A New Approach For Deriving The Mass-loss Rates Of BAL Quasars :- The First Order Moment W_1 Of An Unsaturated P Cygni Absorption Component

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Abstract : Under the reasonable assumption that the broad blueshifted absorption line components observed in the spectra of broad absorption line (BAL) quasars arise from the scattering of line photons in a gas which is -spherically- ejected from a central core, we show that the technique of the first order moment ($W_1 \propto \int (E(\lambda)/E_c - 1)(\lambda - \lambda_{12}) d\lambda$) of an unsaturated P Cygni profile can be conveniently applied to the observations in order to derive the mass-loss rates ($\dot{M}$) of BAL quasars. For non-relativistic flows, the relation between $\dot{M}$ and W_1 is given by :

$$\dot{M}(\text{-}M_\odot/\text{year-}) = -5.28\ 10^{-14} v_{max}^2(\text{-km/sec-}) R_q(\text{-pc-}) W_1 / (f_{12}\lambda_{12}(\text{-}10^3 Å\text{-}) A(\text{element}) \bar{n}(\text{level})),$$

where $\bar{n}$(level) is the mean fractional abundance of the relevant ion and where the other symbols have their usual meaning.

1. Introduction

When visualizing P Cygni type profiles such those observed in the spectra of broad absorption line (BAL) quasars (see Weymann, 1983 and Turnshek, 1983, these proceedings), we are led to consider "at least" three different basic models in order to account for the observations :

- In the first model (model I, the "disconnected" model), the expanding absorbing gas is located far away from the emission line region (cf. Fig. 1.a). The resulting P Cygni line profile that would be observed by a distant observer is then simply given by the superposition of a broad blueshifted absorption component with a "classical" emission line (see Fig. 1.b).
- In the second model (model II, the "mixed" model), the absorbing gas is closely connected with the emission line region (cf. Fig. 2.a). The corresponding P Cygni line profile results from a complex radiative interaction between the line photons and both the emitting and absorbing gas (cf. Fig. 2.b).
- The third conceivable model (model III, the "ad-hoc" model) consists of an absorbing region which has a very adequate conical geometry (cf. Fig. 3.a, adapted from Fig. 4 of Junkkarinen, 1983, Ap. J. 265, 73). The resulting P Cygni line profile is also a "kind" of superposition between a blueshifted broad absorption component and a "classical" emission (see Fig. 3.b).

Taking advantage of the general similarities existing be-

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tween the P Cygni line profiles observed in the spectra of early-type stars (cf. the UV resonance line transitions) and BAL quasars, and, since it seems to be well established that for the first class of objects, models I and/or II provide a reasonable description of the geometry -spherically symmetric- necessary to account for the observations (cf. Castor and Lamers, 1979, Ap. J. Suppl. 39, 481 and references therein), we show hereafter that the first order moment (W_1) of an unsaturated P Cygni line profile can be conveniently applied in order to derive mass-loss rates ($\dot{M}$) of BAL quasars. Let us point out that if model III would turn out to be the correct one, there would be consequently no hope to derive any meaningful mass-loss rate for BAL QSOs since the value of $\dot{M}$ would depend on where the distant observer is actually located in space with respect to the observed quasar.

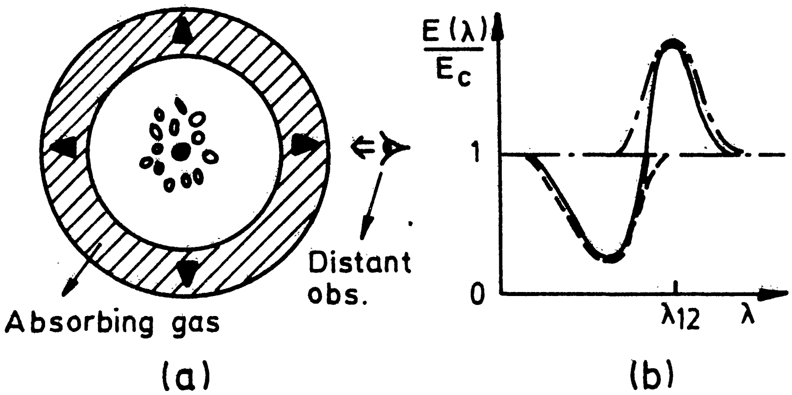

Figure 1 :
Model I (see text)

