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STAR FORMATION AND ABUNDANCES IN THE NEARBY IRREGULAR GALAXY VII Zw 403

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ABSTRACT

The galaxy VII Zw 403 is similar in characteristics with objects that have alternatively been called extragalactic H II regions or blue compact galaxies, but VII Zw 403 is close enough that it is well resolved into individual stars and emission regions. From a detection of the H I radio emission, we determine an indicative mass to be $2\times10^8\ M_\odot$ and the H I mass fraction to be 20%. Photometry in J, H, and K bands reveals that there is an unresolved source of infrared emission associated with the brightest H II region in the galaxy, and the colors suggest the presence of a substantial number of K and M supergiants, in addition to the hot O stars that must be present to account for the ionized gas. Spectrophotometry of this emission region leads to the following conclusions: (*a*) Reddening is substantial, and the interpretation of the observed Balmer decrement in terms of reddening is not straightforward. (*b*) The primary nucleosynthesis products O, S, and Ne are underabundant compared with the Sun by a factor of 15. (*c*) N is underabundant compared with the Sun by a factor of 160. (*d*) The helium abundance is $Y=0.24\pm0.05$. Observational dangers associated with the determination of the He abundance are discussed. The very low value for the nitrogen abundance suggests that either there could have been only a small number of star formation episodes or the galaxy is younger than the time scale of the process that deposits N in the interstellar medium. There is evidence for a diffuse stellar component which would require that there was at least one previous star formation episode and which suggests that the system is not extremely young.

Subject headings: galaxies: individual — galaxies: photometry — galaxies: stellar content — stars: formation

I. INTRODUCTION

Among the presently known dwarf irregular galaxies near enough that individual stars can be resolved, the system that is most vigorously forming stars today is VII Zw 403 (UGC 6456). Broad-band blue and ultraviolet and 20 Å Hα photographs of this galaxy were published by Fisher and Tully (1979). We show two photographs of the object in Figures 1 (Plate 1) and 2 (Plate 2). There are very blue resolved stars, extended star complexes, and discrete emission knots and arcs covering a region of 45″×35″. VII Zw 403 has been detected in the 21 cm line of neutral hydrogen at a heliocentric velocity of -92 km s^{-1}. By the degree of resolution and by its proximity in velocity and on the plane of the sky with M81, VII Zw 403 is almost certainly a member of an extended M81 group. We accept the distance to this galaxy to be the distance to the group of 3.25 Mpc ($\mu_0=27.56$ mag) proposed by Sandage and Tammann (1974), although, between the uncertainty in the distance to the group as a whole and the uncertainty associated with the depth of the group, the modulus may be in error by 1 mag or more. Although assigned to a group, VII Zw 403 is relatively isolated. It is 10° (570 kpc projected) from NGC 4236 and 12° (660 kpc projected) from M81.

It was Carozzi, Chamaraux, and Duflot-Augarde (1974) who first drew attention to VII Zw 403. They presented a spectrum that shows a continuum break at 4000 Å and makes a case for the existence of Ca H and K and G-band absorption features. This spectrum may be interpreted as evidence for an older population of stars. The extended, unresolved emission seen in Figure 1 over roughly 3 times the diameter of the region of the active star formation is further evidence for such a population.

The highest surface brightness structure in the galaxy, both in continuum light and in line emission, is a stellar association/H II complex toward the southern extremity of the active region, and most of the discussion which follows will pertain to that specific region. There is a component in the bright H II complex marginally more extended than the seeing disk with $B\approx18$ mag ($M_B\approx-9.5$ mag). We have spectra which intersect this semi-stellar component (see Fig. 2) which can be classified as O type because the continuum is strongest in the UV and there is no significant Balmer discontinuity. In these spectra, there is a plateau of 6″ (90 pc) extent over which emission lines are of approximately constant intensity. Weaker emission is detected to 9″ east and 12″ west of the center of this plateau. Only the strongest lines are detected outside the region of high emissivity, so no chemical analysis has been attempted at the locations of weaker emission. However, it is clear that variations in the relative strengths of lines (for example, between [O III] and Hβ) can occur as a function of location.

II. OBSERVATIONS

a) *Spectrophotometric Observations*

The emission region identified in Figure 2 was observed with the Cassegrain image tube spectrograph on the 2.24 meter telescope at Mauna Kea. Table 1 provides a log of the plate material.

A photographic density to relative intensity conversion was achieved by observing an LED source through the spectrograph and through a series of calibrated neutral density filters. The system response was determined through observations of subdwarf standards (Hayes 1970) with each grating setting used during each run. The plate material was raster scanned on a PDS microdensitometer with a projected aperture of 12 μm square and at increments of 12 μm. The sky plus extended source continuum background and airglow emission were removed at each wavelength increment by averaging across that part of the 32″ spectrograph slit that was outside the domain of the emission region.

The observed relative line intensities in the 6″ core of the strongest H II region are listed in Table 2. The uncertainties are the quadrature summation of photon counting statistics, contributions from the noise, and errors that arise in coupling strong lines observed on short exposures with weak lines observed on long exposures or in coupling the red and blue portions of the spectrum. These formal uncertainties do not include errors that might arise from the system response correction or from variations in the projected location of the slit, problems that are discussed below.

The intrinsic flux in the Hβ line could be roughly estimated by comparison with the Na D airglow lines at 5890–5896 Å. Steiger (1967) has compiled 7 years of data on the strength of these lines over nearby Haleakala Observatory. From the anticipated intensity of the Na D feature at the time the observations were made and from the relative strength of Hβ to this feature, we conclude that the flux associated with Hβ in the 6″ core of the emission region is 116 rayleighs (photons cm^{-2} s^{-1} sr^{-1}), accurate to a factor of 2. Consequently, the flux in a circle of 6″ diameter is $I_{H\beta}=2\times10^{-14}$ ergs cm^{-2} s^{-1} and the intrinsic flux at the galaxy is 2×10^{27} ergs s^{-1}.

With the image tube spectrograph it was possible to reach very low flux levels with moderately high spectral and spatial resolution. However, spectrophotometry is not straightforward with a photographic recording medium. In the first place, the dynamic range required to cope with the strongest and weakest observed lines is 400. It was necessary to interrelate the long and short exposures through the intensities of the lines of intermediate strength: [S II] λ6717+λ6731 in the red and Hγ, Hδ, [Ne III] λ3869, [Ne III]+Hϵ, and He I+H8 in the blue.

