Panchromatic Properties of the Extreme Fe II Emitter PHL 1092

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ABSTRACT
We present near-infrared spectroscopy of the NLS1 galaxy PHL 1092 (z = 0.394), the strongest Fe II emitter ever reported, combined with optical and UV data. We modeled the continuum and the broad emission lines using a power-law plus a black body function and Lorentzian functions, respectively. The strength of the Fe II emission was estimated using the latest Fe II templates in the literature. We re-estimate the ratio between the Fe II complex centered at 4570 Å and the broad component of Hβ, \( R_{4570} \), obtaining a value of 2.58, nearly half of that previously reported (\( R_{4570} = 6.2 \)), but still placing PHL 1092 among extreme Fe II emitters. The FWHM found for low ionization lines are very similar (FWHM \( \sim 1200 \) km s\(^{-1}\)), but significantly narrower than those of the Hydrogen lines (FWHM \( H\beta \sim 1900 \) km s\(^{-1}\)). Our results suggest that the Fe II emission in PHL 1092 follows the same trend as in normal Fe II emitters, with Fe II being formed in the outer portion of the BLR and co-spatial with Ca II, and O I, while \( H\beta \) is formed closer to the central source. The flux ratio between the UV lines suggest high densities, \( \log(n_H) \sim 13.0 \) cm\(^{-3}\), and a low ionization parameter, \( \log(U) \sim -3.5 \). The flux excess found in the Fe II bump at 9200 Å after the subtraction of the NIR Fe II template and its comparison with optical Fe II emission suggests that the above physical conditions optimize the efficiency of the Lyα-fluorescence process, which was found to be the main excitation mechanism in the Fe II production. We discuss the role of PHL 1092 in the Eigenvector 1 context.

Key words: galaxies: active – techniques: spectroscopic – individual: PHL 1092

1 INTRODUCTION

Narrow-line Seyfert 1 (NLS1) galaxies are a particular subclass of active galactic nuclei (AGN) that show narrow permitted emission lines (FWHM_{H\beta} < 2000 km/s) and weak [O III]\( \lambda\lambda 4959,5007 \) lines ([O III]/H\beta < 3) (Osterbrock & Pogge 1985; Goodrich 1989) than classical Type I AGN. Besides, NLS1 have other interesting properties across the electromagnetic spectrum. In the optical and UV they show strong asymmetries in the [O III] lines (Zamanov et al. 2002; Bian et al. 2005; Boroson 2005) and high velocity blueshifted CIV lines (Sulentic et al. 2000c; 2002; Wills et al. 2000; Leightly & Moore 2004). One of the most intriguing properties of NLS1 is the strong Fe II emission, with numerous multiplets across the UV, optical and NIR spectrum that form a pseudo-continuum mostly in the UV and optical regions. The strength of this feature, usually represented by the flux ratio Fe II/H\beta between the Fe II bump centred at \( \lambda 4570 \) Å and the broad component of H\beta (hereafter \( R_{4570} \)), is about twice or larger than that measured in normal AGN (Zhou et al. 2006), with NLS1 reaching values higher than 1 (Joly 1991; Marziani et al. 2001; Shen et al. 2011; Rakshit et al. 2017).

Several models have tried to explain the Fe II emission in AGN. The most recent ones incorporate excitation mechanisms such as collisional excitation, continuum fluorescence, self-fluorescence of Fe II lines and Lyα-fluorescence (Sigut & Pradhan 1998; Verner et al. 1999; Sigut & Pradhan 1999; Verner et al. 1999; Sigut & Pradhan 2000).
A decade ago, Bruhweiler & Verner (2008) considerably improved this approach by considering an Fe II ion with 830 levels, noticing that an appropriate number of energy levels must be taken into account in order to reproduce the observed Fe II emission. Understanding this emission in AGN is important at least for 4 reasons: (i) the Fe II emission is one of the strongest cooling agents in the broad line region (BLR). It accounts for up to 25% of the total energy output of that emission region (Wills et al. 1995); (ii) it represents a strong component all over the spectrum. The myriad of Fe II multiplets forms a pseudo-continuum from the UV to NIR (Sigut & Pradhan 2003) with more than 344,000 transitions (Bruhweiler & Verner 2008). (iii) The gas emitting Fe II probes the structure and kinematics of the BLR (Kovačević et al. 2010; Hu et al. 1998; Samushia et al. 2011; Martínez-Aldama et al. 2015; Cracco et al. 2016). (iv) The strength of Fe II relative to the peak of [O III] and width of the H β line forms the optical plane of the Eigenvector 1 (hereafter E1) (Boroson & Green 1992). It is believed to be associated to fundamental properties of AGN such as the accretion power and super massive black hole mass (Boroson & Green 1992; Sulentic et al. 2000c; Shen & Ho 2014). Boroson & Green (1992) studied correlations among observed features in a complete radio-quiet sample of quasars using the Principal component analysis (PCA) technique. They found that most of the quasar properties are related to Eigenvector 1. E1 was later expanded to a 4-dimension eigenvector 1 (4DE1) parameter system to include the blueshift of C IV and the X-ray photon index (Sulentic et al. 2000c, 2002, 2007). The 4DE1 defines a main sequence for quasars that is believed to be ultimately driven by the Eddington ratio (L/LEdd) (Marziani et al. 2001; Shen & Ho 2014) and that, in addition to the four parameters of 4DE1, is correlated with low- and high-ionisation line profiles, systematic shifts of broad and narrow high-ionization lines (see Marziani et al. 2018, for a review). Moreover, it is possible to identify two populations of type-I AGN in the optical plane of the 4DE1 (defined by the FWHM(H β) and the R4570): “Population A” AGN, with FWHM(H β)<4000 km s^{-1} and strong Fe II emission; and “Population B” AGN, characterized by FWHM(H β)>4000 km s^{-1} and weaker Fe II emission (Sulentic et al. 2000a,b, 2002). More recently, Panda et al. (2018) showed that the Eddington ratio is not enough to drive the quasars through the E1 sequence, suggesting that higher abundances and high densities may also be necessary to place AGN at the high R4570 end of the E1. Marziani et al. (2001), while looking for a physical interpretation of the E1, pointed out to one particular AGN –PHL 1092– as an extreme outlier in the high-end of strong Fe II emitters. They considered this source as a rare case that should probe extreme conditions in the BLR.

PHL 1092 is a relatively nearby radio-quiet quasar (z = 0.396) with many interesting properties all over the electromagnetic spectrum. Its X-ray emission is known as one of the weakest and variable in a non-BAL AGN spectrum (Miniutti et al. 2009). In the UV, broad C IV and Lyα lines, with a high blueshifted and asymmetric profile in C IV are observed (Miniutti et al. 2012). The Near-UV spectrum is dominated by the pseudo-continuum formed by Fe II. In the optical region its outstanding Fe II emission reaches extreme values, with R4570 varying from 1.81 to 6.2 (Lawrence et al. 1997; Bergeron & Kunth 1980). The main cause of this extreme variation is attributed to the method employed in measuring the optical Fe II emission. The narrowness of the Balmer lines (FWHM~1800km/s) and the low ratio [O III]/H β~0.9, together with the strong Fe II emission, classify this AGN as a high luminosity NLS1 (Osterbrock & Boggs 1985). Although PHL 1092 was already observed in many regions of the electromagnetic spectrum, to the best of our knowledge, no report of its properties in the NIR exists up to today.

The NIR has several advantages over the UV and optical for the study of the Fe II emission. For instance, the most conspicuous Fe II lines are nearly isolated features, allowing an accurate analysis of their intensities and line profiles. Moreover, emission lines, such O I and Ca II are isolated or moderately blended with adjacent lines (Martínez-Aldama et al. 2015; Marinello et al. 2016). While in the optical the Fe II is severely affected by the underlying Fe II, the Paschen lines in the NIR are completely isolated (Rodríguez-Ardila et al. 2002). As pointed out by Sigut & Pradhan (1998, 2003); Rodríguez-Ardila et al. (2002) and (Marinello et al. 2016), this spectral window holds key features for understanding the physics of Fe II in AGN. For example, the Fe II bump centered at λ9200 and the four isolated Fe II lines at λ9998, 10502, 10900, 11127 Å (known collectively as the 1 μm Fe II lines), carry important information about the excitation mechanisms of this ion (Sigut & Pradhan 1998, 2003; Marinello et al. 2016). Therefore optical and NIR observations combined improves the description of the excitation mechanism behind the extreme Fe II emission in this source.

In this paper we analyze for the first time NIR spectroscopy of PHL 1092 in combination with optical observations around the H β region in order to obtain a full coverage of the most important Fe II features of this source. Our goals are threefold: (i) To obtain a consistent estimation of the Fe II intensity; (ii) to measure the Fe II and other BLR features (H I, O I and Ca II) in order to get clues about the location, excitation mechanism, and physical conditions of the regions where they are emitted; (iii) To study the role of the PHL 1092 in the E1 context.

