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ARE THERE ANY SHOCK-HEATED GALAXIES?

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ABSTRACT

We study the spectroscopic characteristics of low ionization nuclear emission-line regions (Liners) in galaxies, and compare them with other active galactic nuclei. We show the results of new, extensive photoionization model calculations and use them to investigate line ratio diagrams, such as [O III] λ5007/Hβ versus [O II] λ3727/[O III] λ5007, and [O I] λ6300/[O III] λ5007 versus [O II] λ3727/[O III] λ5007. On the diagrams broad line objects, Seyfert 2 galaxies, and Liners form a continuous smooth sequence of decreasing ionization parameter. This suggests a common origin for line excitation in all of them. The observed optical continuum of Liners is also consistent with ionization by a power-law source. The intensity of several weak lines such as [O III] 4363, He I 5876, He II 4686, and the Balmer decrement can decide between photoionization and the other proposed excitation mechanism—viz., shock wave. We believe that photoionization is more plausible, and that Liners are, indeed, another group of active nuclei.

Subject headings: galaxies: nuclei — galaxies: Seyfert — shock waves

I. INTRODUCTION

Strong nuclear emission lines are a defining property of Seyfert galaxies. These objects are characterized by both low and high excitation emission lines, and a prominent power-law nonthermal continuum. It is this continuum which is generally believed to heat and ionize the emission line gas (Osterbrock 1977; Koski 1978). A large fraction of normal spirals also show nuclear emission lines that are not excited by normal stellar radiation. These spectra tend to exhibit lower excitation, a much weaker nonthermal continuum, and smaller velocity dispersion (Heckman 1980; Shuder and Osterbrock 1981).

The relationship between these two classes of emission line objects is unclear at present. In some ways the spectra of normal galaxies resemble supernova remnants, and this fact, together with the weakness of the nonthermal continuum, has led some authors to propose that narrow emission line galaxies are shock heated rather than photoionized (Heckman 1980; Baldwin, Phillips, and Terlevich 1981, hereafter BPT). In this view the Seyfert and narrow emission line galaxy phenomena are fundamentally different in many ways.

It is the purpose of this paper to examine the nuclear spectra of normal galaxies, in the context of the scenario developed for Seyfert nuclei. Past photoionization studies have concentrated on the range of parameters which reproduce Seyfert spectra. Here we extend photoionization calculations to very low values of the ionization parameter and show that photoionization is at least as successful as shock heating in reproducing the spectra of these objects.

In the next section we give a spectroscopic definition of the Seyfert and narrow emission line galaxy phenomena. In § III a grid of photoionization model calculations is presented, which shows that the full range of these phenomena are reproduced by a factor of 10^2 change in the ionization parameter. Some consequences of these calculations are discussed in § IV, and our conclusions are summarized in the last section.

II. SPECTROSCOPIC DEFINITION OF SAMPLE GALAXIES

Nuclear emission in galaxies ranges from the intense broad lines of Seyfert 1's, to the very weak narrow lines found in some spirals. Here we are interested in classifying these nuclear emission lines into groups, according to their level of excitation. For this we compare several line ratios in different galaxies.

We follow Heckman (1980) and BPT and distinguish between high-excitation and low-excitation nuclear emission regions, via the [O II] λ3727/[O III] λ5007 line ratio, together with several other low-excitation lines. The high-excitation group includes Seyfert 2's (e.g., Koski 1978), narrow line radio galaxies (e.g., Costero and Osterbrock 1977), several narrow line X-ray galaxies (e.g., Shuder 1981), and finally the narrow line regions of Seyfert 1's and broad line radio galaxies (Osterbrock 1977; Grandi and Osterbrock 1978). They represent only a small fraction of all galaxies, perhaps 1% (Weedman 1977). For low-excitation galaxies we treat only those that show signs of activity (i.e., processes not generally associated with normal stars [Heckman 1980]; therefore giant H II regions are not included). They are much more common than Seyfert's; perhaps one-third of all

TABLE 1

DEREDDENED LINE INTENSITIES IN LINERS

Line/Galaxy	3C 178	PKS 2322−12	Mrk 298	Mrk 700	NGC 6764	NGC 2841	M81[a] = NGC 3031	NGC 3998[a]	NGC 4036
[O II] λ3727	1.5	7.18	4.49	1.27	2.43	3.81	6.01	2.9	11.1
Hγ	0.26	0.41	0.43	...	0.43	...	0.71	0.50	0.32
[O III] λ4363	...	<0.07	0.047:	...	0.042:	...	...	...	...
He II λ4686	≤0.11	≤0.06	...	...	0.062	...	...	...	...
Hβ	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
[O III] λλ5007+4959	0.79	0.86	2.58	0.72	0.63	1.94	2.79	1.24	1.25
He I λ5876	0.09	0.07	0.1	0.036:	0.11	...	...	...	...
[O I] λ6300	0.09	0.85	0.4	0.33	0.14	0.98	1.39	1.16	1.19
Hα	2.84	2.65	2.68	2.88	2.88	2.8	2.80	2.8	2.80
[N II] λ6584	1.63	2.21	0.7	5.04	1.95	4.01	3.84	2.46	5.19
[S II] λλ6716+6730	0.78	2.78	1.17	1.19	1.01	2.09	1.45	2.3	2.8

galaxies belong to this group. Heckman refers to these objects as Liners (for low ionization nuclear emission-line regions).

The emission line luminosities of most Liners are much smaller than those of Seyfert galaxies, although some overlap can occur. We postpone the detailed discussion of the spectroscopic differences between these groups to the fourth section. For the moment we draw the dividing line between Liners and high-excitation objects at [O II] λ3727/[O III] λ5007 = 1.

