Mon. Not. R. astr. Soc. (1988) **232**, 539–550

The environment of active galactic nuclei – I. A two-component broad emission line model

Suzy Collin-Souffrin *Institut d'Astrophysique, 98 bis Boulevard Arago, Paris 75014*

J. E. Dyson *Department of Astronomy, The University, Manchester M13 9PL*

Jonathan C. McDowell★ *Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire SK11 9DL*

Judith J. Perry *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

Accepted 1987 November 23. Received 1987 November 20; in original form 1987 April 23

Summary. The flowing interstellar medium in the central parsec of an active nucleus plays a crucial role in determining its observed emission line features. Mass loss from the central stellar cluster acts as one source of material in this flow. Since the flow is likely to be hypersonic, shock waves will be created in it. Gas in thermal equilibrium with the central radiation field and at the stagnation pressure of the flow has an ionization parameter corresponding to that deduced from observations of the high-ionization broad emission lines (HIL). The thermal equilibrium is obtained as the shocked gas cools rapidly by Compton scattering of the central continuum. The entire flow back-scatters X-rays which can illuminate the outer regions of an accretion disc thus providing the deep X-ray heating needed to produce the low-ionization broad emission lines (LIL). The outer region where this disc becomes optically thin radiates most of these LIL and perhaps the observed near-infrared bump. This two-component model resolves the well-known cloud confinement problem by gravitational confinement for the LIL and by advocating a transient cloud population for the HIL. It also leads to a simple explanation for the systematic velocity shifts observed between high- and low-ionization lines.

1 Introduction

Superimposed on the visible and UV continuum of active galactic nuclei (AGN) are intense emission lines whose profiles are made up mainly of two components: a broad component corresponding to a typical Full Width at Half Maximum (FWHM) of $\sim 10^4\,\mathrm{km\,s^{-1}}$ and a narrow

★Present address: Harvard–Smithsonian Center for Astrophysics, 60 Garden St, Cambridge, Massachusetts 02138, USA.

component corresponding to a FWHM of less than $10^3\,\mathrm{km\,s^{-1}}$. We are concerned here only with the broad lines which, unlike the narrow lines, are due to permitted transitions only and are produced in a relatively dense medium ($n > 10^8\,\mathrm{cm^{-3}}$).

The work of Collin-Souffrin *et al.* (1982, 1986) and Wills, Netzer & Wills (1985) implies that the broad emission spectrum may be divided into two parts. The first consists of lines which we will call the HIL (High Ionization Lines) including Lyα, C III], C IV, He I, He II, and N V lines emitted by a highly ionized region which has a relatively low density (at most a few times $10^9\,\mathrm{cm^{-3}}$). The upper density limit is imposed by the requirement that the semi-forbidden C III] line must not be collisionally de-excited. The second consists of LIL (Low Ionization Lines) which include the bulk of the Balmer lines, Mg II, C II, and Fe II lines, emitted by a mildly ionized medium which has a much higher density ($n > 10^{11}\,\mathrm{cm^{-3}}$). However, it is clear that this model is highly schematic and that the true state of affairs may be much more complex.

We have argued [e.g. Perry & Dyson 1985 (PD)] that a hypersonic flow of interstellar matter (the ISM) must exist in the environs of the central engine of an active galactic nucleus in order to confine or create the broad emission line clouds, and proposed that the lines arise in cooling gas behind shocks in the flow. In this paper we retain this model for the formation of the high-ionization broad emission lines, but in the light of the work suggesting a different origin for the low-ionization lines (Collin-Souffrin, Dumont & Tully 1982; Collin-Souffrin 1987) we suggest that these other lines are formed in the outer part of the accretion disc. Our model invokes the scattered continuum radiation from shocks in the flow to illuminate the outer disc from above, solving the 'energy budget' problem (Netzer 1985; Collin-Souffrin 1986) and linking the production mechanism of the LIL both to that of the HIL and to the bolometric luminosity.

To estimate the physical quantities involved in the problem, we now parameterize the black hole mass and the accretion rate in terms of the Eddington luminosity and an overall mass conversion efficiency. The mass M of the central hole can be cast in terms of the ratio f_L of the bolometric luminosity to the Eddington luminosity which corresponds to M,

$$M = 8.0 \times 10^8 \left(\frac{L_{47}}{f_L}\right) M_\odot. \tag{1.1}$$

It is assumed that the observed non-thermal and thermal continua arise from the conversion of accreting matter to radiation with overall efficiency ε, i.e. $L_{\mathrm{Bol}} = \varepsilon \dot{M} c^2$. We wish to consider the AGN as a single system; it is an engine which is fuelled by a mass accretion rate at large radii, $\dot{M}$, and converts this mass accretion into both radiative energy L_{Bol}, the total observed radiation from the object, and kinetic energy of a wind containing some fraction of the accreted matter which 'misses' the hole. Some fraction of the accreting mass flux may be lost into the wind at relatively large radii, and some of the luminosity may also be produced far from the black hole. We emphasize that the definition of the quantity ε is sensitive to the size of the notional black box drawn around the black hole, as both the input mass flux and the output luminosity depend on the size of this box.

