

TWO GALAXIES WITH WOLF-RAYET FEATURES IN THEIR SPECTRA¹

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ABSTRACT

Spectral scans are presented of two galaxies, NGC 6764 and Mrk 309, which show the Wolf-Rayet emission band $\lambda 4650$ in the spectra of their nuclei. Their spectra are discussed and compared with the spectra of two previously known dwarf galaxies which show this same feature, as well as with the spectrum of the H II region NGC 604 in M33. The numbers of Wolf-Rayet stars in the nuclei of NGC 6764 and Mrk 309 similar to those in our Galaxy, or of supermassive Wolf-Rayet stars similar to the one which may be present in 30 Dor, are estimated.

Subject headings: galaxies: individual — galaxies: nuclei — galaxies: stellar content — stars: Wolf-Rayet

I. INTRODUCTION

In a continuing program at Lick Observatory on radio and Seyfert galaxies, spectral scans have been obtained of many objects suspected from previously published work of being active galaxies (Osterbrock 1976). Among the objects observed, two were found to be narrow emission-line galaxies with the broad Wolf-Rayet emission feature usually described as $\lambda\lambda 4640, 4650, 4686$ strong and easily apparent in their spectra.

One is NGC 6764, for which a "high-dispersion" blue scan is shown in Figure 1. It was classified as a Seyfert galaxy by Rubin, Thonnard, and Ford (1975). In his systematic study of Seyfert 2 galaxies, Koski (1978) included NGC 6764 but noted that it has relatively weak [O III] and an emission-line spectrum very similar to that of a normal galaxy. More recently, Shuder and

Osterbrock (1981) concluded that NGC 6764 is not a Seyfert 2 galaxy. None of these authors mentioned the broad Wolf-Rayet emission blend that is apparent in the spectrum of NGC 6764 in Figure 1.

Mrk 309 = IV Zw 121 was identified as a galaxy with a bright ultraviolet continuum and noticeable H α emission by Markarian and Lipovetskii (1971), who concluded that it possibly has Seyfert characteristics. Arakelian, Dibai, and Esipov (1972) noted the presence of diffuse H α in emission, as well as [N II] $\lambda\lambda 6548, 6583$. Afanasev *et al.* (1980) reported the same lines and stated that Mrk 309 may be a Seyfert 2 galaxy. None of these papers mentioned the presence of the Wolf-Rayet emission feature that can be seen in Figure 2.

Only three other galaxies are known to us which have the Wolf-Rayet $\lambda 4650$ emission band detectable in the spectra of their nuclei. They are He 2-10 (Allen, Wright, and Goss 1976), NGC 3125 = Tololo 3, and (with $\lambda 4650$

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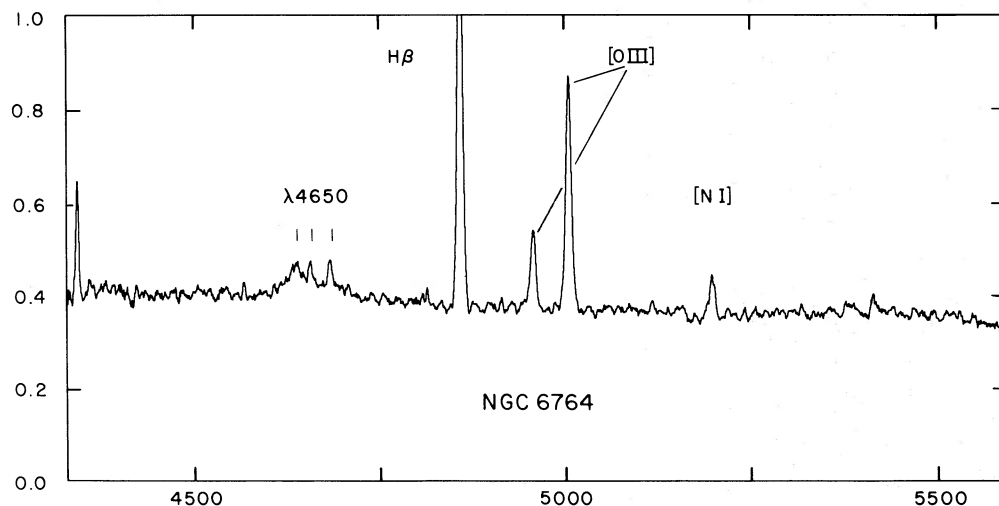


