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O-STAR PHOTOIONIZATION MODELS OF LINERS WITH WEAK [O I] λ6300 EMISSION

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ABSTRACT

Low-ionization nuclear emission-line regions (LINERs), defined by the criteria [O II] λ3727/[O III] λ5007 ≥ 1 and [O I] λ6300/[O III] λ5007 $\geq \frac{1}{3}$, are generally thought to be related to classical active galactic nuclei powered by nonstellar continua. Based on the results of new photoionization models, however, we suggest that those genuine LINERs having *weak* [O I] λ6300 emission (i.e., [O I]/H$\alpha \lesssim \frac{1}{6}$) may instead be powered by hot ($T_{\rm eff} \gtrsim 45{,}000$ K) main-sequence O stars irradiating solar-metallicity clouds of gas. The derived ionization parameter (U) is in the range $10^{-3.7}$ to $10^{-3.3}$, a factor of $\sim$20 lower than in normal H II regions. Very high [N II]/Hα ratios sometimes observed in LINERs may require a selective enhancement of nitrogen above the solar value. The presence of unusually hot stars (spectral type O3–O4) in such high-metallicity environments, together with low values of U, may be a natural consequence of the high gas densities, pressures, and masses in galactic nuclei. We also find that many weak-[O I] "LINERs" in the literature are not genuine LINERs, since they do not satisfy the [O I]/[O III] criterion; they were classified as LINERs only on the basis of their [O II]/[O III] or [N II] λ6583/Hα intensity ratios. These objects can easily be explained with our O-star photoionization models by increasing U up to $\sim 10^{-3}$.

Subject headings: galaxies: abundances — galaxies: active — galaxies: interstellar matter — galaxies: nuclei — H II regions

1. INTRODUCTION

Over a decade ago Heckman (1980, hereafter H80) described a class of galactic nuclei whose optical spectra are quite distinct from those of both H II regions and active galactic nuclei (AGNs). These objects, dubbed "low-ionization nuclear emission-line regions" (LINERs), are characterized by narrow emission lines of relatively low ionization. Specifically, membership in this class was *defined* by only two line intensity ratios, which we call the "H80 criteria": [O II] λ3727/[O III] λ5007 ≥ 1, and [O I] λ6300/[O III] λ5007 $\geq \frac{1}{3}$.[2]

By contrast, (1) H II regions exhibit prominent [O II] λ3727 and/or [O III] λ5007 emission (depending on the metallicity), but [O I] λ6300 is extremely weak due to the small volume of the transition zone between neutral and ionized hydrogen; and (2) the narrow-line regions (NLRs) of Seyfert nuclei have substantial [O I] and [O II] emission, but they are dominated by the very strong [O III] line. It was noted that unambiguous LINERs, such as NGC 1052, have [N II] λ6583/H$\alpha \gtrsim 0.6$. Thus, the [N II]/Hα ratio has often been adopted to readily distinguish LINERs from H II regions, which are characterized by [N II] λ6583/H$\alpha \lesssim 0.6$, although one must remember that it is *not* part of the original definition (H80).

Spectroscopic surveys of nearby galaxies showed that LINERs are very common; H80 (see also Heckman, Balick, & Crane 1980) estimated that over one-third of all spiral galaxies are LINERs. H80, as well as the extensive samples published by Stauffer (1982), Keel (1983a, b), Filippenko & Sargent (1985, hereafter FS85), Véron-Cetty & Véron (1986), and Phillips et al. (1986), demonstrated that LINERs are especially numerous among ellipticals and early-type spirals—perhaps 80% of Sa galaxies, and over 40% of Sb galaxies, are LINERs. Although the emission-line gas in a majority of LINERs is concentrated near the nucleus ($r \lesssim 200$ pc), in some cases (e.g., cooling-flow galaxies, starburst-driven winds) it extends over much larger regions. Thus, LINERs almost certainly constitute a very heterogeneous class (Heckman 1987; Filippenko 1989), but in this paper we address only those confined to galactic *nuclei.*

