GAS DYNAMICS AND FORMATION OF THE BROAD LINE REGION OF QSOs

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ABSTRACT Observational and theoretical constraints on self-consistent gas dynamical models of the line emitting regions of QSOs and AGNs are reviewed. General equations governing the global flows are analysed and models for the formation and acceleration of the line emitting "clouds" are discussed.

INTRODUCTION Currently, both theoretical and observational studies place QSOs at the centres of young galaxies. Yet a striking feature of QSO spectra is the appearance of broad emission lines from heavy elements whose abundances do not appear to differ significantly from solar. The emitting gas must have been first processed in stars and later released into the local interstellar medium (ISM). The observed nonthermal continuum is equivalent to several solar masses of rest mass energy per year. If, as it is usually assumed, this radiation comes from the conversion of the gravitational energy of gas accreted by a massive black hole then mass fluxes through the emission line region must be at least, roughly, the rest-mass equivalent of the radiation. Under the quite reasonable assumption that the accretion is not spherically symmetric (there is reason to assume that most QSOs, like Seyferts, are in spiral galaxies (Malkin et.al., 1984; Hutchings et.al., 1984; MacKenty & Stockton, 1984)) the continuum radiation, which is intense enough to be important dynamically, can drive a powerful wind over a large solid angle. Outflow is directly observed in a significant fraction of QSOs, those which have broad absorption lines (BAL) in their spectra (Turnsek, 1984). Whatever the global flow pattern in any particular object, whether accretion, winds or some complex combination of the two, it must be optically thin to electron scattering above the photosphere of the non-thermal emission region. This requirement severely limits the allowed gas density in the flow; the interaction of the non-thermal radiation with this low density ambient gas determines the electron temperature, which is estimated to be $\sim 10^8$K. Yet immersed in this hot gas are relatively cool, very dense clouds or condensations which emit the observed broad lines. The widths of the lines imply Mach numbers of the line emitting gas with respect to the hot ISM, $M > 4$.

The presence of a QSO in the nucleus of a galaxy must have profound

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consequences for the structure and evolution of the host galaxy. Both their intense radiation fields and their high energy gas flows will significantly alter the ISM (Begelman, 1985; Dyson & Perry, 1985). The broad emission line region (BLR) can be viewed as a tracer of such activity, and cannot be treated out of the context of the QSO-galaxy interaction. For example, the apparently normal abundances restrict the source of the line emitting gas. Accretion of primordial intergalactic gas is ruled out if it is assumed that density perturbations in such flows give rise to the line emission.

Theoretical explanations of QSO spectra require an understanding of the structure and evolution of the parent galaxy. Sadly, we have no direct measurements of the central stellar density, its initial mass function (IMF), or the mass of the purported central black hole; nor is there any reason to assume, a priori, that the IMF is the same as that in normal galaxies. Yet, as we shall see, the stellar population may well be the most important contributor to the phenomenon. The challenge facing theorists is that of constructing a self-consistent dynamical model which can account, simultaneously, for the central fuel supply and for the appearance of high speed cool clouds containing heavy elements abundant enough to produce the observed broad emission lines. Hopefully, such models will contribute to our understanding of the host galaxies.

RADIATION FIELD Because of the paucity of x-ray and γ-ray observations estimates of the bolometric luminosities of QSOs and AGNs are uncertain. On the basis of available spectra it is reasonable to use a 'canonical' value of $L_{bol} = 10^{47} L_{47}$ erg/s. (then $0.1 < L_{47} < 100$ for QSOs and $10^{-5} < L_{47} < 10^{-2}$ for AGNs.) The equivalent mass consumption rate, at a conversion efficiency of ε, is $\dot{M}_a = 1.75(L_{47}/\varepsilon)\ M_\odot$ per year.

Inverse Compton cooling and electron-scattering radiation driving depend on only the bolometric luminosity. Uncertainties in the dynamics arise because all other radiation - gas interactions depend on both the spatial and the spectral distribution of the radiation neither of which is fully known. It is conventional to use extrapolations to fill in the unobserved parts of the spectrum, subject to constraints from observations of e.g. the x-ray and γ-ray background. The canonical spectra of Krolik, McKee and Tarter (1981, hereafter KMT) are used here.