Before discussing detailed properties of the various types of objects, we note that there may be some ambiguity as to the exact size of the "nuclear emission region." In most cases this is simply determined by the spectrometer entrance aperture used by the observer, and is often equivalent to several hundred parsecs at the source. This number will be used in later sections when we compare observations with model calculations.

Several other properties of Liners are worth mentioning. According to Heckman (1980), there is no evidence for a featureless continuum in the blue, and 90% or more of the observed flux at 3600 Å is stellar. On the other hand, some of the galaxies studied by Koski (1978) and Shuder and Osterbrock (1981) are Liners by our definition, and they show a featureless continuum which is rather strong. There is also a tendency for these objects to have a compact nuclear radio source (Heckman 1980). Heckman has noted that the Hα/Hβ ratio in his sample of Liners may be somewhat steeper than the Balmer decrement predicted by recombination case B. This result is difficult to establish, because the high Balmer lines are weak or blended, and are not reliable reddening indicators. Line width is another important parameter. Heckman (1980) found Liners to have line widths comparable to Seyferts' narrow lines. Shuder and Osterbrock (1981) found that galaxies with [O III] λ5007/Hβ > 3 (which they call Seyfert 2) have broader forbidden lines than galaxies with [O III] λ5007/Hβ < 3. This second group would be classified as Liners by our [O II] λ3727/[O III] λ5007 criterion. We note also that the Liners in Shuder and Osterbrock's (1981) list have larger Hα fluxes than those of Heckman (1980).

The purpose of the present study is to compare Liners with Seyfert nuclei, and to check the hypothesis that the class of low excitation objects may be shock-heated. For this we have chosen from the literature a sample of galaxies which represent the two groups. Our sample is not complete in any sense, but does cover a large range in line strengths and ratios. For Liners we take the objects from Heckman, Balick, and Crane (1980) that have been chosen by BPT as examples of shock-heated galaxies. We also take several galaxies from the lists of Koski (1978) and Costero and Osterbrock (1977), which are called Liners by Heckman (1980). Another source is Shuder and Osterbrock (1981). A list of all our Liners, and their dereddened line intensities, is given in Table 1. Heckman, Balick, and Crane (1980) do not give reddening-corrected line intensities, so we have used their data to derive the extinction, by assuming an intrinsic case B Hα/Hβ ratio. This may not be fully justified, as explained above, but other lines are too weak to be reliable measured.

Our comparison group contains Seyfert galaxies, radio galaxies and broad and narrow lines, and quasars. Here again we choose galaxies from BPT that were originally taken from Koski (1978) and Costero and Osterbrock (1977). We also took some Seyfert 2's from Shuder and Osterbrock (1981). The narrow component of broad line objects presents some problems. For broad line radio galaxies we used Grandi and Osterbrock's (1978) measurements of the narrow component, and corrected them for reddening using Hα/Hβ. Another reference is Netzer (1982). Quasars' narrow lines are listed in Baldwin (1975), but they are very uncertain. Another reference is Netzer, Wills, and Wills (1982). There is no compilation of narrow line components in Seyfert 1's, but Osterbrock and Shuder (1981) show line profiles that can be used to estimate [O III] λ5007/Hβ (narrow) in several cases. We used those together with Osterbrock's (1977) data. We also used Osterbrock and Koski (1976) and Boksenberg and Netzer (1977). All this is rather uncertain; the reddening correction is not known, and not all required line ratios can be obtained. Several line ratios in broad line objects should therefore be considered uncertain. Table 2 lists the galaxies selected and the references used.

TABLE 1—*Continued*

Line/Galaxy	NGC 5371	NGC 2911	NGC 4278	NGC 5005	Mrk 1158	Ark 160	Mrk 739	Kaz 26	NGC 1052	NGC 5077
[O II] λ3727	20.3	5.0	6.5	68.0	2.8	8.93	5.92	1.63	8.0:	3.9
Hγ	...	...	0.55	...	0.47	...	0.28:	0.41	0.48	...
[O III] λ4363	...	...	...	$\leq$0.64	$\leq$0.007	$\leq$0.14	$\leq$0.17	$\leq$0.048	0.18:	...
He II λ4686	...	...	...	$\leq$0.17	$\leq$0.011	$\leq$0.095	...	$\leq$0.044	...	...
Hβ	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
[O III] $\lambda\lambda$5007+4959 ..	2.4	2.33	1.62	3.59	2.93	2.24	1.35	0.49	3.0	2.8
He I λ5876	...	...	...	0.36	0.13	0.09:	0.057	0.1	...	...
[O I] λ6300	2.31	0.96	0.81	1.05	0.02	0.09:	0.12	0.03	1.47	2.0
Hα	2.80	2.80	2.8	2.85	2.4	2.85	1.93	2.54	2.86	2.8
[N II] λ6584	4.43	5.89	3.59	11.67	0.51	0.92	1.11	1.33	3.0	4.1
[S II] $\lambda\lambda$6716+6730 ...	4.40	5.52	3.04	5.36:	0.39	1.25	0.52	0.53	3.0	3.9

[a] Broad component to Hα.

NOTE.—A colon indicates a large uncertainty.

III. PHOTOIONIZATION CALCULATIONS

In this section we present photoionization calculations which extend the range of physical conditions to include those likely to characterize both high-excitation and low-excitation narrow emission line galaxies.

