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PHOTOEROSION OF NUCLEI IN QUASAR EMISSION-LINE REGIONS

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ABSTRACT

Several active galactic nuclei are now known to be sources of $h\nu \geq$ MeV γ-rays. In this *Letter* we point out some consequences of this radiation for elemental abundances in nearby emission-line regions. A series of (γ, n) and (γ, p) reactions result in mass degradation, a process we refer to as photoerosion. Heavy nuclei such as Fe and Ni are destroyed on time scales of roughly 10^3 yr for regions in NGC 4151, while most light nuclear abundances change little on such time scales. Many odd-z nuclei, particularly B, have large abundance increases. Photoerosion may account for several previously unexplained phenomena, e.g., the large spectral differences between radio-loud and radio-quiet AGN and the observed aluminum overabundance. The predicted increase in boron abundance remains to be observationally verified. That abundance, along with those of other nuclides, will determine the lifetime of broad-line region clouds in the observed radiation environment, thus constraining models of the formation and survival of the line-emitting gas.

Subject headings: galaxies: nuclei — galaxies: Seyfert — gamma rays: general

I. INTRODUCTION

The spectra of active galactic nuclei (AGN) are characterized by a featureless continuum extending past 10 MeV (Zdziarski 1986) and many prominent ultraviolet, optical, and infrared emission-lines (Osterbrock 1984). Two major goals of recent research into the emission-line regions can be identified. The first is to use them to probe regions nearest the central object, while the second is to understand the emission-line formation process to the extent that these lines can be used as a reliable indicator of the intrinsic luminosity of, and hence distance to, these luminous objects (see, for example, Baldwin 1977).

The calculations involved in predicting the intensities of AGN emission lines are sufficiently complicated that it is necessary to test specific assumptions rather than deduce properties directly (see the discussion by Davidson 1977 and Davidson and Netzer 1979). Unfortunately it is not even clear that all of the physics affecting the broad-line region (BLR) clouds has been identified; Netzer (1985) stresses that current models do not reproduce the observed emission-line spectrum when a realistic continuum is used. Even though one of the goals of emission-line research is measurement of the composition BLR clouds directly, all previous theoretical studies have assumed a solar composition, basically by Occam's razor (see Davidson 1977).

It is the purpose of this *Letter* to point out that the γ-ray continuum observed in AGNs has major implications for the composition of BLR clouds. The major effect of $h\nu > 10$ MeV radiation is to produce (γ, n) and (γ, p) reactions which selectively photodissociate iron and nickel while increasing the abundances of odd-z nuclei and especially of boron. We will call this process photoerosion of the nuclei. In the very low luminosity Seyfert galaxy NGC 4151, the time scale for these changes can be estimated and is $\sim 10^3$ yr. This photoerosion of mass from the abundant nuclei may account for the spectral differences between radio-loud and radio-quiet objects, as well as other evidence for unusual abundances. Observational limits to abundances of elements such as B, Cr, V, Ti, or Sc could provide important constraints on the lifetime of clouds in this radiation environment.

II. CALCULATIONS

In this section we describe some of the physical conditions and properties which may pertain to the broad-line region of active nuclei.

a) *The γ-Ray Continuum*

Four AGN are now known to be emitters of ~ 10 MeV radiation: the radio-loud objects 3C 273 (Bignami *et al.* 1981), Cen A (Gehrels *et al.* 1984; van Ballmoos, Diehl, and Schronfelder 1987), and the radio-quiet objects NGC 4151 (Perotti *et al.* 1981*a*; Baity *et al.* 1984) and MCG 8-11-11 (Perotti *et al.* 1981*b*). These detections suggest that AGN continua have relatively flat spectral indices at X-ray energies ($f_\nu \propto \nu^{-0.7}$, below several hundred keV), increasing to a steeper slope at energies much greater than 1 MeV ($f_\nu \propto \nu^{-1.7}$) as required by observations of the γ-ray background (see the discussions by Rothschild *et al.* 1983; Zdziarski 1986).

In order to estimate the effects of radiation upon emission-line gas, it is necessary to know the distance of the gas from the source of the γ-rays. (We assume that all ionizing radiation originates near the central object, which therefore is effectively a point source.) At one time the source-cloud separation was set by thermodynamic arguments (see Davidson and Netzer 1979), but it now seems clear from reverberation studies that this seriously overestimates the distance

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(Peterson *et al.* 1983; Peterson *et al.* 1985; Peterson, Crenshaw, and Meyers 1985). The only case where reverberation studies have measured the source-cloud separation and γ-ray observations exist is the very low luminosity intermediate Seyfert galaxy NGC 4151 (Gaskell and Sparke 1986; Perotti *et al.* 1981*a*; Baity *et al.* 1984). Baity *et al.* fit hard X-ray observations as a power law:

$$\frac{\partial N}{\partial E} = 3 \times 10^{-5}\left[\frac{E}{100 \text{ keV}}\right]^{-1.4} \text{photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}. \quad (1)$$

