The emission-line spectrum of KUG 1031+398 and the Intermediate Line Region controversy

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Abstract. We present results based on the analysis of optical spectra of the Narrow-Line Seyfert 1 (NLS1) galaxy KUG 1031+398, for which evidence was reported of a line-emitting region “intermediate” (both in terms of velocity and density) between the conventional Broad and Narrow Line Regions (BLR and NLR, respectively). From our observations and modeling of the spectra, we get a consistent decomposition of the line profiles into four components: an extended H II region with unresolved lines, two distinct Seyfert-type clouds identified with the NLR, and a relatively narrow “broad line” component emitting only Balmer lines but no forbidden lines. Therefore, although we find this object to be exceptional in having line-emission from the BLR with almost the same width as the narrow lines, our interpretation of the data does not support the existence of an “intermediate” line region (ILR).

1. Introduction

1.1. The Intermediate Line Region

It is commonly accepted that line-emission in AGN comes from two well separated regions: one, compact (< 1 pc) and lying close to the central engine, has a high electron density ($N_e > 10^8$ cm$^{-3}$) and is responsible for the production of broad (FWHM ∼ thousands of km s$^{-1}$) permitted lines—the BLR; the other, more extended and lying further away from the central source (10–1 000 pc), has lower electron densities ($N_e ∼ 10^5$ cm$^{-3}$) and emits lines with a lower velocity dispersion (∼ hundreds of km s$^{-1}$)—the NLR. A “gap” of line-emission is usually observed between the two regions; most objects show optical spectra which can be fitted by line profiles corresponding to clouds belonging to one or the other line-emitting regions. This line-emission gap can be explained by the presence of dust mixed up with the gas (Netzer & Laor 1993). Nevertheless, the existence of an intermediate region, both in terms of velocity and density ($N_e ∼ 10^{6.5}$ cm$^{-3}$) is expected; at this density, the [O III] lines are partially collisionally de-excited such that $\lambda 5007/H\beta ∼ 1$ [this ILR should not be confused with the ILR found in QSOs by Brotherton et al. (1994), which is much smaller and denser, with velocity dispersion of the order of 2 000 km s$^{-1}$ and density ∼ $10^{10}$ cm$^{-3}$]. To the best of our knowledge, no uncontroversial report of the existence of an ILR has ever been made. Crenshaw & Peterson (1986) and Van Groningen & de Bruyn (1989) have found broad wings in the [O III] lines of a number of
Seyfert 1 galaxies, implying the presence of an ILR in these objects; however, they all show strong Fe ii emission, and the observed broad [O iii] components could be due to the inaccurate removal of the Fe ii blends (Boroson & Green 1992). The claim by Mason et al. (1996) that KUG 1031+398 showed evidence for an ILR induced us to conduct new spectroscopic observations and modeling of its emission-line features.

1.2. KUG 1031+398

KUG 1031+398 has an unusual X-ray spectrum with a very strong soft X-ray excess (Pounds et al. 1995; Puchnarewicz et al. 1995); the broad component of the Balmer lines is relatively narrow (FWHM \( \sim \) 1500 km s\(^{-1}\)) and, consequently, this object has been classified as a NLS1 by Puchnarewicz et al. (1995). However, our spectra do not show strong Fe ii lines, another characteristic of many NLS1.

2. Observations

Observations were made with the spectrograph CARELEC (Lemaître et al. 1989), attached to the OHP 1.93 m telescope. The resolution, as measured on the night-sky lines, was \( \sim 3.4 \) Å for the blue and \( \sim 3.5 \) Å for the red spectral regions; the spectral ranges were \( \lambda \lambda 4780–5780 \) Å and \( \lambda \lambda 6175–7075 \) Å, respectively. The slit width was 2\′′. Our spectra were flux calibrated using the standard stars EG 247 (Oke 1974) and Feige 66 (Massey et al. 1988), also used to correct the red spectrum for the atmospheric B band at \( \lambda 6867 \) Å.

