

SPECTRA OF SEYFERT GALAXIES AND SEYFERT GALAXY CANDIDATES¹

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ABSTRACT

New spectral classifications of a number of Seyfert galaxies, as well as of other objects that are not but were earlier suspected of being Seyfert galaxies, are presented. Measured redshifts for all these objects are also given. Mrk 266 SW and Mrk 1066, two galaxies near the lower end of the Seyfert 2's and close to Liners (low-ionization nuclear emission-line regions), are studied spectrophotometrically. Their relative emission-line spectra agree much better with published models for photoionization by a low-luminosity power-law-like radiation source than by shock-wave heating. The spectra of Mrk 883 and Mrk 1320, which are borderline Seyfert galaxies, of Mrk 984, a double emission-line galaxy, and Mrk 1459, a galaxy photoionized by a hot-star population, are briefly discussed.

Subject headings: galaxies: redshifts — galaxies: Seyfert — spectrophotometry

I. INTRODUCTION

Since 1974 a spectral survey of Seyfert galaxies, suspected Seyfert galaxies, and other active galactic nuclei has been underway at Lick Observatory (Osterbrock 1976). We have attempted to obtain reasonably high-quality spectra of every known or suspected Seyfert or radio galaxy that is observable from Mount Hamilton with the 120 inch (3 m) Shane telescope and its image-tube image-dissector scanner. From the spectra obtained in this program, spectrophotometric measurements have been made for many of the objects and published in a number of papers, most of which are referenced below. Two very complete lists of Seyfert galaxies, based on the work of many observers, have been published by Weedman (1977, 1978). Classifications and, in some cases, brief descriptions of the spectra of many additional galaxies obtained in our survey at Lick Observatory have been reported at various American Astronomical Society and Astronomical Society of the Pacific meetings and published in brief abstracts. In the present paper we collect (and in some cases correct) these classifications and give in addition the measured redshifts of the galaxies. Also, a few of the galaxies are discussed in more detail, particularly Mrk 266 SW and Mrk 1066, for the light they shed on the fuzzy borderline between Seyfert 2 galaxies and narrow emission-line galaxies that are not Seyfert galaxies. For these two galaxies, spectrophotometric measurements of line strengths are compared with published photoionization and shock-wave models. The spectra of the marginal Seyfert 1.9 galaxy Mrk 883, the marginal Seyfert 1.5 galaxy Mrk 1320, the double-nucleus galaxy Mrk 984,

and Mrk 1459, a galaxy whose nucleus is photoionized by O stars, are also briefly discussed.

II. CLASSIFICATIONS AND REDSHIFTS

The galaxies observed were mostly selected from the lists of Markarian and his collaborators (Markarian, Lipovetskii, and Stepanyan 1979*a, b*, 1981, and earlier papers mentioned in these three references). We attempted to get good spectral scans of all the objects described as "predicted" (or "expected") Seyfert galaxies, as well as of those with Seyfert characteristics "possibly present" or "suspected." A very large proportion of these objects turned out, in fact, to be Seyfert galaxies. We also obtained check spectra of many of the Markarian galaxies described as possible or certain Seyfert galaxies on the basis of slit spectra taken with image-tube spectrographs and recorded on photographic plates by Denisjuk and Lipovetskii (1974, 1977), Kopylov *et al.* (1974, 1976), and Afanasev *et al.* (1980). We also obtained spectra of a few suspected Seyfert galaxies from the lists of Arakelian (1975), Kazarian (1979*a, b*), and the Michigan observers (MacAlpine and Lewis 1978 and earlier papers referenced there). Galaxies from these sources are listed as Akn, Kaz, and UM, respectively, in the present paper. A few other galaxies were observed whose spectra had been described in the papers listed in the remarks columns of Tables 1 and 2, but for these as for all the other objects, the spectral classifications and descriptions given in the present paper are our own, based entirely on Lick scans. In most cases they agree well with those given by the original authors. One or two objects were observed as a result of papers presented at scientific meetings, the

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 TABLE I
 SEYFERT 1, 1.5, 1.8, AND 1.9 GALAXIES AND QSOs

Galaxy	Seyfert	z	Remarks
Mrk 359	1	0.0169	= MCG 3-41-41; Davidson and Kinman 1978
Mrk 471	1.9	0.0341	= MCG 6-32-14
Mrk 493	1	0.0313	= MCG 6-35-17; narrow H I and Fe II emission lines, Fe II strong
Mrk 634	1	0.0665	
Mrk 662	1.5	0.0553	
Mrk 716	1.5	0.0558	Fairly strong absorption-line spectrum
Mrk 728	1.9	0.0357	
Mrk 744	1.8	0.0090	= NGC 3786; Goodrich and Osterbrock 1983
Mrk 783	1	0.0670	Very narrow H I emission lines but noticeably wider than [O III]
Mrk 813	1	0.1105	Seyfert 1 or QSO; Fe II weak if present at all
Mrk 830	1	0.2101	Seyfert 1 or QSO; Fe II strong
Mrk 845	1	0.0455	= MCG 9-25-22
Mrk 849	1	0.0823	
Mrk 854	1	0.1553	
Mrk 877	1	0.1146	Fe II weak but present
Mrk 883	1.9	0.0380	= MCG 4-39-8; Shuder and Osterbrock 1981; see text
Mrk 885	1	0.0250	= MCG 11-20-16; absorption lines strong
Mrk 896	1	0.0262	= MCG - 1-53-8; relatively narrow H I, relatively strong Fe II
Mrk 915	1.5	0.0239	= MCG - 2-57-23
Mrk 975	1	0.0491	= MCG 2-4-14
Mrk 992	QSO	0.6544	Strong broad Mg II, narrow [Ne v], [Ne III], [O II]
Mrk 1014	1	0.1631	Seyfert 1 or QSO; [O III] relatively broad as in QSOs, but nebulous image on PSS
Mrk 1040	1	0.0164	= NGC 931; Fe II weak but present
Mrk 1044	1	0.0163	= MCG - 2-7-24; strong narrow Fe II
Mrk 1098	1	0.0359	= MCG 5-37-2
Mrk 1126	1.5	0.0104	= NGC 7450; quite narrow broad lines but definitely present
Mrk 1146	1	0.0386	= MCG 2-3-1
Mrk 1152	1.5	0.0527	
Mrk 1179	1.9	0.0376	
Mrk 1187	1	0.0449	
Mrk 1218	1.8	0.0283	= NGC 2622
Mrk 1239	1	0.0194	Relatively narrow broad H I
Mrk 1243	1	0.0352	= NGC 3080
Mrk 1269	1.5	0.1200	
Mrk 1298	1	0.0598	Strong Fe II
Mrk 1310	1	0.0193	
Mrk 1320	1.5	0.1030	See text
Mrk 1347	1	0.0503	
Mrk 1383	1	0.0862	
Mrk 1400	1	0.0293	
Mrk 1447	1.5	0.0959	
VII Zw 118	1	0.0795	Kunth and Sargent 1979
VII Zw 244	1	0.1323	= MCG 13-7-2; Kunth and Sargent 1979
UM 146	1.5	0.0172	= MCG 1-5-48
Stoughton 1	1	0.0764	Stoughton and Osterbrock 1980