We set $\varepsilon = 0.1 f_\varepsilon$; the factor f_ε is conventionally assumed to be of order unity for the conversion of matter into energy near a black hole; since not all of the mass flux may reach small radii, the overall efficiency may be much smaller than this. The accretion rate, in $M_\odot\,\mathrm{yr^{-1}}$, is then

$$\dot{M} = \frac{17.5}{f_\varepsilon} L_{47} \quad M_\odot\,\mathrm{yr^{-1}}. \tag{1.2}$$

The Schwarzschild radius of the central hole is $R_S = 2GM/c^2$. In terms of the fraction of Eddington luminosity, f_L,

$$R_S = 7.6 \times 10^{-5} f_L^{-1} L_{47} \quad \mathrm{pc}. \tag{1.3}$$

In Section 2 we present a discussion of the current state of observational knowledge about the broad emission lines. In Section 3 we formulate a description of the ISM which satisfies various observational constraints. In Section 4 we study the effect of shocks created by obstacles in the flow. In Section 5 we explain the formation of the LIL in the accretion disc as a result of the illumination from the shocks. Finally, in Section 6 we summarize the implications of our model. The symbols we use are listed for completeness in the glossary in Appendix I.

2 The broad emission lines

The thermal and ionization state of optically thin gas in equilibrium with a radiation field is determined by the ionization parameter which was defined by Davidson (1977). Davidson found this parameter to be approximately constant in AGN, but this result applies only to the HIL. Collin-Souffrin (1985) has pointed out that in the LIL emitting region the ionization parameter can take a larger range of values and is smaller than in the HIL emitting region. The column density is limited by photoionization models to a few $10^{22}\,\mathrm{cm}^{-2}$ in the HIL region, but it must be orders of magnitude larger in the LIL region.

Krolik, McKee & Tarter (1981, hereafter KMT) redefined the ionization parameter as $\Xi = F_{\mathrm{ion}}/nckT$ where F_{ion} is the ionizing flux, n the particle number density, and T is the gas temperature. This is equal to the ratio of radiation pressure to electron thermal pressure, and is $2.3P_{\mathrm{rad}}/P_{\mathrm{gas}}$ for fully ionized gas of cosmic abundance. The limit of high Ξ corresponds to hot gas held at the Compton temperature. The limit of low Ξ corresponds to the case analogous to the familiar gaseous nebulae where the temperature is determined by the balance of photoionization heating and cooling by heavy element line emission. For our choice of parameters, and with the ratio of ionizing to bolometric luminosity equal to 0.19 (as for the KMT spectrum),

$$\Xi = 3.8 L_{47} \left(\frac{R}{1\ \mathrm{pc}}\right)^{-2} \left(\frac{nT}{10^{13}\ \mathrm{cm}^{-3}\ \mathrm{K}}\right)^{-1}. \tag{2.1}$$

The canonical value of Ξ deduced from photoionization models for the HIL emitting region is 0.5 (see for instance Kwan & Krolik 1981). Combining this with the derived HIL region density and temperature gives a distance of the HIL region from the central illuminating source of

$$R_{\mathrm{HIL}} = 2.8 \left(\frac{10^{13}\ \mathrm{cm}^{-3}\ \mathrm{K}}{nT}\right)^{1/2} L_{47}^{1/2}\ \ \mathrm{pc}. \tag{2.2}$$

The luminosity emitted in the broad lines represents about 20 per cent of the optical luminosity (or equivalently of the ionizing luminosity). The HIL contributes about one quarter of this luminosity and the LIL about three quarters. It is commonly assumed that the lines are drawing the bulk of this energy from the central continuum. Then the covering factor of the central source by the line emitting material is easily deduced for the HIL from the equivalent width of Lyα which is mainly formed by recombination (Kwan & Krolik 1981). It is found to be variable from high- to low-luminosity objects from $\sim$0.03 up to $\sim$0.3. This value agrees with the absence of large Lyman continuum absorption in high-redshift quasars.

The covering factor of the LIL emitting region raises a problem. It was shown by Collin-Souffrin (1986, 1987) that the observed soft-X-ray non-thermal spectrum up to a few keV is not sufficient to account for the LIL, and that hard X-rays must also be absorbed in the emitting region to get the right amount of energy. The LIL intensities require that, if they are drawing their energy from the continuum source, the emitting region must have a covering factor of order 0.1 and also a large column density ($>10^{25}\,\mathrm{cm}^{-2}$). This is necessary in order to absorb a fraction of the hard X-ray continuum which is about equal to the fraction that it gets from the ionizing continuum. The fact that X-ray observations do not show absorbing column densities larger than $10^{23}\,\mathrm{cm}^{-2}$ at least in low-luminosity AGN, led her to propose that the LIL could be emitted in the outer regions of an X-ray-illuminated accretion disc. The disc is then heated partially by the Compton process to a relatively low temperature (~6000 K).

The rather different physical parameters of the HIL emitting region have been shown to agree well with the transient clouds formed as a result of cooling gas behind shock fronts around obstacles in the hypersonic flow (PD).

The broad lines vary within time-scales of the order of a few weeks in low-luminosity AGN (Seyfert I). Variation time-scales of a few months have also been observed in some quasars. The dimensions implied by these values agree roughly with those deduced from the value of the ionization parameter of the HIL, assuming a density of a few $10^{9}\,\mathrm{cm}^{-3}$. We note that recent studies of line variability which imply short variability time-scales concentrate on the LIL (e.g. Zheng *et al.* 1987), where short time-scales are not unreasonable, and place no constraint on the size of the HIL. However, detailed studies of the line profiles can be interpreted as implying that, in Seyfert nuclei, the time-scales are shorter for the HIL than for the LIL (e.g. Gaskell & Sparke 1986). In the PD model the large number of HIL clouds are associated with a small number of obstacles generating the shocks. The observed HIL variability time-scale may then relate to the scale size of these obstacles rather than the overall size of the region.

