EMISSION-LINE KINEMATICS AS A PROBE OF THE CENTRAL ENGINE IN QSOs

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ABSTRACT. We investigate the constraints on dynamic models for the line-emitting regions in quasars and AGN. The parameters characterising the central energy source (Mass, efficiency, accretion rate) are calculated in terms of the physical conditions in the line emitting gas. In a large sample the central mass (calculated assuming the emission-line clouds are bound) is proportional to the continuum luminosity. We find typical values of $L/L_E \sim 10^{-2\pm 0.5}$, $e \sim 0.1-1\%$, and $\dot{M}/\dot{M}_E \sim 1-10$.

1. INTRODUCTION

The two most typical features of quasars and AGN are their prominent emission lines and their powerful nonthermal continuum radiation source, the "central engine". While the former is fairly well explained in terms of a photoionization model (e.g. Davidson and Netzer 1979), there is little consensus on the mechanism producing the nonthermal continuum. Most of the recent models, however, invoke a massive compact object, in the potential well of which energy is extracted from accreted matter (Rees 1983). The currently favoured picture of the broad line-emitting region (BLR) features a size of 0.1-1pc, an ensemble of fast ($\lesssim 10^4$km/s), dense ($n \sim 10^9-10^{11}$ cm^{-3}) cloudlets or filaments, partially photoionized (ionization parameter in the range $0.3 \lesssim \Xi \lesssim 3$) by the UV continuum.

Evidently the physical conditions in the BLR are governed by the central source: the ionization state and the temperature are fixed by the continuum radiation, while the velocity dispersion of the clouds, which is reflected in the line width, is induced by the central object, via radiative acceleration (Blumenthal and Mathews 1979), gravity (Kwan and Carroll 1982; Wandel, Milgrom and Yahil 1985), a wind or other mechanisms, such as shocks, relativistic particles or jets. If the primary energy source is indeed release of rest mass energy of matter accreted by the central object, the fuelling matter presumably comes through (or from) the BLR, which provides an additional link between the line emission and the central source. It is therefore attractive to use the extensive emission-line data available, in the context of a kinematic model, in order to constrain the parameters characterizing the central engine (such as M, e and dM/dt), which are essential (though, to date, quite undetermined) for any model of the central source.

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2. RADIATION PRESSURE VERSUS GRAVITY

The forces which the radiation and gravity of the central source exert on a cloud have an opposite direction and the same functional dependence on the distance from the central object, r, hence their ratio for a given cloud is independent of r. The radiation force on an optically thick cloud is $F_R=L_{ion}S/4\pi r^2c$, where S is the cloud's cross section and L_{ion} is the ionizing radiation (between 1 and 100 Rydberg). The gravitational attraction by the central mass is $F_G=GMM_c/r^2$, where $M_c\sim SNm_H$ is the cloud's mass and N - its column density (N_{23} in units of $10^{23}cm^{-2}$). The ratio of the two is

$$F_G/ F_R = 4\pi m_H cGMN/L_{ion}= \sigma_T N\left(\frac{L_{ion}}{L_E}\right)^{-1} \approx 0.06\ N_{23}\left(\frac{L_{ion}}{L_E}\right)^{-1} , \qquad (1)$$

where $L_E= 4\pi GMm_H c/\sigma_T$ is the Eddington limit, and σ_T - the Thomson cross section. As this ratio depends only on the column density, for a given value of L/L_E there is a critical column density, $N_{cr}=1.6\times10^{24}(L_{ion}/L_E)$ cm^{-2}; clouds with $N>N_{cr}$ are bound, while smaller clouds are radiatively accelerated outwards. Note that the relevant parameter is the column density of the whole cloud, not only that of the ionized part. Photoionization models require an ionized column density of $N_{23}\approx1$ (e.g. Kwan and Krolik 1982). The above result branches into two different self consistent scenarios: radiatively accelerated clouds with $L/L_E\approx1$, and gravitationally bound clouds with $L/L_E\ll1$. Models in which the line width is induced by gravity imply high central masses, with $L/L_E\ll1$ (Wandel and Yahil 1985; Joly et al. 1985). This in turn gives $F_G\gg F_R$, consistent with the basic assumption of those models, that gravity dominantes the clouds' dynamics. Radiative acceleration, on the other hand, is possible if $L\approx L_E$ and if the clouds do not have large neutral parts beyond the photoionized front, which are both postulated by the radiative acceleration model (Mathews 1982).