This paper is structured as follow: Section 2 presents the observations and data reduction. Section 3 describes the technique applied to fit the Fe II templates and measuring the emission lines properties of the broad lines in the observed spectra. Section 3 and 4 discusses the location of the Fe II emitting region, its physical conditions and the excitation mechanism driving this emission. The role of PHL 1092 in the E1 context is presented in Section 5. Conclusion are given in section 6.

2 OBSERVATIONS

2.1 GNIRS/Gemini spectroscopy

NIR spectra of PHL 1092 were obtained during the night of August 17, 2014, with the 8.1 m Gemini North telescope in Mauna Kea Observatory (Program ID GN-2014B-Q-29). We employed the Gemini Near-IR spectrograph (GNIRS, Elias et al. 2006) in the cross-dispersed mode, which allows simultaneous z+J, H and K band observations, covering the spectral range 0.8 – 2.5μm in a single exposure. The average seeing of the night was 0.7 arcsecs. The instrument setup
includes a 32 l/mm grating and a 0.8×15 arcsec slit, giving a spectral resolution of R∼1300. Individual exposures of 180 s each were taken, nodding the source in a pattern ABBA along the slit, with a total integration time of 36 minutes. Right after the observation of the science frames, an A0V star was observed at a similar airmass, with the purpose of flux calibration and telluric correction.

The NIR data were reduced using the XDGNIRS pipeline (v2.0) \(^1\), which delivers a full reduced, wavelength and flux calibrated, 1D spectrum with all orders combined (see Mason et al. 2015, for a more detailed description of the software). Briefly, the pipeline cleans the 2D images from radiative events and prepares a master flat constructed from quartz IR lamps to remove pixel to pixel variation. Thereafter, the s-distortion solution is obtained from daytime pinholes flats and applied to the science and telluric images to rectify them. Arc images are used to find the wavelength dispersion solution. The 1D spectrum is then extracted from the combined individual exposures. The telluric features from the science spectrum are removed using the spectrum of a A0V standard star. Finally, the flux calibration was achieved assuming a black body shape for the standard star (Pecaut & Mamajek 2013) scaled to its K-band magnitude (Skrutskie et al. 2006). The orders are finally combined in to a single spectrum as shown in the top panel of Figure 1.

2.2 Goodman/SOAR spectroscopy

Optical spectroscopy of PHL1092 was obtained on the night of December 12, 2014, with the 4.1 m Southern Observatory for Astrophysical Research (SOAR) Telescope at Cerro Pachón, Chile. The observations were carried out using the Goodman Spectrograph (Clemens et al. 2004), equipped with a 400 l/mm grating and a 0.8 arcsec slit width, giving a resolution R∼1500. The target was observed for a total of 45 minutes in three individual exposures of 15 minutes each. The standard star LTT 1020 was observed for flux calibration. HgAr arc lamps were observed after the science frames for wavelength calibration. Daytime calibrations include bias and flat field images.

The optical data was reduced using standard IRAF tasks. First, the bias frames were combined and subtracted from the remaining images. The images were then divided by a single averaged and normalized master flatfield image. The wavelength calibration of the science and star frames were achieved by applying the dispersion solution obtained from the arc lamp frames. The 1D spectra of LTT1020 were then extracted and combined to derive the sensitivity function, later applied to the PHL1092 1D spectrum. The two atmospheric bands, at 6870 and 7600 Å, were modeled and removed using the following procedure. First, we interpolate the continuum between the two ends of each atmospheric bands. Second, we divided the original standard star spectrum to that without the atmospheric bands. The ratio between them produce a template were the continuum is equal to one except in the regions containing the atmospheric bands. Third, We divided the PHL1092 spectrum to that of the template. The final flux calibrated optical spectrum of PHL1092 is shown in the middle panel of the Figure 1.

2.3 STIS/HST spectroscopy

Ultraviolet spectroscopy for PHL1092 was available at the Hubble Space Telescope science archive. The spectrum was taken on August 20, 2003 using the Space Telescope Imaging Spectrograph (STIS) in combination with the filter G230L and a total integration time of 5746 s. It covers the rest frame wavelength interval 1120 Å − 2240 Å with a resolution of R∼600 km s\(^{-1}\). The bottom panel of the Figure 1 shows the UV HST spectrum with the emission lines relevant to this work identified by black arrows.

Note that neither UV, optical nor NIR spectra of PHL1092 were taken simultaneously. As no overlap region exists between the different data sets, no effort was made to put them into a common flux level mostly because of potential variability effects, which may produce relative shifts between the continuum levels and emission lines along the UV, optical and infrared regions. However, the spectral gap between the optical and NIR observations is only 300 Å and the continuum flux at the red end of the Goodman spectrum and blue edge of the GNIRS spectrum is consistent with an underlying power-law continuum (see figure 1). This consistency suggest no (or very small) variability between the two observations. Assuming a conservative scenario, we consider the mean value of AGN fractional variability from Kollatschny et al. (2006) as representative of the variability effect in PHL 1092. They estimated an uncertainty of ∼11% on the optical fluxes due to variability. Du et al. (2018) found a fractional variability ∼10 % for a sample of high accretion rate AGN. This value is also in good agreement with Hu et al. (2015), who found an average fractional variability of 10% for Fe\(^{ii}\) when compared with H\(\beta\). Therefore, we use this values as a variability bias on all our measurements in this work.

3 SPECTRAL FEATURES

3.1 Continuum and Fe\(^{ii}\) Emission

In order to measure the Fe\(^{ii}\) content in PHL1092 we first carry out a proper continuum emission subtraction. To this purpose, we assume that the rest-frame UV to optical continuum is represented by a power-law function. Besides, hundreds of thousands of blended Fe\(^{ii}\) multiplets form a pseudo-continuum from UV to NIR (Sigut & Pradhan 2003). Because both components are spatially unresolved, it is not possible to measure them independently. Moreover, in moderate to strong Fe\(^{ii}\) emitters, it is difficult to find out spectral windows free of both continua. Therefore, in order to disentangle them, the best approach is to model these two components simultaneously.

The Fe\(^{ii}\) emission is best represented by templates, usually derived from I Zw 1, the prototype NLS1. In the optical, Boroson & Green (1992) constructed an empirical template of the Fe\(^{ii}\) from the I Zw 1 spectrum by removing all other lines different from Fe\(^{ii}\) in that AGN. Vestergaard & Wilkes (2001) employed a similar approach to obtain an empirical

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\(^1\) Based on the Gemini IRAF packages
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Figure 1. Observed PHL1092 spectrum with GNIRS, Goodman, and STIS. The spectra were corrected by redshift, $z = 0.396$. Top panel: Full reduced and flux calibrated NIR spectrum of PHL1092 observed with GNIRS/Gemini North. The gray shade areas mark the regions affected by telluric abortion. Middle panel: Fully reduced and flux calibrated optical spectrum of PHL1092 observed with Goodman/SOAR. Bottom panel: Ultraviolet spectrum of PHL1092 as observed by STIS/HST. In all three panels, prominent emission lines and FeII multiplets are identified by the arrows.
UV template of this ion using a high S/N spectrum of I Zw 1 observed with HST/STIS.

Other authors have constructed templates using theoretical models based on assumptions about the physical conditions in the Fe II emission region. Kováčević et al. (2010), for instance, used the relative intensities of groups of multiplets and physical constrains to construct their template. Tsuzuki et al. (2006) combined the empirical approach of Boroson & Green (1992) and Vestergaard & Wilkes (2001) with theoretical models of the Fe II lines using CLOUDY (Ferland et al. 1999) to develop their templates. In the NIR, the only template available in the literature is from Garcia-Rissmann et al. (2012). It covers the wavelength interval 8000-11600 Å and was constructed using a semi-empirical approach, that is, by combining Sigut & Pradhan (2003) models with modifications to match the observed spectrum of I Zw 1. Marinello et al. (2016) and Martínez-Aldama et al. (2015) already demonstrated that this template successfully reproduces the NIR Fe II emission in several AGN.

Thus, in order to fit the optical continuum of PHL 1092 we will use a power-law plus the Fe II template from Boroson & Green (1992). Because the lines of our interest are concentrated in the region between 4000-5700 Å, we restrict the fit to this region.

The continuum plus Fe II emission were fit using Equation 1:

\[ F(\lambda) = F_{PL}^{\lambda} + (F_{FeII}^{\lambda} * G_{\lambda}) \]  

where \( F_{PL}^{\lambda} \propto \lambda^{-\alpha} \) describes the power law, and \( F_{FeII}^{\lambda} \) represents the Boroson & Green (1992) Fe II template convolved with a Gaussian kernel, \( G_{\lambda} \), in velocity space, \( V_{FeII} = \sqrt{V_{temp}^2 + V_{conv}^2} \). To fit the continuum and the emission lines (see next section) we used our own python code, which makes use of the SCIPY library and the curve_fit function. All fitting procedures in this work use this python function to estimate the best parameters in each case, obtained by minimizing of the \( \chi^2 \) along the spectral region of the fit, masking the emission lines Hβ, [O iii] \( \lambda\lambda4959,5007 \) and Hγ. The final model, its components and the pure emission line spectrum resulting from its subtraction can be seen in middle panel of Figure 2.