The regions emitting the LIL and HIL display different kinematics, as can be deduced from studies of the profiles and linewidths. In quasars, Gaskell (1982) and Wilkes (1984) have shown that the C IV line is blueshifted with respect to the Mg II line and Ward (private communication) has shown that Lyα is blueshifted with respect to Hα. Therefore it seems that the HIL are systematically blueshifted with respect to the LIL by an amount which is characteristically 1000 to $2000\,\mathrm{km\,s}^{-1}$. This can be understood if the HIL are produced in clouds undergoing predominantly outward motions, if the clouds receding from us are hidden by an opaque structure such as a disc (dust is unlikely to exist in the hot ISM) and finally if the LIL are produced in a region with little or no radial motion, such as in the disc itself.

In Seyfert nuclei the profiles are generally more complex than in quasars. This can be readily understood within the context of the PD model if the HIL are formed behind shock waves, since the number of shocks which are large enough to produce line emission should be greater in quasars than in Seyferts (PD). Detailed profile studies of the C IV line show that the lines can be decomposed into two components, the broadest one being blueshifted with respect to the narrow lines. In contrast, the broadest component of the Hα line seems more systematically redshifted (Boisson, private communication). In some cases the Balmer lines display double-peaked profiles, possibly the signature of rotational motion (van Groningen 1983; Alloin, Boisson & Pelat 1987). Finally, the Hβ wings are systematically broader than Hα (Crenshaw 1986). Since high density favours Hβ emission (Drake & Ulrich 1981; Collin-Souffrin *et al.* 1986) this observation could be interpreted in terms of an emitting region of high velocity and high density [this has already been suggested by van Groningen (1985)]. The accretion disc is a particularly suitable region for this Hβ emission. However, we note that the mechanism for HIL production may in fact be different for Seyferts since at the low bolometric luminosity characteristic of Seyfert nuclei, any gas flow around the central region is likely to be thermally unstable (PD).

3 The interstellar medium

Most of the volume in the central regions must be filled with low-density gas. The interaction of the non-thermal continuum radiation with this gas will heat it to the Compton temperature T_{C}, which is between 10^{6} and 10^{8} K depending on the shape of the input spectrum (KMT; Fabian *et al.* 1986; Collin-Souffrin & Perry 1988, in preparation). We set $T_{\mathrm{C}}=10^{8}T_{8}$ K. For the spectrum used by KMT, $T_8=1.4$, but for the canonical spectrum of an AGN with a large blue bump, larger optical–UV to X-ray luminosity ratio, and an X-ray spectrum with flux varying at $\nu^{-0.7}$, the Compton temperature is smaller by a factor of about 10.

As has been widely discussed (e.g. Kippenhahn, Perry & Roser 1974; Kippenhahn, Mestel & Perry 1975) the interstellar medium in this region is likely to be in supersonic bulk motion. The large observed HIL linewidths give observational support for this view. High-velocity outflow is inferred in broad absorption line (BAL) quasars (Turnshek 1984) which may make up 10 per cent of the observed QSO population (Turnshek & Grillmair 1986). We postpone discussion of the detailed hydrodynamics to a future paper as those details are irrelevant for our present purpose. The only essential feature we require here is the presence of a supersonic flow. The sound speed is

$$v_s/c=4\times10^{-3}T_8^{1/2}. \tag{3.1}$$

This should be compared to the escape velocity from radius R,

$$\frac{v_{esc}}{c}=0.01L_{47}^{1/2}f_L^{-1/2}\left(\frac{R}{1\ \mathrm{pc}}\right)^{-1/2}. \tag{3.2}$$

Any wind escaping from within R must be hypersonic. The kinetic energy flux in the wind is a modest fraction of the radiative luminosity,

$$\varepsilon_K=\frac{1/2\dot{M}_W v_W^2}{L_{Bol}}=5.0\times10^{-4}f_\varepsilon^{-1}f_W\omega^2, \tag{3.3}$$

for a wind mass loss rate of $\dot{M}_W=f_W\dot{M}$ and wind speed $v_W=0.01\omega c$.

It is interesting to note that electron scattering radiatively driven winds have typical efficiencies of about 10^{-3} (Beltrametti & Perry 1980) which is in agreement with this value provided that the wind is super-Eddington with a mass flux of the same order as the accretion rate. To drive significantly larger mass fluxes would require mechanical energy input, perhaps from sonic or magnetosonic modes in the disc in a manner analogous to the driving of the solar wind.

A substantial part of the ISM will be supplied by mass injection from the central cluster. The hydrodynamics of simple mass-loaded flows has been studied by Beltrametti & Perry (1980), and Perry (1986). The density and velocity structure of a mass-loaded ISM is a complicated problem. We therefore cover the likely range of possibilities by considering two extreme density profiles. A $1/r^2$ density profile will arise if a spherical supersonic flow is dominated by a wind from the central portion of the disc. This would require negligible mass injection from the stellar cluster. Mass injection decelerates the supersonic flow and flattens the density profile. The extreme case of a flat density profile can arise when the mass injection dominates the flow (Perry 1986).