In the second place, the system response correction was sometimes quite large. In the vicinity of 5000 Å on the blue spectra our grating efficiency was low and there was poor agreement in the overlap region with the red spectra on the relative strengths of Hβ and [O III] $\lambda\lambda$4959, 5007. From a comparison of the [O III] doublet line strengths with the predicted ratio it was concluded that the problem was confined to the blue spectra. The relative flux of all lines shortward of 4800 Å might be too high with respect to Hβ by as much as 15%.

There was a problem with the system response function for exposure KC-980 A which required that a correction be applied to obtain an agreement with exposure KC-848 B on the relative strengths of [S II] $\lambda\lambda$6717/31 to He I λ5876 and [S II] $\lambda\lambda$6717/31 to Hβ. This plate KC-980 A was used only to provide the intensities of the weak lines relative to sulfur in the restricted wavelength interval between 6584 and 6731 Å.

The slit was set by eye on the emission region, but, because the nebulosity was at the limit of detectability, it is very possible that the slit was not at precisely the same location on the three different nights that the object was observed. A (H$^+$, He^0) zone must have been included in the slit on plate KC-984 A since (1) He I was quite significantly weakened and [N II] was relatively strong compared with the other exposures, and (2) it was evident from the line strengths that the slit was not on

TABLE 1

OBSERVING LOG

Plate No.	Date	Exposure (minutes)	Wavelength (Å)	Dispersion (Å mm^{-1})	Slit Width
KC-848 A ...	1978/5/2	10	3600–5100	48	200 μm=1″.8
KC-848 B ...	1978/5/2	10	4600–7200	96	200 μm=1″.8
KC-980 A ...	1979/3/23	45	4600–7200	96	300 μm=2″.7
KC-981 A ...	1979/3/23	30	3780–5400	48	300 μm=2″.7
KC-981 B ...	1979/3/23	60	3100–4600	48	300 μm=2″.7
KC-984 A ...	1979/3/24	90	5700–6900	48	300 μm=2″.7

TABLE 2

LINE INTENSITIES

λ	Species	Plate	$F(\lambda)$	Case 1 $f(\lambda)$	Case 1 $I(\lambda)$	Case 2 $f'(\lambda)$	Case 2 $I'(\lambda)$
3727	[O II]	KC-848 A	0.608±0.055	0.308	1.00+0.09	0.350	1.36±0.12
3750	H12	KC-981 B	0.013±0.003	0.301	0.034±0.008	0.340	0.028±0.006
3771	H11	KC-981 B	0.020±0.003	0.296	0.053±0.008	0.330	0.043±0.006
3798	H10	KC-981 A&B	0.017±0.003	0.288	0.045±0.008	0.315	0.035±0.006
3835	H9	KC-981 A&B	0.030±0.005	0.278	0.077±0.014	0.298	0.060±0.010
3869	[Ne III]	KC-981 A&B	0.151±0.010	0.269	0.233±0.016	0.283	0.290±0.019
3889	He I+H8	KC-981 A&B	0.096±0.007	0.263	0.147±0.011	0.273	0.180±0.013
3967/70 ..	[Ne III]+H7	KC-981 A&B	0.142±0.010	0.242	0.210±0.014	0.243	0.248±0.017
4026	He I	KC-981 A&B	0.012±0.003	0.226	0.017±0.004	0.225	0.020±0.005
4102	Hδ	KC-981 A&B	0.167±0.012	0.205	0.246±0.017	0.200	0.265±0.019
4340	Hγ	KC-981 A&B	0.349±0.024	0.138	0.445±0.031	0.130	0.471±0.033
4363	[O III]	KC-981 A&B	0.064±0.006	0.132	0.079±0.007	0.123	0.085±0.008
4472	He I	KC-981 A&B	0.034±0.005	0.103	0.040±0.006	0.095	0.042±0.006
4686	He II	KC-981 A	<0.012	0.046	<0.013	0.040	<0.013
4861	Hβ	KC-848 A&B	1.000	0.000	1.000	0.000	1.000
4959	[O III]	KC-848 B	1.45±0.05	−0.025	1.39±0.05	−0.017	1.39±0.05
5007	[O III]	KC-848 B	4.75±0.14	−0.037	4.48±0.13	−0.027	4.46±0.13
5876	He I	KC-848 B	0.093±0.013	−0.227	0.065±0.009	−0.155	0.065±0.009
6563	Hα	KC-848 B	4.83±0.17	−0.352	2.70±0.10	−0.237	2.80±0.10
6584	[N II]	KC-980 A	0.031±0.009	−0.355	0.017±0.005	−0.240	0.018±0.005
6678	He I	KC-980 A	0.033±0.010	−0.370	0.018±0.005	−0.250	0.019±0.006
6717	[S II]	KC-980 A	0.072±0.014	−0.377	0.039±0.008	−0.253	0.040±0.008
6731	[S II]	KC-980 A	0.071±0.014	−0.379	0.039±0.008	−0.255	0.039±0.008
7065	He I	KC-980 A	<0.02	−0.390	<0.011	−0.290	<0.010
7136]......	[Ar III]	KC-980 A	det.				

NOTES.—log $I(\lambda)$=log $F(\lambda)$+c$f(\lambda)$. $I(\mathrm{H}\beta)=2\times10^{-14}$ ergs cm^{-2} s^{-1}. Case 1: Normal reddening (c=0.7), 2 Å equivalent width underlying absorption. $E(B-V)$=0.5. Case 2: Modified reddening (c=1.0). $E(B-V)$=0.7. [Ar III] 7136 was detected but the system response correction was too uncertain at this wavelength to permit an estimate to be made of the line strength.

the highest intensity portion of the emission nebula. As a consequence, plate KC-984 A has not been used except, with low weight, in the derivation of the electron density from the sulfur doublet ratio.

Although the consequences were more subtle, it is probable that exposures KC-848 A and B also intersected a neutral helium zone. The strength of the He I λ5876 line and an upper limit for the He I λ4472 line determined from these plates are in contradiction with the helium abundances determined from exposures KC-981 A and B.

b) *Infrared Photometry*

The infrared observations were obtained on the Mauna Kea Observatory 2.24 m telescope on 1978 March 12. The data were obtained with an InSb detector and broad-band filters centered at 1.25, 1.6, 2.2, and 3.8 μm. An 8″ aperture was used, and the beam was chopped 15″ between object and sky reference. A strong signal was detected at the location of the prominent H II region in the southern part of the galaxy. The data are summarized in Table 3. We moved the beam systemati-

TABLE 3

INFRARED PHOTOMETRY

Bandpass	J	H	K	L'
λ(μm)	1.25	1.6	2.2	3.8
S_ν(mJy).......	7.3±0.7	7.3±0.7	5.8±0.5	<5.5[a]
Magnitude ...	13.5±0.1	12.9±0.1	12.6±0.1	>11.8[a]

