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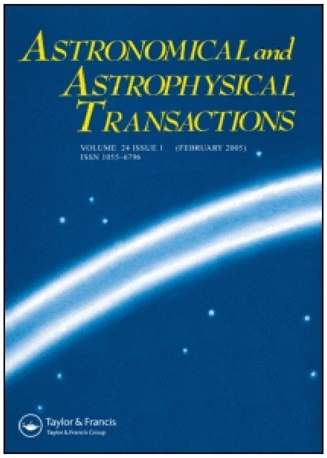


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# RADIATION PRESSURE AND MASS OUTFLOWS FROM HOT STARS AND QUASARS

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We consider the radiation pressure effects in the most luminous astrophysical objects, stellar winds of the O–B stars and the broad-absorption-line (BAL) quasistellar object (quasar) (QSO) matter outflows. Although the objects have different physical natures, there are many similarities in the behaviours of their gas envelopes in the strong radiation fields. We discuss both smooth and structured stellar wind models, and the dynamic and kinetic instability of the winds. We consider also the dynamics of the absorbing gas in the BAL QSO, the nature of the line-locking effects and the sources of the outflowing gas.

*Keywords*: Stellar winds: theory, variability, structure–quasars: absorption lines, line-locking effect

## 1 INTRODUCTION

Radiation pressure (RP) plays a very important role in most astrophysical objects, affecting the star's structure, stellar wind dynamics and the matter outflows in the process of the stellar evolution. In the review presented, we consider a particular but very important part of the dynamic effects, connected with the RP acting on the cosmic plasma dynamics in the vicinity of the most luminous quasistationary objects, O–B stars and quasistellar objects (QSOs) (quasars). Investigations of these objects are at the front line of modern astrophysics, and are still far from being completely understood. Nevertheless, considerable progress has been achieved in the last few decades, and many new physical ideas appear among various theoretical approaches to the explanations of the phenomena.

There have been many reviews devoted to stellar winds and to the broad-absorption-line (BAL) QSOs; also there is a monograph on general RP theory (Mihalas and Mihalas, 1984). In comparison with these, our brief review plays an intermediate role; we do not give a very detailed description of particular objects and do not pretend to give the general theoretical solution of the problems. The purpose of the present review is to give very briefly the history of the investigation of these objects in connection with the work performed at the Fessenkov Astrophysical Institute, to stress some new physical ideas and to draw some conclusions about future development. The review is not comprehensive; it is connected mostly with the scientific interests of the present authors.

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## 2 STELLAR WIND FROM O–B STARS

Although there have been some indications of mass loss from massive stars (Beals, 1929), the manifestation of very strong matter outflows from most O–B stars shown by the first rockets (Morton *et al.*, 1972) and satellites (Copernicus and IUE) far-ultraviolet (uv) observatioins were accepted as a challenge to our ability to understand the physics of the phenomenon. In fact, the idea of the matter outflows generated by the RP has been expressed a long time ago (Milne, 1926; Beals, 1929; Pikelner, 1947), but the concept of stellar winds as a very common phenomenon appeared owing to the UV observations because, in the UV band, one can see the detail of the outflow process in the various P Cygni-type line profiles. The subsequent development showed that the RP indeed is the main reason for the hot-star winds, but the physics of the outflows are very complicated and, in spite of great progress, the theory is still not yet complete. Investigation has shown that the successes of the theory are closely related to the results from all-band observations.

### 2.1 The smooth radiation-driven wind model

The key theoretical approach to the stellar wind theory was found by Lucy and Solomon (1970), who have unified the Parker hydrodynamic approach to the matter outflow with the Sobolev theory of radiation transfer in the moving star's envelope (Sobolev, 1947).

The radial steady stellar wind is described by hydrodynamic equations, including mass, momentum and energy conservation laws:

$$\dot{M} = 4\pi r^2 \rho(r) v(r), \tag{1}$$

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{1}{\rho(r)}\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{GM_*}{r^2} + g_{\mathrm{rad}}(r), \tag{2}$$

$$\mathrm{div}\,\mathbf{\Phi} = S(r), \tag{3}$$

where $v(r)$, $\rho(r)$ and $p(r)$ are the gas velocity, density and pressure respectively, $\dot{M}$ is the mass loss rate from the star, $M_*$ is the mass of the star, $g_{\mathrm{rad}}$ is the acceleration due to the RP, and $\mathbf{\Phi}$ and $S$ are the energy flow and the power respectively of the energy sources.

In the first approximation, the temperature of the steady wind of the O–B stars may be considered as a constant close to the effective temperature of the star; so one need only two (mass and momentum) equations, which can be reduced to a single 'wind equation':

$$\left(1 - \frac{a^2}{v^2}\right) v\frac{\mathrm{d}v}{\mathrm{d}r} = \frac{2a^2}{r} - \frac{GM_*}{r^2} + g_{\mathrm{rad}}(r). \tag{4}$$

Generally, the radiative acceleration in the hot star's atmospheres is defined by the processes of Compton scattering, ionization and bremsstrahlung, and by line scattering:

$$g_{\mathrm{rad}} = \frac{1}{c\rho(r)}\left(\sigma_{\mathrm{T}}\frac{L_*}{4\pi R_*^2} + 4\pi\int \chi_\nu^{\mathrm{C}} H_\nu(r)\,\mathrm{d}\nu + 4\pi\sum_j \int \chi_\nu^j H_\nu(r)\,\mathrm{d}\nu\right), \tag{5}$$

where $\sigma_{\mathrm{T}}$ is the electron scattering absorption coefficient, $L_*$ and $R_*$ are the star luminosity and radius respectively, $\chi_\nu^{\mathrm{C}}$ is the total bound–free and free–free continuum absorption coefficient, $\chi_\nu^j$ is the $j$th-line absorption coefficient and $H_\nu$ is the monochromatic flux.

