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活动星系核中的“FeⅡ发射线问题”

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提 要

活动星系核(AGNs)的光谱中出现非常强的FeⅡ发射线是用标准的光致电离模型解释发射线问题时碰到的一个难题，这个问题的存在是我们认识活动星系核的物理结构和能源机制的一大障碍。本文首先介绍了自从FeⅡ发射线在类星体3C273中被首次认证以后有关活动星系核的FeⅡ发射谱的研究工作。归纳了FeⅡ发射谱的观测特征及其理论解释，较全面地评述了目前有关活动星系核中“FeⅡ发射线问题”的研究进展，并提出解决这一困惑的新途径。

“Fe Ⅱ Problem” in Active Galactic Nuclei

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Abstract

The photoionization model of broad line region fails to explain the very strong FeⅡ lines in the spectra of active galactic nuclei. The existence of this puzzling problem is an obstacle to understand the physics and power mechanism of active galactic nuclei. In this paper, we review the progress of the studies of FeⅡ emission since the first identification of FeⅡ lines in the spectrum of QSO 3C 273, including both the observations and the theoretical explanations. And we suggest a new way to attack this problem.

1. Analysis of Observations

FeⅡ emission lines were first identified by wampler and Oke[1] in 1967. They analysed the emission spectrum of QSO 3C 273, and found that there were some unidentified emission features in optical band with strong intensity and broad width. They tried to fit these features with some known emission lines of some other elements, but failed to do so. Comparing the spectrum of 3C 273 with that of Hercules Nova at the maximum of light curve (where FeⅡ emission lines are prominent),

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they found that there are many similarities between the two spectra, and concluded that these unidentified emission features of 3C 273 in the ranges of 4450–5500 Å and 5100–5500 Å were the overlapping Fe Ⅱ line-series. They analysed the formation mechanism of these Fe Ⅱ emission lines, and inferred that the absorption of UV continuum photons emitted from the core region was the exciting mechanism of Fe Ⅱ lines. The absence of forbidden lines [Fe Ⅱ]in observations implies that the electron density in the Fe Ⅱ emission region is larger than $10^6\mathrm{cm}^{-3}$–$10^7\mathrm{cm}^{-3}$. Afterwards, Sargent[2] observed and analysed the emission spectrum of Seyfert 1 galaxy I Zw1, and found that there were abundant broad emission lines with FWHM~3000 $\mathrm{km\cdot s^{-1}}$ in superposition on the strong continuum background (without absorption lines). By analogy with the spectrum of QSO 3C273, the broad emission lines of I Zw1 are identified as Balmer lines and overlapping Fe Ⅱ lines. Therefore the emission lines were confirmed again. However, the individual Fe Ⅱ lines could not be identified in detail because of the broad line-characteristics of the Fe Ⅱ features.

Since the first identification of these unknown features in the spectrum of QSO 3C273 and their reconfirmation in Seyfert galaxy I Zw1, Fe Ⅱ emission lines have been identified in many other objects. Osterbrock[3] firstly surveyed Seyfert 1 galaxies systematically, and found that nearly all of this kind of objects have Fe Ⅱ emission lines with three peaks which are located at wavelengths λ4570 Å, λ5190 Å, λ5320 Å. Phillips[4,5,6] observed the spectra of many samples of Seyfert galaxies and quasars, and discussed the properties of Fe Ⅱ emission lines in detail. In the following, we try to summarize systematically the observational characteristics of Fe Ⅱ emission lines:

(1) Fe Ⅱ emission lines exist in most active galactic nuclei with broad lines[7]. In the optical band, 90% to 100% of Seyfert 1 galaxies have optical Fe Ⅱ emission lines, but these lines hardly appear in Seyfert 2 galaxies. A few Seyfert 2 galaxies (e.g.Mrk 42) appear to have Fe Ⅱ emission features, but they seem to be more like Seyfert 1 galaxies in other observation respects. In fact, Mrk 42 was first attributed to Seyfert 1 galaxies[8]. Although the first identification was made for QSO 3C273, Fe Ⅱ emission lines are seldom present in the spectra of other quasars as in Seyfert 1 galaxies. The survey of 20 quasars with redshift $0.35<z<0.70$ by Phillips[4] showed that only ~10% of these samples have optical Fe Ⅱ emission. Up to 1977, although Fe Ⅱ emission had been observed in a large number of Seyfert 1 galaxies, only 5 quasars had Fe Ⅱ emission, i. e. 3C273[1], PKS 0736+01[9], 3 C48[4], PHL 1093[10] and PKS 1510-08[4]. Therefore the Fe Ⅱ emission is weak in low-redshift quasars. In the UV band, Wills and Netzer[11] first observed UV Fe Ⅱ emission of quasars with middle-redshift in 1980. One of their conclusions is that all quasars

(and Seyfert 1 galaxies)have very strong UV Fe Ⅱ emission;despite of the intensities of optical Fe Ⅱ emission. This means that for different AGNs the ratio of optical and UV Fe Ⅱ emission intensity can be very different from each other.

