 and Bender et al. 1991; (U) Whitford 1978; (V) Worthey et al. 1992; (W) Bender et al. 1993

oxygen abundances for individual planetary nebulae in several nearby DHGs. Oxygen abundances are now available for planetary nebulae in M32, the bulges of M31 and the Milky Way, and the dwarf spheroidals NGC 205, NGC 185, Sagittarius, and Fornax. These observations have considerably changed the complexion of the abundance problem in DHGs.

In this paper, we focus specifically upon the energy balance and temporal aspects of chemical evolution in DHGs, independent of models. In a following paper, we address issues such as the yield of oxygen, the gas fractions when star formation ceased, and the importance of gas flows during the period of star formation. We begin by examining how well the oxygen abundances in planetary nebulae should trace those in the stars in DHGs (Sect. 2). Next, we define our criteria for selecting planetary nebulae in DHGs and outline the limitations of the mean oxygen abundances derived from these samples (Sect. 3). Then, we consider the implications of the data for the chemical evolution of DHGs, paying particular attention to the energy balance between supernovae and the gravitational potential, and the time scale for star formation (Sect. 4). Following that, we present our calibration of the Mg_2 index (Sect. 5). Finally, we summarize our conclusions (Sect. 6).

2. Planetary nebulae as probes of stellar oxygen abundances

The oxygen abundances in planetary nebulae offer several advantages and new possibilities for studying the chemical evolution of DHGs. First, spectroscopic studies of planetary nebulae yield oxygen abundances directly. Second, oxygen is produced almost exclusively by type II supernovae (e.g., Timmes et al. 1995), so its evolution within a galaxy is easily understood and modelled. Third, the precursor stars to planetary nebulae do not modify their initial oxygen abundances significantly (e.g., Richer 1993; Forrestini & Charbonnel 1997). Fourth, the mean oxygen abundance found for a planetary nebula popula-

tion should be a mass-weighted mean of the oxygen abundances in the stellar populations from which the planetary nebula population arises. Since the stellar populations comprising most of the mass in any given DHG are old, they should have similar rates of both stellar death and planetary nebula production (e.g., Renzini & Buzzoni 1986). Consequently, the stellar populations in DHGs should produce planetary nebulae in numbers proportional to the mass of each stellar population. Unless there are strong gradients in the production of bright planetary nebulae among the stellar populations in DHGs, the mean oxygen abundance for bright planetary nebulae should be a mean of the stellar oxygen abundance weighted according to the mass in different stellar populations. In contrast, spectroscopic metallicity indicators weight stellar populations according to their luminosity. Finally, a comparison of the oxygen and iron abundances, when the latter exist, can be used as a measure of the star formation time scale. As iron is produced in significant quantities by type Ia supernovae as well as type II supernovae, its enrichment time scale is significantly longer than that for oxygen, so the ratio of the two abundances depends upon the history of star formation and is a reasonably reliable measure of the star formation time scale (see Sects. 4.1 and 4.2).

While Richer (1993) showed that bright planetary nebulae are good tracers of the interstellar medium abundances in the Magellanic Clouds, doing so for DHGs is much more difficult. The Milky Way bulge is the only system in which we can directly compare oxygen abundances in stars and planetary nebulae. McWilliam & Rich (1994) found $[\text{Fe}/\text{H}] = -0.23 \pm 0.40$ dex and $[\text{O}/\text{Fe}] \sim 0$ dex for the stars in the bulge. Within errors, their oxygen abundance is identical to that quoted for planetary nebulae in Table 1. This agreement suggests that the stars observed by McWilliam & Rich (1994) and the planetary nebulae selected by Stasińska et al. (1998) probe the bulge's stellar populations in the same way, and are thus directly comparable. (Throughout, we use logarithmic abundances relative to their

solar values, i.e., $[A] = \log A - \log A_{\odot}$, and adopt the solar abundances of Anders & Grevesse (1989).

One worry is that McWilliam & Rich (1994) derived large aluminum enhancements for the stars they observed. This raises the spectre that whatever process enhances aluminum and depletes oxygen in some globular cluster giants (e.g., Kraft et al. 1995) may also be operating in bulge giants. Obtaining nitrogen and carbon abundances for these stars would be extremely helpful in investigating this possibility, for nitrogen is enhanced and carbon depleted in oxygen-depleted stars in globular clusters. The stars observed by McWilliam and Rich (1994) have other abundance peculiarities, notably the α -elements Mg, Ca, Si, and Ti do not share a common abundance enhancement relative to iron as is usually found. This puzzling abundance pattern in bulge stars might simply reflect a complex enrichment history, so one should consider the possibility of oxygen depletion very carefully. Briley et al. (1996) found sodium-enriched main sequence stars in the globular cluster 47 Tuc, suggesting that some of these abundance anomalies might have a primordial origin (sodium enrichment normally accompanies oxygen-depletion; e.g., Denissenkov et al. 1998). Both models and observations hint that oxygen depletion is more efficient at low metallicity, $[\text{Fe}/\text{H}] \leq -1$ dex (e.g., Norris & Da Costa 1995; Cavallo et al. 1996). Finally, abundance anomalies (and oxygen depletion?) appear to be less frequent among metal-poor field stars than among globular cluster giants (Langer et al. 1992; Pilachowski et al. 1996). It is therefore not clear whether Milky Way bulge stars are oxygen-depleted, nor how the oxygen abundances in planetary nebulae could be corrected to account for oxygen depletion, since the depletion observed in globular cluster stars varies among stars within a cluster and its severity varies from cluster to cluster (e.g., Kraft et al. 1995).

