ELUCIDATING THE CORRELATION OF THE QUASAR $\text{Fe}^{\text{II}}/\text{Mg}^{\text{II}}$ RATIO WITH REDSHIFT

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Received 2004 March 11; accepted 2004 April 22; published 2004 May 12

ABSTRACT

Interpretation of the Fe $\text{II}$(UV)/Mg $\text{II}$ emission ratios from quasars has a major cosmological motivation. Both Fe and Mg are produced by short-lived massive stars. In addition, Fe is produced by accreting white dwarf supernovae somewhat after star formation begins. Therefore, we expect that the Fe/Mg ratio will gradually decrease with redshift. We have used data from the Sloan Digital Sky Survey to explore the dependence of the Fe $\text{II}$(UV)/Mg $\text{II}$ ratio on redshift and on luminosity in the redshift range of $0.75 < z < 2.20$, and we have used predictions from our 830-level model for the Fe $\text{II}$ atom in photoionization calculations to interpret our findings. We have split the quasars into several groups based on the value of their Fe $\text{II}$(UV)/Mg $\text{II}$ emission ratios and then checked to see how the fraction of quasars in each group varies with the increase of redshift. We next examined the luminosity dependence of the Fe $\text{II}$(UV)/Mg $\text{II}$ ratio, and we found that beyond a threshold of Fe $\text{II}$(UV)/Mg $\text{II}$ = 5, and $M_{17015} < -25$ mag, the Fe $\text{II}$(UV)/Mg $\text{II}$ ratio increases with luminosity, as predicted by our model. We interpret our observed variation of the Fe $\text{II}$(UV)/Mg $\text{II}$ ratio with redshift as a result of the correlation of redshift with luminosity in a magnitude-limited quasar sample.

Subject headings: atomic processes — line: formation — methods: numerical — quasars: emission lines

1. INTRODUCTION

Recently, the number of observational efforts focused on Fe $\text{II}$(UV)/Mg $\text{II}$ emission ratio measurements has increased because of the potential use of these ratios to trace star formation history. Both Fe and Mg are produced by short-lived massive stars (Type II supernovae), and additional Fe is produced by accreting white dwarf supernovae (Type Ia) sometime later. Thus, one expects that the Fe/Mg ratio is low at high redshift and that it gradually increases with decreasing redshift, with the increase starting at a redshift of about 4, corresponding to an age for the universe of 1.5 Gyr (Hamann & Ferland 1993; Yoshii et al. 1998), or even as early as a redshift of 6 if star formation begins at (Matteucci & Recchi 2001).

Although many independent ways to measure Fe $\text{II}$(UV)/Mg $\text{II}$ ratios observed in the UV-to-IR range have been developed and applied to different data sets, the common conclusion is that the Fe $\text{II}$(UV)/Mg $\text{II}$ ratio shows a large scatter at all redshifts and little evolution with redshift (Kwan & Krolik 1981; Wills et al. 1985; Kinney et al. 1991; Kawara et al. 1996; Thompson et al. 1999; Iwamuro et al. 2002; Dietrich et al. 2002; Freudling et al. 2003; Barth et al. 2003; Dietrich et al. 2003; Maiolino et al. 2003). Furthermore, it is usually assumed that there is a linear dependence between the Fe $\text{II}$(UV)/Mg $\text{II}$ and Fe/Mg ratios because the ionization potentials of Mg II (7.65 eV) and Fe (7.87 eV) are nearly the same.

In our previous study, we showed that the Fe $\text{II}$(UV)/Mg $\text{II}$ ratios are more sensitive to other physical properties of the emitting region than to abundance (Verner et al. 2003, 2004). If the physical conditions are different in the broad-line regions (BLRs) of different quasars, the resulting scatter of Fe $\text{II}$(UV)/Mg $\text{II}$ ratios obscures any dependence on abundance. Thus, it is important to explain the origin of the observed scatter before attempting to derive the Fe/Mg relative abundance in quasars.

Although the prominent emission lines observed in quasars generally allow us to evaluate the metallicity of galactic nuclei, to link specifically the Fe $\text{II}$ emission with Fe abundance is not a simple task. Compared with many other ions, the Fe $\text{II}$ ion has a very rich spectrum because of its half-filled 3$d$ shell. As a result, the Fe $\text{II}$(UV) band from 2200 to 3000 Å (hereafter Fe $\text{II}$(UV)) can contain hundreds of strong lines. The Fe $\text{II}$(UV)/Mg $\text{II}$ emission ratio is therefore heavily affected by many Fe lines but by only the two Mg $\text{II}$ doublet lines at 2800 Å. Nevertheless, in order to measure the Fe/Mg abundance ratio, obtaining the Fe $\text{II}$(UV)/Mg $\text{II}$ ratio is unavoidable.