(2) The intensities of Fe Ⅱ emission lines are large.The ratio of the total intensity of Fe Ⅱ emission lines to that of Lyα, I(Fe Ⅱ$_{tot}$)/I(Lyα) is near to/or larger than unity, and Lyα is usually the strongest one among the broad lines of active galactic nuclei. This is what Wills et al.[12] called "Fe Ⅱ /Lyα Problem".But Collin-Souffrin[13] pointed out that it is more precise to call it "Fe Ⅱ /Hβ Problem".From observations, the value of ratio Fe Ⅱ opt/Hβ is among 0.4–26 with a mean value of about 7, while the mean value of Fe Ⅱ tot/Hβ is about 12 with a maximum value larger than 30.

(3) As to the line profile, It seems that Fe Ⅱ lines have similar width as HI lines[5]. Generally, HI lines have both broad-line and narrow-line components, but there is no evidence to show that Fe Ⅱ lines have narrow-line components. The similarity of line-width of Fe Ⅱ and HI implies that they may be formed in the same line emission region. It is very difficult to get a precise Fe Ⅱ line-width, because Fe Ⅱ emission features are always composed of a large number of Fe Ⅱ lines which overlap one another (perhaps including some emission lines of other elements).

(4) Analysis of observations shows that there is no correlation between Fe Ⅱ emission and the power-law continuum emitted from the core region. Osterbrock[3] analysed the relation between the line-intensity of Seyfert 1 galaxies and color index U-B, and found that the intensity of Hβ increased with the line-width of HI, but the intensities of Fe Ⅱ lines are uncorrelated with its width (taking the line-width of Fe Ⅱ as that of HI). Phillips[6] analysed the observed Fe Ⅱ lines and the spectral index, and concluded that there is no correlation between them.

(5) It has been unsuccessful to find any correlation between Fe Ⅱ lines and other spectral characteristics, but some other possibilities have been suggested. For example:

(1) There could be a negative correlation between the optical Fe Ⅱ lines and the radio emissions[3,14,15], i. e., the radio quiet AGNs have stronger optical Fe Ⅱ lines than radio loud ones. But the UV Fe Ⅱ lines seem to be uncorrelated with the radio emission. The relation of Fe Ⅱ lines with the radio objects seems to be different for different radio configurations[16-20].

(2) In Seyfert 1 galaxies the optical Fe Ⅱ lines have some correlations with the IR emission[21].

(3) Joly[22] analysed Fe Ⅱ and Ca Ⅱ lines, and found that there is a remarkable correlation between the two.

(4) It seems that, the stronger the intensities of Si Ⅳ lines are, the stronger

the intensities of Fe Ⅱ lines would be[23].

(5) It was proposed that there could be a correlation between the optical Fe Ⅱ lines and X-ray emission[24]. However, Boroson[16] negated the existence of such a correlation, and Zheng and O'Brien's analysis[26] also shows that there is no correlation between the optical Fe Ⅱ lines and the index of soft X-ray continuum.

2. The Theoretical Study

The basic picture of traditional model of active galactic nuclei is as follows. Power-law continuum is produced from the central dense core region, where the central object is generally thought to be a black hole. The source of released energy is just the accretion onto the black hole. Around the core region there is a line-emission region where exist a lot of gas cloudlets. Based on their physical properties,the line-emission region is further divided into two subregions, i. e. the broad line region and the narrow line region. Our knowledge of the active galactic nuclei mostly comes from the study of the spectra of line-emissions. The broad emission line region is one of the most important characteristics of this kind of objects. The research of broad line region enables us to infer the main properties of these objects such as the distance,size,louminosity etc. So far the generally accepted model for the broad line region is the photoionization model in which the gas clouds are illuminated by the continuum from the core region. This is the most successful theory at present to explain the formation and properties of the broad emission lines.