The bright planetary nebulae in the Milky Way bulge, however, do not have the chemical signatures of the oxygen-depleted stars in globular clusters. The bright planetary nebulae in the Milky Way bulge have $[\text{N}/\text{O}]$ ratios identical to those found in bright planetary nebulae in the Magellanic Clouds (Stasińska et al. 1998), and the latter have not significantly depleted their initial store of oxygen (Richer 1993). In fact, no planetary nebula sample for any of the galaxies we consider here has the high $[\text{N}/\text{O}]$ ratios observed in oxygen-depleted giants (e.g., $[\text{N}/\text{O}] > 1$ dex; Kraft et al. 1995) or the even higher ratios allowed by models (e.g., Denissenkov et al. 1998). Similarly, these same models predict much larger $[\text{Ne}/\text{O}]$ ratios for oxygen-depleted stars than are observed, on average, in the planetary nebula sample in the Milky Way bulge (or anywhere; Stasińska et al. 1998). In short, the bright planetary nebulae in the Milky Way bulge appear to have normal abundance ratios, and so they presumably probe the oxygen abundances when their progenitor stars formed.

A second worry is that the number of bright planetary nebulae per unit luminosity in external galaxies decreases in more luminous or redder galaxies (e.g., Hui et al. 1993). These trends are of unknown origin, effects due to both age and metallicity of the progenitor stellar populations have been suggested, and they could have an impact when comparing samples of planetary

nebulae in galaxies of very different luminosities. If a metallicity effect is involved, planetary nebulae will sample the mean oxygen abundance in stars in a systematically different way in galaxies of different luminosity. If an age effect is involved, it will probably only affect the mean oxygen abundance obtained from planetary nebulae if a galaxy contains stellar populations of such different ages that the stellar death rates from these populations are markedly different.

Neither of these worries should invalidate our approach. Although it is unclear whether the stars in the Milky Way bulge do or should have modified abundances, the planetary nebulae have normal abundances. Likewise, the abundances for the planetary nebulae in M31, M32, and NGC 205 (Table 1 and Stasińska et al. 1998) appear to be unmodified, consistent with the arguments presented above. For the planetary nebulae in Sagittarius and Fornax, both $[\text{N}/\text{O}]$ and $[\text{Ne}/\text{O}]$ are normal (Walsh et al. 1997; Maran et al. 1984), so they presumably likewise measure the initial oxygen abundances in the stars from which they descend. By interpolation, we have no reason to believe that the planetary nebulae in NGC 185 should have oxygen abundances that have been significantly modified by the evolution of their progenitors. In the very worst case, the stars in the Milky Way bulge could be oxygen-depleted, and the planetary nebulae then under-estimate the mean initial abundance for the stars, since the planetary nebula abundances then agree with those in oxygen-depleted stars. Such an error is in the sense of being conservative, and even such a lower limit is very useful for our purposes. At any rate, should any pathology affect the relationship between oxygen abundances in stars and planetary nebulae in the Milky Way, we assume that the same effect occurs in all of the DHGs included here. Finally, the trends in planetary nebula production in different galaxies do not appear to seriously affect our results, for our results agree with completely independent evidence concerning the evolution and star formation history of DHGs (Sect. 4.2).

3. Mean stellar oxygen abundances

Spectroscopic observations exist of individual planetary nebulae in all of the galaxies listed in Table 1. To uniformly sample the stellar populations, we restrict our attention to the brightest planetary nebulae in each galaxy, specifically those within 2 mag of the peak of the planetary nebula luminosity function. For these bright planetary nebulae, Table 1 quotes the mean and the standard deviation of $12 + \log(\text{O}/\text{H})$ as well as the number of objects included in these calculations. We adopt these mean oxygen abundances for the bright planetary nebulae as the mean oxygen abundances for the stars. The source of the original spectroscopic data is found in the last column.

It is important to note that the manner in which the mean oxygen abundance was calculated varied from galaxy to galaxy. For the Milky Way, electron temperatures exist for every planetary nebula in the sample save two. Apart from these two exceptions, for which we could only derive lower limits to the oxygen abundance, we were able to determine the actual oxygen abundances and obtain a mean value directly. For M32 and

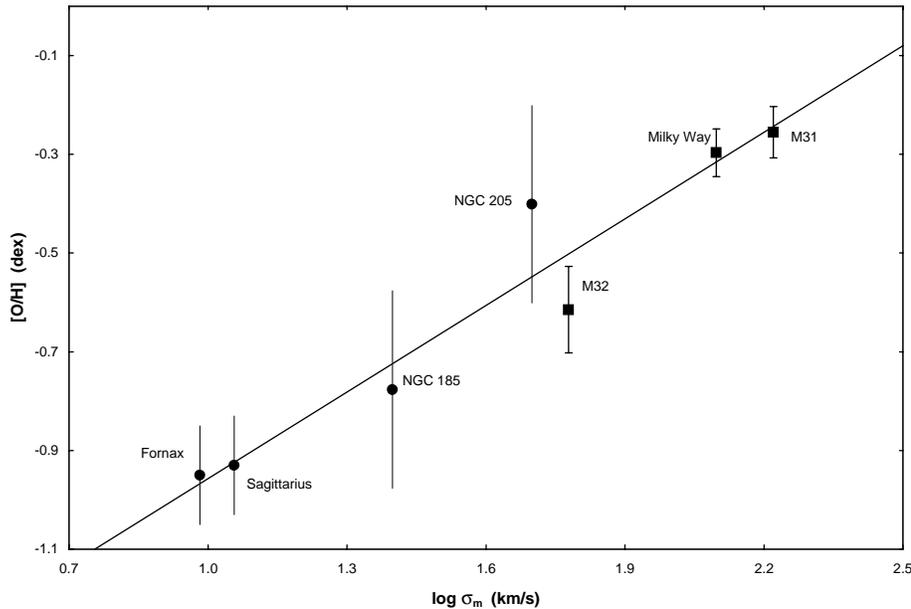


Fig. 1. The oxygen abundances in DHGs are correlated with their mean velocity dispersions. Since the oxygen abundance is a measure of the energy input from type II supernovae and the velocity dispersion is a measure of the gravitational potential, the correlation observed arises naturally if energy input from supernovae is the agent that eventually stops chemical evolution in DHGs. The error bars denote the uncertainty in the mean $[O/H]$: For the dwarf spheroidals, this uncertainty was estimated empirically, but for M32 and the bulges of M31 and the Milky Way the uncertainty is the standard error in the mean.

the bulge of M31, electron temperatures and the corresponding oxygen abundances could be measured for only half of the planetary nebulae (Richer et al. 1998). For the other half, only temperature-based lower limits to the oxygen abundance exist. Thus, the tabulated mean abundances for M32 and the bulge of M31 are lower limits to the true mean values, but are likely within ~ 0.1 dex of their true values (Stasińska et al. 1998; Richer et al. 1998).