3. Data Analysis

Assuming that the emission-line profiles observed in KUG 1031+398 are the result of the contributions from several clouds, we tried to model the observed spectra with the smallest possible number of line sets, each set including three Gaussians (modeling H\( \alpha \) and the [N ii] lines, or H\( \beta \) and the [O iii] lines) having the same velocity shift and width, with the additional constraint that the intensity ratio of the two [N ii] (respectively [O iii]) lines was taken to be equal to the theoretical value of 3 (respectively 2.96) (Osterbrock 1974). In a physically meaningful and self-consistent model, the components found when fitting the blue and red spectra should have velocity shifts and widths compatible within the measurement errors.

The spectra were de-redshifted assuming \( z = 0.0434 \) and analyzed in terms of Gaussian components as described above. We discovered first that the core of the lines could not be fitted by a single set of narrow Gaussian profiles. To get a satisfactory fit, two sets of Gaussian components are needed: the first, unresolved (and subsequently taken as the origin of the velocity scales) has \( \lambda 6583/H\alpha = 0.55 \), \( \lambda 5007/H\beta = 1.27 \), and corresponds to a H ii region; the second is resolved (FWHM \( \sim 350 \) km s\(^{-1}\), corrected for the instrumental broadening), blueshifted by \( \sim 95 \) km s\(^{-1}\) with respect to the narrow components and has line intensity ratios typical of a Seyfert 2 (\( \lambda 6583/H\alpha = 0.84 \), \( \lambda 5007/H\beta > 10 \)).
Figure 1. Blue (a) and red (b) spectra of KUG 1031+398 in the rest frame; in (b) we also give the spectrum before correcting for the atmospheric absorption (dotted line). The narrow core components (c and d) were fitted with Gaussians and subtracted from the original data, the result being shown in (e) to (h). In (e) and (f), we show our best fit (solid line) together with the data points (crosses); the lower solid lines represent the residuals. In (g) and (h) we give the fit and residuals obtained when an “intermediate” component is imposed, as described in the text.

At this stage, we removed from the blue and red spectra the best fitting core (the H\textsc{ii} region and the Seyfert 2 nebulosity, Fig. 1c and d), obtaining two spectra we shall call “original data − core”. The blue one was then fitted with a broad H\textbeta Gaussian component and two sets of three components modeling the narrow H\textbeta and [O\textsc{iii}] lines. The result is very suggestive: one set has a strong H\textbeta line and very weak negative [O\textsc{iii}] components, while the other set displays a strong [O\textsc{iii}] contribution and a weak negative H\textbeta component, showing that we have in fact a H\textbeta component with no associated [O\textsc{iii}] emission and [O\textsc{iii}] lines with a very weak (undetected) associated H\textbeta; in other words, the region producing the H\textbeta line does not emit forbidden lines, while the [O\textsc{iii}] emitting region has a high λ5007/H\textbeta ratio, which are the characteristics of the “broad” and “narrow” line regions in Seyfert 1 galaxies, respectively.

With these results in mind, we optimized this last fit by using a Lorentzian profile for the H\textbeta line, with no associated [O\textsc{iii}] emission, and a set of three Gaussians for the remaining contribution coming from the “narrow” components; to avoid an unphysical negative intensity for the H\textbeta line, we forced λ5007/H\textbeta to be equal to 10, which is the ratio usually found for the narrow component in Seyfert galaxies. The best fit is presented in Fig. 1e. The H\textbeta Lorentzian component is blueshifted by 160 km s\(^{-1}\) with a width of 920 km s\(^{-1}\); the [O\textsc{iii}] lines are blueshifted by \(\sim 395\) km s\(^{-1}\) and their width is \(\sim 1 120\) km s\(^{-1}\).