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Practically, in the O–B stellar winds the second term in equation (5) is negligible, and the third term (the line scattering) is dominant. After integrating over the Doppler profile of lines, in the optically thin case it can be expressed in the form $g_{\rm rad}^{\rm Lin} = (1/c\rho)\sum_j \chi_i F_j\, \Delta v_D^j$, where $F_j$ is the radiation flux density at the $j$th line frequency, $\Delta v_{\rm D}^j$ is the Doppler width of the $j$ line and $\chi_j$ is the $j$th line absorption coefficient given by

$$\chi_j = \frac{\pi e^2}{m_{\rm e}c}\frac{g_{\rm l} f_j}{\Delta v_{\rm D}^j}\left(\frac{N_{\rm l}}{g_{\rm l}} - \frac{N_{\rm u}}{g_{\rm u}}\right). \tag{6}$$

where $e$ and $m_{\rm e}$ are the electron charge and mass respectively, $f_L$ is the oscillator strength, $N_{\rm l}$ and $N_{\rm u}$ are the number densities of the lower and upper levels respectively, and $g_{\rm l}$ and $g_{\rm u}$ are the degeneracies (statistical weights) of the lower and upper levels respectively.

In the Sobolev theory, the radiative acceleration in the radial outflow depends on the optical depth $\tau_j$ as

$$g^j_{\rm rad} = \frac{\chi_j}{c\rho}\Delta v^j_{\rm D} F_j \frac{(1 - {\rm e}^{-\tau_j})}{\tau_j}, \tag{7}$$

where the optical depth $\tau_j$ is

$$\tau_j = \frac{\chi_j v_{\rm th}}{{\rm d}v/{\rm d}r}. \tag{8}$$

In the cosmic plasma of standard composition there are many different line transitions of different strengths, and because of this the RP acceleration may be approximated by the sum of the acceleration in thick lines ($\tau_i \gg 1$), which is independent of the line strength and proportional to the number of thick lines multiplied by the velocity gradient, plus the sum of thin-lines RP acceleration ($\tau_i \ll 1$), independent of the velocity gradient. As the ratio of the number of thick lines to the number of thin lines depends on ${\rm d}v/{\rm d}r$ as well, the total RP acceleration depends on the velocity gradient as $g_{\rm rad}^{\rm Lin} = \sum g^j_{\rm grad} \propto ({\rm d}v/{\rm d}r)^\alpha$, $0 < \alpha < 1$.

The idea of interpolation of the RP acceleration by the power function of ${\rm d}v/{\rm d}r$ was realized by Castor, Abbot and Klein (CAK) (1975), who scaled the line scattering relative to the electronic scattering. Introducing the 'optical depth parameter'

$$t = \sigma_{\rm T} n_{\rm e} v_{\rm th}\left(\frac{{\rm d}v}{{\rm d}r}\right)^{-1}, \tag{9}$$

and using the relation $\tau_j = (\chi_j/\sigma_{\rm T} n_{\rm e})t = \eta_j t$, they defined the 'line force multiplier'

$$M(t) = \frac{g_{\rm rad}^{\rm Lin}}{g_{\rm rad}^{\rm T}} = \frac{1}{F}\sum_j F_j \Delta v^j_{\rm D}\frac{1 - {\rm e}^{\eta_j t}}{t}, \tag{10}$$

where $F = L_*/4\pi r$.

Now the wind equation (4) can be expressed in the form

$$v\frac{{\rm d}v}{{\rm d}r} = \frac{1}{1 - a^2/v^2}\left(\frac{2a^2}{r} - \frac{GM_*}{r^2} + g_{\rm rad}^{\rm T}[1 + M(t)]\right), \tag{11}$$

where $g_{\rm rad}^{\rm T} = n_{\rm e}\sigma_{\rm T} F/c\rho$ is the acceleration due to the electron (Thomson) scattering.

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CAK evaluated the line Force multiplier $M(t)$ for the spectrum of the ion C III and scaled it to account for the total abundance of C and other elements. Their results were well fitted by the relation $M(t)=kt^{-\alpha}$ with $k=0.3$ and $\alpha=0.7$. Later, an exhaustive analysis (Abbot, 1982a) based on a complete line list of all relevant ion of the elements from H to Zn yielded more exact values for the parameters and the more accurate expression

$$M(t) = kt^{-\alpha}C(n, r), \tag{12}$$

where $C(n, r)$ is a correction that takes into account the more sensitive dependence on the density and the finite size of the stellar disc viewed from a distance $r$ (Pauldrach *et al.*, 1986). The $\alpha$ and $k$ parameters are independent of the distance from the star's surface and are completely defined by the star's effective temperature $T_{\rm eff}$ and radius $R_{\rm s}$ (Abbot, 1980, 1982a). The parameters of the force multiplier were calculated with a very large line number, up to a quarter of a million lines (Abbot, 1982b) and even more (Shimada *et al.*, 1994).

It allows us to reduce the technically difficult problem of the exact calculation of the RP force in the gas-dynamics equation to the solution of the nonlinear equation

$$\left(1-\frac{a^2}{v^2}\right)v\frac{dv}{dr} = \frac{2a^2}{r} - \frac{da^2}{dr} - \frac{GM_*(1-\Gamma_{\rm E})}{r^2} + \frac{C_1}{r^2}\left(r^2 v\frac{dv}{dr}\right)^{\alpha}, \tag{13}$$

where the acceleration due to the electron scattering is included in the gravitation acceleration term and $\Gamma_{\rm E} = L_*/L_{\rm Ed}$ is the ratio of the star luminosity to the Eddington luminosity.

A complete analysis of equation (13) was made by CAK.

Introducing the dimensionless variables $w = 1/2v^2$, $u = -1/r$, $w' = dw/du$, they considered equation (13) in the form

$$F(u, w, w') = \left(1 - \frac{1}{2}\frac{a^2}{w}\right)w' - h(u) - C(w')^{\alpha}, \tag{14}$$

where $h(u) = -GM_*(1-\Gamma_{\rm E}) - 2(a^2/u) - da^2/du$.

