Broad emission lines in the duelling wind model of active galaxies

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Accepted 1988 October 20. Received 1988 October 20; in original form 1988 June 15

Summary. We investigate the broad-line emission from clouds formed by the interaction of a nuclear mass outflow and a disc wind in the context of a quasar model. The line ratios and profiles are shown to be in general agreement with observation. Particular results include (i) a density range compatible with suggested solutions to the Lyα/Hβ problem which nevertheless yields the correct C IV λ1909 flux; (ii) broader lines from the inner higher density region despite an accelerated outflow; (iii) compatibility between BLR sizes from variability arguments and ionization parameters; (iv) blueshifted line-peaks apparently uncorrelated with line asymmetry.

1 Introduction

It is commonly believed that the radiation from active nuclei is produced by disc accretion on to a black hole. If we add the assumption that associated with the outflow of radiation there is also a particle outflow or wind, then we are led to what we have called the ‘duelling wind’ model of active nuclei. In this model the disc is illuminated, either directly or by scattering in the wind, by the X-ray continuum from the central source, thereby giving rise to a mass outflow from the disc surface. The interaction between the nuclear and disc winds leads to the formation of a cloud system which is identified with the broad line clouds (Smith & Raine 1985). Smith & Raine (1988) discuss a version of this model in which it is supposed that the clouds can be effectively ram pressure confined, at least for not substantially less than a crossing time of the broad line region (BLR). In this case the cloud trajectories can be readily computed and unambiguous predictions for emission line intensities and profiles can be obtained. Since the cloud densities and ionization parameters fall in the range normally assumed for the BLR, we expect the line ratios to be in reasonable agreement with observed values. Smith & Raine show that the line profiles should be at least approximately logarithmic in the wings (intensity ∝ constant-log |λ − λc|) in agreement with a significant subset of observed profiles. If the clouds are not confined by ram pressure, a cloud system still forms but the trajectories cannot be obtained without detailed hydrodynamic calculations essentially because one cannot estimate the initial conditions for the trajectories a priori. However, our results are not particularly sensitive to initial conditions, so we expect the two variants of the
model to yield somewhat similar results. In this paper we carry out photo-ionization calculations to obtain detailed predictions of the broad line ratios and profiles in the ram-pressure confined version of the duelling wind model.

A successful model for the BLR must yield correct average behaviour for the line intensities and profiles. For intensities this means agreement within a factor 2 for the main ‘diagnostic’ line ratios (Carrol & Kwan 1983) and a reasonable fit to the complete set of measurable lines (Krolik & Kallman 1988). For profiles we require something like logarithmic wings and a reasonable kurtosis (peakiness), although it is more difficult to decide what constitutes the average or typical case. Indeed, to be worthy of further consideration, a theory must produce also the range of observed behaviour within the range of acceptable parameter space. This means exhibiting differences between profiles for different lines in a given object as well as for different systems and possible asymmetries and shifts. It is also necessary to show how observed time variations of lines and continua are at least compatible. (A complete treatment would require a time-dependent hydrodynamical model.) This is the programme we embark on in this paper. One can then, and only then, explore detailed fits to individual sources in the knowledge that the variety of detail in the apparently single family of broad-line objects can be accommodated in a single model. This final comparison with observations will not be attempted here (although preliminary results have been reported in Mardaljevic, Raine & Walsh 1988); it needs a refinement of the physics to limit the parameter space.

In Section 2 we describe the duelling wind model and the choice of parameters. The dynamical model is used in Section 3 to fix the characteristics of the BLR clouds and predict the line ratios in the BLR via photo-ionization calculations. Predicted line profiles are presented in Section 4 followed by a study of time variability in Section 5. We summarize our conclusions in Section 6.

2 Duelling wind model

Were the duelling wind model complete, then just two parameters would characterize the source (black hole mass and the accretion rate) and one parameter (the disc inclination) would specify the relation of the source to the observer. The present incompleteness of the model means we have to add a number of parameters expressing either ignorance of physics or our inability to do numerical computations of three dimensional radiation hydrodynamics. In order to avoid the number of parameter configurations becoming unmanagably large, we identify a ‘fiducial model’ and examine the effect of variations of parameter values away from this case within a specified range. The parameters and their ranges are:

(i) Black hole mass, $M_{bh} = 10^8 m_b M_\odot$. We choose $m_b = 0.1$ (see below) and explore the range $0.01 < m_b < 1$ usually estimated for active nuclei.

(ii) The luminosity $L$, as a function of the Eddington limit, $L_{Edd}$, specified through $\lambda = L/L_{Edd}$. For a given efficiency $\lambda$ is related to the disc accretion rate. We take $\lambda = 1$ and consider the range $0.1 < \lambda < 10$.

