A NEW DUAL-COMPONENT PHOTOIONIZATION MODEL FOR THE NARROW EMISSION LINE REGIONS IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

Having found that type 1 Seyfert nuclei have excess \([\text{Fe} \text{ vii}] \lambda 6087\) emission with respect to type 2 nuclei, Murayama & Taniguchi have proposed that the high-ionization nuclear emission line region (HINER) traced by the \([\text{Fe} \text{ vii}] \lambda 6087\) emission resides in the inner wall of dusty tori. The covering factor of the torus is usually large (e.g., \(\sim 0.9\)). Further, electron density in the tori (e.g., \(\sim 10^5 - 10^6 \text{ cm}^{-3}\)) is considered to be significantly higher than that (e.g., \(\sim 10^3 - 10^4 \text{ cm}^{-3}\)) in the narrow-line region (NLR). Therefore, it is expected that the torus emission contributes to the majority of the higher ionization emission lines. Taking this HINER component into account, we have constructed new dual-component (i.e., a typical NLR with a HINER torus) photoionization models. Comparison of our model with the observations shows that if the torus emission contributes \(\sim 10\%\) of the NLR emission, our dual-component model can explain the observed high \([\text{Fe} \text{ vii}] \lambda 6087/\lambda 5007\) intensity ratios of the Seyfert 1 nuclei without invoking any unusual assumptions (e.g., the overabundance of iron).

Subject headings: galaxies: active — galaxies: Seyfert

1. INTRODUCTION

It has been often considered that emission-line regions around active galactic nuclei (AGNs) are photoionized by the nonthermal continuum radiation from central engines (Davidson 1977; Kwan & Krolik 1981; see, for a review, Davidson & Netzer 1979; Osterbrock 1989). However, this photoionization scenario has sometimes been confronted with several serious problems: (1) any single cloud photoionization models underpredict the \([\text{O} \text{ iii}] \lambda 4363/\lambda 5007\) intensity ratio (e.g., Filippenko & Halpern 1984); (2) any (ionization-bounded) single cloud models cannot explain the large temperature difference between \(T_{\text{[O iii]}}\) and \(T_{\text{[N ii]}}\) (e.g., Wilson, Binette, & Storchi-Bergmann 1997); (3) any single cloud photoionization models underpredict higher ionization emission lines including ultraviolet emission lines such as \(\lambda 1909\) and \(\lambda 1549\) (e.g., Pelat, Alloin, & Bica 1987; see also Dopita et al. 1997); and (4) any single cloud photoionization models require the overabundance in some particular elements such as nitrogen and iron (e.g., Ho, Shields, & Filippenko 1993; Hamann & Ferland 1992, 1993). In order to reconcile the above dilemmas, multicomponent cloud models have been proposed (Stasińska 1984a, 1984b; Filippenko & Halpern 1984; Binette 1985; Ferland & Osterbrock 1986; Binette, Robinson, & Couvoisier 1988; Binette, Wilson, & Storchi-Bergmann 1996; Komossa & Schulz 1997; Ferguson, Korista, & Ferland 1997b; Ferguson et al. 1997a). Although this approach seems to be the natural extension of the single cloud photoionization models, there is no guiding principle for the multicomponent modeling because we do not have any unambiguous observational constraint on the geometrical structure of the ionized clouds in AGNs.

Recently Murayama & Taniguchi (1998; hereafter, MT98) have found that type 1 Seyfert nuclei (S1’s) have excess \([\text{Fe} \text{ vii}] \lambda 6087\) emission with respect to type 2 nuclei (S2’s). The S1’s exhibit broad emission lines that are attributed to ionized gas very close to the central engine (e.g., \(\sim 0.01 \text{ pc}\)), whereas the S2’s do not show such broad lines. The current unified model of AGNs explains this difference as the broad-line region in the S2’s being hidden from the line of sight by a dusty torus if we observe it from a nearly edge-on view toward the torus. Therefore, the finding of MT98 implies that the high-ionization nuclear emission line region (HINER) (Binette 1985; Murayama, Taniguchi, & Iwasawa 1998) traced by the \([\text{Fe} \text{ vii}] \lambda 6087\) emission resides in the inner wall of such dusty tori. Since the covering factor of the torus is usually large (e.g., \(\sim 0.9\)) and the electron density in the tori (e.g., \(\sim 10^5 - 10^6 \text{ cm}^{-3}\)) is considered to be significantly higher than that (e.g., \(\sim 10^3 - 10^4 \text{ cm}^{-3}\)) of the narrow-line region (NLR), the contribution from the torus dominates the emission of the higher ionization lines (Pier & Voit 1995). Taking this HINER component into account, we construct new dual-component (i.e., a typical NLR with a HINER torus) photoionization models and examine whether these models can explain the observations without invoking any unusual assumptions.