FIG. 1.—High-dispersion spectrum of the nucleus of NGC 6764, showing nebular emission lines, $\lambda 4650$ Wolf-Rayet emission feature, and continuous spectrum, plotted in energy units per unit time per unit wavelength interval versus wavelength in angstrom units in the rest frame of the object. Exposure: 32 min, 1977 Jul 9/10.

WOLF-RAYET GALAXIES

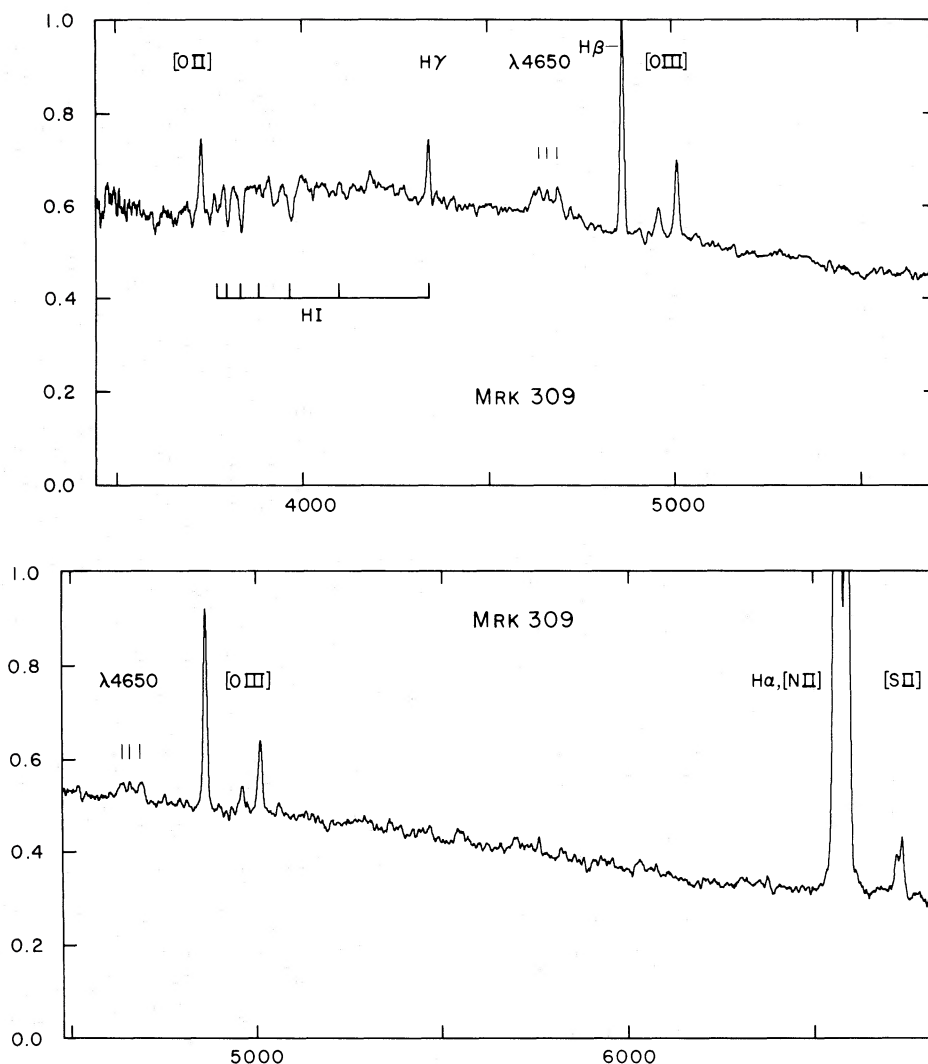


FIG. 2.—Normal-dispersion spectra of the nucleus of Mrk 309, blue spectral region above, red spectral region below; units as in Fig. 1. The wavelengths of the H I Balmer lines from H δ to H11 are marked; several of the higher ones are seen in absorption. Total exposure: 144 min, 1981 Oct 5/6, Oct 31/Nov 1, and Nov 22/23.

much weaker) II Zw 40 (Kunth and Sargent 1981). All of these galaxies show, like NGC 6764 and Mrk 309, strong emission lines of ionized gas, qualitatively similar to the spectra of H II regions.

