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SEYFERT GALAXIES

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1. INTRODUCTION

This review appears nearly a decade after the Tucson conference "Seyfert Galaxies and Related Objects" held in February, 1968. At that time, realization of the similarities between the QSOs and the nuclei of Seyfert galaxies led 56 astrophysicists to contribute their ideas regarding Seyfert galaxies [*Astronomical Journal*, Vol. 73 (1968), pp. 836-943]. A number of questions were posed regarding the energetic events in Seyfert galaxies. Most of these remain unanswered. Progress has been made in increasing the sample of Seyfert galaxies, in describing the physical conditions in their nuclei, and in delineating the relation between Seyferts and QSOs. Two basic aspects of the Seyfert galaxy problem have been emphasized. One is the nature of redshifts and whether a study of Seyfert galaxies leads to proof that QSO redshifts, by analogy, are cosmological. The other is the search for an explanation of the extraordinary energy source that powers the nuclei of Seyfert galaxies. There are many reasons to believe that the same mechanism of energy generation operates within most Seyfert nuclei as in the QSOs. To a certain extent, this has been a frustrating research problem because of the lack of progress in deciphering the fundamental mechanisms involved. On the other hand, far more observational research is being directed toward Seyfert galaxies than ever before, so this deserves to be chronicled.

This review makes no attempt to incorporate the numerous observations and theories concerning the general problem of galactic nuclei, even though this is certainly relevant to Seyfert galaxies. Some judgment had to be used as to the point when the review was sufficiently comprehensive to encourage new researchers to consider the problems but not so encyclopedic as to be intimidating. An earlier review in this series provided a comprehensive discussion of galactic nuclei including data on Seyferts known at the time (Burbidge 1970). Somewhat more recent summaries of observational work on Seyfert galaxies are given by Osterbrock (1971), Sargent (1971), and Ulrich (1974). A comprehensive theoretical review is that of Saslaw (1974). Listings of Seyfert galaxies and notes on the morphology and spectra of individual objects are given by Khachikian & Weedman (1974) and Adams (1977). The relation between Seyferts and other emission-line galaxies has recently been discussed by van den Bergh (1975a) and Weedman (1977). Osterbrock (1977a) compares the properties of Seyfert and radio galaxies. The role of Seyfert

galaxies in the redshift controversy is discussed by Weedman (1976a). The present review emphasizes the description of the Seyfert galaxy phenomenon as synthesized from recent observational studies; most of this summary is based on work done since 1970. Unfortunately, we have so far been unable to explain much of what we see.

2. SEYFERT GALAXIES CURRENTLY KNOWN

After looking at only a few galaxies through a telescope, the distinctive properties of Seyfert galaxies are readily apparent. An ordinary galaxy, spiral or elliptical, has a concentration of light in the center which is usually called a "nucleus." In such cases, there is a gradual brightening of the galaxy toward the nucleus, and the surface brightness at the center is much fainter than that of a star whose magnitude is comparable to the total magnitude of the galaxy. In any photograph, no matter how short the exposure, such a galaxy looks fuzzier than a star. A Seyfert galaxy, however, can readily be recognized at the telescope (which greatly simplifies the use of finding charts) because it looks like a bright star surrounded by a faint envelope. In short-exposure photographs, it cannot usually be distinguished from a star. Consequently, the morphological definition of a Seyfert galaxy is the presence of an unresolved, very bright nucleus. The extent to which the nucleus dominates the galaxy depends both on the nucleus/galaxy luminosity ratio and the distance to the system. Beyond redshifts of about 0.1, objects bright enough to have been identified as Seyferts probably have a nucleus so dominant in photographs that the galactic envelope is unclassifiable. While the lowest redshift Seyferts have been classified morphologically, there have been only limited attempts to define Seyfert galaxies on the basis of their photographic appearance (de Vaucouleurs & de Vaucouleurs 1968, Morgan et al. 1971). There are few direct measures of the actual sizes of Seyfert nuclei. The largest (NGC 1068) has emission lines arising over a region 8" in diameter (Walker 1968) although the continuum source is unresolved. Photographs of NGC 4151 from a balloon-borne telescope give an upper limit of 0".08 to the diameter of the continuum source (Schwarzschild 1973). VLBI results for 3C 120 measure individual radio sources, which presumably are no smaller than the optical source, to be as small as 0".001 (Kellermann et al. 1973). Many Seyfert nuclei are variable in brightness on time scales of years, which sets limits to their sizes if light-travel-time arguments are used.

There is also a spectroscopic definition of a Seyfert galaxy, which requires that they have strong and broad emission lines in their spectra (Seyfert 1943). Such lines are never seen in galaxies without bright nuclei, but there are some galaxies with bright nuclei that do not have such emission lines. In my experience, there are no galaxies without Seyfert spectroscopic characteristics whose nuclei are as bright relative to the galactic disk as they are in Seyferts. However, this opinion has not been quantitatively verified. Certainly, the presence of a compact luminosity source is a necessary prerequisite for having broad emission lines. This spectroscopic definition seems uncomfortably qualitative until it is realized that there are few ambiguous cases. Many galaxies have emission lines in their spectra, but these are generally narrow lines with widths less than a few hundred km sec^{-1}. Seyfert galaxies have emission lines with full widths of 10^3 km sec^{-1} or more, which means that only in a few cases is it necessary to argue whether an emission line is broad enough to call a galaxy a Seyfert. Astrophysically, the broad emission lines are just one indication of the activity that distinguishes Seyfert galaxies. There are other properties that are found to correlate with the Seyfert definition, such as the nature of the continuous spectra.

It is inappropriate to include too many parameters within a definition, so for this review a Seyfert galaxy is considered to be any object appearing nonstellar (nebulous) in photographs and having broad emission lines in its spectrum. This can include N galaxies as well as objects called QSOs, if they are accompanied by surrounding nebulosity. The implication will be that the nebulosity is in fact the disk of a galaxy, but this requires proof and so is irrelevant to the observational definition. Because the most homogeneous photographic data generally available for galaxies is that of the *National Geographic Society - Palomar Observatory Sky Survey*, the working definition of a Seyfert galaxy in this review requires that it appear nonstellar on the *Sky Survey*. This means in practice that it must have a diameter greater than about 7" for the nebulosity around the nucleus to be visible. We therefore are not including objects occasionally called galaxies because improved photographs show nebulosity associated with them (e.g. Kristian 1973). In Table 1, a list is given of 88 Seyfert galaxies that satisfy our working definition. This list is an update of that given by Khachikian & Weedman (1974) with 23 galaxies having been added and 6 deleted because there was uncertainty in their initial classification as Seyferts. Other than such updating, the differences between Table 1 and the Seyfert listing by Vorontsov-Velyaminov & Ivanisevich (1974) arise because the latter authors include a number of narrow-line galaxies. *The listing in Table 1 is conservative, generally omitting galaxies referred to by spectroscopists as probably or possibly being Seyferts* unless *UBV* photometry also showed the characteristic Seyfert colors. Galaxies are included only if a published reference contains their Seyfert designation, although a few unpublished Seyferts exist in various private collections. Redshifts are given in km sec^{-1}, as *cz*. The *UBV* colors are given for the smallest apertures used so as to represent primarily the nuclei. Magnitudes are not listed because they are dependent both on aperture and epoch. Most are between 14 mag and 16 mag although a few NGC objects are as bright as 11 mag. Angular diameters θ" are the maximum diameters that I measured on the *Sky Survey* prints, except for a few southern objects for which other photographs were used. References to photometry, spectroscopy, and other studies are usually included only for work published since 1970. No morphological properties are listed in Table 1 because these are summarized by Adams (1977). This list is intended to include those Seyfert galaxies reported in the literature before Sept. 1, 1976, but will certainly be incomplete when published. For example, two new Markarian lists (through the 800 series) were in press as of this date and may contain perhaps 20 more Seyfert galaxies.