Our knowledge of active galactic nuclei becomes much deeper as our understanding of the broad line region becomes better. Though there are different models, almost everyone agrees that the broad line region consists of many gas cloudlets, moving rapidly around the central UV and X-ray source. But there are still some questions which are difficult to answer, such as: Is the broad line region an uniform emission region or composed of several subregions with different densities and ionization parameters? Is there only a central illuminating source or there are other sources? Is there any dust? Are the elements in the same abundance as in the sun? In order to answer these questions, we must not only determine the physical parameters of the broad line region, but envisage a shape of the continuum spectrum in 10-100Å which has not been observed yet in order to get the dynamical parameters and to understand the energy mechanism of active galactic nuclei. Nevertheless, detailed models have been suggested for active galactic nuclei[28] by use of a similar approach to the research of photoionization of planetary clouds. Davidson and Netzer[30] gave a review for all research work before 1979. However, a really important progress in the study of AGNs was made after 1979, when the ionization of the hydrogen from excited states and the resonant absorption calculated by use of the method of escaping probability were taken into consideration[31,32]. Kwan and Krolik[33] suggested an important model(standard model)in 1981 to calculate the broad emission lines, and obtained a good fitting with the observed spectra of quasars. They also discussed the dependence of the emission-line intensity on the physical conditions. Collin-Souffrin et al.[34,35] set up a more detailed model for broad line region. They solved the radiative transfer equation instead of using the escaping possibility method, and discussed the properties of the emission lines in the case of column density larger than $10^{23}cm^{-3}$. All these models are based on the assumption that all the broad emission lines are produced in the gas clouds of the broad line region. Afterwards, Collin-souffrin et al.[36] began to take the line-emission of accretion disk into consideration. The detailed research work concerning to the physics of the outer region of the accretion disk ($R\sim10^4Rg$) was presented in their systematic papers[36-42]. They suggested that the outer part of the accretion disk illuminated by X-rays is a favourable region for producing the low-ionization lines (the main components of broad emission lines). This is a very important progress in the discussion on the broad emission line region. It impels researchers to think that the gas clouds in broad line region are not an unique place to produce the broad emission lines.

The study of Fe Ⅱ emission lines is strongly dependent on the development of the photoionization model. In order to research Fe Ⅱ line emission, one must know the details of the transitions among the energy levels and the excitation mechanism of Fe Ⅱ. From the Grotrian diagram[26] of Fe Ⅱ we see that the usual optical Fe Ⅱ emission lines come from the transitions from energy levels 3 with odd parity (~5.5 eV, this level is labelled as "Z" in the diagram) to energy levels 2 with even parity (~3 eV, the metastable energy levels labelled as "a", "b"). The transition from levels 2 to levels 1 with even parity (the ground state and near ground states labelled as "a" including three energy levels as a^6D, a^4F, a^4D) is forbidden because both levels 2 and 1 have even parity, while the transition from levels 3 to levels 1 produces UV photons. Therefore, in order to produce optical Fe Ⅱ emission lines, it is necessary to excite firstly the ion Fe^+ from the ground state to levels 3. So far the proposed mechanisms of excitation from levels 1 to levels 3 are as follows.

(1) Resonant fluorescence: The absorption of the UV photons (2300-2800Å) of the power-law continuum from the core region excites Fe^+ ions from levels 1 to levels 3. There are two radiative transition paths, i. e. 3→1 and 3→2. The former produces UV Fe Ⅱ photons, and the latter produces optical Fe Ⅱ lines. If this excitation mechanism is the main one, then we expect that the intensities of Fe Ⅱ emission lines must correlate with the spectral index α and the intensity of UV continuum,

therefore the stronger the UV continuum is, the larger the intensity of Fe Ⅱ emission lines would be. We have pointed out above that the observations do not support this point. Moreover, for this Fe Ⅱ excitation mechanism, there is another difficulty which concerns the intensity of Si Ⅱ lines. The Si Ⅱ emission line λ5979Å and Fe Ⅱ line λ5169Å must be present simultaneously due to the fact that they have nearly the same ionization potential. But such an expectation is not supported by observations, for example, for I Zw1, taking the abundance $Si/Fe \simeq 1.4$ same as that of the sun, we can calculate that $I(Si\,Ⅱ\,\lambda5179)/I(Fe\,Ⅱ\,\lambda5169) \sim 0.46$, but the observed value is very small (less than 0.1), and it is very difficult to observe.

(2) Collisional excitation: The electron density of the emission region can be estimated as $n_e \gtrsim 10^7 cm^{-3}$ due to the fact that the forbidden line [Fe Ⅱ] has not been observed yet. In such a high density, the collisional excitation is one of the important excitation mechanisms for Fe Ⅱ emission[27]. But the observed ratio of the intensity of a typical collisionally excited line Mg Ⅱ λ2798Å to that of Fe Ⅱ emission is much less than the expected value. It is a difficult problem for this mechanism.