[a] 3σ upper limit.

cally around the position of peak flux and found no other sources within a square area approximately 12″ on a side centered on the H II region. These observations showed that the source is unresolved in our beam, or that it is smaller than about 4″. At the assumed distance of the galaxy, the corresponding upper limit for the linear diameter of the near-infrared source is 65 pc. Our data cannot exclude the possibility that there is extended emission on a scale of about 15″ or larger.

c) *Neutral Hydrogen Observations*

The galaxy was observed in the 21 cm line by J. R. Fisher with the 91 m telescope at Green Bank. One minute integrations were made at intervals of 3′ in right ascension, with declination held constant. The galaxy was detected at a heliocentric velocity of -92 km s^{-1}, which adjusts to $+96$ km s^{-1} assuming a solar motion of 300 km s^{-1} toward $l=90°$, $b=0°$. The observed flux is $3.4\times10^6\ D^2 M_\odot$ where the distance is D. The observed half intensity line profile width (FWHM) is 54 km s^{-1}. The source was not significantly extended when observed with the 10′ beam. If the spatial distribution of the gas intrinsic to the source is approximated by a Gaussian, then the spatial FWHM is less than 9′.

III. DISCUSSION

a) *Reddening*

It became apparent that the observed line ratios were not consistent with the usual screen model for absorption and the Whitford (1958) reddening curve. The standard reddening correction to line intensities is given by the relationship $\log I(\lambda)=\log F(\lambda)+cf(\lambda)$. The values for $f(\lambda)$ are taken from Burgess (1958), and the expected Balmer line intensities were those calculated by Brocklehurst (1971) interpolated to 16,000 K. It was found that the expected Balmer line ratios with respect to Hβ could be derived only if the coefficient c increased monotonically from $c=0.7$ at Hα to $c=1.4$ for H9–H12.

We have considered five possible explanations for this anomaly: (i) there are observational errors in the line strengths, (ii) the Balmer decrement deviates from the predictions of case B recombination theory, (iii) the higher order Balmer lines are sitting in absorption troughs, (iv) the reddening law is peculiar, or (v) the obscuration and emission arise out of the same region. Concerning (i), it was noted that there was uncertainty in the system response which might affect the Hβ flux with respect to the lines blueward of 4800 Å; but while the most probable sense of a correction for the system response, a relative increase in Hβ, could be reconciled in the blue by assuming somewhat more reddening, the situation with regard to Hα/Hβ would be aggravated. It seems unlikely that the anomaly can be attributed to observational error. Concerning (ii), there seems little reason to entertain that radiative processes are not the dominant cause of excitation of the Balmer series. The prerequisite population of O stars obviously is present, the upper limit on He II λ4686 precludes the existence of very high energy photons that might be anticipated were there a power law spectrum, and in similar objects (cf. Lequeux *et al.* 1979; French 1980) no evidence has arisen which suggests that collisional mechanisms may ever be important.

Concerning (iii), the progressive weakening of the Balmer lines toward the higher members of the series is in the sense anticipated if stellar absorption in the continuum were a problem. The absence of a break in the underlying continuum at the Balmer limit leads to an O star spectral assignment, so equivalent widths in the range 1–3 Å at Hγ can be anticipated (Conti 1973). Shields and Searle (1978) found that by assuming 2 Å equivalent widths they were able to resolve discrepancies in the Balmer decrement in M101 H II regions. Likewise, we find that assuming hydrogen line absorption features of 2 Å equivalent width and an extinction coefficient $c=0.7$ eliminates the reddening anomaly. Line intensities derived on the basis of these assumptions are recorded as case 1 in Table 2. This model offers a plausible explanation for the observed line ratio anomaly. However, there remains some concern because the line emission has been summed over 6″, two to three times the extent of the continuum. The equivalent widths of the Balmer features in the continuum emission then must be roughly 4 Å, which is substantial if the continuum emission arises from O stars.

Concerning (iv), it is true that peculiarities in the reddening law of the same order of magnitude have been observed in other objects (Whiteoak 1966, Anderson 1970), but never in the necessary sense. The observed decrement would require the presence of an excess of small scatterers in VII Zw 403 compared with the local grain population. It will be argued that metal abundances are down from solar values by one to two orders of magnitude, so it is conceivable that the differences in chemistry are enough to produce a different reddening law.

Finally, concerning (v), the emission and absorption might be enmeshed in a complicated region where the optical depth in the continuum can get quite large. One would be looking deeper into the nebula in the red. If the line emissivity goes up deeper into the nebula, due to an increase in the electron density, then the consequence would be a steepening of the Balmer decrement as we observe. It is certainly the case that there is substantial reddening. The coefficient $c=1.0$ derived from Hβ/Hγ/Hδ and the Whitford reddening law implies $E(B-V)=0.7$. At a galactic latitude of 37° the contribution from the foreground will be insignificant.

If our explanation (v) is the right one, then the detailed reddening correction could be quite complicated. Given that any explanation except (ii) or (iii) is correct, intensities will be properly adjusted to first order by modifying the reddening function in a smooth fashion to force the Balmer decrement to agree with the predictions of case B recombination theory. Fortunately, there is only one important line (He I λ5876) which is not near one of the members of the Balmer series in wavelength, so relative line intensities should be accurate as long as our assumption about the intrinsic Balmer decrement is correct. The required reddening law is tabulated with corrected intensities in Table 2 as case 2. A comparison of the line strengths computed with the "normal" reddening function but 2 Å equivalent width underlying absorption (case 1) and "modified" reddening function (case 2) provides an estimate of uncertainties in the relative intensities of red and blue lines.

b) *Electron Temperature and Density*

The relative intensities of the [O III] lines: $(I_{5007}+I_{4959})/I_{4363}$ are dependent on the electron temperature (see Osterbrock 1974). We find $T_e=15{,}000$ K if case 1 reddening is assumed, $T_e=15{,}500$ K if case 2 reddening is assumed, and conclude $T_e=15{,}300\pm800$ K.

The relative line strengths of the [S II] λ6717+λ6731 doublet are sensitive to the electron density (Pradhan 1978). The mean of three exposures gives $I_{6717}/I_{6731}=1.03\pm0.07$. With the electron temperature already determined, $N_e=850\pm230$. Naturally, the errors are only a gauge of the accuracy of the measurements and do not provide any estimate of the fluctuations in T_e and N_e within the emission complex.

c) *Oxygen Abundance*

Oxygen is the only heavy element which can be observed in all its important ionization states. The coincidence of the hydrogen and neutral oxygen ionization potentials assures us that oxygen will be ionized throughout the hydrogen ionization zone, and the coincidence of the ionization potentials to He^{++} and O^{+++} assures us that since He II λ4686 is not seen then there is not a significant amount of triply ionized oxygen. The dominant ionization states will be O^+ and O^{++}.