The physical state of optically thin gas in equilibrium with these radiation fields is most conveniently discussed through its ionization parameter (KMT), defined as $\Xi = F_{ion}/cnkT = 2.3P_{rad}/P_{gas}$. F_{ion} is the ionizing flux, n the number density of the gas, T the gas temperature and c and k the speed of light and Boltzman's constant. P_{rad} is the radiation pressure and P_{gas} the thermal gas pressure.

At high Ξ (> 10) the gas temperature is determined by the balance between x-ray Compton heating and inverse Compton cooling and is roughly 10^8 K. At low Ξ (< 0.3), the gas temperature is determined by the balance between photoionization heating and line cooling and is about 10^4 K. KMT demonstrated that a two-phase pressure equilibrium can exist only in the relatively narrow range $0.3 < \Xi < 10$.

If a QSO 'turns on' in a 'normal' galaxy, the ISM undergoes strong heating towards the Compton temperature (Begelman, 1985). There is a concommittant increase in pressure which will have strong gas dynamical effects. Unless input of cool material from stars can balance this the radiation field can e.g. excavate out the cool ISM to ~ 10 kpc.

In addition to its role in determining the thermal state of the ISM, the radiation field plays an important gas dynamical role through the force it exerts on the gas (Mushotzky, et. al. 1971, Kippenhahn et. al., 1974, 1975; Mathews, 1974,1982; Mestel et.al., 1976). We return to this effect later.

OBSERVED PROPERTIES OF THE LINE EMITTING AND INTERCLOUD GAS The observed excitation of the line emitting gas is compatible with $T \sim 10^4$ K for the high ionisation lines and with somewhat cooler gas for the low ionisation lines. Although detailed interpretation of the line spectra is difficult, there appears to be agreement that the gas is in clouds or filaments of mean density $n \sim 10^9$ (but, in some cases, of 10^{11} cm^{-3}, Collin, 1985). Photoionisation models based on the 'canonical' spectrum provide the best agreement with observations and restrict Ξ to the range $0.3 < \Xi < 2$ (KMT). However, before dynamical models are worked out in detail, the extent of the admixture of shock heating and collisional ionisation will remain uncertain. Based on existing models, the characteristic distance of the emitting gas is determined from the ionisation parameter of the gas. This is determined (in parsecs) to be $r_{pc}{}^2/L_{47} \sim 1$. The clouds or filaments occupy at most 10% of the volume available, and are often characterised by volume filling factors as low as 0.1%. The total amount of line emitting gas present is not well determined, and is very model dependent. Estimates of the mass (in solar masses) generally yield a rough limit of $M_c < 200\ L_{47}M_\odot$.

The extremely small size inferred for the clouds implies that their sound crossing or expansion time scale (~ 1 yr) is very much shorter than the dynamic crossing time of the BLR itself (~ 150 yr). If clouds are created continuously at a rate equal to that of their destruction no difficulty exists. If, however, it is assumed that they are injected into the region and survive to cross it, an external confinement must operate throughout their journey. The thermal pressure in the line emitting gas is inferred directly from observation; there is no serious question as to its lower limit. No direct observations of the intercloud medium itself exist. It is, however, constrained to be optically thin above the effective photosphere of the central source. Unless current extrapolations of the QSO continuum are seriously in error, its temperature must be $\sim 10^8$ K. These two conditions, when combined, place severe upper limits on the intercloud thermal pressure. These limits immediately rule out models of pressure confined clouds in equilibrium with intercloud gas whose density varies as r^{-2}(as in e.g. a wind) since these flows are either optically thick or their thermal pressure at the BLR is insufficient to confine the observed filaments.

