THE ASTROPHYSICAL JOURNAL, 266:485–501, 1983 March 15

NEARBY GALAXIES WITH SEYFERT-LIKE NUCLEI

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Received 1982 May 27; accepted 1982 August 4

ABSTRACT

From optical, X-ray, and radio observations of a sample of 23 nearby high-excitation emission-line galaxies, we find that the activity in the nuclei of nearly all of these galaxies is very closely related to that observed in "classical" type 2 Seyfert galaxies. The strongest resemblance to the Seyfert 2 galaxies is found in the relative intensities and profiles of the optical emission lines. However, the luminosities of the nearby galaxies tend to be less than those of classical type 2 Seyferts, although greater on average than similar measurements of galaxies with H II region nuclei. Likewise, the widths of the optical emission lines of the high-excitation galaxies on average tend to be less than those of the classical Seyferts. We suggest that these differences have arisen from the original definition of a Seyfert galaxy as an object possessing "strong broad emission lines arising in a bright semistellar nucleus." Instead, the classical type 2 Seyferts appear to represent the high-energy extreme of a continuous distribution of galaxies with nuclear activity which can be ascribed to photoionization by a nonthermal source of radiation. This implies that such activity is considerably more common in the nuclei of spirals than had been suspected.

Subject headings: galaxies: nuclei — galaxies: Seyfert — radio sources: galaxies — X-rays: sources

I. INTRODUCTION

Seyfert galaxies are defined as that class of objects which show strong, broad emission lines arising in a bright semistellar nucleus (Khachikian and Weedman 1974). Their obvious spectroscopic similarities to QSOs have made Seyfert galaxies the focus of numerous investigations at all wavelengths. Considerable knowledge of the physical conditions in the nucleus has been gained from the data, although very little is yet understood concerning the ultimate source of the activity.

A major stumbling block in studying the known Seyfert galaxies is the fact that most are rather distant. Until a few years ago, it was widely held that the Seyfert phenomenon was relatively rare, with only about 1% of all galaxies belonging to the class (e.g., Weedman 1977). However, the subsequent discovery at X-ray energies of several nearby galaxies which, except for their narrow nuclear emission lines, were indistinguishable from many classical Seyfert galaxies[5] (e.g., Ward *et al.* 1978; Schnopper *et al.* 1978; Bradt *et al.* 1978) showed that at least a few closely related objects had been overlooked.

The discovery of these narrow-line X-ray galaxies suggested that many other nearby galaxies with Seyfert-like nuclear activity may have gone undetected. We decided to examine this possibility by observing 24 emission-line galaxies identified as being of "high excitation" by Sandage (1978) in his spectroscopic survey of 666 nearby galaxies. Prior to Sandage's work, only one of these objects had been classified as a Seyfert galaxy. In this paper, we describe our new optical, X-ray, and radio data for these galaxies and also for a comparison sample of four galaxies with "normal" H II region nuclei. We then discuss the degree to which the nuclear activity in the Sandage high-excitation galaxies is related to the nonthermal activity found in classical Seyferts.

II. THE SAMPLE

The high-excitation emission-line galaxies singled out in this paper for study were chosen on the basis of the

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[5]In this paper, we define classical Seyfert galaxies as those selected on the basis of the dual criterion of broad emission lines arising in a bright semistellar nucleus.

TABLE 1

SANDAGE HIGH-EXCITATION EMISSION-LINE GALAXIES

Galaxy	Morphology	v_0^{b}	Reason for Selection
UGC 1395[a] ...	SBc(r) I[b]	5281	N2 ≫ Hβ
NGC 1019	SBc(s) I[b]	7288	N2 ≫ Hβ; possible [Ne v] λ3426
NGC 1229[c] ...	SB pec[b]	10594	N2 ≫ Hβ; [N II] ≈ Hα
NGC 1358	SBa(s) I[b]	3878	N2 ≫ Hβ; [N II] > Hα
NGC 1386	Sa[d]	775[e]	N2 ≫ Hβ
NGC 1667	Sbc I–II[b]	4472	N2 ≫ Hβ; [N II] > Hα
NGC 2989	Sc(s) I[f]	3908	N2 ≫ Hβ
NGC 2992	S pec	2067	N2 ≫ Hβ
NGC 3081	SBa[b]	2146	N2 ≫ Hβ; [Ne v] λ3426
NGC 3281	Sa(s)[b]	3153	N2 ≫ Hβ
NGC 3738	Ir IV[b]	265	N2 ≫ Hβ
NGC 3982	Sbc(r) II–III[b]	1073	N2 ≫ Hβ
NGC 4388	SBb(s) pec:[g]	2370[h]	He II λ4686; [O I] λ6300
NGC 4507	SBab(rs) I[f]	3283	N2 ≫ Hβ; [O III] λ4363
NGC 5135	SBb(I)[b]	3968	N2 ≫ Hβ
NGC 5347	SBb$^+$ III[b]	2364	N2 ≫ Hβ
NGC 5643	SBc(s) II[f]	997	N2 ≫ Hβ; [N II] ≥ Hα; [O I] λ6300
NGC 5728	SBb(s) II[f]	2879	Intense N2; [O I] λ6300
NGC 6300	SBb(s) II pec[i]	901	N2 ≫ Hβ; [N II] > Hα
NGC 6890	Sab(r) II[f]	2439	N2 ≫ Hβ; [N II] > Hα
IC 5063	E4[b]	3322	N2 ≫ Hβ; [O I] λ6300
IC 5135	HiSB: filaments[b]	4845	N2 ≫ Hβ
IC 5201	SBcd II[f]	923	N2 ≫ Hβ
IC 1515	SB(s)[b]	6886	N2 ≫ Hβ

[a] Listed by Sandage as 0152+0621.
[b] Sandage 1978.
[c] Listed by Sandage as 0305−2308.
[d] Phillips and Frogel 1980.
[e] Fornax Cluster member. Distance assumed to be that of cluster, which is 14 Mpc for $H_0 = 100$ km s^{-1} Mpc^{-1} (Jones and Jones 1980).
[f] Sandage and Brucato 1979.
[g] Phillips and Malin 1982.
[h] Virgo Cluster member. Distance assumed to be that of cluster, which is taken to be 13.8 Mpc (Hanes 1979).
[i] Dressler and Sandage 1978.

excellent descriptions of plate spectra of 666 bright galaxies given by Sandage (1978). The primary selection criterion was the presence of a large relative-intensity ratio of [O III] λ5007 emission to Hβ, which Sandage indicated by the notation "N2 ≫ Hβ" or with the words "Intense N2." The only exception to this rule was the galaxy NGC 4388, for which Sandage did not give information concerning N2/Hβ, but which, nevertheless, he indicated as possessing a high-excitation emission-line spectrum. Other remarks on the spectra which strengthened our suspicion of Seyfert-like activity, such as [N II] ≥ Hα or the mention of emission lines such as [Ne V] λ3426, He II λ4686, or [O I] λ6300, were noted but were of secondary importance in the selection process.

A total of 24 galaxies in the Sandage paper satisfied the N2/Hβ selection criterion. These are listed in Table 1, along with morphological types and galactocentric radial velocities.

TABLE 2

COMPARISON GALAXIES WITH H II REGION NUCLEI

Galaxy	Morphology	v_0	Reference to Optical Study
NGC 625	Irr(Sm)[a]	318[a]	Phillips, unpublished
NGC 1510 ...	E0–1 pec:[b]	782[b]	Disney and Pottasch 1977; Phillips, unpublished
NGC 7552 ...	SBab(s)pec[b]	1636[b]	Ward *et al.* 1980
NGC 7714 ...	SBb(s)pec:[b]	2980[b]	French 1980; Weedman *et al.* 1981

[a] From Sandage 1978.
[b] From de Vaucouleurs, de Vaucouleurs, and Corwin 1976.

Four galaxies with strong emission-line spectra, but which would not be classified as high excitation, were included in the study to serve as comparison objects. Details of these galaxies are listed in Table 2. Previous studies (see references in Table 2) of these galaxies have indicated that, unlike classical Seyfert galaxies, the gas in their nuclei is photoionized in a "normal" fashion by the radiation of young hot stars.

