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STAR FORMATION AND CHEMICAL ABUNDANCES IN CLUMPY IRREGULAR GALAXIES

ANN MERCHANT BOESGAARD AND SUZAN EDWARDS[1]
Institute for Astronomy, University of Hawaii
AND
J. HEIDMANN
Observatoire de Paris
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ABSTRACT

Clumpy irregular galaxies consist of several bright clumps which are huge H II complexes (about 100 times brighter and more massive than 30 Doradus) and contain about 10^5 O and B stars. Image-tube spectrograms with 1–3 Å resolution have been obtained of the brightest emission regions of three clumpy galaxies and one candidate clumpy galaxy with the Mauna Kea 2.24 m telescope. The electron temperatures were found to be in the range 7000–9000 K and electron densities a few hundred per cm^3—quite typical for normal H II regions. The abundances of O, N, S in Mrk 432 are comparable to those in Orion, while the three clumpy galaxies are slightly deficient in O and S (by factors of 2 to 4) and N (by factors of 3 to 6). The galaxies appear to be normal (like Sc galaxies) in mass and composition. Supernovae remnants are indicated by the high [S II]/Hα ratio. Possible triggering mechanisms for the exceptional star formation activity are discussed.

Subject headings: galaxies: stellar content — nebulae: H II regions — stars: abundances — stars: formation

I. INTRODUCTION

Firsthand information about the star formation processes in galaxies may be found from studies of the giant clumpy irregular galaxies which appear to be undergoing bursts of star formation of exceptional magnitude. These galaxies were initially identified mainly by morphological criteria and by large values of their intrinsic global parameters:

1. They are made up of five to ten high surface brightness clumps loosely scattered in a common envelope; and
2. Their luminosities, dimensions, and internal motions are larger than those of classical irregular galaxies (Casini and Heidmann 1976; Heidmann 1979*a*).

Later work showed that the clumps are hyperactive H II complexes each equivalent on the average to 100 giant H II regions like 30 Doradus. High dispersion spectra of one clumpy irregular, Mrk 296, showed a general rotation leading to a total mass of $10^9\ M_\odot$ for the part containing the eight clumps (Casini, Heidmann, and Tarenghi 1979). A total mass of $\sim 10^{10}\ M_\odot$ for ~ 10 clumps was evaluated for another one, Mrk 297, by Duflot, Lombard, and Perrin (1976), while Taniguchi and Tamura (1981) found $7 \times 10^8\ M_\odot$ for the ionized gas mass in its brightest clumpy region. On the other hand, Börngen and Kalloghlian (1974) showed that for two other clumpy galaxies, Mrk 7 and Mrk 8, each clump has a luminosity $\sim 10^8\ L_\odot$. From these there is a hint that the clumps are each 100 times more massive than 30 Doradus, and it appears that they are 100 times more luminous. Crucial results were obtained from *IUE* low dispersion UV spectra; statistics now available for 10 clumps show that on the average one clump radiates 100 times more than 30 Doradus at 155 nm and that its spectrum can be accounted for by the radiation of 7×10^4 early-type stars (Benvenuti, Casini, and Heidmann 1979, 1980, 1981). Recently Taniguchi and Tamura (1981) determined the number of early stars in the central parts of Mrk 297 to be 1.7×10^5.

These facts strengthen the hypothesis that these clumps are hyperactive H II complexes and that clumpy irregulars are galaxies in which star formation occurs at an extraordinary scale.

Many questions are raised about these objects. The exact nature of the clumps is not settled; though much thermal ionized hydrogen radiation is expected, some clumps show high excitation (du Puy and de Veny 1969; Khachikyan 1972), and the centimetric global radio spectrum is quite steep and nonthermal (Heidmann, Klein, and Wielebinski 1981). Their age should be determined; multicolor photometry indicates an age of 10^{7-8} years (Börngen and Kalloghlian 1974; Huchra 1977). The origin of the grand scale clumpy structure

[1]Current address: Five College Astronomy Department, Smith College.

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and the simultaneous triggering of the huge bursts in each galaxy raises major problems for the origin and evolution of galaxies; the key question is whether clumpy irregular galaxies constitute a transient state of evolution in galaxies—and, if yes, how it is produced and where from—or whether they form a different class of objects (Heidmann 1979*b*).