Calculations are performed with the program described by Ferland and Truran (1980). The equations of statistical and thermal equilibrium are solved in the standard manner (see Davidson and Netzer 1979), to produce a self-consistent model of the run of ionization and temperature with depth into the cloud. Care has been taken to include X-ray ionization effects, such as inner shell photoionization, the Auger effect, and secondary ionization by suprathermal electrons (see Netzer 1980; Halpern and Grindlay 1981). Charge exchange will be particularly important in Liners, because we anticipate a relatively large hydrogen neutral fraction. Besides the charge exchange reactions mentioned by Ferland and Truran, and by Halpern and Grindlay, we have used the new O^+ neutralization rate coefficient computed by Chambaud *et al.* (1981). Over 120 collisionally excited fine structure, forbidden, and optically allowed lines for the 11 elements we treat are included in the cooling function. Solar abundances are taken from Lambert (1978) and Lambert and Luck (1978). Relative to hydrogen they are:

$$\mathrm{He:C:N:O:Ne:Mg:Si:S:Ar:Fe} =$$

$$(10^3:4.7:0.98:8.3:1.1:0.26:0.40:0.33:0.063:0.16) \times 10^{-4}$$

by number.

Several hydrogen line transfer processes are also included in these calculations (see Netzer 1980; Kwan and Krolick 1981; Weisheit, Shields, and Tarter 1981), although most of these are not significant in this context. One process which is significant for low ionization gas, is excitation of some Balmer lines (particularly Hα) by collisions from the ground state (Netzer 1977). Rate coefficients, quoted by Drake and Ulrich (1980), are employed in these calculations.

Photoionization models are parameterized by the luminosity and shape of the ionizing continuum, the distance of the emission line clouds from this source, and the density and chemical composition of the gas. Some of these parameters can be set by direct observation. For instance, Shuder and Osterbrock (1981) find that the emitting gas in their sample galaxies have a density of $N_e \sim 10^3$ cm^{-3}, as deduced from the [S II] $\lambda\lambda$6717, 6731 doublet ratio. Our calculations assume constant gas pressure, and we set the hydrogen density at the inner face of the cloud to $N_{\rm H} = 10^3$ cm^{-3}. Since it is our intention to check whether Liners can be understood in terms of the Seyfert phenomenon, we employ a power-law ionizing continuum, with spectral index of 1.5 ($f_\nu \propto \nu^{-1.5}$) and no cutoff or extinction. This continuum is fairly representative of the class of Seyfert 2 nuclei. Intensities of the main cooling lines, such as the strong [O III] $\lambda\lambda$5007, 4959, [O II] λ3727, and [N II] $\lambda\lambda$6548, 6584 optical lines, are not sensitive to the exact continuum, although weak lines such as [O III] λ4363 are sensitive. The chemical composition of the gas in active galaxies is generally unknown, but if an analogy to giant extragalactic H II regions is appropriate, then heavy element abundances between solar and 1/10 solar can be found (French 1980). In our calculations we hold the He/H ratio constant (0.1 by number) and vary the metal abundances by a uniform factor.

TABLE 2

NARROW LINES IN BROAD-LINE OBJECTS

Object	References
NGC 4151	Osterbrock and Koski 1976
NGC 3516	Boksenberg and Netzer 1977
Mrk 279, Mrk 79, Mrk 704, Mrk 374, MCG 8-11-11	Osterbrock 1977; Osterbrock and Shuder 1981
PKS 1417−19, PKS 2349−01, 4C 29.06, IV Zw 29	Grandi and Osterbrock 1978
3C 390.3	Netzer 1982
PHL 1186, 4C 25.40, 3C 323.1, PKS 2135−14	Baldwin 1975
3C 351	Netzer, Wills, and Wills 1982

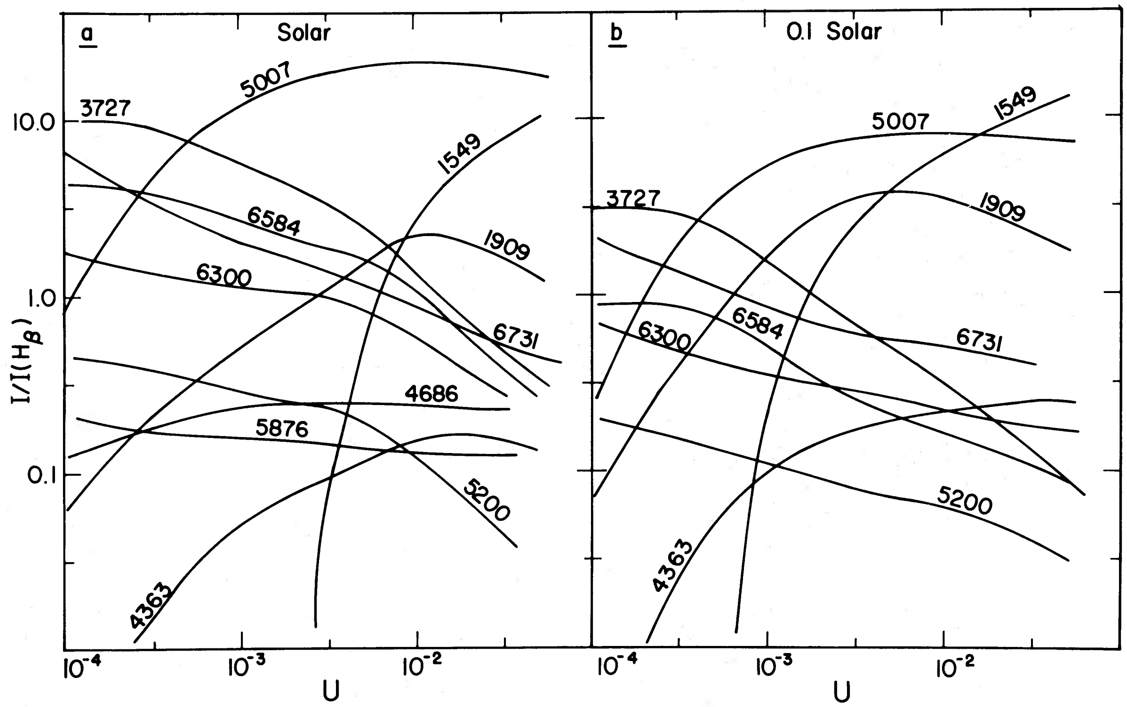

FIG. 1.—Line intensities vs. the dimensionless ionization parameter U in a photoionized gas cloud. The calculations are for a constant pressure model with $N_{\rm H} = 10^3$ cm^{-3} at the illuminated face of the cloud, and an $f_\nu \propto \nu^{-1.5}$ continuum. (*a*) Solar metal abundances (see text); (*b*) 0.1 solar metal abundances. Helium lines are not shown since they have the same relative intensities as in Fig. 1*a*. (*Note.*—6584 includes also 6548, 6731 includes also 6716; 5007 includes also 4959; 6300 includes also 6364.)

