THE INTERACTION OF QUASAR WINDS AND THE CIRCUMQUASAR ENVIRONMENT

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High speed winds from quasars interact with the gas and stars in a surrounding galaxy and produce a variety of effects. The winds sweep up the general interstellar matter into fast moving shells of cool gas which can produce lower velocity ($\lesssim$ 0.01c) sharp absorption line systems. The impact of the wind on dense interstellar clouds may contribute to the narrow emission line region. Finally, supernovae or stellar winds near the QSO set up shock waves in the outflow. Shocked QSO wind material is responsible for the broad emission line material.

1. INTRODUCTION

It has become very clear that stellar mass loss, either impulsive or continuous, plays a dominant role in establishing the dynamical and structural properties of the interstellar medium. The evidence for the existence of this mass loss is indisputable. Explosive ejection of stellar material has been observed (if not entirely appreciated) over thousands of years. The P Cygni type profiles of UV resonance lines in the spectra of early type stars unambiguously demonstrate continuous mass loss from their surfaces. The success of theories of the state of interstellar matter based on the interaction of mass loss with its surroundings is firmly based on observation.

This is unfortunately not the case for QSOs. Arguments for the existence of mass outflow are indirect and have recently been reviewed by Carswell (1982) and Smith (1982). Carswell (1982) has argued that the profiles and relative velocity shifts of emission lines are evidence for mass outflow. Smith (1982) considers the broad absorption line (BAL) features seen in about 10% of QSOs and, essentially by analogy with galactic objects, argues that they are evidence for mass loss. It is not clear however, whether the BAL is produced in outflowing material or in material interacting with this outflow.

Instead of waiting patiently for direct observational evidence to become available, the starting point of this discussion will be the

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assumption that some form of outflow does occur. It will be shown that this leads to explanations of various features of QSO spectra and the sceptical reader can decide the value (or not) of this premise in the light of these.

2. THE ADOPTED OUTFLOW MODEL

A necessary property of any postulated outflow is that its optical depth to electron scattering must be no more than of order unity. This requirement, together with the scale size of the regions deduced from observation, sets restrictions on the gas density in the flow. The gas velocity can be related to the other parameters only if some specific outflow model is adopted. For convenience, the steady state electron scattering driven wind models of Beltrametti and Perry (1980) will be adopted. A more general discussion is given in Perry and Dyson (1982) - henceforth PD.

These winds have essentially constant velocity, V_W, above a quasar 'surface' of radius R_0 ($\sim$ 0.1 - 0.01 pc), and density varying as r^{-2}, where r is the distance from the centre of symmetry. The wind velocity $V_W \propto (L_{BOL}/R_0)^{\frac{1}{2}}$, where L_{BOL} is the bolometric luminosity of the QSO. Characteristically $\omega (\equiv V_W/3 10^8) \sim 2$ for $L_{BOL} \sim 10^{47}$ erg s^{-1}, $R_0 \sim 0.1$ pc. Throughout this discussion these characteristic parameters will be implicit. The consequences of their variation is discussed in detail in PD. The density and mass loss rate in the wind are most conveniently parametrised in terms of the electron scattering optical depth $\tau_e (\lesssim 1)$. The wind density and implied mass loss rate are $n_e(r) \sim 5\ 10^5\ \tau_e\ R_0\ r^{-2}$ cm^{-3}; $\dot{M} \sim 440\ \tau_e\ R_0\ \omega\ M_\odot\ yr^{-1}$. Here (and henceforth) R_0 and r are measured in pc. ($\dot{M}$ is an upper limit since the mass outflow is unlikely to cover the entire sky as seen from the central object). The wind mechanical luminosity L_W ($\equiv \frac{1}{2} \dot{M} V_W^2$) $\sim 10^{-3}\ L_{BOL}$ typically.

3. THE THERMAL STATE AND STABILITY OF THE WIND

The wind temperature is determined by the QSO radiation field. The relative importance of the various heating and cooling processes depends strongly on the spectral distribution of the radiation. The various rates can be expressed in terms of integrals over the frequency distribution (PD). The discussion here is limited to radio-quiet QSOs. A more general treatment extended to flat-spectra radio loud objects is given in PD. Table I gives the adopted spectral distribution.

