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SPECTROPHOTOMETRY OF SEYFERT 1 GALAXIES*

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ABSTRACT

Relative emission-line intensities are given for 36 Seyfert 1 galaxies, measured from image-tube–image-dissector spectral scans taken with the Lick 120 inch telescope. Equivalent widths for Hβ were measured to link the emission-line strengths to the continuum. Information is also given on the broad emission-line profiles, which cover a wide range in velocity and often appear somewhat asymmetric. The measured Hα/Hβ/Hγ ratios do not fit the calculated recombination values and probably indicate that self-absorption and collisional excitation from H I in levels $n \geq 2$ are important excitation mechanisms. Nearly every Seyfert 1 galaxy has Fe II emission in its spectrum, but there is a wide range in its strength. Broad-line radio galaxies in general have much weaker (if any) Fe II emission and steeper Balmer decrements than Seyfert 1 galaxies. The Fe II emission strengths are not well correlated with ultraviolet excess or broad emission-line width, in apparent disagreement with the resonance-fluorescence excitation mechanism, though specific models will be needed to test this conclusion. The narrow emission-line spectra of Seyfert 1 galaxies are quite similar to the emission-line spectra of Seyfert 2 galaxies. The distribution of line widths of Seyfert 1 galaxies shows that rotation is not the main line-broadening mechanism.

Subject headings: galaxies: Seyfert — radio sources: spectra — spectrophotometry

I. INTRODUCTION

A considerable amount of spectrophotometric data on Seyfert galaxies is available from the work of Anderson (1970), Wampler (1971), Adams and Weedman (1975), Shields and Oke (1975), Neugebauer *et al.* (1976), and others. Some of these papers contain medium- and low-resolution measurements on fairly large numbers of Seyfert galaxies, while others give detailed high-resolution measurements of a smaller number of galaxies. As many properties of Seyferts still remain unclear, a systematic spectrophotometric survey has been carried out at Lick Observatory at a resolution of approximately 10 Å, aimed at observing as many Seyfert galaxies as possible that are accessible in reasonable integration times (Osterbrock 1976*a*, *b*). Part of the motivation was to see if there are any correlations between various line ratios that might shed light on the Seyfert phenomenon; part was to provide a body of optical data for comparison with photometric (Weedman 1973), infrared (Stein and Weedman 1976; Allen 1976), and radio data (de Bruyn and Willis 1974; Kojoian *et al.* 1976). For all these reasons, a fairly large body of homogeneous observations is needed; and therefore as many Seyfert galaxies as possible, including bright objects previously observed by other authors including those mentioned above, were remeasured independently in the Lick program. The present paper gives line and continuum measurements for 36 Seyfert 1 galaxies measured to date, while another paper (Koski 1977; see also Koski 1976) will give the measurements for the Seyfert 2 galaxies. Though the classification of Seyfert galaxies into types 1 and 2 as described by Khachikian and Weedman (1971, 1974) is a good concept, there is a continuous range of properties (Osterbrock and Koski 1976) and a few intermediate objects exist, some of which are included in this paper, others in Koski (1977).

II. OBSERVATIONS AND REDUCTIONS

The galaxies to be observed were taken from the list of Khachikian and Weedman (1974), supplemented by galaxies described as probable Seyfert galaxies in the discovery lists of Markarian and Lipovetsky (1973, 1974) extending from Mrk 508 to Mrk 700. An attempt was made to observe every Seyfert galaxy included among the Markarian and Zwicky objects in these sources, but the NGC objects were not all observed systematically, though some of them were measured as time permitted. Only a few Markarian galaxies known to be Seyferts were not measured, mostly in the north galactic pole region, because of insufficient observing time. Note in this paper "Seyfert galaxies" is used as a name only for objects first identified on the basis of their optical spectra, while galaxies first identified on the basis of their radio emission are referred to as "radio galaxies," even though they have emission-line spectra strikingly similar to Seyfert galaxies. Measurements of two very peculiar objects which were observed are not included in the present paper, Mrk 231 (Boksenberg *et al.* 1977) and Mrk 609, a galaxy with a very strong absorption-line spectrum and an intermediate type emission-line spectrum close to Seyfert 2, on which work is continuing.

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All the observations were obtained with the image-tube spectrograph (Robinson and Wampler 1972, 1973) at the Cassegrain focus of the 120 inch (3 m) telescope in the years 1974–1976. The "new" spectrograph (Miller, Robinson, and Wampler 1976) was used with a 600 lines mm^{-1} grating, giving a dispersion of approximately 130 Å mm^{-1} at the front of the first image tube, or approximately 150 Å mm^{-1} at the image dissector. The two entrance apertures were set to 0.70 × 1.0 mm, projecting to 2″.7 × 4″ on the sky, separated by 35″, and the resulting spectral resolution is approximately 10 Å (full width at half-maximum of a much narrower comparison line). The exposures were guided visually on the nuclei of the galaxies observed in all cases. At the start of the program the long axis of the slit was usually oriented north-south, but later in the program it was oriented approximately in the great circle through the zenith, to minimize the effects of atmospheric dispersion, if the zenith distance were more than about 35°. In a few cases of galaxies with close comparisons or nearby stars, or stars that would fall in the comparison slit 35″ on either side of the object, the slit was oriented at a different angle to minimize these disturbances.

The spectral region that can be observed at one setting of the grating used is approximately 2400 Å, and therefore each object was observed with two settings, one the "blue" setting, generally extending from below λ3727 to above λ5007, the other, the "red" setting, generally extending from below λ4861 to above λ6731 (in the rest system of the object). Although over 80% of the Seyfert 1 galaxies were observed in this way, it was not possible for all of them, because of the range of redshifts of radio and Seyfert galaxies observed on a single night, but in all cases there was a spectral interval of several hundred angstroms in common between the blue and red scans. Observing times were typically 32 minutes for each scan, but ranged from 8 minutes for the brightest objects to 64 minutes for the faintest, and if at all possible each galaxy was observed in immediate succession in the two spectral regions on a single night. In about 20% of the cases this was not possible, but almost always the blue and red scans of a given Seyfert galaxy were taken within one or at most two days of each other. Of the 39 Seyfert 1 galaxies in the program, only five were observed on two or more occasions separated by 3 months or more; and one of these five, NGC 7603, was found to show strong spectral variations, as reported elsewhere (Tohline and Osterbrock 1976). There is no strong evidence in the Lick data for spectral variations of any of the others, and therefore except for NGC 7603, which is not included in this paper, all the measurements for each galaxy were averaged together to give the final data reported.

The spectral scans were calibrated into energy units by measurements taken each night of standard early-type stars chosen to have as few lines in their spectra as possible. Generally two of the standard stars, Hiltner 102, HZ 15, Feige 15, Feige 34, Feige 56, BD +33°2642, BD +25°3941, BD +28°4211, and BD 40°4032 were observed each night, one at the beginning and one at the end; though occasionally because of changing weather only one could be observed, and the measurements in energy units of these stars by Stone (1974, 1977), which in turn are based on the calibration of Hayes (1970), were thus transferred to the Seyfert 1 galaxies.