This flux appears to vary by about a factor of 2 over time scales of less than a year, and the spectral index is uncertain by about 30%. The slope of this continuum must increase to be consistent with both background and *SAS-COS B* observations (Baity *et al.*); we assume a break at 1 MeV to the slope of -2.7, as suggested by background observations. The nuclear reactions discussed below begin at a characteristic energy of 10 MeV; the integrated flux density of photons with energies greater than this is $\sim 2.4 \times 10^{-5}$ photons cm^{-2} s^{-1} at Earth. Gaskell and Sparke (1986) report that the high ionization emission-line gas is located at distances between 2 and 6 lt-days from the continuum source. (Gas exists on distance scales as large as several kpc, of course.) The flux of $h\nu > 10$ MeV photons at the inner edge of the emission-line region (assuming a distance to NGC 4151 of 19 Mpc; $H_0 = 50$ km s^{-1} Mpc^{-1}), is $\phi = 2.9 \times 10^{15}$ photons cm^{-2} s^{-1}.

b) Photonuclear Cross Sections

Photonuclear cross sections have been published for many nuclei (see, for example, Pywell *et al.* 1983; Veyssiere *et al.* 1974). For most of these nuclei the neutron photoproduction [i.e., (γ, n)] cross section was larger than that for protons. In a few cases (e.g., ^{40}Ca and ^{28}Si) the neutron production is small [because the (γ, n) threshold is large], and proton production is the larger effect. For our purposes (γ, n) and (γ, p) processes are equivalent because one of the two processes usually produces a short-lived nucleus which decays to the one produced by the other processes [e.g., ^{40}Ca (γ, n) produces ^{39}Ca, which decays to ^{39}K, the product of the ^{40}Ca (γ, p) reaction]. Also note that "photoneutron cross sections" often contain cross sections for processes other than just (γ, n), e.g., $(\gamma, 2n)$, (γ, pn), etc. These multinucleon processes, however, always occur at considerably higher photon energies than do the (γ, n) or (γ, p) reactions. Those processes contribute little to the effect we are describing because of the steep slope of the γ-ray continuum.

We have averaged cross sections for nuclei ranging from ^{2}H to ^{60}Ni over the interval 10 MeV–∞ weighted by the power law continuum described above:

$$\langle\sigma\rangle = \int_{10 \text{ MeV}}^{\infty} \sigma(\varepsilon)\varepsilon^{-2.7}\, d\varepsilon \Big/ \int_{10 \text{ MeV}}^{\infty} \varepsilon^{-2.7}\, d\varepsilon. \quad (2)$$

Data for the 20 nuclei we examined in detail are summarized in Figure 1, which shows the averaged cross sections (in millibarns) as a function of the atomic mass. We have approximated the cross sections as a simple function of the atomic mass; it is shown as a solid line on the figure. It can be seen to reproduce all of the values to within a factor of ~ 2. The fluctuations about the average are a result of nuclear structure. We have used the simple approximation because of the lack of data on most nuclei. As a result, the composition calculations presented below are uncertain at the factor of 2 level.

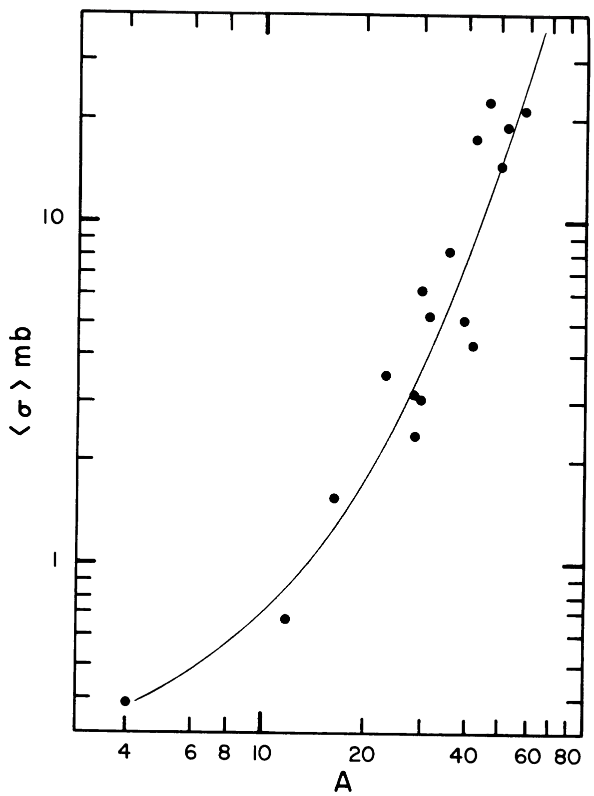

FIG. 1.—Mean cross section vs. atomic number. Averaged cross sections, as defined in the text, are plotted along with the interpolating formula used in the actual calculations. The *y*-axis is in units of 10^{-27} cm^2.