4 Reflection of energy by the interstellar medium

4.1 THE HIGH-IONIZATION LINES

PD studied the details of the shock-produced BLR model in which mass injection by 'astrophysical' obstacles into the flow leads to a flat density profile wind containing shocks. The post-shock gas radiates away part of the flow kinetic energy but the flow remains hypersonic. The gas initially cools by inverse Compton cooling off the intense non-thermal radiation field, subsequently by free–free radiation, and eventually by metal line cooling, as it flows around the obstacle. If it cools enough to reach equilibrium before it expands and rejoins the wind behind the obstacle, it will have the correct temperature and ionization parameter to produce at least the high-ionization broad emission lines. The column density of the clouds formed behind the shock is of the order of

$10^{22}\,cm^{-2}$ and corresponds therefore to that required for the HIL emitting region. The flow velocities will be comparable to the wind velocities and thus also of the right magnitude to provide the broad linewidths.

4.2 REFLECTION OF ENERGY FROM THE SHOCKS

The initial cooling of the shocked gas is due to Compton scattering of the X-ray continuum photons. Some fraction of these Compton-scattered photons will be back-scattered toward the disc. As much as a few per cent of the bolometric luminosity may be available for hard X-ray heating of the disc by this mechanism. Even those shocks which do not have the right size to cool enough to emit the HIL will contribute to the Compton scattering of the central continuum. Indeed, as pointed out by Jones & Raine (1980), the whole hot medium scatters the continuum back towards the disc. In our model a substantial fraction of the optical depth in the hot medium may be contributed by the dense, hot post-shock gas. Since the shocks are distributed throughout the volume out to at least the HIL radius $R_{HIL} \sim L_{47}^{1/2}$ pc, the scattered radiation field may be relatively uniform. Since the optical depth deduced by PD for the dynamical formation of the HIL is less than but of order unity, the fraction of the bolometric luminosity which is reflected at radii corresponding to the outer accretion disc will also be of this order.

Let R_{sh} be the characteristic distance at which the shocks occur. We expect R_{sh} to be smaller than the HIL distance. We suggest that R_{sh} will relate both to the density profile of the wind and to the cusp radius of the central cluster which provides the obstacles to the wind, both of which define size scales which are probably of this order. The covering factor of the hot shocked gas is much larger than the covering factor of the cool broad line emitting gas, and is of order unity. The luminosity of the scattered radiation which falls on the disc is equal to the product of the optical depth, the bolometric luminosity, and a geometric factor of the order of one half. The fraction f_X of this luminosity above one Rydberg can contribute to the line emission. The fraction of the radiation absorbed by the disc is close to unity for large disc column densities. The fraction of the bolometric luminosity which goes into the scattered ionizing radiation field which powers the line emission is then $\frac{1}{2}\tau f_X$. We set $\frac{1}{2}\tau f_X = 10^{-1} f_R$ where f_R is an efficiency factor which is characteristically unity since τ is of order unity and f_X is a few tenths. The non-ionizing part of the scattered radiation field is also absorbed by the disc. It heats the mid-plane of the disc to about 10^3 K and is reprocessed into the infrared.

The shocked gas reflects the incident radiation and emits radiation, through Compton cooling and bremsstrahlung. The energy emitted by the cooling shocks is somewhat less than the energy of the scattered radiation. The emission from the shocks hardens the spectrum of the diffuse radiation field somewhat.

If the density of the scattering gas is constant with radius, the scattered flux decreases as $1/r$, whilst if the scattering material is distributed as $1/r^2$, the flux decreases as $1/r^3$ (Jones & Raine 1980). We adopt a flux varying as $1/r^2$ to estimate characteristic values. Integrating this back-scattered flux $F_R(r)$ gives $10^{-1} f_R L_{Bol} = \int F_R(r) 2\pi r\, dr$. For the inverse square flux dependence this result depends on the limits of integration only through a logarithmic term which we set equal to unity. To this accuracy, the ionizing flux scattered on to the disc is

$$F_R(r) = 10^{-2} f_R \left(\frac{L_{Bol}}{\pi R^2}\right) \tag{4.1a}$$

$$= 5.8\times 10^{15} f_R f_L^2 L_{47}^{-1} \left(\frac{R}{R_S}\right)^{-2} \quad \mathrm{erg\ cm^{-2}\ s^{-1}} \tag{4.1b}$$

where the second equation uses the parameterizations of Section 1.

Comparing equations (4.1) with the rate of dissipation of gravitational energy in the accretion disc, which is (e.g. Shakura & Sunyaev 1973)

$$\frac{3GM\dot{M}}{8\pi R^3}=\sigma T_{\rm eff}^4=1.1\times10^{18} f_L^2 f_\varepsilon^{-1}\left(\frac{R}{R_{\rm S}}\right)^{-3} \quad \text{erg cm}^{-2}\text{ s}^{-1}, \tag{4.2}$$

determines a radius $R_{\rm heat}$ in the disc at which this X-ray heating becomes dominant. This is given by

$$\frac{R_{\rm heat}}{R_{\rm S}}=\frac{190}{f_\varepsilon f_{\rm R}}. \tag{4.3}$$

The disc is also illuminated directly by the central source (effectively, the wind photosphere if it exists). This illumination is very oblique if the disc flares only very gently; the process has been studied in detail by Cunningham (1976) and Begelman & McKee (1983). At a radius R the disc intercepts a fraction H/R of the central luminosity, where H is the thickness of the disc. In the outer (gas pressure dominated, Kramers opacity) region of the standard disc the ratio is

$$H/R=2.6\times10^{-3} L_{47}^{-9/40}(R/1\text{ pc})^{1/3} f_\varepsilon^{-1/10} f_L^{3/8}. \tag{4.4}$$

This fraction is clearly too small to power the line emission. For the isothermal disc (see next sections) the ratio is also too small except perhaps in Seyferts if the discs extend to radii of about 1 pc.

