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WHERE IS THE CORONAL LINE REGION IN ACTIVE GALACTIC NUCLEI?

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ABSTRACT

We report the new finding that type 1 Seyfert nuclei (S1s) have excess [Fe vii] λ6087 emission with respect to type 2 Seyfert nuclei (S2s). The S1s exhibit broad emission lines that are attributed to ionized gas within 1 pc of the black hole, whereas the S2s do not show such broad lines. The current unified model of active galactic nuclei explains this difference as follows: the central 1 pc region in the S2s is hidden from the line of sight by a dusty torus if we observe it from a nearly edge-on view toward the torus. Therefore, our finding implies that the coronal line region (CLR) traced by the [Fe vii] λ6087 emission resides in the inner wall of such dusty tori. On the other hand, the frequency of occurrence of the CLR in the optical spectra is nearly the same between the S1s and the S2s. Moreover, some Seyfert nuclei exhibit a very extended (∼1 kpc) CLR. All these observational results can be unified if we introduce a three-component model for the CLR: (1) the inner wall of the dusty torus, (2) the clumpy ionized region associated with the narrow-line region at a distance from ∼10 to ∼100 pc, and (3) the extended ionized region at a distance ∼1 kpc.

Subject headings: galaxies: active — galaxies: Seyfert — quasars: emission lines

1. INTRODUCTION

Optical spectra of active galactic nuclei (AGNs) often show very high ionization emission lines such as [Fe vii], [Fe x], and [Fe xiv] (the so-called coronal lines). Since the ionization potentials of these lines are higher than 100 eV, much attention has been paid to the understanding of the coronal line region (CLR) (e.g., Oke & Sargent 1968; Osterbrock 1977, 1985; Grandi 1978; Pelat, Alloin, & Fosbury 1981; Penston et al. 1984). It is often considered that the CLR has an intermediate nature between the broad-line region (BLR) and the narrow-line region (NLR) because the high-ionization lines have critical densities for collisional excitation that are on the order of 10^7 cm^{-3} and some Seyfert nuclei show CLR emission lines with FWHM ∼ 1000–2000 km s^{-1} (De Robertis & Osterbrock 1984, 1986; Veilleux 1988; Appenzellar & Ösreicher 1988; Appenzellar & Wagner 1991).

Recent photoionization model calculations have suggested that the CLR is located mostly within the inner 10 pc (Ferguson, Korista, & Ferland 1997). In fact, Oliva et al. (1994) found a compact (<10 pc) CLR in a nearby Seyfert, the Circinus galaxy, using the near-infrared coronal line [Si vi] at 1.92 μm. However, it is also known that some Seyfert nuclei have an extended CLR whose size amounts to ∼1 kpc (Golev et al. 1994; Murayama, Taniguchi, & Iwasawa 1998, hereafter MTI98). The presence of such extended CLRs is usually explained as being the result of very low density conditions in the interstellar medium ($n_{\rm H}$ ∼ 1 cm^{-3}), which makes it possible to achieve higher ionization conditions (Korista & Ferland 1989). The above, complicated situation raises the following question: *where is the CLR in AGNs?*

According to the current unified models (Antonucci & Miller 1985; Antonucci 1993), it is generally believed that a dusty torus surrounds both the central engine and the BLR. Since the inner wall of the torus is exposed to intense radiation from the central engine, it is naturally expected that the wall can be one of the important sites for the CLR (Pier & Voit 1995). Recently, Gallimore, Baum, & O'Dea (1997) discovered a very compact (∼1 pc) ionized region in the Seyfert 2 galaxy NGC 1068 in the radio continuum. Since the inner radius of the accreting molecular ring traced by water vapor maser emission is ∼0.5 pc (Greenhill et al. 1996), this ionized region seems indeed to be the inner wall of the torus. If the inner wall is an important site of the CLR, it should be expected that the type 1 Seyfert nuclei (S1s) would tend to have more intense CLR emission because the inner wall would be obscured by the torus itself in type 2 Seyfert nuclei (S2s). In order to examine whether or not the S1s tend to have the excess CLR emission, we study the frequency distributions of the [Fe vii] λ6087/[O iii] λ5007 intensity ratio between S1s and S2s.

