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CHARACTERISTICS OF THE BLUE STARS IN THE DWARF GALAXIES I Zw 18 AND II Zw 40*

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ABSTRACT

Among dwarf blue compact galaxies, I Zw 18 and II Zw 40 have continuum and emission-line spectra similar to those of giant H II regions in external galaxies. An analysis of the emission-line spectrum shows that the emissive gas is much hotter than normal galactic H II regions and that the heavy elements Z are highly underabundant unless they are in stages of ionization higher than Z^{2+}. A study of the thermal balance (i) confirms an underabundance of elements heavier than He by a factor of at least 10 compared to their cosmic values, and (ii) shows that most of the interstellar gas is ionized by hot stars, $4.0 \times 10^4 \lesssim T_{\rm eff} \lesssim 5.5 \times 10^4$ K. These stars must be massive young O stars, $M \gtrsim 30\ M_{\odot}$. The He II λ4686 line observed in emission in I Zw 18 can arise in the optically thin hot envelopes of radiation-driven winds of Of stars. These blue compact galaxies cannot be old galactic systems with a flat mass distribution of newly formed stars.

Subject headings: galaxies: stellar content — stars: abundances — stars: early-type — stars: emission-line

The dwarf emission-line galaxies observed by Sargent and Searle (1970) have the appearance of isolated extragalactic H II regions. An analysis of the emission-line spectra (Searle and Sargent 1972) reveals an underabundance of elements heavier than helium. The intensity of the continuum radiation in the near-IR and optical increases slowly with frequency in both galaxies, and presumably is of stellar origin (Sargent and Searle 1970). The spectrum is much bluer than that of irregular galaxies and is similar to that of H II regions in external galaxies. Hence the visual continuum emission probably originates from blue stars. The high relative number of such stars, assumed to be young and therefore massive, together with the underabundance of observed heavy ions, raises the possibility that these dwarf galaxies are much younger than normal galaxies (Sargent and Searle 1970; Searle, Sargent, and Bagnuolo 1973). We are reanalyzing the emission spectra using a model based on the coupled equations of thermal balance and ionization. We find that the temperature of the gas is about twice that of usual H II regions, which requires stars of high effective temperature, $T_{\rm eff}$. We are trying to determine accurately the average stellar spectrum of the stars responsible for the heating of the gas and trying to verify whether an underabundance of heavy elements is an inescapable characteristic of these blue dwarf galaxies.

A knowledge of the stellar spectrum is a key element in the determination of the age of these galaxies. In particular, Searle and Sargent (1972) assumed that ordinary O stars, i.e., massive young stars, are responsible for heating the interstellar gas. If the observed gas temperature turns out to imply stellar effective temperatures higher than 6×10^4 K, then older stars, such as the low-mass central stars of planetary nebulae, could be responsible for the blue part of the continuum emission spectrum.

I. AVERAGE STELLAR EFFECTIVE TEMPERATURE

The gas temperature, T_e, can be inferred from the intensities of the forbidden lines of [O III] λλ4363, 5007. The results for I Zw 18 and II Zw 40 are 1.85×10^4 and 1.45×10^4 K, respectively. An error of 25% on the line relative intensity would lead to an error of about 15% in the temperature determination. Most of the gas is indeed at these high temperatures as the number of O^+ ions is smaller than that of O^{++} (the ratio of the emissivities per ion [O II] λλ3726, 3729/[O III] λ5007 is equal to 1 and $\frac{1}{2}$ for $T_e \sim 1.35 \times 10^4$ and 7.2×10^3 K, respectively). Further the abundance of heavy elements, Z, deduced from the line intensity of Z II and Z III only, leads to underabundance relative to hydrogen of oxygen and neon.

High gas temperatures can be achieved with high underabundance of heavy elements (i.e., large reduction of the cooling rate) and intermediate star temperatures (to be determined). For normal abundances but stars with high effective temperatures, the gas temperature can also be high and the heavy elements are then highly ionized (higher stages of ionization than Z III).