5 Line emission from the illuminated disc

5.1 CONDITIONS FOR LINE EMISSION

If the emitting gas resides in discrete clouds, they are inferred to be extremely small, with a sound crossing time two orders of magnitude smaller than the dynamical crossing time for the BLR region (PD; Mathews & Capriotti 1985). There must be a mechanism for replenishing the clouds if they expand, or a means of inhibiting their expansion. This is the well-known 'confinement problem' for the BLR clouds. Confinement requires some external medium to exist unless the clouds are associated with much larger amounts of non-radiating matter which gravitationally binds them. We are here suggesting that the HIL clouds are transient and replenished by an external medium, while the LIL emitting gas is gravitationally bound.

The total luminosity of the HIL is such that the covering factor $f_{\rm c}$ varies from of order 0.1 for high-luminosity QSOs to close to 1 for low-luminosity AGN. They must be formed at a distance of order $L_{47}^{1/2}$ pc from the central source (equation 2.2). The total mass in the radiating warm clouds is less than or of order $10^2 L_{47} M_\odot$ (PD). In contrast, the 100-fold higher density of the LIL region implies that the LIL originate about 10 times closer to the nucleus if it is excited directly by the central continuum. However, it may also originate in the disc region and be photoionized by back-scattered radiation, in which case the available luminosity is less and the diffuse flux leads to different values for Ξ. The large column density inferred for the LIL medium suggests the accretion disc as a natural site for the creation of these lines (Collin-Souffrin 1987). The relative line ratios of the LIL and HIL indicate that deep X-ray heating must be present in the LIL which implies that hard X-rays are illuminating the disc. We have proposed that these X-rays are those back-scattered from the gas behind shocks which are induced in the flow by mass loss from the central star cluster, and are thus essentially the same photons responsible for the initial cooling of the HIL gas (PD). Fig. 1 shows schematically the proposed two-component model of the emitting line regions.

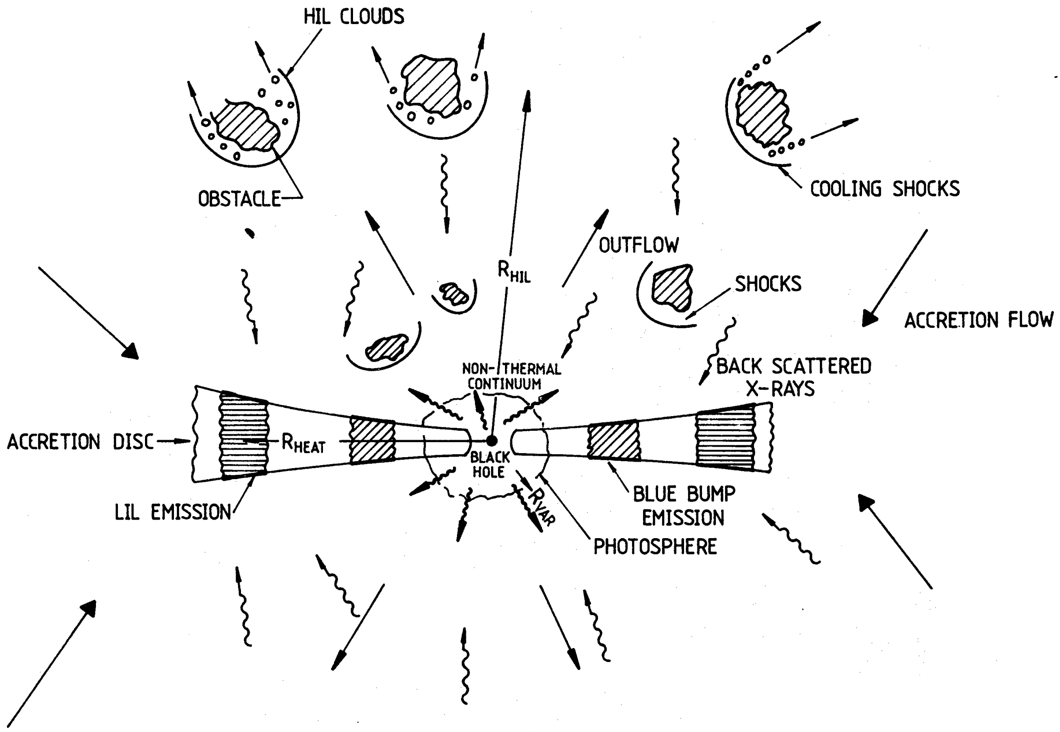

Figure 1. Sketch (not to scale) of the combined-flow/accretion-disc model for broad emission line formation in AGN.