2. DATA AND RESULTS

The data were compiled from the literature (Osterbrock 1977, 1985; Koski 1978; Osterbrock & Pogge 1985; Shuder & Osterbrock 1981) and our own optical spectroscopic data of one S1 (NGC 4051) and four S2s (NGC 591, NGC 5695, NGC 5929, and NGC 5033), which were taken with a CCD spectrograph attached to the Cassegrain focus of the 188 cm telescope at the Okayama Astrophysical Observatory. In total, our sample contains 18 S1s and 17 S2s. Although the sample is not a statistically complete one in any sense, the data set is the largest one for the study of CLRs ever compiled. The average redshifts are similar between the S1s (0.031 ± 0.017) and the S2s (0.024 ± 0.016). There is no correlation between the redshift and the [Fe vii]/[O iii] intensity ratio for both samples.

The result is shown in Figure 1. It is shown that the S1s are stronger [Fe vii] emitters than the S2s. Adopting the null hypothesis that the S1s and S2s studied here come from the same underlying population, the Kolmogorov-Smirnov statistical test shows that the probability of randomly selecting the observed ratios from the same population is only 5.0×10^{-7}. Therefore, the excess [Fe vii] emission in the S1s with respect to the S2s is statistically real. In order to verify that this difference is really due to the excess [Fe vii] emission, we compare the [O iii] luminosity between the S1s and S2s and find that the [O iii] luminosity distribution is nearly the same between the S1s and the S2s (Fig. 2). Therefore, we conclude that the higher [Fe vii]/[O iii] intensity ratio in the S1s is indeed due to the excess [Fe vii] emission rather than to the weaker [O iii] emission in the S1s. The presence of an excess [Fe vii] emission in S1s can be explained only if there is a fraction of the inner

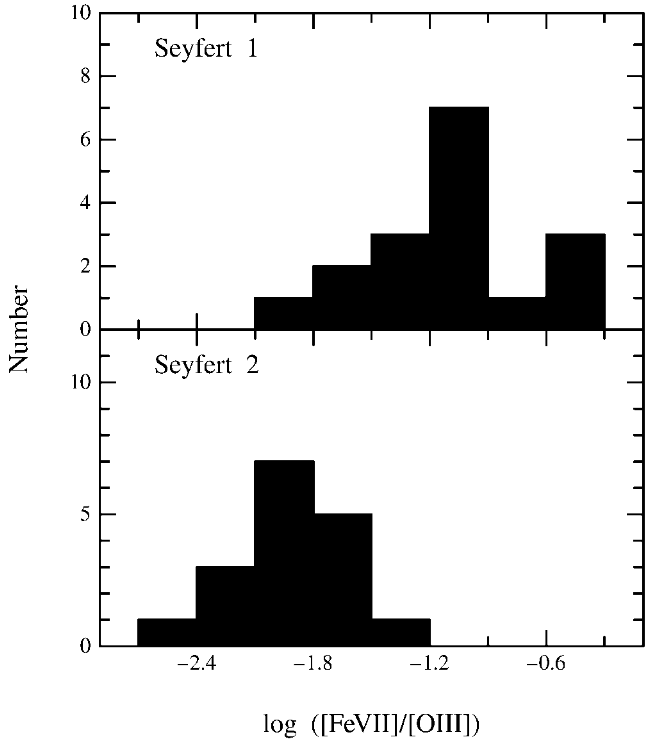

FIG. 1.—Frequency distributions of the [Fe VII] λ6087/[O III] λ5007 intensity ratio between the S1s and the S2s.