(iii) Parameters related to the continuum spectrum, $I_c$. These are the inverse Compton temperature $T_c = h/4k (\langle \nu I_c \rangle/\langle \nu \rangle)$ where the angle brackets denote frequency averages, and the various ionization parameters. The inverse Compton temperature is parameterized by $\tau_c = T_c/10^8 K$. The ionization parameters are (i) the $E_{k,min}$ of Begelman, McKee & Shields (1983) which is the maximum ratio of radiation pressure in ionizing photons ($13.6 \text{ eV} \leq h\nu \leq 1 \text{ MeV}$) to gas pressure at which the disc surface can remain in the low-temperature phase (around $10^4 K$ or below), and (ii) $\Gamma$ defined by $\Gamma = Q/4\pi r^2 n_e c$, the ratio of the flux of ionizing photons, $Q$, to electron density in the photo-ionized gas, $n_e$. The value $E_{k,min}$,
which we write as $\Xi$ henceforth, and of $\Gamma$, and the relation between them, depends on the shape of the continuum spectrum. The value of $\Xi$ is used to determine the approximate cloud densities; its precise value determines only the quantitative relationship between the input parameters and the numerical prediction, and that only marginally. We have therefore fixed $\Xi = 3$ as a 'typical value'. The value of $\Gamma$ as it appears in the photo-ionization calculations characterizes rather sensitively the line ratios and profile differences obtained from the photo-ionization code and is calculated precisely for each input spectrum and each cloud.

For the fiducial spectrum we take the average quasar spectrum given by Mathews & Ferland (1987) as a broken power law approximation to recent data. This gives $\tau_e = 0.1$. We shall also show the effect of varying the relatively unknown slope in the UV-soft X-ray region. In these cases we assume that the clouds see the same spectrum as the observer. To test the sensitivity to this assumption we consider an angle-dependent continuum similar to that discussed by Netzer (1987) and characterized by the ratio of energies in an angle-dependent UV bump and in an isotropic X-ray power law. In this case the relevant inverse Compton temperature is that appropriate to the disc surface, but the ionization parameter $\Gamma$ is angle-dependent.

(iv) The velocity of the nuclear wind, $V_w$. Since the wind is driven from deep in the potential well of the black hole, it must be hypersonic. We take two cases; $V_c = 5 \times 10^5 \text{ cm s}^{-1}$ and $V_w = 10^9 \text{ cm s}^{-1}$, which give rise to rather different cloud systems (see below).

(v) The outer radius of the cloud system, $R_{\text{out}}$. The model gives a well-defined radial extent to the cloud formation region $R_c < R < R_d$ (see below), but we do not predict the time for which clouds can survive. For the broad lines this is not important, because the covering factor falls rapidly ($\propto 1/r^2$) once the input of clouds are turned off beyond $R_d$. However, since the gas density in the clouds falls (also $\propto 1/r^2$) as they move out, we expect weak wings to the forbidden lines if clouds survive at large radii. We can either assume that the clouds are broken up above the critical densities for forbidden lines, or, we can attempt to identify this outer region with the intermediate zones that have been proposed to connect the BLR and NLR and as being responsible for the weak [O iii] $\lambda 5007$ and [O iii] $\lambda 4959$ wings sometimes observed (Heckman, Miley & Green 1984; Whittle 1985). In the fiducial model we put $R_{\text{out}} = 3 R_d$, and concentrate only on the BLR properties.

(vi) The formation time-scale for clouds, $\Delta t_c$. If clouds form instantaneously on the disc surface then the line profiles are far too centrally peaked and we can rule out the duelling wind model. We cannot therefore ignore the fact that the cloud formation occurs at a finite height above the disc surface, or, more correctly, that the initial velocity will not be exactly perpendicular to the disc surface. We do not attempt to estimate this effect precisely, but treat it as a parameter to be specified. This does not mean that the kurtosis of the line profiles can be adjusted through this parameter to match observed values. Fortunately, as long as some small allowance is made for cloud formation time, this effect ceases to dominate the core of the line profiles. We choose $\Delta t_c = 10^6 \text{ s}$, of the order of the cooling time for the gas that forms the clouds (Smith & Raine 1988).

(vii) Cloud shape. The shape of the clouds is important for two reasons. Firstly, the motion of the clouds under ram pressure and radiation acceleration depends on shape. Secondly, for non-spherical clouds the line intensities seen by the observer from each cloud will depend on orientation. We take the clouds to be cylindrical, rather than spherical, with symmetry axis along their direction of motion, because this seems to be a good approximation to their expected shape (Smith & Dickel 1983). However, we assume the line radiation to be emitted isotropically from the clouds. The result is that for the present we have to forego quantitative discussion of red–blue line asymmetries.

We turn now to some dependent parameters which are also needed to describe the model.
The inverse Compton radius, $R_{\text{ic}}$. The inner radius of the disc wind, $R_{\text{in}}$, is the innermost radius from which gas, inverse Compton heated to $T_{\text{ic}}$, can escape from the surface of the disc. We have $R_{\text{ic}} = 3 \times 10^{18} m_8 \tau_8^{-1} \text{cm}$ (Begelman et al. 1983; Smith & Raine 1988). In fact, Begelman et al. show that there will be a weak wind from the region between 0.1 $R_{\text{ic}}$ and $R_{\text{ic}}$. We also expect a viscous heating in the disc atmosphere to assist in driving a wind. We have therefore taken the inner radius of mass loss from the disc to be somewhat smaller than $R_{\text{ic}}$. For the fiducial model we choose $R_{\text{in}} = 0.15 R_{\text{ic}}$. This avoids potential difficulties with covering factors, and possibly also velocities of the broad-line clouds, which would arise from taking $R_{\text{in}} = R_{\text{ic}}$ for $\tau_8 = 0.1$. Alternatively, one can regard our choice of $R_{\text{in}}$ as the inverse Compton radius for $\tau_8 = 0.65$, corresponding to removal of the ‘big-bump’ from the UV spectrum. This would be appropriate if the UV emission were anisotropic and did not illuminate the disc directly. The effect of varying $R_{\text{in}}$ is considered in (4) below.

