The Iron Emission launched from Evaporated Dust in Tidal Disruption Event and its Potential Cosmological Application

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ABSTRACT

Tidal disruption events (TDEs) in active galactic nuclei (AGN) can trigger dramatic change of accretion rate, providing us the greatest opportunity to catch the insight of AGN structure and physics. In this letter, we report the optical Fe\textsuperscript{II} response to the central outburst in PS1-10adi, a well-known TDE candidate in AGN at $z = 0.203$. The Fe\textsuperscript{II} strength rises rapidly and reaches the maximum after 55 days of the optical peak, and then declines gradually. We find an unprecedented phenomenon that the Fe\textsuperscript{II} variation rate (the ratio of Fe\textsuperscript{II} variation to luminosity variation) in the luminosity rising stage is significantly greater than that in the decreasing stage, forming an evolutionary trajectory of "Λ" shape. At the same luminosity, the Fe\textsuperscript{II} strength in the decreasing stage is significantly larger than that in the rising stage. This suggests that the amount of gas producing Fe\textsuperscript{II} in the decreasing stage is larger than that in the rising stage. Therefore we propose a scenario that the dust at torus inner radius gradually sublimates into gas as the central luminosity increases. During this process, the irons released from the sublimated dust contribute evidently to the Fe\textsuperscript{II} emission. Combined with the weak response of H\textbeta, this scenario naturally explains the positive correlation between the relative Fe\textsuperscript{II} strength and Eddington ratio. Our result also reveals a potential application of the Fe\textsuperscript{II} emission in outburst events of AGNs: since the Fe\textsuperscript{II} emission is launched from the evaporated dust at inner radius (related to the central luminosity, i.e., $R_{\text{sub}} \propto L^{1/2}$) of torus, the Fe\textsuperscript{II} time lag-luminosity relation can be adopted as a "standard candle" candidate in cosmology.

Keywords: galaxies: individual (PS1-10adi) — galaxies: active — galaxies: nuclei — infrared: galaxies — cosmology: distance scale

1. INTRODUCTION

Active galactic nucleus (AGN) powered by the supermassive black hole (BH) accretion disk, is the most luminous persistent celestial object in the universe, and can be observed up to at $z > 7$ (Mortlock et al. 2011; Bañados et al. 2018; Yang et al. 2020). The Eddington ratio $L/L_{\text{edd}}$, i.e., the AGN luminosity normalized by the BH mass is one of the most important quantity to contextualize the BH accretion system. The relative strength of optical iron, is one of the major characteristics of "Eigenvector 1" driven by Eddington ratio (Boroson & Green 1992; Boroson 2002; Shen & Ho 2014). The physical mechanism responsible for the increase in Fe\textsuperscript{II} strength with Eddington ratio has been studied by a lot of literatures (e.g., Wang et al. 1996; Lawrence et al. 1997; Marziani et al. 2001; Ferland et al. 2009; Shields et al. 2010; Dong et al. 2011). However, the emission region of optical iron as well as the reason why optical iron can be used as an indicator of accretion rate are still open questions. Thus, studying the origin of Fe\textsuperscript{II} can promote our understanding of AGN structure.

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Meanwhile, some features of AGN have the potential to establish as standard candles, such as the broad line region (BLR) size and luminosity relation (Watson et al. 2011; Czerny et al. 2013; Wang et al. 2020), nonlinear relation between UV and X-ray luminosities (Risaliti & Lusso 2019) or flux variability (Sun et al. 2018). However, the reliability of AGN as a standard candle depends on our understanding of AGN structure and related physical process.