c) Time-dependent Abundance Calculations

We introduce the approximation that all other decay processes are fast compared to the time scale for (γ, n) and (γ, p) reactions (of order 10^3 yr). In this case we can determine the composition as a function of time by solving a set of coupled differential equations relating the abundances of nuclei with adjacent atomic masses:

$$\frac{\partial N_i}{\partial t} = N_{i+1}\langle\sigma_{i+1}\rangle\phi - N_i\langle\sigma_i\rangle\phi, \quad (3)$$

where i is the mass number. In nearly all of the cases considered here it is possible to unambiguously relate atomic mass number and element; we do not report abundances in cases where one mass could correspond to more than one element. Initial abundances used are those of Cameron (1982).

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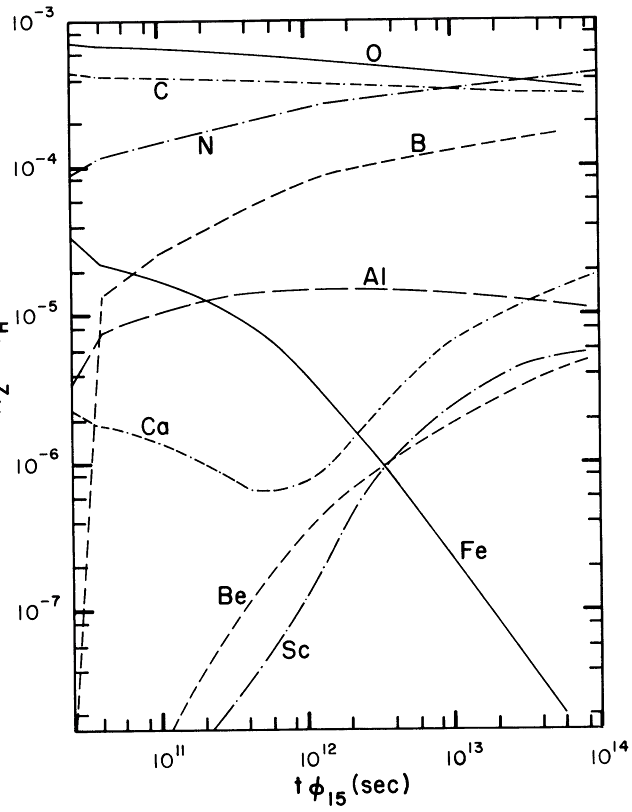

FIG. 2.—Chemical composition vs. time. The abundances relative to hydrogen are shown. The initial composition is shown as the point on the left edge of the graph, and was taken from Cameron's (1982) compilation. Time is given on the x-axis for an $h\nu \geq 10$ MeV flux of $\phi_{15} \equiv \phi/(10^{15}$ cm^{-2} s$^{-1}) = 1$; if $\phi_{15} > 1$ then the actual time will be correspondingly shorter.

Results are presented in Figure 2, where we have assumed an $h\nu \geq 10$ MeV photon flux of $\phi_{15} \equiv \phi/10^{15}$ photons cm^{-2} s^{-1} = 1. For the case of the inner emission-line regions of NGC 4151, $\phi_{15} \approx 2.9$, and the actual time scales will be 2.9 times smaller than illustrated. For $\phi_{15} = 1$, Fe is destroyed on time scales of $\sim 10^3$ yr, and the B abundance is increased by significant amounts on time scales of less than a year.

III. DISCUSSION

The time scale for photoerosion of the nuclei ($T \approx 10^3$ yr for NGC 4151, a very low luminosity object) must be comparable to the exposure time expected for BLR gas if these effects are to be significant. At the very least the gas is exposed for an orbital time $\tau_{\rm orb} \approx 2\pi r/v$, where $r \approx 2$ lt-days is the distance to the inner BLR (Gaskell and Sparke 1986) and $v \approx 6000$ km s^{-1} (Osterbrock and Koski 1976). We find $\tau_{\rm orb} \approx 1$ yr for NGC 4151. Although the kinematics of gas in AGN are unknown at the present time, orbital motion, perhaps in an accretion disk, is an attractive hypothesis (Shields 1978; Osterbrock 1984). In this case $\tau_{\rm orb}$ must be multiplied by the number of orbits η the gas survives to find the exposure time. There is no way to estimate η, which could easily be as large as $\eta \approx 10^2$–10^4. Thus, in the case of NGC 4151, gas may be exposed to radiation for times of order 1–10^4 yr or longer. If, instead of orbital motion, the gas is infalling or outflowing, the time scales should be of order $\tau_{\rm orb}$. The time scales for exposure to the γ-rays are basically unknown but could be deduced from determination of the abundances. (The fact that NGC 4151 is an Fe II emitter suggests that either the bulk of the BLR gas has been exposed for a time shorter than 10^3 yr or is considerably more distant from the nucleus than $r = 2$ lt-days.)