Therefore, it is of interest to determine the physical conditions and chemical abundances in these most peculiar objects. Together with other data now being collected, such information will help in the understanding of the origin and evolution of such high star formation rates through appropriate chemical and dynamical evolutionary modeling.

Previous attempts to determine the physical and chemical parameters were made with low dispersion spectrographs. Bottinelli *et al.* (1975) and Alloin and Duflot (1979) obtained upper limits or rough estimates of the electron temperature; Tamura and Hasegawa (1979), with an assumption about the temperature, obtained rather low oxygen abundances for the clumpy galaxy Mrk 325. In their last work, Taniguchi and Tamura (1981) obtained O, N, and S underabundances for Mrk 297. Here we report on high dispersion spectrographic work on three clumpy irregular galaxies and one suggested candidate clumpy galaxy, Mrk 432.

II. OBSERVATIONS AND DATA REDUCTIONS

Spectrograms of complexes of ionized hydrogen in four peculiar clumpy galaxies were obtained with the Cassegrain image tube spectrograph on the 2.24 m telescope at the Mauna Kea Observatory in 1980 February and April. The grating used has 1200 l mm^{-1} and is blazed in the first order red at 6700 Å. Three wavelength regions were observed in different grating positions: in the red covering the Hα, [N II], and [S II] lines; in the green covering Hγ, Hβ, and [O III]; and in the blue covering [O II] through Hδ. Kodak II a-O plates were used for all exposures; a Schott GG 475 filter was used for the red plates; and a combination BG 38 and BG 25 Schott filter was used for the blue plates. With this system, it is possible to obtain fairly high spectral resolution (2.5 Å in the red, 1.2 Å in the blue) and fairly high spatial scale (57″ mm^{-1} on the plate) in reasonably short exposure times. A log of the observations is given in Table 1. The slit length was 50″ long for all plates except the last two, for which it was 62″; the slit width

TABLE 1
SPECTROSCOPIC OBSERVATIONS

Object	Plate Number	Wavelengths	Exposure (min)	Dispersion (Å mm^{-1})	Slit Position Angle (°)
Mrk 7......	KC-1085 A	5400–7300	25	54	90
	KC-1085 B	5400–7300	45	54	90
	KC-1085 C	4100–6100	45	54	90
	KC-1085 D	4100–6100	15	54	90
Mrk 432...	KC-1086 A	4100–6100	45	54	0
	KC-1086 B	4100–6100	15	54	0
	KC-1086 C	5400–7300	45	54	0
	KC-1086 D	5400–7300	15	54	0
	KC-1129 A	3500–4150	36	27	0
	KC-1129 B	3500–4150	12	27	0
VV 523 ...	KC-1129 C	3500–4150	10	27	30
	KC-1129 D	3500–4150	25	27	30
	KC-1130 A	5400–7300	45	54	30
	KC-1130 B	5400–7300	15	54	30
	KC-1130 C	5400–7300	5	54	30
	KC-1131 A	4100–6100	45	54	30
	KC-1131 B	4100–6100	15	54	30
	KC-1131 C	4100–6100	5	54	30
Mrk 296...	KC-1126 A	5400–7300	45	54	166
	KC-1126 B	5400–7300	15	54	166
	KC-1126 C	4100–6100	45	54	166
	KC-1132 A	4100–6100	25	54	166
	KC-1132 B	5400–7300	30	54	166
	KC-1132 C	3500–4150	60	27	166
	KC-1132 D	3500–4150	25	27	166
	KC-1132 E	3500–4150	10	27	166