2. PHOTOIONIZATION MODELS

2.1. Single Cloud Models

In order to investigate the HINER of Seyfert galaxies within the framework of photoionization, we first perform single cloud photoionization model calculations using the spectral synthesis code CLOUDY version 90.04 (Ferland 1996), which solves the equations of statistical and thermal equilibrium and produces a self-consistent model of the run of temperature as a function of depth into the nebula. Here we assume that a uniform density, dust-free gas cloud with plane-parallel geometry is ionized by a power-law continuum source.

The parameters for the calculations are (1) the hydrogen density of the cloud \(n_{\text{H}}\), (2) the ionization parameter \(U\), (3) the spectral index of non-ionizing continuum between 10 \(\mu\)m and 250 \(\mu\)m (\(\alpha = f_{\text{c}} \approx n_{\text{H}}\)) , and (4) the chemical compositions. We adopt the following continuum spectrum, taking account of the one actually observed in AGNs (see Ho, Shields, & Filippenko 1993): (1) \(\alpha = 2.5\) for \(\lambda > 10 \mu\)m, (2) \(\alpha = -2\) to \(-1\) for \(250 \mu\)m < \(\lambda < 10 \mu\)m, and (3) \(\alpha = -2\) for \(\lambda < 250 \mu\)m. The total amount of metals is expressed as \(Z\) in units of \(Z_{\odot}\). In this Letter, the abundance of each element is defined as a number fraction relative to hydrogen and is expressed by bracketed quantities, e.g., \([\text{Fe}]/n(\text{Fe})/n(\text{H})\). All of the abundances are in units of...
solar values. However, taking into account the many lines of evidence in favor of a nitrogen overabundance (see Storchi-Bergman et al. 1996; Hamann & Ferland 1992, 1993), we adopt twice the solar nitrogen abundance as the standard value in our model calculations following Ho et al. (1993). Namely, all elements have solar values except for nitrogen, whose abundance will be twice the solar value. Adopted solar abundances relative to hydrogen are taken from Grevesse & Anders (1989). The calculations were stopped when the temperature fell to 4000 K, below which it was verified that little optical emission took place.

We are not going to present a detailed description of these single cloud models because the main purpose of this Letter is to present new dual-component photoionization models. Therefore, we give a summary of the single cloud models briefly (see Murayama 1998 for details) and describe the difficulty of the models. We have performed several model runs covering the following parameter ranges: (1) \( \alpha = -2, -1.5, \) and \(-1\), (2) \( \log U = -2.5, -2, -1.5, \) and \(-1\), (3) \( \log n_H \) (cm\(^{-3}\)) = 4, 5, 6, and 7, (4) \( |Z| = 1, 2, 5, \) and 10, and (5) \([\text{Fe}] = 1, 2, 5, \) and 10, keeping the other elemental abundances to the solar values. These parameter ranges were adopted in order to reproduce the observational properties of the HINER. We have confirmed that the intensity of \([\text{Ca} \, \text{ii}] \lambda 6087\) is always less than 5\% of that of \([\text{Fe} \, \text{vii}] \lambda 6087\) in all of the cases, providing the validity of the use of the \([\text{Fe} \, \text{vii}] \lambda 6087\) emission line.

