THE ASTROPHYSICAL JOURNAL, 347:875–882, 1989 December 15

OXYGEN ABUNDANCES IN NEARBY DWARF IRREGULAR GALAXIES

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Received 1988 September 22; accepted 1989 June 19

ABSTRACT

Oxygen abundances are obtained by optical spectrophotometry of H II regions in seven nearby dwarf irregular galaxies. All of these yield oxygen abundances of less than 1/10 of the solar value, and most are in the range of 3%–5% of the solar value. This suggests that observations of nearby dwarf galaxies may provide an effective means for studying the chemical evolution of low-mass galaxies and, possibly, the primordial helium abundance. In one case, a planetary nebula (PN) was discovered. A strong correlation is found between the oxygen abundances and absolute magnitudes for nearby irregular galaxies. This correlation will be useful for estimating abundances of irregular galaxies without observable H II regions, and possibly as a distance indicator for irregular galaxies with known abundances. It is inferred from this relationship that infall is no more important in irregular galaxies with extremely large H I halos than in typical irregular galaxies. Dwarf ellipticals closely adhere to the abundance-luminosity relationship defined by irregulars. The similar abundance-luminosity relationships may be taken as support of the popular theory that dwarf ellipticals are formed by stripping the gaseous component of dwarf irregular galaxies.

Subject headings: galaxies: abundances — nebulae: H II regions — nebulae: planetary

I. INTRODUCTION

The average chemical abundance in irregular galaxies is known to be lower than that found in typical spiral galaxies (Pagel and Edmunds 1981). For this reason, H II regions in irregular galaxies have been chosen for studies requiring low abundance environments. Two examples are the study of the primordial helium abundance and the evolution of relative chemical abundances. For both of these studies, the most interesting candidates are those galaxies showing the lowest abundances. Thus, methods to select regions of extremely low abundance are important. In the past, searches for low abundance regions gathered candidates from objective prism surveys (e.g., Kunth, Sargent, and Kowal 1981), selecting out regions with large $\lambda5007/\lambda4861$ emission-line ratios (usually blue compact galaxies). Campbell, Terlevich, Melnick (1986) have pointed out that very metal poor objects will be less easily identified in objective prism surveys because the oxygen lines $\lambda\lambda4959$, 5007 become weaker relative to Hβ as the oxygen abundance decreases below ~10% of the solar value.

An alternate strategy for identifying very low abundance regions is to study H II regions in nearby low-mass dwarf irregular galaxies. Lequeux *et al.* (1979), Talent (1980), and Kinman and Davidson (1981) all arrived at the conclusion that the chemical abundance scales with total galaxian mass for irregular galaxies. While the work of Hunter, Gallagher, and Rautenkrantz (1982) cast some doubt on this conclusion, recent work by Skillman *et al.* (1988*a*) has corroborated this relationship. This paper presents a search for low abundance regions based on this premise. The present search therefore represents an alternative method of searching for low abundance regions. We have chosen to obtain spectra of H II regions in nearby, low-mass irregular galaxies discovered via Hα imaging. The intention is to find new regions of extremely low abundance for the types of studies cited above.

Observing nearby dwarf irregulars for this purpose offers several secondary advantages as well. Since a relatively complete sample of galaxies can be surveyed, the compositions of the local dwarfs may be more representative of the chemical evolution of low-mass galaxies, i.e., free from the possible effects of self-enrichment from abnormal star formation histories which may influence abundance surveys based on the relatively rare starbursting dwarf emission-line galaxies. Another benefit of this study is the measurement of abundances for galaxies near enough that stellar population studies have been conducted (see Hoessel and Anderson 1986, and references therein). An advantage of studying nearby galaxies is that these galaxies are more promising for accurate mass determinations via H I synthesis mapping. This sample is useful for studying relationships between abundance and galaxian mass, fractional H I mass, and mass surface density.

II. OBSERVATIONS AND DATA REDUCTION

Candidate H II regions were selected from an Hα survey of dwarf irregular galaxies (Hodge and Kennicutt 1989). Observations were conducted during the four nights, 1987 March 26–29, with the NOAO 2.1 m reflector on Kitt Peak, using the IIDS spectrometer. Further observational parameters are listed in Table 1. The first two nights of observations consisted of a "survey" where we observed one or more H II regions in

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TABLE 1

TELESCOPE PARAMETERS

Telescope	Instrument	Aperture	Resolution (Å)	Wavelength coverage (Å)
KPNO 2.1 m .	IIDS	6″ circular	8.0	3500–5300
			9.5	4650–6850
			3.0	4050–4700
INT 2.5 m	IPCS	2″ long-slit	2.2	3400–5400

each galaxy with a spectral range of 3600–5100 Å. With these spectra it is possible to judge the total oxygen abundance (from the strengths of the [O II] and [O III] lines relative to Hβ), and to estimate the excitation of the nebula (from the λ3727/λ5007 ratio).

