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Velocity Diagnostics of the Broad Emission-Line Region of Active Galactic Nuclei

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Abstract. We present a brief review of emission-line velocity differences, and describe an ongoing project to determine the driving mechanisms responsible. We conclude with a brief outline of the use of velocity differences as probes of the conditions in the nuclear region of AGNs.

1. Introduction

On the basis of their empirical properties, the broad emission lines of AGN may be split into two main ionization classes with a dividing line at ~ 40 eV. The high-ionization lines (e.g., C IV $\lambda1549$) in general have broader line widths and show blueshifts with respect to their low-ionization counterparts (e.g., Mg II $\lambda2798$, the Balmer lines). Lyα $\lambda1216$ can also be placed in the high-ionization line class on the basis of its observed properties, and is most likely due to emission from hot, thin clouds. There is mixed evidence for a spread of cloud properties between the two extremes, but for now this evidence is not uniformly convincing.

The correspondence between the redshift of stellar absorption features and the peak of [O III] $\lambda\lambda4959, 5007$ emission lines in low-redshift AGN (e.g., Nelson & Whittle 1996), shows that the gas responsible for the narrow-line emission lies close to the systemic velocity of the host galaxy. The peak of the low-ionization lines in low-redshift QSOs also agrees well with the narrow [O III] emission-line redshift (Marziani et al. 1996), and so supports the use of the Balmer-line redshift for those objects which have weak narrow-line emission, or where the AGN redshift is such that [O III] emission moves into the infrared.

2. A New Velocity-Difference Study

In order to study velocity differences, we have undertaken a study with the aim of obtaining data from as many objects as possible, reduced in a consistent manner (e.g., removal of underlying continuum, fitting of the emission-line profiles to account for the presence of any absorption features). The goal is to produce a large data set which will be used to determine the key properties responsible for the observed line shifts, and how these differences vary between AGN types (e.g., radio-loud/radio-quiet QSOs).

The data set is composed mainly of published and archival data supplemented by new spectra of high-luminosity objects specifically obtained for this program (Espey & Junkkarinen, in preparation). The sample consists primarily

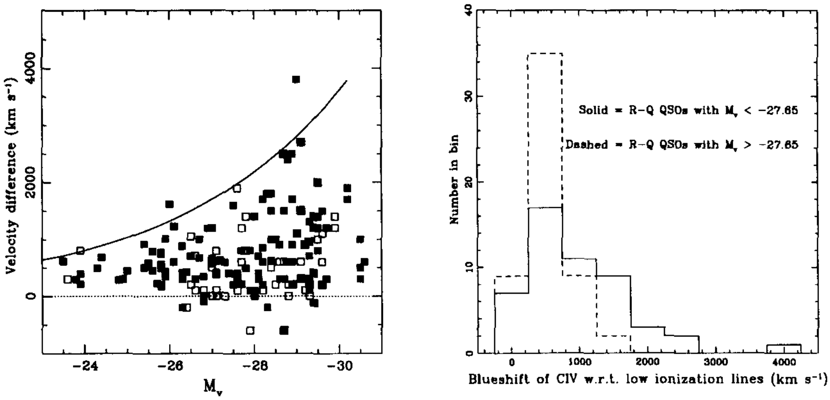

Figure 1. Distribution of emission-line velocity differences in terms of luminosity. Solid squares indicate radio-quiet objects, open squares indicate radio-loud objects. Increasing velocity difference represents the blueshifting of C IV with respect to the low-ionization lines. The right-hand plot shows a comparison of an equal number of low and high-luminosity radio-quiet objects.

of measurements of velocity differences between C IV λ1549 and Mg II λ2798 as these two lines are unblended, strong, and relatively easy to measure from UV or optical spectra over a wide range of wavelengths. So far the data sample includes $\sim$ 170 objects, biased towards radio-quiet QSOs. The parameters chosen for inclusion are velocity difference, absolute magnitude M_V, the C IV rest equivalent width EW(C IV), and its width FWHM(C IV). Absolute magnitude was chosen as a parameter as not all the spectra used have spectrophotometric calibrations.

Preliminary study of this sample yields results which are consistent with previous findings (e.g., Espey & Junkkarinen 1993). Application of the non-parametric Kendal τ partial rank-correlation test shows that the largest correlations are, in order of decreasing importance, between velocity shift and EW(C IV), FWHM(C IV), and M_V.