III. OBSERVATIONS

a) *Low-Dispersion Optical Spectroscopy*

Low-dispersion spectra (5–10 Å resolution) were obtained for 22 of the 24 program galaxies as well as for two of the comparison galaxies, using telescopes at the Las Campanas, Anglo-Australian, Lick, and European Southern observatories. Details of these observations are summarized in Table 3, and representative spectra are shown in Figures 1 and 2. Las Campanas spectra of IC 5063 and NGC 4388 have been illustrated elsewhere (Caldwell and Phillips 1981; Phillips and Malin 1982). Of the two program galaxies not observed by us, NGC 2992 has previously been studied by Shuder (1980) and Ward *et al.* (1980), while no suitable data are available in the literature for NGC 5347. Relative emission-line intensities measured from the combined data are listed in Tables 4 and 5. The estimated accuracy of these line intensities is 10%–20%, except for those values followed by a colon which are uncertain by as much as a factor of two or more. Absolute [O III] λ5007 fluxes measured by us for three of the program galaxies and drawn from the literature for six more are listed in Tables 6 and 7, after having been corrected for extinction by assuming an intrinsic $H\alpha/H\beta$ intensity ratio of 2.87.

b) *High-Dispersion Optical Spectroscopy*

Emission-line profiles were measured for 16 of the high-excitation and two of the comparison galaxies, using principally the image photon counting system (IPCS) spectrometer on the AAT at resolutions of 1.95 or 0.65 Å. Profiles of the [O III] and Hβ emission lines in six representative high-excitation galaxies are il-

TABLE 3

Summary of Low-Dispersion Spectroscopy

Galaxy	Telescope/Detector	Date	Entrance Aperture (arcsec)	Resolution (Å)	Wavelength Range (Å)
NGC 1019 NGC 1386 NGC 6300 NGC 6890 IC 5063 IC 5135 IC 5201 IC 1515	Las Campanas 2.5 m/ Intensified Reticon[a]	1979 June	2×4	5	3250–6850
NGC 625 UGC 1395 NGC 1358 NGC 1510 NGC 1667 NGC 2989 NGC 3081 NGC 3281 NGC 5135	Las Campanas 2.5 m/ Intensified Reticon[a]	1980 Jan	2×4	5	3600–6900
UGC 1395	ESO 3.6 m/IDS[b]	1979 Aug	2×4	10	5800–8800
NGC 3738 NGC 3982	Lick 3 m/IDS[b]	1980 Jan	2.4×4	10	3650–7400
NGC 4507 NGC 5643 NGC 5728	AAT 3.9 m/IPCS[c]	1981 Aug	2, 10[d]	6	3200–7300
NGC 1229	AAT 3.9 m/IPCS[c]	1981 Dec	1.7[d]	6	3200–7200

[a]Shectman and Hiltner 1976.
[b]Image disector scanner (Miller, Robinson, and Wampler 1976).
[c]Image photon counting system (Boksenberg and Burgess 1973).
[d]Long-slit spectroscopy.

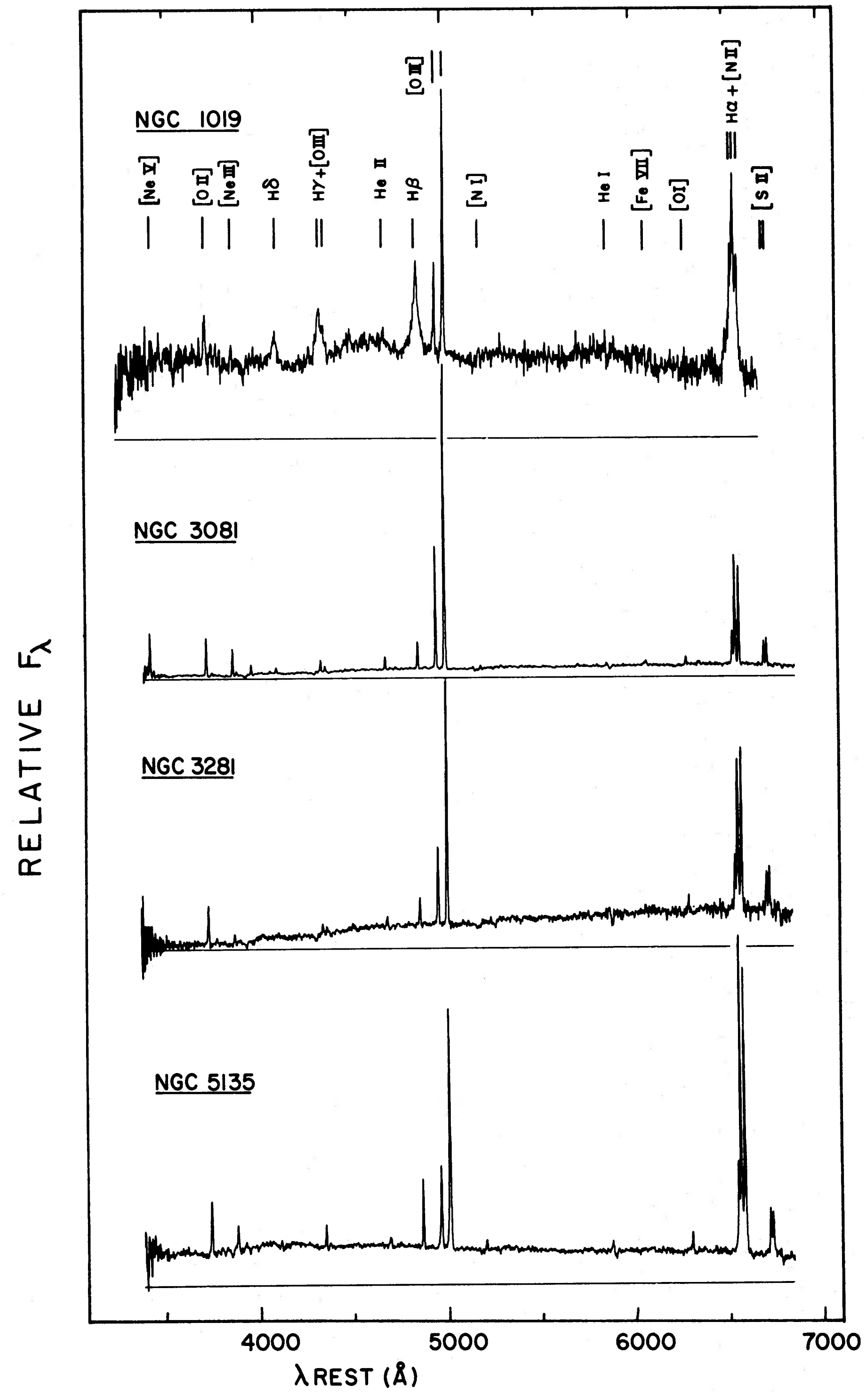

FIG. 1.—Low-dispersion optical spectra of seven representative high-excitation emission-line galaxies obtained with the Las Campanas 2.5 m du Pont telescope. The spectra have been shifted onto the same rest-wavelength scale.