In each galaxy where more than one region was observed, we were searching for the region with the highest excitation. Higher excitation nebulae are preferable for oxygen abundance studies because more of the oxygen is in the O^{++} ionization state. This has two advantages, the first being that the temperature in the O^{++} zone can be determined directly. The second is that the O^{+} abundance is very sensitive to errors in the reddening correction, because of the short wavelength of the [O II] λ3727 line.

Two following nights were dedicated to obtaining additional spectra for the best candidates in each galaxy. These consisted of red spectra covering the wavelength range from 4650 to 6850 Å (which provided Hα/Hβ ratios necessary for accurate reddening estimates), and a higher resolution blue spectrum from 4050 to 4700 Å (which provided accurate [O III] λ4363 measurements necessary for accurate electron temperature estimates). In addition, an observation of an H II region in Sextans A was made with the IPCS detector on the 2.5 m Isaac Newton Telescope of the Roque de los Muchachos Observatory in the Canary Islands in 1986 December.

Each night, two or more of the Kitt Peak IIDS/IRS standard stars were observed. On some of the nights, the observations were affected by the presence of cirrus clouds or poor seeing ($>2''$), so that reliable absolute spectrophotometry was not possible. However, since the main goal of this program is relative line strength ratios, this is acceptable.

The observed line ratios, corrected for reddening, are shown in Table 2. The reddening was determined assuming the intrinsic Balmer-line ratios calculated by Brocklehurst (1971), corrected for an assumed stellar absorption of 2 Å EW in each line (see Shields and Searle 1978; Skillman 1985). In some of the blue spectra, the signal-to-noise ratio in the Hγ line was insufficient to determine a reddening, and in these cases no reddening was assumed. Since these are low abundance systems, the assumption of zero reddening is reasonable for objects at high-Galactic latitudes. The Galactic reddening law of Whitford (1958) was used.

III. CHEMICAL ABUNDANCE DETERMINATIONS

For those objects where an [O III] λ4363 line was measured, an electron temperature for the O^{++} zone could be derived using the (λ5007 + λ4959)/λ4363 ratio (Seaton 1975; Aller 1984). The electron temperature in the O^{+} zone was estimated from the relationship discussed by Campbell, Terlevich, and Melnick (1986),

$$T_e(O^+) = T_e(O^{++}) - 0.3[T_e(O^{++}) - 1.0] , \qquad (1)$$

where T_e is the electron temperature in units of 10^4 K. By assuming an electron density of 100 cm^{-3}, it is then possible to derive a total oxygen abundance $\equiv O/H = O^{++}/H^{+} + O^{+}/$

TABLE 2

INDIVIDUAL SPECTRA AND DERIVED PROPERTIES

A. SEXTANS A

Region Number	Number 1 (Blue)	Number 1 (Red)	Number 1 (High)	Number 2 (Blue)	Number 3 (Blue)	Number 4 (Blue)
3727 [O II]	2.04 ± 0.10	...	1.61 ± 0.08	2.74 ± 0.22	1.64 ± 0.17	3.77 ± 0.21
3868 [Ne III]	0.18 ± 0.03	...	0.24 ± 0.06	...	...	...
4101 Hδ	0.25 ± 0.05	...	0.24 ± 0.04	0.34 ± 0.21	0.25 ± 0.13	0.40 ± 0.08
4340 Hγ	0.46 ± 0.03	...	0.47 ± 0.03	0.66 ± 0.19	0.35 ± 0.07	0.43 ± 0.08
4363 [O III]	0.08 ± 0.03	...	0.05 ± 0.03	...	...	...
4861 Hβ	1.00 ± 0.05	1.00 ± 0.05	1.00 ± 0.05	1.00 ± 0.17	1.00 ± 0.09	1.00 ± 0.25
4959 [O III]	0.78 ± 0.04	0.80 ± 0.04	0.81 ± 0.04	0.57 ± 0.17	0.60 ± 0.09	0.22 ± 0.25
5007 [O III]	2.40 ± 0.12	2.45 ± 0.12	2.44 ± 0.12	1.22 ± 0.17	1.92 ± 0.10	0.44 ± 0.25
5876 He I	...	0.13 ± 0.02	...	...	...	...
6563 Hα	...	2.71 ± 0.14	...	...	...	...
c(Hβ)	0.3	0.1	0.3	0.0	0.0	0.0
F(Hβ)(10^{15})	6.8	8.1	4.1	2.2	7.2	5.1
EW(Hβ)Å	41	43	53	67	70	88
T(O III)(10^4 K)	2.02 ± 0.47	...	1.55 ± 0.45	...	...	...
(O III + O II)/Hβ	5.2 ± 0.2	...	4.9 ± 0.1	4.5 ± 0.3	4.2 ± 0.2	4.4 ± 0.4
$O^+/H(10^5)$	1.1	...	1.7	...	...	...
$O^{++}/H(10^5)$	1.3	...	2.1	...	...	...
$O/H(10^5)$	2.5 ± 2.0	...	3.8 ± 3.0	...	...	...
$(O/H)_{emp}$ (10^5)	3.2 ± 0.1	...	3.0 ± 0.1	2.7 ± 0.2	2.5 ± 0.2	2.6 ± 0.3