Using several newly defined diagnostic diagrams (e.g., \([\text{Fe} \, \text{vii}] \lambda 6087/[\text{O} \, \text{iii}] \lambda 5007\) vs. \([\text{O} \, \text{ii}] \lambda 6300/[\text{O} \, \text{iii}] \lambda 5007\), \([\text{Fe} \, \text{x}] \lambda 6374/[\text{Ne} \, \text{v}] \lambda 3426\) vs. \([\text{Fe} \, \text{vii}] \lambda 6087/[\text{Ne} \, \text{v}] \lambda 3426\), and \([\text{Fe} \, \text{x}] \lambda 6374/[\text{O} \, \text{iii}] \lambda 5007\) vs. \([\text{Fe} \, \text{vii}] \lambda 6087/[\text{O} \, \text{iii}] \lambda 5007\), we have compared the model results with the observations (Osterbrock 1977, 1985; Koski 1978; Osterbrock & Pogge 1985; Shuder & Osterbrock 1981; Murayama 1998) and found that (1) the most probable values of \( \log U \) and \( \alpha \) are \(-2\) and \(-1\), respectively, (2) \( n_H \sim 10^{4} - 10^{7} \) cm\(^{-3}\), and (3) an unusually high iron abundance, up to 10 times the solar value while keeping the remaining elements the solar values, was required to explain the observed very high \([\text{Fe} \, \text{vii}] \lambda 6087/[\text{O} \, \text{iii}] \lambda 5007\) ratios for the S1’s (Murayama 1998). To briefly demonstrate these results, a comparison between the observations and the models is shown in Figure 1, which is a diagram of \([\text{Fe} \, \text{vii}] \lambda 6087/[\text{O} \, \text{iii}] \lambda 5007\) versus \([\text{O} \, \text{ii}] \lambda 6300/[\text{O} \, \text{iii}] \lambda 5007\). Note that we adopt \( \log U = -2 \) and \( \alpha = -1 \) for all of the models presented here. A serious problem is that a wide span in the iron abundance extending up to 10 times solar is required to explain the observational data points. Although the circumnuclear star-forming regions in Seyfert nuclei show a nitrogen overabundance of up to a factor of 3 at most (e.g., Storchi-Bergmann et al. 1996), it is quite unlikely that the NLR in the Seyfert nuclei shows a factor of 10 overabundance of iron because this overabundance cannot be explained in the terms of ordinary star formation history in galaxies. We also mention that single cloud models predict a tendency toward smaller \([\text{O} \, \text{ii}] \lambda 3727\) with increasing iron abundance. This may be due to the fact that when one increases the iron abundance, the contribution of \( \text{Fe}^+ \) and \( \text{Fe}^+ \) to the cooling within the partly ionized region increases more than that of \( \text{O}^+ \).

### 2.2. Dual-Component Cloud Models

As shown in MT98, the observed \([\text{Fe} \, \text{vii}] \lambda 5007\) ratios are systematically higher in S1’s than in S2’s. This suggests that the major contributor to the HINER emission in Seyfert nuclei has a viewing angle dependence in accordance with current unified models of AGNs (e.g., Antonucci 1993). It is reasonable to consider that the most probable site of this HINER emission corresponds to the inner edges of dusty tori. We therefore proceed to construct dual-component models in which the inner surface of a torus is introduced as a new ionized-gas component in addition to the traditional NLR component. The observed \([\text{Fe} \, \text{vii}] \lambda 5007\) ratios of the S1’s are \( \sim 0.1 \) on average, while those of the S2’s are \( \sim 0.01 \) (MT98). It is hence suggested that the typical NLRs have intensity ratios of \([\text{Fe} \, \text{vii}] \lambda 5007\) \( \sim 0.01 \) and that the higher ratios observed in S1’s than in S2’s are mostly due to the contribution from the HINER torus.