That part of the interstellar gas heated by hot stars should be distributed in discrete H II regions. For high $T_{\rm eff}$ ($T_{\rm eff} > 35{,}000$ K) the H^+, He^0 Strömgren region does not exist and the heavy elements observed would be mainly in the form of Z III in the H^+, He^+ Strömgren region. The size of the H^+, He^{++} Strömgren sphere is a function of the discontinuity at

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54.4 eV in the emergent radiation flux from the stellar atmosphere. For intermediate and high surface gravity (log $g \geq 4$) this discontinuity is smaller than one decade if $T_{\rm eff} \gtrsim 1.0 \times 10^5$ K (Hummer and Mihalas 1970; Mihalas 1972). It is somewhat larger than 10^4 for $T_{\rm eff} = 5.0 \times 10^4$ K (computations for more massive stars have not been performed).

a) *Abundance of Heavy Elements*

The assumption of normal abundance of heavy elements and high $T_{\rm eff}$ does not appear to be satisfactory. The ions of stages of ionization higher than Z III are only found in the $\rm He^{++}$ Strömgren region. This region must therefore be much larger than the $\rm He^+$ region. This occurs only for very high $T_{\rm eff}$ ($> 3 \times 10^5$ K). [Ne III] is observed; thus [Ne V] should be detected but it is not. Therefore, Ne must be either in the form of $\rm Ne^{3+}$ or in stages of ionization higher than $\rm Ne^{4+}$. Both of these alternatives are shown to be unsatisfactory.

In the first alternative, the continuum radiation spectrum must be deficient in photons of energy $E_\nu \gtrsim$ 100 eV, i.e., $T_{\rm eff} \lesssim 1.0 \times 10^5$ K (Hummer and Mihalas 1970), and the amount of interstellar gas within the $\rm He^{++}$ Strömgren region cannot be larger than that within the $\rm He^+$ Strömgren region. This is obviously in contradiction to a large relative abundance of $\rm Ne^{3+}$. The second alternative requires an unreasonably high blackbody radiation temperature, $T_r \gtrsim 1 \times 10^6$ K. A bremsstrahlung spectrum does not lead to a high enough degree of ionization of the heavy elements. The dwarf galaxies would then be very powerful detectable soft X-ray sources, $L_X \gtrsim 10^{45}$ ergs s^{-1}.

In either case a large relative abundance of $\rm He^{++}$ is expected. However, this is not found. The galaxy II Zw 40 does not exhibit any He II recombination lines in its emission spectrum. In I Zw 18 only a small amount of $\rm He^{++}$ is present, about 5% under the assumption of equal temperatures in the $\rm He^+$ and $\rm He^{++}$ regions. Even if the temperature of the $\rm He^{++}$ regions were much higher than that of the $\rm He^+$ regions, the ratio $\rm He^{++}/He$ could not be raised by more than a factor 10. For such a large factor, one faces the problem of an overabundance of He. Therefore, the $\rm He^+$ regions must contain at least half and probably most of the interstellar matter, and the elements heavier than He are underabundant.

b) *Effective Temperature of the Ionizing Radiation Sources*

Having shown the underabundance of heavy elements, we are now able to determine the gas temperature T_e as a function of $T_{\rm eff}$. T_e is given by the solution of the coupled ionization and balance equations (Bergeron and Collin-Souffrin 1974). The radiation spectra considered were either pure blackbody spectra or computed emergent spectra from stellar atmospheres (Mihalas 1972).

To achieve very precise determinations of T_e, the transfer for the ionization radiation due to recombinations should be treated. However, a good approximation for the thermal equilibrium near the star is obtained, not with the "on the spot" approximation, but with the use of α_t, the total recombination coefficient of hydrogen, in both the ionization and thermal balance equations (Rubin 1968). Rubin shows that an optical depth of unity at the Lyman limit, as measured from the star, is not reached until about two-thirds of the radius of the H II region, and that, in this inner region, the stellar radiation flux is highly dominant over the diffuse radiation flux. Therefore, solutions of a numerical program for optically thin cases and α_t (Bergeron and Collin-Souffrin 1974) should be rather accurate.

For very large underabundance, the cooling processes reduce to free-free and free-bound of H and He for stellar UV heating. The maximum temperature of the gas is then reached. This situation is almost realized for I Zw 18.

