EXTREME CORONAL LINE EMITTERS: TIDAL DISRUPTION OF STARS BY MASSIVE BLACK HOLES IN GALACTIC NUCLEI?

Ting-Gui Wang1,2, Hong-Yan Zhou1,2,3, S. Komossa4,5,6,7,8, Hui-Yuan Wang1,2, Weimin Yuan7, and Chenwei Yang1,2
1 Key Laboratory for Research in Galaxies and Cosmology, The University of Sciences and Technology of China (USTC), Chinese Academy of Sciences, Hefei, Anhui 230026, China; twang@ustc.edu.cn
2 Department of Physics and Astronomy, University of Kentucky, Lexington, 40506 Kentucky, USA
3 Center for Astrophysics, USTC, Hefei, Anhui 230026, China
4 Department of Physics, Technische Universität München, Fakultät für Physik, Lehrstuhl für Physik I, James Franck Strasse 1, 85748 Garching, Germany
5 Excellence Cluster Universe, TUM, Boltzmannstrasse 2, 85748 Garching, Germany
6 Max Planck Institut für Plasmaphysik, Boltzmannstrasse 2, 85748 Garching, Germany
7 National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100012, China

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ABSTRACT

Tidal disruption of stars by supermassive black holes at the centers of galaxies is expected to produce unique emission-line signatures, which have not yet been explored adequately. Here we report the discovery of extremely strong coronal lines from [Fe x] up to [Fe xiv] in a sample of seven galaxies (including two recently reported cases), which we interpret as such signatures. This is the first systematic search for objects of this kind, by making use of the immense database of the Sloan Digital Sky Survey. The galaxies, which are non-active as evidenced by the narrow line ratios, show broad emission lines of complex profiles in more than half of the sample. Both the high-ionization coronal lines and the broad lines are fading on timescales of years in objects observed with spectroscopic follow-ups, suggesting their transient nature. Variations of inferred non-stellar continua, which have absolute magnitudes of at least −16 to −18 mag in the g band, are also detected in more than half of the sample. The coronal line emitters reside in sub-L* disk galaxies (−21.3 < M_B < −18.5) with small stellar velocity dispersions. The sample seems to form two distinct types based on the presence or absence of the [Fe vii] lines, with the latter having relatively low luminosities of [O iii], [Fe x], and the host galaxies. These characteristics can most naturally be understood in the context of transient accretion onto intermediate-mass black holes at galactic centers following tidal disruption of stars in a gas-rich environment. We estimate the incidence of such events to be around 10^{-3} yr^{-1} for a galaxy with −21.3 < M_B < −18.5.

Key words: black hole physics — galaxies: nuclei — line: formation — supernovae: general

Online-only material: color figures

1. INTRODUCTION

It is generally accepted that nearly all massive galaxies host supermassive black holes at their centers, and that the black hole masses are well correlated with the stellar masses or velocity dispersions of the galactic bulges (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000). In the low-mass regime, detections of active galactic nuclei (AGNs) in a small number of dwarf or bulgeless galaxies suggest that black holes in the mass range of a few times 10^4–10^6 M☉ do exist in such galaxies (Green & Ho 2004; Dong et al. 2007; Greene & Ho 2007; Dong et al. 2012). However, it is not clear how common they are among quiescent galaxies, as they are difficult to be explored with the stellar and gas kinematics currently used, given the small spheres of gravitational influence. Tidal disruption of stars by massive black holes will provide a signpost for the presence of such black holes in quiescent galaxies. Theoretically, the event rate is estimated to be 10^{-4} to 10^{-5} galaxy^{-1} yr^{-1} (Rees 1988; Magorrian & Tremaine 1999), and might be highest in nucleated dwarf galaxies (Wang & Merritt 2004). Thus, the detection of a significant number of such events can be used to estimate the incidence of dormant black holes in small galaxies. Black hole tidal disruption events (TDEs) have other astrophysical consequences as well. They may contribute significantly to the present-day black hole mass growth in galaxies fainter than 10^7 L☉ (Magorrian & Tremaine 1999; Milosavljević et al. 2006; Brockamp et al. 2011). The ejected unbound debris may have a significant impact on the energetics balance in the nuclear environment of small galaxies (Rees 1988). Follow-up observations of the highly variable, flaring continuum, and line emission may provide a way of exploring the gas and dust distribution of galactic nuclei (Komossa et al. 2008), with a technique similar to reverberation mapping used in the study of the broad emission line region of AGNs (Peterson 2007); they may also provide a way of measuring the spin and mass of the black holes (Beloborodov et al. 1992; Gezari et al. 2009).

Several observational signatures were predicted by theories. A star is tidally disrupted as it plunges into the tidal radius of a massive black hole, rp < aMH/Mbh (Hills 1975). Less than half of the debris fall back and form an accretion torus around the black hole, giving rise to a flare of electromagnetic radiation. The flare will last for a few months to a year with a peak at the Eddington luminosity for a black hole mass less than 10^7 M☉ (e.g., Rees 1988). For a black hole with a mass in the range of 10^7–10^8 M☉ and a solar-type star, the peak luminosity will be sub-Eddington. The optically thick radiation of the accretion disk is peaked in the extreme-UV or soft X-rays. The exact peak frequency depends on whether the fallback material forms a thick torus at the pericenter radius or a thin disk extending to the least stable orbit, or launches an optically thick wind around the disk. The bound and unbound debris, ionized by radiation from the accretion torus, is predicted to emit broad emission lines (e.g.,
Ulmer 1999; Eracleous et al. 1995; Strubbe & Quataert 2009; Clausen & Eracleous 2011). Numerical simulations showed that the unbound debris is kinematically complex, producing complicated and variable line profiles (Bogdanovi{\c{c}} et al. 2004). UV and X-ray photons illuminate interstellar gas, resulting in narrow emission lines, which last even longer (e.g., Ulmer 1999). Due to the hard ionizing continuum, the emission line spectrum is characterized by strong high-ionization lines, such as He ii λ4686.

So far, about a dozen candidates of TDEs were identified from X-ray, UV, and optical surveys (e.g., Komossa & Bade 1999; Komossa et al. 2004; Gezari et al. 2009; van Velzen et al. 2011; Cenko et al. 2012). Follow-up observations confirmed that the X-ray or UV luminosity declines with time as $t^{-5/3}$ (e.g., Komossa & Bade 1999; Halpern et al. 2004) as predicted by theoretical models. The peak luminosities are around $10^{42}$–$10^{45}$ erg s$^{-1}$ in soft X-rays and $10^{44}$–$10^{46}$ erg s$^{-1}$ in the ultraviolet. These observations are consistent with the scenario of the tidal disruption of a solar-type star by a supermassive black hole of a few $10^6$ to $10^8 M_\odot$. However, no high-ionization emission-line signatures have been reported from these X-ray- and UV-discovered events.9 Yet the emission lines would provide further diagnostics for TDEs, and may even provide a new means of detecting them.