To model the continuum in the UV we used a single power law function, \( F_{PL}^{\lambda} \). The Fe II emission, if present, is at the continuum level and blended to the noise of the spectrum. We found a power law index of \(-1.2\), consistent with the optical counterpart of the PHL 1092 spectrum. The bottom panel of Figure 2 shows the modeled continuum and the pure emission lines spectrum. Prominent lines present in the spectrum are Lyα, C IV \( \lambda\lambda1549,1550 \), C III] \( \lambda\lambda1909 \), Al iii \( \lambda\lambda1860 \), and Si iii \( \lambda1892 \).

The NIR continuum were modeled using similar approach to that of the optical region. However, it was necessary to include a third component to account for the excess of continuum emission over the underlying power-law component redwards of \( \sim 1 \mu m \), attributed to dust heated by the AGN (Landt et al. 2008). Thus, a three component model were used for this purpose: (i) The same power-law observed in the optical, extended to the NIR; (ii) the Garcia-Rissmann et al. (2012) template for the NIR Fe II pseudo-continuum; and (iii) a black body function, to account for the dust emission. This model is represented by equation 2:

\[ F(\lambda) = F_{PL}^{\lambda} + F_{BB}^{\lambda} + (F_{FeII}^{\lambda} * G_{\lambda}) \]  

where \( F_{PL}^{\lambda} \propto \lambda^{-\alpha} \) is the power law, \( F_{BB}^{\lambda} = B_{\lambda}(T) \) is a Planck function for the warm dust, \( F_{FeII}^{\lambda} \) is the Garcia-Rissmann et al. (2012) template broadened by convolving it with a kernel, \( G_{\lambda} \), using as reference the width (in velocity space) of the line Fe ii \( \lambda1602 \), the strongest isolated Fe II line in the NIR. The best fitted model, the individual components and the residual emission line spectrum are plotted in the top panel of Figure 2.

The FWHM of the kernel employed to convolve the NIR template was 1150 km s\(^{-1}\), consistent with the value of 1200 km s\(^{-1}\) obtained for the optical template. Moreover, the power law index obtained for the optical and NIR are 1.26 and 1.39, respectively. Within uncertainties, they are consistent, implying that we are indeed observing in the NIR...
the optical extension of the continuum associated to the central source. The small difference between these two values is probably due the missing part of the spectrum, which introduces a small uncertainty in the individual slopes. Finally, the black body temperature obtained from the fit was 1290 K, which is consistent with the temperature of warm dust found in AGN (Granato & Danese 1994; Rodriguez-Ardila & Mazzalay 2006), close to the sublimation temperature of the dust grains, ∼1600 K.

From figure 2, we see that the Fe II template suitably reproduces the optical Fe II. There have been claims in the literature that a narrow component of Fe II could also contribute to the emission in this spectral region (Véron-Cetty et al. 2004; Bruhweiler & Verner 2008; Dong et al. 2010). The models from Bruhweiler & Verner (2008) imply that a significant part of Fe II bump at 4570 Å could be produced by a narrow system of Fe II lines. Dong et al. (2010), using template modeling, found residual narrow Fe II emission in a SDSS sample of NLS1, although much weaker than the broad component. They also noticed that narrow permitted Fe II lines are completely absent in Seyfert 2 galaxies. We did not identify residual narrow Fe II lines neither in the optical nor in the NIR spectrum of PHL 1092. If this narrow component is present, it should be visible, at the very least, in the isolated NIR Fe II lines such as Fe II λ10502 and Fe II λ1127 after subtraction of the broad component. We therefore conclude that the strength of a putative contribution of a narrow component to the Fe II spectrum should be negligible.

Three features, though, call the attention in the NIR pure emission line spectrum: the broad emission line around λ9200, the small bump redwards of He I λ10830, and a set of unidentified lines at λ11400.

In order to search for their origin, we should recall first that the Fe II template of Garcia-Rissmann et al. (2012) was constructed based on the models of Sigut & Pradhan (2003) with modifications in some multiplet strengths to match the spectrum of I Zw 1. The three features mentioned above were, in fact, modified during the construction of the template. Since PHL 1092 is a super-strong Fe II emitter, it is very likely that these features had their intensities underestimated from the template derived from I Zw 1. In this context, the observed excess of emission at 9200 Å, 10800 Å and 11400 Å is genuine and not properly modeled by the Garcia-Rissmann et al. (2012) template (see next section). Note, however, that the residual bump redward of He I could also be due to an additional broad component of that line. If this hypothesis is correct, we should also detect a similar broad component (in FWHM and relative position from the rest-wavelength of the line) in Pa β, which is not the case. We conclude that the Fe II transitions leading to the emission lines at 9200 Å, 10800 Å and 11400 Å are enhanced in PHL 1092. In order to confirm whether that excess of Fe II emission is common in extreme Fe II emitters, a larger sample of such objects would be necessary.

### 3.2 The BLR spectrum of PHL 1092

The fit described in the previous section allowed us to remove from the observed optical to NIR spectrum the continuum emission due to the central source and the Fe II pseudo-continuum. The pure nebular spectrum is clearly dominated by low ionization lines such as O I, Ca II, and H I emitted in the BLR. Narrow forbidden emission lines such [Fe II]λ12570, [O III]λ4959 and [S II]λ6716 are rather faint. In the UV spectra, emission lines of He II, C IV, Al III, Si III, C III, Si IV and O IV were identified. Parameters of the broad lines (flux and width) were derived assuming that the line profiles can be represented by a single or a combination of Lorentzian or Gaussian functions. The best solution was obtained when the reduced χ² of the fit reaches the minimum value. All line widths presented here were corrected for instrumental broadening using $FWHM(\text{real})^2 = FWHM(\text{observed})^2 + FWHM(\text{instrumental})^2$, where $FWHM(\text{instrumental})$ is 300 km s⁻¹, 180 km s⁻¹ and 80 km s⁻¹ for GNIRS, Goodman and STIS, respectively.

The UV spectrum of PHL 1092 has three main features that carry important information about the BLR: Si IV, C IV, and the blend around 1900 Å, formed by the contribution of different species (see below). Since PHL 1092 has a strong Fe II emission and narrow broad lines, it is classified as a population “A” AGN. In such type of sources, the broad lines profiles are better represented by a Lorentzian function. The emission line at 1400 Å is actually a blend of Si IV λ1397+O IV λ1402 (Martinez-Aldama et al. 2018a). We fit that feature using two Lorentzians to represent the rest-frame component of the blend, and a combination of two Gaussians profiles to represent the blue asymmetry observed in the line. The C IV line were fit using a Lorentzian with the addition of two Gaussians to account for the blue asymmetry, usually associated to outflows (Coatman et al. 2016). This approach in both fits warrants a proper modeling of the asymmetry without ad-hoc assumptions about its origin. The flux and the FWHM of these lines are listed in Columns 2 and 3, respectively, of Table 1 and the best fit with the individual components can be observed in Figure 3 (a) and (b). Note that the broad components of C IV, Si IV, and O IV are especially uncertain due to the much stronger emission of the Blue component. For that reason, the fluxes associated to the broad components of these lines are marked with a “+”. We also measured the specific flux in a small range at ≈ 1400 Å and at 1549 Å where we expect the rest frame component emission of Si IV, and C IV, respectively. We obtain 5·10⁻¹⁶ erg cm⁻² Å⁻¹ for Si IV and 3·10⁻¹⁶ erg cm⁻² Å⁻¹ for C IV. The ratio Si IV / C IV is therefore ≈ 1.7, consistent with the ratio reported in Table 2.

The blend at 1900 Å is composed of Fe II, Fe III, C III λ1909, Si III λ1892, and Al III λ1860. We follow the procedure outlined in Martinez-Aldama et al. (2018a) to fit this bump. First, we used the Vestergaard & Wilkes (2001) UV Fe II+Fe III template with Lorentzians profiles to model the last three lines. Note that Al III λ1860 is actually a doublet at λ1854,1862, with equal intensity (1:1). We found that Si III and C III has a prominent blueshifted component, which according to Martinez-Aldama et al. (2018a) is rare although observed before in even more extreme regimes than that observed in PHL 1092 (Martinez-Aldama et al. 2018b). We modeled the blueshifted components with a Gaussian profile. The corresponding FWHM, fluxes and line shifts are listed in Table 1. The best fit can be observed in Figure 3 (c).