(3) Radiative recombination: Recombination-cascade processes are also one of the mechanisms for producing emission lines. For Fe Ⅱ, taking sun abundance, we may make a crude estimation as $I(Fe\,Ⅱ)/I(H\beta) \leqslant N_e N_{Fe^{2+}} \alpha_T(Fe^{2+} \to Fe^+)/(N_e N_p \alpha_H) \leqslant 7.6 \times 10^{-4}$. Therefore, the intensity of Fe Ⅱ emission lines from this mechanism will be much less than the observed value except the abundance of Fe is anomaly increased.

(4) Line fluorescence: The superposition among Fe Ⅱ lines or between Fe Ⅱ lines and Mg Ⅱ, HI, C Ⅳ lines causes a resonant absorption. For example, the superposition between Fe Ⅱ λ1623.714Å ($z^4I^0 \to a^6D$) and Fe Ⅱ λ1623.707A ($z^2F^0 \to a^4F$) will cause the line fluorescence. This is a new kind of excitation mechanism proposed by Netzer et al.[28] and Wills et al.[12] in order to explain the UV Fe Ⅱ emission lines which come from the transitions from the upper levels with high energy larger than 8 eV. For the ordinary temperature of broad line region($T \sim 10^4 K$), it is very difficult to excite the Fe^+ ions into high energy levels larger than 8 eV by use of other mechanisms.

From observations we see that Fe Ⅱ lines are as broad as HI lines. Therefore it is generally thought that Fe Ⅱ lines are also produced from broad line region and the excitation mechanism for producing Fe Ⅱ lines is the resonant fluorescence[1,6]. But Netzer[27] pointed out that collisional excitation mechanism is better than resonant fluorescence mechanism for explaining the formation of Fe Ⅱ emission lines. The standard model of Kwan and Krolik[32] gives a detailed discussion on the formation of the emission lines of the gas clouds in broad line region. Based on the photoionization model, for the gas clouds which are opticaly thick to Lyman series, taking the photoionization and collisional ionization of the excited states of hydrogen into consideration, they calculated the emission lines and continuum of hydrogen, all emission lines of helium and the emission lines of heavy elements which have been observed. They obtained a moderately success in the explanation of the broad emission lines problem of quasars and Seyfert 1 galaxies. They also discussed and calculated Fe Ⅱ multiplts. Though they set up a successful standard model to explain the emission lines from the broad line region, Fe Ⅱ problem is still unsolved. The calculated intensities of Fe Ⅱ lines are much less than the observed values. Wills, Netzer and Wills[12],and Netzer and Wills[28] researched into all the formation mechanisms of Fe Ⅱ lines in active galactic nuclei, they not only considered a lot of transition lines (~3000 lines) but also the interaction between these emission lines and fluorescence. They successfully explained the well-known 3000Å bump by use of Fe Ⅱ lines and Balmer continuum. Furthermore because the model of broad line region with unitary component is not satisfactory, Collin-Souffrin et al.[34,35] proposed a two-components model with two kinds of gas clouds, in which the high and low ionization lines come from different gas clouds. This model differs from the models of H Ⅱ and HI region formed by the photoionization of the gas clouds in broad line region. They suggested such a model to explain the difficult Fe Ⅱ emission lines problem. In this model the broad line region is composed of two kinds of gas clouds. One is the gas clouds with comparatively low column density ($<10^{23}$cm^{-2}), the main component being H Ⅱ, where produce the high-ionization lines (CⅣ, CⅢ, Lyα, He Ⅱ et al), and another one is the clouds with higher column density ($>10^{23}$cm^{-2}), the main component being HI, where produce the low-ionization lines (e. g. Fe Ⅱ, C Ⅱ et al). However, such a two-components model is also unable to explain the observed ratio of Fe Ⅱ/Hβ. Therefore the multi-components photoionization model can not improve the situation of "Fe Ⅱ Problem". From this analysis, they supposed that there maybe exists another kind of gas clouds without the photoionization effect. Joly[43] analysed the emission region of Fe Ⅱ lines, and found that optical Fe Ⅱ lines may be produced from a cool region with high density ($n_H>10^{11}$cm^{-3}, column density 10^{22}cm$^{-2}<N_H<10^{25}$cm^{-2}, 6 000K$<T<$8 000K). In order to solve Fe Ⅱ problem, Collin-Souffrin, Hameury and Joly[13] discussed another kind of emission region. They assumed that these emission lines mainly come from a thick gas shell (column density$>10^{25}$ cm^{-2}) heated by the compton scattering of hard X-rays. Their discussions are still in the framework of photoionization assumption, and their resultant value (Fe Ⅱ$_{opt}$/Hβ$\simeq$10) is still much less than the observed ratio. However they had greatly improved the "standard model", and revealed that the accretion disk is a favorable region for producing Fe Ⅱ lines. A deficiency of this model is that X-ray heating is based on the correlation of Fe Ⅱ lines with the spectral index of X-ray continuum given by Wilkes, Elvis and McHardy[24], which has been negated in recent reports[16,25]. Therefore the existence of X-ray heating region (where producing Fe Ⅱ emission) is questionable. In breif, so far the problem of the strong Fe Ⅱ emission lines still stands and can not be solved by any previous models. Table 1 gives the comparison of the ratios from some comparatively successful models with the observed values.