As quasar spectra (line intensities and continuum) are heavily affected by Fe $\text{II}$ emission, it is possible to learn more about BLRs in quasars by studying how the Fe $\text{II}$ originates. To achieve such a goal, we have constructed an 830-level model for the Fe $\text{II}$ atom and investigated how Fe $\text{II}$(UV)/Mg $\text{II}$ ratios vary with changes in hydrogen density, microturbulence, and abundance. The model also predicts that the Fe $\text{II}$(UV)/Mg $\text{II}$ ratio strongly depends on the ionizing flux of the central source.

In this Letter, we have investigated whether or not there is any dependence of Fe $\text{II}$(UV)/Mg $\text{II}$ ratios with redshift. For the first time, our approach combines model predictions with measurements (provided by F. Iwamuro [2004, private communication]) of the Fe $\text{II}$(UV)/Mg $\text{II}$ ratios of quasars in the extended redshift range, $0.75 < z < 2.20$, for quasars in the Sloan Digital Sky Survey (SDSS).$^4$

2. Fe $\text{II}$(UV)/Mg $\text{II}$ DEPENDENCE ON REDSHIFT

The Fe $\text{II}$ spectrum has a rich and complicated mixture of forbidden and permitted lines. Russell (1926), in his pioneering work on the term analysis of singly ionized iron, reported 61 energy levels. Since work on Fe $\text{II}$ energy measurements is still not completed (Johansson 1978; S. Johansson 2004, private communication), it is not surprising that the very first attempts to explain Fe $\text{II}$ in BLRs were not able to reproduce large

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$^4$ See http://www.sdss.org.
Fe ii(\text{UV})/Mg ii ratios when assuming solar abundance (Kwan & Krolik 1981; Wills et al. 1985).

Our 830-level model for the Fe ii atom in photoionization calculations is able to account for nonabundance factors (e.g., microturbulence, hydrogen density, and ionizing flux). This model is a natural extension (up to 14.1 eV) of our earlier model for Fe ii, which included 371 energy levels below 11.6 eV (Verner et al. 1999). The increase in the number of transitions from 68,638 to 344,035 is largely due to the increased density of energy levels at higher energy. The Fe ii(\text{UV})/Mg ii ratios have been investigated by assuming ranges of iron abundances (1, 5, and 10 in solar units) and microturbulence (\(v_{\text{turb}} = 0, 1, 10, \) and 100 km s\(^{-1}\)). Based on our model predictions, we conclude that the Fe ii(\text{UV})/Mg ii ratio is less sensitive to abundance than the Fe ii(\text{UV})/Fe ii(\text{optical}) ratio [where Fe ii(\text{optical}) is at 4000–6000 Å; Verner et al. 2003, 2004].

After we found that the abundance is not the strongest factor that determines the Fe ii(\text{UV})/Mg ii ratio in BLRs of quasars, calculations were repeated for a wide range of physical conditions, assuming solar abundance, a constant km s\(^{-1}\) stray line, and a UV-to-optical spectral index, \(\alpha_{\text{UV}} = -1.4\). Figure 1 presents the results of model calculations of the Fe ii(\text{UV})/Mg ii ratio as a function of density and ionizing photon flux. Although solar abundance is assumed throughout, our model predicts that the Fe ii(\text{UV})/Mg ii ratio may reach values as large as 40 under conditions of high density and high ionizing photon flux. Most observed values lie in the range \(2 < r < 5\), with only a small fraction falling in the range \(10 < r < 20\), where \(r\) is the Fe ii(\text{UV})/Mg ii ratio. The Fe ii(\text{UV})/Mg ii ratio should be relatively constant at low density and weak ionizing photon flux, but should rise steeply with ionizing photon flux beyond \(\Phi = 10^{20.0}\) photons cm\(^{-2}\) s\(^{-1}\) and \(n_{\text{H}} > 10^{11}\) cm\(^{-3}\).

Our large Fe ii model used in photoionization calculations predicts that the Fe ii(\text{UV})/Mg ii ratios can have the same value over a wide range of physical conditions (Fig. 1). Therefore, the typical observed Fe ii(\text{UV})/Mg ii ratio of ~4 may arise from different excitation and density regimes.

The SDSS database (Schneider et al. 2003) includes 11,677 objects within 0.75 < \(z\) < 2.2. F. Iwamuro (2004, private communication) was able to measure the Fe ii(\text{UV})/Mg ii ratio for 10,670 of these quasars, and these are included in the sample under study. The smallest and the largest selected redshifts are \(z_{\text{min}} = 0.7485\) and \(z_{\text{max}} = 2.1964\), correspondingly. The median redshift of the sample is \(z_{\text{med}} = 1.4573\).