Formally, the last parameter which must be specified is the density of ionizing radiation at the inner face of the cloud (or equivalently, the luminosity in ionizing radiation and the separation between source and cloud). It is customary to specify this quantity in terms of the dimensionless ionization parameter, defined as:

$$U = Q({\rm H})/4\pi r^2 N_e c\ , \qquad (1)$$

where Q(H) is the number of ionizing photons emitted by the central object per second, r is the distance between source and cloud, N_e is the electron density at the inner face of the cloud, and c is the speed of light. The ionization parameter is directly related to the level of ionization of the gas (Davidson 1972; Davidson and Netzer 1979). In our units, broad line region clouds of high-redshift quasars tend to favor $U = 10^{-2}$ (e.g., Baldwin and Netzer 1978; Shuder and MacAlpine 1979; Weisheit, Shields, and Tarter 1981). We anticipate a lower value of U for Liners, because of the prominence of low-excitation emission lines. If the ionizing flux and gas density are set by direct observations, then changing the ionization parameter is equivalent to varying the distance between the source and cloud.

The results of a grid of model calculations, with both solar abundances (Fig. 1*a*) and a heavy-element composition reduced by a factor of 10 relative to the Sun (Fig. 1*b*), are shown as intensities relative to Hβ. As anticipated, low values of U give impressively strong emission in low excitation lines. To enable a more direct comparison with observations, Figures 2 and 3 show the calculated relations between several line ratios, as developed by BPT.

IV. DISCUSSION

In their paper on classification criteria for gaseous nebulae, BPT argued that several easily measured line ratios could convey a great deal of information on the physical environment in the emitting region. In this section, we compare their classification criteria with the model calculation outlined above. We treat, in several subsections, the most important lines and processes, and comment on the theoretical predictions. Table 3 summarizes the mean Liner spectrum to facilitate comparison with model calculations for both shock-wave and photoionization.

a) The Diagnostic Diagrams

BPT discuss four basic line intensity diagrams, which help define the Seyfert and Liner phenomena. The main excitation indicator is the abundance-insensitive [O II] λ3727/[O III] λ5007 ratio, as discussed above. BPT found that, when Liners and Seyfert nuclei are sorted by this excitation criterion, systematic differences between [O III] λ5007/Hβ, [N II] λ6584/Hα, and [O I] λ6300/Hα become apparent. Diagrams similar to those discussed by BPT are shown as Figures 2 and 3. Liners, Seyfert 2 nuclei, and the narrow lines of broad-line objects are all plotted and compared with predictions

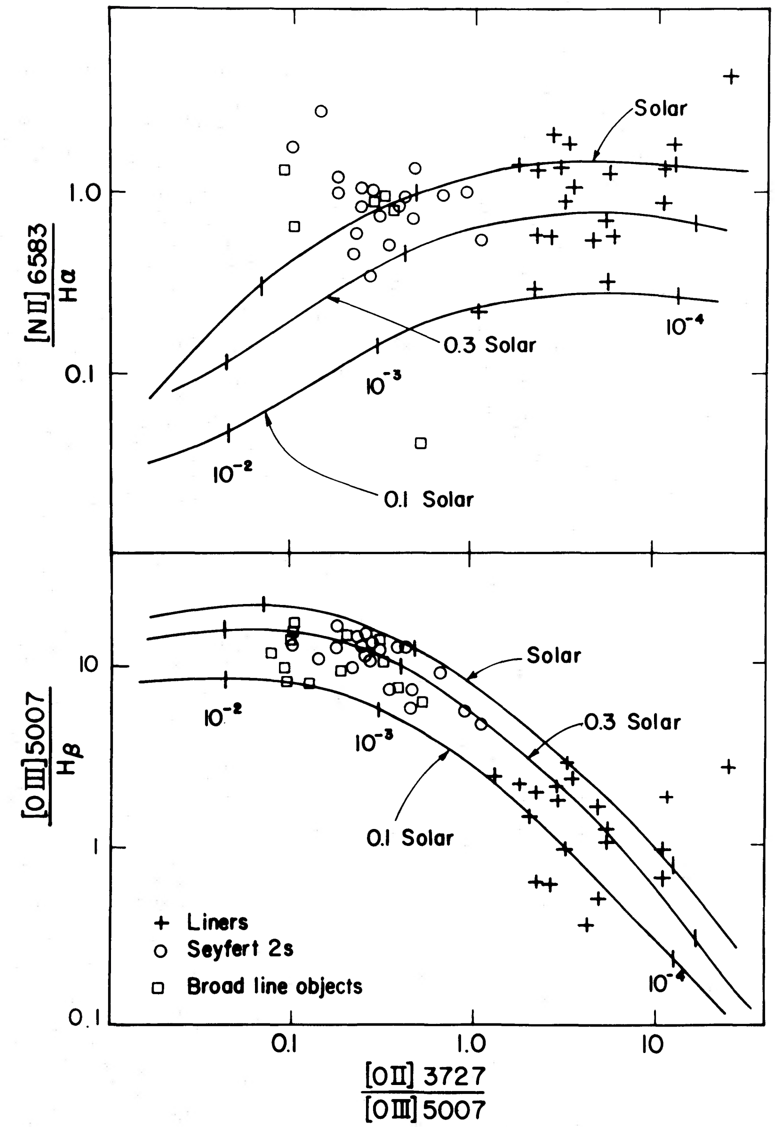

FIG. 2.—Dereddened observed narrow line ratios for broad line objects. *Open squares*, quasars, broad-line radio galaxies, and Seyfert 1's. *Open circles*, Seyfert 2's (including narrow-line radio galaxies); *plus signs*, Liners. Curves show theoretical results of photoionization calculations for three values of metal abundances, as marked. The ionization parameter U changes smoothly along the curves, and is marked at 10^{-2}, 10^{-3} and 10^{-4}.

of model calculations. Various values of the ionization parameter (indicated by the fiducial marks on the lines) and heavy-element abundances are shown.

