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A DUTY CYCLE HYPOTHESIS FOR THE CENTRAL ENGINES OF LINERs

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ABSTRACT

A recent ultraviolet snapshot imaging survey of the nuclei of nearby galaxies detected a compact nuclear ultraviolet source in only five of the 26 LINERs (low-ionization nuclear emission-line regions) included in the observed sample. Motivated by this observational result, we examine the possibility that *all* LINERs are powered by photoionization from a nuclear source, which is, however, active only for 20% of the time. We show that the decay times of low-ionization species can be of the order of one to a few centuries, and we demonstrate through time-dependent photoionization calculations that if the nuclear ionizing source is active for only a fraction of the time, this would not be readily noticeable in the emission-line spectrum. We suggest that the activity cycle is related to episodic accretion events which are associated with the tidal disruption of stars by a central black hole. The time interval between tidal disruptions is of the same order as the emission-line decay time, with the accretion episode following each disruption lasting a few decades. These estimates appear to support the duty cycle hypothesis. Some observational consequences of the proposed scenario are also discussed.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: nuclei — line: formation

1. INTRODUCTION

Low-ionization nuclear emission-line regions (LINERs) are thought to be examples of low-level nuclear activity, analogous to that observed in Seyfert galaxies. They were identified as a class by Heckman (1980) and were shown to be very common in nearby galaxies (Stauffer 1982; Keel 1983; Filippenko & Sargent 1985). Their defining spectroscopic characteristic is the exceptional strength of their low-ionization lines (Hα, Hβ, [N II] $\lambda\lambda$6548, 6583, [S II] $\lambda\lambda$6717, 6731, [O I] λ6300, [O II] λ3727) relative to the high-ionization lines. The excitation mechanism of the lines, and by extension the very nature of LINERs, has been the subject of considerable debate (see, for example, the reviews by Keel 1985; Heckman 1987; Filippenko 1989). Excitation by shocks was the original suggestion put forth by Heckman (1980). This was later followed by the proposal that the observed spectra are the result of photoionization of circumnuclear gas either by a weak UV continuum with a power-law spectrum (Ferland & Netzer 1983) or by X-rays (Halpern & Steiner 1983). Photoionization is currently favored over shocks as the excitation mechanism in LINERs (see, for example, the recent work by Ho, Filippenko, & Sargent 1993), but at the same time it is also recognized that there could be substantial heterogeneity within the class.

A relatively clean signature of photoionization is the presence of a compact nuclear UV source. Unfortunately, X-ray observations cannot be relied upon to provide unambiguous information about the presence of a nuclear ionizing source in LINERs, although the observed X-ray spectra are very suggestive of this (e.g., Halpern & Steiner 1983; Fabbiano, Kim, & Trinchieri 1992; Reichert 1994; Petre et al. 1993; Serlemitsos 1994). Thus, the detection of a compact, nuclear UV source in most LINERs could provide strong support for the photoionization scenario. To this end, in an extensive recent effort, Maoz et al. (1995) undertook a snapshot imaging survey of nearby, galactic nuclei with the *Hubble Space Telescope* (*HST*) in search of low-luminosity nuclear activity. As part of the survey, they obtained UV images of a complete sample of 110 objects in a bandpass centered on 2300 Å, which excludes most starlight from the host galaxy, and makes any compact, nuclear, nonstellar continuum sources easily detectable. *Of the 26 LINERs included in the observed sample, only five were detected.* A comparison of the optical spectral properties of the UV-bright and UV-dark LINERs did not show any significant differences, which prompted the authors to suggest that obscuration by dust along the line of sight may conceal the UV source in 80% of the LINERs. They also drew attention to an alternative interpretation that only 20% of LINERs are powered by photoionization, while some other mechanism is responsible for powering the other 80%. Alternative excitation mechanisms, consistent with the absence of a compact UV source, may include shocks (e.g., Heckman 1980), or photoionization by old stars (e.g., Binette et al. 1994). While we consider these two interpretations quite plausible, we investigate in this Letter a third (admittedly more speculative but, in our view, more interesting) possibility for the absence of a compact UV source in the majority of LINERs. Namely, *we examine the hypothesis that all LINERs are powered by photoionization but that the source of ionizing radiation is active for only* 20% *of the time.*