Table 2 provides UV line ratios relevant to the classification (PHL 1092 meets the “extreme Population A” criteria of
Marziani & Sulentic 2014), and to the tentative definition of the BLR physical conditions (Sect. 4.3).

We fit H$\alpha$ and H$\beta$ with Lorentzian profiles, representing the BLR contribution. In addition, we noticed a blue asymmetry in these lines, which was fit with a Gaussian component, following the approach of Negrete et al. (2018). Moreover, we employed one Gaussian to model each of the [O\textsc{iii}]$\lambda$4959,5007 doublet. We did not find evidence of the [N\textsc{ii}] doublet around H$\alpha$. Note that the [S\textsc{ii}]$\lambda$9531, usually the strongest NIR narrow forbidden line (Landt et al. 2008; Riffel et al. 2006; Mason et al. 2015), was not detected in our spectrum, suggesting that the NLR contribution is likely below the detection limit of the spectrograph. The lack of [N\textsc{ii}] and [S\textsc{ii}] detection is consistent with the weakness of [S\textsc{iii}] and [O\textsc{ii}]. Since the [O\textsc{ii}] and [S\textsc{iii}] are usually the strongest narrow lines in the optical and NIR, respectively, and [N\textsc{ii}] and [S\textsc{ii}] are just a fraction of [O\textsc{ii}] ($\sim$0.3), it is not expected that they show up in the spectrum. The panels (d) and (e) of Figure 3 show the best fit for H$\beta$ and H$\alpha$, respectively. The parameters of the fit are listed in Table 1. Moreover, the Fe$\textsc{ii}$ emission bump centered in $\lambda$4570 was measured using the template fit in the previous section. The flux labeled Fe$\textsc{ii}$ (4570 Bump) presented in Table 1 is the integrated flux of the bump in the wavelength interval 4434--4684Å (Boroson & Green 1992).

The O\textsc{i} $\lambda$8446 and the Ca\textsc{ii} triplet ($\lambda$8496, 8542, and 8663) were fitted considering two constraints. First, O\textsc{i} $\lambda$8446 was constrained to have the same FWHM (in velocity space) as O\textsc{i} $\lambda$112297. Second, Ca\textsc{ii} $\lambda\lambda$8496,8542 and 8663 were constrained to have the same width (Rodriguez-Ardila et al. 2002). The values obtained are listed in Table 1 and the fit is presented in Figure 3(f).

The bump at 9290Å is a blend of Fe$\textsc{ii}$ and Pa9. Marinello et al. (2016) showed that the NIR Fe$\textsc{ii}$ template usually underestimates the total flux in that feature. The residual emission left after subtraction of the template is Fe$\textsc{ii}$ and the fit is presented in Figure 3(f).

In order to include PHL 1092 in the Eigenvector 1 diagram it is necessary to estimate its corresponding R$4570$. Using the values measured in the previously section (see Table 1), we estimate R$4570$$\sim$2.58. The Fe$\textsc{ii}$ emission in AGN can be divided into basically three categories. Weak Fe$\textsc{ii}$ emitters, with $R_{4570}\leq 1$, strong Fe$\textsc{ii}$ emitters, with $1<R_{4570}<2$, and super-strong Fe$\textsc{ii}$ emitters, with $R_{4570}\geq 2$. Typical AGN are weak Fe$\textsc{ii}$ emitters, with $\sim$90% of them in this category, and highly concentrate around $R_{4570}\sim 0.6-0.8$ (Shen & Ho 2014). Strong Fe$\textsc{ii}$ emitters are less common, occurring in about 5% of the AGN population (Lawrence et al. 1988). Super-strong Fe$\textsc{ii}$ emitters are even more rare, roughly an order of magnitude less (Mooran et al. 1996; Lipari et al. 1993). In this scheme, PHL 1092 is in the category of super-strong Fe$\textsc{ii}$ emitters.

Bergeron & Kunth (1980) were the first to identify PHL 1092 as a super-strong Fe$\textsc{ii}$ emitter. They showed that the optical spectrum was dominated by intense Fe$\textsc{ii}$ lines and that such emission could only arise from gas of high electronic density, $n_e \sim 10^5$ cm$^{-3}$, and low temperature, $T \sim 10000$ K. However, the value of R$4570$ they reported was surprisingly high, $R_{4570}=6.2$, making PHL 1092 the strongest Fe$\textsc{ii}$ emitter ever identified. Lawrence et al. (1997) proposed
that values of $R_{4570}$ in the interval 4–8, published in the literature by Joly (1991), could be too high. They indeed found for PHL 1092 a $R_{4570}$ of 1.8.

The large discrepancies in the value of $R_{4570}$ found here and those in the literature are likely due to the method employed to measure the flux contained in the FeII bump. In Bergeron & Kunth (1980), most of the flux redwards of Hβ was associated to FeII multiplets, reducing the amount of Hβ flux in the broad Lorentzian wings of the line profile and thereby increasing $R_{4570}$ to higher values. The continuum level set in the measurements is also a factor that can lead to a smaller value of $R_{4570}$. Figure 2 shows that a flat continuum under the FeII A4570 bump would underestimate the integrated flux of that feature. The value of $R_{4570}$ presented here is based on a simultaneous fit to the continuum and the FeII spectrum observed in the UV/optical region.
Table 1. Emission line fitting results.

| Line       | Flux (x10^{-16} erg s^{-1}) | FWHM (km s^{-1}) | Integrated S/N | Line shift^{a} (km s^{-1}) |
|------------|-------------------------------|------------------|----------------|-----------------------------|
| H\beta_{BC} | 112.01±2.43                  | 1850±100         | 46             | 0                           |
| H\beta_{Blue} | 21.85±1.85                  | 2300±200         | 8              | -2470                       |
| [O iii] \lambda 4959 | 1.58±0.30                  | 300±50           | 3              | 0                           |
| [O iii] \lambda 5007 | 3.13±0.35                  | 300±50           | 5              | 0                           |
| H\alpha_{BC}  | 363.58±4.15                  | 1715±100         | 116            | -218                        |
| H\alpha_{Blue} | 28.11±1.18                  | 2350±210         | 6              | -2700                       |
| O i \lambda 8446 | 31.26±1.90                  | 1350±100         | 23             | -95                         |
| Ca ii \lambda 8495 | 29.47±1.85                  | 1250±120         | 23             | 0                           |
| Ca ii \lambda 8543 | 35.12±1.84                  | 1250±120         | 29             | 0                           |
| Ca ii \lambda 8662 | 29.23±1.90                  | 1250±120         | 31             | 0                           |
| Fe ii \lambda 9998 | 24.90±2.20                  | 1150±75          | –              | 0                           |
| Fe ii \lambda 10502 | 23.14±0.90                  | 1150±75          | 25             | 0                           |
| He i BC \lambda 10829 | 30.25±1.50                  | 1860±150         | 26             | -219                        |
| Fe ii \lambda 10863 | 22.315±0.90                 | 1150±75          | 23             | 0                           |
| Pa i BC \lambda 1127 | 43.53±2.00                  | 1900±130         | 35             | 0                           |
| Fe ii \lambda 11127 | 13.10±1.12                  | 1150±75          | 20             | 0                           |
| O i \lambda 11287 | 19.06±1.45                  | 1350±100         | 23             | -55                         |
| Fe ii \lambda 11400 | 18.21±1.10                  | 1150±75          | 23             | -105                        |
| Si iv \lambda 1397 | 32:                         | 2500±150         | 3              | -101                        |
| O iv \lambda 1402 | 27:                         | 2500±150         | 3              | -106                        |
| Si iv+O iv \lambda 1389: | 186.84±17.15                 | 9400±1030        | 17             | -4700                       |
| C iv \lambda 1549 | 30:                         | 3800±175         | 4              | -184                        |
| C iv \lambda 1640 | 255.11±22.93                | 5350±295         | 10             | -3500                       |
| C iii \lambda 1690 | 14.51±1.02                  | 4200±315         | 3              | 0                           |
| C iii \lambda 1692 | 29.35±1.78                  | 1800±115         | 7              | -1100                       |
| Si iii \lambda 1892 | 76.64±3.29                  | 3100±150         | 12             | 0                           |
| Si iii \lambda 1909 | 141.25±12.67                | 3400±160         | 23             | -1750                       |
| Al iii \lambda 1860^{b} | 70.06±1.12                  | 2150±175         | 9              | 0                           |
| Al iii Blue | 111.27±17.12                 | 3700±175         | 20             | -950                        |

\(^{a}\) Negative values are regarded as blueshifts
\(^{b}\) Summed flux of the lines in the doublet

Table 2. Broad emission line ratios.

| Line Ratio | Value          |
|------------|----------------|
| R_{4570}  | 2.58\pm0.13   |
| R_{920}   | 1.02\pm0.10   |
| R_{ijm}   | 1.02\pm0.11   |
| Al iii/Si iii | 0.91\pm0.09 |
| C iii/Si iii | 0.19\pm0.07 |
| Si iv+O iv/Si iii | 0.76:  |
| C iv/Al iii | 0.42:  |
| C iv/Si iii | 0.39:  |
| Si iv+O iv/C iv | 1.94:  |

\(^{a}\) Ratio between the summed flux of BC and Blue.

resulting in more robust approach. In order to compare the different values reported in the literature with ours, we show in Figure 4 our spectrum and template, and how it would look if the R_{4570} were 1.8 and 6.2. As shown in Figure 4, a R_{4570} of 6.2 is unrealistic, being the value of R_{4570} = 2.58 far more suitable to the observations.