A convenient compilation of the relevant equations for the determination of ionic chemical abundances has been given by Peimbert and Costero (1969), taken largely from the work of Czyzak *et al.* (1968). From the observed intensities of [O II] λ3727 and [O III] λ5007 we can find values for $N(O^+)/N(O^{++})$ and thus $N(O^{++})/N(O)$ and $N(O^+)/N(O)$ for both reddening functions.[1] The intensity of the λ3727 doublet relative to Hβ and λ5007 relative to Hβ give O^+/H^+ and O^{++}/H^+, respectively. Abundances ratios are recorded in Table 4. Eighty percent of the oxygen is in the form of O^{++}. The total O/H abundance ratio is 5.8×10^{-5}, down by a factor of 15 from solar.

This low abundance is consistent with the empirical correlation between oxygen abundance and nebular temperature given by Alloin *et al.* (1979). Temperatures are high because the cooling provided by oxygen and other heavy elements is ineffective. In a region in which the temperature is as high as 15,000 K, the oxygen abundance should be down by at least an order of magnitude. In fact, the only objects known to have lower O/H are the high temperature regions in I Zw 18 (Lequeux *et al.* 1979) and CG 1116+51 (French 1980) with $O/H=1.5\times10^{-5}$ and 4.3×10^{-5}, respectively.

Following Lequeux *et al.* (1979), the heavy element abundance by mass, Z, can be estimated by assuming it to be proportional to oxygen. For VII Zw 403, $Z\sim 0.0014$. Lequeux *et al.* show that Z determined this way is strongly correlated with total mass. They derive the linear relation $\log M_T=8.18+229\,Z$ from 8 galaxies, including I Zw 18 and II Zw 40 which both have characteristics similar to those of VII Zw 403. The relation suggests $M_T=3\times10^8 M_\odot$ for VII Zw 403. This value is in excellent agreement with the mass derived from the neutral hydrogen line profile width.

d) *Nitrogen Abundance*

The ratio of the intensity of Hα to [N II] λ6584 is 157, indicating a very low N abundance. We do not detect the companion [N II] line at 6548 Å. Only in the case of

TABLE 4

CHEMICAL ABUNDANCES IN VII Zw 403

Ratio	Case 1	Case 2
O^+/O	0.17	0.21
O^{++}/O	0.83	0.79
O^+/H^+	1.0×10^{-5}	1.2×10^{-5}
O^{++}/H^+	4.9×10^{-5}	4.5×10^{-5}
O/H	5.9×10^{-5}	5.7×10^{-5}
[O]	−1.15	−1.17
N^+/H^+	1.2×10^{-7}	1.2×10^{-7}
N/H	7.1×10^{-7}	5.6×10^{-7}
[N]	−2.14	−2.24
N/O	0.012	0.010
Ne^{++}/H^+ ...	6.2×10^{-6}	7.0×10^{-6}
Ne/H	7.5×10^{-6}	8.9×10^{-6}
[Ne]	−1.25	−1.17
Ne/O	0.13	0.16
S^+/N^+	1.57	1.50
S/H	1.1×10^{-6}	8.4×10^{-7}
[S]	−1.16	−1.28
S/O	0.019	0.015

NOTE.—$[X]=\log X/H-\log (X/H)_\odot$. Case 1: Normal reddening, underlying absorption. Case 2: Modified reddening.

[1] Hereafter abundance ratios by number, $N(A)/N(B)$, will be given as simply A/B.

I Zw 18, where [N II] has not yet been detected (French 1980), do we know of a system with a comparably high ratio of Hα/[N II]. It must be cautioned that because of our limited dynamic range in a single observation, the flux in the weak λ6584 line could only be compared with the Balmer series through an intermediate comparison with the moderate intensity [S II] $\lambda\lambda$6717/31 doublet.

Following Peimbert and Costero (1969), we can calculate N^+/H^+. The total nitrogen abundance is determined by assuming $N^+/N=O^+/O$. The results are given in Table 4. Nitrogen is deficient by a factor of about 160 relative to solar N. In VII Zw 403, N/H is lower than in any other system in which N is observed. The upper limit in I Zw 18 is about 50% greater than the observed value in VII Zw 403 (French 1980).

Whereas oxygen will be produced in first generation, pure hydrogen-helium stars and hence is a primary nucleosynthesis product, it is possible that nitrogen contains both primary and secondary production components. The primary N could be produced during asymptotic branch evolution when new carbon, produced by helium burning, has been dredged up by He shell flashes; then ^{14}N is produced from ^{12}C through the CNO cycle in a hydrogen-burning shell (Iben and Truran 1978). Alternatively, after carbon and oxygen have been recycled back into stars, the CNO cycle can produce nitrogen, which then escapes to the interstellar medium through mass loss from red giants, planetary nebulae, or supernovae. Alloin *et al.* (1979) have argued that at least some of the interstellar nitrogen must be of primary origin. Both Lequeux *et al.* (1979) and French (1980) extrapolate the primary N/O component to be 0.02.

In VII Zw 403, the ratio N/O is 0.011, a much lower value than found in any other observed system and only one-half the minimum value expected by Lequeux *et al.* (1979) and French (1980) if there is *no* reprocessing of material. There is easily a factor of 2 uncertainty in our value of N/O. Consequently, our results are not incompatible with the conclusions of French and Lequeux *et al.*, but only if essentially all the nitrogen we observe is of primary origin. At face value, our measurement suggests that at least 90% of the nitrogen in our Galaxy is of secondary origin since N/O in galactic H II regions is about 0.092. Even if all the N in VII Zw 403 is of secondary origin, from the low value of N/O one might conclude there have been few bursts of star formation and little recycling of matter through stars.

Implicit in the above reasoning is the assumption that processed material is returned to the interstellar medium on a relatively short time scale. However, Edmunds and Pagel (1978) have proposed that most interstellar nitrogen may have been produced in stars of sufficiently low mass (1–2.5 $M_\odot$) that roughly 10^9 years separates the epoch of star formation and the epoch of nitrogen enhancement in the interstellar medium. Specifically, Dufour and Talent (1980) argue that type I planetary nebulae are responsible for much, or most, of the nitrogen enrichment of the interstellar medium. If this general viewpoint is correct, then the conclusion would be that essentially all the star formation in VII Zw 403 has occurred in the last 10^9 years.

e) *Neon and Sulfur*

Both neon and sulfur are thought to be primary nucleosynthesis products along with oxygen. The [Ne III] λ3869 line can be used to find the total neon abundance, Ne/H, from $(Ne^{++}/H^+)\times(O/O^{++})$ (Lequeux *et al.* 1979). Table 4 shows that Ne is underabundant relative to the Sun by the same factor as O. The ratio of Ne/O is 0.15, the solar value, somewhat lower than the mean values found by French (1980) of 0.23 or by Smith (1975) of 0.21 for H II regions in spiral galaxies.