Photoerosion of BLR nuclei may introduce a luminosity dependence among AGN. The relative intensities of strong carbon and hydrogen lines are known to depend only slightly on luminosity (Davidson and Netzer 1979). This requires that the "ionization parameter," the ratio of photons to nucelons, be roughly constant, so that $r_{\rm BLR} \propto L^{1/2}$ if the gas density does not depend on luminosity. If the kinematics are the same in high-luminosity and low-luminosity AGN, then r will be roughly 30 times larger in high-luminosity objects, and clouds will be exposed to radiation for roughly 30 times longer than we estimate for NGC 4151, or $\tau \approx 30$–3×10^5 yr. Thus photoerosion should be relatively more important in luminous objects. In addition, Zamorani *et al.* (1981) found that radio-loud AGN tend to be also X-ray–loud. If this is also true for γ rays, then the radio-loud objects, which are also the most luminous AGN, should show the most severe effects of nuclear photoerosion. Abundance anomalies should be noticed in the most luminous objects, especially those which are radio-loud.

Osterbrock (1977) and Grandi and Osterbrock (1978) found that the major spectral difference between radio-loud and radio-quiet objects is the weakness of iron emission lines in the radio-loud objects (see also Peterson, Foltz, and Bayard 1981). Recent photoionization studies (Wills, Netzer, and Wills 1985) show that Fe II emission is a natural consequence of material with a solar composition. Within the context of these models, the real question seems to be: why do radio-loud objects lack Fe II emission? The destruction of Fe would be one of the first effects noticed in a γ-ray environment. Thus iron would be expected to be significantly depleted in luminous radio-loud objects. Another observable effect would be the creation of significant amounts of odd-z nuclei, such as Al. Al must be overabundant if the feature often observed at λ1859 is Al III (Uomoto 1984). The feature has a mean intensity relative to C III λ1909 of 0.17 ± 0.09 in the sample of Baldwin *et al.* (1987) and Baldwin and Wampler (1987). A comparison with unpublished photoionization models suggests that Al is overabundant by a factor of ~ 7 relative to C. The calculations presented above predict an overabundance of ~ 6. The actual predicted overabundance depends on the exposure time so this agreement must be regarded as somewhat fortuitous. Photoerosion may also explain why emission-line regions of AGN appear to have an inner boundary; gas closer to the nucleus would have its composition radically altered on short time scales and would not produce the familiar UV and optical emission lines. Gas throughout the BLR will be affected by photoerosion if BLR clouds form from a long-lived hot phase in hydrostatic equilibrium.

Our hypothesis that nuclear photoerosion occurs in AGN emission-line region gas can be tested by measuring abun-

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dances of such products of these reactions as Sc, Ti, V, and Cr. Measurements of these abundances, expected to be enhanced if photoerosion is important, would sharply constrain models of the formation, destruction, and lifetime of BLR clouds. Spectra of low ionization stages of Sc, Ti, V, and Cr tend to be fairly complex, but emission lines of Sc III λ3916, Ti III λ2618, and Cr III λ2012 (the wavelengths are approximated centers of the multiplets) may be observed. The most extreme overabundance should be B, which reaches densities within 10^{-4} of H in 10^4 yr for $\phi_{15} = 1$. Judging from photoionization models (e.g., Wills, Netzer, and Wills 1985) and ionization potentials, the dominant stage of ionization should be B^+ which should have an ionization fraction fairly close to that of C^+. In this case the intensity ratio B II λ1362/C II λ1335 should be close to the predicted abundance ratio of $\sim 1/10$. To the best of our knowledge data of sufficiently high signal-to-noise ratio to check this prediction do not now exist. Roughly 5% of the boron should be doubly ionized, and the higher electron temperature in its creation zone suggests that B III λ2066 should actually be the stronger line. A feature is often present in quasar spectra at roughly this wavelength ($\lambda \approx 2075$ Å), and Baldwin and Wampler (1987) note that it is probably a blend. High-resolution, high signal-to-noise ratio data on this feature and the region near 1362 Å would offer a direct test of our ideas.

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