The other axis of the E1 plane is the FWHM of H\beta, FWHM(H\beta). The value obtained for the broad component is 1850 km s^{-1}, consistent with the classification of PHL 1092...
as a NLS1 AGN. It also places PHL 1092 in the “population A” of the E1 optical plane (Marziani et al. 2001), as shown in Figure 5. In that plot, grey points represent the sources from Sulentic et al. (2007), green triangles are those of Lipari et al. (1993) and blue squares are AGN from Šniegowska et al. (2018). PHL 1092 is represented by the red star. Even after reducing the estimate of $R_{4570}$ for PHL 1092, it still remains as outstanding source.

Other objects with super-strong Fe ii emission were presented by Lipari et al. (1993): IRA07598+6508, Mrk 231, Mrk 507, and IRAS 15508-7815. All of them with $R_{4570}>2$. Shen & Ho (2014), analyzing the physical drivers of EV1, derived the same diagram for all SDSS (DR7) sources from Shen et al. (2011). An immediate result from their work is the lack of sources with $R_{4570}>3$. In fact, in their E1 diagram, it is possible to see an upper $R_{4570}$ cutoff around $R_{4570} \sim 2.2$. Šniegowska et al. (2018) re-analyzed 27 of the strongest Fe ii emitters ($R_{4570}>1.3$) from the Shen et al. (2011) catalog. Their results show that many sources in Shen et al. (2011) had their $R_{4570}$ overestimated, very likely due to the automated procedure employed to derive this quantity and the low S/N of some of the spectra. That is the case of SDSS125343.71+122721.5, which has $R_{4570}=1.75$ in Shen et al. (2011) but is reported with negligible Fe ii emission in Šniegowska et al. (2018). They also identified another outstanding source of Fe ii emission, SDSS125343.71+122721.5. This AGN has a $R_{4570}=2.12$ in Shen et al. (2011) catalog and after Šniegowska et al. (2018) analysis, they presented two different values: (i) $R_{4570}=3.0$ and $\text{FWHM}(H\beta)=1445\text{ km s}^{-1}$ for a Gaussian profile to fit $H\beta$, and (ii) $R_{4570}=2.12$ and $\text{FWHM}(H\beta)=936\text{ km s}^{-1}$ using a Lorentzian profile instead.

Similarly, Negrete et al. (2018) analysed a sub-sample of 302 AGN up to redshift 0.8 and Eddington ratio close to 1, extracted from the much larger sample of Shen et al. (2011). In their work they found that these sources are characterized by strong Fe ii emission. In particular, it was found that 16 sources have $R_{4570}>2$, with 5 of them displaying $R_{4570}>2.5$. The higher values of $R_{4570}$ are sometimes due to the very narrow profile of $H\beta$. In these extreme NLS1 galaxies, the $H\beta$ line is dominated by a narrow component. The distinction between the contribution from the BLR and NLR is extremely subtle and, in some cases, can only be fully evaluated by means of multi-wavelength spectra (i.e. optical and NIR data). Therefore, a careful fit to the H$\beta$ region, taking into account the power-law continuum and simultaneously the Fe ii emission, is crucial to derive consistent values of $R_{4570}$.

Zamanov et al. (2002) pointed out that in Population A of AGN, strong Fe ii emitters with narrow H$\beta$ profiles tend to have a large blueshifted component in $[\text{O iii}]$. This trend, though, is not observed in PHL 1092. This may be due to an intrinsic effect caused by the low strength of the $[\text{O iii}]$ lines. This is in agreement with Boroson & Green (1992) and Shen & Ho (2014), who found a negative correlation between the intensity of $[\text{O iii}]$ and the strength of the Fe ii. As the blueshifted $[\text{O iii}]$ component is usually weaker than the main narrow component, if the former is present, it is probably below our detection limit or heavily blended with the adjacent Fe ii features. A higher spectral resolution spectrum is indeed necessary to uncover the presence of such outflow component.

Another implication of the E1 is that strong Fe ii emitters should host low black hole masses and high Eddington ratio (Negrete et al. 2018). In order to estimate the black hole mass in PHL 1092, $M_{BH}$, we used Vestergaard & Peterson’s (2006) single epoch black hole mass equation:

$$
\log (M_{BH}) = \log \left\{ \left[ \frac{\text{FWHM}(H\beta)}{10^{3}\text{ km s}^{-1}} \right]^2 \left[ \frac{\lambda L_{\lambda}(5100)}{10^{44}\text{ erg s}^{-1}} \right]^{0.5} \right\} + (6.91 \pm 0.02)
$$
For PHL 1092 we measured a FWHM(\(\text{H}\beta\))=1850 km s\(^{-1}\) and \(L_\lambda(5100) = 1.497 \times 10^{44}L_\odot\). It translates using Eq. 3 in a black hole mass of \(\log(M_{BH}) = 7.89M_\odot\). Other works in the literature report different values of \(M_{BH}\) for PHL 1092. For instance, Dasgupta et al. (2004) using optical scaling relation for the BLR radius and single epoch method found \(\log(M_{BH}) = 8.20M_\odot\). Czerny et al. (2001) found \(\log(M_{BH}) = 6.09M_\odot\) using X-ray variability and \(\log(M_{BH}) = 8.26M_\odot\) from accretion disk fitting method. Nikolajuk et al. (2009) found \(\log(M_{BH}) = 8.46M_\odot\) using more recent scaling relations for the optical single epoch recipe. By the same method, Miniutti et al. (2012) found \(\log(M_{BH}) \sim 8.48M_\odot\). From x-ray observations, and considering a non-spinning BH Miniutti et al. (2012) found a \(M_{BH} = 8.38M_\odot\), consistent with their optical measurement. Our result is only factor 1.2 lower than the average of previous values presented in literature. However, note that they estimate the \(M_{BH}\) using different methods and scaling relations. Moreover, the black hole mass obtained here for PHL 1092 is consistent with the average of masses obtained by Rakshit et al. (2017) and Negrete et al. (2018). The Eddington ratio is defined by the ratio between the bolometric luminosity and the Eddington limit, e.g., \(L/Edd = L_{bol}/L_{Edd}\), where \(L_{Edd} = 1.5 \times 10^{38}(M_{BH}/M_\odot)\) (Netzer & Marziani 2010). The bolometric luminosity can be obtained applying a correction factor to the optical luminosity measured from the continuum at 5100Å, \(L_{bol} = c \times F_\lambda(5100\AA)\), where \(c = 7\) (Netzer & Trakhtenbrot 2010). We estimate a \(\log(L_{bol})\) = 45.72 erg s\(^{-1}\) and \(L/L_{Edd} = 1.24\). Negrete et al. (2018) using a sample of 334 high Eddington ratio AGN found that strong Fe\text{ii} emitters (\(R_{Fe\text{ii}} > 1\)) are associated with high \(L/L_{Edd}\). Our results presented above show that PHL 1092 follows this same trend, having a high accretion rate and \(M_{BH}\) typical of Population A AGN. Despite the number of sources of \(R_{Fe\text{ii}}>2\) is much smaller than weaker Fe\text{ii} emitters, those analyzed by Negrete et al. (2018) and here suggest that indeed these characteristic are common to all extreme Population A AGN.

4.2 The Fe\text{ii} Emission Region

The Fe\text{ii} emission arises from clouds located in the broad line region, which is unresolved even for closest AGN at subarc second resolution observations. For this reason, the structure and location of the gas where these lines are produced must be derived using integrated spectra. Better estimates of the BLR structure can be achieved using reverberation mapping. Indeed, studies focused on variability have detected Fe\text{ii} time lags for a few AGN (Rafter et al. 2013; Barth et al. 2013; Du et al. 2016). The main result gathered from these works is that the clouds emitting Fe\text{ii} are located at distances that coincide with that of the \(\text{H}\beta\) emission region and up to twice that from the central source. However, no consensus regarding the precise location of the Fe\text{ii} emission region has been achieved.