In addition, scans were taken each night of the line spectra of Ar, He, Hg, and Ne comparison lamps to determine the wavelength calibration, and of the continuous spectrum of an incandescent lamp with a quartz bulb, to determine local sensitivity variations in the image-tube cathodes.

The measurements of the Seyfert 1 galaxies were then reduced using standard Lick Observatory PDP-8 and IBM 360 programs, as described by Robinson and Wampler (1973), Miller, Robinson, and Wampler (1976), Osterbrock and Miller (1975), and Osterbrock, Koski, and Phillips (1976), to the form of spectral scans expressed in energy units, measured at the top of the atmosphere, as a function of wavelength. Note that because the fraction of the light from a star or galaxy nucleus that enters the slit is highly dependent on seeing and passing clouds, both of which often vary through the night, the absolute value of the flux measured is not completely significant; but since these effects vary only weakly with the wavelength, the spectral distribution is quite meaningful.

The observations were designed primarily to measure relative emission-line intensities. The intensity of a single isolated line can be measured quite straightforwardly, for the PDP-8 reduction programs permit any scan to be displayed on a cathode-ray tube, the part of the scan containing the line to be enlarged, the continuum and limits of the line to be indicated with a cursor and displayed, and the area contained in the line to be integrated and listed numerically (Robinson and Wampler 1973; Miller, Robinson, and Wampler 1976). The complications in Seyfert 1 galaxies are due to the fact that the H I, He I, He II, and Fe II lines are broad (see, for instance, the spectrum of Mrk 106 in Fig. 1), and it is therefore difficult in many cases to define uniquely the area included within a given line. The problem is not only to define the limits of the wings of broad lines, but also to define the underlying continuum in a spectrum which in many regions is almost completely covered with lines. One very powerful method we have used is a "deblend" program developed largely by A. T. Koski, which permits an arbitrary line profile, usually taken from the scan being reduced, to be shifted in wavelength, to be scaled in intensity and width, and to be combined with other similar profiles and subtracted from the observed profile. In most cases [O III] λλ4959, 5007 were removed from Hβ in this way, and [N II] λλ6548, 6583 from Hα, using the criteria that ratios of the forbidden-line intensities be close to their known universal ratios, fixed by transition probabilities alone, and that the remaining H I profiles be relatively smooth. This program was also always used to separate [O III] λ4363 from Hγ, to separate λ6369 from [O I] λ6364, and often to measure other single lines by subtraction.

A special problem in intensity measurements is

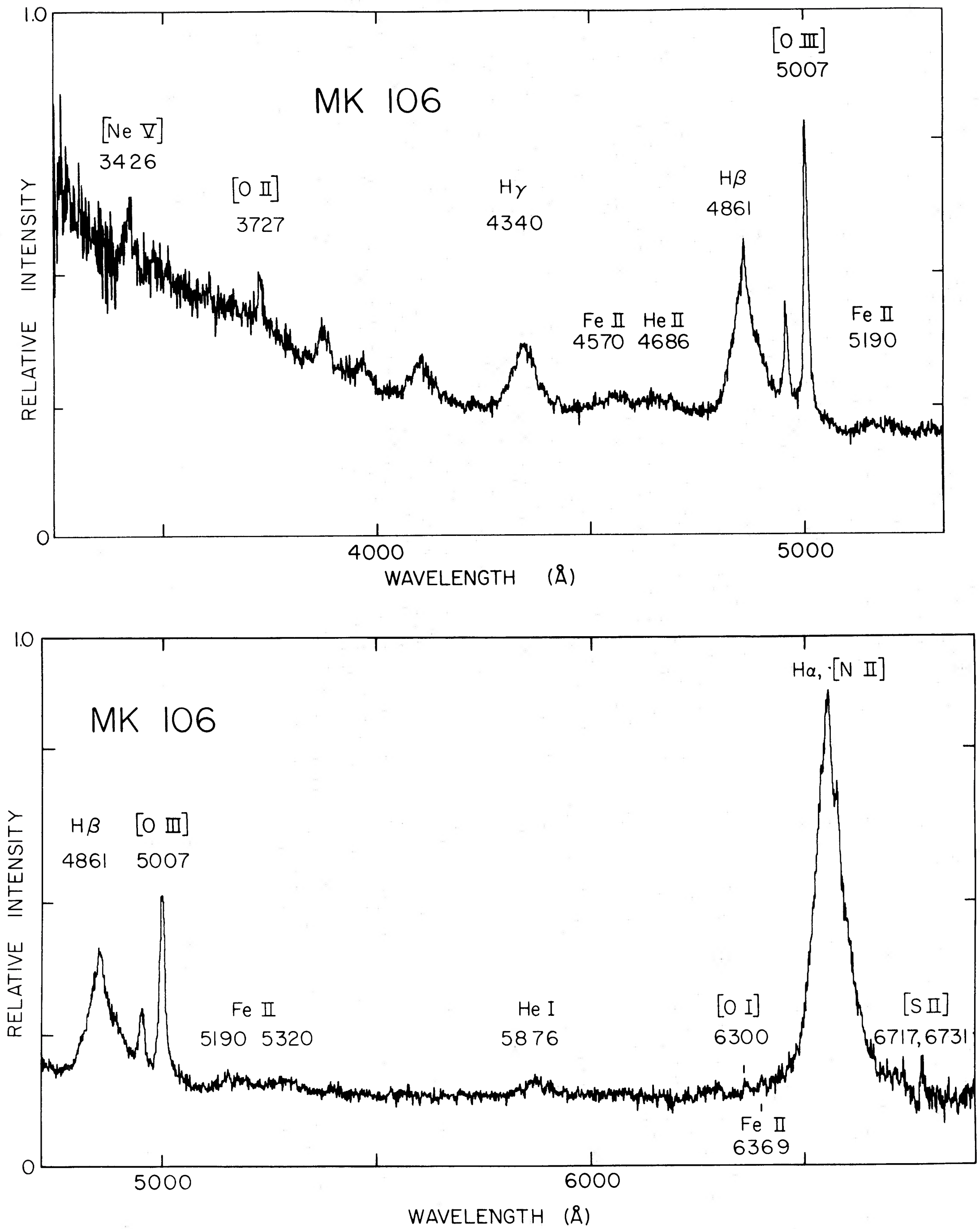

FIG. 1.—Spectral scans of Seyfert 1 galaxy Markarian 106, in relative energy units (ergs cm^{-2} s^{-1} Å^{-1}) versus wavelength units (Å). Upper scan shows "blue" spectral region, lower shows "red" region; wavelengths are indicated in the rest system of Mrk 106.

provided by the Fe II emission lines which are present in nearly every Seyfert 1 galaxy (Osterbrock 1975; Boksenberg *et al.* 1975). These permitted lines, first identified in the quasar 3C 273 by Wampler and Oke (1967) and confirmed in the Seyfert galaxy I Zw 1 by Sargent (1968), occur in several closely spaced multiplets and are blended to greater or lesser degrees in all Seyfert 1 galaxies, depending upon the widths of the Fe II lines. In the present survey the blend of Fe II lines between Hγ and Hβ, due to multiplets (37) and (38), was measured as one feature, called λ4570 in the figures and tables. The group of Fe II lines just to the