Of particular interest, Komossa et al. (2008) discovered an extreme coronal line emitter (hereafter ECLE), SDSS J0952+2143, that showed strong [Fe x]λ6376 comparable to [O iii]λ5007, from the Sloan Digital Sky Survey (SDSS). Follow-up observations (with BAO 2.16 m and NTT) showed that both the high-ionization coronal lines and broad emission lines were strongly fading (Komossa et al. 2009). As soft X-ray photons are needed to produce the coronal lines (hereafter CLs), these authors proposed that the CLs are echoes of a recent stellar tidal disruption flare, and the broad lines are emitted from the unbound debris, photoionized by the radiation from the accretion disk (Komossa et al. 2008). Very recently, another ECLE, SDSS J0748+4712, was discovered by Wang et al. (2011), which shows strong high-ionization CLs, such as [Fe x]λ6376, [Fe xii]λ7894, [Fe xiv]λ5304, [Ar xiv]λ4414, and [S xii]λ7612, but no [Fe vi]. Interestingly, it also shows, in addition to a blue continuum, very broad bumps, which can be interpreted as the blueshifted He ii and Balmer lines from a super-Eddington radiation driven wind (Strubbe & Quataert 2009). By comparison of the SDSS photometric and spectroscopic data, the authors could constrain that the SDSS spectrum was taken at most four months after the peak of the flare. The CLs and broad features became very weak or absent in spectra taken 4–5 years later, while the [O iii] line luminosity increased by a factor of 10. Despite the strong CLs, the traditional line ratio diagnostics (the BPT diagram; Baldwin et al. 1981) indicates that it is not an AGN. Although in that case the possibility of observing a supernova (SN) cannot be completely ruled out, the scenario faces some fatal difficulties: the CL luminosities are 1–2 orders of magnitude higher than those in SNe with the most luminous CLs; there is a lack of low-ionization lines or He i with similar line profiles to CLs as is usually seen in SNe with CLs; the broad bumps cannot be self-consistently explained. Thus, TDE is left as the most promising scenario (Wang et al. 2011).

In this paper, we present a comprehensive study of a small, uniform sample of ECLEs culled from the spectroscopic data set of SDSS Data Release 7 (DR7; Abazajian et al. 2009). Our goal is to explore their nature and to estimate the rate of such events. The two previously reported events, SDSS J0952+2143 and SDSS J0748+4712, are also included. The sample selection and data reduction are described in Section 2. The properties of these ECLEs are presented in Section 3. We discuss the nature of these objects in Section 4 and summarize our results in Section 5. Throughout the paper we adopt a Λ-dominated cosmology with $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_L = 0.7$, and $\Omega_M = 0.3$.

2. SAMPLE AND DATA REDUCTION

We carried out a systematic search for ECLEs in the spectroscopic samples of galaxies and low-redshift quasars from the SDSS Data Release 7. We restrict redshifts $z < 0.38$ to ensure that the main CLs, such as [Fe x]λ6376, [Fe xiv]λ5304, and [Fe vii]λ6088, and H$\alpha$ fall within the spectral coverage. The continuum fitting is done separately for galaxies and quasars. For galaxies, the continuum is fitted with six IC templates derived from the stellar populations with Ensemble Learning Independent Component Analysis (Lu et al. 2006). For quasars and AGNs, a power law and Fe ii templates are added to model the AGN continuum and the Fe ii pseudo-continuum. We adopt the I Zw 1 templates (Véron-Cetty et al. 2004) for the broad and narrow Fe ii lines, which are modeled with a single Gaussian of the same width and same redshift for narrow or broad components. This should be sufficient for narrow emission line measurements used in the sample selection stage. In the continuum fit, prominent emission lines are masked, as well as bad pixels.

After subtracting the continuum, we fit the emission line spectrum with a number of Gaussians: one or two Gaussians for each CL, [O iii]λ5007 and [Ne iii]λ3896, which often show an additional broad wing: two or three Gaussians for narrow and broad H$\alpha$ and H$\beta$; one Gaussian for other low-ionization or weak narrow lines, such as [N ii]λ6583, [O i]λ6300, and [S ii]λ6716. In the case of a multi-Gaussian fit, the addition of one more Gaussian is justified based on a F-test. In the fit the line widths and centers of [O iii]λ5007, [N ii]λ6583, [S ii]λ6716, and the [O i]λ6300 doublets are tied, and the flux ratios of [O iii]λ5007, [N ii]λ6583, and the [O i]λ6300 doublets are set to the theoretical values.

ECLEs are then selected through the following criteria: (1) at least one CL is detected at the 5σ level; (2) for at least one CL, the strength is more than 20% of the [O iii]λ5007 strength, or it is not spectroscopically classified as AGN according to narrow-line diagnostics. Note that the strength of the CLs is typically only a few percent of [O iii]λ5007 in Seyfert galaxies (e.g., Nagao et al. 2000). The selected spectra were then inspected manually to reject false detections. The final sample includes seven galaxies. Figure 1 shows the SDSS spectra of the objects.

The spectra are then re-fitted with refined models. The continuum is now fitted with a combination of starlight and a power law representing the contribution of a possible non-thermal component. The starlight is modeled as a linear combination of IC templates, which are broadened to match the absorption line widths. The reddening of the starlight component is treated as a uniform dust screen. A broadened Fe ii template is added in the spectrum of SDSS J1055+5637, in which an excess at the optical Fe ii wavelengths is clearly visible. With these fits we also obtain other parameters, such as the stellar velocity dispersions, the reddening of the stellar and the Fe ii continua.
that the power law is not an independent component from the ICs, and therefore the decomposition of the power law and the starlight is not reliable. In the case of SDSS J0748+4712, the broad bumps are modeled as Gaussians (Wang et al. 2011). After the continuum is subtracted, the emission line spectrum is re-fitted. While narrow lines are fitted with the same models as before, broad lines are fitted with as many as three Gaussians. The \( \text{H}\alpha \) and \( \text{H}\beta \) lines are simultaneously fitted with models of the same profiles. An example of emission-line fits is shown in Figure 2. The basic data of the ECLE sample are tabulated in Table 1, and the emission line fluxes are listed in Tables 2 and 3.

3. RESULTS

3.1. Continuum Variability

We examine the possible continuum variability of the ECLEs by comparing their fiber magnitudes obtained in the SDSS imaging survey and the spectral magnitudes obtained in the spectroscopic survey. The two surveys were four months to two years apart. The fiber magnitudes are measured within an aperture of the size of the SDSS fibers from the SDSS images assuming a typical seeing of \( 2.0 \)′′. The spectral magnitudes are synthesized from the SDSS spectra, which are spectrophotometrically calibrated using standard stars in the three SDSS bands \( g \), \( r \), and \( i \). This calibration can lead to a difference between fiber and spectral magnitude for extended sources even if there is no variability. This is because of different seeing during the spectroscopic observations and object-to-object differences in radial profiles, and so there are both systematic offsets and random scatter, which vary from plate to plate. We estimate the mean offset and random scatter from the distributions of their offsets in the \( g \), \( r \), and \( i \) bands using galaxies in the plates of the ECLEs (Figure 3), which can be well fitted with one Gaussian (outliers are likely those containing AGNs). Based on the results, the
Figure 2. Example of emission-line fits for strong coronal lines, [O\textsc{iii}] 5007, He\textsc{ii}, [O\textsc{i}] 6300, and Balmer lines of SDSS J0938+1353. The peak of the emission line has been normalized. The black solid line in each panel represents the observed profile, the red dashed line the fit, and the green line the blended other lines.

(A color version of this figure is available in the online journal.)