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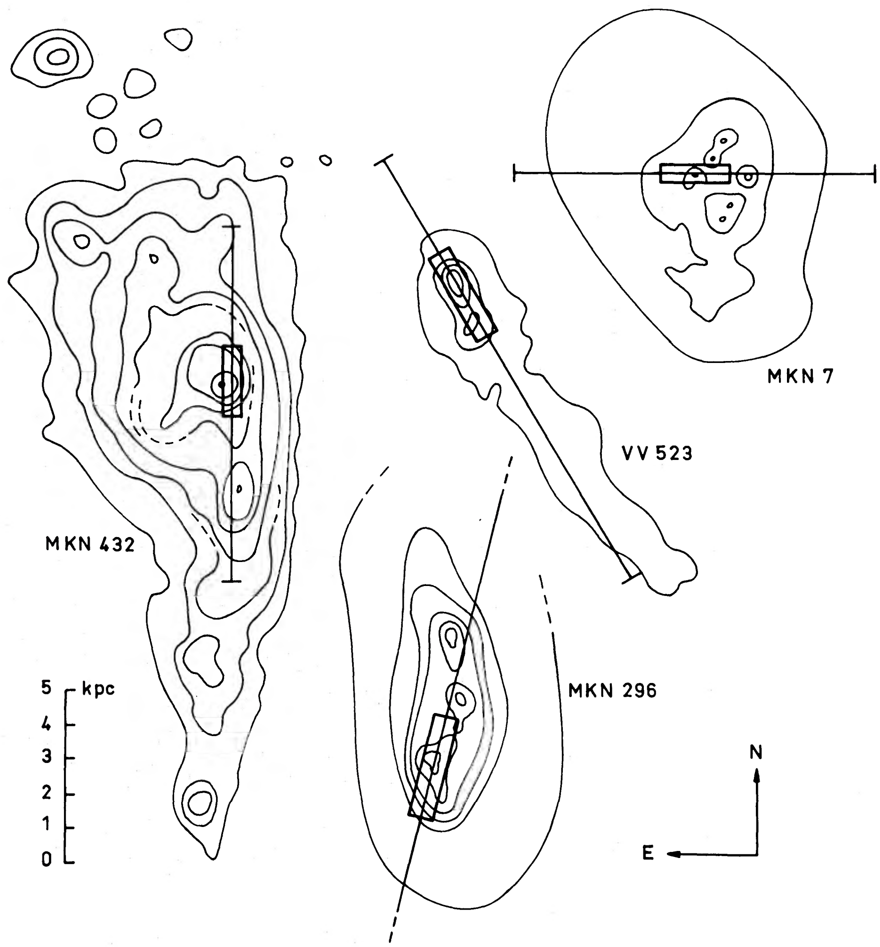

FIG. 1.—Isophotes of the four galaxies showing the slit orientation and extent. The central rectangle shows the area over which we integrated for the line intensity measurements. The slit width was approximately 2″.

was 2″. Figure 1 shows the orientation of the slit on each of the four galaxies.

The spectrograms were calibrated photometrically by means of a series of exposures of an LED source through calibrated neutral-density filters with the spectrograph and image tube. To determine the system response, spectrograms were taken of standard stars of known spectrophotometric properties (Hayes 1970) for each night for each grating setting. The plates were raster-scanned with a 12 $\mu \times 12$ μ slit on the PDS microdensitometer at the Institute for Astronomy and corrected through the appropriate characteristic curve to yield intensities. The calibrated scans of the standard stars were integrated along the slit and used to define the system response and to correct the scans of the galaxy spectra. These corrected, calibrated galaxy scans were then plotted on a Gould plotter with various degrees of contrast. From these plots, scan lines were selected to determine the sky background and the regions of strong emission. The integrated night sky was then subtracted from the integrated emission spectra for each wavelength region for each galaxy.

Strengths of all emission lines were measured on the corrected, integrated intensity tracings. Intermediate strength lines were used to scale long and short exposure plates. Strong lines which were saturated on long exposures were not used. Table 2 lists the wavelengths and identifications of the features measured in each object, the measured intensities relative to $H\beta = 100$, $F(\lambda)$, and the exposures used to derive those intensities.

The plates covering the three different wavelength regions were interrelated through the Balmer lines. First, the reddening was found through the observed intensity ratio of $H\beta$ to $H\gamma$ which appear on the same (green) region of the spectrograms. Then the measured $H\alpha$ intensity was forced to match Case B reddening (as derived by Brocklehurst 1971); the [N II] and [S II] lines were scaled to that and corrected for reddening using values of $f(\lambda)$ from Burgess (1958) and standard relationship $\log I(\lambda) = \log F(\lambda) + cf(\lambda)$, where c was found