TABLE 1

RELATIVE EMISSION-LINE INTENSITIES IN SEYFERT 1 GALAXIES

Line	Mk 10	Mk 40	Mk 69	Mk 79	Mk 106	Mk 110	Mk 124	Mk 141	Mk 142
3727 [O II]	0.081	0.36	0.18	0.073	0.058	0.22	0.24	0.062	0.063
4340 Hγ	0.52	0.14	0.34	0.38	0.37	...	0.42	0.38	0.56
4363 [O III]	0.023	0.12	0.036	0.020	0.009	0.025	0.049:	0.031	0.017
4570 Fe II	<0.11	0.22	0.23	0.19	0.20	0.092	0.72	0.56	0.57
4686 He II	0.45	0.21	0.42	0.14	0.28	0.19	0.24:	0.18	0.37
4861 Hβ	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4959 [O III]	0.31	0.25	0.13	0.14	0.089	0.18	0.22	0.14	0.076
5007 [O III]	0.93	0.72	0.43	0.40	0.29	0.54	0.67	0.38	0.25
5190 Fe II	<0.049	0.20	*	0.078	0.082	0.025	0.70	0.34	0.25
5320 Fe II	<0.073		0.12	0.089	0.10	0.056			0.32
5876 He I	0.19	0.32	0.21	0.19	0.11	0.10	0.11	0.088	0.27
6087 [Fe VII]	<0.006	0.29	...	0.014	<0.005	0.063	...	...	...
6300 [O I]	0.016	0.080	...	0.017	0.012	0.023	0.043:	...	...
6364 [O I]	...	0.045	...	...	0.009	...	0.018:	...	...
6369 Fe II	...	...	...	...		...	...	...	...
6548 [N II]	0.036	0.061	0.16	0.033	0.022	...	...	0.11	0.12
6563 Hα	3.06	3.46	3.01	3.37	3.39	3.71	5.9	3.06	2.91
6583 [N II]	0.11	0.19	0.46	0.10	0.065	0.072	...	0.36	0.33
6716 [S II]	0.036	0.069	0.067	0.024	...	0.049	0.082:	0.077	0.075
6731 [S II]	0.035	0.035	0.084	0.043	...	0.045	0.079:	0.066	0.062

Line	Mk 236	Mk 279	Mk 290	Mk 291	Mk 304	Mk 335	Mk 352	Mk 358	Mk 374
3727 [O II]	0.085	0.10	0.054	0.46	0.008	≤0.01	<0.007	0.10	...
4340 Hγ	~0.34	0.37	0.33	0.40	0.28	0.48	0.47	0.44	0.43
4363 [O III]	~0.037	0.014	0.027	0.10	0.007	0.019	...	<0.026	0.034
4570 Fe II	0.30	0.15	0.096	0.45	0.16	0.22	0.20	0.48	0.52
4686 He II	0.37	0.16	0.16	0.88	0.15	0.33	0.44	0.60	0.28
4861 Hβ	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4959 [O III]	0.14	0.062	0.20	0.32	0.022	0.076	0.046	0.15	0.14
5007 [O III]	0.46	0.20	0.63	0.97	0.066	0.23	0.11	0.43	0.43
5190 Fe II	0.37	0.081	0.046	0.51	0.068	0.10	0.027	0.15	0.14
5320 Fe II		0.078	0.060		0.11	0.11	0.095	0.33	0.22
5876 He I	0.22	0.15	0.18	0.20	0.16	0.16	0.15	0.093	0.25
6087 [Fe VII]	...	≤0.008	0.018	...	≤0.004	...	...	...	0.13
6300 [O I]	0.033	0.026	0.021	0.10	≤0.003	...	...	<0.042	...
6364 [O I]	...	...	0.008	...	...	...	...	...	...
6369 Fe II	...	...	...	...	...	...	...	0.089	...
6548 [N II]	0.024	0.004	0.016	0.35	0.008:	...	...	0.042	...
6563 Hα	3.45	2.89	3.32	4.53	2.98	2.60	2.66	2.82	3.25
6583 [N II]	0.073	0.11	0.048	1.07	0.025:	<0.34	...	0.14	0.027
6716 [S II]	0.057	0.028:	0.022	0.29	0.004	...	...	0.17	0.021
6731 [S II]	0.061	0.028:	0.019	0.18	0.008	...	...		0.021

TABLE 1 -- Continued

Line	Mk 376	Mk 382	Mk 478	Mk 486	Mk 504	Mk 506	Mk 509	Mk 541	Mk 590
3727 [O II]	...	0.070	0.074:	...	...	0.14	0.032	0.040	0.12
4340 Hγ	0.55	0.55	0.65:	0.49	0.52	0.26	0.41	0.43	**
4363 [O III]	...	0.028	...	...	0.008	0.034	...	0.051	0.11
4570 Fe II	0.58	0.54	1.20	0.42	0.34	0.22	0.12	0.56	...
4686 He II	...	0.63	...	0.19	0.41	0.29	0.29	0.58	...
4861 Hβ	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4959 [O III]	0.05	0.30	0.083	0.091	0.10	0.25	0.080	0.076	0.20
5007 [O III]	0.15	0.87	0.25	0.22	0.26	0.74	0.24	0.23	0.55
5190 Fe II	0.18	0.84	0.86	0.17	0.21	0.24	0.014	0.60	...
5320 Fe II	0.22			0.27			0.024		...
5876 He I	0.15	0.19	0.09	0.12	0.19	0.31	0.19	0.35	<0.2
6087 [Fe VII]	...	...	...	0.019	...	0.16	...	0.057	...
6300 [O I]	...	...	0.012:	...	...	0.046	...	...	0.11
6364 [O I]	...	...	...	...	...	0.020	...	...	...
6369 Fe II	...	...	...	0.058	...	...	...	...	...
6548 [N II]	...	0.10	...	...	...	0.090	...	0.15	0.10
6563 Hα	3.66	3.71	4.32	4.40	3.79	4.29	2.83	2.41	4.19
6583 [N II]	0.15	0.29	...	...	...	0.26	...	0.45	0.30
6716 [S II]	0.02	0.60	0.023:	0.017	0.031	0.085	0.014	...	0.077
6731 [S II]		0.079	0.030			0.076	0.015	...	0.052