3. CONSTRAINTS ON THE BLR

3.1 Size. The distance of the emission-line gas from the central source can be expressed in terms of the the ionization parameter, defined as $\Xi = L_{ion}/4\pi r^2 cknT = 2.3\ P_{rad}/P_{gas}$,

$$r_{pc}= 0.44\ (L_{ion,45}/\Xi n_9)^{1/2} , \qquad (2)$$

where subscripts indicate units and $T=10^4$K has been assumed. A different method is to estimate the size of the emitting region, using the luminosity in a specific emission line I, $L(I)=4\pi r^3 f_v j_I n^2$. Here j_I is the emissivity and f_v is the volume filling factor. Expressing the later in terms of the covering factor f_a ($f_v\approx f_a N/rn$) (here N is the column density of the photoionized part of the cloud), yields (for the H_β line)

$$r_{pc}\approx 0.082\ [L(H_\beta)_{43}/ f_a n_9 N_{23}]^{1/2} , \qquad (3)$$

where we have assumed the emissivity is enhanced by a factor of 3 over the case B value, due to collisional exitation (Mathews, Blumenthal and Grandi 1980).

3.2 Intercloud medium. In order to confine the clouds by thermal- or ram pressure, a hot intercloud medium (HIM) must be invoked. A "standart" quasar spectrum would heat the HIM to typically 10^8K (Krolik, McKee and Tarter, 1981), but this value depends on the assumed UV continuum. Equating the ram pressure to the thermal pressure in the clouds gives $n_h \sim 2.3\ knT_c/m_H v^2 \approx 2\times10^3 n_9 T_{c4} v_4^{-2}$ cm^{-3} , where subindices c and h refer to the cool (cloud) and hot (HIM) phases, respectively. In this case, however, the cloud's trailig end is not supported, and eventually the clouds will diffuse. On the other hand, confinement by the thermal pressure of the HIM gives $n_h=10^5 n_9 T_{c4}/T_{h8}$ cm^{-3} . In the case of radiative accelration, radiation pressure must balance the ram pressure,

$$L_{ion}/4\pi r^2 c \gtrsim \rho_h v^2 \ . \qquad (4)$$

For ram-pressure confined clouds this yields $\Xi>2.3$, which excludes this combination for most objects. For thermal-pressure confinement of radiatively accelerated clouds, on the other hand, eq. (4) gives $v<10^3(\Xi T_{h8})^{1/2}$ km s^{-1} , or, $T_h>10^{10}v_4{}^2/\Xi$ K, requiering an unplausibly high temperature. Observations of continuum variability and sharp lines constrain the BLR to be optically thin to electron scattering, giving a lower limit for T_h: $\tau_{es}=n_h r\sigma_T \approx 0.1(L_{ion,45}n_9/\Xi)^{1/2}T_{c4}/T_{h8}<1$.

3.3 Mass flow and efficiency. Unless the HIM is a part of a wind or in global outflow, in which case the mass supply to the central energy source is undetermined, the hot gas can be assumed to have a net inward velocity component (for example, quasispherical accretion, turbulent disk-like flow, or shocked infall). As we have seen, the clouds must be nearly comoving with the HIM, so it is not unreasonable that the later has velocities of the order of those inferred from the line width. In the absence of significant sources (for example, stellar mass loss) or sinks (reejection, for example by jets, wind or outflowing clouds) of matter between the BLR and the central source, the HIM-inflow can provide an estimate of the fuelling rate of the central engine,

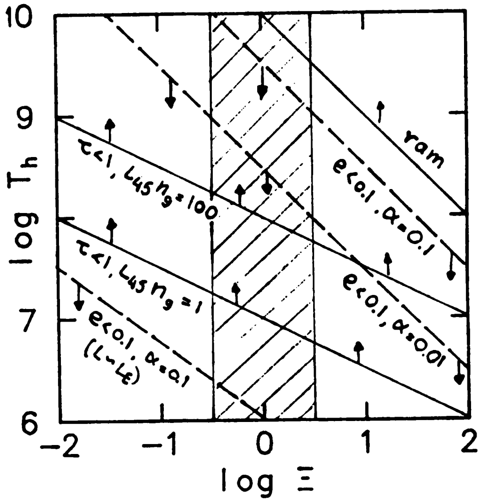

Fig. 1. Constraints on the HIM imposed by the ram pressure, efficiency (e<0.1) and optical depth (τ_{es}<1) conditions. The observed range of Ξ is hatched.