CLOUD KINEMATICS Line widths are well defined. These exceed 3000 km/sec, are characteristically about 5000 km/sec, and in extreme cases are known to extend to over 10,000 km/sec. It has not been possible to demonstrate that all the observations are compatible with only a single general flow pattern. Significantly, this suggests that, in fact, there is no universal flow pattern. The only spectra whose interpetation demands a particular flow pattern are those in which BALs are present. The BAL gas appears to have a higher ionisation, lower density, higher velocity and to be further away from the nucleus than is the BLR gas. Interpretation of the BAL spectra demands outflow, although no fully successful model exists to date. Hartig and Baldwin (1985) find possible kinematic differences between the BLR in QSOs with and without a BALs.

Many QSOs, and most AGNs, have a narrow emission line spectrum superimposed upon the ubiquitous and defining broad emission line spectra. These lines arise in gas whose density is orders of magnitude less than that of the BLR. Typically situated well outside the BLR it is characterised by velocity widths compatible with Keplerian motion. Narrow emission lines appear to be absent in spectra which show broad absorption lines. This lends support to the supposition that gas flows in QSOs vary markedly between objects. Thus whatever mechanism is responsible for the BLR must be operative in a wide variety of flows.

We use units of 0.01c (=3000 km/sec) throughout, and designate speeds in these units by ω. The "clouds" then typically have $\omega = 5/3$; ω ranges from >1 to ~ 4. Gas at 10^8 K has a sound speed $\omega_c \sim 0.4\sqrt{T_8}$, so the Mach number of the line emitting gas with respect to the hot gas is $M = 2.5\,\omega\,T_8^{-1/2}$. M is thus > 4. Whether it is assumed that the line emitting gas is carried along in a global flow, or is moving through an extended atmosphere, it is clear that supersonic phenomena are involved.

If a central black hole (of $10^8 M_8\ M_\odot$) dominates the gravitational mass in the core the Keplerian velocity at r_{pc} is $\omega_k \sim 0.22\sqrt{(M_8/r_{pc})}$. To account for the observed line widths in terms of Keplerian velocities requires $M_8 > 20$.

INTERCLOUD MEDIUM It is not possible to discuss cloud dynamics without invoking an intercloud medium, either to provide thermal or ram pressure confinement in the case of long lived clouds, or to provide a source for the clouds in transient cloud models.

As a measure of mass-flux rates in the core of the QSO-galaxy we use units of the mass-flux equivalent of the bolometric luminosity, $\dot{M}_a$, defined earlier. The total mass of gas in the ISM interior to the observed BLR at r_{pc} is $M_T \sim 0.1\,\Gamma\, n r_{pc}^3 M_\odot$, where n is the number density of the ISM at the BLR. Γ is a geometrical factor which depends on the radial dependance of n ($\sim r^{-\alpha}$). For flat density profiles (α=0) $\Gamma = 1$; for $\alpha = 2$ profiles $\Gamma = 3$. Flat density profiles arise naturally in mass loaded flows, (Perry & Dyson, 1985b), see below. The gas must leave the region in, roughly, the mean dynamical crossing time, $t_d \sim 475\ r_{pc}/\omega$ yr. (A more complete discussion of mass flux rates in a variety of flows is given in Perry & Dyson, 1985a, hereafter PD. For example, in a thermal wind $\omega \sim 1.2$, whereas in a flow whose velocity is the same as that of the clouds $\omega \sim 1.7$.) Thus the gas must be replaced, or injected, at a rate $\dot{M} \sim 2\ 10^{-4}\Gamma\ n\,\omega\, r_{pc}^2\ M_\odot$/yr. We follow current theory and adopt $\varepsilon > 0.1$. This gives $\dot{M}/\dot{M}_a \sim 1.2\ 10^{-5}\Gamma\ n\omega(r_{pc}^2/L_{47})$, and $n < (8/\Gamma)10^4(L_{47}/r_{pc}^2\,\omega)(\dot{M}/\dot{M}_a)$.