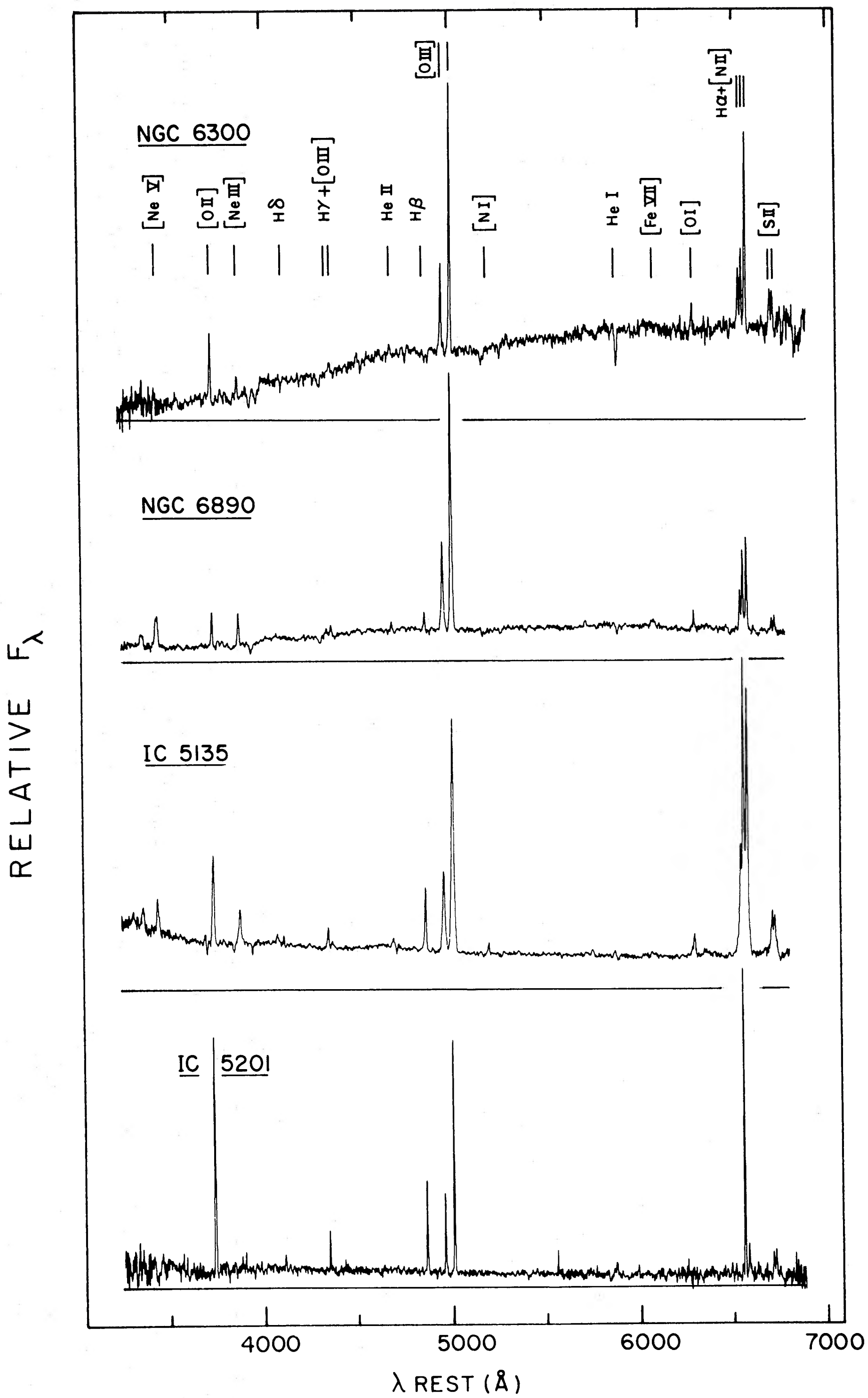

FIG. 1—*Continued*

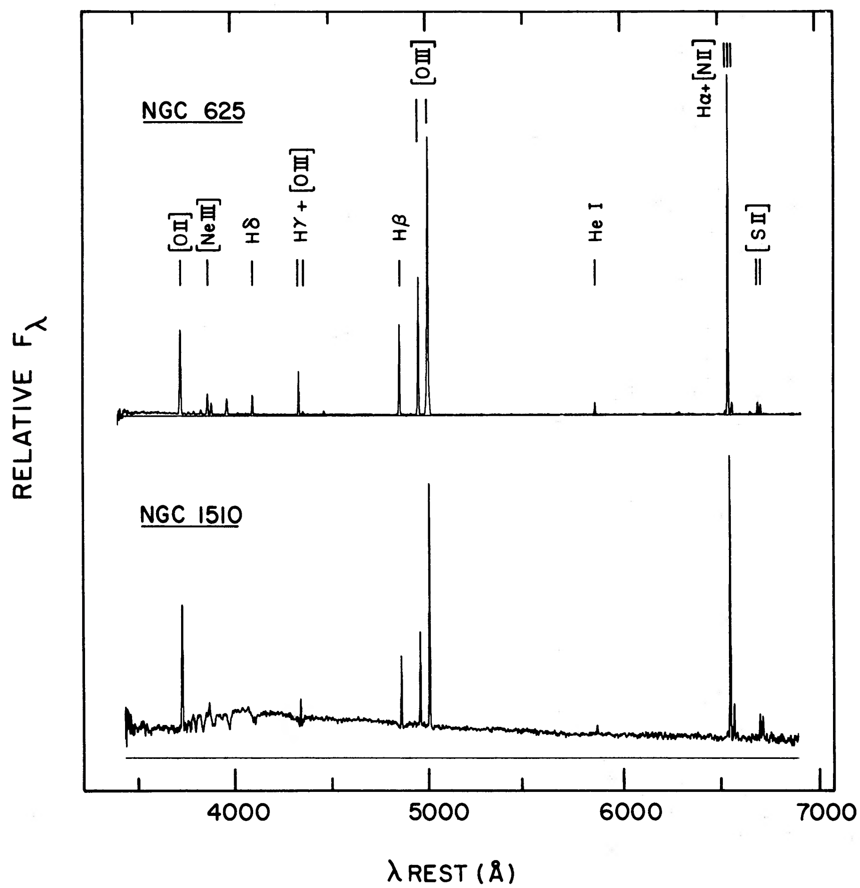

FIG. 2.—Low-dispersion optical spectra of the comparison galaxies NGC 625 and NGC 1510 obtained with the Las Campanas 2.5 m du Pont telescope. The spectra have been shifted onto the same rest-wavelength scale.

lustrated in Figure 3. (See also Caldwell and Phillips 1981 for a similar plot for IC 5063.)

All available data on the full widths at half-maximum (FWHMs) for the program galaxies are given in Tables 6 and 7. These include rather crude FWHM measurements from the Las Campanas and AAT IPCS low-dispersion spectra of the high-excitation galaxies UGC 1395 and NGC 1229 and the comparison galaxy NGC 625. Note that all of the FWHM values have been approximately corrected for the instrumental profile by assuming the relation (observed FWHM)^2 = (intrinsic FWHM)^2 + (instrumental FWHM)^2.

c) X-Ray Data

Observations of seven high-excitation galaxies and three comparison galaxies were made with the imaging proportional counter (IPC) on the *Einstein Observatory* for exposure times of ~ 2000 s. The IPC operates in the 0.2–4.0 keV band with an angular resolution of approximately 1′ (see Giacconi *et al.* 1979).

Five of the galaxies observed with the IPC were detected at the 5 σ confidence level. For all of the positive detections, the X-ray positions are within 1′ of the optical positions given by Sandage (1978) or de Vaucouleurs, de Vaucouleurs, and Corwin (1976), and all are unresolved to the 1′ limit of the IPC. The general character of the data is illustrated by the iso-intensity contour map of NGC 3081 shown in Figure 4. A similar map of the comparison galaxy NGC 7552 has been published by Charles and Phillips (1982).

X-ray fluxes in the 0.2–4.0 keV band were calculated from the IPC data assuming a power-law photon spectrum of index −1.5, which is equivalent to a differential energy flux of the form $F(\nu) = F\nu^{-0.5}$. An average equivalent absorbing hydrogen column density in our own Galaxy of $N_H = 3 \times 10^{20}$ cm^{-2} was also assumed (Radhakrishnan *et al.* 1972). The errors in the fluxes are dominated by the combination of uncertainties in detector gain and the lack of knowledge of the true source spectra. Tables 6 and 7 list the fluxes derived in this manner, along with estimates of the internal errors of

TABLE 4

RELATIVE EMISSION-LINE INTENSITY MEASUREMENTS: HIGH-EXCITATION EMISSION-LINE GALAXIES

A

LINE	$F(\lambda)/F(H\beta)$										
	UGC 1395	NGC 1019	NGC 1229	NGC 1358	NGC 1386	NGC 1667	NGC 2989	NGC 3081	NGC 3281	NGC 3738	NGC 3982
[Ne V] λ3426		...	0.61	...	0.96:	...	...	present[a]	...		
[O II] λ3727	1.46	0.13	2.34	2.64	2.13	2.85	0.98	1.47	1.23	4.35	2.96
[Ne III] λ3869	0.59	0.044:	0.56	0.54	1.05	0.55	0.21:	0.88	0.25:	...	1.44
He I + H8 λ3889	...	...	...	...	...	...	...	0.17:	...	...	...
[Ne III] + Hε λ3967	...	...	...	...	...	...	...	0.37	...	...	...
[S II] λ4071	...	...	...	...	...	...	...	0.08:	...	...	...
Hδ λ4102	...	0.23[b]	...	...	...	...	...	0.18:	...	...	...
Hγ λ4340	...		0.38	0.39	...	...	...	0.40	0.25:	0.45	...
[O III] λ4363	...	0.52[b]	0.31:	0.50	0.58:	...	...	0.20:	0.17:	...	0.03:
He II λ4686	...	...	0.26:	...	0.46:	...	...	0.42	0.28	...	0.32:
Hβ λ4861	1.00:[c]	1.00[b]	1.00	1.00:	1.00:	1.00:	1.00	1.00	1.00	1.00	1.00
[O III] λ4959	4.15	0.20	2.46	3.12	5.67	3.31	0.88	4.53	2.94	1.25	5.79
[O III] λ5007	12.2	0.62	8.91	8.00	15.2	7.69	2.50	13.3	8.18	3.38	19.3
[N I] λ5199	...	...	0.30:	...	...	...	...	0.08:	...	...	...
[Fe VII] λ5721	...	...	...	...	0.58:	...	...	0.16:	...	...	...
He I λ5876	...	...	0.20:	...	...	...	...	0.15:	...	0.16:	0.27:
[Fe VII] λ6087	...	...	...	...	0.53:	...	...	0.36	0.15:	...	...
[O I] λ6300	1.59:	...	0.62	1.71:	0.73	1.08	0.25:	0.37	0.41	0.16:	1.32
[N II] λ6548	...	...	1.42	2.64	2.43	3.46	0.95	1.33	1.96	0.11:	1.24
Hα λ6563	28.2[d]	2.04	4.63	3.36	4.87	4.31	6.73	4.53	6.13	2.62	4.00
[N II] λ6584	...	...	4.26	6.48	7.30	12.2	3.53	3.87	5.89	0.32	3.72
[S II] λ6716	1.95	...	2.71	2.88:	1.52	2.54	0.85	0.99	1.31	0.47	1.13
[S II] λ6731	1.95	...			1.22	2.23	0.50	1.07	1.47	0.37	1.21
log(3727/5007)[e]	...	...	−0.38	−0.42	−0.63	−0.26	−0.05	−0.76	−0.50	0.07	−0.67
⟨E⟩[f]	...	...	0.39	0.47	0.50	0.48	0.15	0.43	0.35	0.14	0.53