The agreement between the envelope of observed ratios and the grid of calculations in the [O III] λ5007/Hβ versus [O II] λ3727/[O III] λ5007 plane is remarkable. This agreement is largely because both theory and observation are on especially firm ground here. The lines are strong and easily measured. The [O II] λ3727 and [O III] λ5007 lines are among the most important coolants in their formation zones, and their strengths are related to the basic thermal and ionization equilibrium, rather than to details of the models. Both Liners and Seyfert 2 nuclei appear to be characterized by heavy-element abundances roughly a third the solar value. According to these models, the only difference between the classes is the ionization parameter, which is $\sim 10^{-2}$ for Seyfert 1 and quasar narrow line regions, $\sim 10^{-2.5}$ for Seyfert 2, and finally $\sim 10^{-3.5}$ for Liners. The second column of Table 3 shows details of the predictions of the Liner model with $U = 10^{-3.5}$.

The upper half of Figure 2 shows the [N II] λ6584/Hα ratio as a function of the [O II] λ3727/[O III] λ5007 ionization indicator. Again, both Seyfert 2 nuclei and Liners lie along a similar line, although a higher metallicity may be indicated. This may indicate that the depletion factor for nitrogen is not as large as for carbon and oxygen, and such a relative enhancement of nitrogen

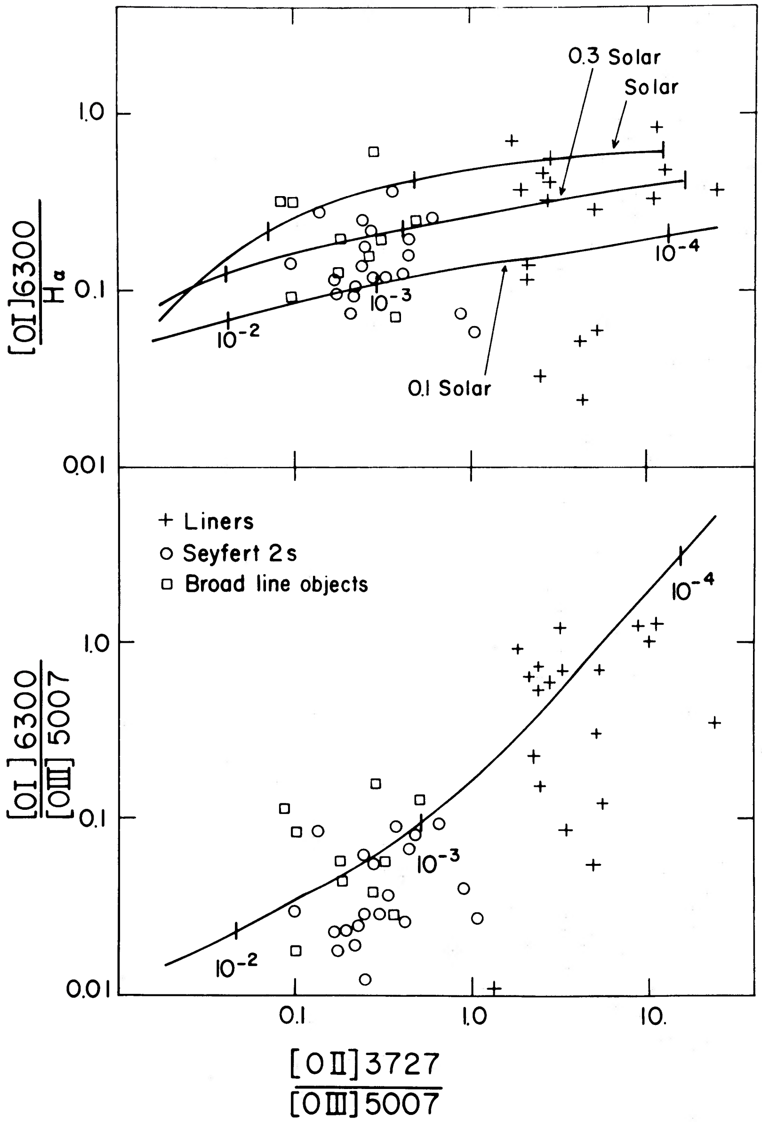

FIG. 3.—As Fig. 2, but different line ratios. All cases from 0.1 solar to solar metal abundances give very similar oxygen line ratios, and are all shown as one curve in the lower half of the diagram.

would be in keeping with the analogy to H II regions (see French 1980). An alternative explanation is suggested by Table 3, which shows that [N I] λ5200 is overpredicted by our models. Both [N II] λ6584 emission and [N I] λ5200 emission are strongly affected by charge exchange, and a smaller rate coefficient would improve the agreement (although the [N I] λ5200 strength may be related to the question of cloud thickness addressed below).