TABLE I

Spectral Index	Log (frequency)
1	12 - 15.5
1.75	15.5 - 17
0.5	17 - 18
1.5	18 - 20

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At very small ($r \sim R_0$) distances from the central source, the wind temperature is determined by the balance of stimulated (infra-red) Compton heating and Compton cooling. The gas temperature is a steep ($\sim r^{-4}$) function of radius. At larger distances - comparable with the scale of the broad emission line region (BLR) - the heating is dominated by direct (x-ray) Compton heating. The wind is isothermal at $T_W \gtrsim 10^7$ K (with the spectrum of Table I). The wind flows hypersonically if $\omega >> 0.13$ which always is satisfied for the BP winds. Any obstacles in the wind will set up shock waves. The wind may also drive shocks into ambient material. These interactions will be discussed shortly.

The thermal stability of outflowing winds is an important question since it has been invoked as a mechanism for the production of the BLR (e.g. Beltrametti, 1981). We comment here only on the case of winds interacting with radiation fields and ignore possible effects of energetic particles (Eilek and Caroff, 1980). As described above, the outflow is thermally stable since Compton cooling is a strongly increasing function of temperature. Thermal instability can occur (with either form of Compton heating predominant) only if bremsstrahlung or heavy element cooling is the main source of energy loss. This can, however, be the case only if the QSO has a very low bolometric luminosity, $L_{BOL} \lesssim 10^{46}$ erg s^{-1} under the most favourable circumstances (PD). Since many QSOs have visual luminosities alone $\sim 10^{46}$ erg s^{-1}, it seems unlikely that this mechanism generally produces the BLR. (It may be significant in much lower luminosity active galactic nuclei.)

The current doctrine of the association of QSOs and galaxies will be faithfully adopted although the nature of these galaxies is a vexing question (Miller, 1981; Boroson and Oke, 1982). The interactions proposed in fact demand certain properties of these galaxies and this ultimately may be one way of observationally confirming their validity.

4. INTERACTION OF A QSO WIND WITH THE LARGE SCALE GAS DISTRIBUTION IN A GALAXY

The impact of a QSO wind on surrounding (uniform) interstellar matter is initially analogous to the interaction between a stellar wind and interstellar gas. The flow pattern set up consists of an outwards facing (and moving) shock in the interstellar gas and an inwards facing (but outwards moving) shock in the wind. The validity of this flow pattern is discussed in detail by Dyson, Falle and Perry (1980) (henceforth DFP). At first, the flow between the shocks is everywhere adiabatic and the outer shock radius, R_S, and velocity, V_S, have the usual dependences, $R_S \sim (L_W/\rho_0)^{1/5} t^{3/5}$, $V_S \sim (L_W/\rho_0)^{1/5} t^{-2/5}$ (where ρ_0 is the ambient density). In a manner analogous to the formation of optical filaments in supernova remnants, catastrophic cooling occurs in the swept up gas when radiative cooling dominates over expansion cooling in the gas just behind the outer shock. Secondary shock waves are generated in this gas during this relatively short lived phase (DFP). The swept up material forms a shell of cool material in equilibrium with the QSO

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radiation field. Table II outlines the physical conditions in the shell immediately after its formation (at time $t \approx 4\ 10^6$ yr) using the characteristic values $L_W = 10^{45}$ erg s^{-1}, $n_0 = 1$ cm^{-3}. The physical conditions are derived using Roeser's (1979) results for spectral indices $\alpha = 1$ and $\alpha = 3$ for comparison purposes.

TABLE II

Shell Parameters

	$\alpha = 1$		$\alpha = 3$
Velocity		0.003c	
Distance from QSO		4 kpc	
Temperature	$2\ 10^4$ K		$8.4\ 10^3$ K
Density	$2.8\ 10^3$ cm^{-3}		$7\ 10^3$ cm^{-3}
Representative ions	CIV, SiIV		CII, SiII
HI column density	$5\ 10^{18}$ cm^{-2}		$5\ 10^{19}$ cm^{-2}

The velocity is particularly insensitive to the choice of parameters (DFP). The model predictions compare well with the observed characteristics of the absorption systems in 3C191 (Williams et al., 1975).

Weymann, Carswell and Smith (1981) have noted that this atypical system has a broad range of ionization. The presence of say, SiII along with SiIV is difficult to explain with a flat ($\alpha \approx 1$) source. Table II shows that the model proposed can account for this if the spectrum is rather steeper. SiII (say) would be formed in the cooled gas in equilibrium with the QSO radiation field whereas SiIV would be formed in the cooling region behind the shock where the temperature drops from its post shock value ($\approx 10^7$ K). The swept up gas is trapped between a shock and a contact discontinuity separating it from shocked wind gas. The contact discontinuity acts as a piston. The velocity spread in the gas is essentially thermal and is much less than the actual shell velocity. This is exactly the situation observed in the sharp metal absorption systems.