TABLE 4—*Continued*

B

Line	NGC 4388	NGC 4507	NGC 5135	NGC 5643	NGC 5728	NGC 6300	NGC 6890	IC 5063	IC 5135	IC 5201	IC 1515
	$F(\lambda)/F(H\beta)$										
[Ne v] λ3426	present[g]	0.60	present[g]	0.63	0.35	...	4.38	0.20:	0.89	...	2.95
[O III] λ3727	1.72	1.64	1.06	2.68	1.84	6.92	2.02	2.90	2.15	3.17	2.88
[Ne III] λ3869	0.48	0.71	0.42	0.89	0.75	1.85	2.08	0.75	1.04	...	1.89
He I + H8 λ3889	0.095:	...	...	...	...	...	...	0.17:	...	...	...
[Ne III] + Hε λ3967	0.22	...	...	...	...	...	...	...	...	...	...
[S II] λ4071	0.096:	0.18	...	...	...	...	...	...	...	...	...
Hδ λ4102	0.22	0.24	...	...	...	...	...	0.23:	...	0.19:	...
Hγ λ4340	0.36	0.42	0.30	0.22:	0.36:	...	0.46:	0.51	0.42	0.39	1.04:
[O III] λ4363	0.13	0.27	0.08:	0.32:	0.34:	0.97:	0.63:	0.22	0.19:	...	0.73:
He II λ4686	0.20	0.16	0.18	0.52	0.29	1.13:	0.38	0.13:	0.21:	...	0.38:
Hβ λ4861	1.00	1.00	1.00	1.00	1.00	1.00:	1.00	1.00	1.00	1.00	1.00
[O III] λ4959	3.83	3.17	1.49	4.85	3.92	8.97	7.71	3.55	2.20	0.94	5.90
[O III] λ5007	11.2	9.53	4.82	16.6	11.8	25.6	20.8	11.0	7.41	2.78	16.9
[N I] λ5199	0.094:	0.09:	0.21	0.21:	...	...	...	0.20:	0.21:	...	...
[Fe VII] λ5721	...	...	...	...	...	...	0.48:	...	0.16:	...	...
He I λ5876	0.16	...	0.17:	...	0.25	...	...	0.15:	0.10:	0.21:	...
[Fe VII] λ6087	...	0.18:	...	...	0.61:	...	1.17	...	0.15:	...	...
[O I] λ6300	0.78	0.86	0.31	1.16	1.00	2.56	1.06	0.68	0.60	≤ 0.19	0.78
[N II] λ6548	0.86	0.93	1.78	2.49	2.79	6.15	2.08	1.18	2.52	0.13:	1.70
Hα λ6563	4.86	5.16	6.12	6.17	5.97	7.44	4.17	5.55	6.07	3.50	3.95
[N II] λ6584	2.59	2.80	5.45	7.17	8.36	19.0	6.46	3.44	7.56	0.39	3.84
[S II] λ6716	1.27	1.10	0.92	2.40	0.99	4.36	1.02	1.50	1.19	0.33	...
[S II] λ6731	1.12	1.23	0.87	2.21	0.97	3.85	0.81	1.31	1.11	0.33	...
log(3727/5007)[e]	−0.59	−0.52	−0.34	−0.47	−0.50	−0.16	−0.85	−0.30	−0.22	−0.14	−0.63
$\langle E \rangle$[f]	0.38	0.36	0.27	0.50	0.46	0.65	0.57	0.39	0.38	≤ 0.11	0.49

[a] Detected in low-resolution Las Campanas spectrum, but not possible to calibrate in flux units.

[b] Broad Seyfert 1 profile.

[c] Narrow component only.

[d] Narrow *plus* broad component.

[e] Intensity ratio of [O II] λ3727 and [O III] λ5007 lines, corrected for reddening using observed $F(H\alpha)/F(H\beta)$ (see BPT).

[f] Average "excess" of the reddening-corrected [O III] $\lambda5007/H\beta$, [N II] $\lambda6584/H\alpha$, and [O I] $\lambda6300/H\alpha$ ratios with respect to normal H II region values for the same value of log(3727/5007) (see BPT for details).

[g] Detected in image-tube spectrogram obtained with 1 m Yale telescope at Cerro Tololo, but not possible to calibrate in flux units.

TABLE 5

RELATIVE EMISSION-LINE INTENSITY MEASUREMENTS: COMPARISON GALAXIES WITH H II REGION NUCLEI

LINE	$F(\lambda)/F(H\beta)$ NGC 625	NGC 1510
[Ne V] λ3426	...	...
[O II] λ3727	1.29	2.41
[Ne III] λ3869	0.25	0.21:
He I + H8 λ3889	0.13	...
[Ne III]+ Hε λ3967	0.21	...
[S II] λ4071	0.01:	...
Hδ λ4102	0.22	...
Hγ λ4340	0.43	0.34
[O III] λ4363	0.03	...
He II λ4686	...	...
Hβ λ4861	1.00	1.00
[O III] λ4959	1.57	1.30
[O III] λ5007	4.76	3.70
[N I] λ5199	...	...
[Fe VII] λ5721	...	...
He I λ5876	0.14	0.14
[Fe VII] λ6087	...	...
[O I] λ6300	0.01:	≤ 0.11
[N II] λ6548	0.04	0.16
Hα λ6563	3.76	4.41
[N II] λ6584	0.16	0.56
[S II] λ6716	0.14	0.36
[S II] λ6731	0.10	0.41
log(3727/5007)[a]	−0.45	0.00
⟨E⟩[a]	−0.04	≤ 0.11

[a] See Table 4, notes e and f.

the measurements, and also the corresponding luminosities.

Einstein Observatory IPC observations have already been published for the high-excitation galaxies NGC 2992 (Maccacaro, Perola, and Elvis 1981), NGC 4507 (Kriss, Canizares, and Ricker 1980), and NGC 4388 (Forman *et al.* 1979), and for the comparison galaxy NGC 7714 (Weedman *et al.* 1981). We have included their X-ray luminosities in Tables 6 and 7.

d) Radio Data

The Parkes 64 m telescope was used to obtain 6 cm continuum measurements for both the high-excitation and the comparison emission-line galaxies. The observations were made in two sessions in 1981 February and August using a 5.0 GHz cryogenic receiver (system noise 80 K, bandwidth 500 MHz). The receiver was switched between two feeds producing similar beams of 4′ (full width at half-power), separated by 10′.1.

A more detailed description of the observing procedure, data reduction, and results of the Parkes measurements will be published separately (Turtle and Phillips 1983). However, absolute powers derived from these data are given here in Tables 6 and 7.

IV. RESULTS

a) Galaxies with Broad Components of Balmer Emission

Three of the Sandage high-excitation emission-line galaxies show straightforward evidence of an active Seyfert nucleus in the form of a broad component of Balmer emission. The most obvious is NGC 1019 (see Fig. 1), where the broad component measures approximately 2000 km s^{-1} FWHM and dominates the Balmer lines. Blended broad Fe II emission lines are also quite likely present between Hγ and Hβ. These properties and the observed blue featureless continuum are all characteristic of a type 1 Seyfert galaxy (e.g., see Osterbrock 1977).

A much weaker broad component of Balmer emission has been observed in the nuclear spectrum of NGC 2992 (Véron *et al.* 1980; Shuder 1980). Here the broad emission is detected only at Hα, and under the criterion given by Osterbrock (1981) the classification of this galaxy would be Seyfert 1.9.