Figure 3 gives the [O I] λ6300/Hα and the [O I] λ6300/[O III] λ5007 ratios. These diagrams show much more scatter because of larger errors in measuring weaker lines, variations in the oxygen abundance (affecting the [O I] λ6300/Hα ratio) and possible differences in the total thickness of the clouds. For nebulae ionized by either a thermal continuum, or a power law with a high energy cutoff, the O^0 lines are largely formed in a well-defined zone, close to the H^+–H^0 ionization front. This is not true of continua with a significant X-ray contribution, because of the deep penetration of high-energy radiation (see, for example, Netzer 1980; Weisheit, Shields, and Tarter 1981). Our calculations were stopped where the electron temperature had fallen below 4000 K and all optical line formation ceased. This occurred at a thickness of $\sim 2 \times 10^{17}$ cm for the model with $U = 10^{-3.5}$. For comparison, the hydrogen half-neutral point occurred at 2×10^{16} cm, by which point essentially all the [O III] λ5007 and [O II] λ3727 emission had been formed, while half the [O I] λ6300 line was formed at a depth greater than 4×10^{16} cm. The fact that our calculations match the upper envelope of observed

TABLE 3

Theoretical Models for Liners

Line	Mean Liner Spectrum[a]	Photoionization[b] $U = 10^{-3.5}$	Shock G[c]	Shock H[c]
[O II] λ3727	5.0	6.4	8.5	5.23
Hγ	0.44	0.47	...	...
[O III] λ4363	≲0.06:	0.025	0.25	0.18
He II λ4686	≲0.08:	0.17	0.12	0.03
Hβ	1.0	1.0	1.0	1.0
[O III] λλ5007+4959	1.9	2.9	7.35	4.1
[N I] λ5200[d]	0.14	0.26	1.7	0.06
He I λ5876	0.11	0.18	0.19	0.15
[O I] λ6300	0.8	0.96	1.8	1.6
Hα	2.8	3.1	2.98	3.06
[N II] λ6584	3.3	1.6	2.96	2.68
[S II] λλ6716+6731	2.3	2.5	3.9	4.62
C II] λ2326	...	1.6	2.36	3.51
C III] λ1909	...	0.37	2.04	2.77
C IV λ1549	...	0.002	8.6	3.13

[a] From Table 1.
[b] 0.3 solar metal abundances.
[c] From Shull and McKee 1979.
[d] From Shuder and Osterbrock 1981, and Koski 1978.
Note.—A colon indicates a highly uncertain value.

points, and that some objects show much weaker [O I] λ6300 than predicted, could indicate that the depth of the warm neutral zone varies from object to object, and that some Liners are effectively matter bounded.

b) Other Lines

Hα/Hβ.—As Table 3 shows, the Hα/Hβ ratio is predicted to be steeper than case B recombination. This is largely the result of collisional excitation from the ground state, which mainly enhances Hα. A_V will be overestimated by ~0.3 mag, and more for a flatter continuum, if only Hα/Hβ is used to deduce the reddening. The collision rate to higher Balmer lines is much smaller, and these lines can be safely used to estimate the reddening. This prediction may explain Heckman's (1980) suspicion that Hα/Hβ is larger than case B in Liners.

[O III] λ4363.—Our model predicts very little [O III] λ4363 emission. It was the strength of this line in NGC 1052 which led Koski and Osterbrock (1976) to first propose shock heating for this object. It is not clear whether this discrepancy is a serious problem since [O III] λ4363 has been seen in only a small fraction of Liners. In our literature search for Liners spectra, we could find only three certain measurements of this line, all with large errors. (See Table 1. We consider the case of NGC 1052 highly uncertain, too; see, for example, Fosbury *et al.* 1978, Fig. 6.) In one of these (Mrk 298) the line indicates low temperature. The observational problem is compounded by the fact that [O III] λ4363 is weak and the continuum underlying the line poorly defined, because of the adjacent Hγ and strong stellar absorption features. Theoretical predictions are uncertain, because the excitation potential is large and the strength a sharp function of the electron temperature, which is affected by both the metallicity and shape of the ionizing continuum. High density is another possibility, but we do not consider it to be the case in Liners emission line gas.

We have also considered the case of charge exchange with hydrogen, $H^0 + O^{+3} \rightarrow H^+ + O^{+2}$, that leaves the O^{+2} in an excited stage, and is followed by cascade via the $^1S_0$ upper level of the 4363 Å line. Although such a transition is likely to occur (Butler, Heil, and Dalgarno 1980), we did not find it important under the temperature and ionization of our model.

He II λ4686.—The strength of this line is predicted by our model to be about a factor of 2 stronger than observed. Here again there are hardly any good enough observations (see Table 1) to decide about the issue. The He II λ4686/Hβ line ratio is determined by both the ionization parameter and the spectral index of the ionizing continuum (Fig. 1). A steeper continuum, or a high frequency turnover, could give a better fit. We note that some shock models also predict too strong He II λ4686 (see below).

He I λ5876.—The intensity of this line, relative to Hβ, increases with decreasing U (Fig. 1). This is because of the overionization of He^0 by high-energy photons (see Shields 1974). Since the [O III] λ5007/Hβ ratio decreases with U, we would predict that objects with exceptionally low [O III] λ5007/Hβ should have the largest He I λ5876/Hβ. This is another difference from shock models, where [O III] λ5007 and He I λ5876 vary together (Shull and McKee 1979). The available observations are not good enough to confirm this.

c) The Ionizing Continuum

The question whether Liners are photoionized is really a question of whether or not an ionizing continuum is present in these objects. Observationally, the situation is unclear. Heckman (1980) noted that, in his Liners, contribution from a featureless continuum does not exceed 10% of the total flux at 3600 Å. On the other hand, several of the Liners in the Koski (1978) and in the Shuder and Osterbrock (1981) samples clearly show a nonthermal component. There are also several Liners with detectable X-ray flux (Heckman 1980; Phillips 1981), which indicate nonstellar nuclear source. Ultraviolet observations are needed to establish whether all Liners form a single group, regarding these properties.