For the HINER torus component, we calculate photoionization models as follows. The single cloud model suggests that the ionization parameter lies in the range of \( \log U = -1.5 \) to \(-2 \). As for the electron density, it is often considered that the inner edges of tori have higher electron densities, e.g., \( n_e \sim 10^{-7} - 10^{-9} \) cm\(^{-3}\) (Pier & Voit 1995). This higher density is also expected in terms of the locally optimally emitting cloud models (Ferguson et al. 1997b). We therefore calculated models covering the following ranges of parameters: \( \log U = -2.2, -2.0, -1.8, -1.6, \) and \(-1.4, \) and \( \log n_H \) (cm\(^{-3}\)) = 6, 7, 8, 8.5, and 9. In order to increase the \([\text{Fe} \, \text{vii}] \lambda 5007\) ratio by 1 order of magnitude, the contribution to the \([\text{Fe} \, \text{vii}] \lambda 5007\) emission of the torus component must be very high. Because the largest \([\text{Fe} \, \text{vii}] \lambda 5007\) ratio of the observed data is \( \sim 0.5, \) \([\text{Fe} \, \text{vii}] \lambda 5007\) of the torus component must be greater than 0.5. However, we find that ionization-bounded models cannot explain the observed large \([\text{Fe} \, \text{vii}] \lambda 5007\) values by simply increasing electron densities up to \( 10^9 \) cm\(^{-3}\). Further, such very high density models yield unusually strong \([\text{O} \, \text{ii}] \lambda 3727\) emission with respect to \([\text{O} \, \text{iii}] \). We therefore assume “truncated” clouds with both large \([\text{Fe} \, \text{vii}] \lambda 5007\) and little low-ionization lines
for the HINER torus. The calculations were stopped at a hydrogen column density when [Fe v]/[O iii] = 1. The results are summarized in Table 1. For all of the models, we also calculated an [Fe x]/[Fe v] ratio. Since the average [Fe x][Fe v] ratio for Seyfert nuclei is ~0.4 (e.g., Pier & Voit 1995), the models with [Fe x][Fe v] > 1 are not appropriate. Also, taking into account the critical density of [Fe v], 3.6 × 10^7 cm^-3 (De Robertis & Osterbrock 1984), we adopt the model with n_H = 10^7 cm^-3 and log U = -2.0, which gives a ratio [Fe x]/[Fe v] of 0.8 as a representative model for the HINER torus. This model has a characteristic thickness of l = N_H/n_H = 10^13 cm. Therefore, if we consider the cloud to be matter bounded, its size is estimated to be ~10^13 cm. On the other hand, if we regard the cloud as an ionization-bounded one, we have to consider the case in which the cloud is so dense and dusty that only its surface is photoionized. This is indeed the cloud model considered by Pier & Voit (1995).

Their model gives a typical thickness of the surface layer at UV dust optical depth τ_d ~ 1, l_s = 6 × 10^{-2}F_{7}^{-1}T_{4} X_{A} cm, where F_{7} is the ionizing energy flux in units of 10^7 ergs cm^-2 s^-1, T_{4} is the gas temperature in units of 10^4 K, and X_{A} is the dust-to-gas ratio relative to the Galactic value. This is nearly the same as the characteristic length of our best model. Therefore, our truncated models can be consistently understood in terms of either matter-bounded models or ionization-bound models.

Now we can construct dual-component models combining this torus component model with the NLR models with α = -1, log U = -2, [Fe i] = 1, and log n_H (cm^-3) = 0-7 (see § 2.1). When we construct a composite model between the NLR and the torus component, we have to take into account the covering factor of the torus. It is known that the NLR shows a biconical emission-line morphology with a typical semi-opening angle of about 30° (e.g., Pogge 1989; Wilson & Tsvetanov 1994; Schmitt & Kinney 1986). This semi-opening angle implies a covering factor of the torus of 1 - ΔΩ/(4π) ~ 0.9, where ΔΩ is the full opening solid angle of the NLR cones in steradians. Therefore, one can infer that the relative contribution of the NLR component may be of the order 10%. In