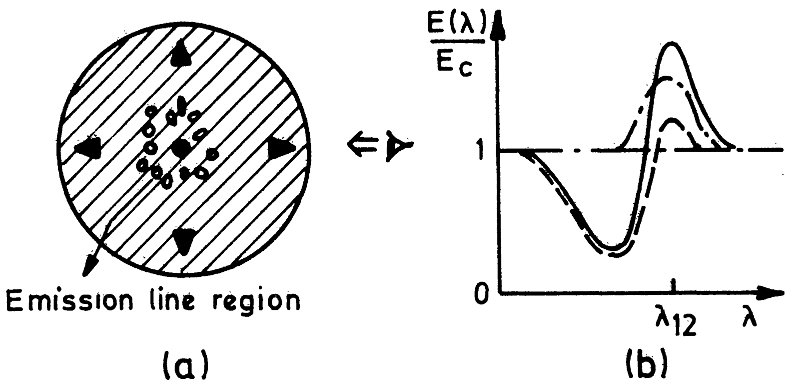

Figure 2 :
Model II (see text)

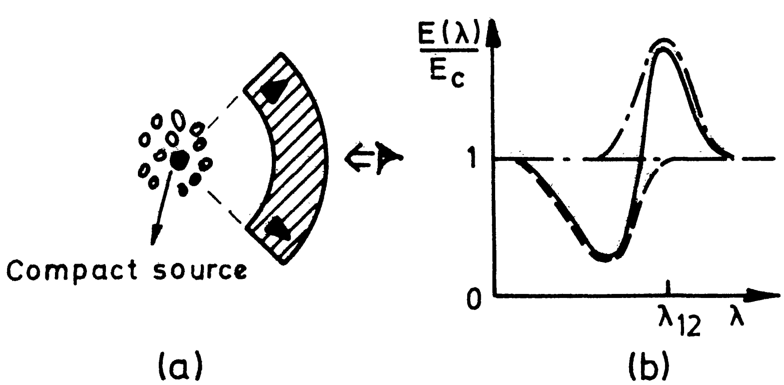

Figure 3 :
Model III (see text)

Note : In Figs. 1-3, part (b) illustrates the resulting P Cygni profile (full line) as formed by a mere superposition or a complex combination of the blueshifted absorption (dotted line) and the "classical" emission (dot-dashed line)

2. The first order moment W_1 for the case of optically thin lines

Castor, Lutz and Seaton (1981, MNRAS 194, 547) have first established that in the framework of the Sobolev approximation (cf. Sobolev, 1960, Moving Envelopes of Stars; transl. from Russian by S. Gaposchkin) and for the case of optically thin lines, the first order moment W_1 of a P Cygni line profile, i.e. the quantity

$$W_1 = (c/(\lambda_{12}v_{max}))^2 \int (E(\lambda)/E_c - 1)(\lambda-\lambda_{12})d\lambda, \qquad (1)$$

provides a good mean of deriving the mass-loss rate $\dot{M}$ of a central object (star, QSO, etc.). Although Castor, Lutz and Seaton have applied this technique for specific distributions of the velocity and line opacity, it is straightforward to show (see below) that a unique relation between W_1 and $\dot{M}$ actually holds, irrespective of the types of velocity and opacity distributions.