TABLE 2

B. SEXTANS B

Region Number	Number 1 (Blue)	Number 2 (Blue)	Number 2 (High)	Number 3 (Blue)	Number 4 (Blue)
3727 [O II]	3.10 ± 0.16	2.36 ± 0.15	...	3.70 ± 0.27	2.94 ± 0.18
3868 [Ne III]	...	0.19 ± 0.09	...	...	...
4101 Hδ	0.33 ± 0.05	0.34 ± 0.08	0.29 ± 0.02	0.26 ± 0.08	0.17 ± 0.14
4340 Hγ	0.41 ± 0.07	0.53 ± 0.07	0.47 ± 0.02	0.52 ± 0.12	0.49 ± 0.09
4363 [O III]	...	...	<0.06	...	...
4861 Hβ	1.00 ± 0.06	1.00 ± 0.06	...	1.00 ± 0.12	1.00 ± 0.09
4959 [O III]	0.63 ± 0.06	0.74 ± 0.06	...	0.27 ± 0.12	0.41 ± 0.09
5007 [O III]	1.71 ± 0.09	2.58 ± 0.13	...	0.77 ± 0.12	1.30 ± 0.09
$c(H\beta)$	0.0	0.0	0.0	0.0	0.0
$F(H\beta)(10^{15})$	7.4	5.8	7.6	5.1	4.6
EW(Hβ) Å	51	90	...	61	47
T(O III)(10^4 K)	...	...	<1.79	...	...
(O III + O II)/Hβ	5.4 ± 0.2	5.7 ± 0.2	...	4.7 ± 0.3	4.7 ± 0.2
O^+/H (10^5)	...	≥ 1.8	...	...	...
O^{++}/H (10^5)	...	≥ 1.8	...	...	...
O/H (10^5)	...	≥ 3.6	...	...	...
$(O/H)_{emp}$ (10^5)	3.4 ± 0.1	3.6 ± 0.1	...	2.8 ± 0.3	2.8 ± 0.2

TABLE 2

C. DDO 47

Region Number	Number 1 (Blue)	Number 1 (High)	Number 2 (Blue)	Number 3 (Blue)
3727 [O II]	0.99 ± 0.05	...	4.57 ± 0.35	2.20 ± 0.43
3868 [Ne III]	0.52 ± 0.05	...	...	...
4101 Hδ	0.24 ± 0.04	0.26 ± 0.07	0.11 ± 0.19	...
4340 Hγ	0.50 ± 0.04	0.47 ± 0.04	0.63 ± 0.18	0.71 ± 0.21
4363 [O III]	0.12 ± 0.04	0.12 ± 0.04	...	...
4861 Hβ	1.00 ± 0.05	...	1.00 ± 0.17	1.00 ± 0.33
4959 [O III]	2.00 ± 0.10	...	0.59 ± 0.17	1.29 ± 0.33
5007 [O III]	6.31 ± 0.32	...	2.01 ± 0.17	4.14 ± 0.33
$c(H\beta)$	0.0	0.0	0.0	0.0
$F(H\beta)(10^{15})$	3.8	...	2.3	1.6
EW(Hβ) Å	95	...	60	109
T(O III)(10^4 K)	1.51 ± 0.24	...	...	...
(O III + O II)/Hβ	9.3 ± 0.3	...	7.2 ± 0.4	7.6 ± 0.6
$O^+/H(10^5)$	1.2	...	...	...
$O^{++}/H(10^5)$	6.7	...	...	...
$O/H(10^5)$	7.8 ± 3.4	...	...	...
$(O/H)_{emp}(10^5)$	6.5 ± 0.3	...	4.8 ± 0.3	5.1 ± 0.5

H^+. Ionic abundances were calculated using the most recent atomic data available in the literature (Mendoza 1983). In the case of Leo A, He^{++} λ4686 was detected. This object is probably a planetary nebula (see § IV). In this case, the abundance of O^{+3}/H^+ was estimated from the ratio of He^{++}/He^+ (as determined from the λ4686/λ4471 ratio), assuming $O^{+3}/O^{++} \equiv He^{++}/He^+$. Errors for the total oxygen abundances were based on the uncertainty in the estimated electron temperature (in essence, the uncertainty in the λ4363 measurement).

Given the faintness of many of the objects observed, it was not possible to measure λ4363 in all cases. In the absence of a λ4363 measurement it is possible to estimate the total oxygen abundance, $(O/H)_{emp}$, from the (λ5007 + λ4959 + λ3727)/λ4861 ratio (Pagel *et al.* 1979; Edmunds and Pagel 1984). This empirical relationship has been discussed for the case of very low abundance objects by Skillman (1988) and we use here the calibration proposed therein. The calculated ionic, total, and empirical total oxygen abundances are listed in Table 2. The errors quoted for the empirical abundances reflect only the error resulting from the line-strength measurements. The empirical method for low abundance objects has an intrinsic error of ≈50% (Skillman 1988). Note that for all galaxies where a λ4363 measurement was obtained, there is quite good agreement between the measured oxygen abundance and the empirically determined oxygen abundance.