In addition, the giant H II region NGC 604 in M33 was recently found to show the Wolf-Rayet emission feature in its spectrum (D'Odorico and Rosa 1981). Even more recently, the spectra of several stars (or possibly small clusters) in a few other giant H II regions in M33 were also found to show this same feature (Conti and Massey 1981).

II. $\lambda 4650$ BAND

The main Wolf-Rayet feature easily visible in our scans of both NGC 6764 and Mrk 309 is the broad emission blend extending from approximately $\lambda 4590$ to approximately $\lambda 4720$. It is slightly broader in NGC 6764 and slightly narrower in Mrk 309. We shall refer to

this blend as $\lambda 4650$ in the remainder of this paper. Its appearance is much the same in both galaxies. Three peaks are clearly evident; their wavelengths, measured in the rest systems of the respective galaxies, are given in Table 1. In our experience, wavelengths of weak features of this type may be measured to an accuracy of about ± 2 Å in scans like these. The wavelengths of the peaks in the two galaxies are so similar that they may be taken to be the same lines, and so the averages of the

TABLE 1
WAVELENGTHS OF PEAKS IN $\lambda 4650$ BLEND

NGC 6764	Mrk 309	Average	Identification
4641.3	4638.6	4640.0	N III
4658.9	4660.8	4659.8	C IV
4685.7	4689.6	4687.6	He II

two determinations are also listed in Table 1, along with the identifications. The positions of these three peaks are indicated by short vertical lines in the figures.

The N III feature is undoubtedly the blended multiplet (3) $\lambda\lambda 4634, 4640, 4642$ that is strong in Wolf-Rayet stars of the WN sequence (Smith 1968; Underhill 1967). The C IV wavelength is given as $\lambda 4650$ in some papers (Hiltner and Schild 1966), but that is the approximate measured wavelength of a blend of C III and C IV. As Edlén (1956) has emphasized, the strongest C IV lines by far in the region are $5^2F^o-6^2G \lambda 4657$ and $5^2G-6^2H^o \lambda 4658$, the latter the stronger. This C IV emission feature is strong in the spectra of Wolf-Rayet stars of the WC sequence. However, it is quite unusual for it to be as strong as it is in both NGC 6764 and Mrk 309 without the C III multiplet (1) $\lambda 4650$ being stronger than it is in these two galaxies (Smith 1968). The He II emission line is multiplet (1) $\lambda 4686$, which is strong in all Wolf-Rayet stars' spectra.

In addition to these three multiplets, there is some indication that N V multiplet (1) $\lambda\lambda 4603, 4619$ is present in the spectra of both galaxies, on the short wavelength side of the $\lambda 4640$ peak but unresolved from it.

The three peaks in the $\lambda 4650$ feature in both Mrk 309 and NGC 6764, although they appear to have widths similar to the widths of the other emission lines in these galaxies, seem definitely to be superposed on much broader wings. Because the features are weak and the wings are blended, their widths are difficult to estimate, but they seem to be about 3000 km s^{-1} in Mrk 309 and about 6000 km s^{-1} in NGC 6764.

The fluxes as well as the equivalent widths of the total $\lambda 4650$ emission feature were measured on the scans of the two galaxies, with the results shown in Table 2. Corresponding measurements of the H β emission line, which seems to come largely if not entirely from ionized gas in the nuclei of these galaxies, are also listed in Table 2.