Clearly, the velocity in Table II is far too low to account for all but a very small fraction of observed systems. Its insensitivity to the choice of parameters has already been mentioned. But now analogies with stellar wind interactions break down because the cooled shell experiences radiative driving and it may be accelerated (Falle, Perry and Dyson, 1981 - henceforth FPD). Acceleration occurs roughly if $L_W\, n_0 \gtrsim 5\ 10^{43}$ erg s^{-1} cm^{-3}, which is satisfied with the parameters used for Table II. The resulting flow is at first that of a thin shell driven by a piston (the shocked wind) plus a body force (the radiative driving). But the piston pressure decays with time. A positive pressure gradient is set up in the (essentially isothermal) shell. The radiative acceleration $g_R \propto \rho$, the local density (e.g. Roeser, 1979). This amplifies the density (i.e. pressure) gradient. In the shock frame, the gas in the shell flows towards the QSO. Provided the gas velocity is everywhere subsonic, the outer shock and piston remain connected. Because of the effects discussed above, the velocity increases with time and a sonic point eventually appears in this region (FPD). The shock no longer feels the direct influence of the piston. The flow then changes character and becomes that of a purely radiation driven wave which sweeps through the interstellar gas. The gas density falls of steeply behind the wave and the important region for the production of absorption lines lies between the shock and the sonic point. The velocity dispersion in the absorbing region is still small compared with the material velocity.

The wave velocity in the treatment of FPD is limited to $\sim 0.01c$, largely by optical depth effects. Falle (1982) has numerically investigated optically thick flows and has shown that waves have a limiting constant velocity $\sim 0.01c$. But this is the limit for a single wave relative to the gas into which it is moving. The radiatively driven phase is unstable (Mestel, Moore and Perry, 1976) and the flow can break up into multiple waves (perhaps forming multiple absorption systems). In principle each wave can move with velocity $\sim 0.01c$ with respect to the wave ahead. It may be possible to produce much higher velocity systems by a series of waves, although no detailed calculations have been carried out.

An important requirement is that the ambient density distribution be reasonably spherically symmetric on a scale comparable to the distance at which the cool shell forms, i.e., a few kpc (DFP). This model is therefore most appropriate to elliptical or young unflattened galaxies. It demonstrates that it is possible to accelerate gas to high speeds and produce very narrow absorption lines. But it does have fairly severe velocity limitations and it is probable that some extrinsic agency (e.g. galactic haloes) are responsible for a large proportion of absorption systems.

5. EFFECTS OF THE WIND ON INTERSTELLAR CLOUDS

If the main wind driven shock hits an interstellar cloud of density n_c ($\equiv \epsilon n_0$) situated distance r_{100} ($\equiv r/100$pc) from the QSO, the shock driven into the cloud has velocity $V_T \gtrsim 2\ 10^4\ \epsilon^{-\frac{1}{2}}\ (L_W/n_0)^{1/3}\ r_{100}^{-2/3}$ km s^{-1}. (From now on, L_W is measured in units of 10^{45} erg s^{-1}). This shock is isothermal if the cloud has dimensions $\Delta \gtrsim (500/\epsilon)\ (L_W^4\ r_{100}^{-8}\ n_0^{-7})^{1/9}$pc and the initial density of the compressed cloud is then $n_{in} \gtrsim 4\ 10^6\ (L_W^2\ n_0/r_{100}^4)^{1/3}$ cm^{-3}. If, as a representative example we take $\epsilon = 500$, $\Delta = L_W = n_0 = r_{100} = 1$, then $V_T \gtrsim 900$ km s^{-1}, $n_{in} \gtrsim 4\ 10^6$ cm^{-3}, which are comparable with parameters inferred for the narrow line regions (NLR) of QSOs. The transmitted shock velocity will be about the maximum velocity which can be given to the cloud.