details of which we unfortunately no longer remember; to the authors of these papers we apologize for not citing their published work.

All our spectra were taken with the image-tube image-dissector scanner on the Lick Observatory 3 m Shane reflector. They were reduced to energy and wavelength units following standard procedures described in several earlier papers (e.g., Osterbrock 1981a).

In our work at Lick we have distinguished between radio galaxies, objects that are strong radio sources and that were in most cases originally discovered by their

radio emission, and Seyfert galaxies, objects that are only weak radio sources, or radio quiet, and that were in most cases originally discovered on the basis of their optical emission, or in a few cases on the basis of their X-ray emission. The present contribution is not concerned with radio galaxies; the most recent papers listing our classifications of these objects are Grandi and Osterbrock (1978) and Miley and Osterbrock (1979). The morphological definition of a Seyfert galaxy is that it has an unresolved, bright nucleus (see Weedman 1977). We assume that all the objects studied here

TABLE 2
 SEYFERT 2 GALAXIES

Galaxy	z	Remarks
Mrk 266 SW	0.0276	Marginal Seyfert 2; see text
Mrk 403	0.0244	Relatively narrow lines, weak [O I], [S II], but He II visible, [O III] $\lambda 4959/H\beta \approx 4$
Mrk 533	0.0289	= NGC 7674
Mrk 686	0.0140	= NGC 5695
Mrk 917	0.0242	= MCG 5-53-9
Mrk 955	0.0349	= MCG 0-2-94
Mrk 1058	0.0169	
Mrk 1066	0.0120	= MCG 6-7-27; Goodrich and Osterbrock 1983; marginal Seyfert 2; see text
Mrk 1073	0.0233	= MCG 7-7-37
Mrk 1157	0.0151	= NGC 591
Mrk 1457	0.0487	
MCG 5-23-16 ...	0.0442	

satisfy this requirement, although we have not verified it ourselves except roughly at the television guider of the 3 m Shane reflector.

We classified all the emission-line galaxies we observed either as Seyfert galaxies, having strong and broad emission lines in their spectra, covering a wide range of ionization, or as "narrow emission-line galaxies" that do not satisfy these criteria (Weedman 1977). The Seyfert galaxies we further classified into the types Seyfert 1, 1.5, 1.8, 1.9, or 2 on the basis of their spectra. This classification scheme was first put forward, in simpler form, by Khachikian and Weedman (1974). The Seyfert 1 galaxies have broad H I and other permitted lines, such as He I, He II, and Fe II, but narrower forbidden lines. The Seyfert 2 galaxies have H I lines and forbidden lines of the same width, up to about 10^3 km s⁻¹ (Weedman 1977). A sensible fraction of Seyfert galaxies have composite H I line profiles, made up of both strong broad and strong narrow components. Just about every possible relative proportion of strong and narrow components seems to occur among observed Seyfert galaxies (Osterbrock and Koski 1976). We call these objects with composite profiles Seyfert 1.5 galaxies (Osterbrock 1977). (We have abandoned the groups Seyfert 1.2 and 1.8 as defined in that reference and now use only the term Seyfert 1.5 for all the galaxies with well-marked composite profiles, except for the Seyfert 1.8 and Seyfert 1.9 galaxies, as defined below.) Many of these Seyfert 1.5 or "intermediate-type" Seyfert galaxies have been studied in detail by Cohen (1983).

Among the Seyfert galaxies with composite profiles, there are several objects with strong narrow components of the H I emission lines and with quite weak, but easily visible, broad components of H α . Some of these galaxies have weak, but definitely present, broad H β components as well; these we call Seyfert 1.8 galaxies in the present classification. In others, broad H β cannot be detected with certainty by mere visual inspection, and these we classify as Seyfert 1.9 galaxies (Osterbrock 1981a). One example is Mrk 728, whose spectrum is

shown in Figure 1; another is Mrk 471, whose H α and H β profiles are shown in Figure 2.

From their spectra, quasars cannot be distinguished from broad-line radio galaxies, nor (radio quiet) QSOs from Seyfert 1 galaxies. There seem to be no QSOs with spectra similar to Seyfert 2 galaxies, or only a very few. This is undoubtedly connected with the fact that in Seyfert 1 galaxies the luminosity in the featureless continuum is nearly always large compared with the luminosity in the integrated stellar absorption-line spectrum of the underlying galaxy, while in Seyfert 2 galaxies the opposite is the case. The presence of very broad permitted emission lines characteristic of Seyfert 1 galaxies and broad-line radio galaxies is strongly correlated with the presence of a featureless continuum (Osterbrock 1978, 1981b). There is increasing quantitative evidence that the same physical phenomenon is occurring in the nuclei of Seyfert 2 galaxies, Seyfert 1 galaxies, and QSOs, with luminosity increasing in that order, and that the QSOs are the most luminous examples, embedded in the nuclei of galaxies, probably spiral galaxies, which are very difficult to observe directly because of their relative faintness (Miller 1982; Hutchings *et al.* 1982; Kriss and Canizares 1982; Meurs 1982; Boroson, Oke, and Green 1982). Thus, evidently if the featureless-continuum luminosity of the active galactic nucleus is so large that the galaxy cannot be detected (by normal visual inspection of a Palomar Observatory Sky Survey plate of the object) and it is classified as a QSO, the featureless continuum is also so bright that the broad H I lines are practically certain to be present.