The third high-excitation galaxy with broad Balmer emission is UGC 1395. As in the case of NGC 2992, the broad component is weak in comparison to the narrow emission-line spectrum. However, in UGC 1395, the broad emission is faintly present at Hβ as well and hence suggests a classification of Seyfert 1.8 (Osterbrock 1981).

b) Galaxies with Narrow Emission Lines

In the remaining 20 high-excitation emission-line galaxies we have observed, the signs of an active nucleus are not quite so obvious. For these we must resort to a comparison of our optical, X-ray, and radio data with similar measurements for both the classical type 2 Seyfert galaxies and galaxies with H II region nuclei. As a representative sample of the former group, we have chosen the Seyfert 2 galaxies studied by Koski (1978) which were measured by him to have reddening-corrected [O III] λ5007/Hβ ratios greater than 5.0. As examples of galaxies with H II region nuclei, we shall employ our four comparison galaxies, supplemented, where appropriate, by published observations of other galaxies with H II region nuclei.

i) *Classification of the Optical Emission-Line Spectra*

The relative intensities of the H I, [O I], [O II], [O III], and [N II] lines can be used to great advantage in understanding the source of ionization of the gas in galactic nuclei showing only narrow emission-line spectra. Such a method has been developed by Baldwin, Phillips, and Terlevich (1981, hereafter BPT). In its complete form, the BPT method utilizes four diagrams in which are plotted combinations of the following five emission-line ratios: Hα/Hβ, [O II]

TABLE 6

Optical, X-Ray, and Radio Properties of High-Excitation Emission-Line Galaxies

Galaxy	$F_{[O\ III]\ \lambda 5007}$[a] ($10^{-13}$ ergs cm^{-2} s^{-1})	$L_{[O\ III]\ \lambda 5007}$[b] ($10^{40}$ ergs s^{-1})	FWHM$_{[O\ III]}$ (km s^{-1})	F_x(0.2–4 keV) (10^{-13} ergs cm^{-2} s^{-1})	L_x(0.2–4 keV) (10^{40} ergs s^{-1})	$P_{6\ cm}$ (10^{20} W Hz^{-1} sr^{-1})
UGC 1395......	...	...	160[c]	...	...	2.9
NGC 1019......	...	...	180[d]	...	...	< 7.9
NGC 1229......	...	...	400[e]	...	...	< 17
NGC 1358......	...	3.8[f]	220[g]	< 4	< 7.4	< 2.2
NGC 1386......	...	8.3[f]	330[h]	...	...	0.4
NGC 1667......	...	...	290[g]	...	...	4.7
NGC 2989......	...	...	70[h]	...	...	< 2.2
NGC 2992......	...	310[f]	250[d,i]	...	84 ± 3[j]	4.5
NGC 3081......	...	18[f]	190[d,i]	4 ± 1.5	2.2 ± 0.8	< 0.7
NGC 3281......	...	...	290[h]	...	...	3.0
NGC 3738......	...	...	...	...	...	...
NGC 3982......	...	...	...	...	...	...
NGC 4388......	...	...	200[g]	...	0.8 ± 0.2[k]	1.4
NGC 4507......	11	81	270[l]	...	7.0[m]	2.9
NGC 5135......	...	...	180[h]	3.1 ± 1.2	6.0 ± 0.2	10
NGC 5643......	8.0	16	200[g]	6.6 ± 2.8	0.8 ± 0.3	0.8
NGC 5728......	6.8	50	400[h]	3.7 ± 1.4	3.7 ± 1.4	2.3
NGC 6300......	...	...	220[g]	...	...	0.2
NGC 6890......	...	3.8[f]	240[d]	< 2	< 1.4	< 0.9
IC 5063	...	87[n]	370[n]	< 2	< 2.7	44
IC 5135	...	...	430[g]	...	...	14
IC 5201	...	...	100[g]	...	...	< 0.1
IC 1515	...	...	150[g]	...	...	< 7.1

Note.—All luminosities are calculated using $H_0 = 100$ km s^{-1} Mpc and $q_0 = 0$.
[a]AAT IPCS 10″ slit.
[b]Corrected for extinction derived from observed Hα/Hβ intensity ratio.
[c]Las Campanas 5 Å resolution.
[d]Véron 1981.
[e]AAT IPCS 6 Å resolution.
[f]Frogel *et al.* 1983.
[g]AAT IPCS 1.95 Å resolution.
[h]AAT IPCS 0.65 Å resolution.
[i]Las Campanas 3.7 Å resolution.
[j]Maccacaro, Perola, and Elvis 1981, mean of two observations.
[k]Forman *et al.* 1979.
[l]Véron, Véron, and Zuiderwijk 1981, [S II] λλ6716, 6731 FWHM.
[m]Kriss, Canizares, and Ricker 1980.
[n]Caldwell and Phillips 1981.

TABLE 7

Optical, X-Ray, and Radio Properties of Comparison Galaxies with H II Region Nuclei

Galaxy	$F_{[O\ III]\ \lambda 5007}$ (10^{-13} ergs cm^{-2} s^{-1})	$L_{[O\ III]\ \lambda 5007}$[a] ($10^{40}$ ergs s^{-1})	FWHM$_{[O\ III]}$ (km s^{-1})	F_x(0.2–4 keV) (10^{-13} ergs cm^{-2} s^{-1})	L_x(0.2–4 keV) (10^{40} ergs s^{-1})	$P_{6\ cm}$ (10^{20} W Hz^{-1} sr^{-1})
NGC 625.......	...	...	50[b]	< 2	< 0.024	< 0.02
NGC 1510......	...	1.4[c]	55[d]	< 2	< 0.15	< 0.09
NGC 7552......	...	8.0[e]	110[f]	7 ± 1	2.3 ± 0.3	3.1
NGC 7714......	...	36[c,g]	194[h]	...	3 ± 1[h]	2.7

Note.—All luminosities are calculated using $H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 0$.
[a]Corrected for extinction derived from observed Hα/Hβ intensity ratio.
[b]Las Campanas 5 Å resolution.
[c]Frogel *et al.* 1983.
[d]Véron 1981.
[e]Ward *et al.* 1980.
[f]AAT IPCS 1.95 Å resolution.
[g]French 1980.
[h]Weedman *et al.* 1981.

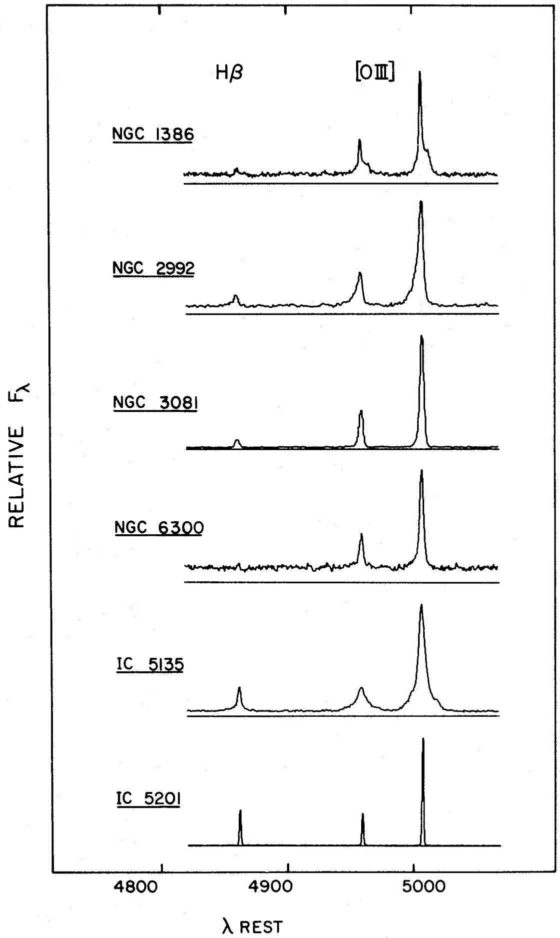

FIG. 3.—High-dispersion emission line profiles of six representative high-excitation galaxies.

λ3727/[O III] λ5007, [O III] λ5007/Hβ, [N II] λ6584/Hα, and [O I] λ6300/Hα. Of the four diagrams, the one which is least sensitive to reddening corrections is that which compares the ratios [O III] λ5007/Hβ and [N II] λ6584/Hα. This is plotted in Figure 5 for (*a*) the high-excitation galaxies without broad components of Balmer emission, (*b*) the four comparison galaxies, and (*c*) the classical Seyfert 2 galaxies. Also plotted in the same diagram as a solid line is the approximate distribution of normal galactic H II regions.

The comparison galaxies all lie close to the H II region line in Figure 5, in confirmation of the original assumption that their emission-line spectra are produced in gas which is photoionized by normal O and B stars. The points for three of the high-excitation galaxies—NGC 2989, NGC 3738, and IC 5201—also fall near the H II region line, implying that the nuclear emission in these galaxies is chiefly from H II regions photoionized by hot stars. However, the remaining 17 high-excitation galaxies segregate into an area of the diagram well away from the H II regions, which is the *same region occupied by the Seyfert 2 galaxies.*

Identical results are obtained from comparison of the other line intensity ratios as illustrated in Figure 6. This BPT diagram plots an average "excess," $\langle E \rangle$, of the reddening corrected [O III] λ5007/Hβ, [N II] λ6584/Hα, and [O I] λ6300/Hα ratios with respect to normal H II region values versus the line ratio [O II] λ3727/[O III] λ5007, which measures the general level of ionization of the gas. Again, the four comparison galaxies and the high-excitation galaxies NGC 2989, NGC 3728, and IC 5201 fall in the domain of the galactic H II regions, while the other 17 high-excitation galaxies are indistinguishable from the Seyfert 2 galaxies.