The [S II] $\lambda\lambda$6717,6731 lines can be compared in intensity with nearby [N II] λ6584 to give the S^+/N^+ ratio. Since the ionization potential of S^+(23.3 eV) is not too different from that of N^+ (29.6 eV), $S^+/N^+\approx S/N$. From a knowledge of the N/H ratio we derive S/H. These results are also listed in Table 4. They are in excellent agreement with values obtained from S^+/O^{++} (Aller and Czyzak 1968) and the ratio O^{++}/H^+ and the ionization correction factor O/O^+. (Total S will be somewhat underestimated by these means of determining the ionization correction.) Sulfur, neon, and oxygen are all deficient by about the same factor, as would be expected, since all three are thought to be primary nucleosynthesis products.

f) *Helium Abundance*

The relative helium abundance in VII Zw 403 is of particular interest because of the extreme metal deficiency. Only in I Zw 18 is there an environment that is known to be more extreme. The interstellar material in VII Zw 403 may be largely unprocessed.

The total He abundance can be found from $y=y^0+y^++y^{++}$, where $y^i=N(He^i)/N(H)$. The dominant contribution will be from He^+ and can be determined by comparing the recombination spectra of H I and He I. An upper limit for the contribution from He^{++} is provided by the absence of the He II λ4686 feature. A correction to account for the contribution of He^0 can be estimated.

We have derived y^+ through the relations given by Peimbert (1975), Peimbert and Spinrad (1970), and Peimbert and Torres-Peimbert (1977), which compare individual He I line strengths with neighboring hydrogen Balmer lines. As a check, we have compared the relative intensities of He I lines with He I λ4472 as calculated by case B recombination theory (Robbins 1968).

Five separate He I lines are observed. The λ3889 line is not used because of blending with H8 and the possibility of self-absorption. The spectral feature that is generally the most useful for helium abundance determinations is He I λ5876. However, the difficulty with the system response on our deep exposure in the red, KC-980 A, meant we had to rely on the short exposure, KC-848 B, to give the flux at λ5876. Consequently, this line is allotted a low weight relative to its strength. Weights for each He I line are assigned according to the formula: weight ∝ (signal/error)^2, where the error convolves the uncertainties quoted in Table 1 with uncertainties in the reddening correction (which are largest for He I λ5876 because of its isolation from the H Balmer series). The individual values derived for y^+ and the weights of each derivation are recorded in Table 5. Final results are insensitive to the form of the reddening correction. If all four He I lines are averaged on the basis of the assigned weights and the two cases are averaged with equal weight, then $y^+=0.073\pm0.008$ (±0.017). The first error is the inverse quadrature summation of *assigned* uncertainties to the individual lines and the error in brackets is the *observed* rms scatter in the individual abundance determinations using the four separate lines over the two cases.

It can be seen that the scatter in the abundance estimates from the individual lines is significantly greater than what was anticipated based on the internal errors that have been assigned for the two stronger lines at λ4472 and λ5876. It is possible that the slit was not situated at precisely the same part of the nebula for the short and long exposures. It is known from plate KC-984 A that relative He I line strengths can be lower at locations within a few seconds of arc of the most intense part of the emission region, so the proximity of He^0 zones is indicated. An upper limit for λ4472 at the short exposure slit position is marginally at odds with the solid detection of this line at the long exposure slit position. Consequently, it is possible that the lower value of y^+ from λ5876 is caused by a contribution to the Balmer emission from a He^0 zone and the abundance determination from the λ4472 line should be favored.

On the assumption that the emission arises out of a single Strömgren sphere, it is possible to estimate the neutral helium contribution through empirical relationships that are calibrated in the Orion Nebula and take advantage of the overlap in the ionization regions of different species (cf. Peimbert 1975). Lequeux *et al.* (1979) have proposed the ionization correction factor:

$$i_{cf}(He^0)=1/[1-0.25\ O^+/O]$$

for objects with low densities and low O^+/O. In our case, $i_{cf}\approx1.055$ and $y^0=0.005$.

An upper limit was obtained for the intensity of He II λ4686. From the relationship given by Peimbert (1975), we determine $y^{++}<0.001$. We conclude that $y=y^0+y^++y^{++}=0.078\pm0.017$ or $Y=4y/(1+4y)=0.24\pm0.05$.

While, in view of the very low heavy-element abundances, the He observed in the interstellar medium of VII Zw 403 might be essentially primordial, the errors we assign are too large to provide useful constraints on cosmological models. From the relationship between the present density and expansion of the universe and the helium abundance produced in the standard big bang model (cf. Yang *et al.* 1979), universes from very open to marginally closed can be accommodated.

Other observers have derived somewhat lower values of Y and assigned smaller errors (Peimbert and Torres-Peimbert 1976; Lequeux *et al.* 1979; French 1980) by comparing He and metal abundances and extrapolating to zero metal abundance. However, there is considerable scatter in helium abundances determined in different emission regions, and our observations cause us to be concerned that part of the scatter may be the result of frequent admixture of He^+ and He^0 zones within the slit of the spectrograph. Our projected slit was 4×10^3 pc^2 on a relatively nearby galaxy. In the absence of very detailed spatial coverage on well-resolved emission regions, a better estimate of the helium abundance may come from the *upper envelope* in the helium versus metal abundance plots (with account taken of observational errors).

If there is underlying absorption affecting the hydrogen line strengths, then a similar effect might cause the helium line strengths to be underestimated. Again, the result would be an underestimate of the abundance of helium.

TABLE 5

He^+ ABUNDANCE DETERMINATIONS

He I λ	Case 1: y^+	Case 2: y^+	Weight
4026	0.075	0.088	1
4472	0.085	0.089	4
5876	0.052	0.052	2
6678	0.053	0.054	1
Weighted mean ...	0.071 ± 0.016	$0.075+0.019$	

g) Stellar Population Associated with the Bright Emission Region

The available visual and infrared data indicate red and blue components to the stellar population within the brightest emission region. The raw near-infrared colors $J-K \sim 0.9$, $H-K \sim 0.3$ lie within the range of colors observed for the nuclei of normal galaxies (Glass 1973; Frogel *et al.* 1978). Frogel *et al.* have shown through a calibrated CO index that these colors correspond largely to late type stars. We presume that the 1–2.2 μm colors of VII Zw 403 also indicate the presence of cool stars. The possibility that the infrared flux is from giant stars is discounted because we do not expect to find an unresolved concentration of mass coincident with a randomly located H II region in a dwarf galaxy. We conclude that there is a population of red supergiants present.