Table 1. Listing of Seyfert galaxies

Object	RA (1950)	δ	Class	cz	θ''	Chart	$(B-V)$	$(U-B)$	UBV	Spectra	IR or Radio
Mkn 335	00h03m45.1s	+19°55′27″	1a	7500	16	1	0.41	−0.70	6	7, 5, 9, 23, 160	8
III Zw 2	00 08.0	+10 42	1	26930	12	2	0.52	−0.70	5, 135	2, 5, 73, 23, 160	161
Zwicky	00 39.5	+40 03	1	30780	8	3	—	—	136	3, 73	—
Mkn 348	00 46 04.4	+31 41 00	2	4200	77	1	0.95	+0.17	6	7, 5, 9, 162	8, 33, 47, 60, 155, 161
I Zw 1	00 51.0	+12 25	1	18280	22	4	0.36	−0.80	4, 5, 93, 135	10, 5, 11, 23, 73, 132, 160	8, 45, 51
Mkn 352	00 57 08.6	+31 33 27	1a	4500	38	1	0.44	−0.66	6	7, 5, 9, 23, 160	8
Tololo	01 09	−38.3	2	3300	135	12	—	—	—	12	—
Mkn 1	01 13 19.5	+32 49 33	2a	4800	34	13	0.90	+0.09	6	5, 14, 15, 30, 162	8, 30, 33, 45, 47, 155, 161
II Zw 1	01 19.5	−01 18	1	16240	15	4	0.57	−0.42	4, 5	4, 5, 23, 160	—
Akn 42	01 21.9	+31 55	1	10800	38	16	—	—	—	17	—
Mkn 358	01 23 45.1	+31 21 13	1	13750	42	1	0.79	−0.32	5	7, 18, 23, 160	—
4C 29.6	02 04 08.9	+29 16 40	1	32700		101	—	—	—	102	—
Mkn 590	02 12.0	−01 00	1	8100	55	20	—	—	—	19, 160	—
Akn 79	02 14.3	+38 11	1	6000	60	16	—	—	—	17	—
Akn 81	02 20.4	+31 58	1	10500	32	16	—	—	—	17	—
NGC 985	02 32.1	−08 59	1	12950	45	72	0.36	−0.95	21	21	—
NGC 1068	02 40.1	−00 14	2a	1090	380	72	1.00	−0.01	22, 77, 26, 124	73, 52, 57, 96, 71, 128, 138, 118, 35, 94, 42, 49, 162	59, 48, 45, 34, 77, 107, 108, 110, 111, 127, 134, 125, 161
Mkn 372	02 46 30.9	+19 05 54	2	9300	23	1	1.05	−0.03	6	7, 5, 9, 162	8
NGC 1275	03 16.5	+41 20	?	5290	68	72	0.64	−0.23	22, 77, 124	89, 73, 71, 9, 5, 94, 79, 81	77, 45, 44, 8, 77, 112, 91, 137, 161
Mkn 609	03 22.9	−06 19	1	9600	17	24	—	—	—	19, 23	—
III Zw 55	03 38.7	−01 27	2	7380	13	4	0.84	+0.17	4	4, 5, 9, 162	8
NGC 1566	04 18.9	−55 04	1a	1170	420	25	0.76	−0.04	26, 27, 133	25, 28, 73, 131	117, 133, 161
3C 120	04 30.0	+05 15	1	9900	42	2	0.58	−0.75	6, 77, 99, 124, 130	58, 56, 9, 73, 23, 106, 160	8, 45, 77, 41, 43, 140, 141, 161
Mkn 618	04 34.0	−10 28	1	10200	68	24	—	—	—	23, 160	—
Akn 120	05 13.6	−00 12	1	9900	60	16	—	—	—	17	—
Mkn 3	06 09 48.1	+71 03 00	2a	4110	44	13	1.15	+0.15	6	5, 15, 14, 9, 30, 162	30, 33, 47, 155, 161
Mkn 6	06 45 43.4	+74 29 07	1a	5290	52	13	0.97	+0.02	6	55, 9, 15, 30, 87, 88, 122, 162	30, 33, 47, 105, 161
Mkn 374	06 55 33.9	+54 15 53	1	13200	41	1	0.70	−0.38	6	7, 5, 9, 23, 160	8, 161
Mkn 376	07 10 35.8	+45 47 07	1	16800	18	1	0.55	−0.58	5	31, 9, 32, 23, 160	8
Mkn 9	07 32 42.0	+58 53 00	1	12040	22	13	0.54	−0.64	6	30, 14, 9, 23	30, 8, 45
Mkn 78	07 37 55.9	+65 17 43	2a	11260	19	38	0.99	−0.31	6	36, 37, 9, 162	161
Mkn 79	07 38 46.9	+49 55 47	1	6580	86	38	0.47	−0.74	39, 6, 66	37, 30, 9, 23, 5, 115, 160	30, 8, 45, 51, 161
Mkn 10	07 43 07.4	+61 03 23	1	8790	95	13	0.67	−0.55	39, 6, 124	14, 30, 23, 160	30, 45
Mkn 382	07 52 03.2	+39 19 07	1	10200	42	1	0.51	−0.63	5	32, 23, 160	8
Mkn 110	09 21 44.4	+52 30 14	1a	10800	47	38	0.76	−0.67	6	40, 5, 9, 160	8, 161
Zwicky	09 34.5	+01 20	1	15150	—	—	—	—	—	139	—
3C 227	09 45 06.3	+07 39 17	1a	25600	8	29	0.98	−0.36	65	54, 23, 160	161
Mkn 124	09 45 24.3	+50 43 26	1	16970	18	38	0.61	−0.47	66	37, 30, 9, 160	30, 8, 161
Akn 223	09 54.7	+07 26	1	6600	21	16	—	—	—	67	—
Mkn 141	10 15 38.7	+64 13 14	1	11700	19	38	0.71	−0.32	6, 66	40, 9, 160	—
NGC 3227	10 20.7	+20 07	2a	1000	330	72	0.82	−0.11	22, 77	69, 9, 71, 73, 5, 118, 160	45, 8, 77, 34, 125, 127, 126, 161
Mkn 142	10 22 23.1	+51 55 40	1	13500	24	38	0.44	−0.58	66	40, 160	8
Ton 524a	10 28.8	+29 06	1	18000	10	121	—	—	—	121	—
Mkn 34	10 30 52.2	+60 17 20	2a	15300	39	13	1.06	+0.07	6	15, 9, 30, 162	30, 45, 161
Akn 253	10 41.4	−01 01	1	7800	34	16	—	—	—	67	—