Begelman & McKee (1983) and Jones & Raine (1980) discussed the illuminated atmosphere of the disc, and derived a condition for line emission, namely that the flux at the line frequency has to be less than the local continuum flux. However, we must also consider two other conditions in the outer part of the disc where the density and thickness are small. First, the column density must be larger than $10^{24}\,\mathrm{cm}^{-2}$ in order for the disc to be able to absorb most of the scattered X-ray flux (at column densities of $10^{25}\,\mathrm{cm}^{-2}$ all the hard X-rays are absorbed by Compton diffusion). Secondly, the ionization parameter must be less than unity in order to avoid thermal runaway of the disc to the Compton temperature. These two conditions define a maximum radius for the disc, in contrast to the flux condition which defines a minimum radius.

For the condition on the flux we follow the arguments of Begelman & McKee (1983), who consider a slab illuminated by an external ionizing flux F_{R} and compare it to the typical flux in a line emitted in the slab, F_{line}. They assume a line conversion efficiency $F_{\mathrm{line}}/F_{\mathrm{R}}$ which is constant up to a critical value of F_{line} above which the line saturates and F_{line} remains constant. The critical flux corresponds to the blackbody limit in the line and is equal to about $10^8\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ for Hα for the intrinsic linewidths expected in these circumstances. This representation for the line conversion efficiency is realistic for large column densities (above $10^{23}\,\mathrm{cm}^{-2}$) over a wide range of ionization parameter, as shown by Collin-Souffrin (1985). Using (4.1b) and adopting Hα as our reference line, and an Hα conversion efficiency of 0.1, the minimum radius for line emission is then

$$R_{\mathrm{min}}=0.18 f_R^{1/2} L_{47}^{1/2} \quad \mathrm{pc}. \tag{5.1}$$

Hβ is more difficult to thermalize than Hα and so the corresponding radius for Hβ will be smaller. The total Hα luminosity coming from both sides of the disc is, from (4.1a),

$$L(\mathrm{H}\alpha)=0.4\times10^{-2} f_{\mathrm{R}} L_{\mathrm{Bol}} \log\,(R_{\mathrm{max}}/R_{\mathrm{min}}) \tag{5.2}$$

where the logarithmic term is of order unity as shown at the end of this section. This is of the order of the observed line luminosity.

The radius $R_{\rm min}$ is within the optically thin regime of the disc discussed by Collin-Souffrin (1987). The temperature in the central plane of the disc is found by Collin-Souffrin (1987) to be maintained near to 2000 K which corresponds to the minimum in the opacity curve. Suppose the temperature in this nearly isothermal outer disc is $T_{\rm thin}=2000 f_{\rm T}$ K. Recent work by Collin-Souffrin, Dubouloz & Moutarde (in preparation) now indicates that $f_{\rm T}$ is probably less than unity. If we take $T_{\rm thin}$ to be the effective temperature of the disc, then the radius $R_{\rm thin}$ at which this temperature is reached is, using equation (4.2),

$$\left(\frac{R_{\rm thin}}{R_{\rm S}}\right)=1.1\times10^{3}\left(\frac{f_L^2}{f_\varepsilon}\right)^{1/3} f_{\rm T}^{-4/3}L_{47}^{-1/3}, \tag{5.3a}$$

or, using (1.3),

$$R_{\rm thin}=0.08(f_L f_\varepsilon)^{-1/3}f_{\rm T}^{-4/3}L_{47}^{2/3} \quad {\rm pc}. \tag{5.3b}$$

We note that

$$\frac{R_{\rm heat}}{R_{\rm thin}}=0.15\left(\frac{f_\varepsilon f_{\rm T}^2}{f_L}\right)^{2/3} f_R^{-1}L_{47}^{1/3}. \tag{5.4}$$

The structure of the optically thin region of the disc is easily obtained from the usual thin-disc equations with the radiative transport condition replaced by the condition of isothermality. Such an isothermal accretion disc has the interesting property that the self-gravity parameter is independent of radius; the disc is either self-gravitating throughout the isothermal region or nowhere in the region. The condition for self-gravity to dominate can be written as

$$L_{47}>0.003 f_{\rm T}^{3/2} f_\varepsilon \tag{5.5}$$

implying that the isothermal regions of discs around quasars are self-gravitating but that those around Seyferts probably are not. The structure in the non-self-gravitating case (Seyferts) is, using standard α-disc theory (Shakura & Sunyaev 1973; Sakimoto & Coroniti 1981; Shore & White 1982),

$$n=2.1\times10^{24} f_{\rm T}^{-3/2}L_{47}^{-1}f_L^2 f_\varepsilon^{-1}(R/R_{\rm S})^{-3} \quad {\rm cm}^{-3} \tag{5.6a}$$

for the density and

$$h=8\times10^{9} f_{\rm T}^{1/2} f_L^{-1} L_{47}(R/R_{\rm S})^{3/2} \quad {\rm cm} \tag{5.6b}$$

for the height. For the self-gravitating case (quasars) the density is

$$n=7.5\times10^{26} f_{\rm T}^{-3} f_L^2 f_\varepsilon^{-2}(R/R_{\rm S})^{-3} \quad {\rm cm}^{-3} \tag{5.7a}$$

and the height is

$$h=2.2\times10^{7} f_{\rm T}^{2} f_L^{-1} f_\varepsilon(R/R_{\rm S})^{3/2} \quad {\rm cm}, \tag{5.7b}$$

although the self-gravity may cause instability which will modify this result. Both cases lead to the same column density through the disc,

$$N=2nh=1.7\times10^{34} f_{\rm T}^{-1} f_L f_\varepsilon^{-1}(R/R_{\rm S})^{-3/2} \quad {\rm cm}^{-2}. \tag{5.8}$$