Recent progresses in the time-domain surveys have led to numerous discoveries of outburst events in AGN (e.g., Kankare et al. 2017; Trakhtenbrot et al. 2019). Among them, tidal disruption events (TDEs) are a star occasionally ripped apart by the tidal force of SMBHs (Rees 1988). TDEs in AGNs are of particular interest that offer us an unique opportunity to revisit open questions on AGN structure and related physics process in a dynamic way in months to years timescale. For example, the luminous infrared emission of AGN TDEs, originated from the dust re-processed emission, can yield valuable information of the dusty torus (Jiang et al. 2019). The other fascinating characteristic associated with those TDE event is the dramatic increase of the Fe II emission after the outburst although they will fade away later on (e.g., Drake et al. 2011; Blanchard et al. 2017; Kankare et al. 2017). The transient Fe II emission has been proposed as a natural result of sublimation of dust grains located in the inner torus due to the sharp increasing of the central emission (Jiang et al. 2017, 2019). The iron elements primarily locked in the dust phase are released and transferred into the gas phase, contributed significantly to the Fe II emission. However, this assumption lacks convincing evidence.

In this work, we carry out a detailed analysis on the well-known TDE candidate in PS1-10adi (an AGN at $z = 0.203$) to study the physical process of optical Fe II emission and its potential cosmological applications. The paper is organized as follows. In Section 2, we present the Data and spectral fitting. In Section 3, we analyze the launch region of optical Fe II in TDE. In Section 4, we propose a standard candle based on Fe II response to TDE. We assume a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_L = 0.7$.

2. DATA AND SPECTRAL FITTING

PS1-10adi was initially discovered by the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and was suggested as an energetic TDE candidate in AGN at $z = 0.203$ (Kankare et al. 2017; Jiang et al. 2019). It stands out from AGN flares reported in the past few years because of the comprehensive observing campaign performed since its discovery, particularly its massive optical spectral data, which has even rarely covered the stage prior to the luminosity peak. The follow-up spectrum taken at different stages (see Fig 1) give us an excellent dataset to explore how the Fe II strength and relative Fe II strength, i.e., $R_{Fe II} = f_{Fe II}/f_{H\beta}$, respond to the large amplitude of variability (accretion rate).

As shown in Fig 1, we use a power-law $f_\lambda \propto \lambda^{-\alpha}$ plus the optical Fe II template (Boroson & Green 1992) to fit the continuum and Fe II emission in the wavelength regions: 4000-4050Å, 4150-4300Å, 4435-4650Å, 5100-5600Å, which are relatively free from the strong emission lines except Fe II. We repeat this fitting process 1000 times. For each time, we add a Gaussian random error to the observed flux. The flux of H$\beta$ are the observed flux by subtracting Fe II emission and continuum: $f_{H\beta} = f_{obs} - f_{Fe II} - f_{con}$. The best-fitted results and the corresponding errors are the mean and standard deviation from the 1000 fittings, respectively. The spectral data and fitting results are shown in Table 1.

![Figure 1. The spectral data of PS1-10adi (from Supplementary Figure 2 of Kankare et al. 2017). A power-law plus the optical Fe II template (Boroson & Green 1992) to fit the continuum and Fe II emission. The black horizontal line mark the fitting regions which are relatively free from strong emission lines except Fe II. The gray shadow regions mark the locations of Fe II 4435-4685Å and H$\beta$.](image-url)
3. THE LAUNCH REGION OF OPTICAL Fe II IN TDE

3.1. The time lag of Fe II relative to the continuum

From Fig 2, it can be easily seen that the Fe II emission and \( R_{Fe II} \) rise rapidly and reach the maximum after 55 days of the optical photometry luminosity \( (L_{optical}) \), here after \( L \) peak, and then decline gradually. Mean while, the H\( \beta \) emission also has a weak response to the change of central radiation. We notice a gap of Fe II observations between day 55 and day 200. Thus, the real Fe II peak might be occur later than 55 days. A theoretical calculation (Namekata & Umemura 2016) of dust sublimation radius is as follows:

\[
R_{\text{sub}} = 0.121 \, \text{pc} \left( \frac{L_{\text{bol}}}{10^{45} \, \text{erg s}^{-1}} \right)^{0.5} \left( \frac{T_{\text{sub}}}{1800 \, \text{K}} \right)^{-2.8} \times \left( \frac{a}{0.1 \, \mu \text{m}} \right)^{-0.5}
\]