In Figure 1, we see that at high flux levels (log \(\Phi > 20.5\)), the Fe ii(\text{UV})/Mg ii ratio behaves differently in the high- (log \(n_{\text{H}} > 11\)) and low- (log \(n_{\text{H}} < 11\)) density regimes. At high density, collisions enhance the Fe ii(\text{UV}) emission, while at low density, the Fe ii(\text{UV}) emission drops relative to the Mg ii emission. Very large values of the Fe ii(\text{UV})/Mg ii ratio, those greater than 10, are expected only at high luminosity and high density. At lower flux levels (log \(\Phi < 20.5\)), the Fe ii(\text{UV})/Mg ii ratio shows little density dependence, and we can generally conclude that the Fe ii(\text{UV})/Mg ii ratio depends on the ionizing flux.

We divide quasars into several groups depending on the value of ionizing flux, keeping the Fe ii(\text{UV})/Mg ii ratios within a relatively small range: (1) the Fe ii(\text{UV})/Mg ii < 2 group shows almost no dependence on hydrogen density and is mainly due to low ionizing flux; (2) the 2 < Fe ii(\text{UV})/Mg ii < 5 group includes most quasars; (3) the 5 < Fe ii(\text{UV})/Mg ii < 7.5 group has a ratio that is a little bit higher than the typical value; (4) the 7.5 < Fe ii(\text{UV})/Mg ii < 10 ratios in this group in previous studies were usually interpreted as having increased Fe abundance; and (5) the Fe ii(\text{UV})/Mg ii > 10 group has large ratios that are relatively rare.

The measured Fe ii/Fe iii ratio depends strongly on the fitting technique. High values of the Fe ii/Fe iii ratio result when the Fe ii contribution to the Mg ii doublet is taken into account using the quasar template from Wills et al. (1985). Results based on the I Zw 1 template (Vestergaard & Wilkes 2001; Dietrich et al. 2002) underestimate the contribution of Fe ii to the Mg ii doublet (see Verner et al. [2003, 2004] for more detailed discussion).

Iwamuro et al. (2002) have developed a parameterized fitting procedure to obtain the Fe ii(\text{UV})/Mg ii ratio. The Fe ii(\text{UV})/Mg ii ratio is defined over 2150–3300 Å to include the majority of Fe ii(\text{UV}) emission and to avoid the feature below 2150 Å. This feature is possibly due to the contribution of a Comptonized accretion disk (Zheng et al. 1998). Iwamuro et al. applied their method to independently obtained data in the wide redshift range, 0 < \(z < 5.3\) (Kinney et al. 1991 and \(HST/FO\) archival data \(z < 0.17\), SDSS archival data \(0.75 < z < 2.29\), Thompson et al. 1999 data \(3.1 < z < 4.7\), and the high-redshift sample \(4.4 < z < 5.3\)). As a result of such examination, they concluded that Fe ii(\text{UV})/Mg ii emission ratios in quasars show large scatter from 1 to 20 with little evidence of the evolution of the Fe ii(\text{UV})/Mg ii ratio with redshift and that luminosity does not have a large effect on the Fe ii(\text{UV})/Mg ii ratio, except for extremely bright objects.

We have reexamined the redshift dependence of the Fe ii(\text{UV})/Mg ii ratios measured by F. Iwamuro (2004, private communication) in the SDSS quasars over the range 0.75 < \(z < 2.20\). We compute the fraction of quasars with various Fe ii(\text{UV})/Mg ii ratios in each redshift bin (\(\Delta z = 0.2\)). We find that the fractions are constant at low redshift but show an increase in the
relative numbers of quasars with Fe ii/(UV)/Mg ii ratio groups. The numbers on the top show the total number of quasars in each bin. The quasar sample comprises those quasars from the SDSS in the redshift range 0.75 < z < 2.20.

In any survey that is magnitude-limited, the most luminous objects will be seen over the entire survey volume, while the least luminous objects will only be seen nearby. This induces a correlation between luminosity and redshift. We adopt a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_m = 0.3$, $\Omega_L = 0.7$ for the estimation of the absolute AB magnitude at rest wavelength 2500 Å, $M_{\text{2500}}$. The smallest and the largest $M_{\text{2500}}$ in the sample are $M_{\text{min}}^{2500} = -21.67$ mag and $M_{\text{max}}^{2500} = -28.64$ mag. The median luminosity of the sample is $M_{\text{med}}^{2500} = -24.86$ mag.