The hot-star component can be estimated from the hydrogen emission-line spectrum. The observed flux density in Hβ is $\sim 2\times10^{-21}$ W cm^{-2}, with a factor of 2 uncertainty. Assuming $E(B-V) \sim 0.7$, this flux density corresponds to an Hβ photon flux of $\sim 6\times10^{49}$ s^{-1}. Using the relationships given in Osterbrock (1974), and assuming case B recombination theory, we derive the corresponding number of photons emitted shortward of the Lyman limit to be $\sim 5\times10^{50}$ s^{-1}. According to the calculations of Panagia (1973) this Lyman continuum flux would require $\sim$ 10 O5 stars.

We might assume that the emission region in VII Zw 403 contains an OB association with cool supergiants such as, for example, Per OB1 which includes the clusters h and χ Per. This galactic association has linear dimensions of 80×160 pc, compared with the diameter of 90 pc of the emitting region in VII Zw 403. From the study of Per OB1 by Humphreys (1978) we estimate that the flux of Lyman continuum photons from the O stars should be approximately 1.5×10^{50} s^{-1}, or about a factor 3–4 below the flux from VII Zw 403 computed above. Furthermore, with our assumed distance, the integrated absolute 2.2 μm magnitude in the VII Zw 403 emission region is $M_K \sim -15$. The corresponding value for the K and M supergiants in Per OB1 is $M_K \sim -13.3$, or about a factor 5 less than that observed from VII Zw 403. The integrated color of the supergiants in Per OB1 is $J-K \sim 0.9$ which agrees with the observed color of the emission region in VII Zw 403. Thus, we conclude that the observed near-infrared and Balmer emission line characteristics in the brightest H II region of VII Zw 403 can be accounted for by a population of stars similar to those in Per OB1 but 3 to 5 times more numerous.

Of course, fewer exciting stars and cool supergiants would be needed to explain our observations if the galaxy is closer than we have assumed. If VII Zw 403 were 1.5 mag closer (at $\mu_0 \approx 26.0$ mag), then a population identical to that found in Per OB1 would suffice. It may be recalled that the distance modulus was considered uncertain by at least 1 mag.

h) Global Properties of the Galaxy and Initiation of the Star Formation Activity

Global parameters describing VII Zw 403 are summarized in Table 6. The indicative total mass was calculated following Fisher and Tully (1975) and assuming the galaxy has an inclination of 55° (obviously, very uncertain).

The present rate of star formation could not be sustained for a significant fraction of the age of the universe without exhausting the supply of neutral hydrogen. There is evidence in the existence of the unresolved disk and the spectrum by Carozzi, Chamaraux, and Duflot-Augarde (1974) that an old population exists. The implication is that star formation has recently been rekindled. Since VII Zw 403 is quite isolated, there is no evidence for outside stimulation.

It is straightforward to estimate the scale length for gravitational instability in a quiescent medium that must have existed in a slightly earlier epoch. The Jeans length is $\lambda_J = s(\pi/G\rho)^{1/2}$, where s is the sound speed and ρ is the density. The central density in VII Zw 403 can be estimated by comparison with Holmberg I, an irregular galaxy of comparable mass and dimensions which has been the subject of a detailed kinematic study (Tully *et al.* 1978). By simple scaling, the central density, ρ_z, is given by:

$$\rho_Z \approx \frac{\sigma_H}{(2\pi)^{1/2} b_Z} \frac{M_Z}{M_H}\left(\frac{a_H}{a_Z}\right)^2,$$

where σ, M, a, and b are surface densities, total masses, major diameters, and minor diameters, and the subscripts Z = VII Zw 403 and H = Holmberg I. Tully *et al.* (1978) give $\sigma_H = 22\ M_\odot$ pc^{-2}, $M_H = 3\times10^8\ M_\odot$, $a_H =$ 5.0 kpc. If we assume $b_Z/a_Z \approx 0.4$, then $\rho_Z \approx 0.02\ M_\odot$ pc^{-3}. If the gas is neutral, then $s \approx 1$ km s^{-1} is reasonable. Hence, $\lambda_J \approx 200$ pc, which is of the order of the dimensions of the observed active star formation region.

Evidently the problem is not that of initiating star formation if there is neutral gas present within the

TABLE 6

GLOBAL PROPERTIES OF VII Zw 403

Distance assumed	3.25 Mpc
Absolute photographic magnitude	−13.8 mag
Intrinsic luminosity.....................	$5\times10^7\ L_\odot$
Intrinsic diameter (Holmberg scale) ...	2.5 kpc
Size of active star formation region	700×550 pc
Neutral hydrogen mass.................	$4\times10^7\ M_\odot$
Indicative total mass	$2\times10^8\ M_\odot$

potential well of the galaxy but rather, in the context of the "burst" model, of the periodic dispersal and reaccumulation of the interstellar medium. Given the system has an escape velocity of 50 km s^{-1}, it is not difficult to think of mechanisms that could disperse the gas effectively.

IV. CONCLUSIONS

If the galaxy VII Zw 403 were 3 times more distant, it would be indistinguishable from the class of objects referred to as "extragalactic H II regions" (Searle and Sargent 1972) or blue compact galaxies (cf. Huchra 1977). In fact, the chemical abundances and nebular excitation conditions are only slightly less extreme than those in I Zw 18, the most extreme case that is known.

With its proximity, VII Zw 403 is well resolved into roughly 60 very luminous blue stars or stellar associations and a dozen separate emission regions, the ensemble extending across 600 pc. *At the present epoch, star formation is proceeding more vigorously in VII Zw 403 than in any of the other well-resolved dwarf galaxies that have been observed, but in this regard it seems only to represent an extremum in a continuum of conditions.* Galaxies such as GR8 = DDO 155 (Hodge 1967) and DDO 53 (Fisher and Tully 1979; Ruotsalainen 1981) are of comparable intrinsic size and are forming stars at a sufficient rate that substantial emission nebulae have been generated. In galaxies like Sex A and B, Leo A, Holmberg I, and several others the prominent blue star populations indicate relatively recent star formation but emission nebulosities do not stand out. Then there are systems like DDO 210 (Fisher and Tully 1979) and M81 dw A (Lo and Sargent 1979), dwarfs that are gas-rich like the others but which are in a much more quiescent state as regards star formation. The extremum at the quiescent end is presently marked by LGS 3 (Thuan and Martin 1979). One of us (R.B.T.) has *UBV* plate material on this system, and most of the resolved stars are evidently red giant branch stars.