Several different studies have shown that the gas in Seyfert 2 nuclei is most likely photoionized by nonthermal radiation (e.g., see Yee 1980; Shuder 1981). This is supported by the unusual strength of the emission lines of very high ionization species such as He^{+}, Ne^{+4}, and Fe^{+6} observed in such objects. A glance at Table 4 shows that the same lines are present in a large fraction of our high-excitation galaxies. Hence, the high-excitation galaxies mimic the type 2 Seyferts in this respect as well. Thus we conclude with confidence that *the predominant ionization source in the majority of the Sandage high-excitation galaxies is not the radiation of young hot stars but rather is nonthermal in origin.*

ii) *Optical Emission-Line Widths and Profiles*

The emission lines of the 17 Seyfert 2–like high-excitation galaxies tend to be slightly broader than those of the galaxies with H II region spectra but considerably narrower than those of the classical type 2 Seyferts. This is seen in Figure 7*a*, which is a histogram of the [O III] λ5007 widths (FWHM) for (*a*) the high-excitation galaxies, (*b*) the classical Seyfert 2 galaxies, and (*c*) galaxies with H II region nuclei (consisting of the four comparison galaxies, supplemented by data given by Balzano and Weedman 1981 and Véron 1981). Note the narrow line widths of the high-excitation galaxies identified in the BPT diagrams as having H II region spectra (NGC 2989 and IC 5201) which are most consistent with the distribution of line widths found for the H II region nuclei. On the other hand, the mean of the distribution in line widths of the remaining high-excitation galaxies is ~100 km s^{-1} greater than that of the galaxies with H II region spectra—although there is considerable overlap between the two groups. Likewise, there is some overlap between the high-excitation galaxies and the classical Seyfert 2 galaxies, but with the mean FWHM of the latter objects much greater.

Ignoring the absolute values of the FWHMs, the overall line profiles of nearly all of the high-excitation galaxies with Seyfert 2–like spectra are distinguished by broad, low-contrast, and often asymmetric wings (see

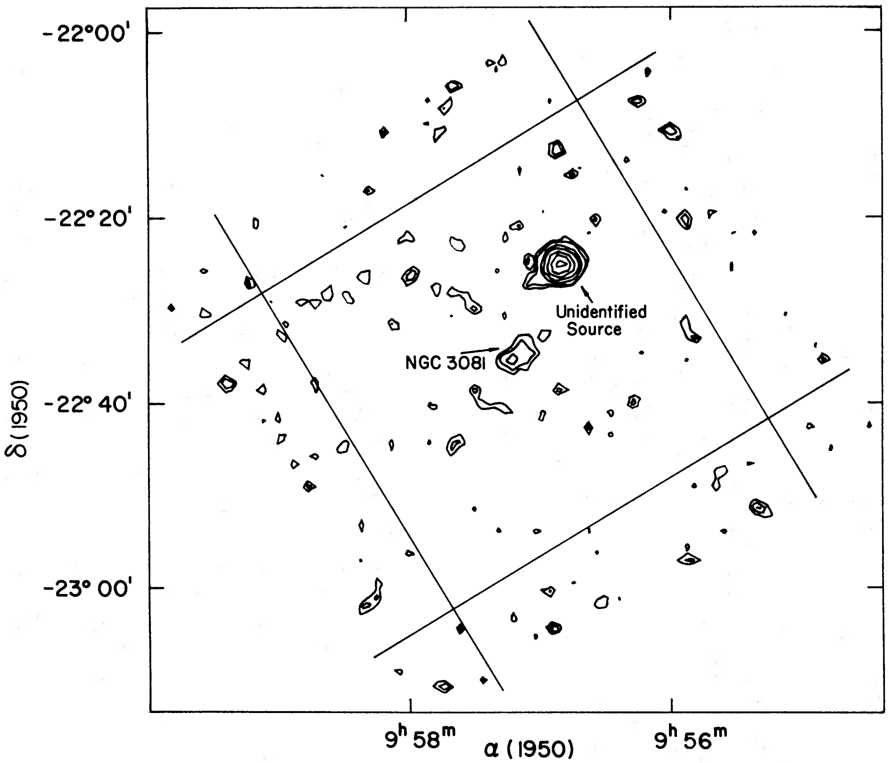

FIG. 4.—Iso-intensity 0.2–4.0 keV X-ray contour map of the field of the high-excitation emission-line galaxy NGC 3081 obtained with the *Einstein* IPC. The data have been smoothed by a 32″ (FWHM) Gaussian filter and are plotted with contours of 2, 3, 5, 7, 10, ..., σ. The shadowing window support structure is indicated by straight lines of 60′ length.

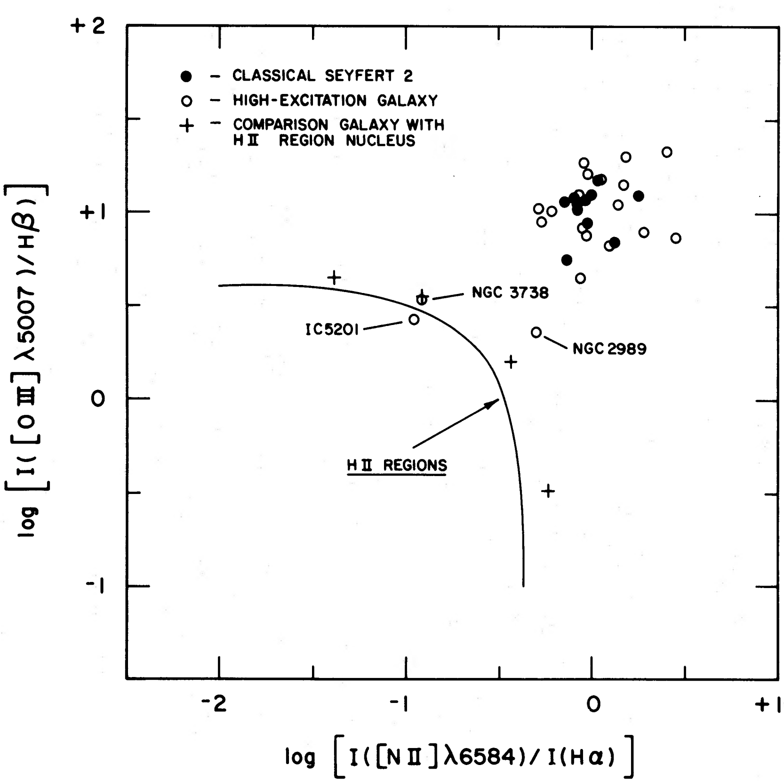

FIG. 5.—BPT diagram displaying reddening-corrected [O III] λ5007/Hβ vs. [N II] λ6584/Hα intensity ratios for the high-excitation emission-line galaxies, classical Seyfert galaxies, and the four comparison galaxies with H II region nuclei.

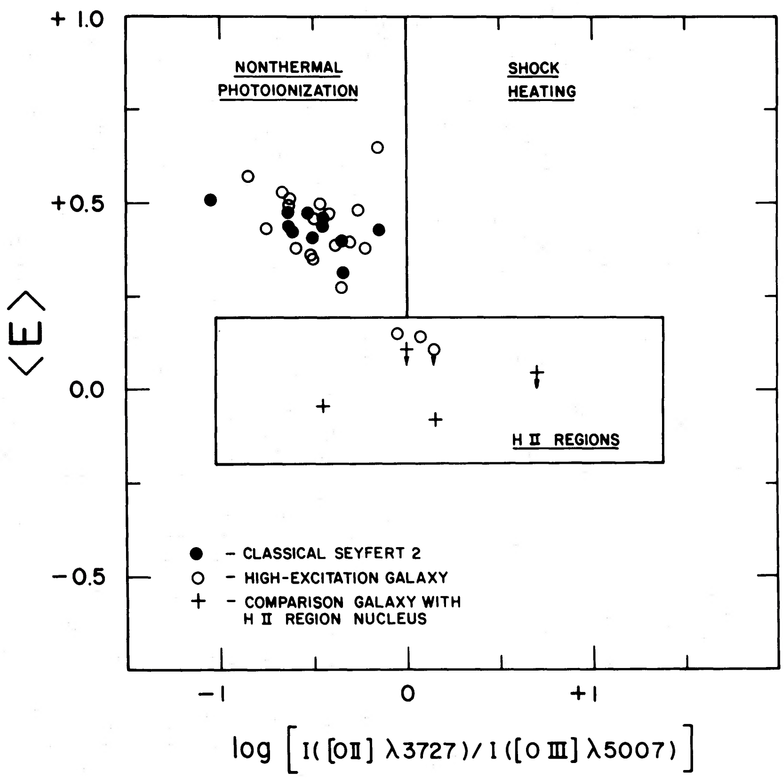

FIG. 6.—BPT diagram displaying the average "excess" $\langle E \rangle$ of the reddening-corrected [O III] λ5007/Hβ, [N II] λ6584/Hα, and [O I] λ6300/Hα intensity ratios with respect to normal H II region values vs. the reddening-corrected line ratio [O II] λ3727/[O III] λ5007. Galaxies displayed are the same as in Fig. 5.