### Table 1

| No. | Name                  | Type | $z$   | $M_{\text{tot}}$ (mag) | $R_{\text{50}}$ (arcsec) | $\Delta g^b$ (mag) | $\Delta r^b$ (mag) | $\Delta i^b$ (mag) | $\Delta t^c$ (day) |
|-----|-----------------------|------|-------|------------------------|--------------------------|-------------------|-------------------|-------------------|-------------------|
| 1   | SDSS J074820.66+471214.6 | No   | 0.0615 | −19.75                 | 4.88                     | 0.23 ± 0.04       | 0.09 ± 0.03       | 0.13 ± 0.04       | 120               |
| 2   | SDSS J093801.64+135317.0 | Yes  | 0.1006 | −21.29                 | 3.77                     | <0.22             | <0.16             | <0.14             | 326               |
| 3   | SDSS J095209.56+214313.3 | Yes  | 0.0789 | −20.41                 | 3.81                     | <0.33 ± 0.03      | −0.19 ± 0.04      | −0.27 ± 0.04      | 375               |
| 4   | SDSS J110552.63+563713.3 | Yes  | 0.0743 | −20.01                 | 3.71                     | −0.20 ± 0.07      | −0.14 ± 0.04      | −0.16 ± 0.05      | 140               |
| 5   | SDSS J124134.26+42639.2 | Yes  | 0.0419 | −19.95                 | 11.10                    | <0.13             | <0.12             | <0.12             | 340               |
| 6   | SDSS J134244.42+053056.1 | No   | 0.0366 | −18.91                 | 4.21                     | <0.30             | <0.23             | <0.22             | 386               |
| 7   | SDSS J135001.49+291609.7 | No   | 0.0777 | −19.76                 | 0.45                     | 0.12 ± 0.04       | <0.12             | <0.13             | 701               |

**Notes.**

- *Type* denotes whether [Fe\textsc{vii}] is present or not.
- *$\Delta g^b$* Magnitude difference within the fiber aperture of 3 arcsec between the SDSS spectroscopic and imaging observations. A negative value means that the object was brighter at the epoch of the imaging observation than at the epoch of the spectroscopic observation, and vice versa.
- *$\Delta t^c$* Elapsed time between the SDSS imaging and spectroscopic observations.

The probability and amount of potential variations are estimated for the ECLEs, as listed in Table 1.

Four out of seven objects show significant ($\geq 3\sigma$) variations with amplitudes ranging from 0.1 to 0.3 mag in the $g$ band and smaller at longer wavelengths between the SDSS spectroscopic and photometric observations. Assuming that the light at the lower state is solely from stars, we derive the minimum brightness of a variable non-stellar component at the higher state, which ranges from $−16.0$ to $−18.0$ mag in absolute magnitude in the $g$ band (Table 1). We note that two ECLEs without [Fe\textsc{vii}] (SDSS J0748+4712 and SDSS J1350+2916 in Table 1) brightened between the two observations while two
Figure 3. Distributions of the difference between the fiber and spectroscopic magnitudes in g, r, and i bands (from left to right) for galaxies on the same plate of the ECLEs. For a comparison, the differential magnitudes of the ECLE are indicated as a red line. The upper panels are for SDSS J0748+4712 and the bottom panels for SDSS J0952+2143.

(A color version of this figure is available in the online journal.)

Table 2
Fe Coronal Line Fluxes^a

| No. | [Fe vii]\lambda3759 | [Fe vii]\lambda5160 | [Fe vii]\lambda5722 | [Fe vii]\lambda6088 | [Fe x]\lambda6376 | [Fe xi]\lambda7894 | [Fe xiv]\lambda5304 | log EM^b |
|-----|---------------------|---------------------|---------------------|---------------------|----------------|----------------|----------------|--------|
| 1   | <18                 | <12                 | <21                 | <21                 | 138 ± 11       | 111 ± 21       | 88 ± 6         | 61.20  |
| 2   | 54 ± 7              | 30 ± 10             | 63 ± 16             | 97 ± 9              | 87 ± 7         | 55 ± 8         | 80 ± 21        | 61.42  |
| 3   | 134 ± 12            | 41 ± 17             | 98 ± 6              | 129 ± 6             | 219 ± 8        | 164 ± 9        | 86 ± 9         | 61.70  |
| 4   | 89 ± 8              | 38 ± 12             | 59 ± 5              | 108 ± 6             | 69 ± 5         | 68 ± 8         | 37 ± 10        | 61.22  |
| 5   | 47 ± 5              | <6                  | 35 ± 4              | 58 ± 2              | 94 ± 4         | 86 ± 7         | 28 ± 3         | 61.06  |
| 6   | <12                 | <18                 | <15                 | <9                  | 57 ± 4         | 72 ± 5         | 36 ± 4         | 60.66  |
| 7   | <9                  | <9                  | <6                  | <6                  | 39 ± 3         | 50 ± 5         | 20 ± 3         | 60.83  |

Notes.
^a Line fluxes and 3σ upper limits are in units of 10^{-17} erg cm^{-2} s^{-1}, and only statistical errors are quoted.
^b Gas emissivity in units of cm^{-3} obtained by summing over the emissivities of [Fe x]\lambda6376, [Fe x]\lambda7894, and [Fe xiv]\lambda5304 divided by the abundance of Fe. A typical uncertainty is estimated to be from 0.1 to 0.3 dex without taking into account of ionization fraction corrections and uncertainties in the atomic data.

Table 3
Other Emission Lines^a

| No. | H\beta^a | H\beta^b | He\alpha^a | He\alpha^b | He n \lambda4686 | [N ii]\lambda6583 | [S ii]\lambda6716 | [S ii]\lambda6731 | [O iii]\lambda5007 | [Ne iii]\lambda3896 |
|-----|----------|----------|------------|------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 1   | 46 ± 4   | <33      | 213 ± 17   | <57        | <9                | 54 ± 3           | 60 ± 5            | 25 ± 2            | 14 ± 2            | <9                |
| 2   | 384 ± 7  | <54      | 1766 ± 25  | 100 ± 33   | 12 ± 5            | 695 ± 20         | 247 ± 5           | 171 ± 4           | 452 ± 23          | 119 ± 15          |
| 3   | 142 ± 47 | <58      | 226 ± 18   | 159 ± 36   | 89 ± 13           | 110 ± 16         | 101 ± 10          | 43 ± 4            | 161 ± 6           | 54 ± 11           |
| 4   | 53 ± 19  | 499 ± 37 | 336 ± 51   | 1704 ± 61  | 22 ± 4            | 74 ± 7           | 23 ± 3            | 26 ± 3            | 219 ± 6           | 56 ± 6            |
| 5   | 66 ± 5   | <38      | 329 ± 7    | <39        | 41 ± 3            | 40 ± 5           | 8 ± 1             | 10 ± 2            | 212 ± 4           | 81 ± 7            |
| 6   | 80 ± 4   | <72      | 401 ± 8    | 67 ± 22    | 20 ± 3            | 78 ± 4           | 48 ± 4            | 32 ± 3            | 104 ± 3           | <27               |
| 7   | 53 ± 17  | 83 ± 24  | 221 ± 29   | 467 ± 37   | <9                | 96 ± 9           | 52 ± 7            | 24 ± 3            | 44 ± 2            | <9                |

Note. ^a Line fluxes are in units of 10^{-17} erg cm^{-2} s^{-1}.

with [Fe vii] (SDSS J0952+2143 and SDSS J1055+5637) show the opposite trend. In the former case, the interval between the two observations can set an upper limit on the ages of the ECLEs during the spectroscopic observation; in the latter case, a lower limit can be obtained. Consequently, the continuum flares occurred within 120 and 701 days prior to the spectroscopic observation for SDSS J0748+4712 and SDSS J1350+2916, respectively, and happened more than 140 and 375 days prior to
the spectroscopic observation for SDSS J1055+5637 and SDSS J0952+2143, respectively.

We have also checked archival UV data for potential variations. SDSS J0748+4712 was detected by the Galaxy Evolution Explorer in both the near- and far-UV bands on 2004 March 10, 20 days after the SDSS spectroscopic observation, and was re-observed in near-UV later on 2010 January 9. The NUV flux dropped by nearly a factor of two at the later epoch. This sets a lower limit to the non-stellar UV luminosity as $2.6 \times 10^{42}$ erg cm$^{-2}$ s$^{-1}$ on 2004 March 10, assuming that the flux at the later epoch is mostly from stellar light.