The locus of the singular points of equation (11) is defined by the condition

$$\frac{\partial F(u, w, w')}{\partial w'} = 1 - \frac{1}{2}\frac{a^2}{w} - \alpha C(w')^{\alpha-1} = 0. \tag{15}$$

The single solution is defined by the additional condition that the solution must pass smoothly through the critical points, which is determined by the regularity condition

$$\left(\frac{dF}{du}\right)_{\rm c} = \left(\frac{\partial F}{\partial u} + w'\frac{dF}{dw}\right)_{\rm c} = 0. \tag{16}$$

CAK showed, in particular, that, with the stellar parameters defined, there is a unique solution of the equation, which connects the subsonic solution continuously with the supersonic radiation-driven solution in the supersonic region and further, far from the star's surface, with the Parker-type solution branch.

As mentioned above, CAK used an approximation for the radiation force, which leads to significant deviations of the theoretical models from the observation results. The observed mass loss rates $\dot{M}$ were systematically less and the terminal wind velocities $v_\infty$ larger than the calculated values. These differences were eliminated with more precise calculations of the RP and, mostly, with the 'finite-cone approximation' instead of the pure 'radial streaming'

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of scattered photons (Friend and Abbot, 1986; Pauldrach *et al.*, 1986). In the case of the 'finite-cone approximation', the optical depth depends on the absorbed photon ray direction $\mu = \cos\theta$, $\tau_i(r, \mu) = \chi_i(r)v_{\rm th}/[(1-\mu^2)v/r + \mu^2\, {\rm d}v/{\rm d}r]$, and the direction-averaged (radial) RP force differs considerably from the 'radial streaming photons' approximation at the base of the wind. The difference can be taken into account by introducing a correction factor to the force multiplier, which leads to reasonable agreement between the improved theory and the observations. This agreement indicates that the concept of a radiation-driven smooth wind is acceptable approximation for the dynamics of time-averaged and quasistationary winds of hot luminous stars.

The result shows that the RP, which is chiefly due to the line-scattering processes, does indeed drive the matter outflows from the O–B stars, but one must keep in mind that the theory of the smooth outflow is only a first approximation. It treats the flow as stationary and purely radial, and it takes into account only the initial scatteriug of photons, but real flows are variable, they depend on the star rotation, and plural scattering of Doppler-shifted photons leads to a much more complicated picture.

The Doppler shifts of the photon's energy dlue to the velocity differences in the escaping and absorbing points leads to the complicated connection of different lines (the multiline processes). However, the calculation technique of determination of the parameter $\alpha$ in equation (12) is based (in agreement with the 'smooth approach' ideology) on the averaging of the radiation flow through finite spectral intervals and, in this sense, it ignores the radiation coupling of different lines. The problem of the interdependence of different lines was first considered by Grachev and Grinin (1975) for individual lines and by Rybicki and Hammer (1978) for the general case. In the case of the radiation-driven stellar wind the multiline problem was investigated by Abbot and Lucy (1985), and in more detail by Puls (1987). He has shown that the line's interaction influences the gas dynamics but, in the spherically symmetrical (and smooth) hot-star winds, the effects of the emission and absorption line interactions partially compensate each other. This result is far from universal; in particular, the line interactions play an important role in the QSO matter outflows.

We stress that the unique solution of the steady smooth wind equation (13) is determined to be a *single* (critical) value of the mass loss rate $\dot{M} = {\rm d}M/{\rm d}t$ (CAK). This means that, if $\dot{M}$ is variable, the formal solution with a disrupted velocity gradient appears, provided that the mass loss is smaller than the critical value (Vilkoviskij and Tambovtseva, 1992). Of course, such a situation is not quite acceptable from the physical point of view, because observations show the real variability of the wind's mass flows, and the analysis of radiation-driven wind stability (Lucy, 1984; Owocki and Rybicki, 1984, 1985, 1986) shows that the winds of hot stars are unstable. Nevertheless, beginning in 1986 (Friend and Abbot, 1986; Pauldrach *et al.*, 1986) the paradigm of the 'smooth steady cold winds' (SSCWs) was established The main observational support for the SSCW approach was connected with the results from the calculations of the UV-line profiles, which were in a satisfactory agreement with the observed values from most O and many B stars (Vilkoviskij and Tambovtseva, 1992).

## 2.2 The unstable structured variable winds with the X-radiation

The SSCW model assumes that the winds are smooth and steady as a first approximation. However, one must keep in mind that the observed line profiles are averaged from the whole stellar wind seen. Because of this we observe the spectrum that is averaged over the wind volume and the exposure time, and the inhomogeneous structure is smoothed in space and time. Nevertheless, the variability (observed most of all in the so-called 'narrow absorption components' and the terminal velocities) is the fundamental property of the stellar winds of all the O–B stars. On the other hand, the deviations of the observed ion relative

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numbers from the 'cold-wind model' are difficult to explain with the ionization from only excited levels, as was assumed by Pauldrach (1987), but they are mostly connected with structure inhomogeneity and the additional X-ray ionization (Rogerson and Lammers, 1975).

The X-ray emission from hot stars, discovered by the Einstein Observatory (Harnden *et al.*, 1979), was understood in terms of the hot-gas emission generated at the fronts of shock waves in the wind. Further observations in the X-ray band show that the O–B stars are the sources of X-radiation power, proportional to the star bolometric luminosity, $L_X \approx 10^{-7} L_B$ (Long and White, 1980; Pallavicini *et al.*, 1981; Chlebowski, 1984, 1989; Scioritino *et al.*, 1990, Berghofer *et al.*, 1996). The earlier idea by Cassinelly and Olson (1979), developed by Waldron (1984), about the inner 'thin hot corona' was transformed later to the model of 'shock-structured' winds (Lucy and White, 1980; Lucy, 1982). In this model the X-rays are assumed to radiate from strong shocks deep in the stellar wind, and the model was supported by observations of non-thermal radio emission from O–B stars (Abbot *et al.*, 1984), interpreted in terms of a shock acceleration model by White (1985).