Indeed, if the P Cygni line profile is not saturated (cf. Fig. 4.b) -i.e. the expanding envelope is optically thin to the line radiation-, one can easily state that (neglecting for the moment the occultation effect) the line radiation emitted from the approaching and receding lobes of the envelope (see Fig. 4.a) will equally contribute to the blue and red sides of the "emission" line profile seen by a distant observer; in other words, the "emission" line profile is a symmetric function with respect to $\lambda-\lambda_{12}$. Denoting by $E_{abs}(\lambda)/E_c$ the profile of the absorption component which arises from the scattering of line photons in the gas just located between the central core and the observer, Equation (1) then reduces to

$$W_1 = (c/(\lambda_{12}v_{max}))^2 \int (E_{abs}(\lambda)/E_c - 1)(\lambda-\lambda_{12})d\lambda. \qquad (2)$$

Since

$$E_{abs}(\lambda)/E_c = \exp(-\tau_{12}), \qquad (3)$$

where τ_{12} is the line opacity and that, in the optically thin approximation

$$\exp(-\tau_{12}) \sim 1-\tau_{12}, \qquad (4)$$

Equation (2) takes the convenient form

$$W_1 = (c/(\lambda_{12}v_{max}))^2 \int \tau_{12}(\lambda)(\lambda-\lambda_{12})d\lambda. \qquad (5)$$

Adopting the Sobolev-type expression of τ_{12} (see Castor, 1970, MNRAS, 149, 111)

$$\tau_{12} = n_1(\Pi e^2/mc)f_{12}\lambda_{12}/\frac{dv}{dr}, \qquad (6)$$

n_1 being the volume population of the lower atomic level of the line transition 1→2, and with the help of the classical Doppler relation

$$(\lambda-\lambda_{12})/\lambda_{12} = v/c, \qquad (7)$$

Expression (5) can be then reduced to

$$W_1 = (\Pi e^2/mc)f_{12}\lambda_{12}/v_{max}^2 \int_{R_q}^{r_{max}} n_1 v dr. \qquad (8)$$

Defining the fractional abundance n(level) of an ion in the lower atomic level 1 by

$$n(\text{level}) = n_1/N(\text{element}), \tag{9}$$

where N(element) is the total number density of the given element which has an abundance

$$A(\text{element}) = N(\text{element})/N_{tot}, \tag{10}$$

N_{tot} representing the total nucleon density at a distance r, it is straightforward to combine Equation (8) with the expression of the mass-loss rate

$$\dot{M} = -4\pi r^2 v N_{tot} \bar{\mu} M_{amu}, \tag{11}$$

to finally obtain

$$W_1 = (\pi e^2/mc) f_{12} \lambda_{12} A(\text{element}) \dot{M} \bar{n}(\text{level}) (1/L_{max} - 1) / (4\pi \bar{\mu} M_{amu} v_{max}^2 R_q), \tag{12}$$

where $\bar{\mu}$ is the mean atomic weight of the nuclei in the flow, M_{amu} the unit of atomic mass and

$$\bar{n}(\text{level}) = \int_1^{L_{max}} n(\text{level})\, d(1/L) \Big/ \int_1^{L_{max}} d(1/L), \tag{13}$$

L representing the dimensionless distance to the central core (R_q)

$$L = r/R_q. \tag{14}$$

This short demonstration has led to the expected result (see Equation (12)) : there exists a unique relation between $\dot{M}$ and W_1, irrespective of any choice for the velocity and/or opacity distributions. Furthermore, if one takes into account the "occultation" effect, detailed calculations (see Surdej, 1982, Astrophysics and Sp. Science <u>88</u>, 31 and Surdej, 1983, Astrophysics and Sp. Science <u>90</u>, 299) show that the following relation

$$\dot{M}(\text{-}M_\odot/\text{year-}) = -5.28\ 10^{-14} v_{max}^2(\text{-km/sec-}) R_q(\text{-pc-}) W_1 / (f_{12}\lambda_{12}(\text{-}10^3 \text{Å-}) A(\text{element}) \bar{n}(\text{level})), \tag{15}$$

where

$$\bar{n}(\text{level}) = \int_1^{L_{max}} (W(L)-1)\, n(\text{level})\, d(1/L) \Big/ \int_1^{L_{max}} (W(L)-1)\, d(1/L), \tag{16}$$

with

$$W(L) = 0.5(1-\sqrt{1-(1/L^2)}), \tag{17}$$

being the geometrical dilution factor, applies very generally since it is independent of :