In order to get clues about the possible location of the Fe\text{ii} emitting region in PHL 1092 we plot in Figure 6(a) the FWHM of Fe\text{ii} versus the FWHM of O\text{i} and Ca\text{ii} from the sample of Marinello et al. (2016). We add the value of PHL 1092 as a red star for comparison. The results show that the FWHM of these lines follow a similar distribution, being slightly scattered around the identity line. Under the virial assumption, the relative values of the line widths can be used as a proxy of the distance ratios from the central source, providing a relative location of the emitting region if variations in FWHM for different ions within the same object are detected. In this context, Figure 6(a) shows that Fe\text{ii}, O\text{i}, and Ca\text{ii} in PHL 1092 are likely formed in gas that is co-spatial, at the same distance from the AGN.

Similar results were already reported in the literature. For instance, Rodríguez-Ardila et al. (2002) studying the physical process behind the O\text{i} emission lines found that Fe\text{ii} and O\text{i} lines share the same profile shape, and very similar FWHM. Using a similar argument, Matsuoka et al. (2007) and Martínez-Aldana et al. (2015) employed the O\text{i} emission line to probe the physical conditions of the emitting region of O\text{i} and Fe\text{ii}. They all agree that these lines are formed in a same portion of the BLR, in dense clouds (\(n_H > 10^{15.5}\) cm\(^{-3}\)) illuminated by a ionizing radiation of \(U < 10^{-2.5}\). Moreover, Matsuoka et al. (2008) compiled O\text{i} and Ca\text{ii} line properties of 11 quasars in a broad range of redshift and luminosity (0.06 < \(z < 1.08\) and \(29.8 < M_8 < 22.1\)) in order to analyze the physical conditions that lead to the production of these lines. They found that the widths of the O\text{i} were remarkably similar over more than 3 orders of magnitude in luminosity, suggesting a similar kinematics for location of the emission region. They also argue about the dust presence and suggest that the emission region should be located near the dust sublimation point at the outer edge of the BLR. Thus, the results for PHL 1092 in Figure 6(a) suggests that Fe\text{ii} is formed in outer portion of the BLR.

In contrast, the hydrogen lines are likely to be produced closer to the central source. Figure 6(b) shows the FWHM of Fe\text{ii} versus the FWHM of Pa\text{beta}(Pa\text{gamma} for PHL 1092). We see that the FWHM of Pa\text{beta} is systematically broader than that of Fe\text{ii}. For PHL 1092, the FWHM of \(\text{H}\beta\) is about \(\sim 60\%\) larger than that of Fe\text{ii} (and the other low-ionization lines analyzed, e.g., O\text{i} and Ca\text{ii}). From the virial theorem, we have that the distance \(D \propto 1/\text{FWHM}^2\), which translates in a Fe\text{ii} emission region 2.5 times more distant than that where the bulk of Hydrogen lines are produced. Marinello et al. (2016) obtained an averaged FWHM for Fe\text{ii} that is 3/4 smaller than that of Pa\text{beta}. In particular, for [Fe\text{ii}1], the strongest Fe\text{ii} emitter of their sample, the results are quite similar to PHL 1092, with the FWHM(Fe\text{ii}) = 1/2 FWHM(Pa\text{beta}).

Our results are also consistent with the BLR scenario proposed by Dultzin-Hacyan et al. (1999). Their BLR model interpret the observed C\text{iv} as a radial outflow from the central source while low ionization species, such as Fe\text{ii} and Ca\text{ii}, arise in the outer portion of the BLR. The intensity and blueshift of C\text{iv} in this case would depend on the observing angle. In this scenario C\text{iv} would be produced in a “cone shaped” inner region. The results for the FWHM(C\text{iv}) and strong blueshifted component, narrower Fe\text{ii}, O\text{i}, and Ca\text{ii} profiles measured not only in PHL 1092 but in a larger sample of objects (Marinello et al. 2016) agree with this scenario.

Note that in the above analysis we did not consider any effects between ionization potential of the ion, FWHM and location of the emitting region as is usually considered for C\text{iv} and Hydrogen lines because all the lines here have very similar ionization potential, \(\lessapprox 13.6\) eV.
4.3 Physical conditions within the BLR

Besides the region where the Fe\textsc{ii} emitting clouds is located relative to the central source, we can also estimate its the physical conditions within the BLR. The line fluxes from the NIR and UV spectra derived in section 3.2 can be used in combination with CLOUDY simulations to constrain the physical properties of the BLR gas such as the ionization parameter (U) and the gas density (n\textsubscript{H}).

Due to the complexity to model the Fe\textsc{ii} ion, a valid approach is to consider the O\textsc{i} and Ca\textsc{ii} ions as proxies of the former, under the assumption that they all form in clouds that are co-spatial. To analyze the role of the excitation mechanisms of O\textsc{i} and the physical conditions of the region emitting this line, Matsuoka et al. (2007) published simulations to probe the density and ionization parameter of this region. A similar approach was followed by Matsuoka et al. (2008) and more recently by Martínez-Aldama et al. (2015). Their results are based on the emission line flux ratios O\textsc{i} $\lambda$11287/$\lambda$8446 and the ratio between the Calcium triplet and O\textsc{i} $\lambda$8446. The first one is related to the role of the Ly\textbeta fluorescence in the O\textsc{i} emission while the second one traces the role of collisional excitation. Their results show that the O\textsc{i}, Ca\textsc{ii} and Fe\textsc{ii} lines arise in a region best characterized with log(n\textsubscript{H})=11.5 cm\textsuperscript{-3} and log(U)=2.5. These values are similar to those found in weak to moderate Fe\textsc{ii} emitters.

The first interesting fact about O\textsc{i}$\lambda$8446 and the Ca\textsc{ii} triplet is that the relative intensities of these lines in PHL 1092 are different from what is usually observed in the literature. While O\textsc{i}$\lambda$8446 is usually stronger than the Ca\textsc{ii} triplet (Riffel et al. 2006; Landt et al. 2008), PHL 1092 shows much stronger Ca\textsc{ii} multiplets. For instance, Matsuoka et al. (2008) analyzing a sample of 11 quasars found a range of line ratios 0.2 < O\textsc{i}$\lambda$11287/$\lambda$8446 < 0.8 and 0.3 < Ca\textsc{ii}/O\textsc{i} < 0.8. PHL 1092 has similar O\textsc{i} line ratios, O\textsc{i}$\lambda$11287/$\lambda$8446= 0.6, but much higher Calcium triplet to O\textsc{i}$\lambda$8446 flux ratio, Ca\textsc{ii}/O\textsc{i}= 3.0. Indeed, each Ca\textsc{ii} line from the triplet has individual fluxes roughly equal to that of O\textsc{i}.

Figure 7 from Matsuoka et al. (2007) shows isocontour curves in the U,n\textsubscript{H} plane using the above line ratios. Based on the O\textsc{i} line ratio measured in PHL 1092, the ionization parameter and density are limited to $-2.4 < \log U < -4$ and $11.5 < \log n\textsubscript{H} < 14$ cm\textsuperscript{-3}, respectively. In addition, the Calcium to Oxygen line ratio measured for PHL 1092 implies $-2.0 < U < -4$ and $11.7 < n\textsubscript{H} < 14$ cm\textsuperscript{-3}. These values can be further constrained using the models presented by Matsuoka et al. (2008). The line ratios found from PHL 1092 place it in the parameter space consistent to log(U,n\textsubscript{H})=(-3.0, 12.5 cm\textsuperscript{-3}).

Negrete et al. (2012) followed a different approach by considering UV line ratios. The set of diagrams presented by them involves flux ratios between emission lines of high- and mid-ionization potential such as Al\textsc{iii}/Si\textsc{iii}, Si\textsc{iv}/Si\textsc{iii}, C\textsc{iv}/Al\textsc{iii}, C\textsc{iv}/Si\textsc{iii}, and Si\textsc{iv}/C\textsc{iv}.

Using Figure 5 of Negrete et al. (2012) and the observed UV line flux ratios in PHL 1092 listed in Table 2, we constrain the physical conditions in the BLR for every ratio employed. In order to achieve convergence, we also followed the approach of Negrete et al. (2012) (see their Figure 6). Given the error in the measurements, we found a convergence point at log(U,n\textsubscript{H})=(-3.5,13.0 cm\textsuperscript{-3}). These values are slightly different from those obtained for I\textsc{zw} 1, log(U,n\textsubscript{H})=(-2.0,12.6 cm\textsuperscript{-3}) by Garcia-Rissmann et al. (2012) and Negrete et al. (2012). Note however that PHL 1092 spectrum differs significantly from that of I\textsc{zw} 1 (and other AGN with strong or weaker Fe\textsc{ii} emission).

Are the above conditions derived from the UV lines consistent to those where the Fe\textsc{ii} lines are formed in PHL 1092? In order to answer this question, we employed the predicted Fe\textsc{ii} ratios listed in Table 2 of Garcia-Rissmann et al. (2012), based on Sigut & Pradhan (2003) models. We found that for log(U,n\textsubscript{H})=(-3.0, 12.6 cm\textsuperscript{-3}), the predicted Fe\textsc{ii} line ratio 10502+11127/9200 A is 0.35. In PHL 1092 it amounts to
0.45, in very good agreement with the models. Other combinations of values of \( \text{U} \) and \( n_\text{H} \) predict values in that ratio that that departs considerably from the observations.