Based on the spectroscopic resemblance between LINERs and supernova remnants, as well as on high electron temperatures (T_e) derived from the [O III] λ4363/[O III] λ5007 ratio, several early studies concluded that the emission lines in LINERs are produced by shock-heated gas (Koski & Osterbrock 1976; Fosbury et al. 1978; H80). In fact, Baldwin, Phillips, & Terlevich (1981, hereafter BPT) used the line intensity ratios observed in LINERs to *define* the region populated by "shock-heated galaxies" in their two-dimensional classification schemes (see also Veilleux & Osterbrock 1987). However, the apparent continuity of LINERs and Seyfert galaxies in the BPT diagrams, together with the discovery of significant X-ray emission in some LINERs, soon led to the development of power-law photoionization models of LINERs (Ferland & Netzer 1983; Halpern & Steiner 1983). In this view, LINERs are genuine AGNs, powered by accretion onto a compact object, but with a low ionization parameter U (ratio of ionizing photons to nucleons at the face of a gas cloud). The discovery of a wide range of densities ($n_e = 10^2$ to 10^7 cm^{-3}) in the NLRs of a few well-studied LINERs removed some of the remaining problems with this hypothesis (Filippenko & Halpern 1984; Filippenko 1985). Moreover, the presence of very broad Hα emission (full-width near zero intensity $\gtrsim 5000$ km s^{-1}) in some LINERs provided additional evidence for a continuity with Seyfert nuclei (Stauffer (1982; Keel 1983a; FS85).

[1] Presidential Young Investigator.
[2] Ideally the line ratios should be corrected for reddening, but in practice these criteria are often more loosely applied to observed spectra. Note that [O II] λ3727 is used to designate the [O II] $\lambda\lambda$3726, 3729 *doublet*, while [O III] λ5007 and [O I] λ6300 refer to *single lines.*

An alternative, however, is that the ionizing continuum in LINERs is produced by very hot, luminous WC and WO (Wolf-Rayet) stars which Terlevich & Melnick (1985) call "Warmers." A vigorous starburst in the high-metallicity nuclear region of a galaxy would produce a collection of such stars after a few million years, and their effective continuum would resemble a power law, $f_\nu \propto \nu^{-1.5}$. Terlevich & Melnick (1985) show that the resulting emission-line spectrum should resemble those of Seyfert 2 galaxies or LINERs, depending on the number of hot stars and the age of the central cluster. Although this hypothesis may be successful in some respects (e.g., Filippenko 1992b), the nearly ubiquitous presence of LINERs implies that the nuclei of *most* early-type galaxies are in a poststarburst evolutionary phase where very hot Wolf-Rayet stars dominate the Lyman continuum. Such conditions are highly unlikely; moreover, we have not identified the *precursor* early-type galactic nuclei whose spectra are dominated by relatively normal H II regions.

On the other hand, suppose it is possible that many LINERs do *not* need extreme Wolf-Rayet stars to power their emission. If a few early-O stars ($M \gtrsim 40\ M_\odot$) embedded in metal-rich gas suffice to produce the measured intensity ratios and luminosities of the emission lines, the problematic aspects of the stellar photoionization hypothesis are eliminated without sacrificing its attractive features. In this *Letter* we show that the emission seen in a significant fraction of galactic nuclei can indeed be explained in terms of solar metallicity H II regions. Preliminary results have been discussed by Filippenko (1992a).

2. LINERS WITH WEAK [O I] λ6300 EMISSION

We have already noted that LINERs were found to be extremely common in large spectroscopic surveys of nearby galaxies conducted during the early to mid-1980s. Most of the objects, however, have weak emission lines, and it was not possible to tell whether the galaxies are genuine LINERs in terms of the two defining oxygen line ratios (H80). Instead, the classification was *generally* based only on the value of [N II] λ6583/Hα; both lines are often visible, partly because the extinction is smaller than at blue wavelengths, and they occur in a sensitive region of typical solid-state detectors. More rarely, only the value of [O II] λ3727/[O III] λ5007 was used. In addition, some theoretical studies (e.g., Ferland & Netzer 1983) made comparisons with LINERs that did not always satisfy both of the H80 criteria, even when the emission lines were quite strong. Thus, objects referred to as "LINERs" in the literature are frequently unconfirmed LINERs, or are not genuine LINERs. It is quite possible that they are not all powered by the same mechanism.