We have also analyzed the “original data − core” red spectrum (Fig. 1f) with one Lorentzian H\alpha component and a set of three Gaussians (for the H\alpha and [N\textsc{ii}] lines) with the constraint that λ6583/H\alpha = 0.9, for which we have found
a FWHM of $\sim 770$ km s$^{-1}$ and a blueshift of 375 km s$^{-1}$. The H$\alpha$ Lorentzian component, blueshifted by 55 km s$^{-1}$, has a width of 1030 km s$^{-1}$, in reasonable agreement with the width of the corresponding H$\beta$ component. The Lorentzian Balmer components, without any measurable associated forbidden line, would qualify KUG 1031+398 as a NLS1 with, in fact, very narrow lines. The other system of lines, with a very high $\lambda5007$/H$\beta$ ratio, $\lambda6583$/H$\alpha$ $\sim 0.9$ and FWHM $\sim 945$ km s$^{-1}$, is analogous to what is usually found in Seyfert 2s and corresponds to a NLR cloud.

At last, we fitted the “original data − core” blue spectrum with a broad H$\beta$ Gaussian component and one set of three Gaussians (modeling H$\beta$ and the [O iii] lines) for which we set the $\lambda5007$/H$\beta$ ratio to the value found by Mason et al. for the “intermediate” component, i.e., 1.42. The red spectrum was fitted with two H$\alpha$ components, for which we fixed the redshifts to the values obtained in the blue spectrum profile fitting analysis. The resulting fits and residuals, shown in Figs. 1g and h, seem to be significantly worse than the ones given in Figs. 1e and f, showing that the presence of an “intermediate” component is not required by the data.

4. Results and Discussion

Our new observations and modeling of KUG 1031+398 yield a consistent decomposition of the emission-line profile into four components: an extended H ii region with unresolved lines; a first Seyfert-type cloud with relatively narrow lines ($\sim 350$ km s$^{-1}$ FWHM), blueshifted by 95 km s$^{-1}$, belonging to the NLR; a second Seyfert-type cloud with somewhat broader lines, blueshifted by $\sim 385$ km s$^{-1}$, also characteristic of the NLR; and finally, a Narrow-Line Seyfert 1 cloud with lines well fitted by a Lorentzian profile of $\sim 975$ km s$^{-1}$ FWHM, blueshifted by 105 km s$^{-1}$ (Table 1).

Table 1. Emission-line profile analysis of KUG 1031+398. I(H$\beta$) and I(H$\alpha$) are in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. The FWHMs are corrected for the instrumental broadening.

| $\Delta V$ (km s$^{-1}$) | FWHM (km s$^{-1}$) | $\lambda5007$ | $\lambda6583$ | I(H$\beta$) | I(H$\alpha$) |
|------------------------|-------------------|----------------|----------------|----------|----------|
| 1                      | 0                 | <80            | 1.27           | 0.55     | 29       | 93       |
| 2                      | −95               | 350            | >10.0          | 0.84     | <9       | 81       |
| 3                      | −385              | $\sim$ 945    | (10.0)         | (0.90)   | (11)     | 68       |
| 4                      | −105              | 975            | −              | −        | 199      | 677      |

The model used by Mason et al. to fit the emission-line spectrum of KUG 1031+398 seems to support the existence of an ILR emitting lines of intermediate width (FWHM $\sim 1000$ km s$^{-1}$); this component dominates the Balmer line profiles, being also a significant contributor to the [O iii] lines, with a flux ratio $\lambda5007$/H$\beta = 1.4$. 

There are two main reasons why our analysis yields different results. First, KUG 1031+398 having a redshift of \( \sim 0.043 \), the [N\textsc{ii}]\( \lambda 6583 \) line coincides with the atmospheric B band. When correcting for this absorption feature, the [N\textsc{ii}] true intensity is recovered (Fig. 1b) and our red spectrum appears different from the published one; different line-ratios and widths are therefore not unexpected.