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TABLE 2

MEASURED AND CORRECTED LINE INTENSITIES

LINE		Mrk 7 $c=0.9$			Mrk 432 $c=1.2$			VV 523 $c=0.85$			Mrk 296 $c=0.66$		
λ	Ident.	Plate(s)	$F(\lambda)$	$I(\lambda)$	Plate(s)	$F(\lambda)$	$I(\lambda)$	Plate(s)	$F(\lambda)$	$I(\lambda)$	Plate(s)	$F(\lambda)$	$I(\lambda)$
3727	[O II]	...	...	...	1129 B	111.8	258.2	1129 C	119.7	218.7	1132 D, E	201.9	322.4
3835	H9	...	...	...	1129 A, B	1.2	2.6	1129 C, D	4.5	7.8	...	...	...
3869	[Ne III]	...	...	...	1129 A, B	10.2	21.2	1129 C, D	14.8	25.1	1132 C, D, E	18.1	27.2
3889	He I+H8. .	...	...	...	1129 A, B	7.6	15.5	1129 C, D	11.0	18.4	1132 C, D, E	7.8	11.6
3967	[Ne III]	...	...	...	...	...	...	1129 C, D	2.5	4.0	1132 C, D, E	4.0	5.8
3970	Hε	...	...	...	1129 A, B	8.4	16.2	1129 C, D	10.7	17.2	1132 C, D, E	9.2	13.3
4101	Hδ	...	...	...	1129 A, B	14.8	25.9	1129 C, D	17.3	25.9	1132 C, D, E	19.0	25.9
4340	Hγ	...	(35.2)	46.9	1086 A, B	32.2	46.9	1131 B	35.8	46.9	1132 A, 1126 C	38.0	46.9
4861	Hβ	1085 C, D	100	100	1086 A, B	100	100	1131 B, C	100.	100.	1132 A, 1126 C	100	100
4959	[O III]	1085 C, D	102.1	96.9	1086 A, B	28.8	26.9	1131 B, C	77.8	74.1	1132 A, 1126 C	93.2	89.7
5007	[O III]	1085 D	266.1	246.5	1086 A, B	89.7	81.1	1131 C	225.0	209.3	1132 A	221.8	209.7
6548	[N II]	1085 A, B	18.0	8.7	1086 C, D	68.7	26.6	1130 A, B[b], C	34.8	17.5	...	...	...
6563	Hα	1085 A, B	591.7	285.3	1086 C, D	742.9	285.5	1130 C	568.2	285.3	1126 B, 1132 B	487.1	285.3
6584	[N II]	1085 A, B	62.6	30.0	1086 C, D	216.5	82.5	1130 A, B[b], C	86.9	43.4	1126 A, B, 1132 B	38.6	22.5
6717	[S II]	1085 A, B	110.6	50.6	1086 C[a], D	106.4	38.2	1130 A, B[b], C	140.1	66.3	1126 A, 1132 B[c]	76.7	43.2
6731	[S II]	1085 A, B	37.0:	16.9:	1086 C[a], D	76.6	27.4	1130 A, B[b], C	94.0	44.3	1126 A, 1132 B[c]	61.6	34.6

[a]Intensities on 1086 C given twice the weight as those on 1086 D for these lines.
[b]Intensities on 1130 A and B were scaled to 1130 C through λ6584 and λ6717.
[c]Intensities on 1132 B given twice the weight of those on 1126 A for these lines.

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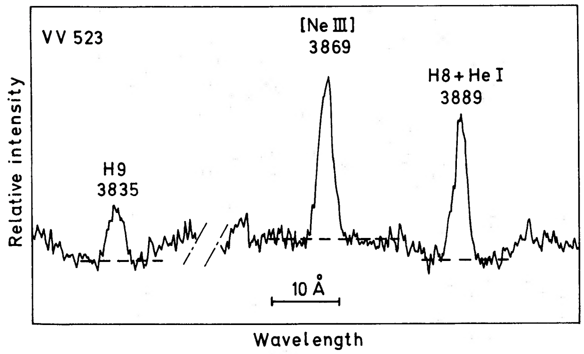

FIG. 2.—A portion of the intensity tracing of a spectrum of VV 523 showing the H I emission lines superposed on the H I stellar absorption troughs; there is no such absorption by the [Ne III] line. The horizontal dashed lines show the local continua used for each line.

from the Hβ/Hγ ratio. Similarly, the measured Hδ intensity was forced to match Case B reddening, and the other lines on the blue spectrograms were scaled to that and corrected for reddening. Table 2 also gives those reddening corrected intensities, $I(\lambda)$, and the derived value of c for each galaxy. The reddening parameters, c, are near the upper end of those observed in other galaxies, especially in Mrk 432. In our spectrograms of Mrk 7, the strength of Hγ is too small to determine a meaningful intensity and therefore reddening parameter, so we have adopted $c=0.9$ as a representative value for this type of galaxy.