(2) The escape velocity from the disc, $V_{\text{esc}} = (3 k T_{\text{ic}} / \mu m_0)^{1/2}$. Since material leaves the disc at barely supersonic velocity (Begelman et al. 1983), we take the disc wind to have velocity $V_{\text{esc}}$. The parameter $\xi = 1 - V_{\text{esc}} / V_{\text{w}}$ then controls the form of the cloud system that develops. For $\xi$ near unity we obtain a flattened disc-like distribution of clouds; however, as $\xi$ becomes smaller the cloud distribution turns to a quasi-spherical system. In fact, the polar angle $\theta$ to which the cloud system extends above the disc (measured upwards from the surface of the disc) is calculated from numerical computation of the cloud dynamics (see below), and is given in radians by $\theta = 0.7 \log(1 - \xi) + 1.46$ for $0.92 < \xi < 0.99$. For our fiducial model we take the disc-like system of clouds obtained with $\xi = 0.98$. Note that since the nuclear wind is highly supersonic, whereas the disc wind is barely so, we always have $\xi > 0$.

(3) The gas density in clouds, $n$, as a function of distance, $r$, from the central ionization source is given by

$$n = 3 \times 10^{10} \left( \frac{\lambda}{m_8} \right) \left( \frac{R_{\text{ic}}}{r} \right)^2 \left( \frac{10^4 \tau_8}{\Xi T} \right)^2$$

(Smith & Raine 1988). For the purpose of evaluating this formula the cloud temperature, $T$, is fixed at $10^4$ K. Note that since $R_{\text{ic}} \propto \tau_8^{-1}$, the density at a given radius is independent of $\tau_8$.

(4) The mass-loss rate from the disc, $dM/dR$, as a function of radial distance along the disc, is given by Begelman et al. (1983)

$$dM/dR \propto 1/R$$

for $0.08 < R_{\text{ic}} < R_d$. We have taken equation (2) to hold for $R_{\text{in}} < R < R_d$ with $R_{\text{in}} = 0.15 R_{\text{ic}}$ in the fiducial model, with $\dot{M} = 0$ within $R_{\text{in}}$. In principle, the introduction of a small amount of high density material within $R_{\text{in}}$ could have a significant effect on the line emission. In fact, since the covering factor of this material will be small, additional clouds within $R_{\text{in}}$, or removal of cloud trajectories originating from close to $R_{\text{in}}$, can at most affect weak lines with highly density dependent emissivities. This is precisely what we find. Introducing this extra material into the fiducial model has essentially no effect on line ratios and profiles with the exception of a factor two increase in N v $\lambda$ 1240, Ovi $\lambda$ 1035 and He II $\lambda$ 5876. We have therefore taken $R_{\text{in}}$ as the inner radius of the cloud system.

(5) The outer radius of the mass outflow, $R_d$. Begelman et al. (1983) show that the wind will be suppressed beyond $R_{\text{iso}} = 10^{18} m_8(\lambda/0.03) \tau_8^{1/2} \text{cm}$. We therefore set $R_d = R_{\text{iso}}$.

We are now in a position to explain the choice of fiducial values for $m_8$ and $\lambda$. In the reference system we want the gas density in BLR clouds to lie in the range $10^{11}$ to $10^{7} \text{cm}^{-3}$ between $R_{\text{in}}$ and $R_{\text{out}}$. The lower density is chosen sufficiently large to reduce the flux in
[O iii] $\lambda 5007, 4959$ to less than 1 per cent of observed narrow line fluxes (as ascertained by subsequent numerical calculation). The upper limit gives us the high densities invoked for the Ly$\alpha$/H$\beta$ problem while still allowing a sufficiently extensive region of density less than $10^{9.5}$ cm$^{-3}$ to yield enough C$\text{iii}] \lambda 1909$. These conditions give two equations for $m_\lambda$ and $\lambda$ from which we derive $m_\lambda=0.1$ and $\lambda=1$, corresponding to an inner radius of $R_{in}=4.5 \times 10^{17}$ cm, an outer disc radius of $R_{out}=3 \times 10^{19}$ cm and $R_{out} \sim 10^{19}$ cm.

The cloud trajectories can now be computed. A cloud at radius $r$ from the central source with velocity $V_0$ is ram pressure accelerated according to

$$ \frac{d^2 r}{dt^2} = \eta \rho_c A \rho_w |V_w - V|/(V_w - V), $$

(3)