In any case, strong X-ray fluxes would be impossible from smooth cold winds at all; so we have to realize that the SSCW model is far from the real nature of the hot stellar wind outflow, and it must be changed to the more adequate model of an unstable structured variable wind (USVW).

As mentioned above, the hot-star winds are unstable, and the instability leads to the wind structure and variability, which depends also on the surface imhomogeneities of the stars (the non-radial pulsation in particular). The instability was first mentioned by Lucy and Solomon (1970) and has been investigated by MacGregor *et al.* (1979), Carlberg (1980) and Lucy (1984). The results of the earliest studies were discrepant; Carlberg (1980) showed that the wind's flows are unstable, but Abbot (1980) concluded that they are stable. However, the more general analysis by Owocki and Rybicki (1984) demonstrated that the stability depends on the wave length of the small perturbations. The most detailed analysis of the line-driven instability has been made by Owocki and Rybicki (1984, 1985, 1986); three-dimensional perturbations were discussed by Rybicki, Owocki and Castor (1990).

Detailed time-dependent hydrodynamic calculations was performed by Owocki *et al.* (1988). The calculations showed that the reverse shocks are stronger than the forward shocks, in contrast with what was assumed in earlier models. The high-velocity gas is accelerated in the intershock low-density space intervals, while most of the wind mass is concentrated in the shocks (Puls *et al.*, 1993). Note that the picture is drastically different from that of the smooth wind and that the calculated UV spectra in the model by Puls *et al.* (1993) are in better agreement with the observed spectra; moreover, the 'narrow absorption details' are interpreted as a consequence of the absorption in the shocks.

As regards the X-ray spectra, it was shown (Corcoran *et al.*, 1993; Hillier *et al.*, 1993) that the high-resolution X-ray spectra of $\zeta$ Puppis can be successfully interpreted in shock-structured wind models, which is available for the Wolf–Rayer (WR) stars as well (Baum *et al.*, 1992). Assuming that the dependence of the shock temperature $T_s$ on the shock velocity $U$ can be expressed as $T_s \approx 2.3[\mu/(1+\gamma)10^5[U\ (\mathrm{km\ s^{-1}})]^2$, and estimating the cooling time of the shock as $t_c \approx 1.5(1 + N_e/N_p)kT_sN_p/(4N_eN_p\Lambda_{ST})$, where $N_e$ and $N_p$ are the number densities of electrons and protons respectively and $\Lambda_{ST}$ is the cooling function, Hiller *et al.* (1993) have estimated the behaviour of $t_c$ with the distance $r$ from the star's surface. The result is that the heated fronts of the shocks in O–B stars are effectively cooled, at distances not too much larger than $r \approx 10R_*$. This means that the outer hot coronae of the winds can exist.

In the structured wind model calculations of Puls *et al.* (1993), it was assumed that small periodic perturbations exist at the base of the wind. The connection of the structure of

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dynamical instability and the variability of the winds with the star vibrations became an important question.

The very complicated problem of the wind variability has been investigated for many years. Winds of O–B stars, as observed in the P Cygny-type profiles in UV spectra, are variable on time scales from many days to hours (see for example, Henrichs (1984) and Prinja and Howarth (1986)). Since the launch of the IUE satellite, the time behaviour of spectral features has been studied carefully, and it became clear that the variations are not chaotic, but occur in defined 'patterns' (Prinja *et al.*, 1987; Henrichs *et al.*, 1988), mostly seen in the discrete absorption components (DACs). These variable DACs have been detected in UV spectra of more than 80% of 203 O stars (Howarth and Prinja, 1989) and represent a fundamental property of radiation-driven winds.

One of the most important questions is the connection of the wind variability with the variability of the velocity structure in the photosphere of the stars. The question has been investigated with correlated ultraviolet (IUE) and optical (H$\alpha$, He II, $\lambda = 4686$ Å and other lines) spectroscopy. Precise observations show that spectroscopic and photometric microvariability is seen in the majority of early-type stars (Balona, 1992; Fullerton *et al.*, 1996). Fullerton *et al.* (1996) showed that the spectroscopic variations in the luminous stars has been attributed to stellar wind effects and suggested that the photospheric line-profile variability in most O supergiants may be due to the evolution of low-velocity stellar wind structures.

A detailed investigation of the correlations of the optical (photospheric) and UV (stellar wind) lines in the O4 supergiant $\zeta$ Puppis was performed by Reid and Howarth (1996). They have shown that there are periods of about 8.54 h (consistent with non-radial pulsations $l = -m = 2$) and 19.6 h (the recurrence time of the DAC), the latter seen in H$\alpha$ features, moving from blue to red at velocities more positive than $-280\,\mathrm{km\,s^{-1}}$ and red to blue at more negaive velocities. This result seems to be extremely important, as it indicates the possibility of the 'fall' of some dense 'pieces' from the critical point regions, while those at larger velocities are involved in the outflow and dragged by the wind.

The investigations of the stellar wind are still in the phenomenological phase, but they are very important as evidence of the deep connection of the behaviour of star atmospheres from astroseismology to wind properties. It may be added that the variability and the properties of some lines (Pa$\beta$, $\lambda = 12818$ Å and others) in the far-infrared band (Kauff, 1993) are still not interpreted in detail. As a whole, we can conclude that the stellar wind phenomenon is still far from being completely understood, that the USVW model is at the beginning of its development and that the problem will reveal new and interesting physics.

### 2.3 Particle acceleration, $\gamma$ radiation and multiple flows

One of the most interesting question in this relation seems to be the possibility of particle acceleration at the shocks in stellar winds. This possibility was discussed by Casse and Paul (1980, 1982). The authors have considered mostly the particle acceleration at the terminal shock of the winds and the acceleration in the turbulent winds. The more detailed analysis of the problem was performed by Cesarsky and Montmerle (1983) in connection with the problem of the origin of $\gamma$-rays from the O–B associations, partly observable by the COS-B instrument (Hermsem *et al.*, 1977; Swanenburg *et al.*, 1981). The notable result of the work is the analysis of different sources of the cosmic rays. In the early age of a star-birth region the main contributor are the stellar winds of O–B stars; then after $(5–6) \times 10^6$ years there is a short period when the acceleration from the WR stars dominated, and finally the SN-dominated phase comes. The duration and the cosmic ray (CR) power of the phases depend on the properties of the O–B associations. In particular, these authors predicted the

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$\gamma$-ray flux from the Orion association to be about $10^{-5}$ photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in the first (wind-dominated) phase and an increase in the flux to that of a 'typical COS-B source'.