The intensities given in Table 2 have probable errors of about 10–30% based on the internal agreement among plates and on previous spectrophotometry with this system. In unfavorable cases, line *ratios*, therefore, could be in error by 1.5–2. For Mrk 432 and VV 523, there is clear evidence of absorption troughs in the higher Balmer lines ($n>7$) which we have tried to correct for in the emission intensities. Figure 2 shows a portion of the intensity tracing of H8 and H9 in VV 523. The absorption is too weak to produce a meaningful effect on the intensities of the Hα–Hδ emission. The presence of Balmer absorption lines is evidence for an early-type stellar population. There is no evidence for absorption at the Ca II K line nor the line-blanketing continuum break near 4000 Å, both of which are late-type stellar population indicators, but only for VV 523 is the continuum clearly well exposed enough to definitely rule out the presence of those two features.

III. TEMPERATURES, DENSITIES, AND ABUNDANCES

a) *Electron Temperature Determinations*

The standard line ratio from which to determine temperatures ([O III] $\lambda5007+\lambda4959$)/[O III] $\lambda4363$, could not be used for these objects because [O III] $\lambda4363$ was too weak to observe. Consequently, two other methods were applied from empirical correlations of line ratios and temperatures. First, Pagel *et al.* (1979) have assembled data on line ratios ([O III] ($\lambda5007+\lambda4959$)+[O II] $\lambda3727$)/Hβ and temperatures and have established an empirical relationship shown in their Figure 8. Second, Alloin *et al.* (1979) show the empirical correlation between temperature and the line ratio [O III] ($\lambda5007+\lambda4959$)/[N II] ($\lambda6584+\lambda6548$) in their Figure 1. Application of these two methods yielded closely similar temperatures; the results are presented in Table 3. The adopted temperatures give double weight to the [O III]+[O II] method since the [O III]/[N II] method makes an implicit assumption about the normalcy of the abundance ratio. If the O/N ratios in these objects are higher than normal, then the temperatures found from the [O III]/[N II] method should be lower. If our reddening corrections are too large, then the [O II] lines are preferentially enhanced and the [N II] lines diminished; for both methods to recorrect for an oversized reddening would reduce the temperature. The errors given on the temperatures result from an estimated error in the line ratios of a factor of 1.2 and from the agreement between the two methods, but do not include the possible systematic effects intrinsic to the methods used or those from incorrect reddening. The temperatures of these H II complexes, 7000–9000 K, are quite typical of galactic and extragalactic H II regions of normal composition (e.g., Smith 1975; Hawley 1978; Shields and Searle 1978). (In metal deficient regions, cooling through

TABLE 3

ELECTRON TEMPERATURES AND DENSITIES

Galaxy	T([O III]+[O II]) (K)	T([O III]/[N II]) (K)	T(adopted) (K)	N_e (e cm^{-3})
Mrk 7	...	8900	8900±200	<100
Mrk 432 ...	7200	7000	7130±200	100
VV 523	8000	8300	8100±200	<300
Mrk 296 ...	8600	8900[a]	8650±250	200

[a]Low weight since $\lambda6548$ of [N II] was not observed, and the ratio 3/1 was used for $I(6584)/I(6548)$.

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radiation in the forbidden lines is less efficient which results in higher temperatures.)

b) *Electron Densities*

The ratio of the [S II] doublet λ6717/λ6731 was used to determine the electron density with the revised collisional rate coefficients of Pradhan (1978). For all four galaxies, this ratio is clearly greater than 1.2 which corresponds to $n_e < 300$. The line ratios and electron densities are presented in Table 3. For VV 523 and Mrk 296, it was also possible to separate the two components of [O II] at λ3729 and λ3726. The ratio λ3729/λ3726 was also >1.2, corresponding to $n_e < 300$ (with collision strengths and rate coefficients from Pradhan 1976). The values given in Table 3 for n_e are consistent with those determined in normal H II regions.

c) *Chemical Abundances*

The basic equation for the determination of abundance ratios is given by Dufour (1975, eq. [3]). We worked from the compilation which incorporates the specific atomic parameters in the paper by Peimbert and Costero (1969), except for *S* where the new data of Pradhan (1978) were used.

i) *Oxygen*

In H II regions, oxygen occurs as O^+ and O^{++} ions, both of which are observed spectroscopically in our galaxies except for Mrk 7 for which no blue spectrograms were obtained and thus no intensities for [O II] λ3727. Table 4 shows the abundance ratios for each of the two O ions and the total O/H abundance. Since both the temperature and the O^{++}/H^+ ratios in Mrk 7 are virtually the same as in Mrk 296, it was assumed that the ratios O^+/H^+ and thus O/H were also the same in Mrk 7 as in Mrk 296. The degree of ionization of O is used later to establish the ionization correction factors for the other elements.