The gas temperature T_e depends on the distance r to the star and its UV luminosity L_*. The ionization rate, $\zeta \propto L_*/r^2$ cannot be accurately determined from the observations alone. This does not drastically affect the estimate of T_e, as the gas temperature is roughly constant within $\rm He^+$ Strömgren zones except for cases of large underabundance. The normal abundances relative to hydrogen are taken equal to their cosmic values of 8.3×10^{-2}, 4.0×10^{-4}, 1.1×10^{-4}, 8.9×10^{-4}, and 1×10^{-4} for He, C, N, O, and Ne, respectively. For abundances smaller than 1/20th of the cosmic abundances, the gas temperature is larger than 1.5×10^4 K for O stars. Free-free and free-bound energy losses are important. Thermal ionization of H is no longer negligible, and T_e increases slowly with $n_{\rm H}{}^+/n_{\rm H}{}^0$ in the $\rm He^+$ Strömgren region.

We have tested the accuracy of our models by computing the gas temperature for normal H II regions. The abundance of heavy elements used is smaller than the cosmic value by roughly a factor 2 ($\rm O/H = 4 \times 10^{-4}$), and the gas density $n_{\rm H}$ employed is 10^3 cm^{-3}. For stellar effective temperatures of 3.0×10^4 and 5.0×10^4 K and log $g = 4$ (Mihalas 1972, non-LTE models) we found gas temperatures of 7700 and 9800 K, respectively. If direct hydrogen recombinations to the ground state are omitted, a gas temperature of only 8100 K is obtained for $T_{\rm eff} = 5.0 \times 10^4$ K. For the input parameters of models 1 and 2 used by Rubin (1968), gas temperatures of 6100 and 5300 K are obtained with our models. These temperatures are very close to those given by Rubin at $\frac{1}{2}$ to $\frac{2}{3}$ of the Strömgren radius, where the Lyman optical depth is reaching unity. For low abundances $\rm O/H < 5 \times 10^{-4}$ and/or high densities $n_e > 100$ cm^{-3} (i.e., radiative losses not entirely dominated by heavy elements and no sharp rise of T_e in the outer part of the Strömgren sphere for $T_{\rm eff} \gtrsim 40{,}000$ K) our method gives a good estimate of the average temperature in the $\rm O^{++}$ zone.

Computations were carried out for several values of D, the ratio of the cosmic abundance of heavy elements to the value used in the model. The results for the gas temperature are presented in Figure 1 for

1977ApJ...211...62B

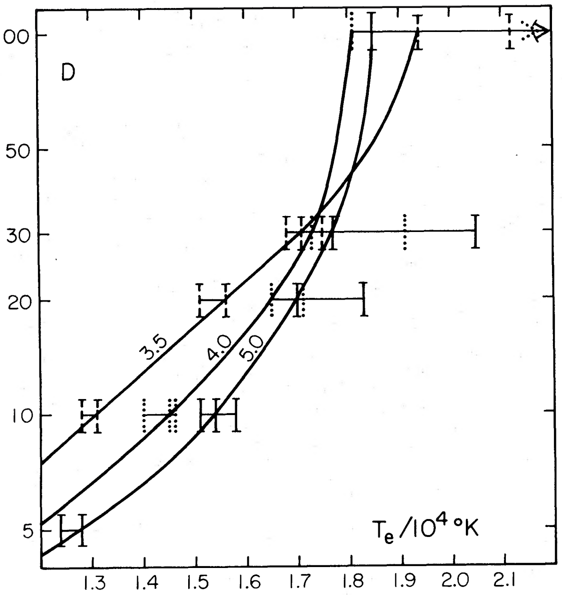

FIG. 1.—D, ratio of the cosmic abundance of heavy elements to the value used in the model as a function of the gas temperature for different stellar effective temperature given in units of 10^4 K. The curves refer to an emission-line ratio [O III] λ5007/[O II] λλ3727, 3729 = 7. For a given value of D, the range of temperatures of the O^{++} region is marked by broken, dotted, and plain vertical dashes for $T_{\rm eff} = 3.5 \times 10^4$, 4.0×10^4, and 5.0×10^4 K, respectively.