Line	Mk 618	NGC 3227	NGC 3516	NGC 5548	NGC 7469	I Zw 1	II Zw 1	II Zw 136	III Zw 2
3727 [O II]	0.054	0.24	0.022	0.10	0.14	...	0.16	0.033	0.046
4340 Hγ	0.45	0.22	0.28	0.27	0.46	≤0.69	0.27	0.75	0.36
4363 [O III]	<0.016	0.038	0.015	0.080	0.026	0.029:	0.032	...	0.009
4570 Fe II	0.26	0.19	0.32	0.17	0.27	1.34	0.53	0.53	0.21
4686 He II	0.40	0.30	0.50	0.02†	0.24	...	0.45	0.13	<0.07
4861 Hβ	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
4959 [O III]	0.16	0.43	0.090	0.26	0.16	0.13	0.43	0.11	0.11
5007 [O III]	0.45	1.33	0.26	0.80	0.53	0.44	1.24	0.36	0.33
5190 Fe II	0.084	0.084	0.061	0.11	0.10	1.50	0.55	0.39	0.10
5320 Fe II	0.20	0.15	0.20	0.10	0.10				0.10
5876 He I	0.28	0.22	0.33	0.074	0.20	≤0.16	0.18	0.16	0.14
6087 [Fe VII]	0.036?	...	0.13	0.038	0.012	...	...	0.016	≤0.004
6300 [O I]	0.024	0.16	0.013	0.037	0.032	0.028:	0.040	...	0.019
6364 [O I]	0.020	0.054	...	0.021	0.060	0.020:	...	...	...
6369 Fe II	0.029?	...	0.008				...	0.020	...
6548 [N II]	0.13	0.22	0.037	0.029	?	...	0.16	...	0.014
6563 Hα	3.85	4.43	2.94	4.21	3.88	4.86	3.41	3.63	3.58
6583 [N II]	0.39	0.72	0.11	0.087	?	...	0.47	...	0.044
6716 [S II]	0.048	0.23	0.027	0.029	0.073	0.013:	0.12	0.018	0.026
6731 [S II]	0.065	0.24	0.023	0.029	0.080		0.13		0.026

* λ5190 in Mk 69 masked by poor night-sky subtraction.
** Hγ in Mk 590 strongly affected by absorption G band.
† λ4686 in NGC 5548 narrow.

red of λ5007, due to multiplets (48) and (49) as well as at λ5138 of multiplet (42), was in the early stages of the program split up into two features, λ5190 and λ5320. These features are indicated in the spectrum of Mrk 106 in Figure 1, and in the spectra of Mrk 376 and Mrk 486 = I Zw 121-1 in Figure 1 of Osterbrock (1976*a*). However, experience showed that the division into two features could not be made consistently, and in the latter parts of the program this whole blend was measured as one feature, and called simply λ5190 + λ5320. Note also the blending of He II λ4686, if present, with Fe II λ4570. He II λ4686 is quite strong and easily apparent in Mrk 486, absent in Mrk 376, and easily detectable in Mrk 106 as a high region in the spectrum to the short-wavelength side of Hβ, where the intensity does not drop to the level of the continuum interpolated from below Hγ to above [O III] λ5007.

The emission lines chosen to be measured in all the Seyfert 1 galaxies were selected on the basis of strength and physical significance. The Fe II blends were included in an attempt to investigate whether they correlate with any other features in the spectrum. [O I] and [Fe VII] were particularly selected to cover a wide range in ionization.

Relative line intensities measured on the blue scans were expressed directly with respect to Hβ, and the red scan taken on the same night (or within a few nights of the same night) was linked to Hβ by measurements of Hβ itself, or of the whole Hβ, [O III] complex, particularly if Hβ is wide and badly blended, or by measurements of the continuum in the region of overlap if Hβ was not included in the red scan. If a Seyfert galaxy was observed on more than one occasion, the relative intensities measured on the separate occasions were averaged together. The final results for the relative emission-line intensities in the 36 Seyfert 1 galaxies measured are listed in Table 1. The names used for the individual galaxies are those listed by Khachikian and Weedman (1974), but it should be noted that Mrk 304 = II Zw 175 and that Mrk 486 = I Zw 121-1.

The internal probable errors of these relative emission-line intensities can be estimated by taking as representative the deviations from the mean for galaxies measured on more than one night. The average errors of the means for the Seyfert 1 galaxies scanned on two different nights found in this way are approximately 15% of the mean ratios listed for [O II] λ3727, He I λ5876, and [O I] λ6300, all representative single lines well separated in wavelength from Hβ, about 8% of the mean for the much stronger Hα line, and 5% of the mean for [O III] λ5007. For the bulk of the galaxies for which only a single measurement is available, these average errors should be increased by a factor 1.4. The

TABLE 2

RELATIVE EMISSION-LINE INTENSITIES IN BROAD-LINE RADIO GALAXIES

Line	3C 120	3C 227	3C 382	3C 390.3	3C 445
3727 [O II]	0.035	0.068	0.026	0.065	0.20
4340 Hγ	0.38	0.17	0.15	0.28	0.049
4363 [O III]	0.054:	0.069	0.032	0.12	0.19
4570 Fe II	...	...	...	...	...
4686 He II	0.21	0.23	0.036	0.017	...
4861 Hβ	1.00	1.00	1.00	1.00	1.00
4959 [O III]	0.32	0.28	0.068	0.34	0.98
5007 [O III]	0.93	0.86	0.20	0.99	2.83
5190 Fe II	0.055	...	...	0.045	0.060
5320 Fe II	0.062	...	...	0.064	0.062
5876 He I	0.28	0.12:	0.17	0.22	0.11
6087 [Fe VII]	0.016:	...	...	0.039	...
6300 [O I]	0.030	0.063	0.014	0.068	0.13
6364 [O I]	...	...	...	...	...
6369 Fe II	...	...	...	...	...
6548 [N II]	0.060:	...	...	0.032	0.11
6563 Hα	6.57	6.36	5.18	6.14	9.50
6583 [N II]	0.20:	0.13	0.008	0.095	0.21
6716 [S II]	0.40:	0.033	0.015	0.057 (6716 + 6731)	0.10
6731 [S II]	0.44:	0.025	0.017		0.088

uncertainties are larger for the [N II] lines, which are always blended with Hα, for [O III] λ4363, blended with Hγ, and for the broad weak Fe II features. In addition, it must be remembered that the definition of the limits of a broad line is never obvious, and there may be additional errors due to this fact. In particular, the broad wing of Hβ extended to longer wavelength, on which [O III] λλ4959, 5007 are superposed, and which may also contain a contribution from Fe II λ4924, is very difficult to define. Empirically, the intensities reported here agree well (usually to about ±15%) with those measured by Wampler (1971) for the relatively few objects in common, and the broad-line intensities agree well with the Palomar measurements (Oke and Shields 1976; Neugebauer *et al.* 1976), though there are some larger discrepancies with their reported intensities of narrow emission lines. Likewise there is very good agreement between our separately published measurements of NGC 4151 (Osterbrock and Koski 1976) and those of Boksenberg *et al.* (1975).

For comparison with the relative intensities of the Seyfert 1 galaxies in Table 1, relative intensities of five broad-line radio galaxies, taken mostly from earlier published papers (Osterbrock and Phillips 1975; Osterbrock, Koski, and Phillips 1976) but supplemented by some new Fe II measurements from the same scans, are listed in Table 2.

To link the emission-line intensities to the continuum, the equivalent width of Hβ was measured from the scans for each Seyfert 1 galaxy and is listed in Table 3. Note that the equivalent widths W measured in the rest system of the Earth were transformed back to the rest system of the galaxies by the formula

$$W_0 = \frac{W}{1+z},$$

and the equivalent widths in the rest system of the galaxies, W_0, are given in the table. From the 15 galaxies for which more than one measurement of the equivalent width is available, the average error of a single measurement is about ±6 Å; or for a galaxy for which two measurements were averaged, the average error of the mean is about ±4 Å.