2. THE DUTY CYCLE HYPOTHESIS

The hypothesis we examine in this section is that the observed line emission from LINERs is driven by photoionization from a source which is *not* "on" all the time. Taken at face value, the results of Maoz et al. (1994) suggest that the duty cycle of the ionizing source (i.e., the fraction of the time during which the source is in the active state) is 20%. We first address the question of what happens to the emission-line spectrum during the low state of the ionizing source, first, by estimating the timescales for the relevant atomic processes, and then by carrying out time-dependent photoionization calculations. For the emission-line gas, the relevant timescales for investigating departures from equilibrium are the recombination and the cooling timescales. In Table 1 we list the decay times (i.e., the

TABLE 1

EMISSIVITY DECAY TIMES AT $n_H = 500$ cm^{-3}

Ion and Transition	Decay Time (yr)
H I λ4861	274
He I λ5876	294
He II λ4686	47
[N II] λ6583	31
[O I] λ6300	62
[O II] λ3727	26
[O III] λ5007	4
[S II] λ6731	112
[S III] λ9531	30
[Ne III] λ3869	13

e-folding times) of important lines after the ionizing source turns off abruptly. The estimates were made following the prescription of Binette & Robinson (1987, hereafter BR87), and assuming a density of $n_H = 500$ cm^{-3}. The decay time is dominated by the fastest of the following three processes: electronic recombination, charge transfer with H I, and temperature decay. Different ions are characterized by different recombination rates and, at near solar metallicity, the cooling timescale of nebular gas is typically an order of magnitude shorter that the recombination timescale of H II (BR87). For some ions, such as O III, the recombination timescale is dominated by recombination charge transfer as shown by BR87. From these simple estimates, we see that the [O III] emission from a single cloud decays in less than 4 yr while the Hβ emission persists for 280 yr.

Since high-excitation lines like [O III] may recuperate enough during the high states to compensate for their decay at low states, we must average the spectrum over a complete cycle to evaluate the long-term effects of a quasi-periodic source on the line ratios. Averaging is also essential to allow for light-travel time effects. In effect, even though the spectrum of each photoionized cloud does vary on short timescales, light-travel time effects across the whole line-emitting region dominate (assuming a nearly spherical cloud distribution over a region 200 lt-yr across), and effectively smooth out all temporal or spatial variations of the lines for a distant observer. For a perfectly periodic source, this averaging over a full duty cycle effectively replaces the need for detailed geometrical modeling of the light-travel time effects across the line-emitting region as a whole.

To make a quantitative assessment of the plausibility of the duty cycle hypothesis, we have used the time-dependent photoionization code MAPPINGS (BR87) to calculate the temporal variation of the emission lines for an ionization-bounded cloud which is exposed to a source which undergoes a periodic high and low ionizing output. The energy distribution corresponds to a power law of index $\alpha = -1.5$ (where $f_\nu \propto \nu^\alpha$). We assume an on-the-spot approximation for H and He and solar abundances of metals. The ionization parameter U (the ratio of ionizing photon density to gas density) for the high and low states was set to be 4.5×10^{-4} and 10^{-5}, respectively which implies a mean value of $\bar{U} = 10^{-4}$ across a full period of duty cycle 20%. The period, Π, of the UV source was set to 43 yr. This period was chosen to be in the range expected for the recurrence times of accretion events (see § 3), and it allows us to span a dynamic range of 100 in the ratio of Π to the recombination time for H II (see Table 2). The time between models was selected according to the rate of change of the ionization level (20 time steps per cycle). Correlations between the velocity width and the critical density of forbidden emission lines found in several objects (Filippenko & Halpern 1984; Filippenko 1985; Filippenko & Sargent 1986; Ho et al. 1993) suggest that the line-emitting regions of LINERs are strongly stratified in density. We have therefore carried out calculations for various cloud densities between 3×10^2 cm^{-3} and 3×10^4 cm^{-3} but all with the same range in U (implying that denser clouds would be proportionally closer to the ionizing source). The low density limit is representative of the value inferred from the [S II] doublet in LINERs (see Fig. 5 of Binette 1985). The