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The optical depth can now be determined, if it is assumed that the density profile steepens outside the BLR (i.e. $\alpha \sim 2$). In that case, $\tau \sim 4\ 10^{-6}\ \Gamma' n r_{pc}$, where Γ' is a geometric factor dependant on α, which for $\alpha = 0$ is $\Gamma' = 1$ and for $\alpha = 2$ is $\Gamma' \sim 50$. Replacing n through $\dot{M}/\dot{M}_a$ and setting $L_{47}/r_{pc}^2 \sim 1$ then yields, for $\alpha = 0$, $\tau = (0.32/\omega)\dot{M}/\dot{M}_a$, whereas for $\alpha = 2$, $\tau = (5.3/\omega)\dot{M}/\dot{M}_a$. The requirement that $\tau < 1$ then, in turn, limits $\dot{M}/\dot{M}_a$: if $\alpha = 0$ $\dot{M}/\dot{M}_a < 3\,\omega$; if $\alpha = 2$ $\dot{M}/\dot{M}_a < 0.2\,\omega$.

The thermal pressure in the ISM in equilibrium with the 'canonical' QSO spectrum corresponds to $\Xi = 4.6(\omega\Gamma/T_8)(\dot{M}_a/\dot{M})$. Cloud confinement may be effected, in a transient manner, by dynamical pressure. The stagnation pressure in any flow is greater than the thermal pressure by a factor $\sim 6.4M^2$. This translates into an ionisation parameter which is reduced by a factor $(T_8/4\omega^2)$ over that in the undisturbed flow (PD). In a region which experiences the stagnation pressure therefore (ie. behind a shock) the ionisation parameter is $\Xi^* \sim (1.2\Gamma/\omega)(\dot{M}_a/\dot{M})$. Imposing the condition that the flow be optically thin, as derived above, then gives, for $\alpha = 0$, $\Xi \sim 1.5/\tau$, $\Xi^* \sim 0.4/\tau\omega^2$; for $\alpha = 2$, $\Xi \sim 74/\tau$, $\Xi^* \sim 19/\tau\omega^2$. A striking 'coincidence' is immediately apparent: the dynamic pressure ionisation parameter in flat profile flows is precisely equal to, or slightly less than, that which is observed in the BLR, implying that dynamic pressure confinement is operating in the BLR. The thermal pressure, in contrast, is less than that required - unless the ISM is optically thick and $\dot{M}$ exceeds $\dot{M}_a$ by a large factor. Another consequence of the difference in pressure confinement mechanisms is in the total mass of the ISM which must be present in the BLR. Let us contrast two ISM whose velocity structure and temperature are the same. If a thermal pressure confined BLR is to exist in the first and a dynamic pressure confined BLR in the second, the density everywhere, and thus the total mass, in the first must be M^2 times that of the second.

Before turning to the gas dynamical details of global flows and of dynamic creation of the BLR we pause to review some of the most important insights which have been gained by study of individual aspects of the problem, in particular in the study of long lived clouds.

CLOUD KINEMATICAL MODELS 'Permanent' cloud models have been extensively studied. Mathews (1982) and his co-workers studied radiatively accelerated cloud models. They showed that in order to achieve the observed velocities, the clouds must be pressure confined by a medium which exerts little drag, i.e. a relativistic plasma. Such ISM simply expand away from the BLR and would have to be continuously regenerated. Furthermore, the clouds are subject to serious disruptive instabilities. Kwan and Carrol (1982) considered low angular momentum clouds which fall into centre of the galaxy from regions 1 kpc distant. The clouds are confined by a combination of ram and thermal pressure exerted by a hot ISM. Extremely massive ($>> 10^9\ M_\odot$) black holes are required to produce the observed orbital velocities. Since ram pressure on the leading edge of the cloud is not balanced to the rear, the clouds will expand and dissipate. It is unclear if they can survive for long enough to explain the observations. The disruptive effects produced by motion through the ISM could be avoided if the clouds were carried along by a fast moving wind. Beltrametti (1981) considered the creation of clouds by thermal instabilities in a wind. However, Compton cooling stabilises the wind unless $L_{47} < 0.1$, which effectively rules out most QSOs. All these models have the inherent difficulty that they require a high density ISM to provide the thermal pressure confinement which, as outlined above, leads to high optical depths and large mass fluxes.