For the planetary nebulae in NGC 185 and NGC 205, only empirical lower limits to the oxygen abundances exist (Richer & McCall 1995). We re-calculated the limits because the original calibration did not allow for the large values of $[O\text{ III}]\lambda 5007/H\beta$ observed in planetary nebulae in M31. On average, the recalibrated abundances for the planetary nebulae in NGC 185 and NGC 205 are slightly lower than the previous values. We used these limits for individual planetary nebulae to estimate the mean oxygen abundance for the planetary nebula population following the prescription given in Richer & McCall (1995). Various tests, based upon the planetary nebulae in the bulges of M31 and the Milky Way and in the Magellanic Clouds, indicate that our estimates of the mean oxygen abundances in NGC 185 and NGC 205 should be within ~ 0.2 dex of the actual mean values.

The oxygen abundances for the planetary nebulae in Fornax and Sagittarius are known accurately, but Fornax and Sagittarius have only one and two planetary nebulae, respectively. Had we assumed that the oxygen abundances in their planetary nebulae were equal to those in their stars, we would obtain $[O/Fe]$ ratios of 0.79 dex and 0.47 dex in Fornax and Sagittarius, respectively. Both values, but particularly that for Fornax, are larger than the value of 0.3 to 0.4 dex observed in the Milky Way halo (e.g., Wheeler et al. 1989), which presumably reflects the maximum $[O/Fe]$ ratio attainable (via pure type II supernova enrichment). Therefore, we estimated mean stellar oxygen abundances in Fornax and Sagittarius by subtracting the dispersion in stellar

iron abundances from the mean oxygen abundances found in their planetary nebulae.

For all of the galaxies we consider, save M31, there exist observations of individual stars from which mean iron abundances have been derived. In the bulge of the Milky Way, these results come from medium-resolution spectroscopy, while in the other galaxies they come from photometry. Table 1 lists the mean stellar iron abundances, the dispersion about the mean, and the original data sources for each galaxy (in the last column). Table 1 also lists absolute blue magnitudes, velocity dispersions, and measured values of the M_{g_2} index. For Fornax and Sagittarius, the velocity dispersion samples the entire galaxy out to beyond one effective radius. For the other galaxies, the velocity dispersion samples the stellar motions inside one effective radius, but excluding any cusps due to central mass concentrations, e.g., as seen in M31 and M32. The M_{g_2} index values are typically those for the nuclei. The sources for all of these data are also found in the last column of Table 1.

4. Chemical evolution of DHGs

4.1. The role of the gravitational potential

The mean oxygen abundances attained in M32, and the bulges of M31 and the Milky Way are not high. Even the maximum oxygen abundance observed is only about twice the solar value. Since these values are modest, they require no exotic stellar initial mass function (IMF) for their production; they are easily achievable with a standard Salpeter (1955) IMF (e.g., see Richer et al. 1997 for the case of closed box models).

Intuitively, galaxies with deeper gravitational potential wells should retain supernova ejecta more efficiently than galaxies with shallower potentials, given broadly similar supernova rates. In Fig. 1, we test this idea directly, plotting the mean oxygen abundance as a function of the mean velocity dispersion for the DHGs in Table 1. The correlation in Fig. 1 is remarkably

tight, and suggests that a common mechanism controls chemical evolution in all of the galaxies. Oxygen is a product of type II supernovae, so the oxygen abundance is a measure of the energy input from type II supernovae. The velocity dispersion is related to the depth of the gravitational potential through the virial theorem. Thus, an $[\text{O}/\text{H}] - \sigma_m$ correlation arises naturally if chemical evolution proceeds until the energy input from supernovae has raised the thermal energy of the interstellar medium beyond its gravitational binding energy, instigating the development of a galactic wind (e.g., Larson 1974). Chemical evolution (and star formation) would cease with the loss of the remaining gas.

There is some indication that the dwarf spheroidals define a relation offset from that defined by M32 and the bulges of M31 and the Milky Way. This offset depends strongly upon the positions of M32 and NGC 205, the latter in particular, and to ascertain its reality would require deeper spectroscopy of the planetary nebulae in NGC 205 and NGC 185 to obtain direct estimates of their mean oxygen abundances. Even if the dwarf spheroidals are offset from the other DHGs in Fig. 1, the conclusion that galactic winds terminated chemical evolution in DHGs would remain intact. For example, an offset could arise if there were systematic differences in gas flows prior to initiation of the wind, say, as a result of differences in mass distributions. What matters is that the oxygen abundance and velocity dispersion are correlated within each group.

Fig. 1 implies a tight connection between energy input from type II supernovae and the gravitational potential. However, if energy input from supernovae is responsible for halting chemical evolution, we ought to consider the energy contribution from type Ia supernovae as well. We can use the oxygen and iron abundances for the stars in these galaxies (save M31) to calculate the fraction of the iron contributed by type Ia supernovae. Then, using the oxygen and iron yields of type Ia and II supernovae, we can calculate the fraction of all supernovae that were of type Ia.