TABLE 2

LINE RATIOS AVERAGED OVER A FULL CYCLE

ION AND TRANSITION	MODELS[a]							
$\Pi/\tau^{\rm H}_{\rm rec}$ =	Equilibrium	Equilibrium	0.1	0.3	1.0	3.0	10.0	
$n_{\rm H}$ (cm^{-3}) =	10^3	10^4	3×10^2	10^3	3×10^3	10^4	3×10^4	NGC 1167[b]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Hα λ6563	2.96	2.96	2.98	3.07	3.24	3.27	3.17	2.49:
Hβ λ4861	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
He I λ5876	0.19	0.18	0.20	0.21	0.20	0.18	0.17	0.12
He II λ4686	0.13	0.12	0.13	0.12	0.12	0.15	0.18	...
[O I] λ6300	2.6	3.0	2.4	2.3	2.3	2.2	2.3	0.94
[O II] λ3727	7.4	4.9	6.9	6.0	4.0	2.6	1.8	6.6
[O II] λ7325	0.16	0.45	0.10	0.16	0.20	0.28	0.47	0.18
[O III] λ5007	0.33	0.43	0.36	0.84	1.4	2.2	3.2	2.8
[O III] λ4363	0.00096	0.0016	0.0015	0.0065	0.0099	0.011	0.018	0.025:
[N II] λ6583	4.1	4.3	3.5	2.9	2.3	2.2	2.4	5.1
[S II] λ4073	0.34	0.45	0.26	0.27	0.28	0.35	0.53	0.29
[S II] λ6731	3.2	3.2	2.9	2.9	2.7	2.5	2.1	2.0
[S II] λ6716	3.7	2.5	3.9	3.4	2.8	2.1	1.4	2.0
[Ne III] λ3869	0.28	0.36	0.24	0.31	0.34	0.39	0.54	0.64
[C III] λ1909	0.067	0.10	0.069	0.21	0.31	0.28	0.29	...
[Ar III] λ7135	0.22	0.24	0.19	0.17	0.15	0.17	0.23	0.23

[a] Cols. (2) and (3) show the results of equilibrium (steady state) models ($U = 10^{-4}$), while cols (4)–(8) show the results of models with a periodically active ionizing source (duty cycle 20%, $\bar{U} = 10^{-4}$).

[b] From Ho et al. 1993, included for comparison.

initial conditions for the cloud were set to correspond to ionization and temperature equilibrium of a photoionization model with ionization parameter $U(t = 0) = \bar{U} = 10^{-4}$. We find that the emission-line ratios (averaged over one full cycle) quickly reach their asymptotic values after only two cycles. Differences in line ratios relative to Hβ between the second and the fifth cycle amount to less than 5%.