where $\rho_c$ and $\rho_w$ are the mass densities in the cloud and the nuclear wind, respectively, $A$ is the area of a cylindrical cloud, $h$ its thickness, $V_w$ the wind velocity and $\eta$ is the drag coefficient. For cylindrical clouds we have $A = \text{constant}$ and, according to Smith & Raine (1988), the column density is $\rho_c h / \mu m_t \leq 6 \times 10^{23}$ cm$^{-2}$ independent of position. We argued there that most of the mass in clouds may be expected to end up in clouds at the upper limit of column density. We therefore restrict our attention to the dynamics of these clouds. For spherical clouds we have $\rho_c h \propto r^{-4/3}$. The velocity of a hypersonic wind is approximately constant and continuity of mass in the nuclear wind gives $\rho_w \propto 1/r^2$. The parameter $\eta$ relates to the way the ram pressure is communicated to the cloud via the flow around it; we take $\eta=1$. For initial conditions, we assume the trajectories start with a velocity $V_{\text{esc}}$ normal to the disc on the disc midplane. We ignore the small azimuthal velocity component. Equation 3 can now be integrated to obtain the cloud trajectories. Representative trajectories are shown in Mardaljevic et al. (1998). In the fiducial case the trajectories cross, those from larger disc radii rising across the paths of clouds from smaller radii. For smaller values of $\xi$ the trajectories do not cross within $R_{out}$. We take the trajectories to be uniformly distributed in $\log R$ across the disc, $R_{in} < R < R_{out}$, to incorporate equation 2. Representative clouds are then placed at certain time intervals along each trajectory starting at $\Delta T_c$ [see Section 2(vi)]. These time intervals are increased at large radii and the intensities weighted accordingly in order to give more detailed coverage of the inner regions where line profile differences are more pronounced. About 20 clouds are taken on each of 10 trajectories in the photo-ionization calculations. We used 60 azimuthal bins giving a total of about 180000 clouds in order to obtain smooth profiles. Fig. 1 presents the change in cloud number density, defined as $\Sigma 1/r_1^3$ summed over clouds at positions $r_i$ in radial bins $r$ to $r + \Delta r$, as a function of radius in our fiducial model of the BLR.

In Fig. 2 we plot the number of clouds as a function of gas density, $n$, for our reference model. Note that we have a roughly gaussian distribution with a peak at $\sim 10^9$ cm$^{-3}$. There will be an extended tail at high density if we include mass loss from within $R_{in}$. This gives us the possibility that significant C$\text{iii}] \lambda 1909$ can be produced in a flow which contains substantial quantities of gas above the critical density of $10^{9.5}$ cm$^{-3}$ for this line. We will confirm this by our photo-ionization calculations later. Note also that the ionization parameter $\Gamma$ is constant from cloud to cloud, because both the radiative flux and the gas density in clouds fall as $1/r^2$; line profile variations come entirely from density variations. This is to be contrasted with models of the BLR which involve clouds with two (or more) ionization parameters.

On the other hand, there must be some contribution to line emission from the disc (Jones & Raine 1980; Collin-Souffrin 1988). Beyond a certain radius the energy generation in the disc is less than the heating from the central source (Begelman et al. 1983), so the disc itself becomes a photo-ionized H$\text{ii}$ region. For the fiducial model this region is in fact beyond $R_{\text{iso}}$ and the contribution to the emission lines is negligible. At smaller radii a cool inner disc is topped by a

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photo-ionized corona. Emission from this, in the lines considered below, can be made small either by assuming the transition from \( \leq 10^4 \) K to gas at \( T_{\text{ion}} \) to involve a negligible amount of material, or by assuming electron scattering in the hot corona (at \( T_{\text{ion}} \)) to be significant, since in this case lines get broadened beyond detectability.

The profile fits by Mardeljevic et al. (1988) to observations of the H\( \beta \) line suggest in any case that in general the disc does not dominate the line profiles. As suggested by Collin-Souffrin (1988) one might expect a natural division between the mainly 'low ionization' lines for which the disc contribution is important, and mainly 'high ionization' lines where the main contribution comes from the clouds. Note that the distinction is really between line ratios at different ionization parameters and does not necessarily correspond to lines of different ionization potentials. In this paper we ignore the contribution from the disc, which will be discussed elsewhere.

Absorption or scattering in the disc are important in relation to the contribution of clouds on the far side of the disc. A hot corona of significant optical depth would certainly broaden
lines from these clouds beyond detectability. If the disc is producing significant emission line fluxes then absorption of cloud line photons is possible, but with a complex pattern of Doppler shifted zones of transparency. For a flattened cloud distribution ($\xi = 0.98$), most of the disc would be transparent since the Kepler velocities in the disc are less than those of escaping clouds. For a quasispherical configuration ($\xi = 0.92$), the relative Doppler shifts of cloud and disc material will not shift emission photons out of the absorption profile of disc gas and hence absorption in the disc will be important. If the disc does not emit significantly in the relevant lines, or scatter incident radiation, then absorption can occur if the cool disc material contains sufficient dust. We conclude that at this stage we do not know to what extent the disc obscures the far side clouds and therefore treat this as another parameter.

3 Line ratios

The photo-ionization code used in this study is described in several papers (Netzer 1980; Netzer & Ferland 1984; Netzer, Elitzur & Ferland 1985). The line ratios we find from this code for the fiducial model are listed in Table 1. We choose constant pressure gas in the clouds and check that using constant density or requiring hydrostatic equilibrium condition for the clouds (with gravity appropriate for local acceleration) makes no significant difference to our conclusions. For fixed cloud orbits the line ratios are not sensitive to variation of column density in the range $10^{21} < N < 10^{23}$, because this exceeds ten times the Strömgren column density as required for the extended X-ray heated partially ionized transition region giving rise to Mg II, Fe II and Balmer emission. In the results presented the stopping condition was in fact set at a column density of $10^{22}$ cm$^{-2}$. The ionization parameter is $\log \Gamma = -1.56$.