Second, the line-profile analysis of Mason et al. differs from ours in that, while we force each Balmer component to be associated with forbidden lines having the same velocity and width, Mason et al. allow these parameters to have different values for the Balmer and forbidden line components. As a result, they found three H\( \beta \) components (a narrow, an intermediate and a broad one), as well as two [O\textsc{iii}] components (a narrow and an intermediate one); they also detected three H\( \alpha \) components (again a narrow, an intermediate and a broad one), but only a single [N\textsc{ii}] component (narrow). The measured width of the narrow H\( \beta \) component is \( 150 \pm 20\) km s\(^{-1}\) FWHM, while the width of the narrow [O\textsc{iii}] lines is \( 265 \pm 10\) km s\(^{-1}\); this last value, significantly larger than the narrow H\( \beta \) line width, suggests that the [O\textsc{iii}] lines may have a complex profile. Moreover, the width of the [N\textsc{ii}] lines is found to be significantly larger (\( 400 \pm 60 \) km s\(^{-1}\)) than that of the narrow H\( \alpha \) component (\( 190 \pm 40 \) km s\(^{-1}\)); this could be due to an inaccurate correction of the atmospheric B band, as we have seen before.

Although our spectra have a lower resolution than those obtained by Mason et al. (3.4 Å compared to 2 Å FWHM), this does not affect the analysis; the narrow core components being identified and subtracted, all the discussion is centered on the broader components, well resolved even with our lower resolution. Similarly, the larger slit width used in our observations (2"1 compared to 1"5 for Mason et al.) does not affect the study of these broader components, since only the contribution from the extended emitting region (the H\textsc{ii} region), removed with the core, changes with the slit width.

We disagree with Mason et al. on the result of the line profile analysis of KUG 1031+398, in the sense that we find no evidence for the presence of an ILR. Nevertheless, we find that this object is exceptional in having a NLR (defined as a region where \( \lambda 5007/H\beta \geq 5 \)) with almost the same width as the BLR (Balmer lines with no detectable associated forbidden lines).

Several authors have suggested that the small width of the broad Balmer lines and the soft X-ray excess characteristic of the NLS1 galaxies could be the effect of a high accretion rate onto an abnormally small mass black hole. Mason et al. (1996) have argued that, although the emission line spectrum in this object is dominated by the ILR, a weak broad component is present with line-widths of the order of 2 500 km s\(^{-1}\) FWHM and that, therefore, at least in this object, such a model is not required. Our analysis of the spectra shows that in the BLR, the Balmer lines are well fitted by a Lorentzian profile with \( \sim 1 000 \) km s\(^{-1}\) FWHM. We have shown (Gonçalves et al. in preparation) that in NLS1s the broad component of the Balmer lines is generally better fitted by a Lorentzian than by a Gaussian; so, in this respect, KUG 1031+398 is a normal NLS1 and could be explained by the same small black hole mass model suggested for the other objects of the same class.
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Discussion

Jack Sulentic: Can we agree that there are three types of Hβ line profiles: a) BLR + NLR components with clear inflection between them; b) Essentially continuous emission at all profile widths between BLR + NLR (this “ILR” emission is reflected in NLR [O iii] line profiles); c) same as b) except “ILR” emission not reflected in NLR [O iii]?

Anabela Gonçalves: The classical Seyfert 1 galaxies usually have a Hβ line profile of type “a”. The NLS1s, which have a broad Hβ component only slightly broader than the narrow component, fall into class “c”. Seyfert 1 galaxies with a genuine ILR would be in class “b”; however, no ILR has yet been found. Nevertheless, b-type profiles are sometimes observed in objects with strong Fe ii emission which blends with the [O iii] and Hβ lines, mimicking an “ILR” component. Moreover, a number of objects exist which have a “composite” spectrum, i.e., a H ii nebulosity and a Seyfert- or Liner-like cloud unresolved on the spectrograph slit; in these objects the [O iii] lines can be broader than Hβ (Véron et al. 1997), but they generally do not have a broad Hβ component.