Table 1

| log n_H (cm^-3) | log U | log L_{O[v]} = log L_{O[iv]}/log L_{Fe [x]} | log N_H (cm^-3) | [Fe x]/[Fe v] |
|----------------|-------|---------------------------------|----------------|--------------|
| 7.0            | -1.4  | 38.8                           | 21.1           | 53           |
| 7.0            | -1.6  | 39.1                           | 20.8           | 12           |
| 7.0            | -1.8  | 39.1                           | 20.3           | 3.0          |
| 7.0            | -1.4  | 38.9                           | 21.3           | 57           |
| 7.0            | -1.6  | 39.2                           | 21.0           | 14           |
| 7.0            | -1.8  | 39.4                           | 20.8           | 3.4          |
| 7.5            | -2.0  | 39.5                           | 20.4           | 0.8          |
| 7.5            | -1.4  | 38.6                           | 21.3           | 11           |
| 7.5            | -1.6  | 39.0                           | 21.1           | 21           |
| 7.5            | -1.8  | 39.3                           | 20.3           | 5.2          |
| 8.0            | -2.0  | 39.3                           | 20.6           | 1.5          |
| 8.0            | -2.2  | 39.1                           | 20.1           | 0.4          |
| 8.5            | -1.4  | 38.3                           | 21.3           | 163          |
| 8.5            | -1.6  | 38.6                           | 21.1           | 52           |
| 8.5            | -1.8  | 38.9                           | 20.9           | 10           |
| 8.5            | -2.0  | 39.0                           | 20.6           | 2.8          |
| 8.5            | -2.2  | 38.8                           | 20.3           | 0.7          |
| 9.0            | -1.6  | 38.2                           | 21.1           | 77           |
| 9.0            | -1.8  | 38.4                           | 20.9           | 20           |
| 9.0            | -2.0  | 38.5                           | 20.6           | 5.3          |
| 9.0            | -2.2  | 38.4                           | 20.3           | 1.4          |

*The intensity ratio of [Fe x] λ6374/[Fe v] λ6087.

Figure 2, we present the results of the dual-component models. Here the lowest dashed line shows the results of the NLR component models with α = -1, log U = -2, and [Fe i] = 1 as a function of n_H from 1 to 10^6 cm^-3. If we allow the contribution from the torus component to reach up to ~50% in the Seyfert nuclei with very high [Fe v][O iii] ratios, we can explain all of the data points without invoking the unusual iron overabundance. Note that the majority of objects can be explained by simply introducing a ~10% contribution from the HINER torus. The important quantities characterizing the models are summarized in Table 2. The model area shown in Figure 2 fits the observed data points better than that in Figure 1. The dual-component models predict the occurrence of a lower cutoff in the [O i]/[O iii] ratio, i.e., no object with log [O i]/[O iii] smaller than -1.8, which is consistent with the observations. However, as shown in Figure 1, single cloud models of both low density and high iron abundance predict, on the contrary, the existence of AGNs with log [O i]/[O iii] < -1.8. This further supports our contention that the dual-component models studied here are more successful than the single cloud models.

3. CONCLUDING REMARKS

There has been a debate about the origin of the high-ionization lines. The possible origins are summarized as follows: (1) a hot collisionally ionized gas with temperatures of T_e ~ 10^6 K (Oke & Sargent 1968; Nussbaumer & Osterbrock 1970), (2) a cool gas (T_e ~ a few times 10^4 K and n_H ~ 10^6 cm^-3) photoionized by the central nonthermal continuum emission (Osterbrock 1969; Nussbaumer & Osterbrock 1970; Grandi 1978), (3) a low-density (e.g., n_H ~ 1 cm^-3) interstellar medium photoionized by the central nonthermal continuum emission (Korista & Ferland 1989; see also Murayama et al. 1998), and (4) a combination of shocks and photoionization by the central nonthermal continuum emission (Viegas-Aldrovandi & Contini 1989). Although photoionization models seem to be a modest
idea, they cannot explain the observed strong high-ionization lines (Murayama et al. 1998 and references therein). However, MT98 found that the S1’s have excess [Fe v ii] \( \lambda \)6087 emission with respect to the S2’s, implying that the majority of the HINER emission in the S1’s arises from the inner wall of dusty tori. Indeed, we have shown that our new dual-component photoionization models incorporating the contribution from the HINER torus can explain the observed higher [Fe v ii]/[O i] ratios in the S1’s. Although shock models can also explain the observations (Dopita & Sutherland 1995, 1996; Dopita et al. 1997; Terlevich et al. 1992), it is important to construct more realistic multicomponent photoionization models in which detailed physical properties of ionized clouds are taken into account (e.g., ionization-bounded and matter-bounded clouds; Binette et al. 1996, 1997; Wilson et al. 1997).

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