Fig. 3). Although occasionally observed in galaxies with H II region nuclei (e.g., see Ulrich 1972), such line profiles are known to occur with such regularity only in Seyfert galaxies (Heckman *et al.* 1981; Véron 1981; Shuder and Osterbrock 1981). Hence the line profile or FWZI, as opposed to the FWHM alone, would appear to provide a better discriminator of Seyfert-like activity.

iii) *Optical, X-Ray, and Radio Luminosities*

Figure 7*b* shows a histogram of the [O III] λ5007 luminosity for (*a*) the high-excitation galaxies, (*b*) the classical type 2 Seyferts, and (*c*) galaxies with H II region nuclei (represented by three of the comparison galaxies and two Sc galaxies observed by Turnrose 1976). A similar histogram of X-ray luminosity in the range 0.2–4.0 keV is given in Figure 7*c*. Here, the data for the eight high-excitation galaxies and three comparison galaxies are plotted along with comparable *Einstein* observations of classical Seyfert 2 galaxies (Kriss, Canizares, and Ricker 1980). The broken line indicates the maximum X-ray luminosities of nearby "normal" spiral galaxies as represented by M31 and M33 (Van Speybroeck *et al.* 1979; Long *et al.* 1981). Finally, a comparison of the radio luminosities of the high-excitation galaxies with those of the classical type 2 Seyferts and the comparison galaxies is made in Figure 7*d*. Included in this histogram is a broken line derived from the 1.415 GHz survey of Hummel (1981) (assuming a mean spectral index of $\alpha = -0.8$), to the left of which would lie 80% of all spiral galaxies with absolute magnitudes between -18 and -21.

In all three wavelength regimes—optical, X-ray, and radio—the high-excitation galaxies with Seyfert 2–like optical spectra have luminosities extending up to those of classical Seyfert 2 galaxies and considerably greater than those of normal galaxies. Likewise, the luminosities of the high-excitation galaxies are greater than nearly all of the galaxies with H II region nuclei, although two obvious exceptions are the comparison galaxies NGC 7552 and NGC 7714, which have luminosities that are greater than or equal to those of several of even the classical Seyfert 2 galaxies. The X-ray and radio emission of NGC 7552 and NGC 7714 is believed to arise from a large number of supernova remnants which have resulted from a giant burst of star formation (Weedman *et al.* 1981; Charles and Phillips 1982), whereas in the case of the classical type 2 Seyferts, the source is more often ascribed to the presence of a supermassive compact object at the nucleus. However, on the basis of the optical, X-ray, and radio luminosities alone, it is clear that such galaxies are virtually indistinguishable.

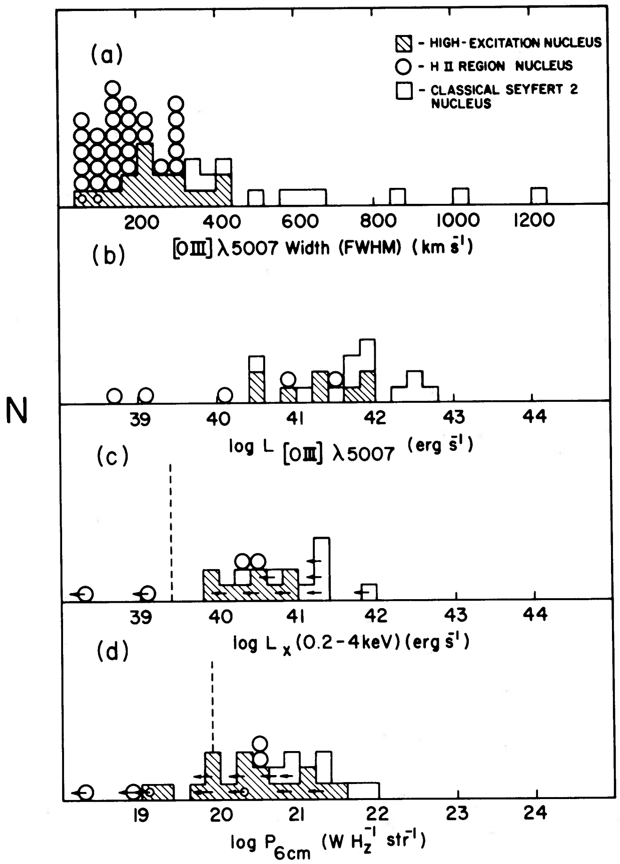

FIG. 7.—Histograms of (*a*) [O III] λ5007 line widths, (*b*) [O III] λ5007 luminosity, (*c*) 0.2–4 keV X-ray luminosity, and (*d*) absolute 6 cm radio continuum power for the high-excitation emission-line galaxies. The data are compared with observations of representative samples of classically selected Seyfert 2 galaxies and galaxies with H II region nuclei. Arrows indicate upper limits. Boxes with small circles are high-excitation galaxies found to have H II region nuclei.

V. DISCUSSION

a) *Definition of Nonthermal Nuclear Activity*

We find that only three of the Sandage high-excitation emission-line galaxies—NGC 2989, NGC 3738, and IC 5201—appear to have normal H II region activity occurring in their nuclei. Three of the remaining galaxies—NGC 1019, NGC 2992, and UGC 1395—clearly show *broad* components of Balmer emission which betray the presence of classical Seyfert-like nonthermal nuclear activity. However, of even greater interest are the other 17 galaxies with *narrow* emission lines only, whose nuclear activity is apparently closely related to that found in classical type 2 Seyfert galaxies. We have shown that in terms of the *relative intensities* of the optical emission lines and the general shape of the emission-line *profiles*, these 17 galaxies are indistinguishable from the classical Seyferts. Why, then, had most of these 20 galaxies not been previously recognized as Seyfert 2–like?[6]

The answer to this question almost certainly lies in the long-accepted definition of a Seyfert galaxy as an object possessing "strong broad emission lines arising in a bright semistellar nucleus." This quite naturally had led to the selection of a small group of galaxies with nuclei characterized by high intrinsic luminosity and broad lines. But rather than being the sole examples of galaxies with nonthermal nuclear activity, our findings indicate that the classical Seyfert galaxies are *the high-energy extreme* of a much broader and continuous distribution of galaxies with nuclear activity which is best understood in terms of photoionization by a nonthermal source of radiation.

Further evidence for the continuity between our high-excitation galaxies and classical type 2 Seyferts is found in Figure 8. Here the [O III] λ5007, 0.2–4.0 keV X-ray, and 6 cm radio luminosities are plotted versus the [O III] λ5007 line width (FWHM). Loose correlations between line width and X-ray and radio luminosity have been presented for the classical Seyfert 2 galaxies by Kriss, Canizares, and Ricker (1980) and Wilson and Willis (1980), respectively. The correlation of the [O III] line width and [O III] luminosity for such active galaxies has apparently not been pointed out before and would imply a relation between the energy input mechanism of the gas and the total spread in velocity. As may be seen, the high-excitation nuclei form a natural low-luminosity and narrow–line width extension of these correlations.

The λ5007 equivalent widths observed for the high-excitation galaxies range from 20 to 600 Å, with a mean of 130 Å. We estimate that, as an upper limit, a nonthermal source could contribute only 0.10–0.30 of the underlying spectrum recorded in our data at λ5007. Correcting for this factor, the [O III] λ5007 equivalent widths relative to the nonthermal continuum are in good agreement with the values ranging up to 5000 Å given by Osterbrock (1978) for classical Seyfert 2 galaxies. There is, therefore, no evidence to suggest that details of the emission-line cloud structure or covering factor differ between the classical type 2 Seyferts and the high-excitation galaxies described here.

b) *Implications of Line Widths and Infrared Colors as Indicators of Nonthermal Activity*

This view of the classical Seyfert 2 galaxies as merely the extreme members of a much larger family of galaxies with similar, but less obvious, optical nonthermal nuclear

[6]The high-excitation galaxy NGC 4507 is the only member of the sample to be found in Weedman's (1977) list of classically selected Seyfert galaxies. However, the Seyfert 2–like nature of the nuclear emission of NGC 2992 was first pointed out by Ward *et al.* (1978). In addition, since this research was begun, the Seyfert characteristics of the high-excitation galaxies NGC 3081, NGC 3281, NGC 5728, NGC 6890, and IC 5135 were independently reported by Véron (1981).