Another way to address the question is by considering the equivalent width of emission lines, since these are easily predicted by photoionization. Yee (1980) and Shuder (1981), drew attention to the point that Seyfert 1, Seyfert 2, and other emission line galaxies show a similar correlation between Balmer line and featureless continuum fluxes. Several of the galaxies they discussed are, in fact, Liners, and this indicates similarity in excitation mechanism to the photoionized Seyfert 1 and 2's.

Assume a power-law continuum, $f_\nu \propto \nu^{-\alpha}$ with no cutoff, $\alpha > 1$, and that each ionizing photon ionizes a hydrogen atom. It is easily shown that the equivalent width of Hβ is given by:

$$W_\lambda(\mathrm{H}\beta) \approx \frac{560}{\alpha}\left(\tfrac{3}{16}\right)^\alpha \text{ Å} . \qquad (2)$$

In our model, $W_\lambda(\mathrm{H}\beta, \alpha = 1.5) = 30$ Å. For comparison, the observed $W_\lambda(\mathrm{H}\beta)$ (considering *all* the continuum inside the aperture used) is typically $\sim$1–3 Å in Heckman's (1980) sample, and $\sim$3–10 Å in Shuder and Osterbrock's (1981) Liners. Clearly, starlight dominates the continuum and the lack of featureless component is no surprise.

Heckman's (1980) has also discussed photoionization by a nonthermal source. He has considered the maximum α capable of producing the observed Hα flux which is still consistent with less than 10% contribution to the flux at 3600 Å. The values he found ranges from 0.67 to 1.63. We have reexamined his data and found that all the objects in Table 1 are consistent with an $\alpha = 1.5$ power law and the observed 3600 Å continuum. Heckman in fact suggested a low ionization parameter as a possible explanation for Liners, but he had no detailed calculations to confirm this.

d) Comparison with Shock Models

Shock wave models have been proposed by Baldwin, Phillips, and Terlevich (1981) and Heckman (1980), as a possible explanation for Liners. Heckman has fitted the preshock and the postshock parameters (density and temperature) of theoretical models (Dopita 1977; Shull and McKee 1979) to the Liners in his samples. He concluded that there is good agreement for some, but others cannot be fitted with any of the models. Fosbury *et al.* (1978) have calculated a model for NGC 1052 and find good agreement with observations.

In order to facilitate comparison with observations we list in Table 3 two such models taken from Shull and McKee (1979). We have chosen this reference since those authors list the calculated intensities of the helium and ultraviolet lines that we consider very important. Cases chosen are G and H of Shull and McKee. Model G has $V(\text{shock}) = 130$ km s^{-1}, $N(\text{preshock}) = 10$ cm^{-3}. Model H has $V(\text{shock}) = 100$ km s^{-1} and $N(\text{preshock}) = 100$ cm^{-3}. Both cases have cosmic abundances.

As seen from the table, both cases give a good fit to the average Liner spectrum. The shock velocity determines the strength of He II λ4686, and for case G it is comparable to the photoionization case. [O III] λ4363/[O III] λ5007 is naturally explained in shock models, where the temperature at the O^{+2} zone is high enough to excite atoms to the $^1S_0$ level. As noted earlier, and discussed also by Heckman (1980), shock models cannot explain the observed Hα/Hβ, while photoionization can. Judging by emission lines only, it seems that the question of photoionization or shock waves depends on the observations of several weak lines (He II λ4686/He I λ5876, [O III] λ4363) and reddening-sensitive line ratios (Hα/Hβ/Hγ).

The case of NGC 1052, although may not be a typical Liner, is of special interest. Fosbury *et al.* (1978) have fitted its optical spectrum with a $V_{\text{shock}} = 130$ km s^{-1} shock model. This should give strong He II λ4686 and He I λ5876, but both lines are not observed. Recent *IUE* observations (Fosbury *et al.* 1981) show the ultraviolet continuum of the galaxy to be too weak, for any nonthermal continuum that can excite the observed Balmer lines. In addition, the emission lines observed, C II] λ2326 and C III] λ1909, are much weaker than calculated by shock models, and C IV λ1549, which is predicted to be very strong (Shull and McKee 1979 models G or H), is not observed at all. We are far from understanding this source.

e) Emission-Line Zone: Size and Dynamics

The physical dimension of the emission line zone can be estimated from Balmer line luminosities. From Heckman (1980), $L(\mathrm{H}\alpha) \approx 10^{39.5-41.5}$ ergs s^{-1} for Liners. Assuming a mean value of $10^{40.5}$ ergs s^{-1}, we found the corresponding number of ionizing photons to be $\sim 2 \times 10^{52}$ s^{-1}. Full coverage and no dust extinction are assumed. Combined with our best value of $U = 10^{-3.5}$ we found:

$$r \approx 130 \text{ pc}\left(\frac{N_e}{10^3 \text{ cm}^{-3}}\right)^{-1/2} , \qquad (3)$$

comparable to narrow line region size in Seyferts. The observed size (determined by the aperture used) is, typically, several hundred parsecs across.

Shuder and Osterbrock (1981) found that Liners tend to have line widths smaller than Seyfert 2's, by a factor of 2–3. It is tempting to associate this difference in velocity to a difference in depth of potential wells at the various narrow-line region radii. If the radii are indeed comparable, it follows that the central mass of Liners is $\sim(V_{\rm Liners}/V_{\rm Seyferts})^2 \sim 4$–10 times smaller than for Seyfert 2's. This factor is of the order of the difference in line luminosity between the two classes of objects, and may suggest a constant mass/luminosity ratio for all of them. The central mass deduced for Liners, assuming $N_e = 10^3$ cm^{-3}, $V = 100$ km s^{-1}, and a gravitationally bound system, is $\sim 10^8\ M_\odot$.