The prediction of the charged-particle acceleration in the shock-structured winds has been supported by the observation of the non-thermal radio emmission from O stars (Abbot *et al.*, 1984). White (1985) explained the observations as the result of electron acceleration at the shock fronts in the unstable hot-star winds.

He argued that the incident particle momentum spectrum $N_0(p)$ is accelerated by a single shock to be

$$N_1(p) = (\mu - 1)p^{-\mu} \int_0^p \mathrm{d}q\, q^{\mu-1} N_0(q),$$

where $\mu = (\chi + 2)/(\chi - 1)$ and $\chi$ is the compression ratio of the shock (Blandford and Ostriker, 1978). If $N_0(p)$ is a monoenergetic spectrum at momentum $p_0$, then after acceleration by $n$ shocks the spectrum will be

$$N_n(p, p_0) = \frac{(\mu - 1)^n}{(n - 1)!} \left[\ln\left(\frac{p}{p_0}\right)\right]^{n-1} p_0^{\mu-1}/p^{\mu}.$$

which after repeated acceleration for $n \geqslant 10$ shocks is reduced (Bell, 1978) to

$$N(p) \approx \frac{\mu - 1}{p}.$$

Of course, the limit $p_{\max}$ must exist for the total energy of accelerated particles that do not diverge, and White (1985) argued that this energy limit is defined by the condition that the particle is able to diffuse from shock to shock. From this condition the energy limits for a typical O star are around 1–10 GeV. White (1985) has shown that the theory is able to explain the observed non-thermal radio spectra from hot stars. He also concluded that high-energy particles in the stellar wind may produce $\gamma$-rays and, moreover, 'shock-accelerated particles near the star may be the stronger (than the terminal shock) source of $\gamma$ rays because the gas density is much stronger there'.

One of the most difficult problems, however, is the injection of particles before further acceleration in the shocks. Let us consider an injection mechanism, which is connected with the RP and allows us to predict some properties of the $\gamma$-radiation from the Orion complex. The reason is that, besides the dynamic instability, there is another instability of the radiation-driven wind flows, which we call the 'kinetic instability' (Vilkoviskij, 1981).

In the above-described analysis of the stellar wind acceleration (Section 1), the ions which provide action of the RP to the whole plasma are assumed to be 'frozen' into the plasma; that is, we neglect the motion of the ions relative to the plasma. However, in reality the motion indeed exists, because the ions absorb a moment from the radiation flux with the resonance scattering of the photons and then give the moment to the 'passive' plasma particles owing to the particle collisions. The crucial fact is that the frictional force, acting on the moving ion owing to Coulomb particle interactions, has a maximum at the velocity of the ion close to the proton thermal velocity. So, if the RP force acting on the ion is larger than the maximum frictional force, the ions are accelerated independently of the rest plasma ('runaway' ions).

Vilkoviskij (1981) showed that, as a rule, in smooth winds (the SSCW model) the 'runaway condition' is fulfilled far from the photospheres of the O and early B stars. The situation in the atmospheres of the A and late B stars was discussed by Babel (1995, 1996) from a

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similar point of view, and he showed that in these stars the separation of the ions by the RP can occur close to the photospheres.

Let us consider the problem in more detail.

The momentum equations for the $i$th particle (Braginskii, 1965; Burgers, 1969) can be written as

$$m_i u_i \frac{\mathrm{d}u_i}{\mathrm{d}r} = f_{i,\mathrm{rad}} - m_i \frac{GM_*}{r^2} + f_{i,\mathrm{drag}} + z_i eE, \tag{17}$$

where $m_i$, $u_i$ and $z_i$ are the mass, velocity and charge (relative to the proton charge) respectively of the particle; on the right-hand side of the equation there are radiation, gravity, drag and electric forces. The drag force, acting on the $i$ particie from the other $k$ species is $f_{i,\mathrm{drag}} = \sum_{k\neq i} \nu_{ik} x_{ik} G_1(|x_{ik}|)$, where $\nu_{ik} = (16\pi^{1/2}/3) n_k z_i^2 z_k^2 e^4 \ln(\Lambda)/2k_\mathrm{B}T$, $T$ is the plasma temperature, $x_{ik} = (u_i - u_k)/(2k_\mathrm{B}T/M_{ik})^{1/2}$, $u_k$ is the average velocity of the particles of the $k$th species, which are assumed to have the Maxwell velocity distribution around the average velocities, and $M_{ik} = m_i m_k/(m_i + m_k)$ is the reduced mass. The Chandrasekhar function

$$G_1(x) = \frac{3\sqrt{\pi}^{1/2}}{4} \frac{\mathrm{erf}(x) - x\mathrm{d}[\mathrm{erf}(x)]/\mathrm{d}x}{x^3}. \tag{18}$$

One of the present authors (Vilkoviskij, 1981, 1994) used $G(x) = xG_1(|x_i|)$. This function may be approximated by $G(x) \sim x/(1+x^3)$, where the maximum at $x \approx 1$ is distinctly seen.