One outstanding question concerning abundances in dwarf galaxies is the variation of abundance within a galaxy. Since star formation in dwarf irregulars is thought to be episodic, and the solid-body nature of the rotation inhibits efficient mixing, it seems plausible that there might be large variations in abundance from region to region. However, the three irregular galaxies for which this has been investigated (SMC, LMC, Pagel *et al.* 1978; NGC 6822, Pagel, Edmunds, and Smith 1980) indicate that the dispersion in oxygen abundance is generally quite small (≈25%). This conclusion is supported by the

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TABLE 2

D. DDO 167

Region Number	Number 1 (Blue)	Number 1 (High)	Number 1 (Red)	Number 2 (Blue)
3727 [O II]	2.08 ± 0.11	...	...	2.81 ± 0.54
3868 [Ne III]	0.33 ± 0.12	...	...	...
4101 Hδ	0.24 ± 0.04	0.34 ± 0.02	...	...
4340 Hγ	0.48 ± 0.03	0.47 ± 0.03	...	0.47 ± 0.16
4363 [O III]	...	0.07 ± 0.03	...	...
4471 He I	0.11 ± 0.03	0.09 ± 0.03	...	...
4861 Hβ	1.00 ± 0.05	...	1.00 ± 0.08	1.00 ± 0.15
4959 [O III]	1.01 ± 0.05	...	0.98 ± 0.09	0.27 ± 0.15
5007 [O III]	3.14 ± 0.16	...	3.25 ± 0.16	0.62 ± 0.15
6563 Hα	...	...	2.90 ± 0.14	...
c(Hβ)	0.0	0.0	0.0	0.0
F(Hβ)(10^{15})	3.0	...	2.6	1.9
EW(Hβ) Å	64	...	57	32
T(O III)(10^4 K)	...	1.64 ± 0.36	...	...
(O III + O II)/Hβ	6.2 ± 0.2	...	...	3.7 ± 0.6
O$^+$/H (10^5)	1.9	...	...	...
O^{++}/H (10^5)	2.7	...	...	...
O/H (10^5)	4.6 ± 2.9	...	...	...
(O/H)$_{\rm emp}$ (10^5)	4.0 ± 0.2	...	...	2.1 ± 0.4

TABLE 2

E. LEO A, DDO 53, AND DDO 187

Region Number	Number 1 (Blue)	Number 1 (Red)	Number 1 (High)	Number 1 (Blue)	Number 1 (Blue)
3727 [O II]	...	...	...	3.72 ± 0.19	1.64 ± 0.57
3868 [Ne III]	...	...	...	0.31 ± 0.14	...
4101 Hδ	...	...	0.24 ± 0.05	0.25 ± 0.09	...
4340 Hγ	0.49 ± 0.10	...	0.47 ± 0.03	0.47 ± 0.10	...
4363 [O III]	...	...	0.11 ± 0.03	...	...
4471 He I	...	...	0.09 ± 0.05	...	...
4686 He II	...	...	0.19 ± 0.03	...	...
4861 Hβ	1.00 ± 0.15	1.00 ± 0.12	...	1.00 ± 0.06	1.00 ± 0.23
4959 [O III]	1.16 ± 0.15	1.14 ± 0.10	...	0.73 ± 0.05	0.75 ± 0.23
5007 [O III]	3.19 ± 0.16	3.24 ± 0.16	...	2.08 ± 0.10	1.63 ± 0.23
6563 Hα	...	2.29 ± 0.20	...	...	...
c(Hβ)	0.0	0.0	0.0	0.5	0.0
F(Hβ)(10^{15})	1.7	2.4	...	6.0	1.0
EW(Hβ) Å	...	...	...	148	22
T(O III)(10^4 K)	...	...	2.08 ± 0.36	...	...
(O III + O II)/Hβ	4.4 ± 0.3	...	...	6.5 ± 0.2	4.0 ± 0.7
O$^+$/H (10^5)	0.0	...	...	...	...
O^{++}/H (10^5)	1.7	...	...	...	...
O^{+++}/H (10^5)	0.2	...	...	...	...
O/H (10^5)	1.9 ± 0.7	...	...	...	...
(O/H)$_{\rm emp}$ (10^5)	2.6 ± 0.3	...	...	4.2 ± 0.2	2.3 ± 0.6

present observations of Sextans A, Sextans B, and DDO 47, where the derived abundances for the separate H II regions in each galaxy agree within the intrinsic error of the empirical method.

We note here the success of our method of searching for low abundance regions. Of the seven galaxies observed, all turned out to have oxygen abundances of less than 1/10 of the solar value, and three of the seven are within a factor of 2 of the lowest oxygen abundance ever detected in an extragalactic H II region (I Zw 18: Searle and Sargent 1972; Davidson and Kinman 1985). Obviously, parent galaxy luminosity should be used as a criterion for all searches for very low abundance H II regions.