The observed and predicted line ratios, corrected for the contribution from the narrow line region, are compared in Table 1. There is reasonable agreement between prediction and observation with the exception of the usual problem with Ly$\alpha$/H$\beta$ and with O vi $\lambda 1035$ and N v $\lambda 1240$ (see below).

<table>
<thead>
<tr>
<th>Line</th>
<th>Predicted</th>
<th>observed$^1$</th>
<th>observed$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O VI $\lambda 1035$</td>
<td>0.01</td>
<td>0.58</td>
<td>2.17</td>
</tr>
<tr>
<td>H I $\lambda 1216$</td>
<td>1.81</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>N V $\lambda 1240$</td>
<td>0.17</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>N IV $\lambda 1486$</td>
<td>0.03</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>C IV $\lambda 1549$</td>
<td>1</td>
<td>0.06</td>
<td>0.048</td>
</tr>
<tr>
<td>H e III $\lambda 1640$</td>
<td>0.051</td>
<td>0.17</td>
<td>0.28</td>
</tr>
<tr>
<td>O III $\lambda 1666$</td>
<td>0.095</td>
<td>0.012</td>
<td>0.048</td>
</tr>
<tr>
<td>N III $\lambda 1750$</td>
<td>0.015</td>
<td>0.012</td>
<td>0.01</td>
</tr>
<tr>
<td>C III $\lambda 1909$</td>
<td>0.195</td>
<td>0.17</td>
<td>0.28</td>
</tr>
<tr>
<td>C II $\lambda 2326$</td>
<td>0.012</td>
<td>0.034</td>
<td>0.05</td>
</tr>
<tr>
<td>M g II $\lambda 2798$</td>
<td>0.06</td>
<td>0.012</td>
<td>0.048</td>
</tr>
<tr>
<td>H e II $\lambda 4686$</td>
<td>0.010</td>
<td>0.01</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>H $\beta$ $\lambda 4861$</td>
<td>0.048</td>
<td>0.05</td>
<td>0.43</td>
</tr>
</tbody>
</table>

$^1$NGC 4151 data from Ferland and Mushotzky (1982).
$^2$3C 273 data from Ulrich et al. (1980).
Since the UV-soft X-ray spectrum is uncertain, we have tested the sensitivity of the line ratio predictions to changes in $L_{\text{UV}}/L_X$, the ratio of UV to hard X-ray ($> 2$ keV). This has been done by altering the slope of the continuum between 52.6 and 365 eV from the value of $-3$ given by Mathews & Ferland (1987) to $-1.5$. The ionization parameter becomes $\log \Gamma = -2$. Most of the line intensities are little changed, but, not surprisingly, some of the low ionization lines are enhanced. Mg II/C IV is increased to 0.40 and C II/C IV to 0.095, well in the observed range of values. Note the change in $\log \Gamma$ from $-1.56$ to $-2$ is also roughly equivalent to the uncertainty in our adopted value of $\Xi$ in Section 2.

As a further test we took a spectrum comprising two separate power laws with indices $-1.4$ in the UV (Mathews & Ferland 1987) and $-0.7$ in X-ray (Zamorani et al. 1981) and $L_{\text{UV}}/L_X = 3$. The resulting line ratios are again close to those listed in Table 1. This relative insensitivity to continuum shape is, of course, the converse of the difficulty of obtaining the continuum from observations of line ratios (Krolik & Kallman 1988). It should be emphasized that the range of density spanned by our clouds makes no difference.

Variations away from $m_8 = 0.1$ and $\lambda = 1$ will change the line ratios through the gas density in clouds and the size of the BLR. The ionization parameter is independent of $m_8$ and $\lambda$ (because it fixes the cloud densities), so the predicted changes in line ratios depend on changes in the range of density which can be altered by a factor $\sim 10$ up or down. The resulting spread of line ratios is roughly compatible with observations.

We turn next to the possibility of an angle-dependence in the continuum radiation suggested by Netzer (1987) for a mixture of a disc source of UV and a spherical source of X-rays. In this case we take

$$F_{\nu} = a(\theta) \nu^{-s} \exp \left( \frac{1 - \nu}{\nu_c} \right) + b \nu^{-\beta},$$

with frequency $\nu$ measured in Rydbergs and $\nu_c = 3$ Ryd. Following Netzer we take $a(\theta) \propto 1/3 \cos(\theta)(1 + 2 \cos \theta)$ with $\theta$ measured from the normal to disc. Netzer's claim was that a suitable distribution of clouds the angle-dependence of the ionization parameter enabled a solution of the O VI and N V discrepancy to be found. In the duelling wind model, the cloud distribution is fixed by the dynamics. For a flattened distribution ($\xi = 0.98$) clouds do not rise sufficiently above the disc to take advantage of the range of $\Gamma$ values. For a quasispherical cloud distribution ($\xi = 0.92$), taking $s = 0.7$ and $\beta = 1.4$, the angle-dependent continuum gives $-2.7 < \log \Gamma < -1.5$. In this case the O VI and N V intensities increase by an order of magnitude as the $L_X/L_{\text{UV}}$ changes from 0.3 to 0.05. However, they are still a factor of 10 weaker than the observed values. Unless we adopt a much stronger dependence of $a(\theta)$ on $\theta$, the O VI and N V problem remains unsolved. It may require a treatment of the process of cloud formation, either for clouds not in ionization equilibrium or for an equilibrium sequence from the low-density, high temperature phase.