Compared to the Orion Nebula (Peimbert and Torres-Peimbert 1977; Pagel 1978), the O/H abundance ratio for Mrk 432 is normal, while the other three are mildly (less than a factor of 2) deficient in O. Following Lequeux *et al.* (1979), the O abundance can be used to determine the heavy element content, *Z*, in these objects. This is also given in Table 4 and is seen to be 1–1.5% by mass, normal in Mrk 432, somewhat metal deficient in the other three. For Orion, *Z* is 1.4–1.9% (Peimbert and Torres-Peimbert 1977; Pagel 1978). This indicates that these galaxies are not composed of unprocessed material or extreme Population II stars.

ii) *Nitrogen*

The λ6584 line of [N II] can be used to find the ratio N^+/H^+ which can be multiplied by the ionization correction factor O/O^+ to give N/H. Those results are also presented in Table 4 and show a range in N deficiency of factors of 1.3 to 6.5, compared to Orion. This range appears to be real rather than an artifact of an incorrect value for the reddening, since the reddening independent ratio Hα/[N II] λ6584 ranges from 3.4 to 12.6 in similar sequence to the abundance ratios. Again, Mrk 432 appears to have a nearly normal N content, while the other three are deficient in N by small but believable amounts. For the Sun and the Orion nebula, N is down by an order of magnitude relative to O. With the probable exception of Mrk 432, in these objects N is more deficient than O by small factors, i.e., O/N is 20–40, rather than ~10. The ratios are listed in Table 4.

iii) *Neon and Sulphur*

The [Ne III] line at λ3869 can be used to find the Ne^{++}/H^+ abundance ratio and O/O^{++} gives the ionization correction factor. However, the determination of

TABLE 4

ABUNDANCES

Abundance Ratio	Mrk 7	VV 523	Mrk 432	Mrk 296
O^+/H^+	...	2.2×10^{-4}	5.0×10^{-4}	2.3×10^{-4}
O^{++}/H^+	1.2×10^{-4}	1.4×10^{-4}	9.4×10^{-5}	1.2×10^{-4}
O/H	3.5×10^{-4}	3.6×10^{-4}	5.9×10^{-4}	3.5×10^{-4}
[O/H]	−0.2	−0.19	0.02	−0.21
Z	0.009	0.009	0.015	0.009
N^+/H^+	6.7×10^{-6}	1.3×10^{-5}	3.7×10^{-5}	5.5×10^{-6}
N/H	1×10^{-5}	2.1×10^{-5}	4.4×10^{-5}	8.3×10^{-6}
[N/H]	−0.8	−0.43	−0.12	−0.84
N/O	3×10^{-2}	5.8×10^{-2}	7.3×10^{-2}	2.4×10^{-2}
Ne^{++}/H^+	...	6.8×10^{-5}	1.0×10^{-4}	4.8×10^{-5}
Ne/H	...	1.7×10^{-4}	1.5×10^{-4}	1.4×10^{-4}
S^+/H^+	1.9×10^{-6}	4.0×10^{-6}	3.6×10^{-6}	2.3×10^{-6}
S/H	2.8×10^{-6}	6.6×10^{-6}	4.3×10^{-6}	3.5×10^{-6}

NOTE.—$[X/H] = \log X/H - \log X/H$ (Orion).

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Ne^{++}/H^+ is sensitive to both temperature and reddening. The results presented in Table 4 show that the ratios of Ne/H and Ne/O are approximately normal (within the errors) except for Mrk 432, but in that case the low temperature and large reddening may be the source of larger errors in the Ne abundance determination. The abundances of Ne and O should go together in a ratio of ~0.2, inasmuch as there is no known nucleosynthetic process to preferentially enrich Ne with respect to O.