### 3.2. Narrow Emission Lines

It is evident that our ECLEs can be divided into two subclasses, with and without the detected [Fe vii] lines (Figure 1 and Table 2). As shown in Figure 4, the lower limits on [Fe vii] give $[\text{Fe x}]_{6376}/[\text{Fe vii}]_{6088} > 3$ for objects without [Fe vii] lines, while those with detected [Fe vii] have $[\text{Fe x}]_{6376}/[\text{Fe vii}]_{6088} < 3$. In Figure 4, we plot the $[\text{Fe x}]_{6376}$ versus $[\text{Fe vii}]_{6088}$ luminosities for our ECLEs; for comparison, those from a sample of Seyfert galaxies from Gelbord et al. (2009) are also overplotted. The ECLEs with [Fe vii] show $[\text{Fe x}]_{6376}/[\text{Fe vii}]_{6088}$ ratios higher than normal Seyfert galaxies, and similar to narrow-line Seyfert 1 galaxies, which are believed to have black holes of relatively small masses accreting at near the Eddington rate. The objects without detected [Fe vii] show much higher ratios.

In Figure 5, we show the $[\text{Fe x}]_{6376}$ versus $[\text{O iii}]_{5007}$ luminosities. The $[\text{Fe x}]_{6376}/[\text{O iii}]_{5007}$ ratios of the ECLEs are 1–2 orders of magnitude higher than those of Seyfert galaxies that is expected from our selection criteria. The ECLEs are outliers, offset from the smooth distribution of the Seyfert galaxies. There is no significant difference in the ratios between ECLEs with and without [Fe vii], although the latter show systematically lower $[\text{O iii}]_{5007}$ luminosity.

To determine whether they are actually Seyfert galaxies, we plot in Figure 6 their locations in the BPT diagrams involving a set of narrow line ratios (Baldwin et al. 1981; Veilleux & Osterbrock 1987; Kewley et al. 2006) which are diagnostics of the ionizing continuum. For comparison, overlaid are the contours of the distributions of narrow emission line galaxies in the SDSS DR4 (Xiao et al. 2012). It can be seen that six of the seven objects lie within the H II locus on the $[\text{S ii}]_{6717,6731}/\text{H}\alpha$ versus $[\text{O iii}]_{5007}/\text{H}\beta$ diagram, and the remaining one (SDSS J0952+2143) borders LINER and H II regions. On the $[\text{N ii}]_{6548,6583}/\text{H}\alpha$ versus $[\text{O iii}]_{5007}/\text{H}\beta$ diagram, three (SDSS J0748+4712, SDSS J1241+4426, and SDSS J1341+0530) locate within the H II (star-forming galaxies) locus, while the other four objects locate in the near H II end of the composite region. However, among those four, the line ratios of three objects are indistinguishable from being H II galaxies due to their relative large uncertainties. For comparison, other galaxies with reliable detections of coronal lines in SDSS DR4 spectroscopic data locate usually far away from the demarcating line (blue points in Figure 6; T.G. Wang et al., in preparation). These results suggest that the bulk of our ECLEs differs largely from Seyfert galaxies, and the conventional narrow-line regions in their galactic nuclei did not see the hard ionizing continuum radiation that produces the strong CLs. The classifications appear to be diverse when the $[\text{O ii}]_{6300}/\text{H}\alpha$ versus $[\text{O iii}]_{5007}/\text{H}\beta$ diagram is considered, where three objects (SDSS J1055+5637, SDSS J1241+4426, and SDSS J0952+2143) are located in the AGN locus and one (SDSS J0938+1353) at the demarcation of H II and Seyfert galaxies. We note that the $[\text{O i}]_{6300}$ line is, compared to other narrow lines (e.g., $[\text{O iii}]$, $[\text{N ii}]$, $[\text{S ii}]$ and H$\alpha$), generally broader and more difficult to accurately measure due to its weakness. In fact, given the high critical density of $[\text{O i}]$, it is possible that a significant part of the $[\text{O i}]$ emission is non-permanent, i.e., is contributed by the continuum flare which also produces the (variable) iron lines, and may come from a region cospatial with...
Figure 5. [Fe x]λ6376 luminosity vs. [O iii]λ5007 luminosity for ECLEs and Seyfert galaxies (Gelbord et al. 2009). Color codes are the same as in Figure 4. (A color version of this figure is available in the online journal.)

Figure 6. Distribution of the ECLEs (red circles) on the BPT diagrams. Emission-line galaxies from the SDSS are overplotted as number density contours. The blue lines represent the borders for extreme star-forming galaxies, the red lines represent the empirical boundary between star-forming galaxies and AGNs; the green lines separate LINERs and Seyfert galaxies (Kewley et al. 2006). For comparison, galaxies with coronal line detection in SDSS DR4 are plotted in blue. (A color version of this figure is available in the online journal.)

The coronal line region. The He II λ4686 line is also prominent in the spectra of most of the ECLEs, suggesting that it is produced in the CL region.

We also compare the profiles of the CLs with those of the other narrow lines (Figure 7). The CLs usually display similar profiles, except that a narrow core is occasionally absent in high-ionization species, such as [Fe x]λ6376, [Fe x]λ7894, and [Fe xiv]λ5304. In most cases, the CLs and [O i] are broader than low-ionization lines (Figure 8). He II λ4686 has a similar profile to the CLs (Figure 2). For quantitative comparisons we calculate the FWHM from the best-fitted model. Note that some of the lines have apparently two components, and the FWHM may only crudely reflect the kinematics of the line-emitting gas. The FWHM of [Fe x]λ6376 has a range from 200 to 1000 km s$^{-1}$, and a median of 480 km s$^{-1}$. In comparison, [O iii]λ5007 has a median FWHM of 230 km s$^{-1}$ and a range from 90 to 340 km s$^{-1}$, and [N ii]λ6583 has similar values of a median 240 km s$^{-1}$ and a range from 110 to 340 km s$^{-1}$. There appears to be no correlation of the line widths between the CLs and the low-ionization lines such as [O iii]λ5007 and [N ii]λ6583; however, the sample is too small for a meaningful test.
Figure 7. Emission line profiles. The first column (from left to right): Hα (black) and Hβ (red); the second column: [Fe xiv] λ 5304 (pink), [Fe xi] λ 7894 (blue), [Fe x] λ 6376 (green), and [Fe vi] (black); the third column: [O iii] λ 5007 (black), [O i] λ 6300 (blue), and [O ii] λ 3727 (green). The objects are in the same order as in Figure 1.

(A color version of this figure is available in the online journal.)

3.3. Broad Emission Lines

Broad emission lines are significantly detected in five out of the seven objects. For the three objects with relatively high signal-to-noise ratio (S/N), the broad Hα and Hβ lines have very similar profiles with complicated structures, such as wiggles and extra peaks (left panels of Figure 7). It should be noted that extra peaks are very rare among Seyfert galaxies, whereas they are present in two of the three objects in our
study. One object is SDSS J0952+2143, which has already been presented in Komossa et al. (2008, 2009). Another one, SDSS J1350+2916, shows a red peak and a blue peak at slightly larger velocities than SDSS J0952+2143. Due to their weakness, the broad He\textsc{ii} \lambda 4686 lines are detected only in SDSS J0938+1353, SDSS J0952+2143, and SDSS J1350+2916. The broad Hα lines have a median FWHM around 1400 km s\(^{-1}\) and a range from 880 to 2600 km s\(^{-1}\). They are much broader than the CLs, suggesting a different emission region. Very broad bumps are also detected in SDSS J0748+4712, which were argued by Wang et al. (2011) as being attributed also to the He\textsc{ii} \lambda 4686 and Balmer lines. The unusually strong He\textsc{ii} \lambda 4686 is probably due to the high helium abundance in the debris of an evolved star that is tidally disrupted. In the follow-up observations carried out thus far, these broad lines either disappeared completely or became considerably weaker. The strong fading and profile wiggle suggest that they are not of AGN origin.