Close inspection of the moderate-resolution, high signal-to-noise ratio spectra around Hα (6200–6880 Å) published by FS85 reveals that LINERs identified only by their large [N II] λ6583/Hα ratio actually come in two basic varieties. One set is characterized by prominent [O I] λ6300 emission (e.g., NGC 4438 and NGC 4579 in Fig. 6 of FS85); it is probable that [O I] λ6300/[O III] λ5007 $\geq \frac{1}{3}$ in most of these objects. The other set, by contrast, has quite weak [O I] λ6300 emission (e.g., NGC 4501 and NGC 4569 in Fig. 6 of FS85). We shall adopt an intensity ratio of [O I] λ6300/Hα = $\frac{1}{6}$ (i.e., log [O I]/Hα = −0.78) as the dividing line between "weak-[O I] LINERs" and "strong-[O I] LINERs."[3] A survey of the literature (e.g., H80; Stauffer 1982; Keel 1983a; FS85) suggests that at least one-quarter of all LINERs may fall in the weak-[O I] category. Based on published line ratios, we know that some of the weak-[O I] LINERs *do* satisfy the H80 criteria for a genuine LINER—but most of them do not. The latter objects were called LINERs by FS85 only because of their high [N II] λ6583/Hα ratio.

Here we postulate that the weak-[O I] LINERs owe their emission lines to solar metallicity gas irradiated by the ionizing continuum from early O-type main-sequence stars, with a considerably lower ionization parameter than in typical H II regions. A very large number of high-energy photons (as provided, e.g., by power-law continua or by Warmers) is unnecessary, given the weakness of [O I] λ6300; the partially ionized zone need not be extensive. In the next section we explore this idea by presenting theoretical models of metal-rich gas photoionized by the continuum from a hot O star.

3. RESULTS OF PHOTOIONIZATION MODELS

Our immediate goal is to determine whether, under certain circumstances, the emission-line spectrum of gas photoionized by the continuum of an O-type star can resemble that of weak-[O I] LINERs. In other words, can "H II regions" sometimes produce LINER-like relative line intensities? Careful inspection of the theoretical diagnostic diagrams published by Evans & Dopita (1985) suggests that this is indeed the case. We further pursue this question by running grids of photoionization models with CLOUDY (Ferland 1991), and by comparing the results with the observed line ratios in LINERs. Ionization parameters lower than the smallest values (−3.5) considered by Evans & Dopita (1985) are emphasized.

To mimic the conditions in typical LINERs, we adopt an electron density of 10^3 cm^{-3}. Given the high metallicities seen in the nuclei of early-type galaxies (e.g., Pagel & Edmunds 1981), we try two sets of parameters: (1) solar abundances, and (2) 1.4 times solar abundances, except nitrogen which is 4 times solar. The latter set is quite arbitrary; it is used only to identify trends with metallicity in the emission-line intensity ratios, and to reproduce the very high values (2–6) of [N II] λ6583/Hα seen in some LINERs (e.g., FS85). Kurucz (1979) model continua are used, although the adoption of Mihalas (1972) continua and slightly lower ionization parameters was shown to give similar results. To increase the strength of [O I] emission, a stellar effective temperature of 45,000 K is assumed for the main-sequence O stars. This corresponds to spectral type O4, hotter than in most models of high-metallicity H II regions (e.g., McCall, Rybski, & Shields 1985; McGaugh 1991). However, the apparent inverse correlation between abundance and stellar effective temperature might not always prevail in H II regions; we surmise that the high gas densities, pressures, and masses in galactic nuclei preferentially favor the formation of giant H II regions having very hot stars.

Our results are illustrated in Figure 1, for log $U = -4$ to -3, using several different BPT diagrams. In regions of overlap (log $U \gtrsim -3.5$) they are consistent with the predictions of Evans & Dopita (1985). Portions of the diagrams occupied by normal H II regions were determined from Galactic and extragalactic H II regions, most of which have relatively low metallicity. The areas populated by LINERs were determined by objects that satisfy *both* of the H80 criteria; these classical LINERs generally, but not always, also have a high [O I] λ6300/Hα ratio. The weak-[O I] LINERs described in § 2, on the other hand, have considerably lower values of [O I]

[3] In this definition, only the *narrow* component of Hα is included, even if there exists an additional component that is broader than the forbidden lines.