From the results above we see that a combination of low ionization parameter and high gas density are necessary within the BLR to produce the observed emission lines. These results are consistent with the parameters derived by Martínez-Aldama et al. (2018a) for a sample of extreme population of quasars at high redshift. Their results show that weak \( \text{C}\text{IV} \) and \( \text{C}\text{III} \) emission, strong \( \text{Al}\text{III} \) and a \( \text{Si}\text{IV}/\text{C}\text{IV} \) line flux ratio \( \sim 1 \) are common properties among quasars of extreme population \( A \), to which PHL1092 belongs. The similar physical properties derived for PHL1092, which is a local source, with those found in objects at high redshift, suggest that the line ratio diagrams presented by Negrete et al. (2012) can be used as a selection method to search for extreme \text{Fe}\text{II} emitters candidates both in the local universe and at higher redshifts (up to \( z \sim 3 \)).

With the launching of the James Webb Space Telescope in the next few years, this method can be used as a proxy to identify strong/extreme \text{Fe}\text{II} sources at a large stretch of cosmic age. There has been a lot of attention concerning the sources with \( R_{4570} > 1.0 \), as these sources (extreme Population \( A \), or \( xA \)) seem to radiate at or toward a limiting Eddington ratio. This property can be exploited, under several assumptions for the use of these sources as cosmological probes (Wang et al. 2013; Marziani & Sulentic 2014).

### 4.4 Excitation Mechanisms

Models employed to study the micro-physics of the \text{Fe}\text{II} transitions in AGN incorporate three main excitation mechanisms: collisional excitation, continuum fluorescence via UV transitions, and self fluorescence via overlapping \text{Fe}\text{II} transitions (see Pradhan & Nahar 2011, for a comprehensive formulation of the problem). Sigut & Pradhan (1998) demonstrated that Lyman-\( \alpha \) (Ly\( \alpha \)) fluorescence has an important role in the production of the optical \text{Fe}\text{II} lines. Their results show a significant increase in the strength of the 4570\( \mu \)m bump when Ly\( \alpha \) fluorescent is fully considered, in comparison when it is weakly (10%) or not included in the calculations.

The key aspect to confirm the fluorescent route for the \text{Fe}\text{II} emission is the presence of a bump of emission centered in 49200 and the detection of the 1\( \mu \)m \text{Fe}\text{II} lines (Rudy et al. 2002; Marinello et al. 2016). The role of the different excitation mechanisms and physical conditions necessary to produce the \text{Fe}\text{II} emission can be investigated by analyzing the observed emission in different regions of the spectrum. NIR probes Ly\( \alpha \) fluorescence and collisional excitation to energy levels of up to \( 
\sim 15 \) eV. Optical spectroscopy probes odd parity transitions of \text{Fe}\text{II} up \( 
\sim 5 \) eV while UV transitions, in addition, carries information about the density and ionization parameter.

In order to study the \text{Fe}\text{II} excitation mechanisms we follow the approach of Marinello et al. (2016), which consists of using line flux ratios between \text{Fe}\text{II} lines and the closest \( \text{H}\text{I} \) lines in the same spectrum. The observable quantities are: (i) \( R_{4570} = \frac{F(\text{Fe}\text{II} 4570)}{F(\text{H}\beta)} \); (ii) the flux ratio of the \text{Fe}\text{II} bump centered at 9200\( \mu \)m and the broad component of Pa\( \gamma \), \( R_{9200} = \frac{F(\text{Fe}\text{II} 9200)}{F(\text{Pa}\gamma)} \); and (iii) the flux ratio of the \text{Fe}\text{II} 1\( \mu \)m lines (\( \lambda 9995, \lambda 10502, \lambda 10890, \lambda 11127 \)) and the broad component of Pa\( \gamma \), \( R_{1\mu m} = \frac{F(\text{Fe}\text{II} 1\mu m)}{F(\text{Pa}\gamma)} \). Figure 7 shows the diagrams involving these quantities for PHL1092 and other AGN from the literature.

The optical \text{Fe}\text{II} emission arises from photons emitted via levels \( z^1\text{D},F \rightarrow \text{b}^1\text{F}^+ \). Figure 8 shows a partial Grotrian diagram for the most prominent transitions of \text{Fe}\text{II} (Sigut & Pradhan 2003; Pradhan & Nahar 2011). In the diagram, red lines represent transitions leading to the bump at 9200\( \AA \), violet lines show transitions responsible for the emission lines around 2800\( \AA \) and 1860\( \AA \) while blue lines show the transitions that form the bump centered at 4570\( \AA \). Table 3 summarizes the main transitions that produce the NIR to UV \text{Fe}\text{II} emission. Note that other transitions are still present but they are weaker by a factor of 10 or more and for this reason they are not shown.
The 9200Å bump is a blend of lines produced by primary cascading from the energy levels around 13 eV, excited by the capture of a Lyα photon by an Fe II ion, via \( u^1(P,D) \rightarrow e^1D \) and \( v^4F \rightarrow e^1D \). Secondary cascading occurs from the levels \( e^1D \), at about 10 eV, to the upper levels from which the optical emission lines are produced, after the emission of UV photons at \( \approx 28000 \AA \), via \( e^1D \rightarrow \text{transition} \). Since the energy to excite the \( u^1(P,D) \) and \( v^4F \) levels are too high to be excited by mechanisms other than Lyα fluorescence, the detection of the 9200Å bump probes unambiguously the presence of that mechanism.

Figure 7(a) shows \( R_{9200} \) versus \( R_{1200} \). The grey dots from Marinello et al. (2016) suggest a correlation between these two ratios. The inclusion of PHL 1092 in the plot introduces some scatter to the high end of the correlation. The 1μm lines result from secondary cascading of the Lyα fluorescence process, e.g., after a Fe II ion captures a Lyα photon, electrons are excited to levels at \( \sim 15 \text{eV} \), \( (t,u)^4G \), which cascade down via \((t,u)^4G \rightarrow (t,u)^4F \) emitting photons at around 18600 Å. In the secondary cascading, the 1μm lines are emitted via \( \text{b}^4G \rightarrow \text{transition} \), populating the energy levels from which the bulk of the optical Fe II is produced. Note that the \( \text{b}^4G \) level needs only \( \sim 6 \text{eV} \) to be excited, thereby collisional excitation is also a possible mechanism to pump this level. The strong correlation observed in Figure 7(a) shows the importance of the Lyα fluorescence in the production of the 1μm Fe II lines.

García-Rissmann et al. (2012) used a grid of Fe II models in the NIR in order to create an Fe II template. They found that models with \( \log(U, \text{H}II) = (-2.0, 12.6 \text{ cm}^{-2}) \) best reproduce the Fe II emission in I Zw1. In their models, the strength of the 1μm lines is reduced relative to that of the 9200Å bump for models with the parameters we derived in this work, e.g., \( \log(U, \text{H}II) = (-3.0, 13.0 \text{ cm}^{-2}) \). This reduction is indeed observed in PHL 1092, producing its departure from the main trend observed in the Figure 7(a).

Figure 7(b) shows \( R_{4570} \) versus \( R_{9200} \). This plot strengthens the importance of the Lyα fluorescence in the production of the optical Fe II emission. Since the 9200Å bump is produced exclusively by that mechanism, the plot gives us a rough estimate of the percentage of its contribution to the optical emission.

Marinello et al. (2016) found a strong correlation between the above two ratios. However, their sample did not include extreme strong Fe II emitters (\( R_{4570} > 2.5 \)). We see that the correlation still holds after the inclusion of PHL 1092 in the diagram. The physical conditions derived in the previous section, \( \log(U, \text{H}II) = (-3.0, 13.0 \text{ cm}^{-2}) \), enhance the Lyα fluorescence. Very likely, the \( R_{9200} \) measured in PHL 1092 is expected to be close to the maximum possible for the given Paβ flux. In PHL 1092 the contribution of Lyα fluorescence to the Fe II emission is not only important, as in AGN with weak Fe II, but also crucial to enhance the Fe II bump at 4570 Å. Since the 4570Å bump can be pumped by other excitation mechanisms (i.e. collisional excitation) we would expect, in theory, that it keeps increasing while \( R_{9200} \) should remain roughly constant, with values around one, at the high end of the correlation. Note that the three strong Fe II emitters (\( R_{4570} > 2.0 \)) displayed in the plot have similar \( R_{9200} \) as \( R_{4570} \) grows. If we assume that the optimal physical conditions for Lyα fluorescence is met, a maximum value for the \( R_{9200} \) should be reached while the \( R_{4570} \) is large.
Figure 8. Partial Grotrian diagram for the Fe$^{ii}$ emission. The diagram show the main transition that from primary and/or secondary cascading after a Ly$\alpha$ photon is absorbed that populate the $z^4$(D,F) levels, from which the optical Fe$^{ii}$ bump (centered at 4570Å) is emitted via $z^4$(D,F)$\rightarrow$b$^4$F$^+$ (blue line). Red lines show the NIR primary and secondary cascade transitions after a Fe$^{ii}$ ion absorbs a Ly$\alpha$ photon, e.g. the bump at 9200Å and the 1µm lines. Violet lines represent the UV transitions that populated directly or indirectly the $z^4$(D,F) levels.

keeps growing towards $R_{4570}\sim 3$. This behaviour is expected from the perspective of photon balance and the intrinsic cascading process of Ly$\alpha$ fluorescence, because every photon from the 9200Å blend produces a photon in the 4570Å bump under the assumption of zero extinction. Note that a photon emitted by the 9200Å bump has an energy equals to $E_{9200} = 2.16 \times 10^{-12}$ erg while a photon from 4570Å has $E_{4570} = 4.35 \times 10^{-12}$ erg, roughly the double of the energy. This means that it is necessary twice as much energy to increase $R_{4570}$ compared with that of $R_{9200}$. Therefore, a flattening in the high end of the correlation is expected.