Vilkoviskij (1981) and Vilkoviskij and Tambovtseva (1988) showed that the runaway ions can heat the wind to a temperature higher than the effective temperature of the star (the warm wind (Lamers and Snow, 1978)). A similar conclusion was made by Springmann and Pauldrach (1992), who have applied the idea to the calculation of the heating of the winds of two particular stars ($\zeta$ Puppis and $\delta$ Sco). Vilkoviskij (1994) concluded that in some cases the process can even lead to the generation of an outer hot coronal region, and runaway ions can produce $\gamma$-radiation by nuclear interactions of the fast ions with the protons and helium nuclei of the wind. The conclusion has become of great interest in connection with the $\gamma$-ray observations from the Orion region by COMPTEL on board the GRO satellite (Bloeman *et al.*, 1994). The unexpected result was the high intensity of the $\gamma$-radiation and the large width of the C and O $\gamma$ lines. Together with the low $\gamma$ flow in the 1–3 MeV band, this leads to the conclusion that mostly the accelerated C and O nuclei interact with the rest H and He nuclei, and a strong deficit of protons and $\alpha$ particles exists among the accelerated nuclei. Altough the result of Bloemen *et al.* (1994) was doubtful, it inspires an interesting discussion. Ramaty *et al.* (1995) have shown that the unusual cosmic-ray composition can be explained by particle acceleration from an object with unusual chemical compositions, such as WR CW-type stars or $25M_\odot$, the progenitor stars of SN explosions; a similar explanation of the CR acceleration by the SN shocks was discussed by Bloemen *et al.* (1997). Nevertheless, questions regarding the absence of H and He nuclei in the Orion low-energy cosmic rays remain. Nath and Biermann (1994) suggested that the cosmic rays may be generated in the stellar winds of O–B stars but still did not explain the preferred acceleration of the C and O nuclei. One of the present authors (Vilkoviskij, 1996, 1997) argued that the results of Bloemen *et al.* (1994) can be explained by the ion acceleration in the hot star winds of the Orion nebula.

It can be shown that the distribution functions $f_i$ of the accelerated ions are well reproduced with the power functions

$$f_i(E) = f_0 E^{-\alpha}, \tag{19}$$

where $\alpha \approx 1$ (Vilkoviskij, 2000).

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The functions are terminated at the maximal energy, defined by the condition $E_{\max} = m_i a_i R_*^2 / R_0$, where $a_i$ is the ion radiative acceleration at $R = R_*$ and $R_0 > R_*$ is the initial acceleration radius. The calculations show that the maximum energies of the ions accelerated from $R \approx R_*$ can reach 20–10 meV per nucleus in O stars, but they are lower in B stars. However, still the maximum energies are sufficient to accelerate the ions above the injection energy that is needed for subsequent acceleration by shocks of the stellar winds even for stars as late as B3.

So one can conclude that the 'ion runaway' induced by the RP could work as a selective injection mechanism, which favours further acceleration in the shocks of the ions with strong resonance lines (such as O V1, Si IV and C IV ions).

With the distribution functions (19) we can calculate the spectra of the $\gamma$-radiation from O–B stars and the output of the radioactive $^{26}$Al isotope. The result shows that (with definite assumptions) the COMPTEL spectrum in the 3–10 MeV band is well produced, and the $^{26}$Al yield could explain its ability in the interstellar environment. The problem of other short-living isotopes (see for example Clayton (1994)) may be considered from this point of view as well.

More precise observations of the X-ray and $\gamma$-ray spectra are needed to resolve many questions about particle acceleration physics in stellar winds.

## 3 THE BROAD-ABSORPTION-LINE QUASAR PROBLEM

Obviously, the RP plays an important role in active galactic nuclei (AGNs), as they contain the most luminous sources. The structure of AGNs in the vicinity of the central object is still unknown in detail; the most promising picture follows from the so-called 'unified models' (Antonucci, 1993; Urry and Padovani, 1995). These models assumed that many differences in the AGN radiation spectra in optical–UV–X and radio bands are explained by the different viewing angles relative to the rotational axis of the objects. In the optical and UV bands it depends on absorption by an 'obscuring torus', and in the radio band mostly on the relativistic effects in the axially moving jets. Of course, some differences cannot be explained by this way, in particular, the difference between the radio-loud and radio-quiet QSOs.

Although the RP effects take place in many processs of AGN physics, we concentrate here on one particular subclass of AGNs, namely the BAL QSOs, showing UV absorptions which in a sense are similar to those of O–B stars. The main difference is that, in BAL QSOs, only wide blue absorptions are seen, in contrast with the classical P Cygni profiles. The difference is naturally explained by non-spherical geometry of the BAL QSO outflows. It should be noted that the broad emission lines seen in the BAL QSO spectra originated not in the outflows, but in the much more compact broad-emission-line region (BELR), which is shielded by the outflowing gas. Evidence of the so-called line-locking effect (Scargle, 1973; Foltz *et al.*, 1987; Korista *et al.*, 1993) is a significant peculiarity of many BAL spectra. This effect indicates the essential influence of the RP in spectral lines on the gas dynamics.

The quasars with BALs in their spectra represent about 10% of all optically detected quasars (Hazard *et al.*, 1984; Turnshek, 1984, 1988). Nevertheless, understanding the physics of this particular subclass of AGNs is extremely important for understanding the AGN physics as a whole. It was shown (Junkkarinen *et al.*, 1987; Steidel and Sargent, 1991) that the emission spectra of BAL QSOs are close similar to those of non-BAL QSOs, but BAL QSOs are mostly radio-quiet objects (Stocke and Foltz, 1992). One can suppose that the 10% part of BAL QSOs to all QSOs) is explained by the non-spherical geometry of the absorbing outflows, and almost all the radio-quiet QSOs contains such flows, shadowing

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approximately 10% of the total $4\pi$ solid angle. In that case the BAL QSO theory would be an essential part of the AGN theory as a whole. Comprehensive reviews of the BAL QSO properties have been given by Weymann *et al.* (1985), Turnshek (1988) and Turnshek *et al.* (1988).

### 3.1 Looking for the theory: the radiation pressure and drag force in broad-absorption-line quasars

While the first BAL QSOs were discovered very early (Lynds, 1967; Burbidge, 1970) and the objects were intensively investigated, there is still no satisfactory theory of the phenomenon. The earliest dynamic models supposed a hot thermal wind or cosmic-ray flow, which drags cold clouds (Weymann *et al.*, 1982), and a wind driven by a flow of relativistic neutrons that are decaying (Begelman *et al.*, 1991). An attempt to consider the line-locking effect was made by Vilkoviskij (1990, 1991), but the observed acceleration to high velocities remains unexplained in the case of smooth gas flow.