Object	RA (1950)	δ	Class	cz	θ"	Chart	(B–V)	(U–B)	UBV	Spectra	IR or Radio
NGC 3516	11 03.4	+72 50	1[a]	2780	80	72	0.77	−0.18	22, 77, 123, 125	84, 73, 68, 71, 9, 119, 128, 138, 160	45, 77, 126, 161
VV 144	11 22 48.0	+54 39 26	1	6150	16	13	0.82	−0.23	6	4, 14, 73, 160	—
Mkn 176	11 29 54.0	+53 13 27	2	8080	25	38	0.89	+0.30	6	37, 5, 9, 55, 162	8, 51, 161
NGC 3783	11 36.5	−37 28	1[a]	2740	72	72	0.56	−0.70	25	25, 28	61, 117
Mkn 42	11 51 05.3	+46 29 20	1	7200	44	13	0.79	−0.19	14	75, 9, 162	8
NGC 4051	12 00.6	+44 48	1	700	280	72	0.73	−0.38	22, 77	71, 73, 5, 118, 128, 138	45, 8, 77, 125, 127, 126, 161
NGC 4151	12 08.0	+39 41	1	990	450	72	0.53	−0.72	22, 77, 124	82, 71, 55, 86, 35, 128, 109, 114, 138, 83, 53, 100, 95, 73	77, 45, 44, 34, 8, 108, 120, 125, 127, 126, 161
Mkn 50	12 20 50.9	+02 57 20	1	6910	16	13	—	—	—	74	—
NGC 4507	12 32.9	−39 38	2	3310	68	72	—	—	—	62	117
Mkn 231	12 54 05.0	+57 08 37	1	12300	27	142	0.84	+0.15	6	78, 142, 143, 5, 149	45, 44, 33, 47, 51, 90, 155, 161
X Comae	12 57 58	+28 40.2	1	27600	10	103	—	—	104, 116	104	—
Mkn 236	12 58 18.0	+61 55 27	1	15600	30	14e	0.66	−0.45	5	145, 160	—
Mkn 64	13 04 47.7	+34 40 23	1	55200	8	15	0.41	−0.74	146	146	—
3C 287.1	13 30 21.1	+02 16 11	1	64700	8	29	0.92	−0.15	148	147	161
Mkn 268	13 38 54.2	+30 37 47	2	12300	36	14e	0.94	+0.28	6	149, 5, 9, 162	8, 161
Mkn 270	13 39 40.7	+67 55 33	2	2700	45	14e	0.92	+0.31	6	149, 5, 162	161
Mkn 69	13 43 51.3	+29 53 03	1	22870	11	13	—	—	—	74, 160	—
IC 4329A	13 46.2	−30 03	1[a]	4140	70	80	0.96	+0.51	80	80, 28	61, 161
Mkn 279	13 51 51.9	+69 33 13	1	9220	43	14e	0.69	−0.45	6	75, 5, 9, 149, 160	161
Mkn 463	13 53 39.8	+18 36 40	2	15140	94	151	—	—	—	150	33, 47, 161
Mkn 464	13 53 45.1	+38 48 54	1	15300	13	151	—	—	—	150	—
NGC 5548	14 15.7	+25 22	1[a]	4990	80	72	0.46	−0.82	77, 123, 124, 22	118, 71, 68, 70, 9, 73, 128, 160	45, 77, 126, 8, 161
Mkn 474	14 33 06.0	+48 52 47	1	12300	22	151	0.97	−0.18	5	152	8
Mkn 478	14 40 04.6	+35 38 53	1	23700	16	151	0.33	−0.84	5	19, 160	8
4C 35.37	15 31 44.9	+35 54 18	1	46950	8	101	—	—	—	102	—
Mkn 290	15 34 45.4	+58 04 00	1	9240	14	144	0.60	−0.62	6	75, 149, 160	8, 161
Mkn 486	15 35 21.5	+54 43 04	1	11700	25	151	0.43	−0.68	5	19, 9, 160	8
Mkn 291	15 52 54.1	+19 20 20	1	10500	35	144	—	—	—	149, 160	—
Mkn 298	16 03 21.7	+17 56 03	2	10350	42	144	1.01	−0.09	6	75, 149, 162	161
Mkn 504	16 59.2	+29 29	1	10800	19	151	0.85	−0.47	5	153, 160	8
Mkn 506	17 20.7	+30 56	1	12900	34	151	0.74	−0.55	5	19, 5, 160	8
3C 382	18 33 11.9	+32 39 18	1[a]	17580	15	29	—	—	—	54, 64, 160	—
3C 390.3	18 45 38.7	+79 43 10	1[a]	17100	12	29	0.68	−0.69	65, 97, 135	54, 64, 85, 23, 92, 160	161
NGC 6764	19 06.9	+50 51	2	2405	128	72	—	—	—	154, 162	161
NGC 6814	19 39.9	−10 25	1	1590	136	72	1.12	+0.37	77, 113, 5	46, 28	45, 77, 8
Mkn 509	20 41.5	−10 54	1	10650	17	20	0.23	−0.93	8	19, 55, 23, 160	8, 51
II Zw 136	21 30.0	+09 56	1	18510	30	156	0.29	−0.90	4, 135, 124, 6	4, 5, 132, 23, 160	51, 8
Mkn 304	22 14 45.2	+13 59 27	1	19950	11	1	0.36	−0.86	5	7, 5, 23, 160	8
NGC 7469	23 00.7	+08 36	1[a]	5020	89	72	0.54	−0.72	77, 124, 22	73, 94, 28, 159, 50, 5, 118, 23, 98, 71, 148, 160	45, 77, 8, 34, 161
Mkn 315	23 01 35.6	+22 21 10	1	11830	19	1	0.82	−0.09	5	18, 7, 5, 162	161
NGC 7603	23 16.4	−00 01	1[a]	8800	55	72	0.72	−0.21	6	129, 76, 5, 23, 9	—
Pks	23 49 22.5	−01 26.0	1	52200	12	158	—	—	—	157	157, 161
Mkn 541	23 53.5	+07 15	1	12300	38	20	—	—	—	19, 23, 160	

[a] Asymmetries have been noted in line profiles.

Table 1 - *continued*

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162. Koski 1976

3. SURVEYS AND MORPHOLOGY

In 1943, Seyfert studied six galaxies that had been noted to have unusual emission lines in the collection of Mt. Wilson spectra accumulated for redshift studies. The sample did not increase significantly for 25 years, until the Markarian and Zwicky surveys. Beginning in 1967, Markarian has published seven lists containing about 700 galaxies (with two more lists in press as of this writing) distinguished by their unusually strong ultraviolet continua (Markarian 1967, 1969a, 1969b, Markarian & Lipovetsky 1971, 1972, 1973, 1974). (Improved positions for some of these are given by Peterson 1973.) These objects have a space density of about one per ten square degrees and were found on low-dispersion, objective prism survey plates obtained with the 1-m Schmidt at Byurakan Observatory. Subsequent studies showed that the majority of the Markarian galaxies have emission-line spectra (see references in Weedman 1977). The Markarian survey reaches to 17 mag but seems to be complete only to about 16 mag (Huchra & Sargent 1973). Approximately 10% of the Markarian galaxies are Seyferts, and the subsequent spectroscopic discovery observations of the Seyferts thus found are referenced in Table 1. In contrast to Markarian's spectroscopic survey techniques, Zwicky compiled lists of compact galaxies based on their morphological appearance on the *Sky Survey* plates. He selected objects that were almost stellar, having soft edges or faint associated nebulosity. These lists were never published, but spectroscopic surveys primarily by Sargent (1970a) of a number of Zwicky's compact galaxies revealed several Seyferts.

Other surveys analogous to these are now underway and have already provided some Seyfert galaxies. A southern hemisphere objective prism survey is being conducted with the 61-cm Curtis Schmidt telescope at Cerro Tololo (Smith 1975, 1976, Smith et al. 1976). The Tololo survey has higher resolution than the Markarian survey and selects objects because they have emission lines in their spectra. An important variety of emission-line galaxies have been found this way; observations so far available indicate that similar sorts of galaxies are found in the Tololo lists as in the Markarian lists. The Tololo survey as instituted and carried out by M. G. Smith covered approximately 3000 square degrees and resulted in the discovery of about 500 emission-line galaxies, whose publication is beginning (Smith et al. 1976). Another portion of the southern sky ($-20° \leq \delta \leq 8°$) is being surveyed in the same way with the Curtis Schmidt by astronomers from the University of Michigan, which owns this telescope. Several hundred emission-line galaxies have been found in this region, and they are accessible from the north (G. MacAlpine, personal communication). Large-scale follow-up studies of all these Tololo galaxies, expected to yield numerous new Seyferts, are underway.

Morphologically oriented surveys have also been conducted recently. A list of 591 galaxies of high surface brightness has been prepared by Arakelian (1975). He estimated the surface brightnesses by comparing the magnitude measures in the Zwicky catalogs of galaxies (*not* the Zwicky compact galaxies) to the diameter measures in the Vorontsov-Velyaminov morphological catalogs of galaxies. Six new Seyferts have already been found in Arakelian's lists (Table 1). A spectroscopic survey of southern galaxies classified as having bright nuclei was carried out by Martin (1976), who found one new Seyfert in this way.