Thus we list in Table 1 Seyfert 1, 1.5, 1.8, and 1.9 galaxies and QSOs. The objects of larger redshift ($z \geq 0.1$) would probably be called QSOs on the basis of their images. In some cases the QSOs can be distinguished spectroscopically by the fact that they have relatively wider narrow (forbidden) lines (Shuder 1982). However, Mrk 1014 is an exception to this rule, as noted in the remarks to Table 1.

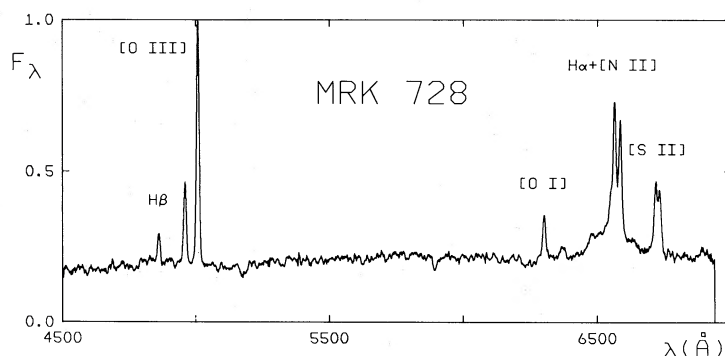


FIG. 1.—Spectral scan of Mrk 728 plotted in the rest system of the object. *Vertical scale*, relative energy flux in flux units per unit wavelength interval. *Horizontal scale*, wavelength in angstrom units.

In Table 2 the objects with Seyfert 2 spectra are listed, while in Table 3 the galaxies with emission-line spectra that are not Seyfert galaxies are listed. Many of them are clearly objects in which the nuclear gas is photoionized by OB stars. For the objects with borderline Seyfert 2 characteristics, it is difficult if not impossible at present to be certain of the classification. One quantitative method of assigning the classification is that of Baldwin, Phillips, and Terlevich (1981), based on several specific line ratios. We have tended to be guided mostly by the criteria of Shuder and Osterbrock (1981),

that for an object to be classified as a Seyfert 2 it must have $[O III] \lambda 5007/H\beta \geq 3$ and that the full width at half-maximum (FWHM) of the emission lines must be $\geq 300 \text{ km s}^{-1}$. The aim of the classification scheme, of course, is to segregate the objects that have common physical characteristics. Two examples are radio emission, which among Seyfert galaxies is strongly correlated with the Seyfert 2 property, or, more quantitatively, with the strength of the narrow emission lines (Sramek and Tovmassian 1975; de Bruyn and Wilson 1976; Ulvestad, Wilson, and Sramek 1981), and X-ray emission, which is strongly correlated with the Seyfert 1 property, or, more quantitatively, with the strength of the broad emission lines (Elvis *et al.* 1978; Shuder 1980; Elvis and Van Speybroeck 1982).

In Table 4 we list the very few objects which were described as possible or probable Seyfert galaxies in the references above, but in which our spectra show no emission lines. In four of the six objects we have been able to detect absorption lines, which are listed in the remarks column. Our spectra of the other two objects do not show any absorption lines that we can certainly identify in the wavelength range (in the rest system of the Earth) specified in the remarks. In both cases the spectra are relatively noisy, but they certainly show no emission lines with peak intensity larger than 20% of the continuum intensity (at 10 Å resolution).

We have listed only the new results in the tables. All the galaxies included in the lists of Weedman (1977, 1978), Osterbrock (1977, 1981*a*), Osterbrock and Phillips (1977), Koski (1978), or Shuder and Osterbrock (1981) have been omitted, unless we have better data which, in our opinion, change the earlier classifications given in these references. Note that I Zw 81, Mrk 298, Mrk 378, Mrk 507, Mrk 700, and NGC 6764, all listed by Koski (1978) as possibly not or probably not Seyfert galaxies, are now definitely excluded from that class, according to Shuder and Osterbrock (1981). Also, Mrk 42 should be classified as a Seyfert 1 (with relatively narrow permitted lines), and Mrk 6, 315, and 372 as Seyfert 1.5 galaxies.

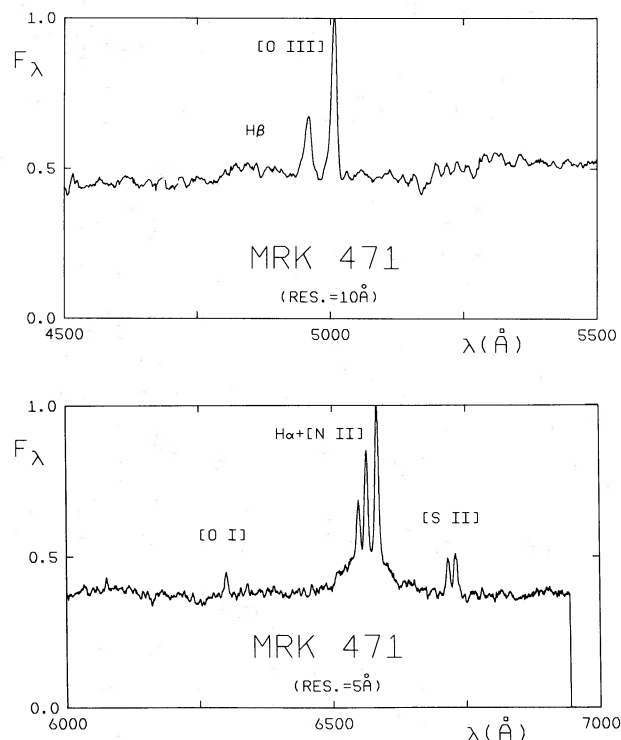


FIG. 2.—Spectral scans of Mrk 471 in $H\beta$ region (*upper*) and $H\alpha$ region (*lower*); otherwise, as in Fig. 1. Note the differing resolutions of the two scans.