We estimate the iron contribution from type Ia supernovae by comparing the $[\text{O}/\text{Fe}]$ ratios in galaxies where type Ia supernovae had, respectively, significant and negligible effects. For galaxies in which type Ia supernovae contributed significantly to the iron abundance, we can express the $[\text{O}/\text{Fe}]$ ratio as

$$\begin{aligned} [\text{O}/\text{Fe}] &= \log(\text{O}/\text{Fe}) - \log(\text{O}/\text{Fe})_{\odot} \\ &= \log\left(\left(\frac{\text{O}}{\text{Fe}}\right)_{II} \frac{1}{(1+f_I)}\right) - \log(\text{O}/\text{Fe})_{\odot} \end{aligned} \quad (1)$$

where $(\text{O}/\text{Fe})_{II}$ is the ratio of the oxygen to iron abundance by number produced by type II supernovae, and $f_I = M(\text{Fe})_I/M(\text{Fe})_{II}$ is the mass of iron contributed by all type Ia supernovae relative to that contributed by all type II supernovae. For galaxies in which only type II supernovae contributed to the iron abundance, the $[\text{O}/\text{Fe}]$ ratio, $[\text{O}/\text{Fe}]_{II}$, is obviously

$$[\text{O}/\text{Fe}]_{II} = \log\left(\frac{\text{O}}{\text{Fe}}\right)_{II} - \log(\text{O}/\text{Fe})_{\odot}. \quad (2)$$

Subtracting Eq. 2 from Eq. 1 yields

$$\Delta[\text{O}/\text{Fe}] = [\text{O}/\text{Fe}] - [\text{O}/\text{Fe}]_{II} = \log \frac{1}{1+f_I}$$

$$\text{or } f_I = 10^{-\Delta[\text{O}/\text{Fe}]} - 1. \quad (3)$$

Finally, the relative number of type Ia and II supernovae is given by

$$\frac{N_{SNI}}{N_{SNII}} = f_I \frac{Y_{SNII}}{Y_{SNI}} \quad (4)$$

where Y_{SNI} and Y_{SNII} are the average masses of iron, in solar masses, produced by individual type Ia and type II supernovae, respectively. We adopt $[\text{O}/\text{Fe}]_{II} = 0.30$ dex, as found for halo stars in the Milky Way (e.g., Wheeler et al. 1989). Within errors, this value coincides with the $[\text{O}/\text{Fe}]$ values observed in the dwarf spheroidal galaxies, so it seems reasonable to assume that type II supernovae completely dominated their iron production. In M32 and the bulge of the Milky Way, Eq. 3 and the oxygen and iron abundances in Table 1 indicate that type Ia supernovae provided 3.6 times as much iron as type II supernovae in M32, and 1.3 times as much iron as type II supernovae in the bulge of the Milky Way.

For type Ia supernovae, we adopt an iron yield of $0.63 M_{\odot}$ (Thielemann et al. 1986). For type II supernovae, we prefer to estimate the typical yield of iron given the predicted yield of oxygen and the $[\text{O}/\text{Fe}]$ ratio observed in halo stars, for the oxygen yields are less model-dependent than the iron yields (cf. Woosley & Weaver 1995 and Thielemann et al. 1996). Convoluting the oxygen yields from Woosley & Weaver (1995; their ‘‘A’’ sequences for $Z = Z_{\odot}$, $0.1 Z_{\odot}$, and $0.01 Z_{\odot}$) with a Salpeter (1955) IMF, we find that a typical type II supernova produces $1.8 M_{\odot}$ of oxygen (we would obtain a similar result using the models of Thielemann et al. 1996). For $[\text{O}/\text{Fe}]_{II} = 0.30$ dex and the solar oxygen and iron abundances (Anders & Grevesse 1989), we deduce that a typical type II supernova produces $0.12 M_{\odot}$ of iron. By Eq. 4, the number of type Ia supernovae per type II supernova was 0.68 in M32, 0.25 in the bulge of the Milky Way, and 0 in the dwarf spheroidals. Thus, the ratio of all supernovae to type II supernovae was 1.68, 1.25, and 1.0 in M32, the bulge of the Milky Way, and the dwarf spheroidals, respectively.

If we assume that type Ia and II supernovae inject comparable quantities of energy into the interstellar medium (e.g., Woosley & Weaver 1986), we can convert the oxygen abundances in Fig. 1 into measures of the total energy injected by all supernovae. To do so, we multiply the oxygen abundances in M32, the bulge of the Milky Way, and the dwarf spheroidals by 1.68, 1.25, and 1.0, respectively. Effectively, these modified oxygen abundances are the oxygen abundances these galaxies would have if all of their supernovae had been of type II.

These modified oxygen abundances, now a measure of the energy injected by all supernovae, are plotted as a function of the mean velocity dispersion in Fig. 2. The oxygen abundance for the bulge of M31 (plotted with a different symbol) was corrected assuming its $[\text{O}/\text{Fe}]$ ratio is identical to that for the Milky Way bulge. The line is a least squares fit to all of the points. Fig. 2 shows that the total energy injected by all supernovae is extremely well correlated with the velocity dispersion. This further supports the contention that energy injection by super-