V. CONCLUSIONS

We have looked at the spectroscopic data available for Liners and other active nuclei, and examined the two major excitation mechanism proposed to explain them. We computed photoionization models for low ionization-parameter cases, and compared them with observed spectra. We have determined the following:

a) Photoionization by a nonthermal source can explain the observed spectra of all active nuclei. There is a continuous sequence of decreasing ionization parameter from broad line objects to Seyfert 2's and to Liners. Line ratios, such as [O II] λ3727/[O III] λ5007, [O III] λ5007/Hβ, [O I] λ6300/Hα, etc., vary smoothly from one class of objects to the next, and there is no need to introduce shock heating to explain them.

b) Several weak lines, especially [O III] λ4363, He II λ4686, and He I λ5876, provide crucial tests for distinguishing between photoionization and shock heated models. At present, measurements of these lines are not good enough to decide one way or the other.

c) The nonthermal ionizing continuum seen in several Liners, and its absence in others, is entirely consistent with observed line fluxes. Its presence, if confirmed by ultraviolet observations, will be a conclusive argument in favor of photoionization. Line width and emission zone size are consistent with the continuum strength.

In summary, the observational evidence, although not conclusive, is at least consistent with the view that Liners and Seyfert nuclei are the same phenomenon, but on a different scale. Liners may indeed by Lipners (low ionization parameter nuclear emission-line regions).

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REFERENCES

Baldwin, J. A. 1975, *Ap. J.*, **201**, 26.
Baldwin, J. A., and Netzer, H. 1978, *Ap. J.*, **266**, 1.
Baldwin, J. A., Phillips, M. M., and Terlevich, R. 1981, *Pub. A.S.P.*, **93**, 5 (BPT).
Boksenberg, A., and Netzer, H. 1977, *Ap. J.*, **212**, 37.
Butler, S. E., Heil, T. G., and Dalgarno, A. 1980, *Ap. J.*, **241**, 442.
Chambaud, G., Launay, J. M., Levy, B., Millie, P., Roueff, E., and Maink, F. T. 1981, *J. Phys. B*, **13**, 4205.
Costero, R., and Osterbrock, D. E. 1977, *Ap. J.*, **211**, 675.
Davidson, K. 1972, *Ap. J.*, **171**, 213.
Davidson, K., and Netzer, H. 1979, *Rev. Mod. Phys.*, **51**, 715.
Dopita, M. A. 1977, *Ap. J. Suppl.*, **33**, 437.
Drake, S. A., and Ulrich, R. K. 1980, *Ap. J. Suppl.*, **42**, 351.
Ferland, G. J., and Truran, J. W. 1981, *Ap. J.*, **244**, 1022.
Fosbury, R. A. E., Mebold, U., Goss, W. M., and Dopita, M. A. 1978, *M.N.R.A.S.*, **183**, 549.
Fosbury, R. A. E., Snijders, M. A. J., Boksenberg, A., and Penston, M. V. 1981, *M.N.R.A.S.*, **197**, 235.
French, H. B. 1980, *Ap. J.*, **240**, 41.
Grandi, S. A., and Osterbrock, D. E. 1978, *Ap. J.*, **220**, 783.
Halpern, J. P., and Grindlay, J. E. 1980, *Ap. J.*, **242**, 1041.
Heckman, T. M. 1980, *Astr. Ap.*, **87**, 152.
Heckman, T. M., Balick, B., and Crane, P. C. 1980, *Astr. Ap. Suppl.*, **40**, 295.
Koski, A. T. 1978, *Ap. J.*, **223**, 56.
Koski, A. T., and Osterbrock, D. E. 1976, *Ap. J. (Letters)*, **203**, L49.
Kwan, J., and Krolik, J. H. 1981, *Ap. J.*, **250**, 478.
Lambert, D. C. 1978, *M.N.R.A.S.*, **182**, 249.
Lambert, D. C., and Luck, R. E. 1978, *M.N.R.A.S.*, **183**, 79.
Netzer, H. 1977, *M.N.R.A.S.*, **178**, 489.
———. 1980, *Ap. J.*, **236**, 406.
———. 1982, *M.N.R.A.S.*, in press.
Netzer, H., Wills, B. J., and Wills, D. 1982, *Ap. J.*, **254**, 489.
Osterbrock, D. E. 1977, *Ap. J.*, **215**, 733.
Osterbrock, D. E., and Koski, A. T. 1976, *M.N.R.A.S.*, **176**, 61.
Osterbrock, D. E., and Shuder, J. M. 1982, *Ap. J. Suppl.*, **49**, 149.
Phillips, M. M. 1981, *M.N.R.A.S.*, **197**, 659.
Shuder, J. M. 1981, *Ap. J.*, **244**, 12.
———. 1982, *Ap. J.*, **259**, 48.
Shuder, J. M., and MacAlpine, G. M. 1979, *Ap. J.*, **230**, 348.
Shuder, J. M., and Osterbrock, D. E. 1981, *Ap. J.*, **250**, 55.
Shull, J. M., and McKee, C. F. 1979, *Ap. J.*, **227**, 131.
Shields, G. A. 1974, *Ap. J.*, **191**, 309.
Weedman, D. W. 1977, *Ann. Rev. Astr. Ap.*, **15**, 69.
Weisheit, J. C., Shields, G. A., and Tarter, C. B. 1981, *Ap. J.*, **245**, 406.
Yee, H. K. C. 1980, *Ap. J.*, **241**, 894.

Note added in proof.—Rose and Searle (1982, *Ap. J.*, **253**, 556) have reached a conclusion similar to ours regarding the excitation mechanism for M51, while Halpern and Steiner (1983, *Ap. J.*, submitted) have come to a similar conclusion for a sample of Liners.

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