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Near infrared hydrogen emission line ratios as diagnostics of the broad emission line region

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Abstract.

Broad emission line flux ratios are a powerful diagnostic of the physical conditions of the broad-line region gas in Active Galactic Nuclei. With recent advances in infrared spectroscopy, previously unstudied emission lines provide a new means to investigate the physical nature of the BELR gas. The hydrogen emission lines are particularly sensitive to the upper limits of both the radius from the central ionising source and the number density of the gas. Using an existing subset of near-infrared quasar spectra from the Glikman et al. (2006) sample [1] together with Cloudy photoionization simulations, we confirm the Locally Optimally emitting Cloud (LOC) model’s ability to reproduce observed emission line flux ratios. The model is then used to constrain physical conditions for individual sources. The photoionization models show that high number density, low incident flux gas is required to reproduce observed near-infrared hydrogen emission line ratios. We also find that comparison to individual sources, rather than composites, is vital.

1. Introduction

Broad emission lines are a prominent feature in quasar spectra, yet the physical state of this gas is not well understood. The locally optimally emitting cloud (LOC) model has been successful in reproducing UV and optical emission line ratios [2, 3], but has not been extensively tested on the hydrogen emission lines. The hydrogen emission lines are interesting because the physics is relatively simple, and there is a negligible dependence on several free parameters of the model: metallicity, column density and slope of the ionising continuum.

A subset of quasars from the Glikman et al. (2006) [1] sample was used to compare to photoionization simulations. The subset has a mean redshift of $z = 0.2$. Deconvolution of the broad and narrow components of the emission lines is not necessary, as the narrow contribution is small in quasars. Using existing near-infrared spectra of quasars together with Cloudy simulations of the broad line region, limits on the physical conditions of the hydrogen emission line region have been inferred.
Figure 1. Logarithmic contours of equivalent width in angstroms (referenced to the incident continuum at 1216 Å) in the plane formed by $n_{\text{H}}$ ($\text{cm}^{-3}$) and $\Phi_{\text{H}}$ ($\text{cm}^{-2}\text{s}^{-1}$). Only $W_{1216} \geq 0.1$ Å contours are shown. The solid lines show 1 decade intervals and the dashed lines show 0.2 decade intervals. $W_{1216} = 0.1$ Å is plotted with a very thick solid contour for each transition. For each each transition, the maximum $\log(W_{1216})$ is quoted in the legend.

2. Photoionization simulations

Following the standard LOC approach [2, 4, 3], large grids of photoionization models were computed using the photoionization code, Cloudy v08.00, last described by [5]. Models that predict hydrogen emission line strengths were generated for a range of hydrogen number density ($n_{\text{H}}$) and hydrogen ionizing flux ($\Phi_{\text{H}}$) values. The plane formed by these parameters represents the range of cloud densities and distances from the ionizing continuum that are expected to exist within the BELR. For each of these simulations, the output emission is computed as an equivalent width ($W_{1216}$) in angstroms relative to the incident continuum at 1216 Å. The equivalent width, $W_{1216}$, describes how efficiently the line is produced from the incident continuum. Full geometric coverage was assumed and a constant column density of $10^{23}$ cm$^{-2}$ was used. Full detail of these simulations will be given by [6].

Figure 1 shows logarithmic contours of $W_{1216}$ in the density-flux plane for three NIR emission lines: Hα, Pa α and Pa β. Light colours indicate a high reprocessing efficiency, i.e. large $W_{1216}$ values. The hydrogen lines are emitted efficiently over a large range in the density-flux plane, and emit particularly efficiently in the high density, low incident ionising flux regime. However, the entire range of parameter space shown in this plot might not be physical. Although the lower limit on the number density of the broad emission line gas can be inferred from the presence of semi-forbidden and absence forbidden transitions, constraining the upper limit is more difficult. Dust grains will condense at low values of incident ionising flux ($\Phi_{\text{H}} \sim 10^{18}$ cm$^{-2}\text{s}^{-1}$) [7], which will clobber any line emission. The hydrogen emission lines emit strongly near these limits. As the predicted hydrogen emission line ratios are sensitive to the upper $n_{\text{H}}$ and lower $\Phi_{\text{H}}$ limits, they can be used to constrain these limits.

3. Predicting broad emission line ratios

Ratios of hydrogen emission lines are a powerful diagnostic of the physical conditions of the BELR gas, as the strength of emission is very dependent on the incident ionising flux and number density, but not on the covering factor. As show by [2], the line luminosity is given by:

$$L_{\text{line}} \propto \int^{r_{\text{max}}}_{r_{\text{min}}} \int^{n_{\text{max}}}_{n_{\text{min}}} W_{1216}(r, n_{\text{H}}) f(r) g(n_{\text{H}}) dn_{\text{H}} dr,$$  \hspace{1cm} (1)
where $W_{1216}(r, n_H)$ is the equivalent width of a particular line (relative to the continuum at 1216Å) from a single cloud at radius $r$ with number density $n_H$. The cloud covering fractions as functions of radius from the ionising source and hydrogen number density are given by $f(r)$ and $g(n_H)$, respectively. For a more complete description of the LOC parameters, see [8]. In the simplest LOC integration model, the covering fractions are given by $f(r) \propto r^{-1}$ and $g(n_H) \propto n_H^{-1}$. The line luminosity can then be simplified to:

$$L_{\text{line}} \propto \int_{\log \Phi_{\text{min}}}^{\log \Phi_{\text{max}}} \int_{\log n_{\text{min}}}^{\log n_{\text{max}}} W_{1216}(\Phi, n_H) \, d\log n_H \, d\log \Phi_H,$$