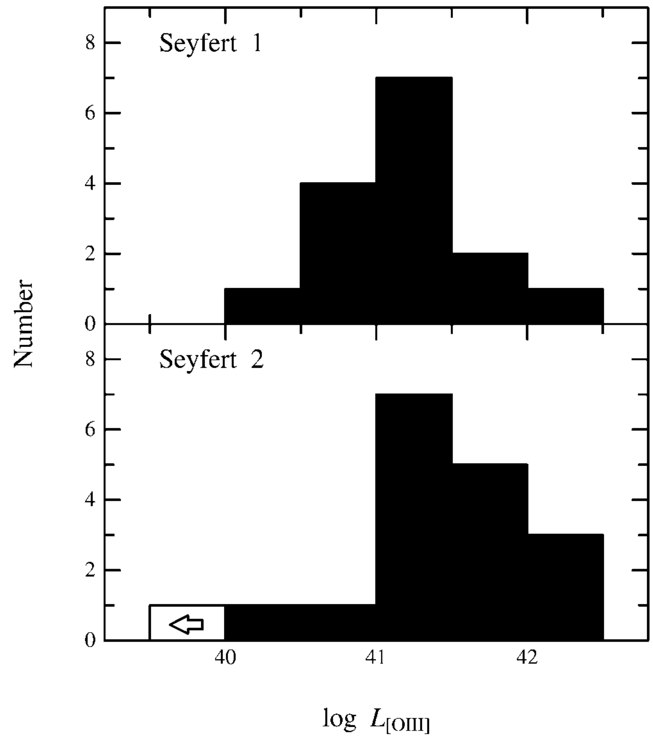

FIG. 2.—Frequency distributions of the [O III] λ5007 luminosity between the S1s and the S2s.

CLR that cannot be seen in the S2s. The height of the inner wall is on the order of 1 pc (Gallimore et al. 1997; Pier & Krolik 1992, 1993). Therefore, given that the torus obscures this CLR from our line of sight, the effective height of the torus should be significantly higher than 1 pc.

Although our new finding suggests strongly that part of the CLR emission arises from the inner walls of dusty tori, we remember that a number of S2s have the CLR. In fact, the fraction of Seyfert nuclei with the CLR is nearly the same between the S1s and the S2s (Osterbrock 1977; Koski 1978). If the CLR were mostly concentrated in the inner 1 pc region, we would observe the CLR only in the S1s. Therefore, the presence of the CLR in the S2s implies that there is another CLR component that has no viewing-angle dependence. A typical dimension of such a component is on the order of 100 pc, like that of the NLR. Ferguson et al. (1997) show theoretically that the CLR can arise from just outside the BLR to $\sim 400 L_{43.5}^{1/2}$ pc, where $L_{43.5}$ is the ionizing continuum luminosity in units of $10^{43.5}$ ergs s^{-1}. Since this size is almost comparable to that of the NLR, it is considered that a substantial part of the CLR coexists with the NLR. MTI98 show that the CLR of the high-ionization Seyfert galaxy Tololo 0109−383 is spatially extended up to a radius of 1.1 kpc. However, ~70% of the CLR emission is concentrated in the inner 220 pc in radius. Since the ionizing continuum luminosity of Tololo 0109−383, inferred from the bolometric luminosity, is $\sim 10^{43}$ ergs s^{-1}, this inner CLR can well be interpreted by the photoionization model of Ferguson et al. (1997), whereas the outer part may have different physical conditions from that of the NLR because the electron density in the outer region ($<10^2$ cm^{-3}; MTI98) is significantly lower than those in the NLR. Thus, the outer CLR in this galaxy can be understood in terms of the low-density CLR suggested by Korista & Ferland (1989).

3. DISCUSSION

The arguments described in the previous section suggest strongly that there are three kinds of CLR: (1) the torus CLR ($r < 1$ pc), (2) the CLR associated with the NLR ($10 < r < 100$ pc), and (3) the very extended CLR ($r \sim 1$ kpc). Therefore, if we take these three emission-line regions into account, we may have a unified picture for the CLR of AGNs. Their basic physical properties are summarized in Table 1. A schematic illustration of the CLR is shown in Figure 3. We mention that there is the large scatter in the [Fe VII]/[O III] intensity ratio in both the S1s and the S2s. This scatter suggests that the contribution of CLR emission from the inner, extended, and very extended CLRs may be different from object to object. Moreover, it should be remembered that a half of Seyfert nuclei

TABLE 1
THREE-COMPONENT MODEL FOR CLR

CLR	r (pc)	n_H (cm^{-3})	FWHM (km s^{-1})	Associated Emission-Line Region
Torus	~1	$\sim 10^7$–10^8	1300[a]	ILR
Clumpy	~1–100	$\sim 10^3$–10^6	400–750	NLR
Extended	~1000	~1	<50[b]	ENLR[c]

[a] An observed FWHM is $2v_{rot} \sin i$, where i is the angle between the line of sight and the rotational axis of the torus. When we observe the torus from a face-on view, the FWHM should be a virial line width, $660 M_8^{1/2} r_1^{-1/2}$ km s^{-1}. Such narrow line widths of the CLR are observed in some Seyfert nuclei (De Robertis & Osterbrock 1984, 1986; Giannuzzo et al. 1995).