It is important, of course, to study the galaxies with bright nuclei that are not called Seyferts in hopes of finding just when and how the Seyfert activity turns on. We do not know, for example, whether there are galaxies with narrow emission lines that have nonthermal continuous spectra like the Seyferts. Certainly there are bright nucleus galaxies like NGC 4385 (Mkn 52) and NGC 7714 (Mkn 538) which have very strong but narrow emission lines with intensity ratios like those in conventional HII regions. The *UBV* colors correspond to collections of hot stars (Weedman 1973, Huchra 1976), but some of these galaxies have infrared luminosities comparable to the Seyferts (Rieke & Low 1972). Another intriguing result is that interacting galaxies seem to have

strong nuclear emission lines unexpectedly often. Representative examples are NGC 2992 (Osmer et al. 1974b) and the aforementioned NGC 7714 (Burbidge 1968). Adams (1977) also noted a probable surplus of interacting systems among the Seyferts themselves. The large samples of galaxies from the Markarian and Tololo surveys may allow us to determine how such galaxies relate to the Seyfert problem.

From the number of Seyfert galaxies among bright Shapley-Ames galaxies, it was concluded that 1% of spiral galaxies are Seyferts (de Vaucouleurs & de Vaucouleurs 1968). This estimate remains valid for the larger sample now available, because Huchra & Sargent (1973) concluded that 5% of all galaxies were Markarian galaxies, of which 10% are Seyferts. Consequently, about 1 galaxy in 200 (of all types) is a Seyfert. Why? Do 1% of spiral galaxies remain Seyferts forever, or does each galaxy spend 1% of its life in the Seyfert phase? The current research relevant to this problem is into the morphological appearance of Seyfert galaxies to determine whether the presence of a Seyfert nucleus is correlated with any other property of a galaxy.

The most striking empirical result is a deficiency of ellipticals among the Seyferts. There are ten galaxies now known to be Seyferts that are bright enough to be Shapley-Ames galaxies. Van den Bergh (1975b) has emphasized the fact that all ten are spirals. A comprehensive morphological study of 80 Seyfert galaxies was recently completed by Adams (1977). He finds that Seyferts occur in a broad distribution of ordinary and barred spirals but that there are very few ellipticals. Counting those galaxies with amorphous but unclassifiable envelopes, Adams finds a maximum allowable limit of 10% for the fraction of Seyferts that could be ellipticals, but the more reasonable limit is 5%. By contrast, 33% of the galaxies in Humason et al. (1956) are ellipticals. Because many of the Seyfert galaxies have such small angular sizes as to be unclassifiable, it is possible that none are ellipticals. The only Seyfert that can be called a giant elliptical because of its dominant appearance in a cluster is NGC 1275. It has many other properties that are unique among Seyferts, so much so that it is clearly an anomalous object. (Had it not been included in Seyfert's original study, it probably would not have been grouped with the other galaxies called Seyferts today, but more likely would be considered a peculiar radio galaxy.) Adams and van den Bergh discuss the implications of this elliptical deficiency for our understanding of QSOs, as the morphology of Seyferts is in dramatic contrast to that of the radio galaxies.

Previous studies had pointed out the peculiar appearance of certain classical Seyferts, especially the presence of faint annular structures (Burbidge et al. 1963, Hodge 1968). Adams adds some examples of these as well. Such effects could be important for demonstrating interactions between the disk and the nucleus, although they would not show whether the nuclear activity triggered changes in the disk or vice-versa. A possible correlation between the spectroscopic properties of the nuclei and the appearance of the galactic disk was suggested by Khachikian & Weedman (1971). To some degree, Adams confirms this in the sense that no Seyferts of spectroscopic class 2 (see below) have spiral structure as conspicuous as that in some of class 1. The only suggested explanation so far for the various peculiarities referenced is that mass outflow from the nuclei of the Seyferts is somehow affecting the galactic disks.

The above-mentioned morphological studies, which demonstrate the spiral nature of many Seyfert galaxies, are of special importance regarding the redshift controversy. Continuity arguments demonstrating a luminosity overlap between Seyferts and QSOs provide empirical evidence for cosmological redshifts of QSOs, if the Seyfert redshifts are cosmological. It is therefore imperative to show that some "Seyfert galaxies" whose cosmological luminosities would compare to QSOs really are distant galaxies. The presence of spiral arms is an acceptable morphological indication that a nebulous object really is a galaxy. For more amorphous envelopes, it has been suggested that absorption lines must be detected in the envelopes before they can be considered as galaxies made of stars (Burbidge 1973). Such absorption lines are difficult to detect. No such lines are found even in the outer disk of the spiral Seyfert NGC 4151 (Simkin 1975). However, extensive photometric studies of the disks of the larger Seyferts show that their colors correspond to those expected for galaxies of stars (Penston et al. 1974, Dibay & Lyutyi 1971, Walker et al. 1974, Zasov & Lyutyi 1973). For higher redshift Seyferts, a morphological demonstration that real galaxies are present is difficult. Adams (1977) finds that only 21% of all Seyferts are unresolved or have amorphous main bodies, but that this fraction is 80% for those with redshifts above 20,000 km sec^{-1}. This is as expected, of course, if the Seyferts are really galaxies whose angular size decreases in proportion to their distance.

4. EMISSION-LINE SPECTRA

Within the past five years, extraordinary progress has been made in the accumulation of spectrophotometric data for Seyfert galaxies. This is because of the multichannel spectrum scanners now available for most large telescopes. Technical details of these instruments can be found in some of the references included in Table 1, primarily the work involving Osterbrock, Oke, or Boksenberg. Earlier studies of bright Seyferts have been repeated with higher accuracy, and precision studies of faint spectral features as well as extensive observations of previously unstudied objects have begun. Perhaps a measure of the progress in our knowledge of Seyfert galaxies is the fact that it is no longer feasible to discuss each one individually in a review. Consequently, recent spectrophotometric studies of the various Seyferts are referenced in Table 1. The review that follows is a synthesis of the generalities that can be deduced from this data.

As the sample of Seyfert galaxies grew, it became obvious that all such objects by no means had identical spectra. The Seyferts were therefore subclassified strictly on the basis of their spectroscopic properties in an attempt to identify those subgroups with

similar physical properties. This, of course, is the motivation for any astronomical classification scheme. Because Seyfert galaxies are characterized by strong and broad emission lines, the nature of these lines was used as the classification criterion. A simple division into classes 1 and 2 (Sy 1 and Sy 2), which depended only on *relative* emission-line widths, was used by Weedman (1970, 1973) and Khachikian & Weedman (1971, 1974). Illustrations of spectra and line profiles are given in these references. The Sy 1 have broad hydrogen lines but narrower forbidden lines, such as the classical Seyfert NGC 5548. Other permitted lines are also broad when the Balmer lines are broad though they do not necessarily have the same profiles (Boksenberg et al. 1975a, Osterbrock 1976, Osterbrock et al. 1976). The only such lines observed are HeI λ5876, He II λ4686, occasional blends of FeII lines, and OI λ8446. These features are so weak relative to the Balmer lines that they have not been measured in all Sy 1. It is probably appropriate to infer that the other permitted lines arise in much the same volume as do the Balmer lines. Comprehensive spectrophotometric data on 40 Sy 1 galaxies are given by Osterbrock (1977b). This includes relative line intensities as well as line profile widths.