TABLE 3
NARROW EMISSION-LINE GALAXIES (NOT SEYFERT GALAXIES)

Galaxy	z	Remarks
Mrk 266 NE ...	0.0277	
Mrk 309	0.0419	Osterbrock and Cohen 1982
Mrk 938	0.0191	= NGC 34
Mrk 945	0.0152	= MCG -1-2-12
Mrk 984	0.0481	= MCG 2-4-21; [O III] $\lambda 5007/H\beta \approx 1$;
	0.0508	apparently unresolved double nucleus; see text
Mrk 1127	0.0251	= NGC 7466
Mrk 1133	0.0247	
Mrk 1149	0.0210	= MCG -3-3-8
Mrk 1178	0.0232	
Mrk 1259	0.0070	= IC 630
Mrk 1308	0.0037	= IC 745
Mrk 1344	0.0105	= NGC 4990
Mrk 1459	0.0267	[O III] $\lambda 5007/H\beta \approx 4.5$ but no He II $\lambda 4686$; lines narrow; see text
Mrk 1485	0.0076	= NGC 5350; [O III] $\lambda 5007/H\beta \approx 1$, $H\alpha/H\beta \approx 8$
Akn 534	0.0161	= MCG 6-39-25; [N II] $\lambda 6583/H\alpha \approx 0.5$, $H\alpha/H\beta \approx 20$
Kaz 27	0.0412	
Kaz 28	0.0471	= MCG 13-9-10

TABLE 4
OBJECTS WITH NO EMISSION LINES SEEN

Galaxy	z	Remarks
Mrk 577	+0.0171	= MCG 2-5-46; $H\beta$, b , D, $H\alpha$
Mrk 959	-0.0011	= IV Zw 30; H, K, G, $H\beta$, D, $H\alpha$; an outlying globular cluster of M31; Mayall and Eggen 1953 No. IV = Sargent <i>et al.</i> 1977 No. 217
Mrk 1278	Scan covers $\lambda\lambda 4920-7460$
Akn 206	+0.0199	= MCG 6-21-59; $H\beta$, b , $\lambda 5269$, D, $H\alpha$
Akn 324	= MCG 10-17-72; scan covers $\lambda\lambda 4760-7300$
Kaz 50	+0.0307	= MCG 11-19-31; H, K, G, b , $\lambda 5269$

For all the objects listed in the tables, we have measured the redshifts (with respect to the Sun) and list them as well as the classifications. For the emission-line objects in Tables 1, 2, and 3, the redshifts were measured from a relatively few (usually two–six per scan) of the strongest narrow lines such as $H\alpha$, $H\beta$, $H\gamma$, [N II] $\lambda 6583$, [S II] $\lambda\lambda 6717$, 6731, [O III] $\lambda\lambda 4959$, 5007, [O I] $\lambda 6300$, [Ne III] $\lambda 3868$, and He II $\lambda 4686$. Note that the zero-point wavelength of each scan was determined from sky lines observed simultaneously with the galaxy directly on the same scan. For many of the galaxies several scans taken on different nights were available. The probable errors of the final values of z listed in the tables are ± 0.0001 in nearly all cases, as judged from the internal consistency of the results. For the objects in Table 4, the redshifts were measured from the absorption lines listed, and the probable errors are estimated to be ± 0.0002 .

III. TWO MARGINAL SEYFERT 2 GALAXIES

Many spiral galaxies that are not Seyfert galaxies have emission lines in the spectra of their nuclei. By far the largest number are galaxies in which gas in the nuclei is photoionized by young, hot, OB stars (e.g., Sargent 1970, 1972; French 1980; Heckman 1980*a*). They generally have narrower emission lines than Seyfert 2 galaxies. There are also some galaxies which have relatively stronger [O I] and [S II] emission lines than these “H II–region nuclei,” but in which the wide range of ionization or the relatively strong lines of higher stages of ionization, characteristic of Seyfert 2 galaxies, are not present. Many of them have line widths larger than in H II regions but close to the lower end of the distribution of line widths in Seyfert 2 galaxies. Heckman (1980*b*) has dubbed these objects *Liners* and has suggested that they are objects in which the ob-

served gas is ionized and heated by shock-wave heating. He has further suggested that a continuity exists between Liners and Seyfert galaxies. Presumably this means with Seyfert 2 galaxies, because there is no indication in Liner spectra of the very broad permitted-line profiles characteristic of Seyfert 1 galaxies. Since Seyfert 2 galaxies appear to be well-established examples of photoionization by a nonstellar, power-law-type continuum extending far into the ultraviolet (Koski 1978), these suggestions certainly deserve further investigation.

More recently Keel (1982) has surveyed the optical spectra of the nuclei of a large number of spiral galaxies and found that many of them have low-ionization emission-line spectra which can best be understood as resulting from photoionization by a low-luminosity power-law continuum. Furthermore, Ferland and Netzer (1983) and Halpern and Steiner (1983) have independently suggested, on the basis of theoretical models, that the observed spectra of Liners can best be understood on the basis of photoionization by a nonstellar, power-law-type continuum of the same type as in Seyfert galaxies but with considerably lower luminosity.

To investigate these ideas further, we have studied in some detail the spectra of two of the objects in the present paper that are close to the border line between Seyfert 2 galaxies and narrow emission-line objects, as we define this border. Both are listed in Table 2 as marginal Seyfert 2 galaxies. One is Mrk 266 SW (its companion, Mrk 266 NE, is not a Seyfert galaxy and is

listed in Table 3), the spectrum of which is shown in Figure 3. The other is Mrk 1066, for which we used the published measurements of Goodrich and Osterbrock (1983).