The scans were also used to obtain some information on the profiles of the emission lines. The forbidden lines, and the narrow components of the H I lines where they exist, are only a little wider than the instrumental profile, which is 10 Å full width at half-maximum, corresponding to about 600 km s^{-1} at Hβ or 450 km s^{-1} at Hα. The broad H I profiles have different forms in practically every galaxy. Though Hβ is usually blended with [O III] λλ4959, 5007, its profile is generally better defined than Hα, which is always blended with [N II] λλ6548, 6583 if present. Therefore the Hβ profiles were inspected and classified as symmetric, slightly asymmetric, or asymmetric, as listed in Table 4. For 33 of the galaxies this classification was done twice, with an intervening time interval of over 6 months, and for 23 of them the classification was the same on both occasions, for 10 the classifications differed by one step (symmetric–slightly asymmetric or slightly asymmetric–asymmetric) on the two

TABLE 3

EQUIVALENT WIDTH OF EMISSION-LINE Hβ

Galaxy	Wo (Å)	Galaxy	Wo (Å)	Galaxy	Wo (Å)
Mk 10	72	Mk 335	87	NGC 3227	55
Mk 40	94	Mk 352	94	NGC 3516	71
Mk 69	52	Mk 358	54	NGC 5548	146
Mk 79	135	Mk 374	80	NGC 7469	105
Mk 106	124	Mk 376	75	I Zw 1	60
Mk 110	151	Mk 382	20	II Zw 1	49
Mk 124	64	Mk 478	76	II Zw 136	153
Mk 141	46	Mk 486	93	III Zw 2	145
Mk 142	67	Mk 504	66		
Mk 236	76	Mk 506	108	3C 120	103
Mk 279	121	Mk 509	146	3C 227	78
Mk 290	138	Mk 541	59	3C 382	114
Mk 291	19	Mk 590	42	3C 390.3	102
Mk 304	122	Mk 618	86	3C 445	87

TABLE 4

LINE-PROFILE CLASSIFICATIONS AND WIDTHS

Galaxy	Profile	Seyfert	Hβ FWHI	Hβ FWOI	Hα FWHI	Hα FWOI	HI FWHI	HI FWOI
Mk 10	s	1	2400	9300	2400	15300	2400	12300
Mk 40	s	1	2000	13300	1900	9100	2000	11200
Mk 69	s	1	1500	11100	1500	8200	1500	9600
Mk 79	s	1.2	5200	12200	3300	17100	4200	14600
Mk 106	sa	1	3700	15700	3300	14200	3500	15000
Mk 110	sa	1	2500	13000	2200	13200	2400	13100
Mk 124	s	1	1400	9800	1400	7500	1400	8600
Mk 141	sa	1.2	5300	12300	2300	14900	3800	13600
Mk 142	s	1	1700	12300	1100	9100	1400	10700
Mk 236	sa	1.2	4900	13000	3700	15100	4300	14000
Mk 279	a	1	6200	18500	4100	16900	5200	17700
Mk 290	sa	1	2500	13000	2500	13000	2500	13000
Mk 291	s	1	1100	8300	500	5200	800	6800
Mk 304	a	1	5900	15400	4700	22100	5300	18800
Mk 335	s	1	1700	10500	1400	9500	1600	10000
Mk 352	sa	1	3800	12500	3100	14300	3400	13400
Mk 358	s	1	2000	7500	1300	8200	1600	7800
Mk 374	a	1.2	4600	10600	3100	15800	3800	13200
Mk 376	a	1	5900	18100	4900	20200	5400	19200
Mk 382	s	1	1500	7400	1400	6900	1400	7200
Mk 478	s	1	1700	10200	1400	9700	1600	10000
Mk 486	s	1	2000	14200	1900	12700	2000	13400
Mk 504	s	1	2300	13900	1900	11900	2100	12900
Mk 506	sa	1.5	3400	12500	3600	11300	3500	12000
Mk 509	s	1	3600	15100	2900	12900	3200	14000
Mk 541	sa	1	3300	10200	2600	10000	2900	10100
Mk 590	s	1.5	3700	9300	3100	13000	3400	11200
Mk 618	s	1	2200	10500	2100	8700	2200	9600
NGC 3227	s	1.2	2500	11800	2400	11400	2400	11600
NGC 3516	s	1	6800	14800	4300	15500	5600	15200
NGC 5548	s	1.5	3700	15400	3300	14900	3500	15100
NGC 7469	sa	1	1900	8500	1700	7800	1800	8200
I Zw 1	s	1	1400	9600	1200	8200	1300	8900
II Zw 1	sa	1.5	1500	11200	1900	12600	1700	11900
II Zw 136	s	1	2300	11400	2200	10100	2200	10800
III Zw 2	a	1	5700	15800	4100	17400	4900	16600
3C 120							2000	15000
3C 227							2500	14000
3C 382							18000	25000
3C 390.3							13000	18000
3C 445							3000	14000

occasions, and for none of the galaxies did the two classifications differ by two steps (symmetric–asymmetric). In every case in which the profile is classified as asymmetric or slightly asymmetric the asymmetry is in the sense that the peak is to the short-wavelength side of the midpoint of the profile at low intensities; or, put another way, the wings extend farther to the long-wavelength side of the peak than to the short-wavelength side. This asymmetry may be due to blending with Fe II λ4924 but appears to be a real feature of the H I profiles; observational work on this problem is continuing.

In addition, each Seyfert galaxy was classified into one of the four groups Seyfert 1, 1.2, 1.5, or 1.8 on the basis of the appearance of its Hβ profile. Here Seyfert 1 means a "typical" member of the class, as described by Khachikian and Weedman (1971, 1974), while Seyfert 1.5 means an object (such as NGC 4151 or

Mrk 6) that is intermediate between typical Seyfert 1 and Seyfert 2 galaxies, with an easily apparent narrow Hβ profile superimposed on broad wings (Osterbrock and Koski 1976). Somewhat finer divisions can be recognized, so the classes Seyfert 1.2 and 1.8 are used to describe objects with relatively weaker and stronger narrow Hβ components, intermediate between Seyfert 1 and 1.5, and Seyfert 1.5 and 2, respectively. These classifications are also listed in Table 4. Three additional intermediate-type Seyfert galaxies, not included in the present paper because they have been studied by Koski (1976), are Mrk 6, Mrk 315, and Mrk 372.