$$\dot{M} \approx 4\pi\alpha r^2 \rho_h v \sim 68\ \alpha v_4 L_{ion,45}/\Xi T_{h8} \quad M_\odot yr^{-1} \ , \qquad (5)$$

where α is the fraction of the flow that actually reaches the central source. The efficiency of mass conversion into ionizing radiation is

$$e_{ion}= L_{ion}/\ \dot{M}c^2 \sim 2.8\times10^{-4}\ \alpha^{-1}\Xi T_{h8} v_4{}^{-1} \ . \qquad (6)$$

For example, if $0.03< \alpha <0.3$, L_{ion}=0.3 L_{bol}, and $\Xi=T_{h8}=v_4=1$, the total

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efficiency e is in the range 0.1-1%. Since e$\lesssim$10%, equation (6) gives a constraint on T_h, namely $T_{h8}<(10-100)v_4/\Xi$. For radiatively accelerated clouds one can derive an even more stringent constraint (Wandel 1986, in preparation), $T_{h8} < 0.5\ \alpha\Xi^{-3/4}(L_{ion,45}n_9)^{1/4}$, which is certainly mutually exlusive with the drag constraint. Fig 1. shows the constraints derived above in the Ξ-T_h-plane.

4. BOUND CLOUDS AND THE CENTRAL MASS

The line width is induced by the gravitational field of the central object in several models of the cloud dynamics: orbital motion, radial inflow, or outflow close to the escape velocity. In either one of these cases, the central mass can be related to the line width by

$$M_8 \approx G^{-1}v_{eff}{}^2 r \sim 58\ v_4{}^2 r_{pc}\ , \qquad (7)$$

where $M_8=M/10^8M_\odot$ and $v_{eff}=(\surd 3/2)\ v(\mathrm{FWZI})$.

4.1 Broad lines. Combining this with the estimates for r for the BLR (section 3.1) we have

$$M_8 \sim 72\ (L_{ion,45}/\Xi n_9)^{1/2} v_4{}^2\ , \qquad (8.a)$$

or

$$M_8 \sim 14\ (L_{H\beta,43}/\ f_a n_9 N_{23})^{1/2} v_4{}^2\ . \qquad (8.b)$$

As demonstrated for NGC 4151 (Ulrich et al. 1984), the BLR may be stratified, with different lines originating at different radii and having different widths. For this reason we consider the emission-volume method, eq. (8.b), as a more consistent one, since it uses the same line in order to determine the distance as well as the velocity. Using this method we have calculated the masses for a sample of 90 quasars and Seyfert 1 nuclei, spanning 4 orders of magnitude in continuum luminosity (Wandel and Yahil 1985). In Fig. 2 the the continuum luminosity (in the B band) is plotted versus the mass. A linear regression gives $\log M_8 \approx (\log L_{45}-1.5)\pm 0.5$, with a correlation coefficient of 0.9, which gives $L_B/L_E \sim 0.001$-0.01. The bolometric L/L_E is of course higher by a factor of $L_{bol}/L_B \approx 3$-10.