For Mrk 266 SW we measured spectrophotometrically the blue and red scans, each 32 minutes exposure, taken in 1982 May 22/23 that are shown in Figure 3. They thus have a good overlap in the $H\beta$ -[O III] region. All the emission lines clearly present were measured with respect to $H\beta$ to get relative intensities. The most difficult part of the procedure is to correct for the underlying absorption-line galaxy spectrum and, thus, to define the correct continuum level (Goodrich and Osterbrock 1983). This is especially crucial for weak emission lines in a region of strong absorption, such as $H\gamma$ and [O III] $\lambda 4363$ in the region just to the red of the G band. We used the spectrum of the absorption-line galaxy NGC 4736, suitably scaled to cancel other absorption lines in the vicinity. The other main uncertainty is connected with deblending the $H\alpha$, [N II] $\lambda\lambda 6548, 6583$ complex. The resulting measured intensities, $F/F(H\beta)$, are listed in Table 5.

These measured intensities were then corrected for interstellar extinction, using the measured Balmer-line ratios to estimate the amount, taken to follow the standard Whitford (1958) law. Since all the theoretical models with which these results will be compared agree that collisional excitation of neutral hydrogen is significant, and that as a result, $I(H\alpha)/I(H\beta) \approx 3.1$ rather than the

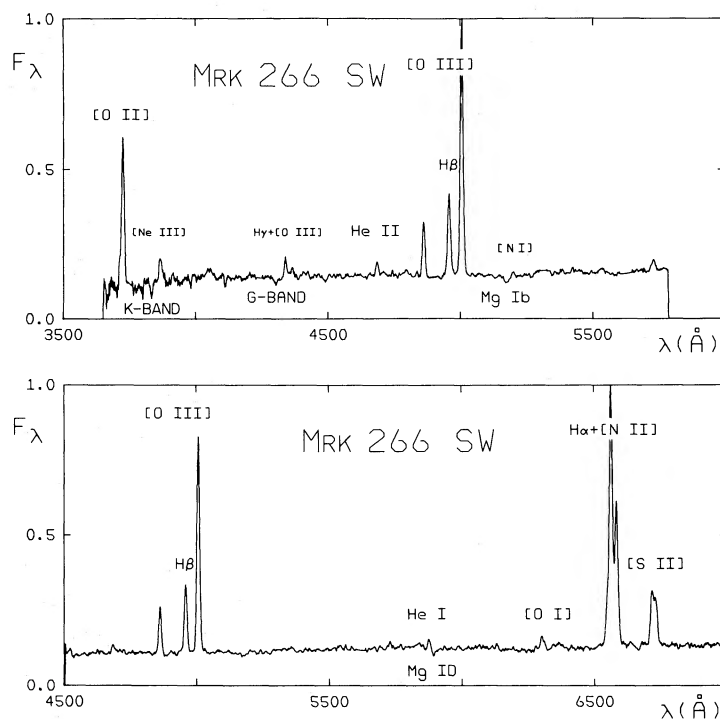


FIG. 3.—Spectral scans of Mrk 266 SW, as in Fig. 1. Upper, $\lambda\lambda 3700$ –5800. Lower, $\lambda\lambda 4500$ –7000.

TABLE 5
RELATIVE EMISSION-LINE FLUXES IN MRK 266 SW

Line	Measured $F/F(H\beta)$	Corrected $I/I(H\beta)$
[O II] λ 3727	3.05	5.23
[Ne III] λ 3869	0.56	0.90
H γ λ 4340	0.24	0.31
[O III] λ 4363	0.06	0.08
He II λ 4686	0.22	0.23
H β λ 4861	1.00	1.00
[O III] λ 4959	1.58	1.50
[O III] λ 5007	4.80	4.50
[N I] λ 5199	0.08	0.07
[N II] λ 5755	≤ 0.05	≤ 0.04
He I λ 5876	0.17	0.12
[O I] λ 6300	0.38	0.23
[N II] λ 6548	1.11	0.63
H α λ 6563	5.95	3.35
[N II] λ 6583	3.68	2.07
[S II] λ 6717	0.54	0.29
[S II] λ 6731	0.46	0.25

standard recombination value 2.85, we have adopted the former value as the intrinsic ratio. For $I(H\gamma)/I(H\beta)$ we have taken the recombination ratio 0.47 (Brocklehurst 1971), which is in good agreement with all the ratios. The observed $F(H\alpha)/F(H\beta)$ is uncertain mainly because of the blending of H α with [N II] λ 6548, 6583, while the observed $F(H\gamma)/F(H\beta)$ is uncertain because H γ is a relatively weak emission line, for which the removal of the underlying galaxy spectrum, in which H γ is in absorption, is quite important. We have therefore given H α double weight, H γ single weight, and derived the total extinction, which corresponds to a color excess $E_{B-V} = 0.52$ mag. The extinction-corrected relative intensities, $I/I(H\beta)$, are listed in the last column of Table 5.

For Mrk 1066 the relative intensities have already been measured and published by Goodrich and Osterbrock (1983). They were originally corrected for extinction assuming $I(H\alpha)/I(H\beta) = 2.85$, the recombination value, so we have applied a slight further correction, assuming $I(H\alpha)/I(H\beta) = 3.1$, as suggested by the models, instead. The corrected relative intensity for the most important emission lines in both Mrk 266 SW and Mrk 1066—those that are important in the diagnostics and that are tabulated in most of the model predictions—are listed in Table 6. Note in this table that [S II] λ 6724 represents the sum of both components of the doublet, as does [O II] λ 3727 and [N I] λ 5199, but [O III] λ 5007, [O I] λ 6300, [Ne III] λ 3868, [N II] λ 6583 refer to single lines.

Before comparing the observed galaxy emission-line spectra with the various models, the line widths may be briefly mentioned. Neither Mrk 266 SW nor Mrk 1066 has any broad Seyfert 1-like component in H α or any of the permitted lines. The FWHM of the [O III] λ 5007 lines in Mrk 1066 was determined from a high-dispersion scan (5 Å resolution) to be 450 ± 100 km s $^{-1}$ (Goodrich and Osterbrock 1983). We have no high-dispersion scans of Mrk 266 SW, but from the normal-dispersion (10 Å resolution) scans, the mean FWHM of H β and [O III] λ 4959, 5007 is 550 ± 150 km s $^{-1}$. Both these values are in the range of FWHM covered by Seyfert 2 galaxies, perhaps closer to the lower limit than the higher (Koski 1978).