For each Fe ii/(UV)/Mg ii ratio, we plot the mean absolute luminosity of the quasars in each redshift bin versus redshift and find a very strong correlation between redshift and luminosity (Fig. 3). We next examine the luminosity dependence of the Fe ii/(UV)/Mg ii ratio in the SDSS quasars over the range 0.75 < z < 2.20. We compute the fraction of quasars with various Fe ii/(UV)/Mg ii ratios in each luminosity bin. We find that the fractions are constant at low luminosity but show an increase in the relative numbers of quasars with Fe ii/(UV)/Mg ii > 5 at high luminosity, $M_{\text{2500}} < -25$ mag. We have found that beyond a threshold, the Fe ii/(UV)/Mg ii ratio increases with quasar luminosity (Fig. 4). This behavior is entirely consistent with our model (Fig. 1). At low flux levels, log $\Phi < 19$, increasing luminosity has little effect on the Fe ii/(UV)/Mg ii ratio, while at higher flux levels, log $\Phi > 19$, the ratio steeply increases.

The much larger number of atomic levels for the Fe ii atom used in the photoionization calculations provides an enhanced accuracy to account for the radiation field and enables us to explain the large Fe ii/(UV)/Mg ii ratios better than in any previous efforts. The complicated level structure of the Fe ii ion leads to a more rapid increase of Fe ii emission with an increase of ionizing flux. More Fe ii levels become populated, and more lines contribute to the total Fe ii emission. Since no iron overabundance is needed to explain the large Fe ii/(UV)/Mg ii ratios that are observed, we have used solar abundances throughout our study (Verner et al. 2003, 2004). Observations of Fe ii/(optical) are needed to find out whether or not the discovered change of Fe ii/(UV)/Mg ii ratio with luminosity also reflects a change in other physical conditions (e.g., hydrogen density) in emitting regions of BLRs.

3. CONCLUSIONS

While the extensive quantitative comparisons between Fe ii/(UV)/Mg ii ratio measurements and model predictions are needed, it is clear that our model predictions are in general agreement with our observational results. Although it has been suggested to us to use the Fe ii/(UV)/Mg ii ratio to trace evolution, the physical processes forming lines in the Fe ii/(UV) band means that the Fe ii/(UV)/Mg ii ratio tells us more about the central ionizing source than about abundances. Thus, we can only convert an Fe ii/(UV)/Mg ii ratio into an Fe/Mg ratio when a measurement of the Fe ii/(optical) band has also been obtained.

Our analysis demonstrates that the observed Fe ii spectra can be produced by a wide range of ionizing flux regimes. The statistical approach applied to physically distinguished Fe ii/(UV)/Mg ii ratio groups will provide a more efficient way to improve...
our understanding of BLRs in quasars than the universal template approach.

Due to the complexity and richness of the Fe\textsuperscript{ii} spectra in quasars, only the comparison between model predictions and extensive observations make it possible to provide accurate measurements of changes of physical conditions and abundances in quasars with redshift. It is possible that the change we see is due not only to luminosity but to the hydrogen density changes in the BLR with redshift as well. Wide-wavelength coverage in the observations is needed for a successful understanding.

We find an increase in the Fe\textsuperscript{ii}(UV)/Mg\textsuperscript{ii} ratio with redshift, while evolutionary models predict a decrease. The Fe\textsuperscript{ii}(UV)/Mg\textsuperscript{ii} ratio is not sensitive to abundance changes (see Fig. 4 in Verner et al. 2003), but it is strongly affected by luminosity. We have found that the relative numbers of quasars with a high Fe\textsuperscript{ii}(UV)/Mg\textsuperscript{ii} ratio increases with luminosity, as predicted by our model. We conclude that the apparent change in the Fe\textsuperscript{ii}(UV)/Mg\textsuperscript{ii} ratio with redshift is simply a result of the correlation of redshift with luminosity in the magnitude-limited quasar sample and is not produced by a change in abundance.

We are very grateful to Fumihide Iwamuro for providing us with his measurements of the Fe\textsuperscript{ii}/Mg\textsuperscript{ii} emission ratios in the spectra of SDSS quasars. We are happy to acknowledge discussions with Professor K. Kawara and his group at the University of Tokyo regarding the chemical evolution of Fe/Mg, the effect of luminosity on Fe\textsuperscript{ii} emission, and the observation of these phenomena. Our analysis provides an independent observational and theoretical confirmation that, for the brightest quasars, the luminosity of the central source affects the Fe\textsuperscript{ii}/Mg\textsuperscript{ii} emission ratio (Iwamuro et al. 2002).

This research of E. V. has been supported by NSF grant 0206150 to CUA and in part by a visiting program at Mount Stromlo Observatory, ANU. Funding for the SDSS has been provided by the Alfred P. Sloan Foundation, the participating institutions, the National Aeronautics and Space Administration, the National Science Foundation, the US Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS is managed by the Astrophysical Research Consortium (ARC) for the participating institutions. The participating institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, the University of Pittsburgh, Princeton University, the US Naval Observatory, and the University of Washington.

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