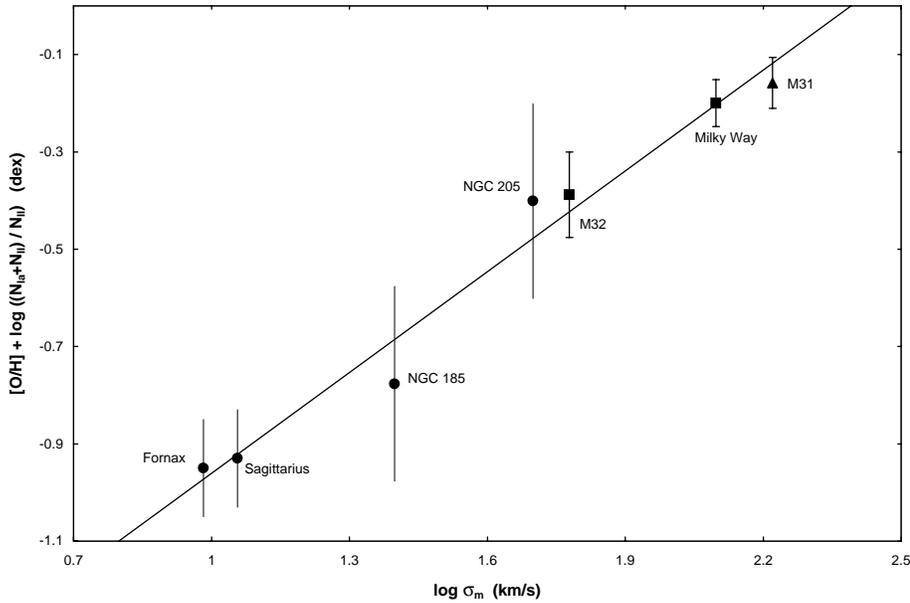


Fig. 2. If we correct the oxygen abundances to account for the energy injected by type Ia supernovae, the correlation with the mean velocity dispersion improves. The required correction is obtained by multiplying the measured oxygen abundances by the ratio of the total number of supernovae to the number of type II supernovae, thereby accounting for the energy input from type Ia supernovae (see text for details). The modified oxygen abundances are proportional to the total energy input from all supernovae per hydrogen atom locked into stars. The excellent correlation strengthens the conclusion that galactic winds terminate chemical evolution in all DHGs. The bulge of M31 is plotted with a different symbol since its [O/Fe] ratio was assumed identical to that for the bulge of the Milky Way. The line is a fit to all of the points. The error bars denote the uncertainty in the mean [O/H] (see Fig. 1).

novae is the mechanism that leads to termination of the chemical evolution of DHGs.

None of the foregoing excludes the formation of DHGs through mergers, but these findings do constrain mergers somewhat. To achieve a correlation between oxygen abundance and velocity dispersion (Fig. 1), the majority of the stars must have been formed either as a result of mergers, or in a potential comparable to that in which they now reside. In other words, mergers would have had to have occurred between systems with much gas or between systems of similar size. None of these arguments prevent minor mergers from occurring up to the present.

4.2. The star formation time scale

The [O/Fe] ratios for the dwarf spheroidals are systematically higher than those for M32 and the bulge of the Milky Way. It is also likely that they are higher than in the bulge of M31, since the bulge of M31 is believed to have a higher nitrogen abundance than the bulge of the Milky Way (Worthey 1996) and nitrogen, like iron, is enriched on long time scales (e.g., Timmes et al. 1995). A related result is Jablonka et al.'s (1996) finding that [Mg/Fe] in bulges correlated with luminosity. Similarly, Jørgensen (1997) found that [Mg/Fe] correlated with velocity dispersion in elliptical and S0 galaxies in clusters. Since both oxygen and magnesium are α -capture elements produced by type II supernovae (formed by successive captures of α -particles on ^{12}C seeds: O, Ne, Mg, Si, S, Ar, Ca, and Ti), these [O/Fe] and [Mg/Fe] ratios have important implications for the formation time scales of bulges and ellipticals.

The time scale for star formation probably has the strongest influence in determining [O/Fe] or [Mg/Fe]. Shortening the period of star formation, flattening the IMF, or selectively losing type Ia supernova ejecta will all increase [O/Fe] or [Mg/Fe] (e.g., Worthey et al. 1992). Shortening the duration of star for-

mation enhances [O/Fe] since there is a fixed time lag before the production of iron from type Ia supernovae. Selective loss of type Ia ejecta enhances [O/Fe] since this iron production is never incorporated into stars. This might occur if forming and previously-formed stars have different spatial distributions, an effect that is more likely to occur if star formation lasts a long time and the star-forming gas settles through dissipation. Flattening the IMF enhances oxygen production by converting a larger fraction of the baryonic mass into the high mass stars that become type II supernovae. Recent studies, however, indicate that the IMF is independent of metallicity, galactic environment, star cluster density, and stellar mass range (e.g., Hill et al. 1994; Massey et al. 1995; Hunter et al. 1997; Chabrier & Mera 1997; Grillmair et al. 1998). So, it is unlikely that the IMF affects [O/Fe] or [Mg/Fe].

The data presented here also favours a constant IMF in the context of supernova-driven winds. Per unit mass of stars formed, a flatter IMF injects more energy and oxygen from type II supernovae into the interstellar medium, but produces fewer long-lived stars. For a flatter IMF, a galaxy will have a lower luminosity and higher [O/Fe] when star formation ceases. This ought to be a sensitive test since both oxygen production and the fraction of long-lived stars depend sensitively upon the IMF slope for slopes near the Salpeter (1955) value (Köppen & Arimoto 1991). Fig. 3 plots the [O/Fe] ratio as a function of absolute blue luminosity for the galaxies in Table 1. Compare M32 and NGC 205. If we attempt to explain the low value of [O/Fe] in M32 as a consequence of a steep IMF, we face a quandary concerning its luminosity. M32 should then have a much higher luminosity than NGC 205, not only on account of its supposedly steeper IMF, but also because it has a slightly deeper gravitational potential, and much more star formation would then have been required to accumulate the necessary energy from supernovae to initiate a galactic wind. Yet, M32 has

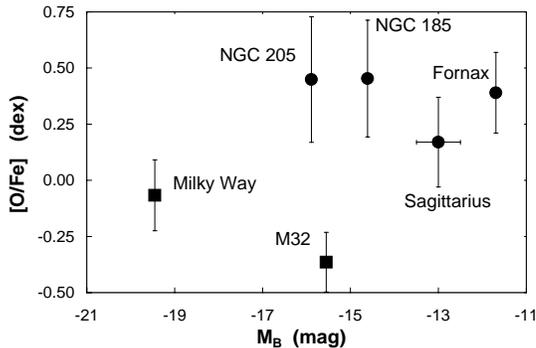


Fig. 3. The relationship between $[O/Fe]$ and luminosity: This is a test of whether the IMF influences the value of $[O/Fe]$. For a flatter IMF, the luminosity is lower and the $[O/Fe]$ ratio is higher when star formation stops. M32 and NGC 205 clearly contradict these expectations: If M32 achieved its low $[O/Fe]$ ratio via a steep IMF, it should have a higher luminosity than NGC 205, for M32 has the deeper gravitational potential. We therefore conclude that the $[O/Fe]$ ratio is set mainly by the time scale for star formation.

the lower luminosity¹. That M32 formed the majority of its stars on a longer time scale and that type Ia supernovae provided the additional energy required to initiate a galactic wind is a far simpler explanation. Henceforth, we shall assume that the star formation time scale governs $[O/Fe]$ or $[Mg/Fe]$.