3. Mechanisms for Producing Velocity Shifts

The most obvious way to produce the observed line profile differences and velocity shifts is to postulate that the two cloud systems have a large relative velocity difference. Assuming that the emission-line material is distributed relatively symmetrically, then it is necessary for emission from some of the clouds to be either anisoptropically emitted, or hidden from our line of sight. Because of the association of the low-ionization material with the AGN rest frame, the high-ionization gas is most likely moving radially outwards, and emission from the far side of the broad-line region is hidden from our view. Comparison with the results of emission-line variability studies suggests that outflow is a less likely occurrence than infall, or Keplerian motion, at least in those systems examined

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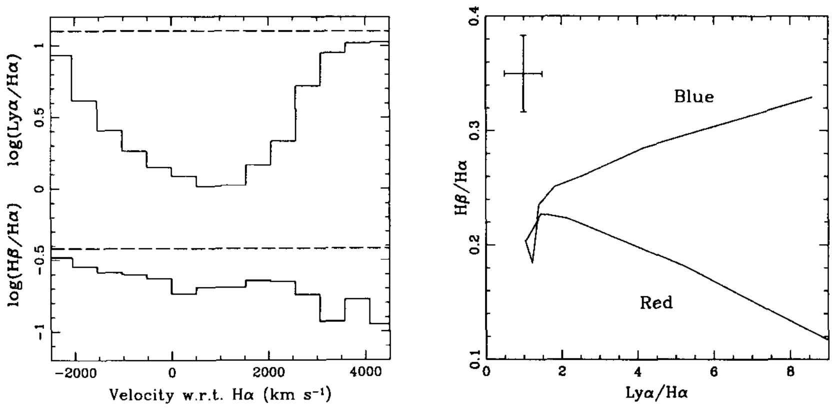

Figure 2. Observed emission-line ratios (corrected for Galactic extinction) in the radio-loud $z = 2.1$ QSO MC 1331 + 170. The dashed lines in the left-hand figure show the predicted Case B ratios for $T_e = 10^4$ K and $n_e = 10^9\,\mathrm{cm}^{-3}$. The right-hand figure shows the trend in the line ratios from blueward to redward of the Hα line peak. A representative error bar is also shown.

to date. A possible solution is to invoke the presence of an outflowing, warm ionized wind which scatters the line photons from the broad emission lines (Gaskell 1994). Observations of polarization in Seyfert 2 galaxies show that sufficient numbers of electrons are present to form a 'mirror' of the nuclear region of at least some active galactic nuclei, and it is plausible that such a medium exists in other objects as well. Electron scattering circumvents the conflict between velocity shift and line variability results if the optical depth to Thomson scattering is small, but provides a mechanism to explain the large velocity differences when the optical depths are larger and/or the emission-line clouds undergo outflow. It can also explain the relatively symmetric nature of the shifted emission lines, which pose a serious problem for other explanations (Netzer 1996).

In the context of more exotic explanations, we mention the Čerenkov mechanism proposed by You et al. (1984) in which the low-ionization lines are redshifted relative to the high-ionization lines, but produced in denser regions of a single cloud population. Cheng et al. (1990) noted two pieces of supporting evidence — the redshift of Lyα with respect to the C IV line, and 'double-peaked' Lyα profiles in four objects of the Espey et al. (1989) data set. The former effect is due, at least in part, to absorption on the blue side of the Lyα profile, and the latter to the presence of relatively narrow N V λ1240 emission, so the evidence is not as strong as they believed. A case where the Čerenkov mechanism may apply, however, is to the redshifted, red-asymmetric Balmer lines of radio-loud objects (Boroson & Green 1992; Marziani et al. 1996), as for these objects the relativistic electrons required for the process are more likely to be present.

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4. Applications

One use for emission-line velocity shifts is to provide a means to resolve (at least in velocity space) the broad emission-line regions of AGN. Although the details, and even the exact mechanism, of the velocity field are unknown, the existence of velocity differences still provides a means to study the emission-line ratios in more detail than can be achieved by simple comparison of their integrated line fluxes.

Figure 2 shows the velocity-resolved ratios of Lyα/Hα and Hβ/Hα for the z = 2.1 QSO MC 1331+170. The mean Lyα/Hα and Hβ/Hα ratios for this object are 3.0 and 0.18, respectively. From the plots, it is obvious that the mean Lyα/Hα ratio is biased by the contribution of the wings the line profile. This plot shows that the well-known 'Lyα/Hβ' problem (Baldwin 1977) is even more acute when considered in terms of point-by-point line ratios.

5. Conclusions

Work continues on extending the available data base of objects used for study of the velocity differences, and in determining the prime driver behind the shifts. In terms of applications to AGN problems, much work remains to be done in studying how line ratios vary across the broad emission-line profiles. Although the mapping from velocity to spatial coordinates is unlikely to be one-to-one, velocity space provides a means to separate out distinct components of the emission-line gas. When coupled with profile variability studies, it will be possible to obtain more detail of the structure of the emission line region. Detailed studies of the time-delayed response of line profiles to changes in the ionizing continuum (e.g., Wanders et al. 1995) should be extended to consider how line *ratios* alter with continuum changes.

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