For S we have only the [S II] doublet λλ6717, 6731 and no lines from other S ions. Consequently, correction for the unobserved stages of ionization and thus total S abundances are uncertain as has been pointed out by several authors (e.g., Natta, Panagia, and Preite-Martinez 1980; Dinerstein 1980). Abundance ratios S^+/H^+ were calculated with the new values for the collision strengths (Pradhan 1978) and with O/O^+ as the correction factor (albeit incorrect) and appear in Table 4. For these temperatures, the use of the new collision strengths gives S^+/H^+ abundances that are typically 2.7 times smaller than those calculated with the old values.

The ratio of this [S II] doublet to Hα has been shown to be large by Westerlund and Mathewson (1966) in supernova shells, 0.9–1.5. Boeshaar *et al.* (1980) suggest that a ratio F ([S II] $\lambda 6717+6731)/F(\mathrm{H}\alpha) \gtrsim 0.12$ may indicate recent supernova ejecta. That ratio for the H II complexes in these clumpy galaxies is Mrk 7:0.25; Mrk 432:0.25, VV 523:0.41; Mrk 296:0.28. Typical values of this ratio for other H II regions are, for example, 0.04–0.12 in M33 (Kwitter and Aller 1981), 0.03–0.29 in the Galaxy (Hawley 1978), 0.09–0.23 in M101 (Shields and Searle 1978), 0.03–0.09 in the blue compact and irregular galaxies (Lequeux *et al.* 1979), while Dopita, D'Odorico, and Benvenuti (1980) give values from 0.7–1.2 for 12 supernova remnants in M33. Thus, the spectroscopic evidence, especially in the case of VV 523, supports the intuition that an admixture of H II regions and supernova shells exists, the natural by-product of the formation and evolution of so many massive O and B stars.

IV. VELOCITY DISPERSIONS AND MASSES

The full-width at half maximum (FWHM) ΔV of several forbidden lines can be measured to yield velocity dispersions. We have measured these widths for [N II] λ6584 and [S II] λλ6717 and 6731 in the red and [Ne III] λ3869 in the blue. The instrumental FWHM was found to be 144 km s^{-1} in the red and 123 km s^{-1} in the blue; Gaussian line profiles were assumed, and the observed width was approximated by the square root of the sum of the squares of the instrumental width and the true width. Between three and seven lines were measured for each galaxy, but only for the case of VV 523 where the measured widths are 190 km s^{-1} are the lines clearly broader than the comparison lines. The true width is 126 ± 29 km s^{-1}.

A virial mass can be estimated from the velocity dispersion. With spherical Gaussian mass and velocity distributions, the virial mass is given by Volders and Högbohm (1961) as

$$M_G = 1.9 \times 10^9 \phi_{1/2} \Delta V^2 \, M_\odot ,$$

where $\phi_{1/2}$ is a clump diameter at half-maximum intensity in kpc and ΔV is the above FWHM velocity dispersion in 100 km s^{-1}. We take $\phi_{1/2}$ to be the order of the seeing disk on the photographs of Casini, Heidmann, and Lelievre (1974), i.e., 1.5 arcsec or 300 pc at 40 Mpc. This corresponds to $9 \times 10^8 \, M_\odot$. This value should be looked at with caution due to uncertainties in the velocity dispersion, the "assumed" diameter, and the hypothesis of the virial model. It is in reasonable agreement with masses of the clumps in Mrk 296 and Mrk 297 discussed in § I.

V. CONCLUSIONS

The spectroscopic studies of the hyperactive H II complexes have shown that the physical conditions—temperature and electron density—are quite typical of normal H II regions in spiral galaxies. The temperatures are in the range 7000–9000 K, and electron densities are a few hundred per cm^3. The observed Balmer decrements in Mrk 296, VV 523, and especially Mrk 432 are quite steep, resulting in rather high values for c (0.7–1.2) and corresponding high values of A_v between 1.4–2.6. This may indicate the presence of a considerable amount of dust. (The values for c were found from $\mathrm{H}\beta/\mathrm{H}\gamma$ ratios; although we detected no evidence for underlying absorption in the lower Balmer lines, if it were there, it would affect Hγ more than Hβ and thus mimic a high reddening value.)