In Fig. 4, we plot the $[O/Fe]$ ratios for the DHGs in Table 1 as a function of the mean velocity dispersion. In addition, we plot McWilliam & Rich’s (1994) $[Mg/Fe]$ measurement for the Milky Way bulge and the $[Mg/Fe]$ relations found by Jablonka et al. (1996) and Jørgensen (1997). Jablonka et al.’s (1996) relation is shown as a long-dashed line in Fig. 4. We converted from luminosity to velocity dispersion using their measured values of the Mg_2 index and the relation between the Mg_2 index and velocity dispersion from Bender et al. (1993). The relation found by Jørgensen (1997) is shown as a solid line. Since Jørgensen’s (1997) relation was purely differential, we arbitrarily set its zero point so that it matched Jablonka et al.’s (1996) relation at a velocity dispersion of 100 km/s. The dashed horizontal line denotes the solar $[O/Fe]$ and $[Mg/Fe]$ values.

The $[Mg/Fe]$ relations agree well with what limited direct information we have concerning $[Mg/Fe]$ in our DHG sample. Jablonka et al. (1996) did not include the bulge of the Milky Way in their sample, but their prediction for $[Mg/Fe]$ is in excellent accord with McWilliam & Rich’s (1994) $[Mg/Fe]$ measurement. The slope of Jablonka et al.’s (1996) relation is somewhat steeper than the change in $[O/Fe]$ we find between M32 and the bulge of the Milky Way, but easily within the error bars. Jørgensen’s (1997) slope is shallower than Jablonka et al.’s (1996), but otherwise is in excellent agreement with the change in $[O/Fe]$ between M32 and the bulge of the Milky Way. The behaviour of $[Mg/Fe]$ and $[O/Fe]$ with velocity dispersion indicates that the fraction of the metallicity contributed by α -elements increases

¹ One might argue that M32 has a low luminosity on account of tidal stripping by M31, but its structural parameters are perfectly typical for an elliptical of its luminosity (Kormendy 1985; Bender et al. 1993).

with increasing galaxy mass. Given our earlier arguments, this result implies a shorter time scale for star formation in more massive ellipticals and bulges, supporting the spectral synthesis conclusion that more massive ellipticals are simpler than lower mass ellipticals from the perspective of their star formation history (e.g., Worthey 1996).

If a relation between $[Mg/Fe]$ and velocity dispersion holds for bulges and ellipticals, it implies an underlying relation between the star formation time scale and the gravitational potential. The data, however, imply that the time scale varies in a manner opposite to that predicted in the classical model of galactic winds (Larson 1974), wherein winds are initiated earliest in the lowest mass galaxies. Matteucci (1994) and Tantaló et al. (1996), among others, have successfully modelled such “inverse” winds by postulating an increasing efficiency of star formation in more massive systems. One advantage of a longer time scale for star formation in lower luminosity DHGs is that it would allow greater dissipation of the baryonic matter, which might explain their higher central stellar densities.

Dwarf spheroidals clearly deviate from the $[O/Fe]$ trend established by bulges and ellipticals. Despite their low luminosities and velocity dispersions, their $[O/Fe]$ ratios indicate that they formed the majority of their stars on a short time scale, consistent with enrichment from type II supernovae only, regardless of luminosity. Nevertheless, dwarf spheroidals did undergo chemical evolution, forming multiple generations of stars, for more massive systems have higher oxygen abundances. Dwarf spheroidals do fit the Larson (1974) picture in the sense that a galactic wind was initiated very early in the evolution of these low mass galaxies. However, within this galaxy class, we cannot tell whether galactic winds were initiated later in more massive systems, because they have uniformly high $[O/Fe]$ ratios.

4.3. The abundance-luminosity relation

We now turn our attention to the relationship between oxygen abundances and luminosities in DHGs. Fig. 5 compares the oxygen abundances for the galaxies in Table 1 with oxygen abundances in dwarf irregular galaxies (Richer & McCall 1995). The oxygen abundances for the DHGs are the mean values for their stars. In contrast, the oxygen abundances for the dwarf irregulars are those for H II regions, and therefore represent the oxygen abundances in the interstellar medium, the highest abundance found in the stellar component, not the mean. To the extent that dwarf irregulars share a common star formation history, in a statistical sense at least, the correction to mean stellar abundance would shift the $[O/H]-M_B$ relation shown to lower abundances.

Fig. 5 demonstrates that all DHGs share a common relationship between luminosity and oxygen abundance. Statistically, the relationships for dwarf spheroidals and other DHGs do not differ in either zero point or slope. One immediate implication is that the history of star formation, and its time scale in particular, has no bearing upon the oxygen abundance that is attained in DHGs. This suggests that the energy reservoir responsible for generating the galactic wind must store the energy input from supernovae rather efficiently.