Figure 7(c) shows $R_{4570}$ versus $R_{1\mu m}$. The importance of this plot is on the fact that the levels $z^4$(D,F), from which the optical Fe$^{ii}$ emission is produced, are populated after the 1µm lines are emitted via b$^4$G$\rightarrow$z$^4$(D,F). The energy necessary to excite b$^4$G is $\sim$6eV and can be reached by two main excitation mechanisms: collisional excitation and Ly$\alpha$ fluorescence (Marinello et al. 2016).

Figure 7(a) confirms the trend between $R_{9200}$ and $R_{1\mu m}$, with some scatter for strong Fe$^{ii}$ emitters, suggesting Ly$\alpha$ fluorescence as an important mechanism for the 1µm lines. Moreover, for PHL 1092 the values of $R_{9200}$ and $R_{1\mu m}$ are similar, which suggests that Ly$\alpha$ fluorescence must have an even more importance in the formation of these lines. If we assume that both transitions have similar probability, then the contribution of the Ly$\alpha$ fluorescence in the production of the 1µm lines should also be optimal for these lines for the physical conditions within the BLR. Note that as in Figure 7(b) we cannot expect the correlation to grow to extreme values of $R_{1\mu m}$.

The results gathered from Figure 7 suggest that the main excitation mechanism pumping the Fe$^{ii}$ emission in PHL 1092 is Ly$\alpha$ fluorescence. In contrast, weaker Fe$^{ii}$ emitters have their emission driven by collisional excitation, as found by Marinello et al. (2016). Note that other parameters

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may also contribute in the enhancement of the Fe ii emission in AGN. For instance, Sigut & Pradhan (2003) showed that the presence of micro-turbulence ($\eta_\perp$) in the BLR clouds can also increase the efficiency of the Fe ii production (their models uses $\eta_\perp = 10 \; \text{km s}^{-1}$). Garcia-Rissmann et al. (2012) showed that for that $\eta_\perp$ and log(U,$\eta_\parallel$)=(-2.0,12.6 cm$^{-3}$) the Sigut & Pradhan (2003) models reproduce well the Fe ii emission even in I Zw 1, a strong Fe ii emitter. Bruhweiler & Werner (2008) found that doubling the turbulence, \( \eta_\parallel = 20 \, \text{km} \, \text{s}^{-1} \), in combination with a larger ionization parameter and a slighter lower density, the predicted Fe ii emission also reproduces well the observed I Zw 1 spectrum in optical/UV regions. Thus, increasing the turbulence velocity increases also the probability of a Ly$\alpha$ photon to be captured by an Fe ii ion, thereby increasing the relevance of the Ly$\alpha$ fluorescence in the observed Fe ii emission. This could be the case for PHL 1092. That is, in that source we are probing a higher turbulence velocity for the gas in the BLR.

Another alternative for the pumping of the Fe ii emission in extreme Fe ii emitters is a higher chemical abundance in the BLR. Based on simulations, Panda et al. (2018) showed that increasing the BLR metallicity leads to a significant increase in $R_{4570}$. They showed that a $Z = 3 \, Z_\odot$ produces nearly twice the Fe ii emission than at solar metallicity. Indeed, an increase of $R_{4570}$ by a factor of 3 can be obtained when $Z = 10 \, Z_\odot$.

Negrete et al. (2012) analyzed the physical condition of the BLR in two strong Fe ii emitters, I Zw 1 and SDSS J20141+0116. They found that an abundance five times solar in Aluminum and Silicon was associated to a higher ionization parameter and a lower density, log(U,$\eta_\parallel$)=(-2.75,12.3 cm$^{-3}$). These values, consistent with Garcia-Rissmann et al. (2012) and Sigut & Pradhan (2003) models, would reproduced the observed UV line ratios in the spectra. One possible route to increase the metallicity in the BLR would be through supernova activity in the circumnuclear region, whose ejecta could enrich the AGN surrounding media. The over-solar matter then would be transported towards the BLR via inflows.

Observations give support to this scenario. Watabe et al. (2008) had already found that the nuclear starburst luminosity in nearby AGN was dependent on the AGN Eddington ratio while Hennig et al. (2018) found in the local NLS1 galaxy, Mrk 42, a starburst nuclear ring. Another possibility is that the strong outflows detected in C iv and Si iv by means of blueshifted components, swept away heavy elements, thereby increasing the metallicity. Atoms such as Carbon and Silicon, are efficiently accelerated by resonance line scattering (i.e., in a “line driven wind” scenario). Therefore, the outflowing gas may appear enriched with respect to the accretion disk gas (Baskin & Laor 2012). Since the models of Sigut & Pradhan (2003) and the template of Garcia-Rissmann et al. (2012) were constructed for Solar abundances, the higher abundance scenario cannot be currently tested. However, the models presented in Garcia-Rissmann et al. (2012) show a clear increase in the 9200 Å bump for the physical parameters obtained in this work and are also consistent with the line ratios in the observed spectrum of PHL 1092. These results support that a lower ionization parameter and a higher density are the most likely cause of the increase efficiency of the Ly$\alpha$ fluorescence in PHL 1092. Simulations with a more focused grid of parameters, high spatial resolution observations, and a bigger sample of extreme Fe ii emitters are necessary to draw more robust conclusions about these hypothesis.

5 CONCLUSIONS

In this work we present a panchromatic (UV, optical and NIR) analysis of the extreme strong Fe ii emitter PHL 1092. We combine optical and NIR spectroscopic observations to estimate several physical properties of this outstanding source. Using template modeling of the Fe ii spectrum, we were able to estimate accurately the intensity of that emission. Emission lines were fitted using a Lorentzian model in order to obtain their fluxes and line widths. The main results obtained from these measurements are summarized below:

- We re-estimated the $R_{4570}$ ratio in PHL 1092 using a more robust approach. Our results show a $R_{4570}=2.58$, significantly smaller than the values reported previously, of up to $R_{4570}=6.2$. This new value, however, still places PHL 1092 among the strongest Fe ii emitters ever observed.

- The FWHM obtained for Fe ii, O i, and Ca ii suggest that the clouds emitting these ions are co-spatial, since they share roughly the same line width and shape. Compared with Hβ, the FWHM of these lines are significantly smaller, suggesting that the clouds emitting low ionization ions are in the outer portion of the BLR while Hβ is emitted in the midportion of that region.

- Emission line flux ratios in the and UV in PHL 1092 suggest high densities ($n_\perp \sim 10^{13.6} \, \text{cm}^{-3}$) and a low ionization parameter (log $U \sim -3.5$) for the Fe ii emitting gas. This result is consistent with the parameters employed to create the NLR Fe ii template in Garcia-Rissmann et al. (2012).

- We found an excess of Fe ii emission in the 9200 Å bump. Since this emission can only be produced by lyman-fluorescence, we suggest that this excitation mechanism is pumping up the bulk of the Fe ii emission in PHL 1092. This result contrasts to what is found in weaker Fe ii emitters, where collisional excitation seems to be the main driver of that emission.

- The re-estimated value of $R_{4570}$ places PHL 1092 among the extreme quasars in the main quasar sequence defined by the optical plane of the Eigenvector 1. In this plane, PHL 1092 is classified as extreme Population A’ AGN due its high $R_{4570}$ and low FWHM$_{H\beta}$.

Our work points out towards intrinsic differences in the physical conditions of the BLR in this extreme Fe ii emitter even though the gas distribution follows the same trend as in normal Fe ii emitters. A follow-up investigation of this issue using a larger sample of ‘PHL 1092-like’ sources is necessary to fully support our conclusions on the physical conditions driving the Fe ii emission along the E1 plane.

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