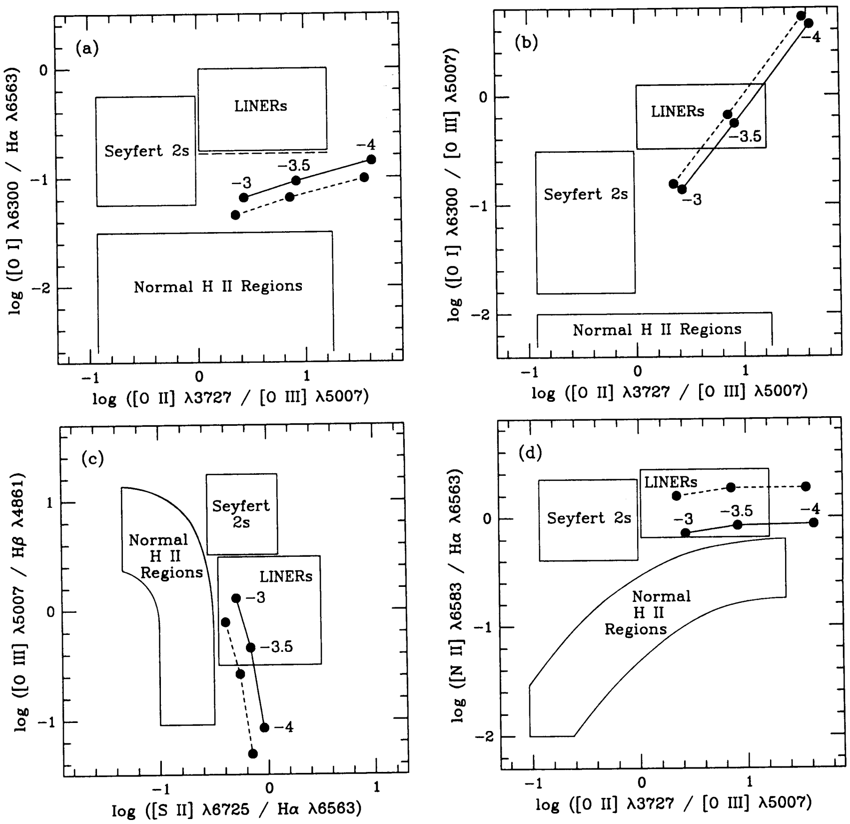

FIG. 1.—BPT diagrams used to classify different types of emission-line galaxies, adapted from Shields & Filippenko (1990). Typical loci of ratio combinations for normal H II regions, Seyfert 2 galaxies (and the NLRs of type 1 Seyfert galaxies), and classical LINERs are shown. Results of O-star photoionization models are marked as line segments joining the points at log $U = -4$, -3.5, and -3; solar (*solid*) and above-solar (*dashed; see text*) metallicities are assumed. "Weak [O I] LINERs" are defined to be objects whose [O I]/Hα ratio is below the long-dashed line in (*a*), but with [N II] λ6583/Hα $\gtrsim 0.6$. In (*c*), [S II] λ6725 denotes the [S II] λλ6716, 6731 doublet.

λ6300/Hα, even if they *do* satisfy both of the H80 criteria. Thus in Figure 1*a* [which shows log ([O I] λ6300/Hα λ6563) versus log ([O II] λ3727/[O III] λ5007)] we see that the locus of points produced by our O-star photoionization models corresponds very well to what we have *defined* as "weak-[O I] LINERs" (log [O I]/Hα $\lesssim -0.78$), especially for solar metallicities. Had we chosen a significantly lower stellar effective temperature (~40,000 K) and higher ionization parameter (-2 to -3), the models would have entered the area occupied by normal high-metallicity H II regions, as expected from previous photoionization modeling of H II regions.

Figure 1*b* plots log ([O I] λ6300/[O III] λ5007) versus log ([O II] λ3727/[O III] λ5007)—the diagram that essentially *defines* LINERs according to the two H80 criteria. We see that the O-star photoionization models are able to reproduce the line ratios of *genuine* LINERs for log $U \approx -3.7$ to -3.3, even though their [O I] λ6300/Hα ratio is smaller than average (i.e., they are weak-[O I] LINERs). Unusual LINERs having exceptionally large [O I]/[O III] and [O II]/[O III] can be explained with log $U \lesssim -4$. Objects with log $U \gtrsim -3.3$ have too low [O I] λ6300/[O III] λ5007 to formally satisfy one of the H80 criteria; however, it is quite possible that many weak-[O I] LINERs fall in this range. Values of log $U \approx -2.5$ to -2 would have intersected areas populated by Seyfert 2 nuclei and high-excitation H II regions. This particular BPT diagram is the least dependent on metallicity, as expected.