The difficulties encountered in producing viable permanent cloud models has led to the consideration of transient cloud models. KMT, in their excellent and wide ranging paper, noted that there should be continuous mass interchange between the hot and cool phases on a timescale less than the dynamical crossing time of the region. The gas velocities result from the expansion of the region as a whole. However, since thermal pressure confinement is required, such two phase models suffer from the same optical depth and mass flux difficulties as the permanent cloud models. Transient clouds confined by dynamical pressure as a way out of these difficulties was first proposed by Dyson and Perry (1982). Such transient models depend on mass injection throughout the region; such mass injection gives rise to flows whose properties are quite different from those where all sources of mass lie outside of the boundaries of the region of the flow. We now turn to these models.

GLOBAL FLOW MODELS We assume that QSOs occur in the nuclei of young galaxies (Rees, 1985). The stellar population must be young; young stars "experience vigorous episodes of mass loss" (Lada, 1985). The extent of this early outflow stage of stellar evolution, and the enormous energies associated with it, are only now becoming apparent, and we refer the reader to Lada's (1985) comprehensive review. Vigorous mass loss in an environment of high stellar density, as is presumed to be present in the nucleus of QSO galaxies, can be expected to create a rich, turbulent and very energetic ISM. Even if external sources such as accretion from the distant reaches of the galaxy, or winds driven off the surface of a central accretion disk, are present, it is necessary to understand what we term mass-loaded flows.

Mass loading has several important consequences, which we consider in turn. Firstly, and most importantly for BLR models, the density profile is dramatically altered from that in external source flows. The mass conservation equation, $\nabla \cdot \rho v = \dot{\rho}$, can be solved (spherical symmetry is used here for simplicity) for $\rho(r)$ in terms of $\dot{\rho}(r)$, the local mass injection rate: $\rho(r) = [\int_{\bullet}^{r} \dot{\rho}(\zeta)\zeta^2 d\zeta\,]/r^2 V(r)$. For any particular velocity profile, the density profile is flatter than in the absence of mass loading. This has immediate and profound consequences resulting from the restrictions on the optical depth, as we have seen. Optically thin, flat density-profile flows, for example, have densities at the BLR orders of magnitude greater than r^{-2} flows of the same optical depth.

Secondly, mass loading, because of its dynamic effects, alters the the topology of the solutions of the wind equation fundamentally. In order to examine these effects we now consider the equation of momentum conservation. The effective acceleration due to the pressure gradient, $g_p = -\nabla P/\rho$, can be rewritten by replacing P through the equations of state and of mass conservation to yield an effective pressure term, g_p:

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$$g_P = v_c\, d(\ln M)/dr + g_D - (v_c/M)(\dot{\rho}/\rho) - R\nabla(T/\mu)\,.$$

g_D is the geometric term which arises because of the divergence of the volume element; absent in plane parallel flows, in spherically symmetric flows it $= 2v_c^{\,2}/r$. The third term is the deceleration due to the local absorption of momentum by the injected mass (we assume the injection is isotropic and contributes no net momentum to the flow). The last term, due to temperature gradients, acts in the direction of decreasing T.

The equation of momentum conservation is

$$d(\rho\mathbf{v})/dt = \rho(g_P + g_R + g_o - g_G)$$

where the radiative acceleration $g_R = \int \varkappa(\nu)F(\nu)d\nu/c$; $F(\nu)$ is the local radiation flux. The acceleration due to the gravitational field of the central hole and of the stellar core population is g_G; g_o is any "other" acceleration such as that due to relativistic particles. We replace the velocity through the Mach number, $M = v/v_c$. Inserting the explicit form for g_P in the momentum equation (and noting that now $d(\rho\mathbf{v})/dt = \rho\dot{\mathbf{v}} + \mathbf{v}\dot{\rho}$) yields the general flow equation:

$$v_c^2\,\frac{M^2 - 1}{M}\,\frac{dM}{dr} = (g_D + g_R + g_o + g_T) - (g_G + g_{\dot{\rho}}) = g+ - g-$$