From the reddening-corrected line intensities collected in Table 6, in the two columns labeled "Observations," it can be seen that both Mrk 266 SW and Mrk 1066 fulfill the criteria for Seyfert 2 galaxies stated by Shuder and Osterbrock (1981). They have [O III] λ 5007/H β > 3 and FWHM > 300 km s $^{-1}$ but not by a large margin in either case.

TABLE 6
OBSERVED EMISSION-LINE SPECTRA OF MRK 266 SW AND MRK 1066 COMPARED
WITH VARIOUS MODEL PREDICTIONS

LINE	OBSERVATIONS		PHOTOIONIZATION		SHOCK	
	Mrk 266 SW	Mrk 1066	Ferland and Netzer	Halpern and Steiner	Raymond	Shull and McKee
[O II] λ 3727	5.2	3.3	4.2	5.3	8.1	7.2
[Ne III] λ 3868	0.9	0.70	...	0.9	0.4	...
[O III] λ 4363	0.08	0.08	0.03	0.07	0.26	0.19
He II λ 4686	0.23	0.13	0.18	0.22	< 0.01	0.06
H β λ 4861	1.00	1.00	1.0	1.0	1.0	1.0
[O III] λ 5007	4.5	3.9	4.0	4.2	4.2	4.1
[N I] λ 5199	0.07	≤ 0.10	0.22	1.7	0.03	1.2
He I λ 5876	0.12	≤ 0.06	0.18	0.16	0.11	0.17
[O I] λ 6300	0.23	0.27	0.7	2.1	0.08	1.2
H α λ 6563	3.3	2.8	3.1	3.1	3.2	3.0
[N II] λ 6583	2.0	2.5	1.6	3.9	1.4	2.6
[S II] λ 6724	0.54	1.1	1.8	...	1.0	4.9

According to the criteria of Baldwin, Phillips, and Terlevich (1981), both Mrk 266 SW and Mrk 1066 are “H II–region galaxies.” From the ratios in Table 6, for Mrk 266 SW, $\langle \Delta E \rangle$ or $\langle E \rangle = +0.29$ and $(3727/5007) = +0.06$ in the notation of these authors, putting it in the “H II regions” zone, close to the boundary with “shock heating” and not far from the triple point where these two zones both touch “power-law photoionization.” For Mrk 1066, $\langle \Delta E \rangle$ or $\langle E \rangle = +0.29$, $(3727/5007) = -0.07$, also in the “H II regions” zone and close to the triple point.

That the gas in these two objects is actually photoionized by OB stars, which is what the “H II–regions” name is supposed to mean, seems quite unlikely to us. The main reason is the relatively great strength of He II $\lambda 4686$ in both objects. This line is not included in the criteria of Baldwin, Phillips, and Terlevich (1981). It is not observed in H II regions nor in nearly any galaxies known to be photoionized by OB stars (French 1980). Normal galactic O stars apparently do not emit enough far-ultraviolet radiation to produce any appreciable amount of ionization from He⁺ to He⁺⁺. The very few examples of actual H II–region galaxies in which He II is observed, with relative intensity typically $F(\lambda 4686)/F(\text{H}\beta) \approx 0.01$ (French 1980), are apparently cases in which the line comes from involved Wolf-Rayet stars, not from ionized interstellar gas (D’Odorico and Rosa 1981). A second reason for rejecting the H II region interpretation for Mrk 266 SW and Mrk 1066 is that in both of them the emission-line widths are considerably greater than in known examples of such objects (French 1980).

Neither Mrk 266 SW nor Mrk 1066 is a Liner, according to the definition of Heckman (1980*b*), which is that $I(\lambda 3727)/I(\lambda 5007) \geq 1$ and $I(\lambda 6300)/I(\lambda 5007) \geq 1/3$. The former condition is satisfied by Mrk 266 SW (barely) but not by Mrk 1066 (also barely), while the second condition is fulfilled by neither. However, their spectra are close to the typical Liner spectra.

Therefore in Table 6 we have compared the observed spectra with the best available photoionization models of the “weak Seyfert galaxy” type and the best available shock-wave models. The photoionization models are from Ferland and Netzer (1983) and from Halpern and Steiner (1983), while the shock-wave models are from Raymond (1979) and from Shull and McKee (1979). In each case a model has been chosen or interpolated that approximately matches the mean $I([\text{O III}] \lambda 5007)/I(\text{H}\beta)$ ratio in Mrk 266 SW and Mrk 1066, and that, if a second parameter is available, also approximately matches the mean $I([\text{O II}] \lambda 3727)/I(\text{H}\beta)$ ratio. From Ferland and Netzer (1983), the interpolated model has abundances logarithmically intermediate between the two cases they give, that is, “abundances 0.32 solar” and $U = 10^{-3.4}$. From Halpern and Steiner (1983) the interpolated ratios are from their “standard model”

with $f = 0.95$. For the shock-wave models we have used model D from Raymond (1979), corresponding to a shock velocity of 81.5 km s^{-1} , and from Shull and McKee (1979) a model interpolated between E and F, corresponding to 105 km s^{-1} . Each of the papers cited may be consulted for more details of the respective models.