The widths of the Hβ and Hα were also measured, at half-intensity and zero intensity, with the results listed in Table 4. The values given are the widths directly from the scans, uncorrected for the finite instrumental resolution. Nearly all the Seyfert 1 galaxies measured have H I line widths much greater than the instrumental full widths at half-maximum mentioned above, or at zero intensity (approximately 34 Å or 2000 km s^{-1} at Hβ or 1500 km s^{-1} at Hα). The corrections for instrumental resolution are therefore small, and of course not well determined, because the intrinsic line profiles are not known, so it seemed reasonable to omit them. Note that the measured widths of Hβ and Hα are, in many cases, not the same. The differences are often larger than the average errors of individual widths, which are approximately ± 400 km s^{-1} and ± 300 km s^{-1} for the full widths at half-maximum of Hβ and Hα, respectively, and ± 1900 km s^{-1} and ± 1000 km s^{-1} for the full widths at zero intensity, as derived from objects for which more than one scan was available. The differences in the full widths at half-intensity are at least in part due to the fact that the H I profiles often seem to be composed of two parts, a narrow component and a broad component, with different relative proportions of each component at Hβ and Hα (or, put in another way, different Balmer decrements). The difference in the widths of Hα and Hβ at zero intensity cannot be explained in this way but may be due to the fact that Hα, being stronger and in a spectral region clear of other emission lines, can be traced out further. It may also represent a real difference in the profiles, relating to different excitation rates in different regions of velocity space. Further observational work at higher dispersion on selected Seyfert 1 galaxies with particularly unusual profiles is continuing in an effort to understand this effect. The columns headed H I in Table 4 give the mean of the Hβ and Hα line widths, and these are the values used in the discussion of the next section.

III. INTERPRETATION

The emission-line measurements of the previous section can be examined in an effort to understand the physical processes occurring in Seyfert galaxy nuclei. For instance, Figure 2 shows the Hα/Hβ/Hγ emission-line ratios measured for the Seyfert 1 galaxies (*filled circles*) and broad-line radio galaxies (*open circles*). The square shows the calculated recombination ratios

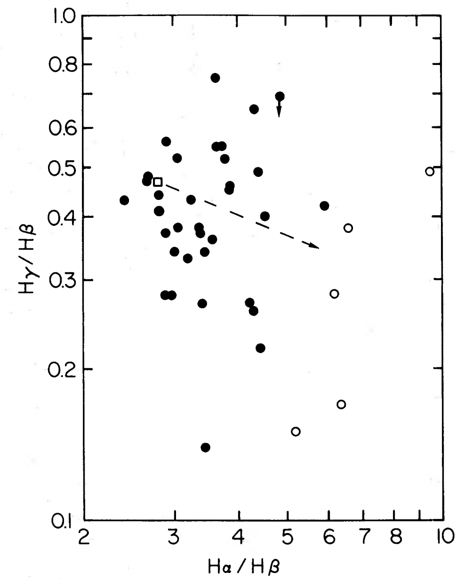

FIG. 2.—Measured Balmer-line intensity ratios for Seyfert 1 galaxies (*filled circles*) and broad-line radio galaxies (*open circles*). Open square shows calculated recombination ratios, and dashed line shows effect of standard interstellar extinction.

(which vary only slightly with temperature and density) for $T = 10^4$ K, $N_e = 10^6$ cm^{-3} (Brocklehurst 1971), and the dashed line shows the effect of interstellar extinction according to the standard Whitford (1958) reddening curve. It can be seen that the broad-line radio galaxies and the Seyfert 1 galaxies fall in different parts of this diagram, so at least for this sample it is possible to distinguish between these two classes of objects (or more precisely, to divide broad-line radio galaxies with large optical-radio indices from those with small optical-radio indices) on the basis of these ratios alone. In general the broad-line radio galaxies have larger Hα/Hβ ratios and steeper Balmer gradients. The deviations of individual points from the reddening line are larger than can be accounted for by the errors of the measurements. This indicates that processes other than recombination and downward cascading alone are involved in the H I line emission. Presumably the other processes are collisional excitation, particularly from the levels $n = 2$, and Balmer and Paschen line absorption, scattering, and fluorescence, as discussed by many authors, most recently Netzer (1975).

The He I λ5876 and He II λ4686 lines have comparable widths to the H I lines, but because of their weakness it is more difficult to measure their widths quantitatively. Figure 3 shows the measured relative strengths of these two He lines. It can be seen that the He I relative intensities fall in a narrow range centered on λ5876/Hβ = 0.18, while the He II relative intensities have a wide range from λ4686/Hβ ≈ 0 to λ4686/Hβ ≈ 1. The interpretation must be that He is ionized to at least He^+ throughout most of the broad-line emitting volume where H is ionized to H^+, but that the amount of He^+ ionized to He^{++} varies widely from one

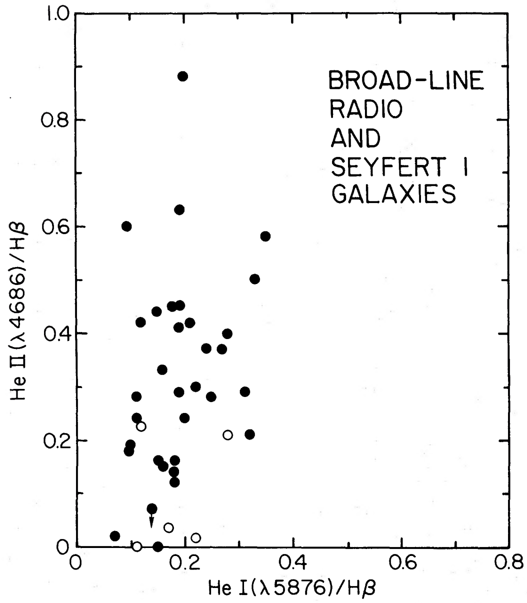

FIG. 3.—Measured H I and He II intensities relative to Hβ in Seyfert 1 galaxies (*filled circles*) and broad-line radio galaxies (*open circles*).

Seyfert 1 galaxy to another. Interpreted by the pure-recombination calculations for $T = 10^4$, $N_e = 10^6$ cm^{-3} (Brocklehurst 1971, 1972), the mean ratio λ5876/Hβ = 0.18 corresponds to $N(\text{He}^+)/N(\text{H}^+) =$ 0.15, while the maximum λ4686/Hβ $\lesssim$ 0.9 corresponds to $N(\text{He}^{++})/N(\text{H}^+) \lesssim 0.08$. The exact values are not significant, because the discussion above shows that more than recombination is involved in the H I emission, and undoubtedly the same is true for at least He I and possibly He II also. However, the recombination emission coefficients are probably approximately applicable, and these results thus show that the helium abundances are approximately normal in most Seyfert 1 and broad-line radio galaxies.

Nearly every Seyfert 1 galaxy has measurable Fe II emission, as indicated in Table 1. The relative intensities of the Fe II λ4570 and Fe II λ5190 + λ5320 features, both with respect to Hβ, are plotted in Figure 4. It can be seen that there is a good correlation between these measured intensities, which strengthens our confidence that these broad and often poorly defined blends have been measured approximately correctly.

It can be seen from Table 1 or Figure 4 that the broad-line radio galaxies have relatively weak Fe II emission. This is further emphasized in Figure 5 where the strength of the total Fe II emission measured (relative to Hβ) is plotted against Hα/Hβ. Here the broad-line radio galaxies are completely separated from the Seyfert 1 galaxies. It will be particularly interesting to see if this relationship holds up as further objects of both classes are measured in the future. If it does, it must imply something about the differences in the physical conditions of structure of radio galaxies and Seyfert galaxies.