(1)

where \( T_{\text{sub}} \) is the sublimation temperature of dust, \( a \) is the radius of dust grain. Given the peak luminosity \( L = 5 \times 10^{44} \, \text{erg s}^{-1} \), the theoretical torus inner radius \( R_{\text{sub}} \) is about 0.085 pc, corresponding to 100 light days. Kishimoto et al. (2007) found that the innermost torus radii based on dust reverberation were systematically smaller than the theoretical prediction of Equation 1 by a factor \( \sim 3 \). Thus, the observed time lag is roughly consistent with the torus inner radius. Nevertheless, the observed time lag is not enough to prove that the Fe II radiation is related to the torus inner radius. In the following two subsections, we will analyze the Fe II emission region by the Fe II evolutionary trajectory.

3.2. The Fe II evolutionary trajectory of "Λ" shape

As shown in Fig 2, to analyze the launch region of optical Fe II, we shift the photometry data for 55 days to align the peaks of Fe II emission and \( L \). Then yield the interpolation luminosities at the corresponding time of spectral observations (green stars in the top panel of Fig 2).

We adopt the power-law function to analyze the line emission response function to the change of central radiation: \( \log_{10} f_{\text{line}} = \alpha \log_{10} L + \beta \), where \( \alpha \) is the power-law slope and \( \beta \) is the intercept. As shown in the left panel of Fig 3, the best-fitted \( \alpha \) is 0.63 \( \pm \) 0.04 and 0.27 \( \pm \) 0.02 for Fe II in the luminosity rising (before peak) and decreasing (after peak) stages, respectively. Interestingly, the Fe II variation rate (described by the slope \( \alpha \)) in the luminosity rising stage is significantly greater than that in the decreasing stage. At the same luminosity, the Fe II strength in the decreasing stage is significantly larger than that in the rising stage. The evolutionary trajectory of Fe II forms a "Λ" shape, which indicates that the amount of gas producing Fe II in the decreasing stage is larger than that in the rising stage. Even if we shift the photometry data for 100 days (corresponding to the theoretical torus inner radius), the Fe II evolutionary trajectory of "Λ" shape will still exist.

3.3. Fe II emission dominated by the evaporated dust at inner radius of torus

As shown in Fig 4, we propose a scenario to interpret the physical process of "Λ" shape. As the central luminosity increases, the dust at torus inner radius gradually sublimes into gas. The metals released from the evaporated dust will boost the observed Fe II line. The amount of evaporated dust reaches the maximum at the peak of central luminosity. The observations of NGC4151(Koshida et al. 2009; Kishimoto et al. 2013) and Mrk 590(Kokubo & Minezaki 2020) suggest the dust condensation/reforformation timescale is around a few years. Thus, the amount of evaporated dust will remain the maximum for at least a few months after the peak of central luminosity. At the same luminosity, the Fe II emission in the decreasing stage will be greater than that in the rising stage. Meanwhile, the best-fitted \( \alpha \) are 0.15 \( \pm \) 0.04 and 0.16 \( \pm \) 0.02 for H\( \beta \) in the luminosity rising and decreasing stages, respectively. There is no significant difference for H\( \beta \) variation rate between this two stages. This result indicates that the H\( \beta \) emitter region is smaller than the torus inner radius and H\( \beta \) is not dominated by the evaporated dust, but by the BLR gas.

In the above scenario, the amount of gas producing Fe II increasing with luminosity, naturally explains the reason of Fe II (or \( R_{Fe II} \)) strength as the indicator of BH accretion rate (or Eddington ratio). As shown in the right panel of Fig 3, \( R_{Fe II} \) increases with the luminosity. The best-fitted \( \alpha \) are 0.47 \( \pm \) 0.01 and 0.11 \( \pm \) 0.01 for \( R_{Fe II} \) in the luminosity rising and decreasing stages, respectively. We note that the "Λ" shape will increase the scatter of correlation between Fe II strength and accretion rate. If we divide a sample into two parts: the luminosity rising and decreasing stages, the correlation between Fe II strength and accretion rate of the luminosity rising stage should be stronger than that of the whole sample.