The results of the O-star photoionization models are also in good agreement with the observed positions of LINERs in the log ([O III] λ5007/Hβ λ4861) versus log ([S II] λ6725/Hα λ6563) BPT diagram (Fig. 1*c*), for solar metallicities and log $U \approx -3.6$ to -3. The models with above-solar metallicities give line ratios that still resemble those of LINERs, but they are closer to the area occupied by normal H II regions. An increase in the metals allows the nebula to cool more efficiently, resulting in a lower T_e and a shift of the dominant coolants to the infrared fine-structure lines. Similarly, larger values of log U produce high-excitation H II regions rather than LINERs.

Figure 1*d* shows the log ([N II] λ6583/Hα) versus log ([O II] λ3727/[O III] λ5007) ratio. Once again, the stellar photoionization models do indeed reproduce the observed positions of LINERs, with log $U \approx -3.7$ to -3. However, this is the only BPT diagram in which the models with above-solar metallicities provide better agreement for typical objects than the solar-metallicity models. It appears that one needs a *selective enhancement* of nitrogen, with roughly solar metallicities for the other elements. This might be possible in the nuclei of galaxies through pollution by massive stars (e.g., Cid Fernandes et al. 1992). It is interesting that Hamann & Ferland (1992) recently suggested an even larger enhancement of nitrogen to explain the emission-line intensity ratios of high-redshift quasars.

4. DISCUSSION

The above results demonstrate that it is possible to explain the major emission-line intensity ratios in "weak-[O I]

LINERs" ([O I] λ6300/Hα $\lesssim \frac{1}{6}$) with O-star ($T_{\rm eff} \gtrsim 45{,}000$ K) photoionization models having a low ionization parameter (log $U \approx -3.7$ to -3). Only a few dozen early-O stars (O3–O4; $M \gtrsim 40\ M_\odot$) are required to produce a typical observed Hβ luminosity of 10^{38} ergs $\rm s^{-1}$. Roughly solar abundances give the best overall fit to the observations, although selective enhancement of nitrogen may be necessary to explain the highest values of [N II] λ6583/Hα. The line ratios produced by the models always meet the H80 criterion that [O II] λ3727/[O III] λ5007 ≥ 1; for a restricted range of ionization parameters (log $U \approx -3.7$ to -3.3) even the second H80 criterion ([O I] λ6300/[O III] λ5007 ≥ $\frac{1}{3}$) is satisfied. Some genuine LINERs, and perhaps many LINER-like objects with high [O II] λ3727/[O III] λ5007 and/or high [N II] λ6583/Hα, could therefore owe their emission lines to O-type stars in their nuclei. If so, these objects should *not* be classified as "AGNs" powered by accretion onto a compact object such as a black hole.

What about the LINERs with strong [O I] λ6300 emission? Many of these could be genuine AGNs, especially those which show a very broad component of Hα as in type 1 Seyfert nuclei; the O-star photoionization models considered in this *Letter* do not produce high [O I] λ6300/Hα ratios (Fig. 1*a*). On the other hand, it is quite possible that the [O I] λ6300 line will become sufficiently enhanced if the models incorporate a *range* of densities in the NLR, as was the case with power-law photoionization models. This idea is further explored by Shields (1992). Of course, LINERs exhibiting weak He II λ4686 or [Ne V] λ3426 in their spectra (e.g., Filippenko 1985) cannot be powered predominantly by O stars; either a nonstellar continuum, or radiation from very hot Wolf-Rayet stars, appears to be necessary. Thus, the case is not yet settled for strong-[O I] LINERs, but Ho, Filippenko, & Sargent (1992) will further address this question using high-quality optical spectra over the range 3400–9900 Å.

The major implication of our study is that the relatively metal-rich nuclei of early-type galaxies may indeed contain O-type main-sequence stars, and that the "H II regions" produced by them have emission-line intensity ratios typical of weak-[O I] LINERs. These objects have previously not been recognized as H II regions because their observed line ratios differ from those of published Galactic and extragalactic H II regions. However, it is important to remember that the observed line ratios in weak-[O I] LINERs require higher stellar effective temperatures ($T_{\rm eff} \gtrsim 45{,}000$ K) than are normally believed to be present in solar-metallicity H II regions ($T_{\rm eff} \lesssim 40{,}000$ K). In addition, the ionization parameters are a factor of ~20 lower than in typical H II regions. Such conditions may be the natural consequence of the generally higher gas densities, pressures, and masses in galactic nuclei than in extranuclear H II regions. This would also be consistent with the observed absence of LINER-like H II regions in the extranuclear parts of galaxies.

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