III. OTHER BANDS

No other emission bands as strong as $\lambda 4650$ are seen in our scans of either Mrk 309 or NGC 6764. However, several fainter Wolf-Rayet features may be present in the spectrum of Mrk 309, for which scans taken on different nights can be compared to test the reality of weak features. One blend, partially resolved, that is almost certainly present is C IV multiplet (1) $\lambda\lambda 5802, 5812$. Another that is apparently present is C III multiplet (2) $\lambda 5696$. More scans will be necessary to confirm or deny

these identifications and to allow us to check carefully for other faint Wolf-Rayet features that may be present.

The Wolf-Rayet emission features at longer wavelengths are hard to see in the spectra of the nuclei of NGC 6764 and Mrk 309, at least in part because these objects have stronger continua in the red than typical Wolf-Rayet stars. The same is true in NGC 3125 (Kunth and Sargent 1981). For He 2-10, no scan of the yellow-red region is shown by Allen, Wright, and Goss (1976), but it appears they had a spectrum of this region but did not see the Wolf-Rayet features. On the other hand, in NGC 604, the Wolf-Rayet bands at longer wavelengths are easily seen (D'Odorico and Rosa 1981). No doubt the galactic nuclei contain larger admixtures of cooler stars than the O and W-R association in the H II region. However, although a strong higher Balmer absorption-line spectrum can be seen in Mrk 309, indicating the presence of late B and A stars, the Mg I *b* $\lambda 5175$ absorption feature is very weak. This suggests that there is not a large contribution from late G and K giants, as in most galactic nuclei.

Likewise, in NGC 6764 a weak Mg I *b* absorption feature can be seen, as well as quite a few other weak absorption lines, which must be stellar. Ca II H and K absorption lines appear to be present in the violet, as well as possibly one or more He I lines. Several long-exposure scans will be necessary to settle this point.

IV. INTERPRETATION

The most straightforward interpretation of the presence of the $\lambda 4650$ Wolf-Rayet emission feature in the spectra of Mrk 309 and NGC 6764 is that these two nuclei contain large numbers of Wolf-Rayet stars. This is not expected in the nuclei of most galaxies, in which the bulk of the stars are quite old, while Wolf-Rayet stars are young and highly evolved objects with masses perhaps $20-30 M_{\odot}$ and considerably larger original masses. Observations show that the Wolf-Rayet feature is in fact very rare in the nuclei of galaxies, but that it does occur in Mrk 309, NGC 6764, and the other objects mentioned in § I.

If we make the working assumption that the Wolf-Rayet stars in these nuclei are similar to the Wolf-Rayet stars in our Galaxy and the Large Magellanic Cloud, then both WC stars and WN stars must be involved to give spectra in which N III $\lambda 4640$, C IV $\lambda 4658$, and He II $\lambda 4686$ have approximately equal strength (see, e.g., Smith 1968).

Probably a range of types of both WC and WN stars is present in these galactic nuclei. The best representa-

TABLE 2
FLUXES AND EQUIVALENT WIDTHS OF EMISSION FEATURES

	MARKARIAN 309		NGC 6764	
	<i>W</i> (Å)	<i>F</i> (ergs cm ⁻² s ⁻¹)	<i>W</i> (Å)	<i>F</i> (ergs cm ⁻² s ⁻¹)
$\lambda 4650$	7.7 ± 1.0	$1.4 \pm 0.3 \times 10^{-14}$	9.2 ± 1.4	$2.3 \pm 0.4 \times 10^{-14}$
H β	11.2 ± 0.5	$2.1 \pm 0.2 \times 10^{-14}$	23.0 ± 0.5	$5.3 \pm 0.2 \times 10^{-14}$

tive mean type for the WN stars is WN8. This is based on the observed features $N\text{ III} \gg N\text{ IV}$ and $N\text{ III } \lambda 4640 \approx \text{He } \lambda 4686$ (van der Hucht *et al.* 1981). This classification was greatly facilitated by comparison of our observed scans with the atlas of WN scans, decomposed into individual lines, of Kuhl and Smith (1981). For the WC stars, the best representative mean type is probably WC8, although it may be WC7. Here we could only use published photographs and descriptions of the spectra. The WC8 classification is based largely on the strength of the $C\text{ IV } \lambda 4658$ feature.