The closest approach to the above-described radiation-driven wind theory was worked out by Arav and Li (1994) and Arav and Begelman (1994). The first idea was to avoid drag forces at all, and to explain the cloud confinement by magnetic pressure, but then a hot intercloud gas was considered as well. They calculated 'force multipliers', defined by analogy with the stellar wind. Two types of radiation spectrum were used: one from the work by Mathews and Ferland (1987), and the other as a cut power law. Then they solved numerically the equation of motion for the clouds, assuming the confining extended pressure to be in the form $p = p_0(r/r_0)^{-\beta}$. Choosing the appropriate free parameters, they calculated the cloud dynamics and the absorption spectra. The resulting absorption 'troughs' are smooth and structureless, far from the observed values, but the terminal velocity is of the correct order of magnitude. The other variant of the cloud dynamics, when the clouds are rigidly coupled with the confining hot gas includes more free parameters and gives profiles more similar to the observed data. The main result of these studies is that the RP force can accelerate the gas clouds in QSOs to the velocities that are observed in the BAL QSOs.

The role of RP was supported in the work by Arav *et al.* (1995) and Arav (1996). They explored the effect of increasing the RP owing to the action of Lyman $\alpha$ ($\lambda = 1216$ A) broad emission line on the N V ion ($\lambda = 1240$ A) resonance transition, which is moved through the Lyman $\alpha$ emission line as a result of the Doppler shift of the absorbing N V line. This leads to a double-trough phenomenon (Korista *et al.*, 1993): the appearance of a 'ghost' emission feature between the two troughs.

The questions of the role of drag forces and of the absorbing matter source remains unsolved. In principle, flow without any confinement is possible (Murray *et al.*, 1995) but, in the usual case, drag forces have to be analysed. In the work by Scoville and Norman (1995) the source of the absorbing clouds is assumed to be the mass loss from red-giant stars, and the dust absorption was considered as the main reason for the RP force. These workers concentrated mostly on the problem of the generation of the absorbing clouds, and they used earlier ideas (Scoville and Norman, 1988) of the red-giant star envelopes as the main sources of the BELR clouds. So, the problems of confinement of the absorbing cloud, the BAL-flow geometry and the source of the absorbing matter are the most difficult questions of the BAL QSO theory.

Our theoretical approach to the problem is based on the assumption that similar processes are responsible for both the broad absorptions and the narrow details of the BAL QSO spectra; so the explanation of the last (more delicate) phenomenon permits us to solve the problem of the broad absorption as a whole. It was Milne (1926), who predicted theoretically the decrease in the acceleration of atoms (ions) by the RP owing to the influence of the

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absorption lines. More than 40 years later, Scargle *et al.* (1970) considered a similar effect due to the shift of the line to the continuum edges such as the Lyman edge. The same phenomenon in the case of two lines was discussed by Mushotzky *et al.* (1972), who call it the 'line-locking' effect. Scargle (1973) had gathered together many examples of discrete quantized outflow velocities (i.e. the shifted absorption line systems) in stars, Seyfert nuclei and QSOs, and he supposed that the peculiarities are a result of the line locking.

Of course, most line-locking features are observed in the BAL QSO spectra, and there are several objects with the very distinct manifestation of the effect in their spectra; the most impressive is the spectrum of Q1303+308 (Foltz *et al.*, 1987). Our investigations (Vilkoviskij, 1991) show that, from the physical point of view, one needs some other force in addition to the RP force to 'push' the gas velocity out of the most deep absorption line shadows. Such a force may be given by the drag force owing to the interaction of the gas clouds with the hot-gas flow.

### 3.2 The hot-gas dynamics

For the full BAL QSO investigation, one has to consider the two-phase medium flow (the cold clouds embedded into the hot gas), which is widely supposed to exist at AGNs. Vilkoviskij *et al.* (1996, 1999), considered the BAL QSO theoretical problems within the more general approach to the AGN theory, which we call 'the interacting subsystems theory'. Namely, we consider the AGN phenomenon to be the result of the physical interactions of the three main subsystems: the central object (CO) (i.e. the massive black hole and the accretion disc), the surrounding compact stellar system (CSS) and the gas subsystem. There have been several studies using similar ideas (see for example Weymann *et al.* (1982), Duncan and Shapiro (1983) and David *et al.* (1987)), but the model calculations of these studies did not include gas dynamics and spectral simulations, and several model parameters were far from the real physical situation in some aspects. We suppose that the thin features of the BAL QSO spectra are sensitive to these 'hidden' parameters of the subsystems (as the CSS and the hot gas are invisible as a rule). Because of this, we have included these parameters into the theory and we use the BAL QSO spectra modelling for more precise determination of the main physical properties of the objects. The main idea is that the BAL QSO spectra contain information about some of these 'hidden parameters', and they can be determined by comparison of theoretical model calculations with the observed spectra.

The heat balance analysis of the two-phase medium situated in the central part of AGNs shows (Krolic *et al.*, 1981; Kwan and Krolik, 1981) that the temperature of the hot gas is rather high, about $10^8$–$10^7$ K. Because of this, the electron heat conductivity is high enough, and we may treat the stream of the hot gas as an isothermal flow at a first approximation. We shall discuss the problem of gas heating below.

Vilkoviskij *et al.* (1994, 1999) Vilkoviskiy and Karpova (1996) considered Parker-type equation for a radial flow of the hot gas in the form

$$v\frac{\mathrm{d}v}{\mathrm{d}r}\left(1-\frac{a^2}{v^2}\right)=\frac{2a^2}{r}-\frac{GM(r)}{r^2}+g_{\mathrm{drag}}+g_{\mathrm{rad}}, \tag{20}$$

where $v$ is the velocity of the hot gas, $a=(kT/m_{\mathrm{p}})^{1/2}$ is the sound velocity, $r$ is the radial distance; on the right-hand side of the equation there are the accelerations due to the gas pressure, to the gravity, to the drag force from cool clouds and to the radiation pressure.