The Sy 2 are like NGC 1068, having hydrogen and forbidden lines of the same width, up to about 10^3 km sec^{-1}. The classification into Sy 1 or Sy 2 is most easily made just by comparing Hβ with an adjacent [OIII] line. The simplest explanation for the spectroscopic difference between Sy 1 and Sy 2 is that the broad Balmer lines characterizing Sy 1 arise in a different part of the nucleus than do the narrower forbidden lines, whereas all lines arise together in Sy 2. There is little ambiguity as to which galaxies are Sy 1, where the Balmer lines often have full widths of 10^4 km sec^{-1}. The problem in deciding whether to call a galaxy a Seyfert is in defining the line width at which an Sy 2 is distinguished from other emission-line galaxies. Those few objects classified Sy 2 whose line profiles have been measured show full widths at half maximum intensity greater than 500 km sec^{-1} (Weedman 1970), whereas such widths for representative narrow-line galaxies (from the same study) did not exceed 200 km sec^{-1}. The ambiguity between Sy 2 and narrow-emission-line galaxies is most serious in low-resolution spectroscopic surveys. For this reason, there are probably a number of Sy 2 in the Markarian and Tololo surveys that have not yet been observed with sufficient resolution to be classified and so are not included in Table 1. To date, the most detailed study of Sy 2 galaxies is by Koski (1976).

After the profile classification was adopted, other properties of the nuclei were found to correlate well with the Sy 1 and Sy 2 classes. A useful secondary classification is the Balmer-line to forbidden-line intensity ratio, especially Hβ : [OIII]. The forbidden lines are unusually strong in Sy 2, with an average Hβ: λ5007 ratio of 0.1, whereas Hβ and λ5007 typically have the same total flux for Sy 1 (Adams & Weedman 1975). For the narrow-emission-line galaxies, Hβ is also comparable to λ5007 in most cases. Correlations with *UBV* colors also exist because the continuous spectra for Sy 1, Sy 2, and narrow-line galaxies are different. It is then possible to use *UBV* colors as a secondary classification (Markarian 1973). Color-color diagrams showing results for Seyfert galaxies along with comparative colors of narrow-line galaxies are summarized in Weedman (1973) and Adams & Weedman (1975). Extensive *UBV* observations of narrow-line galaxies have been made by Huchra (1976), and these can be compared to the Seyfert colors in Table 1. The *UBV* colors provide reasonable distinctions in most cases among Sy 1, Sy 2, and narrow-line galaxies even if high-resolution line profiles are not available.

It is the Sy 1 that have power-law continuous spectra and the resulting ultraviolet excesses like QSOs. This correlation between the presence of very broad Balmer emission lines and a nonthermal continuum is one of the more interesting results established. Searle & Sargent (1968) pointed out the similar equivalent widths of the broad Balmer lines for Seyferts then known and showed that these were too small for the continuum to be emission from the same gas producing the Balmer lines. Adams & Weedman (1975) showed quantitatively that Balmer-line luminosities and continuum luminosities scale together for Sy 1 over six magnitudes of luminosity. They concluded that the Balmer lines therefore arise primarily from ionization by a radiative source that also produces the visible continuum, in accordance with models such as those of Williams & Weymann (1968). Extensions of the observed power-law continua into the ionizing ultraviolet generally provide enough photons to account for the Balmer-line strengths (Osterbrock 1971, 1976, Stein & Weedman 1976). The nature of the continuous spectra in Sy 2 is not as clear because they are affected significantly by starlight. The probable presence of heavy dust reddening and a possible nonthermal contribution means that the nature of Sy 2 continua is not as well understood as Sy 1.

If cosmological redshifts are assumed, the observed forbidden-line luminosities of Sy 1 and Sy 2 range over comparable values, whereas the Balmer lines can be up to ten times more luminous in Sy 1 (Adams & Weedman 1975). Osterbrock & Koski (1976) have emphasized that the broad Balmer-line wings provide the distinction between Sy 1 and Sy 2. The Balmer-line cores in Sy 1 have similar profiles and intensity ratios relative to forbidden lines as in the Sy 2. So, observationally at least, an Sy 2 could be transformed to an Sy 1 by adding a strong power-law continuum accompanied by the broad Balmer-line wings. Conversely, removing these would change Sy 1 to Sy 2. As Osterbrock & Koski put it, "Galaxies in which the broad Balmer line component is relatively strong are classified as Sy 1, while galaxies in which it is invisible are classified as Sy 2....Physically, different Seyfert galaxies must have different relative amounts of the material and physical conditions that emit these two components." They suggest that the Sy 1 have a higher proportion of very dense gas in which the broad wings arise. A similar conclusion was stated by Neugebauer et al. (1976). However, the ease with which an Sy 2 could be converted to an Sy 1 is not necessarily evidence that there is an evolutionary relation between them. They may be totally unrelated phenomena. One particularly troubling aspect is the implication that Sy 2 may be heavily obscured by dust while Sy 1 are not. In this case, the intrinsic

Balmer-line luminosities of Sy 2 would be comparable to Sy 1, and the forbidden lines typically ten times more luminous (Adams & Weedman 1975). Under such circumstances, addition of more Balmer emission would not make the intrinsic properties of Sy 2 match Sy 1.

5. BALMER DECREMENT AND LINE PROFILES

The problem of reddening is directly related to the interpretation of the Balmer decrement in Seyfert galaxies. The Balmer emission in most astrophysical plasmas, such as HII regions and planetary nebulae, arises from radiative ionization followed by recombination. Downward cascades within the newly recombined atoms produce emission lines whose intensity ratios can be calculated. For a nebula optically thick only in the Lyman lines, the ratio of Balmer-line intensities (the Balmer decrement) is Hα: Hβ: Hγ = 2.8:1.0:0.47 for temperatures near 10^4 °K (Miller 1974). In Seyfert galaxies, the decrement is invariably steeper than this, meaning that the redder Balmer lines are relatively more intense than predicted. There are two categories of explanation. One is that some mechanism selectively populates hydrogen energy levels from the ground up, which increases the relative intensity of the redder lines in a series. Such a mechanism could be collisional excitation, radiative excitation by a continuum, or Balmer-line self absorption. That such effects are important under the high-density conditions found in Seyfert nuclei has been shown by Netzer (1975) and Shields (1974). The alternative circumstance is that the Balmer lines are reddened by dust so that the observed decrement is steepened. If sufficient reddening is present to produce the observed decrement, there must be a lot of absorption by the same dust. In some cases, several magnitudes of absorption would be needed in the visible spectrum. This would mean that Seyfert nuclei are even brighter than they appear. Of course, the absorbed energy would have to come out somewhere in the spectrum, and the dust could be expected to reradiate in the infrared. The fact that Seyfert nuclei are strong infrared sources might mean that there is dust in some.

To resolve the decrement problem, it is therefore necessary to consider the effects that reddening would have both on the lines and the continuum. The most accurate spectrophotometric studies to date of the decrements in Sy 1, through the Hγ line, have been unable to account for the decrements with any assumed amount of normal reddening (Osterbrock et al. 1975, Osterbrock 1976). If dust reddening were responsible for the steep decrements, the continua on average should become redder as the decrement increased. However, there are no empirical correlations between the Hα: Hβ ratio and the continuum colors, either in the optical or in the optical vs. the infrared (Adams & Weedman 1975, Stein & Weedman 1976). All of these authors therefore concluded that in the Sy 1 nuclei radiative recombination was not the only contributor to excitation of the Balmer lines. Some other of the effects mentioned above are probably important in the region where the broad Balmer lines arise and account for the unexpectedly steep decrement.

This explanation does not necessarily apply to Sy 2, however. Virtually all of the conclusions about Sy 2 depend on NGC 1068, which has emission-line profiles, relative intensities, and luminosities that are representative of other Sy 2. NGC 1068 also has a steep Balmer decrement; the Sy 2 generally have steeper decrements than the Sy 1. In NGC 1068, relative [SII] line intensities show clearly that some dust reddening is present (Wampler 1968). Such lines are measurable in Sy 2 because of the greater relative intensity of the forbidden lines in these Seyferts.