If we adopt WN8 and WC8 as representing the mean types of the Wolf-Rayet stars in the nuclei of Mrk 309 and NGC 6764, we can estimate the approximate numbers of stars present. From the approximate equality of $\lambda 4640$, $\lambda 4658$, and $\lambda 4686$ in the integrated spectra of the nuclei, it appears that the WN and WC stars make roughly equal contributions to the $\lambda 4650$ emission blend. The equivalent width of $\lambda 4650$ in emission in a WN8 star is approximately 50 Å, according to the Kuhl and Smith (1981) atlas. We can only estimate the equivalent width of the corresponding feature in a WC8 star. According to Conti and Massey (1981), it is definitely larger than in WN8, and from the average of the values they give for WC stars in the Large Magellanic Cloud, we estimate 225 Å.

Thus a population in which the WN8 and WC8 stars make equal contributions to the $\lambda 4650$ emission consists of a mixture in which approximately 82% of the continuum radiation at this wavelength comes from the WN8 stars and approximately 18% from the WC8 stars. Further, if we adopt the absolute magnitudes given by van der Hucht *et al.* (1981)— $M_v = -7$: for WN8 and $M_v = -4.8$ for WC8—or, interpolating with the intrinsic color indices also given by these authors— $M_{\lambda 4650} = -7.1$ for WN8 and $M_{\lambda 4650} = -4.9$ for WC8—this means that 37% (or one-third, to the accuracy of the various estimates used) of the Wolf-Rayet stars in these objects are WN stars, and the remainder are WC stars.

The equivalent width of $\lambda 4650$ emission from this mixture of Wolf-Rayet stars is then 82 Å. From the equivalent width of this feature observed in Mrk 309, it may be deduced that approximately 9% of the continuum radiation near $\lambda 4650$ comes from Wolf-Rayet stars in the nucleus of this galaxy. The corresponding figure for NGC 6764 is 11%.

Finally, the numbers of Wolf-Rayet stars of the

assumed types in each of these galaxies may be estimated. For Mrk 309, for instance, the continuum flux at $\lambda 4650$ is 1.8×10^{-15} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$. Using the calibration of Oke and Schild (1970), this corresponds to a magnitude $m_{\lambda 4650} = 16.3$, with the convention used above, that all intrinsic color indices of an A0 V star are identically zero. The distance to Mrk 309, from the redshift measured on our scans, $z = 0.0419 \pm 0.0001$, is 2.5×10^8 pc for an adopted Hubble constant $H = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$. Thus the absolute magnitude of the continuum radiation from the nucleus of Mrk 309 is $M_{\lambda 4650} = -20.7$. Of this, approximately 9% comes from the Wolf-Rayet stars, and with the absolute magnitudes used above, this corresponds to approximately 2.1×10^4 WN8 stars and approximately 3.5×10^4 WC8 stars.

Correspondingly, for NGC 6764 the continuum flux at $\lambda 4650$ is 2.5×10^{-15} ergs $\text{cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$, the magnitude $m_{\lambda 4650} = 16.0$, and with the redshift 2405 km s^{-1} , measured by Rubin, Thonnard, and Ford (1975), the distance is approximately 4.8×10^7 pc. Since in this nucleus approximately 11% of the continuum radiation comes from Wolf-Rayet stars, the corresponding numbers are 1.2×10^3 WN8 stars and 2.0×10^3 WC8 stars, down by a factor of 10 in comparison with Mrk 309.

The estimated number of Wolf-Rayet stars in these two galactic nuclei, as well as in the nuclei of He 2-10 (Allen, Wright, and Goss 1976) and NGC 3125 (Kunth and Sargent 1981) and in the giant H II region NGC 604 in M33 (D'Odorico and Rosa 1981), are collected in Table 3. The distances, the absolute blue magnitudes of the *entire* galaxies, M_B , derived from the measured magnitudes B_T , and the deduced numbers of Wolf-Rayet stars given by these authors have all been adjusted to $H = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$ adopted here, for purposes of comparison. The apparent magnitude of NGC 6764 is from Sandage and Tammann (1981), and that of Mrk 309 is from Zwicky and Kowal (1968), corrected by the precepts of Sandage and Tammann. Although NGC 3125 and He 2-10 are dwarf galaxies, NGC 6764 and Mrk 309 are not, and the Wolf-Rayet phenomenon can evidently occur in the nuclei of giant galaxies as well as dwarfs. The authors of the other papers cited did not find evidence for WC stars in the nuclei of NGC 3125 and He 2-10. This may indicate a giant-dwarf galaxy difference, but a comparative study of spectra taken with one instrument and with the same signal-to-noise ratio will be necessary before further discussion along these lines is profitable.