stellar effective temperatures of 3.5×10^4, 4.0×10^4, and 5.0×10^4 K, $\log g = 4$, and $n_{\rm H} = 10^3$ cm^{-3}. For a given value of D the range of temperatures of the O^{++} region (defined by a line ratio [O III] λ5007/[O II] λλ3727, 3729 ≥ 7) is shown. This range of T_e arises from the small variation of the gas temperature with the distance to the star. As shown above for small values of D, this range is small and the O^{++} zone can be considered as isothermal. However, for $D > 20$ this is no longer the case. The curves refer to an emission-line ratio [O III] λ5007/[O II] λλ3727, 3729 ≈ 7 (for both galaxies it is the observed value). The corresponding value for H^0/H^+ is highly dependent on $T_{\rm eff}$. It is roughly equal to 1.7×10^{-3}, 4.5×10^{-3}, and 1.0×10^{-2} for $T_{\rm eff} = 3.5 \times 10^4$, 4.0×10^4, and 5.0×10^4 K, respectively. The average value of [O III] λ5007/[O II] λλ3727, 3729 in the O^{++} region cannot be derived from the observations alone. Indeed, some [O II] emission can arise in regions colder than the O^{++} zone, either from dense clumps or from the transition region. Further, within the O^{++} region, the average value for this line ratio is a function of $T_{\rm eff}$, the gas density, and its clumpiness. Any value of T_e within each domain, determined only by D and $T_{\rm eff}$, is therefore compatible with the observed O line ratio.

Gas temperatures larger than 1.4×10^4 K together with an underabundance factor D no larger than 10 imply stellar effective temperatures of at least 4.0×10^4 K. For very large underabundances, $D \gtrsim 100$, a gas temperature of 2.0×10^4 K can be achieved even for $T_{\rm eff} = 3.5 \times 10^4$ K. The results are not affected significantly by a change in either the value of g (i.e., the star luminosity) or n_e. However, the density must be smaller than a few times 10^3 cm^{-3} (negligible electronic de-excitation of [O II] λλ3727, 3729). For an underabundance factor D smaller than 10, lower values of T_e would be obtained for $n_e < 100$ cm^{-3}. The IR line emission is then an important radiative loss and becomes dominant for normal abundances and $n_e \lesssim 10$ cm^{-3}.

The abundances of O (and Ne) in I Zw 18 and II Zw 40 are smaller than those in Orion by factors of 14 and 3, respectively. The abundance within galactic H II regions is difficult to determine accurately. It is a function of the gas temperature and density, both of which vary greatly within the H II region. It is lower than the cosmic abundance by roughly a factor of 2 (Peimbert and Costero 1969) and maybe 4 (Simpson 1973) in Orion. The values for D are thus 30–50 and 6–10 for I Zw 18 and II Zw 40, respectively. The observed gas temperatures imply stellar effective temperatures of at least 4.0×10^4 K for both galaxies. Hence very hot massive stars, still on the main sequence, can account for the high gas temperatures. Low-mass stars in their pre–white-dwarf stage, $4.0 \times 10^4 \lesssim T_{\rm eff} < 6.0 \times 10^4$ K, are also compatible with both the high temperature and large underabundance of the emissive gas. Models with a stellar effective temperature larger than 6.5×10^4 K ($\log g \geq 4.5$) and a large underabundance give gas temperatures higher than those observed.

The computed values for $T_{\rm eff}$ are not very sensitive to the underabundance of heavy elements within the star. Some of the stellar atmosphere models we used assumed normal abundances. For lower abundances of the heavier elements, the stellar effective temperature increases for a given mass (about 10% for a 10 $M_\odot$ star and underabundance factor D of 100 [Alcock and Paczynski 1975]). It is not evident how much the emergent spectrum from the stellar atmosphere could flatten with underabundance. Within the atmosphere the main source of opacity is electron scattering, and small discontinuities in the spectrum (at energies smaller than 54.4 eV) exist in the case of normal abundances for $T_{\rm eff} \lesssim 5.0 \times 10^4$ K. A more important problem exists for large stellar masses. The stellar atmosphere is then unstable due to radiation pressure and some emission lines can form within the stellar wind. This is further discussed in the next section in regard to the presence of He^{++} in I Zw 18.

II. MASS OF THE HOT STARS AND DEGREE OF IONIZATION OF THE GAS

There is a good method to distinguish between ionization by hot, massive, main-sequence stars and by low-mass stars in their pre–white-dwarf stage. For a given total luminosity of the ionizing stars, the ionization level of the individual H II regions is a function of the luminosity of each star and the interstellar clumpiness. The ionization level scales as the ratio of the volume of ionized gas to the area of the Strömgren regions and so depends on the number of ionizing stars N_*. The observed line ratio [O III] λ5007/[O II]

$\lambda\lambda$3727, 3729 gives a lower limit for H^0/H^+, thus an upper limit for N_*.