IV. A PLANETARY NEBULA IN LEO A

The H II region observed in Leo A shows many characteristics of a PN. It is compact, with a high excitation spectrum (relatively strong He II λ4686 and no detectable [O II] λ3727), and shows no detectable continuum emission.

A concern is its anomalous Hα/Hβ ratio, (2.3). A reinspection of our data show no evidence of any unusual problem with the observation of the data reduction, but since blind offsets

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were required to observe the object, we cannot rule out an error which is due to miscentering of the object in the aperture combined with atmospheric dispersion. One possible physical cause for an anomalously low Hα/Hβ ratio might be scattering of the nebular radiation off dust near the PN, but we withhold further interpretation until our observation can be checked.

The oxygen abundance derived for the PN in Leo A has been discussed in the previous section. Since this abundance is based on the λ4363/λ4340, λ5007/λ4861, and λ4686/λ4471 ratios, it is very insensitive to errors in the reddening. Thus, the anomalous Hα/Hβ ratio is not of great concern regarding the derived oxygen abundance.

One might ask whether it is appropriate to compare the oxygen abundance derived from a PN with that derived for H II regions. In his review of PN in the Local Group, Ford (1983) notes that abundances have been measured in PN in three Local Group irregular galaxies: the LMC (Aller 1983); the SMC (Aller *et al.* 1981); NGC 6822 (Dufour and Talent 1980). In all three cases the mean oxygen abundance of the H II regions is approximately equal to the mean oxygen abundance of the PN. Although the oxygen abundance measured in the Leo A PN is about a factor of 6 times lower than those of the SMC and NGC 6822 PN, we take as a reasonable assumption that the oxygen abundance in the Leo A PN is comparable to the oxygen abundance in the interstellar medium (ISM) of Leo A.

Based on the observation of Ford and Jenner (1979) that the brightest PN in Local Group galaxies exhibit a small dispersion in their [O III] λ5007 luminosities, Jacoby and Lesser (1981) suggest using the λ5007 fluxes of PN as an estimator of an upper limit of the distance for nearby dwarf galaxies. From an [O III] λ5007 flux of $6.6 \pm 1 \times 10^{-15}$ ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for the Leo A PN, and using a standard flux of 1.98×10^{-14} ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ at 1 Mpc (Ciardullo *et al.* 1989), one derives a distance upper limit of 1.7 ± 0.5 Mpc. This is in good agreement with the distances derived by Sandage (1986*b*) of 1.6 Mpc from observations of the brightest stars, and de Vaucouleurs (1975) of 1.1 Mpc. Jacoby and Lesser (1981) observed two PN in Leo A, both of which were fainter than the PN discovered here. This new low abundance PN, which appears to be at the maximum of the PN luminosity function, would be of interest for a spectroscopic follow-up study. Unfortunately, the high excitation of the nebula renders detection of the [N II] λ6584 line, and hence, a nitrogen abundance, dubious.

V. GLOBAL PROPERTIES OF NEARBY DWARF IRREGULAR GALAXIES

a) The O/H, M_B *Relationship*

In Table 3 we present absolute magnitudes and oxygen abundances for nearby irregular galaxies. We rely on distances and magnitudes from the compilation of Kraan-Korteweg and Tammann (1979) supplemented with more recent distance determinations from Sandage (1986*a*). Many of the Local Group galaxies have distances determined from Cepheid variable observations, and most of the other galaxies have distances determined through group membership. Abundances as a function of absolute magnitude are plotted in Figure 1. A very good correlation is present in the data. Only one galaxy (IC 5152) is extremely discrepant from the trend. A mean least-squares fit to the data (i.e., a fit obtained by treating first one quantity and then the other as the independent variable, and averaging the results), excluding IC 5152, yields

$$12 + \log\,(\mathrm{O/H}) = -0.153\ M_B + 5.50\ , \tag{2}$$

with a correlation coefficient of −0.88. The rms deviation of the data from the relationship is 0.16 in log (O/H). This 50% dispersion in O/H implies that one can confidently estimate the abundance of a dwarf irregular galaxy within a factor of 3 simply from its luminosity. This will be of use to studies of global properties of irregular galaxies where H II region spectroscopy is lacking.

In the past, studies have concentrated on the strong correlation between O/H and the dynamical masses of irregular galaxies (Lequax *et al.* 1979; Talent 1980; Kinman and Davidson 1981). Studies involving the O/H, M_B relationship avoid the several problems encountered in trying to obtain accurate dynamical masses for irregular galaxies (see discussions in Skillman *et al.* 1987; Skillman *et al.* 1988*b*). Vigroux, Stasińska, and Comte (1987) found a weak, but convincing, correlation between O/H and ln (L_B). The stronger correlation found here may be a result of using logarithmic representation of both variables, better distance estimates, and exclusion of blue compact dwarf galaxies. Wyse and Silk (1985) found no clear trend of O/H with M_B for galaxies of $M_B \geq -18$. This probably is due, in part, to using empirical oxygen abundances derived from ([O II] + [O III])/Hβ ratios (Pagel, Edmunds, and Smith 1980), and misinterpreting low values of the oxygen line ratio to be high oxygen abundances (see Skillman 1988).