TABLE 3
SUMMARY OF WOLF-RAYET STARS IN GALACTIC NUCLEI

Object	D (pc)	B_T	M_{BT}	WN (Numbers)	WC (Numbers)
NGC 604	5.6×10^4	50	...
He 2-10	1.5×10^6	~13	-18	$\sim 3 \times 10^3$...
NGC 3125	1.7×10^7	...	-16.8	3×10^2	...
NGC 6764	4.8×10^7	12.9	-20.5	1×10^3	2×10^3
Mrk 309	2.5×10^8	15.0	-22.0	2×10^4	3×10^4

V. IONIZED-GAS SPECTRUM

Except for the $\lambda 4650$ band, the emission-line spectra of Mrk 309 and NGC 6764 are those of typical low-ionization galaxies with gas in their nuclei apparently photoionized by early-type stars. The emission lines and their relative strengths measured in Mrk 309 are listed in Table 4. This spectrum is similar to that measured and listed by Koski (1978) for NGC 6764, except that in the latter, [N II], [O I], and [S II] are all relatively stronger. The relative intensities in Mrk 309, corrected for extinction in the amount $E_{B-V} = 0.7$ derived from the $H\alpha/H\beta$ and $H\beta/H\gamma$ ratios, are also listed in Table 4. The kinetic temperature $T = 1.2 \times 10^4$ K, derived from $[N II] (\lambda 6583 + \lambda 6548)/\lambda 5755$, is typical of photoionized H II regions. Koski (1978) found a slightly higher temperature, $T = 1.6 \times 10^4$ K, in NGC 6764. Baldwin, Phillips, and Terlevich (1981) assigned this galaxy to the category of objects they designated "H II regions" (meaning galaxies in which the gas is photoionized by early-type stars), but noted it may contain a shock-heated contribution. The low [O III] temperature seems to argue against this possibility.

The number of early-type stars required to produce the observed ionization in Mrk 309 and NGC 6764 can be calculated from the measured $H\beta$ fluxes. For instance, for Mrk 309, from the distance stated above, the luminosity in $H\beta$ is 1.6×10^{41} ergs s^{-1} , corresponding to 3.3×10^{53} ionizing photons absorbed in the ionized gas per second, using formulae given by Osterbrock (1974). This requires the presence of 7.1×10^3 O5 stars to produce all the ionizing photons, or alternatively 4.8×10^4 O7 stars, or 1.9×10^5 O9 stars, using tables in the same source. No doubt a range of types of O stars is involved, but since the observed level of ionization is rather low, the O7 stars are perhaps the best representative sample. Thus the number of O stars is comparable to the number of Wolf-Rayet stars, an unusual situation compared with that in regions near the Sun in our Galaxy or regions in the Large Magellanic Cloud, as D'Odorico and Rosa (1981) and Kunth and Sargent (1981) have emphasized. It is possible, but not

probable according to current ideas (see, e.g., van der Hucht *et al.* 1981), that the Wolf-Rayet stars themselves emit an appreciable fraction of the ionizing radiation in Mrk 309. If so, the number of O stars could be even smaller.

Likewise, for NGC 6764 the luminosity in $H\beta$ is 1.5×10^{40} ergs s^{-1} , requiring either 6.6×10^2 O5 stars, or 4.5×10^3 O7 stars, or 1.8×10^4 O9 stars. On our high-dispersion scan the full widths at half-maximum of $H\beta$ and [O III] $\lambda 5007$ are 400 ± 50 km s^{-1} , confirming the result obtained by Koski (1978) with less precision from the low-dispersion scans.