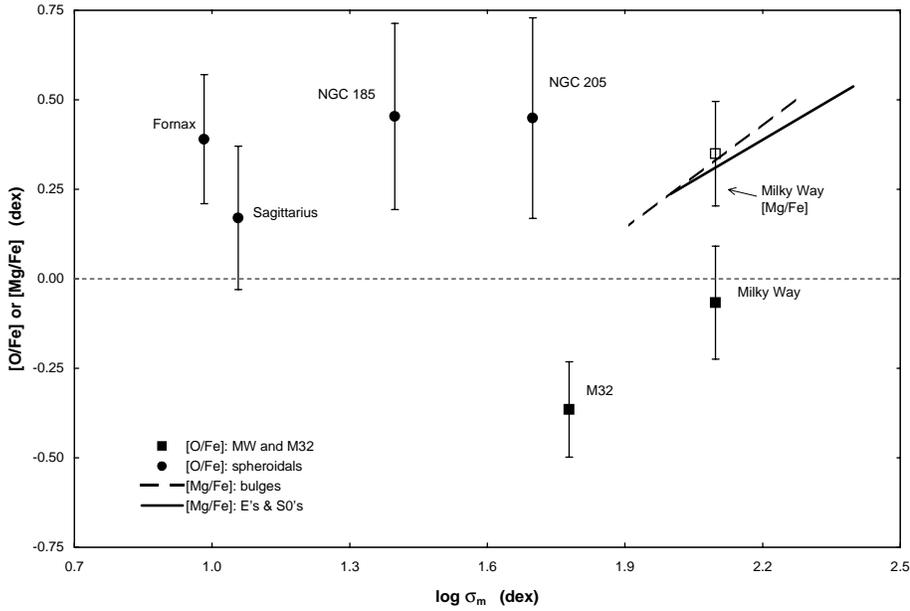


Fig. 4. $[O/Fe]$ and $[Mg/Fe]$ in DHGs: The $[O/Fe]$ ratios derived from Table 1 for the DHGs in our sample are plotted along with $[Mg/Fe]$ relations for bulges and for elliptical and S0 galaxies (Jablonka et al. 1996; Jørgensen 1997). The zero point for the relation for ellipticals and S0's was undefined, so this relation has been arbitrarily adjusted to match that for bulges at a velocity dispersion of 100 km/s. The horizontal line denotes the solar $[O/Fe]$ and $[Mg/Fe]$ ratios. The mean $[Mg/Fe]$ ratio and $\pm 1\sigma$ dispersion observed in the bulge of the Milky Way are shown for comparison (McWilliam & Rich 1994). The error bars for the $[O/Fe]$ values account for the uncertainties in both $[O/H]$ and $[Fe/H]$. Although the $[O/Fe]$ ratios for M32 and the bulge of the Milky Way track the $[Mg/Fe]$ relations, the $[O/Fe]$ ratios for the dwarf spheroidals do not, and are instead consistent with the value expected for enrichment purely from type II supernovae. A correlation of either $[O/Fe]$ or $[Mg/Fe]$ with velocity dispersion implies that the gravitational potential fixes the time scale for star formation. The $[Mg/Fe]$ relations and the oxygen abundances in M32 and the bulge of the Milky Way require that the star formation time scale be shorter in more massive ellipticals and bulges.

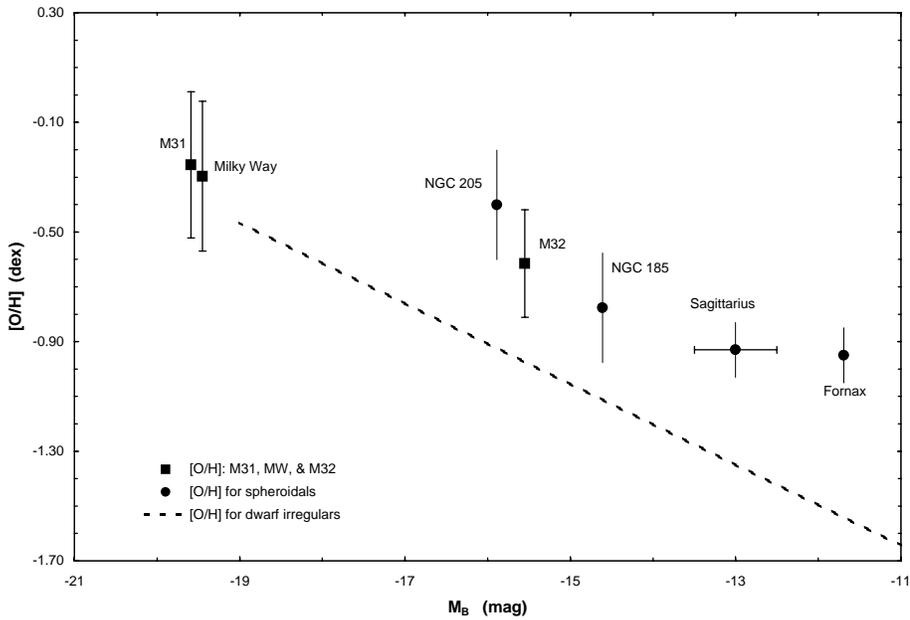


Fig. 5. Oxygen abundance-luminosity relations for galaxies: Oxygen abundances in DHGs are compared with those in dwarf irregular galaxies (Richer & McCall 1995). The luminosities are compared through absolute blue magnitudes. For M32 and the bulges of M31 and the Milky Way, the error bars on the oxygen abundances denote the standard deviations of the abundance distributions. For the dwarf spheroidals, the error bars denote the uncertainty in the mean oxygen abundance. We assume a 0.5 mag uncertainty for the luminosity of Sagittarius, since it is derived rather than measured (Ibata et al. 1997). Note that the oxygen abundance-luminosity relation for DHGs pertains to the mean abundance for the stars, whereas that for the dwarf irregulars pertains to the interstellar medium, i.e., the maximum abundance for the stars. Somewhat surprisingly, all DHGs, even dwarf spheroidals, follow a single $[O/H]$ - M_B relation.

The common $[O/H]$ - M_B relation followed by all DHGs is unexpected. As is well-known, the luminosities of DHGs depend upon both the surface brightness and the size of the system (e.g., Bender et al. 1992), so a “second parameter” is apparently missing from Fig. 5. However, in the supernova-driven

winds scenario, the forces that govern the chemical evolution also govern the luminosity that is attained. Chemical evolution ceases when a galactic wind is initiated. The luminosity in long-lived stars is also determined at this point, for no further star formation may occur. In this case, the luminosity and oxygen

abundance are functions of the same fundamental parameters: the energy injection, the total mass, and the mass distribution. Consequently, a “second parameter” may not be necessary in the $[O/H]-M_B$ relation.