4 Line profiles

We begin by investigating the profile of a representative line, arbitrarily chosen to be C IV $\lambda 1549$, as a function of the model parameters. For our fiducial values of $m_8$ and $\lambda$, Fig. 3 shows the line profiles at various values of $\xi$ and different inclination angles, $i$, for both transparent and opaque discs. These confirm the presence of approximately logarithmic wings. We emphasis that this result follows directly from the local proportionality of densities in the clouds and in the wind, the assumed constancy of the nuclear wind velocity and, particularly, the assumed constancy of the area or column density and mass of the clouds. It is not clear that
the last assumption is a good approximation, but has been chosen because it yields logarithmic profiles. The full-width at half maximum (FWHM) of the broad diagnostic lines range from \( \sim 600 \text{ km s}^{-1} \) in NGC 4051 to \( \sim 7000 \text{ km s}^{-1} \) in Mrk 279 while their full-width at zero intensity (FWZI) ranges from \( 4 \times 10^3 \text{ km s}^{-1} \) in Mrk 359 to \( 3 \times 10^4 \text{ km s}^{-1} \) in Mrk 876 (Osterbrock & Shuder 1982). Taking different combinations of parameters around the adopted fiducial values in the duelling wind model, we can produce the observed ranges in profiles of diagnostic lines. For example, taking \( \xi = 0.92 \) and \( i = 75^\circ \), we predict (for C\text{IV}) a FWHM of \( \sim 500 \text{ km s}^{-1} \) and FWZI of \( \sim 2000 \text{ km s}^{-1} \) while taking \( \xi = 0.98 \) and \( i = 25^\circ \) gives a FWHM \( \sim 6000 \text{ km s}^{-1} \) and FWZI \( > 20 \text{000 km s}^{-1} \) (Fig. 3) in good agreement with the observed range. In the case \( \xi = 0.92 \), for an opaque disc, the profile shifts towards the blue as \( i \) increases and there is an asymmetric tail (relative to the line peak, of course) towards the red. The contributions from cloud systems on both sides of a transparent disc produce a double-

**Figure 3.** Line profiles at \( \xi = 0.92 \) and \( \xi = 0.98 \) for transparent (---) and opaque (...) discs. The inclination angle is measured from the disc to the line of sight. A logarithmic profile shape (solid line on the top-left panel) is shown for comparison.
peaked core. In the case $\xi = 0.98$ and an opaque disc, the dependence of the blueshift on $i$ is much weaker. Therefore, profiles of a given line in this case are rather similar for both one-sided and two-sided cloud systems. We note that the cloud covering factor in the duelling wind model is in the range 0.1–1 (Smith & Raine 1988) with large values possible only for small $\xi$. Thus we predict a relation between line profiles and covering factors which is in principle observable.

Fig. 4 shows a range of profiles as $m_8$ and $\lambda$ are varied around their fiducial values. The profile widths at zero intensity depend on the maximum cloud velocities which are proportional to $(m_8\lambda)^{1/2}$ (Smith & Raine 1988). The outer radius of the cloud system is proportional to $\lambda$ and for small $\lambda$ this gives rise to the dip at the profile centre. It is not, of course, clear whether this reflects our arbitrary choice of $R_{\text{out}} = 3R_d$ or if these cases are to be compared with the exceptional double peaked profiles observed in some objects (Capriotti, Foltz & Byard 1979; Alloin 1988). This depends on the modelling of individual systems which we shall return to elsewhere.

We now turn to the profile differences between different lines in a single object. There is some difficulty here in the interpretation of the observations. For example, $\text{C}\,\text{m}\lambda 1909$ has been observed to be broader than $\text{C}\,\text{iv} \lambda 1549$ (Wilkes 1988). However, this probably results, in at least some cases, from blending with $\text{Al}\lambda 1858$, $\text{Si}\,\text{iii} \lambda 1892$ and an $\text{Fe}\,\text{ii}$ triplet (Joly 1988). Clavel et al. (1987) and Alloin (1988) find the width of the $\text{C}\,\text{m}\lambda 1909$ lines to be narrower than $\text{C}\,\text{iv} \lambda 1458$. This is comparable with our Fig. 5 which is constructed using the fiducial parameters with a viewing angle of 45°. Osterbrock & Shuder (1982) find an average ratio of FWHM for $\text{He}\,\text{ii} \lambda 5876$ to $\text{H}\beta$ in a sample of 19 spectra to be 1.2, close to that in Fig. 5. Wilkes (1988) reports that the wings of $\text{Ly}\alpha$ are as broad as $\text{C}\,\text{iv} \lambda 1549$ in agreement with our results. In Fig. 5 $\text{Mg}\,\text{ii} \lambda 2798$ is narrower than $\text{H}\beta$, as discussed by Osterbrock & Mathews (1986), and as broad as $\text{C}\,\text{iv} \lambda 1549$, in rough agreement with some of the systems observed by Baldwin (private communication) but in possible conflict with the results of Joly (1988) for an
inhomogeneous sample of active nuclei and Clavel et al. (1987) for NGC 4151. This potential discrepancy cannot be removed by altering the disc inclination, but we note that when we consider a variable continuum in Section 5 the profile of C iv λ1549 is found to be broader than that of Mg II λ2798. Similarly, one other discrepancy with observations in Fig. 5, namely the equal blue shifts of the line centres, may be removed for a variable luminosity. The degree of profile differences at FWHM can be expressed through the parameter Σ₅₀ introduced by Whittle (1985), which is essentially the variance of the FWHM normalized to the mean. We find Σ₅₀ = 0.17 for the profiles of Fig. 5, somewhat smaller than the value of 0.3 observed from Baldwin's sample. The relative widths of some lines depend on the angle of inclination of the disc. This is confirmed in the behaviour of Σ₅₀ as function of i; for 5° < i < 85°, Σ₅₀ varies between 0.16 and 0.07 in the fiducial model.