This density is large enough to absorb the X-rays out to very large radii. However, the disc may be cut off at the point where the external irradiation causes thermal runaway to the Compton temperature. This arises when the local ionization parameter exceeds a critical value which is about unity. The radius at which this occurs is

$$R(\Xi=1)=0.2f_{\mathrm{T}}^{-1/2}f_{\mathrm{R}}^{-1}f_{L}^{-1}f_{\varepsilon}^{-1}L_{44}\quad \mathrm{pc} \tag{5.9}$$

for Seyferts. For quasars the ionization parameter in the disc is always much less than unity in the isothermal region. The outer limit is set by the outer radius of the region producing the shocks. The fast fall-off of the scattered radiation field means that $R_{\max}\sim R_{\mathrm{sh}}\sim R_{\mathrm{HIL}}$ and $\log(R_{\max}/R_{\min})\sim 1$.

5.2 DYNAMICS OF THE LIL EMITTING REGION

The Keplerian velocity at $R_{\min}$ is just

$$\frac{v}{c}=\sqrt{\frac{R_{\mathrm{S}}}{2R_{\min}}}=0.014f_{\mathrm{R}}^{-1/4}f_{L}^{-1/2}L_{47}^{1/4} \tag{5.10}$$

which agrees roughly with the observed linewidth–luminosity correlation of Joly *et al.* (1985) and Wandel & Yahil (1985). These authors deduce an incorrect value of f_L since they use values of the density and column density appropriate for the HIL although the correlation has only been shown to exist for low-ionization lines such as Hβ. Inserting the appropriate values from Section 2 into the equations of the above authors implies that high-luminosity AGN typically radiate at the Eddington luminosity. The corresponding velocity at $R_{\max}$ is a factor 2.4 smaller. As noted above, the value of $R_{\min}$ for the Hβ will be smaller and so the wings of this line will be wider in agreement with observation.

6 Discussion

It is generally accepted that the production of the enormous luminosity per unit volume of active galactic nuclei requires the presence of the strong gravitational field of a supermassive compact object. We have not addressed the nature of the very central engine which generates the broad non-thermal continuum making up the bulk of this luminosity. This continuum is presumably due ultimately to energetic processes occurring near the black-hole horizon (Blandford 1985) and secondarily to the processing of this energy as it interacts with the matter and fields within the central photosphere (Becker & Begelman 1986; Cowsik & Perry 1987). The boundary conditions at this photosphere are that an average mass supply of $\dot{M}_{\mathrm{c}}=L/\varepsilon_{\mathrm{c}}c^2$ must be supplied, where ε_{c} is a central mass conversion efficiency and L is the central luminosity. Because of the intense radiation field and the high bulk velocities involved, it is likely that not all the matter will actually be swallowed by the hole, and thus that a mass flux of the same order as $\dot{M}_{\mathrm{c}}$ will be leaving the region and thereby contributing to the general flow.

In this paper we have discussed the interaction of the radiation field, the wind, the star cluster, and the accretion disc, showing that the high-ionization broad lines can be produced in the vicinity of shocks in the wind, whilst the low-ionization lines may be produced in the outer part of the accretion disc as a result of energy reflected from the flow above the disc. The confinement and acceleration problems for the emission lines are solved in two separate ways for the HIL and the LIL. The energy budget problem for the LIL is resolved and their velocity–linewidth correlation is naturally interpreted in the context of this model. The present model has an attractive degree of self-consistency.

To develop the ideas presented here, we must specify a model for the central star cluster. A knowledge of the density profile of the star cluster and the mass function and evolution of the stars are required to model in detail the mass fluxes in the interstellar medium and the distribution of obstacles in the flow. Future papers in this series will address these issues.

Acknowledgments

We thank the Institute of Astronomy, Cambridge, and the Institut d'Astrophysique, Paris, for their hospitality during the writing of parts of this paper. We would like to acknowledge useful conversations with C. Boisson, J.-P. Luminet, J.-P. Lasota, A. Prestwich, and M. Rees. JCM is grateful for a SERC postdoctoral fellowship.