This need not imply that all DHGs follow the same chemical evolution. In forming a given luminosity of long-lived stars, a fixed mass of oxygen is injected into the interstellar medium (supposing the IMF is constant). Injecting a particular mass of oxygen need not yield a unique oxygen abundance, for the oxygen abundance depends upon the mass of gas into which the oxygen is injected and upon the importance of gas flows while star formation takes place. It is easy to imagine that the importance of gas flows and the ease with which they can be driven depends upon the shape or gradient of the potential. Thus, gas flows and gas consumption could easily have had different relative importances to the evolution of different classes of DHGs, if their mass distributions were different. Consequently, dwarf spheroidals and ellipticals of similar luminosity need not convert the same fraction of their original matter into stars, yet may nevertheless attain similar oxygen abundances.

5. Calibration of the Mg_2 index for ellipticals/bulges

We can use the oxygen abundances in Table 1 to make an observational calibration of the Mg_2 index. There are several reasons why a calibration in terms of oxygen abundance is reasonable. Salaris et al. (1993) found that the total metal content and the combined abundance of C, N, O, and Ne had similar effects upon the locations in the HR diagram of the main sequence and the main sequence turn-off. Worthey (1994) has shown that main sequence and main sequence turn-off stars are significant contributors to the light in the blue and visual parts of the spectrum of old stellar systems (contributing $> 45\%$ of the light). Since the abundances of α -elements scale with the abundance of oxygen and account for approximately 70% of the total metallicity in the sun, it is reasonable to expect the oxygen abundance and the Mg_2 index to vary together.

Recently, Grillmair et al. (1996) determined a mean age of 8.5 Gyr for the stars in a field near the centre of M32. Although no comparable study of stars in the inner bulge of M31 or the Milky Way exists, we can use the recent globular cluster age re-calibration based upon Hipparcos data (Reid 1997) to set an upper limit of 13 Gyr on the age of their stars. Concerning the Mg_2 index values, Table 1 provides nuclear values for M32 and the bulges of M31 and the Milky Way. Since we are not using nuclear velocity dispersions (Sect. 3), we chose to compute the Mg_2 index values appropriate to our adopted velocity dispersions using the $Mg_2 - \sigma$ relation from Bender et al. (1993).

Based upon a multiple least-squares fit to the data, the predicted Mg_2 index values vary with the oxygen abundance and age according to

$$\log Mg_2 = (0.331 \pm 0.050)([O/H] + \log Age) + (-0.857 \pm 0.037) \pm 0.022 \text{ dex.} \quad (5)$$

If the sensitivity of $[O/H]$ is forced to be 1.68 times greater than the sensitivity to age, as suggested by the studies of Worthey

(1994) and Casuso et al. (1996), then

$$\log Mg_2 = (0.228 \pm 0.041)(1.68[O/H] + \log Age) + (-0.730 \pm 0.024) \pm 0.026 \text{ dex.} \quad (6)$$

In Eqs. 5 and 6, Mg_2 is the Mg_2 index measured in magnitudes, $[O/H]$ is the logarithmic oxygen abundance relative to solar (from Table 1), and Age is the mean stellar age measured in Gyr. The quoted uncertainties are the standard errors of the fits. The relative age-oxygen abundance sensitivity adopted in Eq. 6 should be valid provided the fraction of the total metallicity represented by oxygen does not depart too significantly from the solar value.

6. Conclusions

We have used the oxygen abundances in the planetary nebulae in M32, the bulges of M31 and the Milky Way, and the dwarf spheroidals NGC 205, NGC 185, Sagittarius, and Fornax to derive mean oxygen abundances for their stars. The mean stellar oxygen abundances are found to be modest, and would be easily attainable in simple models of galactic evolution. Combining the oxygen abundances with the best estimates of the mean stellar ages, we have calibrated the Mg_2 index as a function of age and oxygen abundance.

The oxygen abundances in DHGs paint a very interesting picture of chemical evolution. Our principal result is that the oxygen abundances in all DHGs correlate with their velocity dispersions. Since the oxygen abundance is a measure of the energy input from type II supernovae and the velocity dispersion is a measure of the gravitational potential, a correlation between the two implies a correlation between the energy input from supernovae and the gravitational potential energy of the interstellar medium. The correlation improves if we account for the energy input from type Ia supernovae. A connection between energy input and the gravitational potential arises naturally if a galactic wind is the instrument that terminates chemical evolution.

The $[O/Fe]$ ratios we derive from our oxygen abundances for M32 and the bulge of the Milky Way concur with previous evidence from metallicity indicator studies that the $[\alpha\text{-element}/Fe]$ ratio increases with increasing luminosity for bulges and ellipticals (Worthey et al. 1992; Jablonka et al. 1996; Jørgensen 1997). Thus, the gravitational potential not only determines the metallicity that is attained, but also fixes the star formation time scale. The sense of these $[\alpha\text{-element}/Fe]$ trends is such that more massive galaxies develop galactic winds sooner than less massive galaxies, contrary to the classical picture of galactic winds (Larson 1974). Dwarf spheroidals do not participate in this trend, and instead have $[O/Fe]$ ratios indicative of uniformly short time scales for star formation, regardless of luminosity.

Finally, we find that all DHGs follow a single relationship between oxygen abundance and luminosity. We argue that this relation arises because both oxygen abundance and luminosity are set by the interaction between star formation and the gravitational potential. This is a fundamental consequence of the

supernova-driven winds model of galaxy evolution. In forming a given mass of stars, all DHGs achieve similar oxygen abundances, but they need not follow the same chemical evolution. The systematically larger [O/Fe] ratios observed in dwarf spheroidals indicate that the history of star formation in a DHG does not affect the mean stellar oxygen abundance it attains.

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