To investigate the profiles in Fig. 5 more closely, we have analysed in more detail the fiducial case with i = 45°. In the region r ≤ 1.5 × 10¹⁸ cm, which we refer to as BLR1, the clouds have velocities of up to 10 000 km s⁻¹ along the line of sight and a mean gas density of ∼ 10¹¹ cm⁻³.
This region is the main source of C\textsc{iv} \( \lambda 1549 \), Mg\textsc{ii} \( \lambda 2798 \) and He\textsc{ii} \( \lambda 1640 \). In the next radial zone, \( 1.5 \times 10^{18} < r < 3 \times 10^{18} \) cm (BLR2), the gas density is in the range \( 10^{10} - 10^{9} \) cm\(^{-3} \). The trajectories of the high velocity clouds bend over to make significant angles with the line-of-sight while new material from the disc has not yet been accelerated to maximum speed. There is therefore a decrease in the mean cloud velocity in this zone, which is the main region for C\textsc{iii} \( \lambda 1909 \) (more than 70 per cent of C\textsc{iii} \( \lambda 1909 \) line intensity is produced in this region). At larger radii, \( r > 3 \times 10^{18} \) cm (BLR3), introduction of new low velocity clouds has ceased, so, the average line of sight velocity increases again to around 8000 km s\(^{-1} \). The trends in velocity as reflected in the profiles of C\textsc{iv} \( \lambda 1549 \) are shown in Fig. 6. Thus, even though individual clouds are accelerated outwards, the mean velocity of the cloud system does not increase, and may not even be monotonic.

To investigate the effect of shadowing of outer clouds by inner clouds we make the assumption that clouds on the innermost trajectory at any elevation shadow those behind them completely. The resulting profiles now contain strong dips at zero velocity. We conclude that a large amount of shadowing is incompatible with observation and is therefore unlikely to be a major influence on line profiles in this model.

Finally, we look at the symmetry of the line profiles. It is found that the shift to the blue in the H\textbeta{} profile due to absorption in the disc is accompanied by a small blueward asymmetry in the sense of a slightly extended blue wing. The enhancement of the blue side of the line is more pronounced if this blueshifted line from the clouds is combined with a symmetrical disc line (Mardaljevic et al. 1988). The blueshifted lines sometimes contain more energy in the red core (red relative to the peak, not with respect to the systemic velocity), but we cannot obtain an enhanced red wing, although with a noisy continuum level some of the profiles would appear

![Figure 6. C\textsc{iv} profiles at distances \( r < 1.5 \times 10^{18} \) cm (--); \( 1.5 \times 10^{18} \) cm \( r < 3 \times 10^{18} \) cm (---) and \( r > 3 \times 10^{18} \) cm (-----) from the ionization source.](https://academic.oup.com/mnras/article-abstract/237/4/979/1131921)
to exhibit somewhat extended red wings. Comparison with observation is again made difficult by line blending, but it appears that redward asymmetry (even in blueshifted lines) is at least equally prevalent in the data (Osterbrock & Shuder 1982). There is also the problem of lack of strong asymmetry in Lyα lines in high redshift quasars (Wilkes 1988).

It should be noted that there are a number of ways in which more detailed discussion will introduce either red or blue asymmetry. Self-absorption in clouds (i.e. front–back asymmetry due to radiative transfer effect is, particularly in resonance lines and also probably in Balmer lines) will give asymmetries. Patchy absorption in the disc could also be involved. Time dependence of the continuum emission and in particular the rapid rises and slow falls in luminosity to be inferred from the apparent excess of declining over increasing source brightnesses would produce a preponderance of red asymmetries. Finally, there is the problem of dust which, as in the narrow line region, can be distributed to produce any desired result. Line profile asymmetry can therefore only be discussed properly in the context of more detailed models of the angular-dependence of emission from the clouds and the modelling of individual sources. Nevertheless, we should note that we do obtain a possible blue shift of line peaks of the observed order of magnitude (up to ~2 × 10^8 cm s^-1) which can differ for different lines (see Fig. 7). This would in any case be less prevalent in low ionization lines for which the disc contribution is more important.

5 Variability

Over 75 per cent of the sample of Seyfert 1 galaxies of Peterson et al. (1984, 1985) show significant variation in the strength of the hydrogen lines over a period of 5 yr. The intensities of the broad permitted and semipermitted high ionization lines vary with the continuum. The widths of high ionization lines, C IV λ1549 for example, are also found to vary. The implication is that variations probably result from changing levels of photo-ionization. The response of a BLR cloud to changes in incident radiation flux reveals that different lines may behave very differently, even if they arise in the same physical region (Gaskell & Sparke 1986). We therefore wish to investigate the response of the duelling wind cloud system to changes in the continuum radiation from the central engine.