In Figures 1 and 2, we show the temporal evolution of the line ratios relative to Hβ during the fifth activity cycle, for two representative densities: 10^3 cm^{-3} and 10^4 cm^{-3}, respectively. The higher the density, the larger the ratio of Π to the decay time of the various lines. The recombination of H II [$\tau_{\rm rec}^{\rm H} = 1370\ (n_{\rm H}/100\ {\rm cm}^{-2})^{-1}$ yr] is a natural unit to compare the period with. In Table 2, we present the emission-line ratios of our time-dependent calculations after averaging over a full period (cols. [4]–[8]). These can be compared with steady state equilibrium models, computed with $U = 10^{-4}$ (cols. [2] and [3]), and with a typical example of an observed LINER spectrum (col. [9]: NGC 1167, taken from Ho et al. 1993). We have not attempted to fit particular objects but simply to reproduce the general level of excitation observed in LINERs. We note that observations of LINERs seem to favor nitrogen-to-oxygen abundance ratios higher than solar (e.g., Storchi-Bergmann 1991). At a low density of $n_{\rm H} = 300$ cm^{-3}, although Π (=43 yr) is short relative to the recombination timescale (460 yr), it is nevertheless long relative to the decay time of the [O III] lines (7 yr). The averaged spectrum, however (col. [4]), is not significantly different from that of an equilibrium model for $n_{\rm H} = 10^3$ cm^{-3} (col. [2]). We therefore conclude that models with short periods and/or low densities would not show any significant departure from equilibrium steady state models. At higher densities, however, time-dependent effects do not average out for the line ratios. For example, although [O III] λ5007 disappears completely in the low state, it is strong enough in the high state so that when averaged over a cycle it remains stronger than in the equilibrium case (col. [5]). We find that as $\tau_{\rm rec}^{\rm H}$ becomes shorter relative to the period (i.e., as the density increases), the emission-line gas becomes hotter but with a slightly reduced luminosity in recombination lines of H. This results in a slightly larger He II/Hβ ratio, for example. We stress that the differences between equilibrium and periodic models are small, and that light-travel effects will smear out the sharp decay of the high-ionization lines. Thus, we conclude that if the nuclear source of LINERs were turned off for 80% of the time, this would not be immediately apparent in the emission-line spectrum.

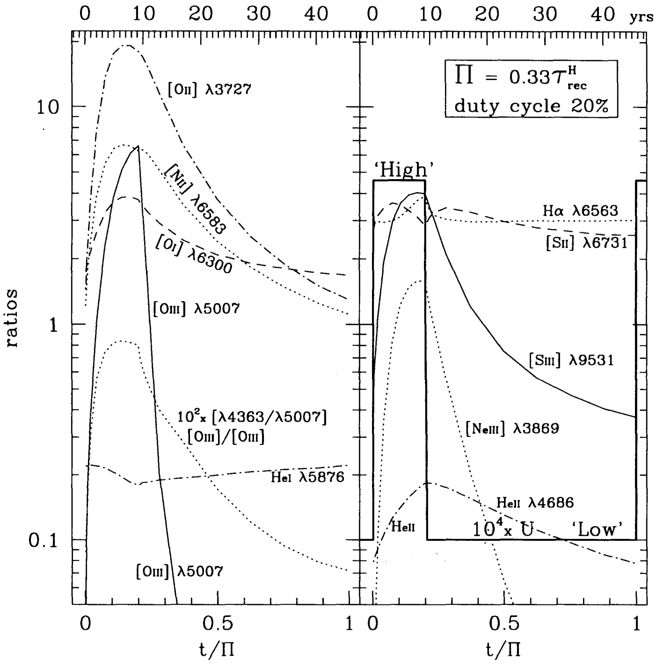

FIG. 1.—The two panels show various emission-line ratios relative to Hβ as a function of time for a cloud of density 10^3 cm^{-3}. In the case of the [O III] λ4363 line, the ratio is expressed relative to [O III] λ5007. The thick line represents the variation of U (scaled by a factor 10^4) over the duty cycle.