The optical line observations (Searle and Sargent 1972) provide an estimate of $n_H{}^2V$, where V is the total volume occupied by the ionized gas of density n_H (with the electronic density $n_e \approx n_H$). The total luminosity L_t of the dwarf galaxy beyond the Lyman limit I_H is given by

$$L_t = N_* L_* = K a_{\mathrm{th,H}^0} \alpha_t n_H{}^2 V\,, \tag{1}$$

where L_* is the average UV luminosity of the hot ionizing stars, $a_{\mathrm{th,H}^0}$ the threshold ionization cross section, and α_t the total recombination coefficient of hydrogen. K is the ratio of the energy of the ionizing photons to the photoionization cross section a_{ν,H^0}, both averaged over the photon spectrum.

The ionizing stars are assumed at first to be identical, and to be surrounded by spherical radiation-bounded H II regions. The primary hydrogen ionization rate ζ_0 in the hydrogen Strömgren sphere of radius r_S could then be written

$$\zeta_0 K = L_*/(4\pi r_S{}^2)\,. \tag{2}$$

For a constant average density within the H II regions, and a clumpiness f, the volume occupied by the ionized gas can be written

$$V = N_* \frac{4\pi}{3} r_s{}^3 f\,. \tag{3}$$

Combining equations (1)–(3) allows the determination of ζ_0/n_H:

$$\frac{\zeta_0}{n_H} = a_{\mathrm{th,H}^0}\alpha_t \left(\frac{n_H{}^2 V \bar{n}_H}{36\pi}\right)^{1/3} \left(\frac{n_H}{\bar{n}_H} f^2/N_*\right)^{1/3}, \tag{4}$$

where $\bar{n}_H$ is the density of the gas averaged over the resolved galaxy which for a spherical optical line region of diameter ϕ is given by

$$\bar{n}_H = \left(\frac{n_H{}^2 V}{\frac{1}{6}\pi\phi^3}\right)^{1/2}. \tag{5}$$

This result applies to the cases (i) an overall clumpiness f independent of the radiation sources, and (ii) an additional macroscopic clumpiness F of matter around the radiation sources. The average density is then defined by

$$\text{i) } \bar{n}_H/n_H = f^{1/2}\,,$$

$$\text{ii) } \bar{n}_H/n_H = (fF)^{1/2}\,. \tag{6}$$

The variation of ζ_0/n_H with the gas clumpiness and the star number is therefore given by

$$\text{i) } \frac{\zeta_0}{n_H} \propto f^{1/2} N_*{}^{-1/3} \propto n_H{}^{-1} N_*{}^{-1/3}\,,$$

$$\text{ii) } \frac{\zeta_0}{n_H} \propto f^{1/2} N_*{}^{-1/3} F^{-1/6} \propto n_H{}^{-1} N_*{}^{-1/3} F^{-2/3}\,. \tag{7}$$

The average ratio of the oxygen ions O^+/O^{++} is found from their forbidden optical line intensities and it provides a lower limit for ζ_0/n_H. Further, the [O II] doublet $\lambda\lambda$3727, 3729 gives an upper limit for the electronic density $n_e \lesssim 10^3$ cm^{-3}. For case (i) and $n_H = \bar{n}_H$ one gets from the O^+/O^{++} ratio an upper and lower limit for N_* and L_*, respectively. Finally, the stellar optical continuum is not resolved into individual sources, and this implies a lower limit for N_* of about 3 to 10.