To sum up, the intriguing "Λ" shape of Fe II or \( R_{Fe II} \) evolutionary trajectory strongly suggest that the increased Fe II emission is linked to the evaporated dust at scale of torus inner radius. In this scenario, the Fe II strength is mainly regulated by the amount of gas-phase iron (see also Shields et al. 2010). As the central luminosity increases, the inner boundary of the dusty
torus will recede to a larger radius. During this process, the iron released from the sublimated dust contribute evidently to the FeII emission. Meanwhile, the weak response of Hβ also implies that its dominant radiation region is likely more closer than that of FeII, which is consistent with the reverberation mapping results (e.g., Barth et al. 2013). As a result, the relative FeII strength has been observed as an indicator of the Eddington ratio of AGNs.

4. A POTENTIAL COSMOLOGICAL STANDARD CANDLE BASED ON FeII

Our results suggest that the FeII emission is boosted by the new evaporated dust at inner radius of torus in TDE. In view of this, the time lag between the optical continuum peak and optical FeII peak can adopted as standard candles in cosmology. The AGN luminosity $L_{bol}$ and the dust sublimation radius $R_{sub}$ can be written as (Hoenig & Kishimoto 2011; Hönig et al. 2017):

$$L_{bol} = 16\pi R_{sub}^2 f_{abs}^{-1} Q_{abs} \rho(T_{sub}) \sigma_{SB} T_{sub}^4$$

where $f_{abs}$ is the fraction of incident AGN flux absorbed per dust particle and $Q_{abs} \rho(T_{sub})$ is the normalized Planck-mean absorption efficiency of the dust. Note that, $f_{abs}$ and $Q_{abs} \rho$ are related with both parameters approaching unity for large dust grains, which emit very similarly to a blackbody. Replacing $R_{sub}$ with the corresponding time lag $\tau_{FeII} = \tau_{sub} = R_{sub}/c$, the AGN luminosity $L_{bol}$ can be written as (Hönig et al. 2017):

$$L_{bol} = 16\pi R_{FeII}^2 f_{abs}^{-1} Q_{abs} \rho(T_{sub}) \sigma_{SB} T_{sub}^4 = k^2 T_{FeII} \tau_{FeII}^2$$

where $k$ is a parameter absorbing $T_{sub}$, $f_{abs}$ and $Q_{abs} \rho$. A luminosity distance $D_L$ independent of redshift is calculated as:

$$D_L = \sqrt{\frac{k}{4\pi F}} \tau_{FeII} c$$

where $F$ is the flux of optical continuum. The parameter $k$ can be calibrated by other cosmic distance ladder or the spatially resolved near-IR interferometry for the inner radius of torus (Hönig 2014). Combination with the size of time lag and the angular diameter $\theta$ from the interferometry for the inner radius of torus, the angular diameter distance can be determined as: $D_A = \tau_{FeII} c/\theta$. According to the relationship $D_L = D_A (1+z)^2$, the $k$ can be determined as $k = 4\pi F (1+z)^2 / \theta^2$. The scatter of $k$ is about 0.13 dex in the lag-luminosity relation of a sample of 17 AGN (Koshida et al. 2014). The scatter of $k$ reflects the actual object-to-object differences in hot-dust composition, geometry, and global distribution in a sample. The low scatter value implies the tighter relation between time lag and luminosity, and the simple physics of the inner radius of torus.

5. CONCLUSION

In this letter, we present the response of FeII emission in the PS1-10adi TDE, an AGN at $z=0.203$. The time lag between optical continuum peak and FeII or $R_{FeII}$ strength peak is consistent with the torus inner radius. Furthermore, we find the FeII variation rate in the luminosity rising stage is significantly greater than that in the decreasing stage. At the same luminosity, the FeII emission in the decreasing stage is significantly greater than that in the rising stage. The evolutionary trajectory of FeII and $R_{FeII}$ form an intriguing "Λ" shape. This result strongly suggests that the FeII emission is boosted by the evaporated dust at scale of torus inner radius. Our results reveal at least two applications of the FeII emission in the TDEs:

1. The indicator of Eddington ratio: we propose that the dust sublimation of AGN torus accompanied with the central outburst plays a key role
Table 1. The spectral data and fitting result for Fe II and Hβ lines.