We suppose the central luminosity to increase by a factor of 10 in the fiducial model, the spectrum remaining fixed. The clouds are assumed to respond instantaneously to the continuum change. Since the sound crossing time is of the order of 10^6 s for the innermost clouds, we certainly cannot resolve changes on time-scales shorter than this. In the duelling wind model the cloud properties are also determined by the luminosity (through dependence on λ). However, these changes occur on a time-scale greater than the sound crossing time of the inner radius of the BLR which is at least 3 × 10^8 s. The assumption of constant λ is therefore justified for shorter times with the consequence that we do not approach an equilibrium model. One should therefore regard this discussion as an illustrative initial exploration of the problem.

Let L_c be the continuum luminosity received by a cloud at radius r corresponding to the line emission observed at t_{obs}, and let L_o be the observed continuum; then

\[ L_c(t_{obs}) = L_o(t_{obs} + \alpha / r / c) \]

where α is the angle between the cloud and the observer as seen from the source.

Fig. 7 shows a sequence of the profiles predicted for C IV λ1549, C III| λ1909 and Mg II λ2798 for a disc inclination of 45° as a function of time, t_{obs}, normalized to the same maximum. Note that because of the geometry of the system, the change in the lines follows the continuum after a time lag of \((1 - \sin i) r / c\), where r is the radius of BLR1. For i = 45° here,
this is $\sim 0.3r/c \sim 1.6 \times 10^6$ s for the fiducial parameters if $r = R_{\text{in}}$; the first of Fig. 7 shows the profiles just before this time. Thus, the size of the BLR is larger (by a factor 3 here) than the light crossing time deduced from time lags by assuming spherical symmetry! This partly resolves the well-known conflict between BLR radii deduced from variability and from ionization parameters (Ulrich et al. 1984). The other part of the resolution is the much higher density in our BLR1 than normally assumed. The time delay here of $\sim 20$ days for C iv $\lambda 1549$ is obtained for $r_{\text{BLR}} = R_{\text{in}}$, $m_\lambda = 0.1$ and $i = 45^\circ$. There is therefore no difficulty in principle of accommodating lags of more than a factor of 10 shorter. We regard this as the main success of the model in relation to variability. It is independent of the detailed choice of parameters and changes in the continuum. Nevertheless, several other points should be noted.

It is clear from Fig. 7 that the blue side of the line appears to respond to the change in luminosity before the red side. In the one well-known example of NGC 4151 (Penston et al. 1981; Ulrich et al. 1984) the observations do not appear to support this behaviour although consistency with radial motion is claimed by Gaskell & Sparke (1986). In any case, for
NGC 4151 if $\lambda = 1$, then $m_d \sim 0.01$ and the effect would be observable with a lag of only $0.3r_d/c \sim 10^5$ s. In addition, the contribution of the accretion disc provides a red wing (relative to the blueshifted cloud line) coming from $R < R_{ic}$, which does indeed respond to continuum changes before the clouds.

For the model we have calculated here, the intensity of C iv $\lambda 1549$ increases by a factor of about 4 with the enhanced continuum, whereas C iii] $\lambda 1909$ decreases by a factor of 4 and Mg ii $\lambda 2798$ declines by a factor of more than 35. This anticorrelation with the continuum results from the more complete ionization of the clouds as a consequence of the rather large increase in luminosity, and hence in ionization parameter, we have taken for illustration. The time lag between the Mg ii $\lambda 2798$ line and the continuum (although not very clearly defined) is about twice that for C iv $\lambda 1549$, while the C iii] $\lambda 1909$ line lags by about 10 times as much. This is, of course, consistent with our discussion of the regions dominating the production of these lines in Section 4.

6 Conclusions

At this early stage of model building a certain selectivity in the comparison of theory and observation is unavoidable. We are aware of the dangers of such selectivity in the qualitative comparison of numerical predictions and large sets of observational data. Nevertheless, in addition to the general agreement of line ratios and profiles, we find from our photo-ionization calculations the following particular points. (i) The range of gas density in the clouds yields sufficient C iii] $\lambda 1909$ while also providing the higher density material apparently necessary for a resolution of the Ly$\alpha$/H$\beta$ problem. (ii) The broad-line clouds are accelerated outwards but the average velocity decreases with radius initially because of the injection of new, lower velocity clouds. Thus we explain how high density inner clouds can produce broader lines in an accelerated outflow, while lines predominantly from large radii could be broader than those from intermediate zones. (iii) The non-spherical distribution of clouds and the range of gas densities allows compatibility between the BLR size deduced from variability and from ionization parameter. (iv) Blueshifts of line peaks can occur, apparently uncorrelated with line asymmetry.

Clearly, a significant contribution to the line emission may come from the disc (especially for low ionization lines). This will be discussed in a future paper.

Acknowledgments

We are grateful to Dr Gary Ferland for allowing us to use the photo-ionization code CLOUDY and to Dr Jack Baldwin for access to his unpublished data. Part of the computations in this project were done on the Cray-XMP at the Rutherford Appleton Laboratory. We thank Dr Roger Evans for his assistance. BM was supported by the SERC.

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B. Mobasher and D. J. Raine