Substantial recent results are also available relative to another problem of spectroscopic interest, which is the cause of the broadening of the line profiles. For the Sy 2, the similar asymmetric profiles in both Balmer and forbidden lines are considered as proof that real mass motions cause Doppler broadening. The classical study of NGC 1068 showing discrete clouds moving at different velocities set the tone of this interpretation (Walker 1968). The gas sometimes escapes the nucleus and can spread through large volumes, having a kinetic energy of 10^{56} ergs. The source of this energy is unknown. The situation was not so well resolved for Sy 1, however, as a difficulty arises if the very broad Balmer-line wings are attributed to Doppler broadening. This is the containment problem, because the emitting gas has to remain in a nucleus on the order of a parsec in diameter while moving at 10^4 km sec^{-1}. The travel time across the nucleus would be only 10^2 years, so the gas must be replaced as it flows out, or it must somehow be bound. To avoid worrying about this, the broad wings were attributed to electron scattering, i.e. scattering between the Balmer-line photons and the thermal electrons (e.g. Mathis 1970, Weymann 1970). This explanation was acceptable for line wings that are smooth and symmetric. However, there are now many unquestionable examples of Sy 1 with asymmetric or structured Balmer-line wings (Table 1) so it seems necessary to attribute these to mass motions of some sort.

The mechanism that accelerates and contains the gas is unknown. The empirical association between the continuum luminosity source and the broad lines implies that the gas may be accelerated by radiation pressure, such as described by Mathews (1974) and Blumenthal & Mathews (1975). An early suggestion by Woltjer (1959) was that the broad profiles are caused by rotation, which would overcome the containment problem. However, Woltjer assumed that the gas rotated about the nucleus with a radius about 100 pc and inferred large nuclear masses both from assigning the line width to rotational velocity and by assuming the nuclear luminosity came from stars. Rotation curves of Seyfert galaxies deduced later by the Burbidges showed no sign of the large masses needed. The rotation models were therefore not pursued, especially after it was decided that the nuclear luminosities were not from stars and that the nuclei of Sy 1 could be much smaller than 100 pc. Rotation models may nevertheless prove useful if applied to accretion disks around massive, condensed objects (Hills 1975). On a much smaller

luminosity scale, such models explain the broad Balmer lines in cataclysmic variable stars (e.g. Warner 1973). (I am indebted to J. S. Gallagher for pointing this out.) Oke & Shields (1976) argue, however, that the FeII emission in some Sy 1 implies that the gas cannot be in ordered rotation around the continuum source. Regardless of whether the high gas velocities are in random filamentary motions or ordered rotation, the association between gas and luminosity source is further emphasized by the correlation between increasing profile width and increasing nuclear luminosity found in some Sy 1 by Osterbrock et al. (1976).

An extensive set of models for explaining line profiles has been produced by Ptak, Stoner and collaborators (e.g. Ptak & Stoner 1973, Stoner et al. 1974, Hubbard 1975, Ptak & Stoner 1975, MacAlpine 1974). These are the most detailed attempts so far to account for the line profiles, especially in trying to fit the asymmetries. They describe their model as follows (Ptak & Stoner 1973): A point source injects high-energy protons into a partially ionized gas cloud. The protons are decelerated by interactions, and "after they have slowed to speeds of a few times the orbital velocities of bound electrons in the atoms of the cloud, the cross-section for charge transfer during collisions with the atoms becomes large enough that the streamers spend a significant amount of time as atoms themselves, and can emit photons characteristic of hydrogen." These models still face the same dilemma as other mass motion models, in that there must be an unknown source for supplying and accelerating the protons. Osterbrock et al. (1976), Osterbrock & Koski (1976), and Katz (1975) contend that the proton-streaming models cannot explain the great width of some profiles, or the relative widths of HeI, HeII, and hydrogen profiles.

It has been accepted for some time that Sy 1 nuclei have a very inhomogeneous distribution of gas, with the broad Balmer-line wings arising in a denser gas than where the Balmer cores and forbidden lines arise (e.g. Oke & Sargent 1968). Because wings have never been seen on any forbidden lines, it is concluded that the Balmer wings arise in gas with $N_e \gtrsim 10^7$ cm^{-3} so that forbidden line radiation is suppressed by collisional de-excitations. Such two-phase models for Sy 1 nuclei have received substantial confirmation from the observation that permitted FeII emission lines are often found in Sy 1 spectra, but are not accompanied by forbidden FeII (Sargent 1968, Phillips & Osterbrock 1975, Osterbrock 1976, Phillips 1976, Oke 1972, Boksenberg et al. 1975a, Adams 1975, Oke & Shields 1976). This requires $N_e \gtrsim 10^8$ cm^{-3}. Because of the high densities, only a small mass of gas is needed to produce the broad Balmer-line emission. The luminosity of recombination emission depends on the product (mass) × (density), so the value derived for the mass is determined by that assumed for the density. Adopting $N_e \geq 10^7$ cm^{-3} Adams & Weedman (1975) found that no more than $4 \times 10^3\ M_\odot$ of ionized hydrogen was ever required to account for the broad lines in Sy 1. Osterbrock et al. (1976) increased N_e to 10^9 and therefore lowered their maximum mass to 26 $M_\odot$. Clearly, only small amounts of gas are needed to produce the Balmer lines if a sufficient ionization or excitation mechanism is present. Proportionally larger gas masses are needed for the emission in the forbidden-line volume, however, because the density is $\lesssim 10^4$ cm^{-3}. The summary scenario of an Sy 1 nucleus is then a highly localized continuum source, accompanied by high-density clouds or filaments that produce the broad Balmer lines. All of this is immersed in a volume, perhaps 10^6 times greater, that contains the lower-density gas producing the Balmer-line cores and the forbidden lines.

6. CONTINUUM RADIATION AND LUMINOSITIES

It is the continuum source that provides the extraordinary luminosity of Seyfert galaxies. The continuous spectra do not look like the composite stellar spectra that characterize other galactic nuclei. At least three different radiation mechanisms - stars, nonthermal radiation such as synchrotron radiation, and reradiation from heated dust - have to be combined in various ways to explain Seyfert continua (e.g. Neugebauer et al. 1976). Absorption lines that presumably arise in stars are seen in the spectra of some Seyferts, even bright Sy 1 (Osterbrock et al. 1976). However, the energy distribution in the continua cannot be explained with starlight. Most Seyfert nuclei have power-law spectra, $f_\nu \propto \nu^{-\alpha}$, so most of the radiation is attributed to a nontherma source. This seems to be so for all Sy 1. For the Sy 2, there are indications that the continua may be due primarily to stars heavily reddened by dust, although this is not conclusive. Certainly, a larger fraction of stellar radiation is present in Sy 2 spectra than in Sy 1 (Osterbrock 1976, Neugebauer et al. 1976).

The first explicit demonstration of a Seyfert power-law spectrum was by Oke & Sargent (1968). In the visible spectrum, the many Seyferts observed since usually have indices $1.0 < \alpha < 2.0$, although α can be as large as 2.7 (Oke 1972, Shields et al. 1972, Osterbrock 1976, Osterbrock et al. 1976, Neugebauer et al. 1976). As infrared observations have accumulated, it has become clear that most Seyferts are strong infrared sources that can be accounted for by extensions of the power-law spectra (Penston et al. 1974, Neugebauer et al. 1976, Stein & Weedman 1976). The infrared continua are important to observe in detail because they contain the bulk of the bolometric luminosity (Rieke & Low 1972). However, there is at present a highly inhomogeneous collection of infrared data for Seyfert galaxies. In some cases, the inference has been made that the existence of strong infrared radiation means that objects are astrophysically similar. This is not the case, and it is important to learn how to distinguish between nonthermal infrared radiation and dust reradiation. This is significant even when comparing Sy 1 and Sy 2.