3.4. Host Galaxy Properties

Figure 9 shows the SDSS images of the ECLEs. Most of these appear to be disk galaxies with the Petrosian radii in the range of 3–5 arcsec, except for SDSS J1241+2240, which shows a relatively large low surface brightness disk. The Petrosian magnitudes are brighter than the point-spread function magnitudes by more than 2 mag in all these galaxies. Therefore, we estimate the absolute magnitude of the host galaxies using the Petrosian magnitudes. The absolute magnitudes in the \(i\) band are in the range of \(-21.3 < M_i < -18.8\), suggesting that they are sub-\(L_\odot\) disk galaxies in the local universe (e.g., Blanton et al. 2003; Shao et al. 2007).

The stellar velocity dispersions, measured by fitting the starlight templates to the continuum (Section 2), are mostly below 70 km s\(^{-1}\), consistent with marginally resolved or unresolved absorption lines. While all are small, we did not...
perform precise measurements, since they are close to (or even below) the spectral resolution of SDSS (69 km s\(^{-1}\)) and the templates used are derived from a stellar population library of low spectral resolution. The small stellar velocity dispersions are also consistent with the narrowness of the [N\(\text{ii}\)] lines: \(\sigma_{\text{line}} < 40\) km s\(^{-1}\) in four objects and only one exceeding 100 km s\(^{-1}\) albeit the large scatter in the \(\sigma_* - \sigma_{\text{[N\(\text{ii}\)]}}\) relation (Greene & Ho 2005).

3.5. Spectroscopic Follow-up Observations

Spectroscopic follow-ups have been carried out for three objects of our sample, and the high-ionization CLs were found to be fading ubiquitously. In the case of SDSS J0952+2143, the lines of [Fe\(\text{x}\)]\(\lambda\)6376, [Fe\(\text{xi}\)]\(\lambda\)7894, and [Fe\(\text{xiv}\)]\(\lambda\)5304 had decreased dramatically several years after the initial SDSS spectroscopic observation. In contrast, the low-ionization lines [Fe VII] remained nearly constant and [O\(\text{iii}\)]\(\lambda\)5007 even brightened in the very last observation (Komossa et al. 2009; H. Y. Zhou et al. 2012, in preparation). The broad lines decreased with time as well. A similar trend was also observed in SDSS J1241+4426 in an MMT spectrum taken four years after the SDSS observation (H. Y. Zhou et al. 2012, in preparation). In SDSS J0748+4712, all the CLs disappeared while [O\(\text{iii}\)]\(\lambda\)5007 increased by a factor of 10 in spectra taken 4–5 years later (Wang et al. 2011). To summarize, in all the cases with follow-up observations thus far, the high-ionization CLs and the broad lines were fading on timescales of several years. The ionization of the line spectrum decreases with time.

4. THE NATURE OF EXTREME CORONAL LINE EMITTERS

4.1. Photoionization versus Collisional Ionization

In this section, we show that the [Fe\(\text{vii}\)] cannot be collisionally ionized, and argue that it is photoionized. For objects with detected [Fe\(\text{vii}\)], the ratios of the [Fe\(\text{vii}\)] lines can be used to constrain the electron temperature and density. The [Fe\(\text{vii}\)]5160/[Fe\(\text{vii}\)]6088 ratios range from 0.1 to 0.3, while the [Fe\(\text{vii}\)]3759/[Fe\(\text{vii}\)]6088 ratios range within 0.5 and 1.0, suggesting a range of the temperature and density values. We calculate the theoretical line ratios for a grid of temperatures and densities using the atomic database CHIANTI (Dere et al. 2009), which are used to constrain the temperature and density of the CL region in each object. The \(\chi^2\) at each grid is computed for the observed line ratios and their uncertainties. In Figure 10, we show the confidence contours at the 68% (~\(\Delta\chi^2 = 2.7\)) and 90% (~\(\Delta\chi^2 = 4.6\)) levels in the density and temperature plane.

In three of the four objects, the gas temperature is constrained to be within a few \(10^4\) K to \(10^5\) K, while it is poorly constrained in the remaining object. These temperatures are less than what is required for collisional ionization (\(T > 10^6\) K), thus...
photoionization is favored. An upper limit on the gas density is set to be $10^7\text{ cm}^{-3}$ for three objects, while a lower limit of $10^7\text{ cm}^{-3}$ is set for the other. Note that these ratios are not sensitive to densities below $10^5\text{ cm}^{-3}$ or above $10^8\text{ cm}^{-3}$. Obviously, spectra with higher $S/N$ are required for better constraints on the density and temperature.

Lower limits on the line emissivity, defined as $n_en_cm_3V$, are estimated for different ions using the collisional strengths from CHIANTI, assuming that collisional de-excitation is not important. Because [Fe $\text{x}$$\lambda$6376 and [Fe $\text{x}$$\lambda$7894 have the critical densities one order of magnitude higher than [Fe $\text{vii}$$\lambda$, objects with detected [Fe $\text{vii}$] are less likely affected by collisional de-excitation. For objects without [Fe $\text{vii}$] detections, there is no good temperature and density diagnostics in the optical band. In this case, we assume a gas temperature $T = 10^5\text{ K}$. Adopting a higher gas temperature will result in a higher emissivity. Assuming these ions are dominant species and the solar abundance, we can estimate a lower limit on the total emissivity $\int n_en_cm_3dV$. These numbers are in the range of $(5-50) \times 10^{60}\text{ cm}^{-3}$ (Table 2). Combing the line emissivity with the density, one can estimate the mass of the line-emitting gas. The typical value is from a few tenths to several solar masses, assuming a gas density of $10^5\text{ cm}^{-3}$.

### 4.2. Constraints on the Soft X-Ray Energy

The ions responsible for the CLs are created by ionizing photons in the soft X-ray band, ranging from energies $>125\text{ eV}$ for [Fe $\text{vii}$], $>361\text{ eV}$ for [Fe $\text{x}$], and to $>650\text{ eV}$ for [Ar $\text{xiv}$]. Therefore, the soft X-ray luminosity corridor on the line region (CLR) can be estimated with a detailed photoionization model. Instead, in this paper, we will use the observed relation between the soft X-ray emission and the CLs in Seyfert galaxies to infer the soft X-ray luminosity, and leave detailed photoionization modeling to future work.