References

Alloin, D., Boisson, C. & Pelat, D., 1987. Preprint.
Becker, P. A. & Begelman, M. C., 1986. *Astrophys. J.*, **310**, 534.
Begelman, M. C. & McKee, C. F., 1983. *Astrophys. J.*, **271**, 89.
Beltrametti, M. & Perry, J. J., 1980. *Astr. Astrophys.*, **82**, 99.
Blandford, R. D., 1985. In: *Active Galactic Nuclei*, ed. Dyson, J. E., Manchester University Press.
Collin-Souffrin, S., 1985. *Structure and Evolution of Active Galactic Nuclei*, eds Giuricin, G., Mardirossian, F., Mezzetti, M. & Ranella, A. M., Reidel, Dordrecht, Holland.
Collin-Souffrin, S., 1986. *Astr. Astrophys.*, **116**, 115.
Collin-Souffrin, S., 1987. *Astr. Astrophys.*, **179**, 60.
Collin-Souffrin, S., Dumont, S., Joly, M. & Pequignot, D., 1986. *Astr. Astrophys.*, **166**, 27.
Collin-Souffrin, S., Dumont, S. & Tully, J., 1982. *Astr. Astrophys.*, **106**, 362.
Cowsik, R. R. & Perry, J. J., 1987. Preprint.
Crenshaw, D. M., 1986. *Astrophys. J. Suppl.*, **62**, 821.
Cunningham, C., 1974. *Astrophys. J.*, **208**, 534.
Davidson, K., 1977. *Astrophys. J.*, **218**, 20.
Drake, S. A. & Ulrich, R. K., 1981. *Astrophys. J.*, **248**, 380.
Fabian, A. C., Guilbert, P. W., Arnaud, K. A., Shafer, R. A., Tennant, A. F. & Ward, M. J., 1986. *Mon. Not. R. astr. Soc.*, **218**, 457.
Gaskell, C. M., 1982. *Astrophys. J.*, **263**, 79.
Gaskell, C. M. & Sparke, L. S., 1986. *Astrophys. J.*, **305**, 175.
Jones, B. C. & Raine, D. J., 1980. *Astr. Astrophys.*, **81**, 128.
Joly, M., Collin-Souffrin, S., Masnou, J.-L. & Nottale, L., 1985. *Astr. Astrophys.*, **152**, 282.
Kippenhahn, R., Mestel, L. & Perry, J. J., 1975. *Astr. Astrophys.*, **44**, 23.
Kippenhahn, R., Perry, J. J. & Roser, H.-J., 1974. *Astr. Astrophys.*, **34**, 211.
Krolik, J. H., McKee, C. F. & Tarter, C. B., 1981. *Astrophys. J.*, **249**, 422.
Kwan, J. & Krolik, J. H., 1981. *Astrophys. J.*, **250**, 478.
Mathews, W. G. & Capriotti, E. R., 1985. In: *Astrophysics of Active Galaxies and Quasi-stellar Objects*, ed. Miller, J., Oxford University Press.
Netzer, H., 1985. *Astrophys. J.*, **289**, 451.
Perry, J. J. & Dyson, J. E., 1985. *Meudon Workshop on Model Nebulae*, ed. Pequignot, D.
Perry, J. J., 1986. In: *Quasars, IAU Symp. No. 119*, eds Swarup, G. & Kapahi, V. K., Reidel, Dordrecht, Holland.
Perry, J. J. & Dyson, J. E., 1985. *Mon. Not. R. astr. Soc.*, **213**, 665 (PD).
Sakimoto, P. J. & Coroniti, F. V., 1981. *Astrophys. J.*, **247**, 19.
Shakura, N. I. & Sunyaev, R. A., 1973. *Astr. Astrophys.*, **24**, 331.
Shore, S. N. & White, R. L., 1982. *Astrophys. J.*, **256**, 390.
Turnshek, D. A., 1984. *Astrophys. J.*, **280**, 51.
Turnshek, D. A. & Grillmair, C. J., 1986. *Astrophys. J.*, **310**, L1.
van Groningen, E., 1983. *Astr. Astrophys.*, **126**, 363.
van Groningen, E., 1985. *PhD thesis*, University of Leiden.
Wandel, A. & Yahil, A., 1985. *Astrophys. J.*, **295**, L1.
Wills, B. J., Netzer, H. & Wills, D., 1985. *Astrophys. J.*, **288**, 94.
Wilkes, B. J., 1984. *Mon. Not. R. astr. Soc.*, **207**, 73.
Zheng, W., Burbidge, E. M., Smith, H. E., Cohen, R. D. & Bradley, S. E., 1987. *Astrophys. J.*, **322**, 164.

Appendix: Glossary of symbols

f_c Covering factor of HIL clouds
f_L Bolometric luminosity divided by Eddington luminosity

f_R Reflection efficiency factor
F_R Diffuse reflected continuum flux
f_T $T_{thin}/2000$ K
f_W Fraction of accreting mass flux lost in wind
f_X Fraction of luminosity above 1 Rydberg
f_ε Radiative efficiency normalized to 0.1
h Static atmosphere scale height
L_{47} Bolometric luminosity in units of 10^{47} erg s^{-1}
M Mass of central black hole
$\dot{M}$ Mass flux in accretion disc
$\dot{M}_W$ Mass flux in wind
n Electron number density
N Column density through the disc
R Distance from central black hole
R_{heat} Radius in disc at which external heating dominates
R_{HIL} Radius of high-ionization line emitting region
R_{max} Maximum radius for line emission from disc
R_{min} Minimum radius for line emission from disc
R_{pc} Radius of HIL region in parsecs
R_S Schwarzschild radius of hole
R_{sh} Typical radius of the reflecting shock region
R_{thin} Radius at which disc becomes optically thin
R_{var} Continuum variability radius
T Gas temperature
T_C Compton temperature
T_{thin} Unperturbed temperature of the optically thin part of the disc
T_8 Gas temperature in units of 10^8 K
v_{esc} Escape velocity
v_s Sound speed
v_W Wind speed
ε Radiative efficiency (bolometric luminosity over accreting mass flux)
ε_K Mechanical efficiency (KE flux over bolometric luminosity)
Ξ Ionization parameter
ω Wind speed in units of $0.01c$