Table 1　Theoretical Calculation Compare with Observations

	KK(1981)[31]	WNW(1985)[12]	CDJP(1986)[35]	CHJ(1988)[13]	obs.[13,43]
Fe Ⅱ$_{tot}$/H$_\beta$	$\simeq 2$	$\simeq 5$	<7	<6	12(4—30)
Fe Ⅱ$_{opt}$/H$_\beta$	$\simeq 1.5$	$\simeq 3$	<6	<5	7(0.4—26)

Obviously, nowadays no model can give a satisfactory explanation to the strong emission of Fe Ⅱ lines. Since the first identification of Fe Ⅱ emission, detailcd theoretical studies have been made extensively. Nearly all mechanisms and regions of Fe Ⅱ line-emissions have been considered by different authors. But Why the theoretical expectations from different models are always much less than the observed intensities of Fe Ⅱ lines? Such a puzzling problem is called "Fe Ⅱ Problem". In order to solve this puzzle, some researchers suggest to increase the abundance of Fe element to an anomalous value. But this is unacceptable before there is an evidence to show the existence of the anomalous abundance of Fe in active galactic nuclei (comparing with the normal abundance in the sun). Therefore the existence of "Fe Ⅱ Problem" is a real obstacle for our understanding of the physical structure and energy mechanism of the active galactic nuclei. And it is very important to find a more believable way to solve this problem.

We suggest that, in order to solve this problem, two points must be taken into consideration[44]:

(1) In the theoretical calculation of broad emission lines, not only the broad line region, but the contribution of the accretion disk to the line-emission must be considered. In fact, the photoionization model of broad line region of active galactic nuclei explains the high-ionization emission lines successfully, but it is uncomfortable to explain the low-ionization lines such as Fe Ⅱ lines. In a series of work, Collin-Souffrin et al. argued that the accretion disk is another favorable region for producing broad emission lines. There are many reasons to believe that the contribution of accretion disk to the broad emission lines is important. Firstly, the broad emission lines of active galactic nuclei have similar profiles and intensities unchanged with

the luminosity of the object. This is just the basic characteristics of the emission lines from the accretion disk. Secondly, the full width of half-maximum of the observed broad emission lines is generally about 5 000—10 000 km·s^{-1}, and this line-width is perhaps just caused by Kepler motion of accretion disk. Thirdly, the observed double peaks structure of emission lines can also be satisfactorily explained by the rotation of accretion disk.

(2) Besides the Fe Ⅱ emission lines, the contribution of FeI emission lines must be taken into consideration. The reason is that: both Fe Ⅱ and FeI emission lines of AGNs are many overlapping line-series, which are too broad to be resolved and distinguished from one another. Therefore, some researchers are in doubt about whether the observed "Fe Ⅱ emission lines" are real Fe Ⅱ lines or not[28]. In fact, FeI lines have also been observed in some samples[7].

Why researchers always neglect the contribution of the observed FeI lines to the broad "Fe Ⅱ emission lines"? Why there is no model to fit the observations by taking FeI emission into consideration? The reason may be that, in the traditional photoionization model, in the thin skin layer of gas clouds illuminated by the UV continuum from the central power house, the element Fe is almost existing in the form of Fe^{+} and Fe^{++}, and the neutral Fe^{0} is hardly present. Therefore the FeI emission lines are extremely weak in this model. But the unilluminated accretion disk is an appropriate place to produce the FeI lines. Based on this new points, a detailed calculatnon has deen done by us. We believe that such an improved model will provide a new way to solve the Fe Ⅱ emission problem.

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