It was found that the fluxes of [Fe $\text{x}$$\lambda$6376 and [Fe $\text{x}$$\lambda$7894 are well correlated with the soft X-ray flux in Seyfert galaxies\textsuperscript{10} (Gelbord et al. 2009). The CLs to X-ray flux ratios are $\log(f_{[\text{Fe} \, \lambda 6376]}/f_{X}) = -3.43 \pm 0.55$ and $\log(f_{[\text{Fe} \, \lambda 7894]}/f_{X}) = -3.52 \pm 0.38$ for both broad and narrow-line Seyfert 1 galaxies. These lines are thought to form in the inner edge of a dusty torus (Murayama & Taniguchi 1998a, 1998b; Rodríguez-Ardila et al. 2002), which has a covering factor about $0.6-0.7$ based on the fraction of type 2 Seyfert galaxies. As shown in Figure 3, the observed [Fe $\text{x}$$\lambda$6376 luminosities of the ECLEs are in the range of $39.2$ (dex)$-40.5$ (dex) in erg s$^{-1}$, similar to those of the CLs detected in AGNs. With the above flux ratios, we estimate the soft X-ray luminosities to be in the range of $42.5$ (dex)$-43.9$ (dex) erg s$^{-1}$. Soft X-rays with a luminosity of $10^{44}\text{ erg s}^{-1}$ (0.1$-$10 keV) were detected in SDSS J0952$+2143$ in 2009 (Komossa et al. 2009). Since the emission line fluxes were almost as high as the quasi-simultaneously measured X-ray flux, the authors suggested that the lines must be the echo of a past X-ray flare with a much higher luminosity. We note in passing that objects in Gelbord et al. (2009) are classical Seyfert galaxies, which are persistent sources, and so they are not affected by the fading effects seen in these ECLEs.

To estimate how much energy in soft X-rays is required, we integrate the CL energy over time. Assuming a lifetime for [Fe $\text{x}$$\lambda$6376 and [Fe $\text{x}$$\lambda$7894 of one year, the integrated [Fe $\text{x}$$\lambda$6376 or [Fe $\text{x}$$\lambda$7894 line energies is in the range of $46.7-48.0$ (dex) erg. With the above $L_{[\text{Fe} \, \lambda 6376]}/L_X$ and $L_{[\text{Fe} \, \lambda 7894]}/L_X$, the total energy in soft X-rays is estimated to be around 50 (dex)$-51.4$ (dex) erg.

### 4.3. Event Rate for ECLEs

We estimate the event rate from the number of ECLEs, the lifetime of CLs and the number of galaxies observed. From the follow-up observations of the three objects, we find that extreme coronal lines are visible for 3$-$5 years. This gives a lifetime of the order of three years. We found seven ECLEs from 676,881 galaxies and quasars at redshifts less than 0.20 in the SDSS DR7 spectroscopic sample. This gives an event rate of $2 \times 10^{-6}\text{ galaxy}^{-1}\text{ yr}^{-1}$.

The event rate is dependent on galaxy luminosity. As mentioned above, the host galaxy luminosities of the ECLEs are clustered in a relatively narrow luminosity range ($\sim 21.5 < M_r < -18.5$; see Figure 11). This dependence may be related to the physical conditions which are required to produce the CLs observed, such as the central black hole mass or the gas environment. Furthermore, in practice there is a lower limit on the spectral $S/N$ ratio for the detection of CLs. Considering this effect, we set a lower $S/N$ cutoff to the spectra as the lowest spectral $S/N$ ratio ($S/N = 14.8$ in the $i$ band) among the detected ECLEs. As a result, we obtain an event rate of about $1.5 \times 10^{-5}\text{ galaxy}^{-1}\text{ yr}^{-1}$ for all the galaxies with the absolute magnitudes in the range of $-21.5 < M_r < -18.5$. Despite a large number of more luminous galaxies that meet the $S/N$ ratio constraints, we did not detect any ECLEs among them.

### 4.4. Difference between ECLEs with and without [Fe $\text{vii}$]

We do not detect [Fe $\text{vii}$] in three of the seven objects. As clearly seen in both Figure 4 and Table 2, the non-detection is not due to the low $S/N$ of the spectra, but due to the weakness or absence of the [Fe $\text{vii}$] lines. The [Fe $\text{vii}$] lines have significantly lower critical densities ($10^6$-$10^7\text{ cm}^{-3}$) and lower ionization potentials than [Fe $\text{x}$$\lambda$6376, [Fe $\text{x}$$\lambda$7894, and [Fe $\text{xiv}$]. The lack of [Fe $\text{vii}$] in the three objects may be due to one or both of the following two factors: [Fe $\text{vii}$] is collisionally de-excited in high-density gas, while [Fe $\text{x}$$\lambda$6376 and [Fe $\text{x}$$\lambda$7894 are not because of their higher critical densities; the gas is overionized under intense soft X-ray radiation. In Section 3.1, we showed that in one object with [Fe $\text{vii}$] detection the CLR density is close to the critical density of [Fe $\text{vii}$]. Therefore, it is possible that some objects may have the densities even higher so that [Fe $\text{vii}$] is collisionally de-excited. On the other hand, it is also plausible that objects without [Fe $\text{vii}$] have higher ionization parameters. All the three objects without [Fe $\text{vii}$] show the $[\text{S} \, \text{ii}]$ $\lambda 7612$ lines, while only two of the four objects with [Fe $\text{vii}$] do. However, we cannot verify this as there is no good density indicator in the optical band for objects without [Fe $\text{vii}$] lines. Below, we investigate several possibilities in order to understand the origin of this difference.

We examine other line ratios, [Fe $\text{x}$] $\lambda 7894/\lambda 4686$, [O $\text{iii}]$ $\lambda 5007/\lambda 4959$, and He $\text{ii}$ $\lambda 4686/\lambda 4680$ and find no significant difference between objects with and without the [Fe $\text{vii}$] lines. The intensity of [Fe $\text{xiv}$] $\lambda 5304$ is comparable to those of [Fe $\text{x}$$\lambda$6376 and [Fe $\text{x}$$\lambda$7894 in both subclasses. However, the [O $\text{iii}]$ $\lambda 5007$ luminosities for objects without [Fe $\text{vii}$] are one order of magnitude lower than those with [Fe $\text{vii}$]. The host galaxies of ECLEs with the [Fe $\text{vii}$] lines appear to be more luminous than those without. All the host galaxies of the ECLEs with [Fe $\text{vii}$] are brighter than $-19.6$ mag in the $i$ band, whereas those without are fainter than this value.
Among the four objects showing continuum variations between the SDSS photometric and spectroscopic observations, the two with [Fe vii] have higher non-stellar luminosities ($M_{var} < -17.5$) than the two without [Fe vii] ($M_{var} > -17.0$), as seen in Table 1. However, these results should be tested with a larger sample in the future.

4.5. Tidal Disruption, Nuclear Activity, or Peculiar Supernova

The strong CLs clearly require a strong soft X-ray ionizing source. In galactic nuclei, a number of processes may produce strong soft X-ray emission: an SN explosion, episodic accretion onto a supermassive black hole following a TDE or disk instability, or encountering a molecular cloud (Komossa et al. 2008, 2009; Wang et al. 2011). Given the large mass and size of a stable molecular cloud, events of a random encounter of a molecular cloud likely last for a much longer timescale. The fact that most of the objects avoid the AGN region in the BPT diagram suggests that the normal narrow-line region did not see the hard ionizing continuum from the accretion disk. This implies that the last nuclear activity was either at least several 10$^7$ years ago (the light crossing time of traditional Narrow Line Region; NLR) or at a very low level. The decay timescales are much shorter than those of limit-cycle outbursts driven by local thermal instability (Lin & Shields 1986) in accretion disks. Thus, episodic feeding by a molecular cloud, a persistent AGN and disk instability are very unlikely.

CLs are observed in a few SNe of type IIn, mostly at a late evolutionary stage. They are produced in pre-shocked regions ionized by radiative shocks from an expanding shell running into clumpy circumstellar medium (Smith et al. 2009). However, the CL luminosities in these SNe are factors of tens to hundreds lower than observed in the ECLEs studied here. Furthermore, the spectra of these SNe also display rich, strong low-ionization lines such as Fe ii at late stages, or strong He i emission lines in the early spectrum of SN 2005ip (Smith et al. 2009); these features are very different from the ECLE spectra. In addition, the current models of SNe do not predict sufficient energy in soft X-rays either. Nakar & Sari (2010) calculated the X-ray light-curves of core-collapsed SN breakouts for various initial masses. Integrating these light-curves yields a total soft X-ray energy about one to several orders of magnitude lower than those estimated in the last section. The X-rays produced in late shocks are also one order of magnitude lower than the those required to power the coronal line luminosity, even in strongly interacting objects (Fabian & Terlevich 1996; Chevalier & Fransson 1994).