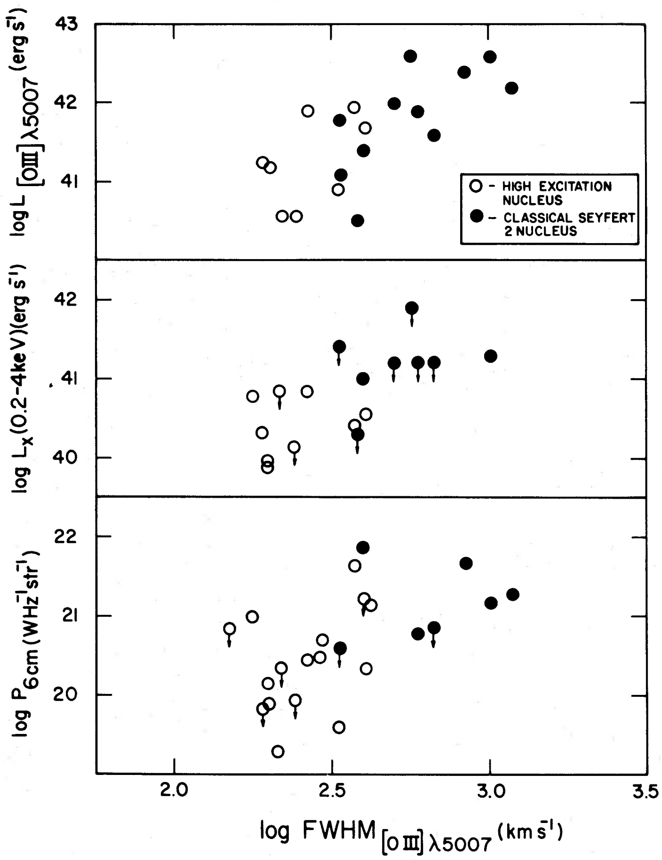

FIG. 8.—Absolute [O III] λ5007, 0.2–4 keV X-ray, and 6 cm radio continuum luminosities plotted vs. [O III] λ5007 emission-line width for classically selected Seyfert 2 galaxies and for the 17 high-excitation galaxies with Seyfert 2–like nuclei.

activity has several important implications. First, the recent suggestion by Balzano and Weedman (1981) and Shuder and Osterbrock (1981) that galaxies having nuclear emission-line widths less than 250–300 km s^{-1} are not characterized by nonthermal activity is clearly incorrect. In hindsight, the artificial nature of this limit is obvious since most of the galaxies considered by Balzano and Weedman and Shuder and Osterbrock as representative of nuclei with nonthermal activity were those which met the classical definition of a Seyfert galaxy. Not surprisingly, therefore, these galaxies were found to have broad emission lines.

Balzano and Weedman also concluded that nonthermal activity in Seyfert galaxies is nearly always associated with a $J - K$ color in excess of 1.1. Infrared photometry through apertures comparable to those used by Balzano and Weedman is available for nine of the Sandage galaxies with Seyfert 2–like relative line intensities: NGC 1358, NGC 1386, NGC 2992, NGC 3081, NGC 3281, NGC 4388, NGC 4507, NGC 5643, and NGC 6890 (Ward *et al.* 1982; Frogel *et al.* 1983). For four of the nine—NGC 1358, NGC 1386, NGC 3081, and NGC 5643—the $J - K$ measurement is $\lesssim 1.1$, and so again, the Balzano and Weedman criterion would exclude a significant number of galaxies with nonthermal nuclear activity if the Sandage sample of galaxies is representative. Certainly the inference from this is that the relative line intensities and the overall profiles of the optical emission lines are better discriminators of nonthermal activity than luminosity, the absolute value of the FWHM, or even the $J - K$ color.

c) *Incidence of Nonthermal Nuclei in Galaxies*

Another important result is that galaxies with optical nonthermal nuclear activity are considerably more common than has previously been realized. This is made obvious in Figure 9, which shows a histogram of galactocentric radial velocity for (*a*) the 17 Sandage high-excitation galaxies with narrow Seyfert 2–like emission lines and (*b*) the sample of classical Seyfert 2 galaxies defined by high intrinsic luminosity and broad lines. Fully 84% of the Sandage galaxies have radial velocities less than 5000 km s^{-1}, whereas the same is

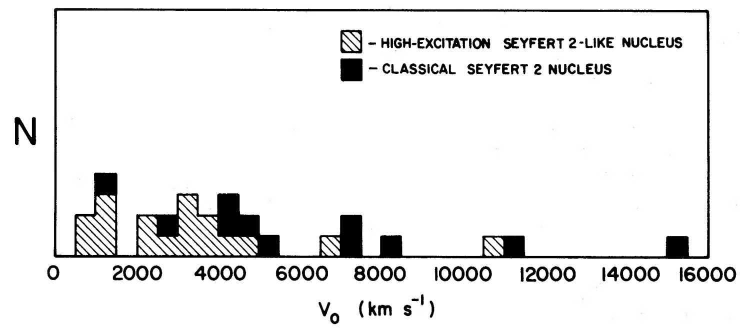

FIG. 9.—Histogram comparing galactocentric radial velocities of classically selected type 2 Seyferts and the 17 high-excitation galaxies with Seyfert 2-like nuclei.

true of only 38% of the classical Seyfert 2 galaxies. Thus the Sandage galaxies—i.e., those with lower luminosities and narrower emission lines—are the most common form of optical nonthermal nuclear activity to be observed. Unfortunately, it is very difficult to be more specific as to the actual percentage of galaxies in which such activity is present. Perhaps a meaningful lower limit is 3%–4%, which is derived from the Sandage sample. If this sample is limited to just spiral galaxies (since only one of the Sandage galaxies with nonthermal activity is an elliptical or S0), then the lower limit becomes approximately 5%.[7]

For many years, type 1 Seyfert galaxies were thought to outnumber those of type 2. Recently, however, in a study of all Seyfert galaxies with radial velocities $v_0 <$ 5000 km s^{-1}, Simkin, Su, and Schwarz (1980) suggested that the distribution of types was more evenly split. Our observations now imply that the division becomes more like 2/1 in favor of the type 2 galaxies. We would point out that this number is still probably an underestimate, since type 2 Seyferts are more likely to be overlooked than those of type 1.

d) *Relation between Nonthermal and* H II *Region Nuclei*

Finally, the degree of overlap in observable parameters between the distribution of galaxies with optical nonthermal nuclear activity and those with H II region nuclei deserves further comment. It has at times been suggested (e.g., see Weedman *et al.* 1981) that a link may exist between luminous "starburst" galaxies such as NGC 7552 and NGC 7714, with H II region nuclei, and the nonthermal activity of the kind observed in the Sandage high-excitation galaxies and the classical type 2 Seyferts. As Weedman *et al.* suggest, a starburst might naturally lead to the formation of one or more massive compact objects in the nucleus, and gas accreting onto such objects could eventually produce the type of nonthermal activity observed. Circumstantial evidence in support of such a link in at least some of the Sandage galaxies is found in the form of a substantial population of young hot stars in the nucleus. This is particularly obvious in the spectra of NGC 5135 and IC 5135, which both show blue nuclear continua which are quite likely due to very young hot stars (see Fig. 1). In the case of IC 5135, narrow low-excitation H II region line emission is observed just outside the nucleus, reinforcing the idea that considerable star formation has occurred recently. Similar cases of an active nucleus lying in the midst of a complex of H II regions are found in the galaxies NGC 1365 (Phillips and Frogel 1980), NGC 7496 (Véron *et al.* 1981), and NGC 7582 (Ward *et al.* 1980; Véron *et al.* 1981). A search for more examples of such galaxies should be undertaken since they represent particularly promising objects for detailed study of the interplay between H II regions and nonthermal activity in the nuclei of galaxies.

[7]We emphasize that the present investigation was limited to only those galaxies which Sandage described as having N2 ≫ Hβ. Little is known of the nature of the nuclear activity in the 14 galaxies in the same sample of 666 for which Sandage noted N2 > Hβ.

VI. CONCLUSIONS

To summarize, the main points of this paper are

1. The nuclear activity in nearly all of the Sandage sample of nearby high-excitation emission-line galaxies appears to be nonthermal in origin and closely resembles that observed in classical type 2 Seyfert galaxies.

2. These Sandage galaxies may be characterized as low-luminosity, narrow–emission-line examples of Seyfert 2 galaxies, whereas classically selected type 2 Seyferts are merely the high-energy extreme of a much broader distribution of nonthermal activity.

3. The Sandage high-excitation galaxies represent the most common form of optical nonthermal nuclear activity, which perhaps occurs in 5% or more of all spiral galaxies.

We gratefully acknowledge the generous allotments of observing time made to us by the respective allocation panels of the Las Campanas and Mount Wilson observatories, the Anglo-Australian Observatory, the European Southern Observatory, the *Einstein Observatory*, and the Australian National Radio Astronomy Observatory. Special thanks are also due to M. Whittle for help in the reduction of the AAT IPCS low-dispersion spectra.

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