Comparing the various predictions with the models, it is clearly seen that to a first approximation the spectrum of a hot gas with fairly “normal” abundances and covering a range of ionization does not depend very greatly on the energy-input mechanism. Finer details of the spectrum must be used to distinguish between the various possibilities. From these faint lines it seems that the photoionization models give a much better fit with the observed spectra of Mrk 266 SW and Mrk 1066 than the shock-wave models do. The most significant line is [O III] $\lambda 4363$, for the $I(\lambda 5007)/I(\lambda 4363)$ ratio is a measure of a mean temperature in the [O III] emitting zone. Under shock-wave conditions, to produce any significant amount of [O III] radiation, the gas must be heated to a high enough temperature so that O is appreciably collisionally ionized to O⁺⁺. The result is a fairly strong [O III] $\lambda 4363$ line. Under photoionization conditions the temperature is not directly linked to the ionization and generally is held in the range $1\text{--}2 \times 10^4 \text{ K}$ by radiative cooling. The result is a weaker [O III] $\lambda 4363$ line, in better agreement with the observed spectra. The other strongly diagnostic line is He II $\lambda 4686$. It is emitted by recombination of He⁺⁺, requiring significant ionization of He⁺, which has an ionization potential of 54.6 eV. For this to occur by collisional ionization in a shock requires high initial temperature (high shock speed), which necessarily produces much more ionization of O to O⁺⁺ and O⁺³ and subsequent emission of [O III] $\lambda 5007$ much stronger than observed. As Table 6 shows, photoionization by a low-luminosity continuum of the Seyfert 2 type, extending far into the ultraviolet, does produce He⁺⁺ and, consequently, He II $\lambda 4686$ in about the observed strength.

The greatest discrepancy between the photoionization models and the observed spectra of Mrk 266 SW and Mrk 1066 is in the lines [O I] $\lambda 6300$, [S II] $\lambda 6724$, and [N I] $\lambda 5199$, all of which are emitted in the long, partly ionized region in the models in which neutral atoms, singly charged ions, and electrons coexist. In the model calculations, Ferland and Netzer (1983) adopted an assumed photoionizing continuum of the form $L_\nu \propto \nu^{-1.5}$, with no high-energy cutoff. Halpern and Steiner (1983) adopted a compound photoionizing continuum, the main term $L_\nu \propto \nu^{-1.1}$ with an exponential cutoff at 1 keV, and a second, smaller (at low energies) “X-ray” term $L_\nu \propto \nu^{-0.7}$ with an exponential cutoff at 0.1 MeV, and they terminated the integration at a total path length $N_{\text{H}} = 2.5 \times 10^{21} \text{ cm}^{-2}$. Both these assumed spectra are based largely on optical and X-ray data from

QSOs and Seyfert 1 galaxies. It would be interesting to make similar calculations using single power laws with cutoffs at various assumed energies between 10^2 eV and 10^5 eV to see if they better fitted the [O I], [S II], and [N I] lines but kept the good agreement with He II. Cohen (1983) in his study of the narrow-line region in "intermediate Seyfert galaxies"—mostly Seyfert 1.5 and some Seyfert 1—found differences in the spectrum that can be interpreted in terms of a lower energy cutoff in the photoionizing continuum of Seyfert 2 galaxies than of intermediate Seyfert galaxies. The two objects studied here may be one step farther in this progression. Quantitative calculations will be necessary to test this suggestion.

In summary, photoionization models fit the observed spectra of Mrk 266 SW and Mrk 1066 much better than shock-wave models and suggest that a low-luminosity continuum of the general Seyfert 2 type, extending far into the ultraviolet, is the main energy-input mechanism to the ionized gas in these objects. There is no evidence for shock-wave heating. Both these objects are near the lower limit of what are generally called Seyfert 2 galaxies.

IV. REMARKS ON MRK 883, 984, 1320, AND 1459

Of all the suspected Seyfert galaxies from the Markarian lists that we have observed, Mrk 883 is the one with the weakest definitely present broad compo-

nent of H α emission. Its spectrum was briefly described by Shuder and Osterbrock (1981), in which it is incorrectly listed as Mrk 833 in Tables 1 and 2 but is listed under its correct name in Table 3 and in the text. A plot of its spectrum from a normal-dispersion scan is shown in Figure 4. The broad component of H α is just barely detectable at the normal scale, but it can be seen easily on the superposed plot with the fluxes expanded by a factor of 3. From a high-dispersion scan of the H α region the profile was carefully deblended, as described originally by Phillips (1978). The resulting broad H α profile, with the narrow component as well as [N II] $\lambda\lambda 6548, 6583$ removed, is shown in Figure 5. The narrow structure is not real (it results from the assumed narrow-line component not quite matching the true ones), but the overall smoothed profile must be approximately correct. The full width of the broad profile at zero intensity (FWOI) is approximately 140 Å, corresponding to 6400 km s^{-1} , while the FWHM is approximately 76 Å, corresponding to 3500 km s^{-1} . The FWOI given here is preferable to the value given by Shuder and Osterbrock (1981), which was based on a poorly defined calculation, not an inspection of the profile. The FWHM of the narrow lines, based on the high-dispersion scan, is $350 \pm 100 \text{ km s}^{-1}$; this is in good agreement with the value listed by Shuder and Osterbrock (1981).

From Figure 4, or the measured relative fluxes given by Shuder and Osterbrock (1981), it can be seen that