Since O/H is a distance independent quantity, the strong correlation in Figure 1 may actually be of use as a local distance indicator. The rms variation from the regression line is only 1.1 mag in M_B. While this is significantly larger than the dispersion of 0.52 for the calibrators of the infrared Tully-Fisher relationship for spiral galaxies (Aaronson and Mould 1983), there may be opportunities where this relationship is useful. For example, the field galaxy IC 5152, for which there is no known distance estimate besides recession velocity, appears to have been underestimated in luminosity by Krann-

TABLE 3

IRREGULAR GALAXY ABUNDANCES AND ABSOLUTE MAGNITUDES

Name	Distance (Mpc)	M_B	12+ log (O/H)	References
Sgr DIG	1.10	−10.5	7.42	1, 2
GR 8	2.34	−12.5	7.43	1, 3
Leo A	1.58	−13.1	7.30	1, 4, 5
DDO 167	4.59	−13.3	7.66	1, 5
DDO 187	2.70	−13.4	7.36	1, 5
DDO 53	3.63	−13.8	7.62	1, 4, 5
WLM	0.95	−14.2	7.74	1, 2, 4
IC 5152	1.50	−14.4	8.36	1, 6
IC 1613	0.77	−14.6	7.86	1, 4, 6
Sex A	1.74	−14.6	7.49	1, 4, 5
Sex B	1.74	−14.6	7.56	1, 4, 5
NGC 6822	0.62	−15.1	8.14	1, 4, 7
DDO 47	4.27	−15.8	7.85	1, 5
IC 10	1.30	−16.2	8.20	1, 8
NGC 2366	3.63	−16.8	7.96	1, 4, 6
SMC	0.078	−17.0	7.98	1, 9
NGC 1569	6.31	−17.9	8.16	1, 4, 6
LMC	0.057	−18.4	8.34	1, 9
NGC 4214	5.44	−18.7	8.34	1, 6
NGC 4449	5.44	−19.0	8.32	1, 6

REFERENCES.—(1) KKT; (2) STM; (3) SMTM; (4) S86; (5) this paper; (6) T80; (7) PES; (8) LPRSTP; (9) PEFW.

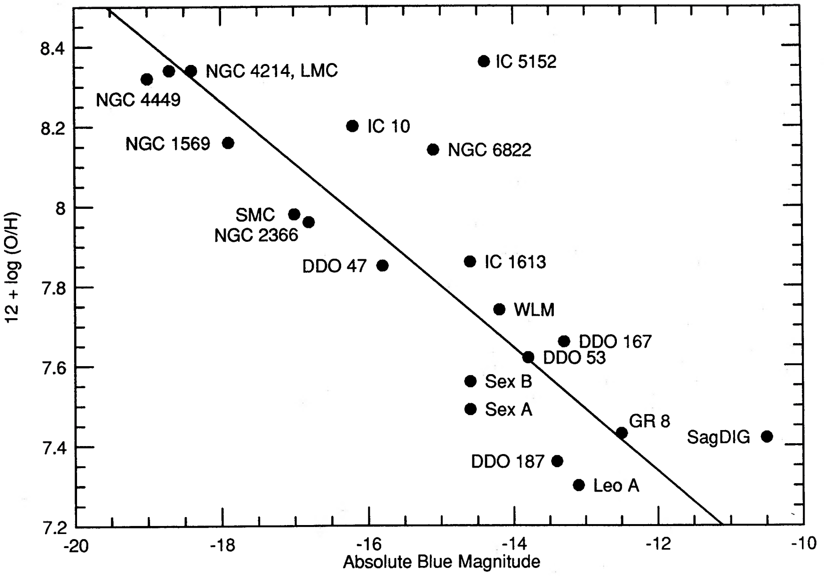

FIG. 1.—A plot of the log of the oxygen abundance vs. the absolute blue magnitude for nearby irregular galaxies. The individual galaxy points are labeled. The solid line shows the result of a mean least-squares fit to the data, excluding IC 5152.

Korteweg and Tammann. The large population of dwarf galaxies in nearby groups and the growing number of dwarf irregulars in the Local Group with accurate distances may provide a sufficient data base whereby the distances to the nearby groups can be checked via the O/H, M_B relationship for dwarf irregular galaxies.