Finally, as discussed in Section 3.1, the UV magnitudes of SDSS J0748+4712 measured 20 days after the detection of the CLs was brighter than $-17$ mag, which is too bright for any current SN model predictions (e.g., Nakar & Sari 2010). For these reasons, we consider SNe to be unlikely either.

Most of the observed properties can be reconciled in the context of tidal disruption of stars by massive black holes at galactic centers (Komossa et al. 2009). Fallback of the bounded tidal debris forms an optically thick accretion torus around the black hole. The luminosity is peaked at or near super-Eddington on the accretion timescale, and then decreases as $t^{-5/3}$ (Rees 1988; Evans & Kochanek 1989; cf. Lodato et al. 2009). If 10% of the radiation goes into soft X-rays, it gives an integrated soft X-ray energy of $\sim 0.01 M \cdot c^2 \approx 10^{52} \text{ erg}$, which is sufficient to power the CLs, assuming 10% radiation efficiency in the accretion disk. A TDE can explain naturally (e.g., Strubbe & Quataert 2009) the bright UV source detected in SDSS J0748+4712 at least 20 days after the CL detection.

Broad emission lines can be produced via reprocessing the disk emission by bound and unbound stellar debris (Eracleous et al. 1995; Bogdanović et al. 2004; Komossa et al. 2008; Strubbe & Quataert 2009). Blueshifted, very broad lines, seen in SDSS J0748+4712, can form in winds driven by super-Eddington accretion during the initial flare (Strubbe & Quataert 2009). As in SNe, unbound material with high velocities may interact with the surrounding ISM, and produce broad emission lines as well (e.g., Khokhlov & Melia 1996; Ayal et al. 2000). In that case, material emitting the Balmer lines can be collisionally excited, rather than photoionized. The debris has...
a range of orbits and may be dynamically unsettled. This produces variable broad lines with complex profiles, as seen in the observed spectra. As a consistency check, the mass of the line-emitting gas should be smaller than that of the disrupted debris. Assuming the broad Balmer lines are produced via recombination, the minimum mass of the H\textsc{ii} region can be written as \( M_{\text{min}} = 1.3 m_p n_e L_{\text{H}\alpha}/(4\pi j_{\text{H}\alpha}br) \) \( \simeq 0.03 n_{e,10}^{-3} L_{\text{H}\alpha,br,41} M_\odot \) using the H\alpha line emissivity from Osterbrock & Ferland (2006) for a temperature \( T = 10,000 \) K, where \( n_{e,10} \) is the electron density in units of \( 10^{10} \) cm\(^{-3}\). The observed \( L_{\text{H}\alpha,br,41} \) luminosities (in units of \( 10^{41} \) erg s\(^{-1}\)) are in the range of \( 0.03-3.0 \), which are consistent with stellar debris of a few tenths solar mass as line-emitting gas for a reasonable gas density.

CLs may come from interstellar medium photoionized by a flare. Typically a flare lasts for a few months, which are longer than the recombination time for the gas density inferred from the [Fe \textsc{vii}] line ratios.\(^{11}\) At any given time, emission lines come from a region within two parabolic iso-delay surfaces of a delay interval of months at large scales as well as from the nuclear region (Figure 12). The ionizing photons, i.e., soft X-rays, must reach a distance of a few light-years in order to explain the presence of the CLs for a few years. In the last section, we have shown that there is a quite large range of densities, from object to object, from a few \( 10^4 \) cm\(^{-3}\) to > a few \( 10^7 \) cm\(^{-3}\) for the coronal line emitters (CLEs) with [Fe \textsc{vii}]. If the line-emitting gas fills completely the region, it would be optically thick to the soft X-rays. Thus, the emission-line region must be clumpy. Only the dense clouds produce the CLs and some recombination lines such as the Balmer lines and He \textsc{ii} line, while the low-density gas is probably completely ionized in the strong radiation field of the flare and is transparent to the soft X-rays.

Tidal disruption may leave significant imprints on the kinematics of the line-emitting gas. Gas exposed to the intense radiation will receive a radial acceleration, and over the period of the passage of the flare, gas will gain a radial velocity of the order \( k(\Delta t/1 \text{ month})(v/1 \text{ month})^{-2} \) km s\(^{-1}\), where \( k = [(\kappa/\sigma_T)L/L_{\text{Edd}}] - 1 \) is the ratio between the radiation force and gravity, and \( \Delta t \) the duration of the UV/X-ray flare. \( k \) can be on the order of \( 10^2 \), even if the gas contains a small amount of dust. This may explain the blueshifts seen in some of the CLs. The radial velocity decreases rapidly with time, thus we expect that the blueshifts become smaller as the flare evolves. Also the line width becomes smaller with time as gas farther out contributes to the CLs. However, the distribution of the line-emitting gas is likely not affected much by TDEs. This is because the timescale of density adjustment is the sound-traveling time within individual clouds, and the timescale for cloud migration is \( r/v \), where \( v \sim 10^2 \) km s\(^{-1}\) is estimated from the emission line widths. A decrease of ionization with time was observed in three objects analyzed so far. Such a behavior is expected in a number of cases: gas density falls less steep than \( r^{-2} \), so the ionization parameter decreases as the emission-line region moves out; if the optical depth to soft X-ray absorption is moderate, the ionizing continuum may be diluted on the way outward. In addition, as the mass accretion rate decreases with time, the ionization parameter in the inner region decreases and the continuum may be softened, too. Detailed photoionization modeling is needed to understand this problem.

If these ECLEs are indeed associated with TDEs, the question arises as to whether any TDEs, regardless whether they were

\(^{11}\) At a temperature of \( 10^5 \) K, the recombination time is \( 5 \times 10^3(n_e/10^6 \text{ cm}^{-3}) \) s for Fe\textsc{iv}, and 20 and 30 times smaller for Fe\textsc{v} and Fe\textsc{x} respectively.

Figure 12. Snapshot of the continuum intensity around a black hole that contributes to the observed emission lines at a specific time in an oversimplified model, in which the ionizing continuum decreases with time as \( \propto t^{-5/3} \) when \( t > t_0 \), where \( t_0 \) is the time of tidal disruption. The observer is to the left of the figure at time \( t_0 \). The overlaid yellow lines are intensity contours with an interval of 2.5 fold.

(\textit{A color version of this figure is available in the online journal.})

12 The one exception is the AGN IC3599, which underwent a large soft X-ray outburst and had an optical spectrum taken within one year. The high-state optical spectrum showed strong coronal lines of [Fe \textsc{xii}] and [Fe \textsc{xvii}], which faded in subsequent years, plus a broad Balmer emission line of 1200 km s\(^{-1}\) width which also faded (Brandt et al. 1995; Grupe et al. 1995; Komossa & Bade 1999). IC3599 had been known to be an AGN before the X-ray flare.
Cenko et al. (2012), but no strong CLEs were detected. These results suggest that most TDE candidates identified so far do not show strong coronal lines. However, Gezari et al. and Cenko et al. rejected objects either with a broad line or with $[\text{O} \, \text{iii}] \lambda 5007/\lambda H\beta > 3$ to remove AGN, while most objects in our sample do show (possibly transient) broad lines and two have $[\text{O} \, \text{iii}] \lambda 5007/\lambda H\beta > 3$. Therefore, by definition, they also excluded any potential TDEs with strong coronal lines. Furthermore, their absorption-line-dominated TDEs do not produce coronal lines as discussed later. We checked their rejected spectra. In fact, among eight objects with UV flares and with optical follow-up spectra in their sample, we find that one object, D2-9 (J100002.0+024216), displayed a very strong $[\text{Fe} \, \text{xiv}] \lambda 5304$ line (see Figure 7 of Gezari et al. 2008). This object was classified as Seyfert 2 based on $[\text{O} \, \text{iii}] \lambda 5007/\lambda H\beta > 3$ by those authors. If its $[\text{Fe} \, \text{xiv}] \lambda 5304$ line turns out to be fading in future observations, it would be one TDE candidate. For most of the other objects, however, the spectra are of too low S/N or do not cover the coronal line regime. Thus, the fraction of TDEs with strong CLs is not constrained.