It is certain that the rate of star formation observed in VII Zw 403 could not be sustained over the age of the universe (cf. the arguments by O'Connell, Thuan, and Goldstein 1978). *Two pieces of evidence suggest that there is an underlying old population*: (1) the unresolved diffuse background extending over 2 kpc (Fig. 1), and (2) the interesting spectrum with a convincing continuum break shortward of 4000 Å obtained by Carozzi, Chamaraux, and Duflot-Augarde (1974). Further corroboration of this point is clearly important since there is great interest in distinguishing between objects experiencing repeated bursts and those that are young.

Although the interpretation is not unambiguous, the chemical abundance analysis provides information regarding past cycles of star formation. *We found the primary nucleosynthesis products* O, S, *and* Ne *to be down by a factor of* 15 *from solar abundances*. This factor is low, but not remarkably lower than found in other galaxies with similar properties. In view of the evidence for an older underlying population, it might be supposed that most of the primary products were generated in one or more earlier episodes of star formation.

At the same time, *nitrogen is down from the solar abundance by a factor of* 160. There are two possible interpretations. (*a*) *If the time scale for the deposition of nitrogen into the interstellar medium is short* then there has been very little star formation since the enrichment of the interstellar medium with primary heavy elements. The conclusion is that *there have been very few bursts of star formation*; *perhaps only one previous event*. It would follow that *there is not substantial recycling of material within a given episode of star formation*. (*b*) By contrast, *if the time scale of the cycle that produces interstellar nitrogen is long*, then there is no information on the number of star formation episodes that have occurred but the conclusion would be that *the galaxy is younger than the time scale associated with the interstellar nitrogen production cycle*. Edmunds and Pagel (1978) suggest that the time scale of this cycle is on the order of 10^9 years.

In general terms, *it is possible to understand the initiation of the star formation burst in terms of the Jeans instability mechanism*. The galaxy is isolated, so the possibility of an outside influence is remote. We calculated that the central density would be roughly 0.02 $M_\odot$ pc^{-3}. After an earlier period of activity has long since ceased, along with an accompaniment of supernovae and other stimulants of the interstellar medium, then gas in the system will once again become unstable on a scale of a few hundred parsecs, a scale comparable with the dimensions of the active star formation region at the present moment. The stochastic star formation processes discussed by Gerola, Seiden, and Schulman (1980) may subsequently lead to the widespread activity that is observed.

Turning our attention to the southern H II region that is the most intense source of line emission and of continuum emission in both the blue and the near infrared, we first note that *the reddening is both moderately large* [$(E(B-V)\approx 0.6)$] *and anomalous in comparison with the standard Whitford law*. We proposed several possible explanations and considered two separate cases which lead to rather different corrections to line intensities as a function of wavelength. The results of our abundance analyses were not significantly different in the two cases. It would be possible to distinguish between the high and low obscuration explanations by observing the strength of infrared hydrogen Brackett recombination lines.

There was evidence for substantial populations of both O stars and cool supergiants cohabiting in the region of the southern luminous H II *region*. It is convenient to compare these populations with those found in the galactic OB association Per OB1, which has similar dimensions.

If our choice of a distance for VII Zw 403 of 3.25 Mpc is correct, then the numbers of hot young stars and K and M supergiants in the prominent H II region in that galaxy are about 4 times the numbers found in Per OB1. Alternatively, if the stellar populations in Per OB1 and the VII Zw 403 H II region are in fact the same, then the galaxy must be at only half the assumed distance (1.5 mag closer in the distance modulus).

There remains the important question of the *helium abundance*. We determined the abundance by number to be $y=0.078\pm0.017$ or, alternatively, the abundance by mass to be $Y=0.24\pm0.05$. Unfortunately, these errors are too large to place interesting restrictions on the value of the deceleration parameter q_0, since both open and closed universes can be accommodated.

Our observations did impress two points on us regarding helium. In the first place, the possibility is very real that helium abundance determinations are frequently and systematically affected by the inclusion of He I zones within the slit. If reddening is significant, then it is likely that the emission nebula is actually a complex of separate excitation zones interlaced with heavily obscured regions. Uncertainty in the contribution of y^0 at the 10% level is important.

However, if these observational difficulties can be circumvented, say, by detailed spatial mapping, then the strongest emission region in VII Zw 403 may be pivotal to the question of the primordial helium abundance. There is good evidence that in the core of this H II region most helium is singly ionized. The nebula is sufficiently bright that several He I lines can be observed to suitable levels of signal to noise. Because of the very low abundances of the heavier elements, the ratio He/H is probably quite close to the primordial value. With a detector with better photometric properties, one could probably improve on our uncertainties by a factor of 3. The cosmological constraints would then begin to be interesting.