[b] Unger et al. 1987.

[c] Another term, extended emission-line regions (EELRs), is also used.

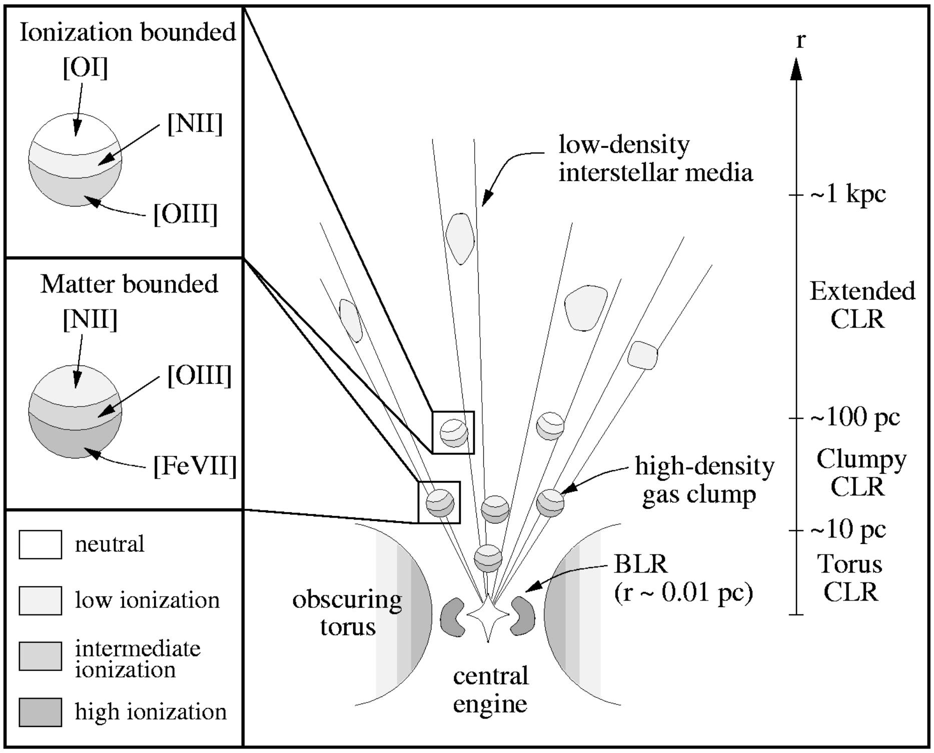

FIG. 3.—A schematic illustration of the three-component model for the CLR. Note that the torus CLR consists of many small ionized gas clumps like the clumpy CLR in the NLR.

show no evidence for the CLR (Osterbrock 1977; Koski 1978). This may be attributed to a gas-rich condition in the circumnuclear region, resulting in a lower ionization condition. This diversity may make it difficult to construct a simple photoionization model for the CLR as well as for the NLR itself (Ferland & Osterbrock 1986).

In view of recent new observations and insights, we discuss the nature of the three kinds of CLRs in AGNs.

1. *The torus CLR*.—Given the current unified model, it is naturally considered that clouds on the inner edges of dusty tori provide important sites for the CLR (Pier & Voit 1995). A typical electron density is estimated to be 10^7–10^8 cm^{-3} (Pelat et al. 1981; Ferguson et al. 1997; Pier & Voit 1995). Since the emissivity of coronal lines is proportional to n_e^2 under conditions of $n_e < n_{cr}$, the torus CLR can be the most luminous component. This is indeed shown in Figure 1. We also have to note that iron is often depleted in the interstellar medium. However, since the inner edges of the tori are exposed to the intense radiation field from the central engine, dust grains may be destroyed (Pier & Voit 1995). This is another reason why the torus CLR is more luminous than the CLR associated with the NLR. We also mention that the torus CLR consists of many small ionized gas clumps, although we illustrate it as shown in Figure 3.