where $g_{\dot{\rho}} = (M^2 + 1)(v_c/M)(\dot{\rho}/\rho)$ and $g_T = -R\nabla(T/\mu)$. The mass injection deceleration, $g_{\dot{\rho}}$, for the general density profile given above becomes $g_{\dot{\rho}} = (M^2+1)v_c^2\, r^2\dot{\rho}(r)\Big/\int \dot{\rho}(\zeta)\zeta^2 d\zeta$. We expect that $\dot{\rho}(r)$ is related to the local IMF, stellar mass density and to local dynamics, such as tidal and collisional disruption. All these effects lead us to suppose that $\dot{\rho}(r)$ may be flat in the core, but most probably falls with r, steepening as r increases; if $\dot{\rho}(r)$ in the core is given by a power law ($\dot{\rho} \sim r^{-\beta}$) then $g_{\dot{\rho}}(r) = [(3-\beta)(M^2+1)]v_c^{\,2}/r$. This combined with g_D gives an inwardly directed effective acceleration, $g_e = [M^2(3-\beta)+(1-\beta)]v_c^2/r$.

Regular sonic points ($M = 1$) exist only if $g+ = g-$ at the sonic point. Analysis of permitted flow topologies then follows from analysis of the relative radial dependence of g+ and g- (Perry & Dyson, 1985b). For example, thermal pressure driven winds have supersonic branches only if $g_D > 0$, i.e. in divergent geometries. Radiatively accelerated supersonic winds occur only if g_R is flatter than g_G, as e.g. in essentially one-dimensional stellar and disk winds where the radiative force does not fall off above the surface as quickly as gravity. Optically thin, radiatively accelerated winds do not exist above point sources because the radial dependence of the radiative and gravitational accelerations are the same; the radiation force contributes only to a reduction in the effective gravity everywhere, reducing the overall density in the flow. This geometrical conspiracy prevents radiative forces from driving point source winds to highly supersonic velocities - even near QSOs. In order to achieve highly supersonic winds the geometrical tie between g_R and g_G must be broken. This can be achieved by QSOs if, for example, the continuum emission is geometrically extended, if the winds originate above extended accretion disks, or if the opacity varies in the flow.

The sonic point condition in mass-loaded flows (when $g_o = 0$) is $g_R = g_G + 2(2 - \beta)v_c^2/r$. For all $\beta < 2$, this gives $g_R > g_G$ at the sonic point. If both terms go as r^{-2}, radiative forces everywhere dominate gravity if they do so at the sonic point. However, the slower decay in $g_{\dot\rho}$ guarantees that this term dominates; hence, regular sonic points do not exist because if M > 1 for $r > r_c$ then dM/dr < 1; the situation is precisely reversed for inflows. [Several aspects of irregular sonic points are discussed by Beltrametti (1981), and references given there. Galactic winds such as those discussed by Mathews and Baker (1971) have regular sonic points in the presence of cooling, when g_T plays the crucial role.] If, in addition to mass loading, geometrical effects conspire to break the tie between g_R and g_G, very highly supersonic winds with flat density profiles can result. The only analytic solutions which currently exist are those of Beltrametti and Perry (1980). Those winds have uniform mass and luminosity generation throughout the core. The velocity increases as r in the core, resulting in a wind density which is independent of r! These winds are radiatively accelerated in their supersonic branches and achieve subrelativistic speeds. Although their models were oversimplified, most of the important physical effects are clearly visible in their solutions. More detailed investigation of the effects of mass loading in more realistic geometries throws up a variety of complex flows (Perry and Dyson, in preparation).

It is certainly unrealistic to assume a strict power law for $\dot\rho(r)$; further complications arise due to the expected sporatic and local nature of the injection. Furthermore, the injection is expected to be time dependent and to depend on the evolutionary history of the galactic core. We will return to these questions elsewhere (Perry and Dyson, in preparation); we now turn to the more local effects of mass injection - in particular to how it creates the broad emission line region in QSOs.