The results for I Zw 18 and II Zw 40 are summarized in Table 1 for a radiation spectrum with $T_{\mathrm{eff}} = 5.0 \times 10^4$ K, $\log g = 4$, a Hubble constant $H = 50$ km s^{-1} Mpc^{-1}, and the redshifts given by Sargent and Searle (1970). The overall diameter of the optical line region, ϕ, is taken to be that of the largest galaxy of the double system for I Zw 18, and is an intermediate value between the two lengths given for II Zw 40 in Sargent and Searle (1970). These assumptions should lead to maximum error for ζ_0/n_H of not more than 50%. Main-sequence O stars of $T_{\mathrm{eff}} = (4.0\text{–}5.0) \times 10^4$ K and mass $M_* = 30\text{–}60\ M_\odot$ are compatible with the observations, with or without some clumpiness of the interstellar gas. For I Zw 18 and $F = 1$, one obtains $f \geq 2 \times 10^{-3}$. The maximum upper limit on the number of ionizing sources is a strict limit, as some O^+ but no O^{++} ions come from the transition region of each Strömgren sphere. It should also hold for $F < 1$, as then the matter concentrated around each source is likely to be in the form of a shell or filaments, i.e., $f \ll 1$. We now consider whether low-mass stars in their pre–white-dwarf stage can account for the ionizing radiation. While an 0.8 $M_\odot$ star evolves from a T_{eff} of 6.5×10^4 K to 5.0×10^5 K, the average luminosity of the star is 1.5 $L_\odot$ (Baglin 1974), in conflict with results for both I Zw 18 and II Zw 40. Further, although these stars evolve faster at higher T_{eff}, their luminosity is much higher in the earlier phases after the planetary nebula phase (Vila 1967). So the number of ionizing photons emitted by these evolved stars is much larger in their earlier hot phases. Therefore, stars in their pre–white-dwarf stage would produce H II regions much hotter than those observed.

TABLE 1

CHARACTERISTICS OF THE H II REGIONS AND OF THE IONIZING STARS

Parameter	I Zw 18	II Zw 40
ϕ (pc)	500	320
$n_H{}^2V$ (cm^{-3})	2.4×10^{64}	1.8×10^{65}
T([O III]) (K)	1.85×10^4	1.45×10^4
$\bar{n}_H$ (cm^{-3})	4	15
$(M/M_\odot)(n_H/\bar{n}_H)$	4×10^6	6×10^6
$\langle O^{++}/O^+\rangle$	7	7
$L_t/L_\odot$	1.8×10^7	1.4×10^8
$\frac{\zeta_0}{n_H}\left(\frac{n_H}{\bar{n}_H} f^2/N_*\right)^{-1/3}$ (s^{-1} cm^3)	2.4×10^{-9}	7.9×10^{-9}
$\left(\frac{\zeta_0}{n_H}\right)_{\max}$ (s^{-1} cm^3)	3×10^{-11}	3×10^{-11}
$N_{*,\max}$	5×10^5	2×10^7
$L_{*,\min}/L_\odot$	35	8
$N_*(M_* \approx 45\ M_\odot)$	90	700

The temperature and ionization degree of heavy elements imply therefore main-sequence massive ($M/M_{\odot} \geqslant 30$), hot ($4.0 \times 10^4 \leqslant T_{\rm eff} \leqslant 5.5 \times 10^4$ K) stars. The blue part of the continuum emission spectrum of I Zw 18 and II Zw 40 is dominated by emission from young massive stars.

Only one feature remains unexplained: the He II recombination line observed in I Zw 18, which leads to a relative abundance $\rm He^{++}/He^{+} \approx 0.05$ (if the lines originate in regions of same temperature). The He II emission cannot arise in the H II regions surrounding the O stars. The $\rm He^+$ Lyman discontinuity in the emergent spectrum from the stellar atmosphere is of order 10^4 for massive O stars and $\log g = 4$. But it should be smaller than 10 to give rise to a $\rm He^{++}$ Strömgren region 1/20th of the $\rm He^+$ Strömgren region.

If these dwarf galaxies are old, some fraction of the stellar population consists of post–main-sequence very hot stars. The temperature of the H II regions associated with these stars is higher than 2.0×10^4 K. A possible model using the same gas density around the young and old stars has the following characteristics: 17% of the interstellar gas is ionized by stars with a blackbody radiation spectrum at 1.2×10^5 K, the temperature of the $\rm He^+$ Strömgren region is close to 2.5×10^4 K, and that of $\rm He^{++}$ is close to 3.0×10^4 K. The fraction of gas ionized by post–main-sequence stars decreases with their effective temperature, but still amounts to 10% of the interstellar matter for $T_{\rm eff} = 2.0 \times 10^5$ K. The [Ne v] line would then be at least 5 times weaker than the [Ne III] or He II lines and so would not have been detectable by Searle and Sargent (1972).