It can be shown that with this particular set of parameters, the cloud is immersed within the hot shocked QSO wind gas for timescales

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$\gtrsim 10^6$ yr and will remain in pressure equilibrium with it. The cloud density as a function of time is $n \gtrsim 10^4 (L_W n_0^4 t_6^{-4})^{1/5}$ cm^{-3}, where $t_6 \equiv t/10^6$ yr. Thus the cloud reaches the lower density limit $\gtrsim 10^4$ cm^{-3} inferred for the NLR, when $t_6 \gtrsim 1$. At this time, neglecting any deceleration, the cloud has moved to a distance $\gtrsim 1$ kpc from the source. Although its density has dropped by a factor $\sim 10^3$, its ionization parameter (Section 6) has changed only by a factor ~ 10 because of its change in position. Clearly, a large number of clouds of pc dimensions can lie within a radius of 100pc from the QSO and this is necessary to produce reasonably smooth line profiles. On this model, interstellar clouds impacted by the main driven shock could be responsible for the NLR which would last for a characteristic time $\sim 10^6$ yr.

6. SHOCK WAVES IN THE OUTFLOWING WIND AND FORMATION OF THE BLR

The State of the Gas Behind the Shocks

So far we have largely ignored the wind itself except as a source of pressure to drive shock waves into ambient material. Here we consider the effects of shock waves in the wind at distances $\sim$ pc (i.e. comparable to the BLR dimensions) from the central source.

Suppose, for simplicity, that a roughly spherical obstacle is introduced into the flow. A stand-off shock is produced in the wind. The shocked wind gas retains a substantial fraction of the inflow velocity as it flows out again into the general wind. The post-shock gas has typical temperature $T_S \gtrsim 10^8 \omega^2 \gtrsim 10^9$ K (neglecting shock obliqueness). Compton cooling is the dominant radiative process in this hot gas and the gas cools from T_S to a temperature T_0 ($\gtrsim 10^6 - 10^7$ K), at which heavy element cooling takes over, in a time $t_{CS} \gtrsim (100\ r^2/L_{47})$ yr (where $L_{47} \equiv L_{BOL}/10^{47}$). The gas further cools from T_0 to temperature T_{eq} ($\gtrsim 10^4$ K) at which it is in equilibrium with the radiation field in a time $t_{CR} \gtrsim 0.1\ t_{CS}$. These times are derived for isobaric cooling since the gas is assumed trapped between the shock and the obstacle.

The cooled gas density is determined by pressure balance and is $n_f \gtrsim 1.5\ 10^{10} (\tau_e L_{47}/r^2 T_4)$ cm^{-3}, where $T_4 \equiv T_{eq}/10^4$. This is in excellent agreement with that deduced for the BLR (e.g. Davidson and Netzer, 1979). The ionization state of the gas is determined by the ionization parameter $\Xi \equiv L_{ION}/4\pi r^2\ n_e\ kTc$ (Krolik, McKee and Tarter, 1981) where L_{ION} is the ionizing luminosity. For the spectrum of Table I and the BP winds, $\Xi_s \gtrsim 0.3\ \tau_e^{-1}$ in the shocked gas (PD), in excellent agreement with the BLR (Krolik et al., 1981). The ionization parameter is constant for a given flow (because of the r^{-2} dependence of density) but will not vary much from one flow to another since a range $0.1 \lesssim \tau_e \lesssim 1$ is compatible with the observations. (The effect of shocks in the wind is to decrease the value of Ξ by a factor $\gtrsim 0.02\ \omega^{-2}$.) The value of Ξ_s necessary for agreement with observation imposes the constraint $\dot{M} \gtrsim 90 (L_{47} R_0)^{\frac{1}{2}} M_\odot$ yr^{-1} (PD). Shock waves in the wind therefore produce material whose physical state is exactly that deduced for the BLR.

The Cloudy Structure of the BLR

Once metal cooling takes over, thermal instability sets in. The gas fragments over a maximum scalelength $L \approx a_{eq}\, t_{CR}$, where a_{eq} is the sound speed in the cooled gas. For $a_{eq} \approx 10$ km s^{-1}, $L \approx 10^{15}(r^2/L_{47})$ cm. The column density of the largest fragments is $N_C \approx 10^{25}(\tau_e/T_4^{\frac{1}{2}})$ cm^{-2}. We estimate $n_H \approx 10^{-3}n$ from Roeser's (1979) results for the spectrum of Table I and the relevant post shock conditions. The Lyman continuum optical depth of these fragments is $\tau_H \sim 10^4\, \tau_e$ and they are optically thick. The implied neutral hydrogen column densities are $\sim 10^{22}$ cm^{-2}. Both high and low ionization states exist within these clouds. Smaller fragments (sizes $\lesssim 10^{12}$ cm) will be optically thin. These fragments will have velocities comparable to ω.