To produce strong CLs, tidal disruption must occur in an environment of rich cold gas. Note that all objects in our sample show narrow emission lines from a region different from the coronal line region as indicated by their widths and/or low-ionization levels, demonstrating the presence of cold gas. The non-detection of coronal lines in absorption-line dominated galaxies appears to be a natural outcome of depletion of cold gas in their nuclei. Whether or not a gas-rich galaxy (i.e., $H\,\text{ii}$-type galaxy) does show strong CLs after a nuclear flare would also depend on the amount of gas near the nucleus that is capable of producing CLs. In addition, it is also necessary to have strong soft X-ray emission from the accretion disk to ensure extreme coronal line emission. While most high-energy flares were indeed characterized by very luminous soft X-ray emission, some UV-detected flares may have been weak in X-rays (Gezari et al. 2009), and the broadband spectral energy distribution depends on the details of the stellar debris evolution, and on possible effects of self-absorption.

As we discussed in Section 3.4, ECLEs are hosted in intermediate-luminosity disk galaxies. Besides, these galaxies do not show apparent bulges in their SDSS images, indicating that the bulge luminosity would be much lower than that of the whole galaxy. This can be seen most clearly in the nearest object, SDSS J1241+4426, where we found only a faint light concentration in the very center of the galaxy. Thus the black hole masses in these galaxies are likely small according to the black hole and bulge mass relation. A similar conclusion can be reached from the $M_{\text{BH}} - \sigma$ relation (Tremaine et al. 2002). If we use the stellar velocity dispersion in Section 3.4, the black hole mass would be at most around $10^5 M_\odot$. Because a high soft X-ray luminosity is required to power luminous CLs, the black hole mass is not likely much below $10^5 M_\odot$.

Wang et al. (2011) speculated that ECLEs with and without $[\text{Fe} \, \text{vii}]$ are at different evolution stages based on the variations of $[\text{Fe} \, \text{x}]$ and $[\text{Fe} \, \text{vii}]$ in three objects with follow-up observations so far. The high-ionization lines faded much faster than $[\text{Fe} \, \text{vii}]$. Thus, we expected higher ionization in earlier stages. The relative fraction of each subclass depends on the time spent in each stage, i.e., the similar numbers detected for each subclass indicate similar time periods spent in each stage. However, this cannot explain their difference in the luminosity of host galaxies, in $[\text{O} \, \text{iii}]$ luminosity and possibly in the luminosity of variable components, if confirmed.

Alternatively, these differences may be understood in terms of the differences in black hole mass, and host galaxy properties. Objects with the $[\text{Fe} \, \text{vii}]$ emission lines appear to be systematically more massive than those without. Less massive galaxies tend to host smaller black holes, which may result in a hotter accretion torus and a harder soft X-ray spectrum (Montesinos Armijo & de Freitas Pacheco 2011). This may lead to overionization of the line-emitting gas, and thus very weak $[\text{Fe} \, \text{vii}]$. Furthermore, if more massive host galaxies have a different gas distribution in their cores (gas mass, density, and column density), it is conceivable that the $[\text{Fe} \, \text{vii}]$ emission would be affected in a systematic way.

5. CONCLUSION

We have compiled a sample of seven ECLEs, which have $[\text{Fe} \, \text{x}]/[\text{O} \, \text{iii}] > 1$ one order of magnitude higher than those of Seyfert galaxies from the SDSS spectroscopic samples of galaxies and quasars. The luminosities of the coronal lines are on the order of $10^{40}$ erg s$^{-1}$, comparable to those observed in Seyfert galaxies. Despite the strong coronal lines, most of these galaxies are located in the regime of star-forming galaxies on the BPT diagrams, suggesting that the conventional narrow-line region did not see the hard ionizing continuum that the coronal line region did. Follow-up observations of three of the ECLEs show that the high-ionization coronal lines had been fading, while the low-ionization lines remained constant or even brightened on timescales of several years. In four objects, variations of the continuum emission are detected between the SDSS imaging and spectroscopic observations which spanned from four months to two years. These also set constraints on the ages of the CLEs from less than four months to more than two years. Broad emission lines are detected in five of the seven objects. These lines exhibit complex profiles, including blue and red peaks in two objects, and a very broad and blueshifted line in one. In three of the objects the broad emission lines diminished, similar to the high-ionization coronal lines, as revealed by follow-up observations. The ECLEs sample can be divided into two subclasses of similar numbers, those with and without the detected $[\text{Fe} \, \text{vii}]$ emission. They do not show significant difference in the $[\text{Fe} \, \text{x}]/[\text{O} \, \text{iii}] > 1$ ratios. The ECLEs with detected $[\text{Fe} \, \text{vii}]$ tend to have brighter host galaxies, higher $[\text{O} \, \text{iii}] > 1$, and higher variable continuum luminosities than those without. In general, their host galaxies are disky and underluminous, in the range of $-21.3 < M_{i, \text{AB}} < -18.9$, and have small stellar velocity dispersions. Based on the current sample, we estimate an event rate for the ECLEs on the order of $\sim 10^{−5}$ galaxy$^{-1}$ year$^{-1}$ for galaxies of $-21.5 < M_{i, \text{AB}} < -18.5$.

Various scenarios are discussed to explain ECLE. The most promising one is tidal disruption of a star by less massive black holes residing in cold-gas-rich galactic nuclei. In this scenario, the broad lines result from the reprocessing of UV/X-ray flares by the unbound and/or bound stellar material, while the coronal lines are produced by the clumpy interstellar medium. The diverse properties of the emission lines may be understood qualitatively in terms of the differences in the gas environment, the shape of the ionizing continuum, and the stage of time evolution. Specifically, the dichotomy between having and lacking the $[\text{Fe} \, \text{vii}]$ lines may be ascribed to the dependence of soft X-ray spectrum on the black hole mass, or nuclear gas density. However, we still do not understand the key physical processes responsible for such a diversity. We are carrying out
spectroscopic follow-ups of these objects in order to study long timescale variations and to further constrain their nature.

If these ECLEs are confirmed to be associated with TDEs, our approach may provide a new method of a systematic search for TDEs from large spectroscopic surveys. The extreme CL phase lasts for a few years, as observed in two objects, much longer than the photometric flaring signatures in the optical and UV. Spectroscopic detections and subsequent monitoring of the long-term evolution of emission lines can provide rich diagnostical on the ISM in the vicinity of a dormant black hole, which can be hardly obtained otherwise. The event rate can be used to constrain the incidence of supermassive black holes in sub-L∗ galaxies, when combined with the host galaxy properties. We plan to carry out such surveys with the Chinese LAMOST telescope to conduct early spectroscopic follow-ups of these objects in order to study long timescale variations and to further constrain their nature.

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