CREATION OF THE BROAD LINE REGION Mass injection into supersonic flows can only occur when mediated by stand off shocks. Furthermore, in the cores of QSO-galaxies, where we expect energetic mass loss by stars and through stellar collisions and tidal disruption, the mass injection is itself supersonic. The collision of two supersonic gas streams results in a classic two shock pattern familiar from interstellar gas dynamics. The shocked wind gas is heated to temperatures well in excess of the equilibrium temperature of the ISM. Its pressure is the stagnation pressure of the flow. Because the gas is superheated it tries to cool. Inverse Compton cooling by the QSO continuum is very effective near the QSO; with increasing distance from the source the diminution of the flux reduces its effectiveness. In the high pressure shocked region the gas cools isobarically by Compton cooling followed by unstable radiative line cooling. We (PD) find that in e.g. shocks around supernovae within about 1 pc of the central source, the trapped gas cools and fragments before it flows out of the high pressure, shocked region. The fragments have densities, temperatures and ionisation parameters in agreement with BLR observations. They are accelerated by the pressure gradients within the shock to speeds characteristic of the local flow, eventually leave the shocked region and reexpand into the flow. (Details of the energy balance, cooling times, flow patterns, are given in PD).

A simple dynamic picture of the BLR thus emerges. Mass injection creates or augments the ISM in the core of a QSO galaxy. In the process stand-off shocks form within which the BLR fragments are created and accelerated. The mass-fluxes required to explain the BLR are equal to the mass-energy equivalent of the luminosity. Increasing the mass flux to provide full thermal pressure cloud confinement conflicts with optical depth constraints and requires excessive mass fluxes. Since shocks are just as effective in creating cool clouds in high mass flows as in more reasonable low mass flows too many BLR clouds are created in thermal pressure confining flows; furthermore, the ionisation parameter of such dynamically confined clouds does not agree with observation.

CONCLUSIONS A picture of the formation of the BLR is emerging in which the BLR is seen to be a consequence of the creation of an energetic ISM by stellar mass loss in the centre of a QSO-galaxy. In the process of injecting the gas destined to feed the central engine, the stars provide both the observed heavy elements and the energy necessary to create the temporary regions of high pressure within which short-lived BLR clouds form. Detailed solutions of the gas dynamical problems raised here can be expected to increase our understanding of the QSO-galaxy interaction. Undoubtedly revisions in details of the picture will become necessary as detailed solutions of mass-loaded flows become available. The shocks which mediate the mass injection require careful attention, as does the evolution of the cool fragments which form in their shadow.

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DISCUSSION

Abramowicz : Mass estimations of the central black hole are based on the observed velocities of the clouds. It is assumed that these veclocities are Keplerian (free motion). In your picture the clouds are not moving freely. How does this influences the estimation of the central mass ?

Perry : Such estimates may well over-estimate the mass of the central black hole by an order-of-magnitude. The mass distribution of the central star "cluster" must be included in analyses of line profiles and self consistent stellar and gas dynamic models are needed before accurate determinations of M_h can be made.

Kundt : What are your objections to replacing the confining IGM by a relativistic pair plasma (which later-on is focussed into the jets by a magnetic pinch) ?

Perry : The size of radio jets which have been resolved places them within the BLR - therefore we would expect focusing to have occurred interior to the BLR in most cases. The most serious objection to a relativistic plasma confining the BLR (to $r \gtrsim 1$ pc) is that plasma would itself have to be confined to the nuclear region by a thermal plasma, or be continuously resupplied.

Wampler : We know that the broad line clouds give about the same line width for objects with nuclear luminosities that range over factors of $10^5 (-30 < M_B < -18)$. We also know that in the upper end of this range $(-30 < M_B < -24)$ the total luminosity in the CIV $\lambda 1548$ line is roughly constant, independent of luminosity (Baldwin effect). Can your model produce both the constant flow velocity and constant $\lambda 1548$ luminosity in the high luminosity quasars ?

Perry : In principle, yes, and I would like to refer you to our Monthly Notices (213, 665) paper for details of the model. In practice, detailed line profiles cannot be computed until the flow behind the radiating cooled shock is analysed numerically with an accuracy not yet available. Such modeling should be available in the next few years, and we shall then be able to give you a reliable answer.

Schilizzi : In a radio loud quasar there will be a radio jet passing through the Broad line Region. What effect might that have on the dynamics of the Inter Cloud Medium ?

Perry : The effect of a jet on a global flow will only be through surface (local) interactions - we would not expect any global effects. There may well be some entrainment and mixing in the surface layer.