The infrared continuum of NGC 1068 indicates the difficulties in interpretation. It is the only Seyfert galaxy whose infrared spectrum has been followed until turnover, at about 100 μ (Telesco et al. 1976). This turnover mimics synchrotron self-absorption so the entire spectrum might be attributed to a nonthermal source on the basis of this observation. In fact,

however, the infrared spectrum is attributed to dust reradiation (Jones & Stein 1975), primarily because the infrared nucleus is resolved (Becklin et al. 1973). The detection of polarization in the optical continuum was initially taken as evidence that the source was nonthermal (Visvanathan & Oke 1968), but Jones and Stein pointed out that dust would also polarize the continuum. Very convincing evidence that dust really does account for the polarization is given by Angel et al. (1976), who found that the continuum is circularly polarized. This would be very unlikely for a nonthermal source but common for dust scattering. Furthermore, they also found the emission lines to be polarized, which is strong evidence that both lines and continuum are strongly affected by dust. We therefore have several independent evidences that the nucleus of NGC 1068 is embedded in dust. A similar conclusion applies to other Sy 2, based on less comprehensive data (Neugebauer et al. 1976). The difference between this and the circumstances deduced for Sy 1 is an important demonstration of the necessity to distinguish between at least two classes of Seyferts.

It is known that continuum radiation exists in Seyfert galaxies out to 10 μ and, in a few cases, to 35 μ (Rieke & Low 1975a). The only Seyfert for which the long wavelength cutoff has been observed is NGC 1068, whose spectrum turns over at about 100 μ. This is deduced from broad-band measures centered at 93 μ and 140 μ (Telesco et al. 1976). Seyfert galaxies are not generally strong radio sources (Kellermann 1972), as indicated by the fact that less than 10% of them are 3C objects. Sramek & Tovmassian (1975) surveyed 506 Markarian galaxies at 6 cm, of which 51 were Seyferts. Only 14% of the Seyferts were detected to a flux limit of 30 mJy. They did find that virtually all detections were of Sy 2, which was the only correlation found between optical and radio properties. A more sensitive survey by de Bruyn & Wilson (1976) with the Westerbork telescope detected 50% of the 43 Seyferts they observed, to a limit of 4 mJy. They confirm that Sy 2 are generally the stronger radio emitters but note that no extended double radio sources are associated with Seyfert galaxies. Another correlation including various Seyferts has been reported between the infrared and 21 cm continuum radiation (Van der Kruit 1971, Rieke & Low 1972). It is not obvious that there is astrophysical meaning to this because such diverse objects as Sy 1, Sy 2, narrow-line galaxies like NGC 4385 and 7714, and weird M82 are all included. Since there is substantial evidence that the infrared radiation from some of these objects is nonthermal, but from others is dust reradiation, it does not now seem appropriate to conclude that there is necessarily a physical relation between the infrared and radio spectra.

Even for those few Seyferts like 3C 120 that are strong radio sources, the radio continuum lies substantially below the extrapolation of the infrared spectrum at 10 μ (Shields et al. 1972). Somewhere - at millimeter, submillimeter, or far-infrared wavelengths - the spectra of all Seyferts must turn over. The point at which they do so is critical for determining their bolometric luminosities. For example, estimated bolometric luminosities for Sy 1 would differ by factors of two to four depending on whether the turnover is put at 3.5 μ or 350 μ (Stein & Weedman 1976). (For the power-law index $\alpha = 1$, the same bolometric luminosity is contained within each decade of frequency, so a spectrum from 350 Å to 350 μ would be twice as luminous as one from 350 Å to 3.5 μ).

As discussed above, the infrared continuum in Sy 1 is attributed to nonthermal radiation while that in Sy 2 probably contains substantial dust reradiation. There must therefore be an extremely luminous ultraviolet source in Sy 2 such as NGC 1068 to explain the production of the emission lines and the infrared reradiation (e.g. Neugebauer et al. 1976, Jones & Stein 1975, Shields & Oke 1975a). Whether this source is thermal or nonthermal is not known, but Sy 2 can be interpreted consistently by invoking large numbers of hot stars as the radiation source (Adams & Weedman 1975, Angel et al. 1976, Harwit & Pacini 1975). ther than NGC 1068, the Seyfert that shows the strongest evidence for dust reradiation is the pathological Sy 1, Markarian 231. In addition to having a very steep infrared spectrum, Mkn 231 has the silicate signature at 10 μ that characterizes dust radiation for infrared sources (Allen 1976 and private communications therein). The initial distinction of Mkn 231 was because of the extremely strong absorption lines of NaI and CaII in its spectrum (Arakelian et al. 1971, Adams & Weedman 1972, Adams 1972a). These lines have components and are blueshifted relative to the emission line spectrum, so they are attributed to interstellar absorption within the nucleus. There are also absorption lines attributed to early type stars at the emission-line redshift. The presence of extreme interstellar absorption, a steep Balmer decrement, and unusual continuum colors are all evidence that this galaxy is heavily dust reddened. A thorough study of Mkn 231 has been prepared by Boksenberg et al. (1977). The empirical demonstration that structured absorption lines, blueshifted relative to the galaxy, can arise in an Sy 1 is an important analogy for the absorption line QSOs. However, Boksenberg et al. (1977) emphasize that the absorption lines are broader and shallower than in most QSOs. Mkn 231 has also been reported to be the most luminous galaxy in the universe (Rieke & Low 1972). While it is of great interest to understand how Mkn 231 achieved such a distinction, it must be realized that it also has unique spectroscopic properties so that an explanation of it may not be generally applicable to other Seyferts.

Empirical evidence therefore exists that Seyfert galaxies have a luminous continuum from the far infrared down to the ionizing ultraviolet. How much further does it go? The only Seyferts so far detected as X-ray sources are NGC 1275 and 4151 (Gursky et al. 1971) and possibly NGC 3783 (Cooke et al. 1976). NGC 1275 is intrinsically much more luminous but, as remarked previously, is atypical of Seyferts and more, nearly resembles the giant elliptical radio galaxies. Other Seyferts have been observed but not detected (Ulmer & Murray 1976). Baity et al. (1975) detected hard X-rays from NGC 4151 and concluded that the X-ray luminosity was comparable to that in all other parts of the spectrum. These X-rays are too strong to arise from an extrapolation of the power-law spectrum in the optical, but they could arise from a similar nonthermal mechanism such as synchrotron radiation. Other suggested alternatives are that the X-rays are Compton scattered optical photons or are thermal

emission from a very hot gas (Baity et al. 1975), but the soft X-ray data imply that the X-rays are not thermal and probably arise in the same volume as the optical nonthermal spectrum (Ives et al. 1976). Baity et al. emphasize that NGC 4151 could not be typical of Seyfert galaxies or else the contribution from Seyferts alone would give a diffuse X-ray background 100 times greater than observed. On the basis of this, it seems that Seyferts are not in general strong X-ray sources.

7. RELATION TO QSOs

The similarities between the nuclei of Seyfert galaxies and QSOs have been pointed out many times, and numerous efforts have been made to demonstrate a continuity between these objects (e.g. Sandage 1971, Lynden-Bell 1971, Notni & Richter 1972, Arakelian 1971, Weedman 1976a). It is the Sy 1 nuclei whose properties most closely resemble the QSOs. It is argued that as long as compact sources of high luminosity are known to exist in the nuclei of Seyfert galaxies, there should be no objection to interpreting QSOs as distant, more luminous examples of such sources. The Seyfert nuclei are therefore used to demonstrate empirically that QSOs really have cosmological redshifts. The most recent presentation of this continuity argument is by Khachikian & Weedman (1977). They consider the magnitude-redshift and angular diameter-redshift diagrams for Seyfert galaxies. There is substantial scatter in the former (the Hubble diagram), which is attributed to the differences in absolute luminosity among the various Seyfert nuclei. Assuming a linear redshift-distance relation gives a scatter $\sigma(\delta m) = 1.04$ mag for Seyferts compared to Sandage's 0.28 mag for first ranked ellipticals. It is argued that angular diameters should be a more reasonable measure of relative distance for Seyferts since such diameters are determined by the galactic disks rather than the nuclei. The angular diameters measured from the *Sky Survey* decrease with redshift and have a scatter about the mean line of $\sigma(\delta \log \theta) = 0.21$ for Sy 1. This compares to 0.11 for first-ranked ellipticals. It is therefore argued that, while Seyferts are not as homogeneous as first-ranked ellipticals, they still show good evidence for a linear redshift-distance relation.