VI. SUPERSTAR INTERPRETATION

Another possibility is that the Wolf-Rayet features in the nuclei of these galaxies do not arise in ordinary Population I Wolf-Rayet stars but in much more luminous, presumably more massive objects. This would explain why the structure of the $\lambda 4650$ emission band observed in NGC 6764 and Mrk 309 does not seem to be exactly matched by the spectrum of any mixture of galactic Wolf-Rayet stars. Cassinelli, Mathis, and Savage (1981) have suggested, on the basis of observational evidence, that the central object R136a in the H II region 30 Dor in the Large Magellanic Cloud is a single, hot, highly luminous, super Wolf-Rayet "star," with $T \approx 6 \times 10^4$ K, $M_V \approx -10$, and $M \approx 10^3 M_\odot$. This superstar is supposed to produce both the observed Wolf-Rayet spectral features and the ultraviolet photons that ionize the gas in 30 Dor.

It is difficult to calculate just how many of such superstars would be required to produce the observed Wolf-Rayet features in the nuclei of Mrk 309 and NGC 6764. The spectrum of the one known possible example, R136a, as described by Ebbets and Conti (1981), does not match the structure of the $\lambda 4650$ emission band observed in the two galaxies. However, if such superstars had roughly the same equivalent widths in the $\lambda 4650$ band as the mixture of WN8 and WC8 stars assumed above, then, since the absolute magnitudes of these nuclei are $M_{\lambda 4650} \approx -18$ and $M_{\lambda 4650} \approx -15$ in Mrk 309 and NGC 6764, respectively, the numbers of super Wolf-Rayet objects with $M_{\lambda 4650} \approx -10$ would be about 1.5×10^3 and 1×10^2 , respectively. They would produce more than enough ionizing photons, according to the figures given by Cassinelli, Mathis, and Savage (1981), by a factor of about 10. This interpretation is not ruled out by any of our observational data, nor is it supported over the interpretation in terms of ordinary Wolf-Rayet stars.

VII. CONCLUSIONS

The observational data presented in the present paper and in the earlier papers of Allen, Wright, and Goss (1976) and Kunth and Sargent (1981) show conclusively that strong Wolf-Rayet emission features are present in the spectra of the nuclei of a few galaxies, ranging from dwarfs to giants in luminosity. These features also occur in some H II regions in other galaxies (D'Odorico and Rosa 1981). The simplest interpretation is that they arise

TABLE 4
RELATIVE EMISSION-LINE
STRENGTHS IN MARKARIAN 309

Line	Measured	Corrected ($E_{B-V} = 0.7$)
[O II] $\lambda 3727$	0.26	0.46
H γ $\lambda 4340$	0.24	0.32
W-R $\lambda 4650$	0.74	0.84
H β $\lambda 4681$	1.00	1.00
[O III] $\lambda 4959$	0.17	0.16
[O III] $\lambda 5007$	0.42	0.39
[N II] $\lambda 5755$	0.063	0.042
[N II] $\lambda 6548$	1.38	0.71
H α $\lambda 6563$	5.61	2.87
[N II] $\lambda 6583$	4.40	2.24
[S II] $\lambda 6717$	0.23	0.11
[S II] $\lambda 6731$	0.31	0.15

from large numbers of Wolf-Rayet stars in these galactic nuclei. The apparent ratios of numbers of Wolf-Rayet stars to numbers of O stars are unusually large with respect to typical H II regions or OB associations in our Galaxy. Hence, massive star formation must have occurred recently (about the time required for an O star to evolve to a Wolf-Rayet star, roughly 10^7 yr ago) and over a time fairly short in comparison with this age.

Alternatively, it is possible that the Wolf-Rayet spectral features in these nuclei originate in massive, superluminous objects similar to R136a in 30 Dor. In any case, large amounts of gas, highly processed by thermonuclear reactions and rich in He, C, and N, are evidently flowing from massive stars of some type into the interstellar gas in these nuclei. This may be related

to the high abundances of N, and perhaps He, observed in the gas near the nuclei of many spiral galaxies, including our own (see, e.g., Talent and Dufour 1979 and other references given there).

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