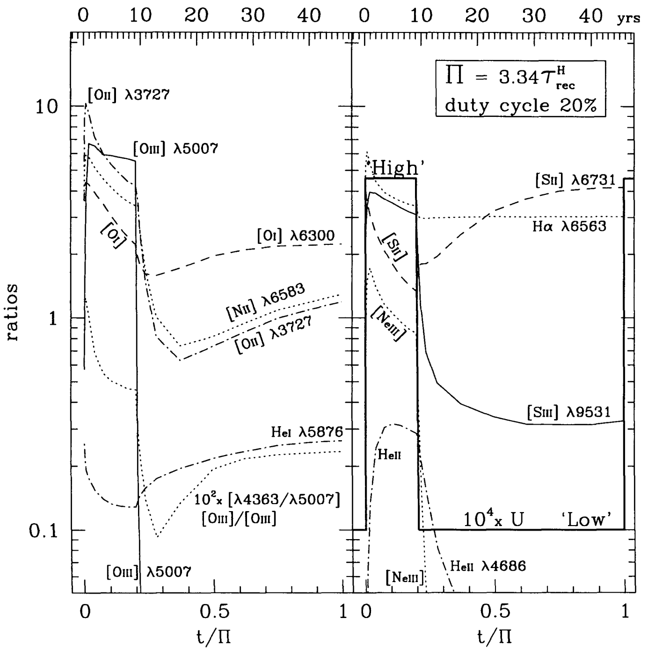

FIG. 2.—Same as in Fig. 1 for a cloud of density 10^4 cm^{-3}

3. TIDAL DISRUPTION OF STARS AS A PHYSICAL MECHANISM FOR THE DUTY CYCLE

If LINERs are indeed low-luminosity active galactic nuclei, powered by accretion onto a supermassive black hole, then a duty cycle may result from episodic accretion, which in turn may be due to an intermittent supply of fuel. Thus, we speculate that the source of fuel in LINERs is provided by stars which are tidally disrupted at irregular intervals, rather than by gas which can be accreted at a quasi-constant rate and sustain a steady output of ionizing photons. Below we investigate the merits of this idea by estimating the expected rate of tidal disruptions, and the duration of the accretion events. We adopt as an illustrative example the tidal disruption of a 1 $M_\odot$ star by a 10^6 $M_\odot$ black hole, a case which has been studied extensively and hence results are available for us to draw on (see, for example, the reviews by Rees 1988, 1990).

The frequency with which stars come to within a distance $r_{\rm min}$ of a central black hole in a galactic nucleus is estimated roughly by Rees (1990) (under the assumption of an isotropic velocity distribution at the radius where the black hole starts to dominate the dynamics) as $f(r < r_{\rm min}) \approx 10^{-3} M_6^{4/3} N_6 \sigma_2^{-1} (r_{\rm min}/r_T)$ yr^{-1}, where M_6 is the mass of the black hole in units of 10^6 $M_\odot$, N_6 is the nuclear stellar density in units of 10^6 pc^{-3} (a typical value for the cores of nearby galaxies according to Lauer et al. 1991, 1992), and σ_2 is the stellar velocity dispersion in the core of units of 10^2 km s^{-1}. r_T is the tidal disruption radius, defined as the distance from the black hole at which the tidal acceleration across a star is equal to its surface gravity (e.g., Press & Teukolsky 1977). Since a close encounter with $r_{\rm min}/r_T \approx 2$–3 is sufficient to dislodge the outer layers of a star, especially if it is evolved, and since typical velocity dispersions in the cores of nearby galaxies are in the range of 80 to 400 km s^{-1} (e.g., Kormendy et al. 1994), the expected tidal disruption rates fall between 8×10^{-2} and 8×10^{-4} yr^{-1} for black hole masses of 10^6–10^7 $M_\odot$.