| Time (days) | log $L$ (ergs$^{-1}$) | Fe II ($\times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) | Hβ ($\times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$) | $R_{Fe II}$ |
|-------------|------------------------|-----------------------------------------------|-----------------------------------------------|------------|
| -8.6        | 44.36                  | 1.101 ± 0.030                                 | 0.997 ± 0.004                                 | 1.10 ± 0.03|
| -4.5        | 44.38                  | 1.167 ± 0.012                                 | 1.097 ± 0.002                                 | 1.06 ± 0.01|
| 27.1        | 44.56                  | 1.665 ± 0.015                                 | 1.205 ± 0.003                                 | 1.38 ± 0.01|
| 54.5        | 44.71                  | 1.888 ± 0.011                                 | 1.218 ± 0.002                                 | 1.55 ± 0.01|
| 200.8       | 44.34                  | 1.604 ± 0.012                                 | 1.113 ± 0.002                                 | 1.44 ± 0.01|
| 228.3       | 44.27                  | 1.573 ± 0.011                                 | 1.129 ± 0.002                                 | 1.39 ± 0.01|
| 274.8       | 44.16                  | 1.362 ± 0.052                                 | 1.038 ± 0.006                                 | 1.31 ± 0.04|
| 303.9       | 44.10                  | 1.135 ± 0.013                                 | 0.860 ± 0.002                                 | 1.32 ± 0.01|
| 348.8       | 44.00                  | 1.195 ± 0.039                                 | 0.946 ± 0.005                                 | 1.26 ± 0.03|

Note—The luminosity corresponding to each spectrum is the result of interpolation in the optical photometry luminosity (green stars in Fig 2).

Figure 3. The Fe II and Hβ lines evolution under the luminosity variation in the TDE. Left panel: the dots and stars are the Fe II and Hβ, respectively. The values of best-fitted $\alpha$ for each line are marked. The $\alpha$ in the luminosity rising stage is significantly greater than that in the decreasing stage. At the same luminosity, the Fe II emission in the decreasing stage is significantly greater than that in the rising stage. The evolutionary trajectory of Fe II forms a ”Λ” shape, which indicates that the amount of gas producing Fe II in the decreasing stage is greater than that in the rising stage. Meanwhile, there is no significant difference for Hβ variation rate between the two stages. This result indicates that its dominant radiation region is likely more closer than that of Fe II and is not dominated by the evaporated dust. Right panel: similarly to Fe II, the evolutionary trajectory of Fe II forms a ”Λ” shape. Compared to Fe II, the dispersion of $R_{Fe II}$ evolutionary trajectory is more smaller.

in the rapid increase of Fe II strength. The irons, which were originally locked in the dust grains, get a chance to enter into the gas phase due to the sublimation and boost the Fe II emission. The Fe II strength is thus directly dependent on the amount of evaporated dust, which increases with the central luminosity. However, the evaporated region might contribute much less to the Hβ emission. This indicates the Hβ prefers significantly smaller emission radius. As a result, this scenario naturally explains the physical mechanism leading to the increase of Fe II strength with Eddington ratio.

2. The potential cosmological application: since the Fe II emission is dominated by the evaporated dust at inner radius of torus, which is related to the central luminosity, i.e., $R_{sub} \propto L^{1/2}$, the Fe II time lag relative to the central luminosity can be adopted as a potential standard candle.
in cosmology. In the future, we can follow up on the optical spectrum observation after the optical burst of a TDE. We are entering an age of accelerating development of time domain astronomy with advent of a batch of dedicated modern surveys (e.g., ZTF, LSST, WFST (Lou et al. 2016)). For instance, the predicted TDE number found by LSST every year can be a few of thousands (e.g., Thorp et al. 2019; Bricman & Gomboc 2020), which could include hundreds of events in AGNs assuming a AGN fraction of 10%. Timely spectroscopic observations of them are highly encouraged to capture the peak of Fe II emission. The notion of Fe II "cosmological standards" can be soon tested and applied based on large sample studies.

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