The chemical abundances are quite normal—typical of galactic and extragalactic H II regions. Relative to Orion (Peimbert and Torres-Peimbert 1977), Mrk 432 has comparable abundances of O, Ne, and S. (Its apparent enhanced Ne abundance is probably an artifact of the large reddening and relatively low T as discussed earlier. Nonetheless the Ne abundance is similar to some H II regions in our Galaxy observed by Hawley 1978.) The three clumpy galaxies show small deficiencies relative to Orion in the primary nucleosynthetic products, O, Ne, and S, with the partly primary, partly secondary nucleosynthetic product N being preferentially deficient. However, the values derived are well within the range observed for typical H II regions in normal spiral galaxies such as M33 (Smith 1975; Kwitter and Aller 1981), M101 (Smith 1975; Shields and Searle 1978), and the Galaxy (Hawley 1978; Peimbert, Torres-Peimbert, and Rayo 1978). The abundances are similar to those found in H II regions in the disk, near the galactic nuclei of Sc–Scd galaxies.

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The ratio of F([S II] λ6717, 31)/F(Hα) is larger than is typical of galactic H II regions, especially for VV 523. In fact this ratio approaches those found in supernovae remnants (Dopita, D'Odorico, and Benvenuti 1980). This raises the intriguing possibility that in addition to the 10^5 O and B stars within the H II complexes, the clumps contain numerous supernova shells.

Masses of the clumps fall in the range $1-10\times10^8\ M_\odot$ for VV 523 and for Mrk 296 and Mrk 297 (Casini, Heidmann, and Tarenghi 1979; Duflot, Lombard, and Perrin 1976; Taniguchi and Tamura 1981). Total masses were roughly indicated by the O content which gives the Z content which appears to correlate with mass for irregular galaxies following Lequeux *et al.* (1979). Masses of about $10^{10}\ M_\odot$ were found this way, except for Mrk 432 which was $\sim2\times10^{11}\ M_\odot$, but off-scale of the Lequeux *et al.* (1979) relation.

The normal abundances indicate that the material has been processed through previous episodes of star formation. The roughly determined masses imply that these galaxies are more similar to late-type spirals than to classical irregular or blue compact galaxies. Nonetheless, there is spectroscopic evidence of huge numbers of O and B stars from *IUE* spectra (Benvenuti, Casini, and Heidmann 1979, 1980, 1981). The obvious Balmer absorption troughs in VV 523 and Mrk 432 give further evidence of an early stellar population. The combination of processed or enriched gas with a large population of young stars leads to the conclusion that the clumpy galaxies are not evolutionarily young but have recently undergone a large scale burst of star formation.

The causes of the sudden, recent episode of star formation can be of two different types: external, such as a collision or close encounter with another galaxy; or internal, such as shocks produced by supernovae leading to compression and collapse of multiple protostars. The external agents can take the form of a collision with an intergalactic cloud or another galaxy, a merger, or a close encounter. Recently Fisher and Tully (1981) have estimated the density of intergalactic clouds to be exceptionally low, and even though clumpy irregular galaxies are rare, this seems to be an unlikely triggering mechanism for star formation. Alloin and Duflot (1979) have suggested that the structure of Mrk 297 results from a collision of two galaxies. We have searched for evidence of double nuclei or spiral arms in the optical pictures of these galaxies. In the case of Mrk 432, the most massive in our sample, there is an indication of rudimentary spiral structure and Casini, Heidmann, and Testor (1981) have recently presented evidence that it is a barred spiral, though knotty and asymmetric. Mrk 296 is part of a small group of galaxies which contains Mrk 297 and the Seyfert sextet, and its peculiarities may be related in some way to this bizarre environment. Mrk 7 is near another clumpy galaxy Mrk 8 and the peculiar galaxy VV 141.

The internal source, shocks produced by supernovae leading to star formation, may be the explanation for VV 523, since the supernova remnant indicator, [S II]/Hα, is especially large for this object. Supernovae represent a natural consequence of the evolution of massive stars, and thus supernova shells may be an effect rather than a primary cause of star formation. The exceptionally high internal motions noted by Casini and Heidmann (1976) may be related—both cause and effect—to the broad scale star formation process.

While the clumpy irregular galaxies show many common properties (morphology, composition, luminosity, etc.), the origin of these objects may not be due to the same source. Nonetheless, the phenomenon of such widespread (several clumps per galaxy) and exceptionally active (10^5 O and B stars) star formation is extraordinary and the elucidation of the source a challenge.

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ANN MERCHANT BOESGAARD: Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822

SUZAN EDWARDS: Five College Astronomy Department, Clark Science Center, Smith College, Northampton, MA 01063

JEAN HEIDMANN: Radio Astronomie, Observatoire de Meudon, 92190 Meudon, France

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