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PLATE 1

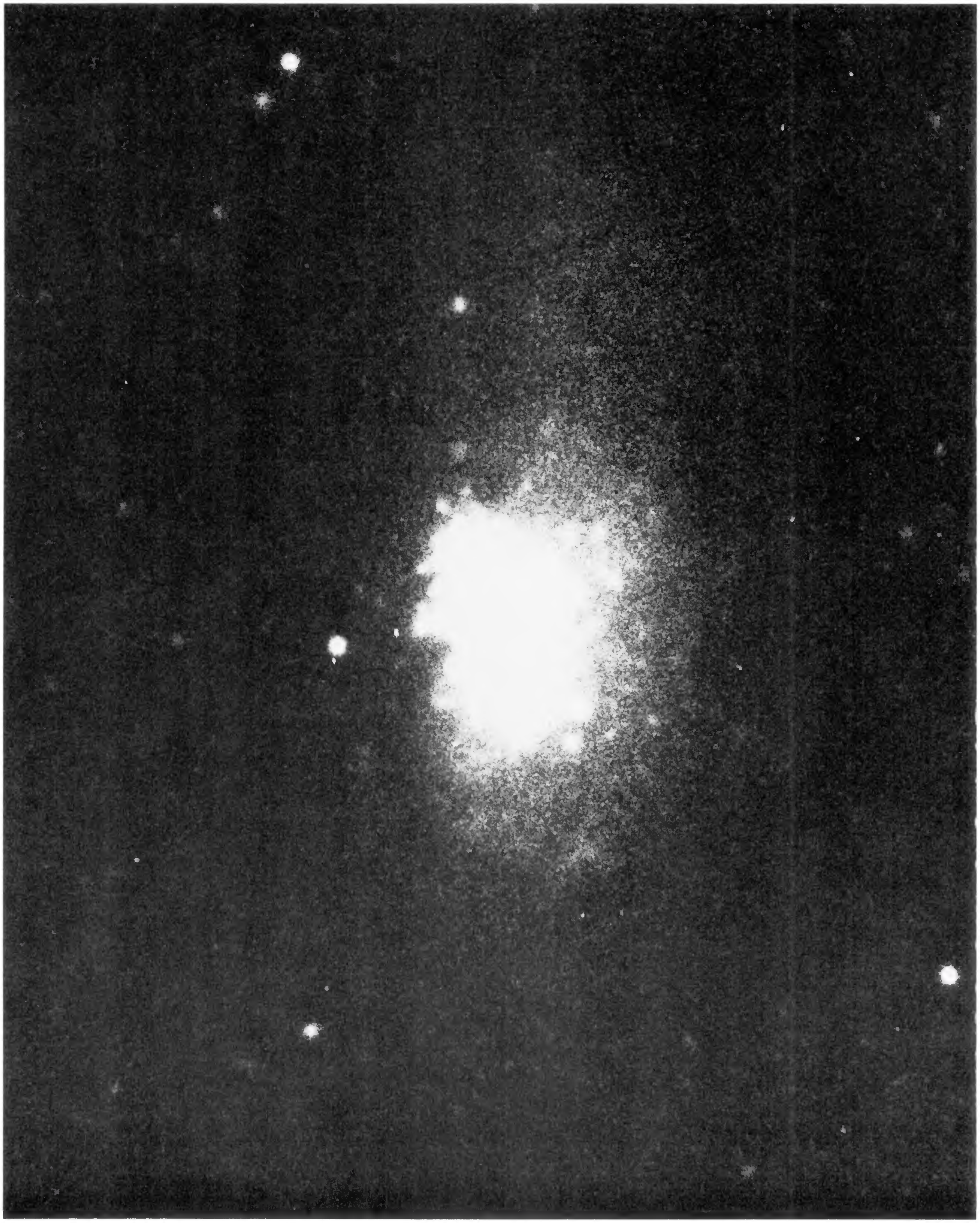

FIG. 1.—A 95 min exposure of VII Zw 403 obtained at the prime focus of the Kitt Peak 4 m telescope with an N_2 baked IIIa-J emulsion+GG 385 Schott filter. Note the extended unresolved component that can be detected over a diameter of 135″. The scale on the reproduction is 1″.00 mm^{-1}.

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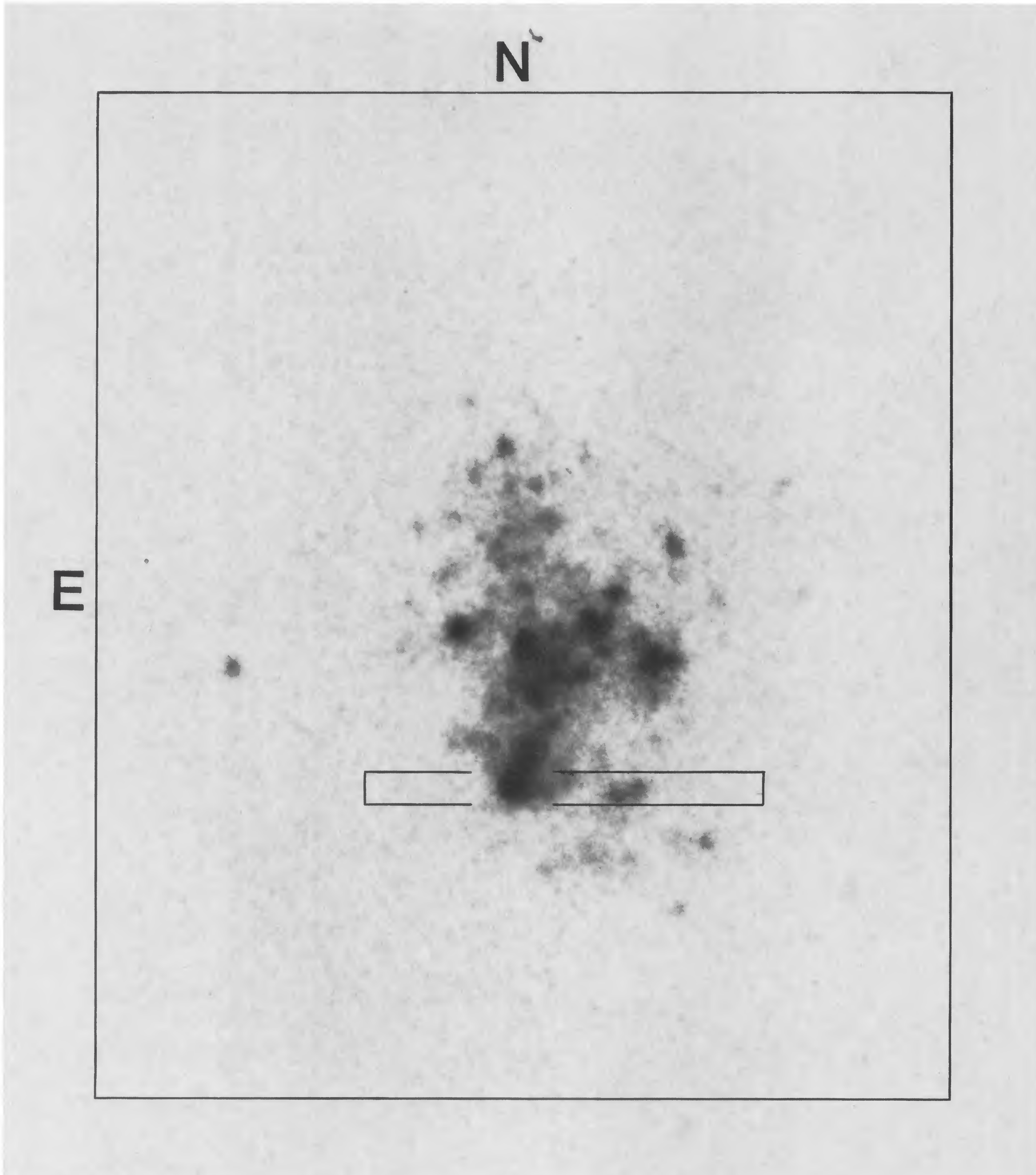

FIG. 2.—An 8 min exposure obtained at the Cassegrain focus of the 2.24 m telescope at Mauna Kea Observatory with a two-stage image intensifier + sensitized IIIa-J emulsion + U bandpass. The superposed slit position intersects the brightest H II nebula at the break in the rectangular outline. This emission region is coincident with the most luminous blue stellar association and the prominent source of near infrared emission. The projected slit length is 32″.

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