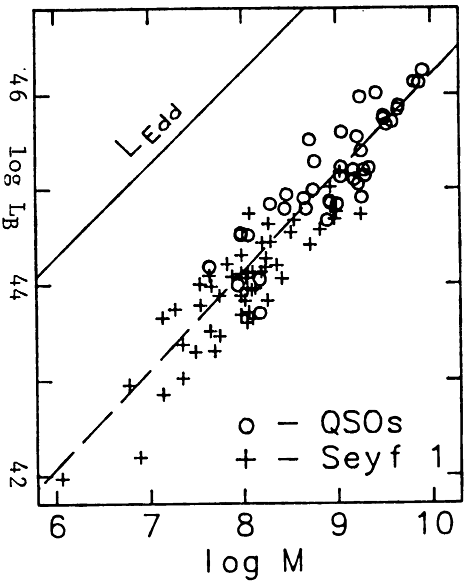

Fig. 2. Luminosity vs. mass calculated from the Hβ line

4.2 Narrow lines. The same method may be applied to the narrow line region (NLR). The later has the advantage that it is more likely to be dominated by gravity (i.a. the width of the forbidden narrow lines seems to be correlated with the stellar velocity dispersion, cf. Wilson and Heckman 1984), but on the other hand, it may be affected by the mass of stars of the galactic nucleus, as its size is much larger than that of the BLR. An expression for the mass inside the NLR, analogous to eq.(8.b), can be derived by appying the emission-volume method to the [OIII] line. For typical parameters one has

$$M_8 \approx 32 \, (L_{OIII,43} / \, f_a n_5 N_{20})^{1/2} (v/300 \text{ km s}^{-1})^2 \, , \qquad (9)$$

where v is the half-maximum velocity width of the [OIII] line and v_{eff} has been taken as $\sqrt{3}v$. Calculating the masses with the OIII method for a sample of 50 objects (Wandel 1985) yields a correlation similar to the one found for the BLR (with masses larger by a factor of 1-5; the normalization depends on the choise of parameters, which are less certain for the NLR than for the BLR), and $L_B/L_E \sim 10^{-3\pm0.5}$. Combining this result with the estimate of the efficiency (sec. 3.3), it is possible to estimate the dimensionless accretion rate. For $\alpha \sim 0.1$ and assuming $L_B/L_{ion} \sim 0.3$ we get $\dot{M}/\dot{M}_E \equiv L/eL_E \approx 3L_B/L_E e_{ion} \approx 1-10$.

4.3 Comparison with variability method. The mass of the central object may be estimated from X-ray variability (Barr and Mushotzy 1985). The masses found by this method closely match those calculated by the volume emission-line method (Wandel and Mushotsky, in preparation). The agreement of these completely independent methods provides strong evidence that the velocity dispersion of the line-emitting material is indeed induced by the gravity of the central object.

5. CONCLUSIONS

The physical conditions in the emission-line regions are governed by the radiation and gravity of the central source. This relation imposes constraints on models of the line emitting regions, as well as on the basic parameters defining the central engine. The dimensionless parameters of the energy source - L/L_E, e and $\dot{M}/\dot{M}_E$ - seem to be restricted to rather narrow ranges over many orders of magnitude in the continuum luminosity. More statistical research on large samples, spanning a wide range in luminosity is needed in order to overcome the spread introduced by differences between individual objects, confirm the conclusions of this work and bring out further characteristics of the quasar phenomenon.

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DISCUSSION

Filippenko : 1) You have concluded that $L \simeq 0.01\ L_{Edd}$, but surely this must refer only to the optical luminosity. If one considers the bolometric luminosity, one has a much higher fraction of the Eddington luminosity. In this case, shouldn't radiation pressure play an important role in galactic nuclei ?

2) Your correlation between L and M seems almost too tight to be true, and leads me to suspect that circular reasoning is involved. I must admit, however, that I have not discovered where the flaw is (if it indeed exists).

Wandel : 1) That is correct. Since the expression for the ratio of radiation pressure to gravity is derived for optically thick clouds, the ionizing luminosity (~1-100 Ryd), not the bolometric, is the relevant one. This luminosity could still be significantly larger than the visual luminosity we have used, yielding a larger L/L_E ratio. The L/L_E ratio would also be larger if a larger density is used, since $M \propto n_c^{-1/2}$

2) It should be kept in mind that the mass is actually a combination of two observables, namely, $M \propto V_{FWZ1}\ L^{1/2}$ (Hβ). The tight correlation between M and L is therefore a reflection of the known correlation between L and L (H β). The slope of the M-L correlation ($M \propto L$), however, is a direct result of the independent correlation between the line width and the luminosity. If they were uncorrelated, L/M would not be constant, but rather vary as $L^{1/2}$. Finally, the correlation between log M and Log L(r=0.92) is significantly better than expected from the linear combination of the Lβ -L correlation (r=0.93) and the L-V correlation (r=0.93) and the L-V correlation (r=0.4).

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