If we assume that the inner wall obeys a Keplerian rotation, we obtain a typical line width FWHM $\simeq v_{rot} \simeq 1320 M_8^{1/2} r_1^{-1/2}$ km s^{-1}, where M_8 is the dynamical mass within a radius r_1 in units of $10^8\ M_\odot$ and r_1 is the radius of the NLR in units of 1 pc (Pier & Voit 1995). This fiducial value is almost comparable to those of coronal lines whenever they are broad (De Robertis & Osterbrock 1984, 1986; Appenzellar & Östreicher 1988; Appenzellar & Wagner 1991; Giannuzzo, Rieke, & Rieke 1995). It has been known that some Seyfert nuclei and quasars have ionized regions whose line widths are a few 1000 km s^{-1} (Brotherton et al. 1994; Mason, Puchnarewicz, & Jones 1996). Since these line widths are intermediate between those of the NLR and the those of the BLR, it has been suspected that there is an intermediate-line region (ILR) in addition to the traditional NLR and BLR. We propose that this ILR is located just at the inner wall of the tori and thus that the torus CLR may be associated spatially with the ILRs.

2. *The CLR associated with the NLR* (*the clumpy CLR*).—The recent *Hubble Space Telescope* observations of the NLR in a number of nearby Seyfert nuclei have shown that the NLR consists of a large number of gas clumps and thus that the structure of the NLR turns out to be much more complex than what we thought (Wilson et al. 1993; Bower et al. 1995; Capetti et al. 1996a; Capetti, Macchetto, & Lattanzi 1996b). Therefore, we refer to this CLR as the clumpy CLR. It is naturally expected that the cloud surface facing the continuum radiation may be the major site of a CLR. MTI98 found that there is no correlation between [Fe VII] and an optical Fe II feature at 4570 Å, which is presumed to arise from warm neutral or partially ionized regions of gas clouds. Furthermore, there is no correlation between [Fe VII] and [O I] (Murayama 1998). These properties imply that highly ionized gas clumps are decoupled from low-ionization gas clumps. We may interpret this as the CLR arising from matter-bounded ionized clumps and the low-ionization lines arising mostly from

ionization-bounded gas clumps.[1] Since the [Fe VII]–emitting region rather than the [O III] region should be exposed to the harder and stronger radiation field, the radiation pressure exerted from the central engine is higher for high-ionization gas clumps than for the low-ionization ones, and thus the high-ionization clumps may be accelerated more efficiently, leading to the systematic blueshift of the high-ionization clumps with respect to the lower ones. This property has been observed often in many AGNs (Grandi 1978; Appenzellar & Ösreicher 1988; Gaskell 1982; Wilkes 1984).

3. *The extended CLR*.—The very extended CLR ($r \sim 1$ kpc) is found in both NGC 3516 (Golev et al. 1994) and Tololo 0109−383 (MTI98). If the interstellar medium consists of very low density gas clouds (e.g., $n_H \sim 1$ cm^{-3}), the high-ionization condition can be achieved (Korista & Ferland 1989). Therefore, it is reasonable that some Seyfert nuclei have the very extended CLR. The extended CLR seems to be related to the so-called extended ($r \sim 1$–10 kpc) narrow-line region (ENLR) (Unger et al. 1987), which is thought to be the interstellar medium photoionized by the continuum radiation from the central engine. The CLR may be the lower density parts of the ENLR because the CLR needs a higher ionization condition than the typical [O III]–emitting region.

[1] Recently, measuring the electron temperatures of both O^{2+} and N^{+} regions in the extended emission-line regions of several Seyfert galaxies, Wilson, Binette, & Storchi-Bergmann (1997) proposed that the [O III] emission arises mostly from the matter-bounded clouds, while the [N II] emission arises from ionization-bounded clouds, because the observed electron temperature difference between the [O III] and [N II] regions is too large (e.g., ~5000 K) to be accounted for in terms of photoionization of ionization-bounded clouds (see also Binette, Wilson, & Storchi-Bergmann 1996 and Binette et al. 1997). On the analogy of this finding, we consider that the NLR also consists of the two kinds of clumps.

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