One interesting feature to note in Figure 1 is the positions of galaxies with extremely large H I/optical diameter ratios ($D_{\rm H\,I}/D_{\rm O}$). If infall is more important for those irregulars with very large H I halos, one might expect that these galaxies would lie at low values of O/H for their respective absolute magnitudes. Four galaxies in Table 3 have exceptionally large values of $D_{\rm H\,I}/D_{\rm O}$. These are 13 for NGC 4449 (van Woerden, Bosma, and Mebold 1975), seven for IC 10 (Shostak 1974; Cohen 1979; Huchtmeier 1979), six for Sextans A (Huchtmeier, Seiredakis, and Materne 1981), and four for NGC 6822 (Davies 1972; Roberts 1972). Only one of these galaxies (Sextans A) lies significantly below the O/H, M_B relationship. IC 10 and NGC 6822 both lie significantly above the regression line. Both IC 10 and NGC 6822 lie at low-Galactic latitude (3° and 18°, respectively), and therefore may suffer from underestimated absolute magnitudes. Nonetheless, the preliminary inference is that the presence of a very large H I halo does not lead to an exceptional infall rate. This comes in spite of the fact that high-resolution H I observations of two of these galaxies (Sextans A, Skillman *et al.* 1988*b*; IC 10, Shostak and Skillman 1989) show disturbed internal kinematics that are most likely related to an interaction between the H I halo and the galactic disk.

b) A Comparison with the Dwarf Eliptical Galaxies

The dwarf elliptical galaxies are also known to show a good correlation between absolute magnitude and abundance (Mould, Kristian, and Da Costa 1983; Mould 1984; Buonanno *et al.* 1985; Aaronson 1986*a*; Suntzeff *et al.* 1986). In Figure 2 we have plotted the values for the dwarf elliptical galaxies discussed in Aaronson (1986*b*) with the irregulars shown in Figure 1. As a first pass, we have converted the [Fe/H] values (where the square brackets indicate logarithmic abundances relative to the solar value) to [O/H] values by assuming [Fe/O] = 0.0 and adopting a value of $\mathrm{O/H}_\odot = 8.3 \times 10^{-4}$ (Lambert 1978). We have corrected M_V for the dwarf ellipticals to M_B by assuming $B-V = 0.65$ (Hodge 1971). The result is the striking adherence of the dwarf ellipticals to the O/H, M_B relationship defined by the dwarf irregulars. Evidence of this coincidence has been noted previously by Aaronson (1986*a*).

Before discussing this result, we point out that we have made the simplest assumptions in comparing the dwarf ellipticals to the dwarf irregulars. Although these assumptions should not affect the qualitative behavior of the relationships, we can estimate the effects quantitatively. The abundances measured in the dwarf irregulars are interstellar abundances, while those for the dwarf ellipticals are mean stellar abundances. The interstellar abundances in dwarf irregulars are thought to be rather uniform, but the measured stellar abundances in some dwarf ellipticals show a range of more than a factor of 10 (Da Costa 1984; Buonanno *et al.* 1985; Aaronson and Mould 1985). This effect may be quantifiable in the following way. If we assume a simple "closed box" evolution with the instant recycling approximation for the irregular galaxies, the difference between the abundance in the ISM and the mean stellar abundance can be calculated from equation (12) of Pagel and Patchett (1975)

$$Z_1 - \langle Z \rangle_1 = p\left(\frac{\ln(1/\mu_1)}{1-\mu_1} - 1\right) \tag{3}$$

where Z_1 is the heavy element abundance in the ISM, $\langle Z \rangle_1$ is the mean stellar abundance, p is the heavy element yield, and μ_1 is the present gas mass fraction. If we take 0.3 as a typical gas mass fraction, and $p = 0.0025$ (Pagel 1986), then assuming $Z = 25$ O/H, yields a difference in O/H of 7.2×10^{-5}. This is ~9% of the solar oxygen abundance. Thus, only for the lowest luminosity dwarf irregulars will the difference between the ISM and stellar abundances be significant relative to the dispersion in the O/H, M_B relationship. (Note the problem for galaxies with $\mathrm{O/H} < 0.1\ \mathrm{O/H}_\odot$ yet $\mu > 0.3$.)