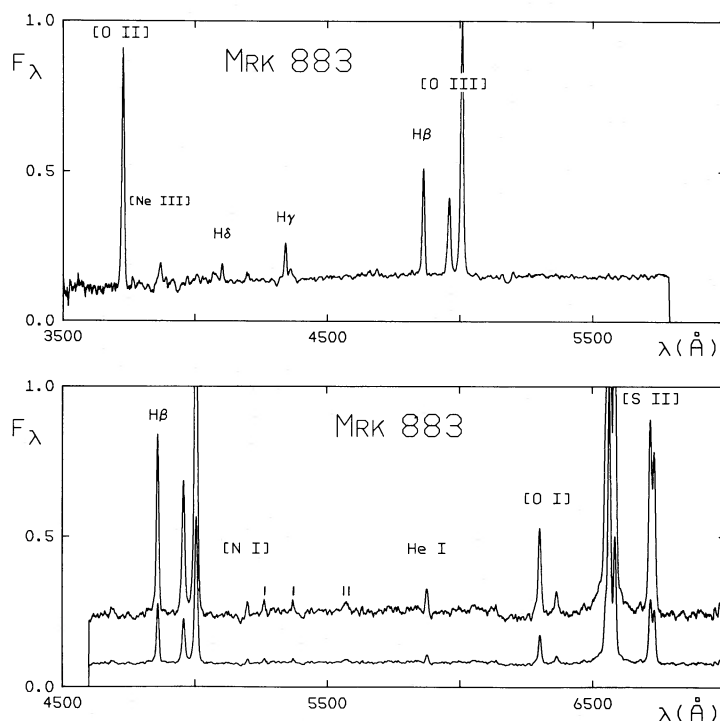


FIG. 4.—Spectral scans of Mrk 883, as in Fig. 1. *Upper*, $\lambda\lambda 3500\text{--}5750$. *Lower*, $\lambda\lambda 4600\text{--}7000$. The lower scan is plotted at normal scale and also with the vertical scale enlarged by a factor of 3 to show the very weak broad component of H α clearly. In the enlarged scan the short vertical ticks indicate the lines Hg I $\lambda 5461$, [O I] $\lambda 5577$, and Hg I $\lambda\lambda 5770, 5790$ of the incompletely canceled sky spectrum.

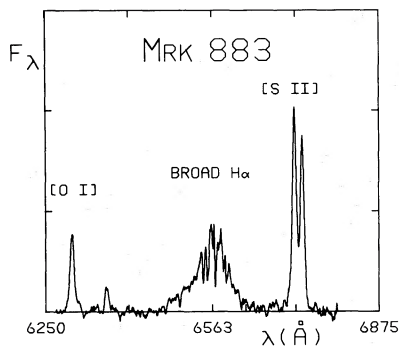


FIG. 5.—Enlarged high-resolution spectral scan of Mrk 883 showing broad $H\alpha$ component; otherwise, as in Fig. 1. The narrow component of $H\alpha$ and $[N\ II]\ \lambda\lambda 6548, 6583$ have been removed, but $[O\ I]\ \lambda\lambda 6300, 6364$ and $[S\ II]\ \lambda\lambda 6717, 6731$ have been left and give the relative intensity scale.

$[O\ III]\ \lambda 5007/H\beta < 3$ (just barely), and according to our criterion Mrk 883 should not be called a Seyfert 2 galaxy. But it does have the very weak broad $H\alpha$ profile, and the narrow-line FWHM is barely greater than $300\ \text{km s}^{-1}$. Thus, we now would call it a marginal Seyfert 1.9 galaxy. Its narrow-line spectrum is quite similar to those of Mrk 266 SW and Mrk 1066, discussed above, with the high-ionization features $He\ II\ \lambda 4686$ and $[O\ III]\ \lambda\lambda 4959, 5007$ even weaker in Mrk 883. Among the Seyfert 1.8 and 1.9 galaxies, its spectrum is most similar to that of Mrk 516 (Osterbrock 1981a).

Two other interesting borderline objects of different types are Mrk 1320 and Mrk 1459. The former has composite $H\ I$ emission-line profiles. The broad components of $H\alpha$, $H\beta$, and $H\gamma$ are all moderately weak but easily visible. Thus it is a Seyfert 1.5 galaxy but toward the lower limit of these objects in the strength of the broad components. The ratio of broad-line intensities is $F(H\alpha\ \text{broad})/F(H\beta\ \text{broad}) \approx 3.5$. The narrow-line ratio $F([O\ III]\ \lambda 5007)/F(H\beta\ \text{narrow}) \approx 5$, relatively weak for a Seyfert 1.5 galaxy, and high-ionization lines like $[Fe\ VII]\ \lambda 6087$ are not present. From a single normal-dispersion scan the FWHM of $[O\ III]\ \lambda 5007$ is $425 \pm 150\ \text{km s}^{-1}$. In every respect Mrk 1320 is a Seyfert 1.5 galaxy, toward the lower limits of that group.

Mrk 1459, on the other hand, although it has $[O\ III]\ \lambda 5007/H\beta \approx 4.5$, fairly large, does not appear to be an object in which the Seyfert phenomenon is occurring. It has $[N\ II]\ \lambda 6583/H\alpha \approx 0.08$, $[S\ II]\ \lambda\lambda 6724/H\alpha \approx 0.15$, $[O\ I]\ \lambda 6300/H\alpha \approx 0.02$. No $He\ II\ \lambda 4686$ can be seen on the scan, and a safe upper limit is $\lambda 4686/H\beta \leq 0.05$. Its emission-line spectrum is very similar to that of the

central part of the Orion nebula. Undoubtedly, Mrk 1459 is a galaxy in which the nuclear gas is photoionized by a population containing a relatively high proportion of O stars. The emission lines on our normal-dispersion scans are no wider than the instrumental profile; the FWHM of $[O\ III]\ \lambda 5007$ and of $H\alpha$ are estimated as $\leq 200\ \text{km s}^{-1}$.

Finally, Mrk 984, although clearly not a Seyfert galaxy, is an interesting example of a double object. The emission-line profiles of $[O\ II]\ \lambda 3727$, $[O\ III]\ \lambda\lambda 4959, 5007$, $[O\ I]\ \lambda 6300$, $[S\ II]\ \lambda\lambda 6717, 6731$, $H\alpha$, and $H\beta$ are all broader than in typical Seyfert 2 galaxies, narrower than the $H\ I$ profiles in most Seyfert 1 galaxies, and irregular and different from ion to ion. Inspection shows that the profiles are in fact double, with somewhat different relative emission-line strengths in the two spectra, although in both $[O\ III]\ \lambda 5007/H\beta \approx 1$ and $[O\ II]\ \lambda 3727/[O\ III]\ \lambda 5007 \approx 4$. The spectrum, like all the others, was taken with a slit $2''7 \times 4''$ in size. Evidently there are two nuclei, with a measured difference in velocity of $840\ \text{km s}^{-1}$. In some respects the spectrum of Mrk 984 is similar to that of NGC 6240 (Fried and Schulz 1983) but with a larger velocity difference between the two components. We have no high-resolution direction images of Mrk 984. On the Palomar Observatory Sky Survey the nuclear region is overexposed, and the object appears to be a highly distorted galaxy, quite possibly a pair, quite possibly single. There is an elliptical galaxy nearby, as seen in the sky, for which we do not have the redshift.

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