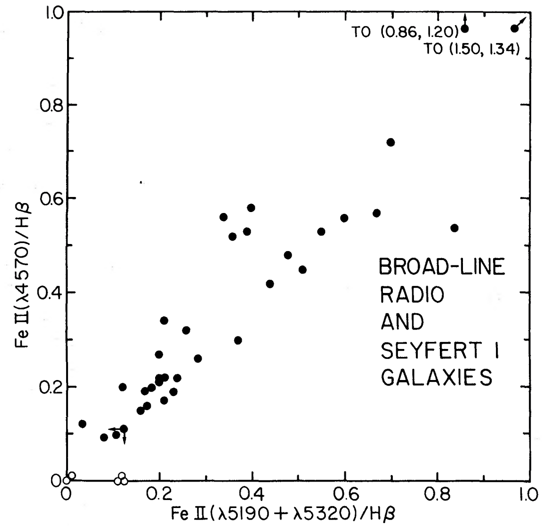

FIG. 4.—Measured Fe II intensities relative to Hβ in Seyfert 1 galaxies (*filled circles*) and broad-line radio galaxies (*open circles*).

The excitation mechanism originally suggested to explain Fe II emission in 3C 273 (Wampler and Oke 1967) and in I Zw 1 (Sargent 1968) is resonance fluorescence excited by absorption of photons in the continuum around λ2500. It has been generally assumed that this same process is responsible for the Fe II emission in all Seyfert 1 galaxies (Boksenberg

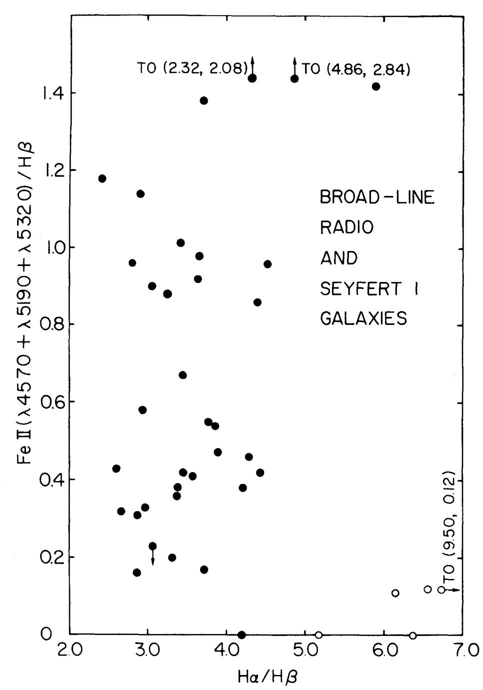

FIG. 5.—Measured Fe II and Hα intensities relative to Hβ in Seyfert 1 galaxies (*filled circles*) and broad-line radio galaxies (*open circles*).

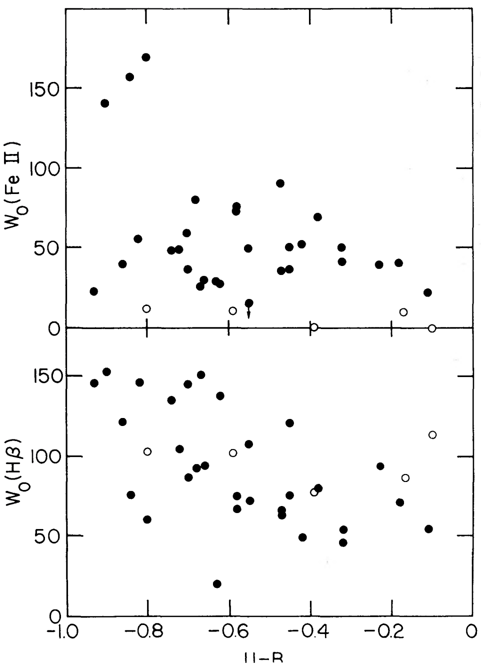

FIG. 6.—Measured equivalent widths of Fe II features (as defined in text) and Hβ versus measured $U - B$ color indices for Seyfert 1 galaxies (*filled circles*) and broad-line radio galaxies (*open circles*).

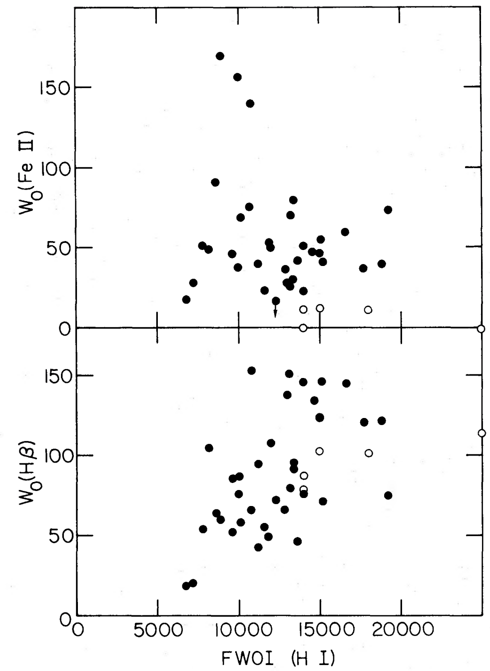

FIG. 7.—Measured equivalent widths of Fe II features (as defined in text) and Hβ versus measured H I full width at zero intensity (expressed in km s^{-1}) for Seyfert 1 galaxies (*filled circles*) and broad-line radio galaxies (*open circles*).

et al. 1975; Osterbrock 1976*a*; Oke and Shields 1976). Some simple tests of this idea can be made with the present data. It would seem that if the Fe II excitation were due to resonance fluorescence, there should be a correlation between the strength of the Fe II features and the ultraviolet color of the galaxy, assuming that the slope of the continuum remains more or less constant down to λ2500. The evidence is shown in Figure 6. Here, in the upper part, the approximate total equivalent width of the Fe II features measured, defined by

$$W_0(\text{Fe II}) = \left[\frac{\lambda 4570 + \lambda 5190 + \lambda 5320}{\text{H}\beta}\right] W_0(\text{H}\beta)\,,$$

is plotted against the $U - B$ color index, taken from the compilation by Weedman (1977). It can be seen that although the three Seyfert 1 galaxies with the strongest Fe II emission (I Zw 1, Mrk 478, and II Zw 136) all have large negative $U - B$ indices, there is little other correlation between the Fe II strengths and $U - B$. The lower part of Figure 6 shows Hβ equivalent widths plotted against $U - B$, and it appears there is a weak correlation, in the sense that the Seyfert 1 galaxies with the strongest H I emission tend also to have the strongest ultraviolet continua. Physically, this may result from photoionization, or the correlation may be indirect, for the source of the observed ultraviolet continuum and the source of the energy input to the ionized gas may be physically related, but not identical.