A second ambiguity arising in the comparison of dwarf ellip-

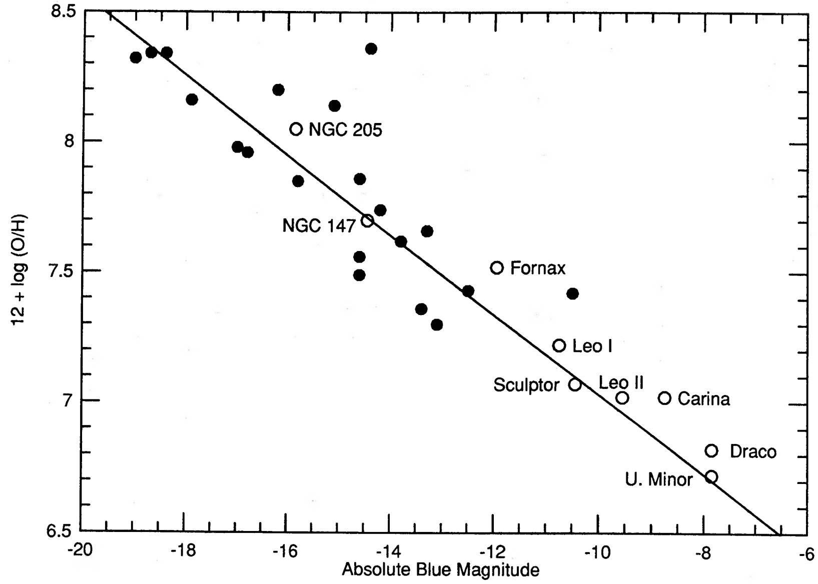

FIG. 2.—A plot of the log of the oxygen abundance vs. the absolute blue magnitude for nearby irregular and dwarf elliptical galaxies. The filled circles are the irregular galaxies from Fig. 1. The labeled open circles represent the dwarf elliptical galaxies. The abundances and absolute blue magitudes for the dwarf elliptical galaxies are derived quantities as described in the text. The solid line is the relationship derived from the irregular galaxies alone, and is the same as show in Fig. 1.

ticals and dwarf irregulars is the assumption of constant [Fe/O] = 0.0. This is suspect since at low abundances [Fe/O] = −0.6 in galactic field subdwarfs of low metallicity (Sneden, Lambert, and Whitaker 1979; see also Sneden 1985; Barbuy 1988). On the other hand, Russell, Bessell, and Dopita (1988) find no such over abundance of oxygen in the metal-poor stars of the LMC and the SMC.

The errors in the conversion of M_V to M_B are probably not critical, considering the inherent scatter in the relationship and the fact that the $(B-V)$ colors of typical irregulars are, on average, only a few tenths of a magnitude less than those of the dwarf ellipticals (de Vaucouleurs 1961). And, finally, and perhaps most importantly, a correction of order of 1 mag or more may be appropriate for "fading" to compare the absolute magnitudes of star-forming dwarf irregulars to quiescent elliptical galaxies.

Despite these ambiguities, we find Figure 2 quite intriguing. Aaronson (1986*a*) has pointed to the close similarity of the abundance-luminosity relationship of dwarf irregulars and dwarf eliptical as a warning against using such a relationship to infer similar evolutionary histories for the dwarf ellipticals and more luminous ellipticals (which appear to obey a similar relationship). We would like to consider the converse proposition, that the similarity of the abundance-luminosity relationship is not coincidental, and therefore holds a clue toward the understanding of the evolutionary histories of these systems.

Recently, a number of lines of evidence have pointed to the stripping of gas from dwarf irregulars as a way to form dwarf ellipticals. Einasto *et al.* (1974) noted that dwarf ellipticals are found preferentially closer to large parent galaxies than dwarf irregulars. Faber and Lin (1983) pointed out that the luminosity profiles of dwarf ellipticals are exponential, like those of irregular galaxies. Dwarf irregulars and dwarf ellipticals share the same relationships between central surface brightness, core radii, and absolute magnitude (Kormendy 1985). Binggeli (1986) notes that the volume density of dwarf ellipticals is higher in the core of the Virgo Cluster than in the periphery, while just the opposite is true for irregulars. To date, the abundance-absolute magnitude relationship has not been used to explore this hypothesis.

If the gas is stripped from a dwarf irregular, the absolute magnitude will decrease by as little as 1 mag or as much as 4 mag, depending on its present color (Lin and Faber 1983; Binggeli 1986), while the average stellar abundance remains constant. Thus, we would expect the dwarf ellipticals to be offset to the right of the O/H, M_B relationship in Figure 2 by ~2 mag. There is no evidence of such an offset in Figure 2.

Given the assumptions outlined above, the lack of the predicted shift cannot rule out the stripping hypothesis. For example, if one assumes [O/Fe] = 0.6 in the range $-2 \leq$ [Fe/H] ≤ -1 (Lambert 1987), then all of the dwarf spheroidals should be placed 0.6 dex higher in Figure 2, corresponding to an offset in M_B of 4 mag, producing more than the predicted shift. (Note that this also solves the problem of the lack of very low luminosity ($M_B > -10$) irregulars requisite to serve as progenitors to the least luminous dwarf ellipticals.) Despite the ambiguities inherent in the comparison, we point to the close similarity of the abundance-luminosity relationships as supportive of the stripping hypothesis.

VI. CONCLUSIONS

Dwarf irregular galaxies appear to be a rather well behaved class of galaxies with strong correlations of abundance with both luminosity and mass. These relationships can be used in the studies of individual galaxies. Understanding the cause of these relationships and similar relationships for the dwarf elliptical galaxies remains an unsolved problem.

We wish to thank D. Garnett, G. Jacoby, B. Pagel, G. Shields, and R. Terlevich for helpful discussions. E. D. S. gratefully acknowledges support from the Netherlands Foundation for Radio Astronomy for much of this work. This study was supported in part by Robert A. Welch Foundation grant F-910 to the University of Texas at Austin, and National Science Foundation grant AST-8613257 to R. C. K. The Isaac Newton Telescope is operated on the island of La Palma by the Royal Greenwich Observatory at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

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