The Nature of the Obstacles

In order to produce cool clouds as described above, the gas must cool when trapped between the shock and the obstacle. Once it escapes from this region, it rapidly re-expands (i.e. Ξ increases) and it heats up. We require therefore that the cooling length in the shocked gas be no greater than the scale size of the obstacle. (A further requirement is that the obstacle last at least a cooling time. We discuss only the previous criterion here but note (PD) that satisfying it generally leads to satisfying the second criterion.) There are two particularly suitable types of obstacle, supernovae and winds from early type stars.

Supernova ejecta of energy E_* will expand into the wind until its internal pressure is about equal to the momentum flux in the wind. This occurs when it reaches a radius $d_o \approx (E_*/\rho_W V_W^{\,2})^{1/3}$. For cooling, $d_o \gtrsim \ell_{cs}$, where $\ell_{cs} \approx V_W t_{cs}$ is the cooling length behind the shock. This criterion is satisfied provided the obstacle lies no further than a distance $r_{CRIT} \approx 5(E_{52}\, L_{47}^{\frac{1}{2}}\, \tau_e R_0^{\,3/2})^{1/4}$ pc from the central source, where $E_{52} \equiv E_*/10^{52}$. For characteristic parameters, $r_{CRIT} \approx 1$ pc and the ejecta expands to a size $d_0 \approx 5\; 10^{17}$cm. The remnant acts as an obstacle for time t_0 before being convected away by the wind. As a rough estimate t_0 is taken as the time for a mass of wind material equal to the ejecta mass M_{ej} ($\approx 5\, M_\odot$) to collide with the remnant. This is then the mass of wind material turned into cool clouds by each supernova.

The clouds contribute to the BLR for a time on the order of their internal sound crossing time. This determines their destruction rate. The required supernova rate is found by balancing the rate of creation of the clouds with their rate of destruction. If it is assumed that the mass of cool clouds present in the BLR at any one time is $\approx 10 - 100\, M_\odot$ (Smith, 1981) and that a typical cloud has size $\approx L$, the required supernova rate is between (0.1 - 10) yr^{-1}, depending on the various parameters. It is extremely unlikely that these would be directly observable. Apart from a very short ($\sim$ 2000s) initial pulse, a type II supernova has bolometric luminosity $\lesssim 10^{42}$ erg s^{-1} (Weaver and Woosley, 1980). This is much lower than the QSO luminosities in the appropriate spectral region.

The cooling of the wind material behind the shocks also produces X-rays in the few Kev energy range. The estimated fluxes are at most a few percent of those observed in QSOs.

Groups of early type stars also provide obstacles via their energetic winds. (It is easily shown that single stars cannot provide large enough obstacles for cooling to take place.)

The scale size of the groups must be $\gtrsim \ell_c$ and the groups must contain large ($\gtrsim 10^7$) numbers of O stars each having winds of mechanical luminosity $\gtrsim 10^{36}$ erg s^{-1}. These obstacles have the clear advantage over supernovae of lasting much longer ($\sim 10^7$ yr). The number of groups required to provide the necessary cool cloud injection is of the order of ten. The numbers of stars involved is very high but these numbers are derived for BP winds. The numbers of stars in a group $\propto$ ($\omega^6/L_{47}{}^3$), and if the actual outflow velocity (for a given luminosity) is, say, a factor of 3 or so less than predicted for the BP winds, the required numbers are reduced by a factor $\sim 10^3$ (PD) and become much more plausible.

The number of clouds produced by any obstacle can be very large. For example, a single supernova can produce more than 10^6 clouds of dimensions $\sim 10^{14}$cm during its lifetime. This is completely consistent with the observational requirements.

7. SUMMARY AND CONCLUSIONS

The model presented above for the formation of the BLR has various appealing features. The clouds are continuously generated and need no confinement mechanism. They retain an appreciable fraction of the wind velocity and recourse to controvertible acceleration mechanisms is not necessary. The clouds will be a mixture of optically thin and optically thick ones. Although the wind flow is assumed radial, the velocity pattern of the BLR will be much more random. The bow shocks will hardly be symmetric since overlap and clustering of obstacles, their orbital motion etc. will all affect the detailed flow. The line profiles then should be symmetric. The BLR will vanish if either the wind ceases or suitable obstacles are not available. This latter could, for example, occur if all supernova progenitors had been exhausted. There is a possible evolutionary cut off present.

The interaction of winds with surrounding material also may produce at least some sharp metal absorption line systems and contribute to the NLR formation. These interactions seem to lead to a coherent understanding of many features of QSO spectra and this is at present the strongest pointer to the existence of winds.

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