(2)

where the integration limits are free parameters of the model and $\Phi_H \propto r^{-2}$. This is simply a sum over each point in parameter space between the integration limits, as the grid simulations are weighted evenly per decade. Since only three independent ratios were measured, the model can only have two free parameters. The free parameters of the model are $n_{\text{max}}$ and $\Phi_{\text{min}}$, which the hydrogen ratios are particularly sensitive to. As shown in Figure 1, the hydrogen line emission is only weakly dependent on $n_{\text{min}}$ and $\Phi_{\text{max}}$ (varying these limits causes the predicted hydrogen ratios to change by less than 1%). These parameters are fixed in this model.

4. Data

Very few quasars have been observed in the infrared with high signal-to-noise. Glikman et al. (2006) [1] published a set of 27 quasars, presented as a composite quasar spectrum. Rather than using the measured emission line flux ratios from the composite, individual spectra with the highest signal-to-noise ratios were used. Emission line fluxes were measured for the strongest hydrogen lines. Glikman et al. [1] found the $\text{Pa}_\alpha/\text{Pa}_\beta$ composite ratio to be $0.64 \pm 0.01$. However, values measured from individual objects are significantly higher and consistently above 1.0. Further detail of the measurements will be given by [9].

5. Fit to data

A set of ‘best fit’ $\Phi_{\text{min}}$ and $n_{\text{max}}$ integration limits was found for each object by comparing simulated and measured flux ratios. The most likely set of $\Phi_{\text{min}}$ and $n_{\text{max}}$ limits was found by minimising $\chi^2$:

$$\chi^2 = \sum_{i=1}^{N} \frac{(R_{\text{obs},i} - R_{\text{model},i})^2}{\sigma_{\text{stat},i}^2 + \sigma_{\text{sys},i}^2},$$

(3)

where $R_{\text{obs}}$ and $R_{\text{model}}$ are the observed and predicted ratios, and $\sigma_{\text{stat}}$ and $\sigma_{\text{sys}}$ are the statistical and systematic uncertainties on each measured ratio. The sum is over each emission line flux ratio used to find the best model: $\text{Pa}_\alpha/\text{Pa}_\beta$, $\text{Pa}_\gamma/\text{Pa}_\beta$ and $\text{H}\alpha/\text{Pa}_\beta$. $R_{\text{model}}$ is the predicted ratio for each combination of $\Phi_{\text{min}}$ and $n_{\text{max}}$ values considered.

Figure 2 shows $\chi^2$ contours for two objects in the $\Phi_{\text{min}}$–$n_{\text{max}}$ plane. The point where $\chi^2$ is minimised (shown with a red diamond) is at high density and low ionising flux. Results for all measured objects will be presented by [9].

6. Summary

A simple LOC model can reproduce measured near-infrared hydrogen broad emission line ratios. The measured $\text{Pa}_\alpha/\text{Pa}_\beta$ ratio for individual sources was inconsistent with the value presented by [1], which was measured from the composite spectrum.

Limits on the physical conditions of the BELR gas were inferred by comparing measured line ratios to simulations. The predicted outer radius of the BELR is consistent with the radius of dust sublimation calculated by [7]. The predicted upper limit on the gas number density is high compared to previous calculations, however, all predictions stated here should be considered...
Figure 2. Measured ratios are compared to the best fit models for two quasars. Left: Contours of reduced $\chi^2$. The location of the minimum $\chi^2$ in the $n_{\text{max}}$-$\Phi_{\text{min}}$ plane is shown with a red diamond. Right: The emission line flux ratio plotted as a function of $\Phi_{\text{min}}$ and $n_{\text{max}}$. The solid, dashed, dot dashed and dotted lines show the simulated $\text{Pa}\alpha/\text{Pa}\beta$, $\text{Pa}\gamma/\text{Pa}\beta$ and $\text{H}\alpha/\text{Pa}\beta$ ratios, respectively. The measured values are shown as a band with 1σ uncertainties in a corresponding colour. The best fit $\Phi_{\text{min}}$ and $n_{\text{max}}$ parameters are given in the legend for each object.

estimates, because of the simplicity of the model and limitations in the quality and number of spectra. This model can be extended to predict other emission line ratios, such as $\text{H}\alpha/\text{H}\beta$. This ratio can also be compared to measured values and can be used to estimate the amount of intrinsic dust.

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