The postdisruption debris will very likely form an (elliptical) accretion disk (e.g., Syer & Clarke 1992, 1993), for which the viscous time is (Eracleous et al. 1995) $\tau_{\rm visc} \sim 56\alpha^{-4/5}\dot{m}^{-3/10}M_6^{3/2}\xi_3^{5/4}$ yr, where $\dot{m}$ is the accretion rate in $M_\odot$ yr^{-1}, ξ_3 is the radius from the central object in units of 10^3 GM/c^2 (M is the mass of the black hole), and α is the viscosity parameter in the prescription of Shakura & Sunyaev (1973). According to the calculations of Cannizzo, Lee, & Goodman (1990; see also Roos 1992) the initial accretion rate is sustained at a high level, producing a bolometric luminosity of about 10^{40}–10^{42} ergs s^{-1} for a period of up to a decade, depending on the viscosity parameter. This initial burst may be preceded by a brief, super-Eddington flash. At later times, the accretion rate, and hence also the luminosity, decline roughly as t^{-q}, with $q \approx 1.2$–1.7. The duration of the initial burst corresponds to the viscous time of the inner accretion disk (up to $\xi \sim 100$), according to above estimate of the viscous time. The time required for the luminosity to decline by an order of magnitude is about a century, corresponding approximately to the viscous time of the outer accretion disk ($\xi \sim 1000$).

The above estimates demonstrate that a plausible time interval between tidal disruptions is 100–200 yr. It is also reasonable to expect that a powerful ionizing source will be present for a few decades, before the rate of accretion of the postdisruption debris decreases significantly. Hence a duty cycle of about 20% is attainable, consistent with the observational results of Maoz et al. (1994). Moreover, the mean time interval between disruptions can be short enough, so that the line emission excited by a burst of ionizing radiation can persist until the next tidal encounter.

4. DISCUSSION

The tidal disruption scenario proposed above as a possible physical mechanism for the duty cycle was inspired by recent observations of spectral variability in the LINER NGC 1097. This object was observed to transform from a LINER to a Seyfert 1 galaxy with the sudden appearance of broad, double-peaked Balmer lines and a featureless continuum in its optical spectrum (Storchi-Bergmann, Baldwin, & Wilson 1993). The nature of the double-peaked profiles (redshifted peak stronger than the blueshifted peak), and the abrupt appearance of the broad Balmer lines led Eracleous et al. (1995) to suggest that they may originate in an elliptical accretion ring, which has recently formed from the debris released by the tidal disruption of a star by a supermassive black hole. This suggestion was supported by subsequent observations of variability of the Balmer line intensities and profiles (Storchi-Bergmann et al. 1995). The variability was found to be consistent with a modest precession of the elliptical ring and a decline of the ionizing continuum. The rate of precession of the ring inferred from the variability of the profiles yielded an estimate of the black hole mass of about 10^6 $M_\odot$. If this event is indeed associated with the tidal disruption of a star by a supermassive black hole, then we may have already observed the beginning of the active phase of the ionizing source in this object.

The duty cycle hypothesis has a number of consequences which can serve as observational tests, as we outline below.

1. Since broad-line emission is expected to originate within a few thousand gravitational radii from the central ionizing source (i.e., a few light-days), the broad lines are expected to fade immediately if the ionizing continuum declines. Thus there should be a correlation between the presence of broad Balmer-line wings and the presence of a nuclear UV source in LINERs. We note, however, that an obscuring torus scenario (analogous to that considered for Seyfert galaxies) makes the same prediction, and hence this type of observation cannot distinguish between these two particular hypotheses.
2. As pointed out originally by BR87, and reiterated here, the flux of the [O III] λ5007 line decays almost instantaneously with the decline of the ionizing flux. Hence, the [O III]–emitting region should have the form of a fairly narrow ring (or shell) around the position of the ionizing source. This may be testable by imaging nearby, UV-dark LINERs, with high spatial resolution (e.g., using the *HST*) in a narrow band centered on the [O III] doublet.
3. The predicted duty cycle, i.e., the product of the tidal disruption frequency and the lifetime of the UV source: $f\tau_{\rm visc}$, is extremely sensitive to the mass of the central black hole ($\propto M^{17/6}$) but not to any of the other properties of the nuclear stellar population. This implies that in order to reproduce the observed duty cycle of order 0.2, the mass of the central black hole cannot exceed 10^7 $M_\odot$. Accurate determinations of the masses of the hypothesized central black holes in LINERs can serve to test this prediction (see, for example, Greenhill et al. 1995, and references therein).

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