The He II line can also be an intrinsic emission line from the stellar envelope of Of stars (Castor, Abbott, and Klein 1975). The rate of mass loss can be large ($6 \times 10^{-6}\, M_{\odot}\,\rm yr^{-1}$ for an O5 star), and there is sufficient mass in the expanding envelope for the emission of $\rm He^+$ to be important. The He II λ4686 has an equivalent width EW of a few angstroms in emission. The EW = 6 Å for star models with $T_{\rm eff} = 5.0 \times 10^4$ K, $\log g = 4$, and $T_{\rm eff} = 4.0 \times 10^4$ K, $\log g = 3.5$ (Castor 1975). The equivalent width of Hβ for I Zw 18 is 100 Å, and the intensity of He II λ4686 is 5×10^{-2} that of Hβ. This result is consistent with the high stellar effective temperatures derived from the observed gas temperature for I Zw 18. The absence of the He II line in II Zw 40 would imply a stellar population of lower mass than in I Zw 18.

III. CONCLUDING REMARKS

A large number of galaxies have intrinsic colors much bluer than those of the normal galaxies of the Hubble sequence. Among them are the dwarf galaxies I Zw 18 and II Zw 40 for which both photoelectric and spectroscopic data are available. Their continuum and emission-line spectra are similar to those of giant H II regions in external galaxies.

The analysis of both the emission-line spectrum and the thermal balance of the gas shows (i) that the gas in these galaxies is much hotter than the normal galactic H II regions, and (ii) that these high temperatures are a direct consequence of an underabundance of elements heavier than He. Indeed, these high gas temperatures cannot be the result of a very high effective temperature of the ionizing sources ($T_{\rm eff} > 6.5 \times 10^4$ K), for the heavy elements Z cannot be mostly in stages of ionization higher than Z^{2+}. This last alternative would lead either to line intensities of He II and [Ne v] in contradiction to the observations, or to an unrealistic overabundance of He, together with a power radiated in soft X-rays 10^5 times larger than that in the optical.

The heavy elements are underabundant in I Zw 18 by at least a factor 30, but He is not underabundant: He/H ~ 0.1. Helium must thus have a very different origin from that of the heavy elements. Further, the large underabundance of elements heavier than He is in contradiction to the alternative of old galactic systems with a mass distribution of newly formed stars flatter than the Salpeter function (1955). The possibilities of either a very young system highly reddened or a composite system with an old underlying component and bursts of star formation remain (Huchra 1975).

The knowledge of the underabundance of the heavy elements (which are mainly in the form of Z^{2+}) and the gas temperature allows a precise determination of the amount of ionizing stellar radiation as it emerges from the stellar atmosphere. Most of the gas is ionized by stars of $4.0 \times 10^4 \leqslant T_{\rm eff} \leqslant 5.5 \times 10^4$ K. These stars must be massive main-sequence O stars with $M/M_{\odot} \geqslant 30$. The ionizing source cannot be pre–white-dwarf stars. Indeed, the average photon flux of post–planetary-nebula stars corresponds to $\langle T_{\rm eff} \rangle$ closer to 8×10^4 than to 5×10^4 K, and this would lead to an inconsistently high gas temperature.

The presence of $\rm He^{++}$ in I Zw 18, and in a few other extragalactic H II regions (Searle 1975), can be accounted for either by an optically thin stellar wind, or by an additional radiation source as from very hot post–main-sequence stars. In either case, massive main-sequence stars constitute the main heating source.

The first alternative follows directly from the existence of very massive young stars. These stars have large mass loss, and there is sufficient mass in the envelope for recombination to produce the emission line He λ4686 observed in I Zw 18. This stellar wind emission can also account for the presence of the He II emission line in some large extragalactic H II regions. The absence of this line in the emission-line spectrum of II Zw 40 suggests a population of young stars in II Zw 40 of lower mass than in I Zw 18. We therefore come to the following conclusions:

i) The heavy-element abundance is smaller than the cosmic abundance by factors 30–50 and 6–10 for I Zw 18 and II Zw 40, respectively. In contrast the abundance of He is normal: He/H ~ 0.1.

ii) Very massive main-sequence stars with strong stellar winds are responsible for the blue part of the continuum spectrum and for the heating of the interstellar gas.

iii) In I Zw 18 these stars can be also responsible for the He II λ4686 emission line. Their typical characteristics are $T_{\mathrm{eff}} = 5.0 \times 10^4$ K, $\log g = 4$, $M = 60\ M_\odot$, and total luminosity $L \approx 10^6\ L_\odot$.

iv) The main-sequence stars in II Zw 40 are on average somewhat less massive and colder ($T_{\mathrm{eff}} \approx 4.0 \times 10^4$ K) than in I Zw 18.

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