- the velocity field v(r) } i.e. matter needs not being ejec-
- the opacity distribution τ_{12} } ted in a continuous flow !
- the collisional excitation parameter ε
- a possible rotation of the expanding atmosphere
- the presence of an underlying photospheric absorption line ($\Delta\dot{M}/\dot{M} \lesssim 20\%$) and similarly of an underlying "emission" line

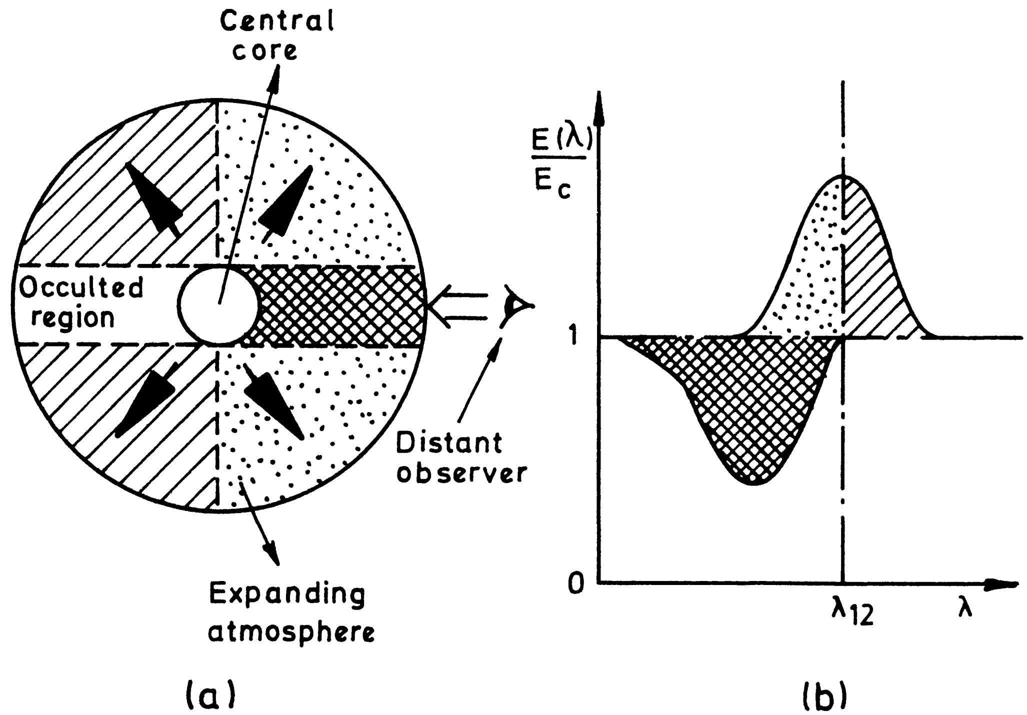

Figure 4 : The different geometrical regions of the expanding atmosphere from which (red- and blue- shifted) emission and absorption of line radiation contribute to the formation of a P Cygni line profile (see part (b)) are represented in part (a) of this illustration

(cf. model II)
- the multiplet structure of a resonance line transition
- the existence of a strong limb darkening law of the central core
- the Sobolev approximation used for handling the transfer of line radiation.

It is without saying that for the case of a BAL quasar, the first order moment W_1 is to be calculated after reduction of the observations (P Cygni line profile) into the rest frame of the QSO.

We intend to investigate in the near future the correction(s) -if any- which should be applied to Equation (15) for the case of relativistic flows.