There is not yet agreement, however, that the extended nebulosities associated with "Seyfert galaxy" nuclei are really the disks of galaxies (Burbidge 1973). The morphological studies discussed previously (Section 3) have demonstrated that a lot of Seyferts are spiral galaxies, but such demonstrations are difficult for the high redshift Seyferts that are critical in providing a transition to QSOs. There are a few Sy 1 that look like spiral galaxies whose luminosities would approach those of cosmologically redshifted QSOs. These include Mkn 79 and 618, NGC 7469, IC 4329A, I Zw1, and II Zw 136.

If cosmological redshifts are accepted for Seyferts and assumed for QSOs, there is an overlap in luminosity between the nuclei of Sy 1 and the QSOs. This is summarized in Khachikian & Weedman (1977). The luminosity indicators in their redshift-luminosity diagram are the broad hydrogen lines from Sy 1 and QSOs. Such lines arise only in the nuclei and are roughly proportional to the luminosity of the nonthermal continuum that carries most of the energy. The Hβ lines of lower redshift objects are related to the Lα lines in high redshift QSOs by assuming an intrinsic Lα: Hβ ratio of 40 (Davidson 1972). Luminosities are given for 37 Sy 1 and 62 QSOs using fluxes collected in Weedman (1976b) and Osmer & Smith (1976). The optically brightest QSOs are presumably included because nine of the high redshift QSOs were discovered from their strong Lα emission on objective prism survey plates (Smith 1976). The Sy 1 nuclei cover a luminosity range of 10^3, and most QSOs are less than 10 times brighter than the brightest Seyfert. The entire phenomenon, from faintest Sy 1 to brightest QSO, covers a factor of 10^5 in luminosity. As the bolometric luminosities are approximately 10^3 times the Hβ luminosity (Weedman 1976b), this corresponds to a luminosity range of 10^{43} ergs sec^{-1} to 10^{48} ergs sec^{-1} (for $q_0 = 0$ and $H_0 = 50$ km sec^{-1} Mpc^{-1}). Improvements in these numbers can be expected as more far-infrared data are accumulated (e.g. Rieke & Low 1975a) and as better composite spectra of Sy 1 and QSOs are assembled (e.g. Chan & Burbidge 1975, Baldwin 1975).

A key link between the nuclei of Seyfert galaxies and the QSOs is the fact that both can be variable in luminosity. As a consequence of the small radiating volumes implied by this variability, there are severe constraints on theoretical models of the radiation sources. Extensive considerations of such compact, nonthermal sources have been presented by Jones et al. (1974a, b) and Burbidge et al. (1974). Results relevant to this problem are also reviewed by Stein et al. (1976) in the context of the BL Lacertae objects. The energy-density paradox that arises in a luminous source that varies rapidly was first pointed out by Hoyle et al. (1966). Simply put, the problem is that electrons producing photons via synchrotron radiation will lose their energy in subsequent Compton scatterings with the very photons they created. The radiation source quickly quenches itself unless there is continuous injection of high-energy electrons and/or rapid source expansion (see references in Stein et al. 1976). Recent VLBI measures of the nuclei of the Sy 1 3C 120 and other radio sources do indicate relativistic expansions, or at least separations of individual radio-source components at relativistic speeds (Schilizzi et al. 1975, Wittels et al. 1976). The references cited include numerous references to earlier work in which such expansion was suspected (e.g. Shapiro et al. 1973, Kellermann et al. 1973 for 3C 120). The important progress in the recent work has been the demonstration that source contraction is never observed. This means that "Christmas-tree" models, in which the changes in source structure are attributed to flaring at random places in the source, are ruled out.

The long-term monitoring of Seyfert galaxies with different techniques has shown that variability is a common property. At one time or another, observers of all parts of the spectrum have reported a variable Seyfert galaxy. As such variability is the only measure of source size for most Seyfert nuclei, it is certainly important to know about. Data on the optical variability of Seyferts

has been assembled by Cannon et al. (1971), Lyutyi (1973), Penston et al. (1974), Lyutyi & Pronik (1975), and Scott et al. (1976). Other studies of individual objects are included in the *UBV* references in Table 1. (Some useful comparison star sequences are in Penston et al. 1971.) One Seyfert (X Comae) was even discovered because of its variability (Bond 1973). The problem in interpreting the results is the tedious accumulation of data required before correlations can be searched for. Are there, for example, any correlations between variability and source luminosity (e.g. Elliot & Shapiro 1974)? It appears at the moment that the optical continua of all Sy 1, like the QSOs, are variable if observed closely enough. It is of great importance to demonstrate whether the continua of Sy 2 are variable as it is not yet known whether or not these sources are nonthermal.

Reports have existed for some time that the emission lines can also vary in Seyfert galaxies. Such variations have been reported for NGC 1068, 1275, 1566, 3227, 3516, 4151, 5548, 7469, 7603, 3C 390.3 and Markarian 6 (references to Table 1 and Lyutyi & Pronik 1975). Such variations are important for understanding the volume of the ionized gas and the location of the gas relative to the variable continuum source. Unavoidably, most of the observations from which line variability has been deduced are very inhomogeneous. Results from different observers using different spectrographs have been compared and changes claimed. Sometimes, the emission lines have been monitored with narrow-band interference filters without obtaining spectra. NGC 1068, in which the emission arises from a resolved nucleus has been observed with entrance apertures smaller than the nucleus. Consequently, much of the data regarding emission-line variability is hard to evaluate with certainty. It is particularly perplexing when such results are reported for NGC 1068 in which low-density gas is thought to encompass a volume several hundred parsecs in diameter. It is important to continue attempts to confirm such results, however, especially because there are convincing cases in which line variability has been carefully monitored under the same observing conditions. The best examples seem to be the emission-line variations in NGC 7603 (Tohline & Osterbrock 1976) and the variable interstellar absorption lines in NGC 4151 (Anderson 1974a). As systematic monitoring of any sort requires diligence and patience, it is likely to be quite some time before sufficient data is accumulated to understand the nature of variability in Seyfert nuclei.

8. CONCLUSIONS

Mark Twain said that the nice thing about science is that one gets such wholesale returns of conjecture from such a trifling investment of fact. Amazingly, he said it without even being exposed to modern astrophysics. The purpose of this review has been to summarize the facts now known about Seyfert galaxies, but the reason for their existence remains one of the most pressing astrophysical mysteries. The primary difficulty in explaining Seyfert nuclei is in accounting for their energies. Many have bolometric luminosities as great as 10^{45} ergs sec^{-1}. Even this is 10^{12} solar luminosities, which has to arise in a volume about a parsec in diameter. Such a nucleus can be visualized by imagining the Crab Nebula radiating 10^7 as much energy as it does, since the absolute size, nonthermal radiation, and filamentary structure of the Crab likely resemble that of Seyfert nuclei. Obviously, some very efficient mechanism of energy production that can arise in a small volume is called for. The various possibilities for a theoretical explanation of the energy source(s) are reviewed by Saslaw (1974) and Burbidge (1970). To the extent that there is now a developing consensus, it seems to be in the direction of using gravity to explain things. This is not so much because of improvements in the theory of galactic nuclei, but is because observations of stellar X-ray sources have demonstrated empirically that gravitational accretion onto compact objects is a potent energy source (e.g. Blumenthal & Tucker 1974). Admittedly, such accretion is on a much smaller scale than needed in Seyferts. However, if a 10^7 $M_\odot$ black hole or even 10^7 neutron stars were inserted into a galactic nucleus, most of the activity in Seyfert nuclei could be made to happen as a consequence of accretion onto these objects. But an explanation of how the required compact objects get into the nuclei requires comprehensive knowledge of galactic evolution, and that's another story.

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