Figure 7 shows a plot of the Fe II equivalent width against the full width at zero intensity of the H I lines, taken from the last column of Table 4. If resonance fluorescence were the excitation mechanism, a correlation would seem to be expected between the Fe II line widths and strengths, for in a galaxy with wider lines more energy is available in the continuum for conversion into observable Fe II line photons. Furthermore, the widths of the individual Fe II lines are approximately the same as the widths of the H I lines (Phillips 1976), so a correlation would be expected between the Fe II equivalent widths and the H I line widths. However, the upper part of Figure 7 shows that the three Seyfert 1 galaxies with the strongest Fe II have relatively narrow lines, and that otherwise there is little if any correlation between W_0(Fe II) and the H I full width at zero intensity (FW0I). On the other hand, the lower part of this figure shows that there is a reasonably good correlation between the W_0(Hβ) and the H I FW0I, indicating a close connection between the energy input mechanism to the ionized gas and the line width or total velocity spread. Thus these data provide little if any evidence supporting the hypothesis of resonance-fluorescence excitation of Fe II emission in Seyfert 1 galaxies, and on simple physical grounds seem to contradict it. Detailed predictions from a specific model are necessary to be certain of this conclusion.

A wide range of H I line widths occurs in Seyfert 1 galaxies, as listed in Table 4. The statistics of the distribution of the FW0I, grouped in 2000 km s^{-1} intervals, are shown in Figure 8. It can be seen that the mean

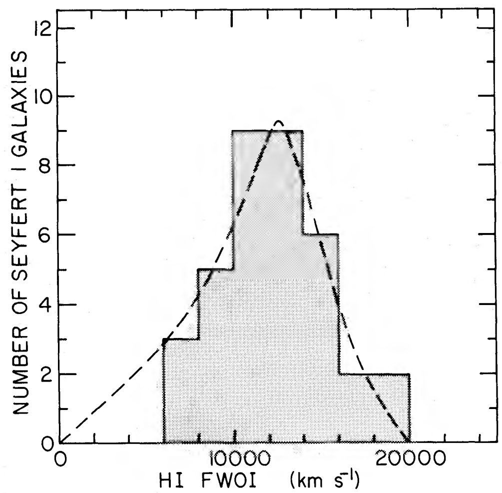

FIG. 8.—Distribution of H I full widths at zero intensity (expressed in km s^{-1}) for Seyfert 1 galaxies. The shaded bar graph is the observed distribution, the dashed curve is an approximately fitted analytic distribution function as described in the text.

FW0I is about 13,000 km s^{-1}, with a broad distribution extending from 6000 to 20,000 km s^{-1}. As rotation has often been suggested as at least a partial source of the large velocity spread in Seyfert galaxies (e.g., Hills 1975), it is of interest to compare the observed distribution with the distribution expected to result from rotational velocities alone. Presumably the rotational axes of the Seyfert 1 galaxies would be distributed at random, and it would be expected that at least a few objects would be seen nearly pole-on, and therefore appear with FW0I less than 6000 km s^{-1}. This argument can be made more quantitative following the analysis of Chandrasekhar and Münch (1950) in the corresponding stellar problem. They calculated the expected observed distribution function for a series of true rotational-velocity distribution functions of a general form described by two parameters, essentially the mean velocity and the dispersion in rotational velocity. The dashed curve shows an approximate fit of this type of function, chosen to represent the observed data as closely as possible between 6000 and 20,000 km s^{-1}. The extension of the calculated predicted distribution shows that four or five Seyfert 1 galaxies should be expected in the range 0 to 6000 km s^{-1}, though in fact none are observed. It might be objected that since Seyfert 1 galaxies are defined by the property of having broad H I emission lines, the pole-on objects, if they existed, would automatically not be included in this survey. However, they should then presumably show up as Seyfert 2 galaxies, but in fact the emission-line spectra of these objects are sufficiently different from Seyfert 1 galaxies to say that this is certainly not the case. In particular, not only is the [O III]/Hβ ratio generally considerably weaker in Seyfert 1 galaxies than in Seyfert 2 galaxies (Khachikian and Weedman 1974; Adams and Weedman 1975), but also nearly every Seyfert 1 has Fe II emission in its spectrum while only a single Seyfert 2 (classified on the basis of line width alone) has Fe II approaching comparable strength. This object is Mrk 42, which was originally classified as a Seyfert 1 by Khachikian and Weedman (1974), presumably on the basis of its [O III]/Hβ ratios rather than its line widths. Its spectrum is described in detail by Koski (1976), and it is the only Seyfert 2 which turned up in our fairly homogeneous survey that could perhaps be described as a "pole-on Seyfert 1." Therefore on statistical grounds it seems likely that the main H I line-broadening mechanism in Seyfert 1 galaxies is not rotation. The major contributor to the width of the lines must be a more or less spherically symmetric velocity field, presumably due to expansion, contraction, or turbulence.

The present scans confirm that only H I, He I, He II, and Fe II emission lines have broad profiles in Seyfert 1 galaxies, and that all the forbidden lines have narrower line profiles (see, e.g., Adams and Weedman 1975; Neugebauer *et al.* 1976; and references given there) with half-widths typically of order 500 km s^{-1}. This confirms, as these and earlier authors have stated, that in the broad-line emitting regions the electron density is high ($N_e \gtrsim 10^9$ cm^{-3}). The measured [O III] (λ4959 + λ5007)/λ4363 ratios range from 7 to 54; the median value is about 25. This implies that, as in the narrow-line region of the broad-line radio galaxies (Osterbrock, Koski, and Phillips 1976), the mechanism of ionization is probably not collisions, but can be photoionization, with temperatures in the O^{++} zone of order 10,000 K to 15,000 K and mean electron densities ranging approximately from 10^4 cm^{-3} to 10^6 cm^{-3}. On the other hand, in all these Seyfert 1 galaxies the mean electron densities derived from [S II] λ6731/λ6716 are of order 10^3 cm^{-3} or less. This probably implies that the [S II] emission comes from a region in which H and He are mostly neutral, and the bulk of the free electrons are produced by ionization of C, Si, Fe, Mg, etc. The wide range of ionization of the observed lines, from [O I] and [S II] to [Fe VII], is also consistent with photoionization (Osterbrock and Miller 1975). The strengths of most of the forbidden lines are strongly correlated with one another, although [O II] λ3727/[O III] (λ4959 + λ5007) ranges from nearly 0 up to a maximum of about 0.3. In general the forbidden-line spectra of Seyfert 1 galaxies are very similar to the emission-line spectra of Seyfert 2 galaxies, but a detailed comparison must await the publication of Koski's (1977) results. Although in general there is a fairly good anticorrelation between [O III]/Hβ and Fe II/Hβ (Shectman and MacAlpine 1975; Boksenberg *et al.* 1976), there are several Seyfert 1 galaxies in which both these intensity ratios are large, namely II Zw 1, Mrk 291, Mrk 382, Mrk 124, and NGC 3227.

Visual inspection of the scans show that all the Seyfert 1 galaxies described in this paper have continuous spectra consisting of smooth continua extending into the blue, combined in many cases with absorption-line spectra of galaxies, as described previously for many Seyfert 1 galaxies (Wampler 1971; Stein and Weedman 1976; Neugebauer *et al.* 1976).

The chief absorption lines seen are Ca II K, Mg I *b*, and Na I D, which is almost always detectable against the broad He I λ5876 emission line. The smooth continuum is seen by the weakness of the absorption lines, but more strikingly by the general flatness of the spectrum into the ultraviolet, in strong contrast to normal galaxies' spectra.

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