The notable difference between equation (20) and the Parker solar wind equation is that the mass $M(r)$ depends on the distance $r$. The $M(r)$ is the mass under the $r$ sphere and it is the sum

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of the masses of the CO (the massive black hole) and the 'distributed mass' of the compact stellar cluster (the stellar kernel). The last can be much more massive than the first, and this leads to important consequences. As was shown in our work (Vilkoviskij and Karpova, 1996), in the common case equation (20) has three peculiar points instead of the single critical point of the Parker solar wind equation. Because of this, the point of the supersonic transition may be either the first point (internal point, close to the CO) or the third (outer) point, situated out of the character kernel radius.

The position of the transonic point depends mostly on the relations $\xi = M_{\rm k}/M_{\rm CO}$ of the two masses, the kernel mass to the CO mass. lt can be argued that the second case (the outer critical point) is more preferable for the BAL QSO models. Physically it means that BAL QSOs contain a very massive and compact stellar kernel, so that the hot gas is confined inside the kernel gravitational potential hole, and the hot-gas stream is subsonic in the kernel and becomes supersonic out of the kernel radius, where broad absorptions are formed.

Of course, the isothermal flow is considered by us as a first approximation only. There are several mechanisms of hot-gas heating; the most important seems to be bow shocks and dissipation of the energy of cosmic rays. As the details of the heating mechanism are still indefinite, we used the simplest approximation of a 'constant temperature gradient'. Because the terminal velocity of clouds is connected with the hot-gas termninal velocity, and the observed maximum velocities of the BAL QSO troughs are rather high, we suppose that the hot-gas temperature rises below the transonic transition point from $10^8$ K to several $10^9$ K. Introducing the positive temperature gradient into the hot-gas flow equation (20) and solving the equation, we have the solutions with the terminal velocities as much as four to five times the sound velocity, that is, up to 30 000–40 000 km s$^{-1}$.

### 3.3 Radiation transfer in the clouds and the cloud dynamics

For the BAL QSO spectra modelling, we have to derive and to solve the equation system of the three interacting flows: the cold clouds, the hot gas and the radiation flows. This approach allows us to explain both the wide BALs and the line locking.

In the general case we must solve together the radiation hydrodynamic equation system, including the mass continuity equation, the momentum and the energy equations for both gas flows, and the radiation transfer equations for both the continuum and the lines. Finally the equation system requires the photoionization and the heat balance equations for the clouds and the hot gas. All the equations depend on the CO and the stellar kernel parameters: the CO mass, luminosity and spectrum, and the CSS mass and mass distribution.

We assume that the radiation transfer in the spectral lines is determined by the resonance scattering process in the clouds only, because the optical depth in the intercloud medium is very thin. Also, we shall take into account only one scattering as the first approximation, neglecting multiscattering processes between the clouds.

For a line we determine the optical depth of a cloud at the line centre as $\tau_i = (\pi e^2/mc)N_i f_i/\Delta\nu_{\rm D}$, where $e$ and $m$ are the electronic charge and mass respectively, $N_i$ is the cloud's column density of the ions which absorb (scatter) the photons with the frequency $\nu_i, f_i$ is the oscillator strength and $\Delta\nu_{\rm D} = \nu_i \upsilon_{\rm t}/c$ is the turbulent Doppler width ($\upsilon_{\rm t}$ and $c$ are the ion turbulent velocity and the light velocity respectively). Every cloud absorbs the $1 - \exp(-\tau_{\rm i})$ part of the radiation flow at a line centre, and the clouds can shield each other. Then we have the differential equation for the spectral density of the radiation flow $\Phi(\nu)$:

$$\frac{{\rm d}\Phi(\nu)}{{\rm d}r} = -\Phi(\nu)N_{\rm cl}S_{\rm cl}\left[1 - \exp\left(-\sum_i \phi(\nu - \nu_i)\tau_i\right)\right], \tag{21}$$

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where $N_{\rm cl}$ is the number of clouds in a volume unit, $S_{\rm cl}$ is the geometrical cross-section of a cloud (so $N_{\rm cl}S_{\rm cl}\,{\rm d}r$ is the probability that a photon meets a cloud at a distance d$r$); within the exponent there are the normalized line profile functions $\phi(\nu{-}\nu_i)$ and the optical depths $\tau_i$ for the resonance scattering at the line centres in a cloud. The Doppler-shifted frequency is $\nu_i = \nu_{i0}((1+V/c)/(1-V/c))^{1/2} \approx \nu_{i0}(1+V/c)$, where $V$ is the cloud's velocity and $\nu_{i0}$ is the appropriate $i$ in line central frequency.

Therefore both the filling factor and the velocity of the clouds are taken into account; in the case of a finite length (when integrating over d$r$) it leads to the equation which had been proposed by Kwan (1990). The equation of the ionizing radiation transfer can be written similarly (Vilkoviskij *et al.*, 1999).

Now we can consider the dynamics of the clouds, taking into account both RP and radiation transfer effects. The equation of motion of a separate cloud can be written as

$$m_{\rm cl}\frac{{\rm d}V}{{\rm d}t} = F_{\rm lin} + F_{\rm cont} + F_{\rm drag} - F_{\rm gr}, \tag{22}$$

where $m_{\rm cl}$ is the cloud's mass and $V$ is its velocity; on the right-hand side of the equation there are the forces of the RP due to the scattering of the radiation by the ion lines ard due to continuum absorption, the drag force due to the velocity difference of the cloud and the hot-gas stream, and the gravitational force.

In numerical solutions we define the radiation force acting on a cloud as the difference between the radiation flow moments before and after the cloud crossing:

$$F_{\rm rad} = F_{\rm lin} + F_{\rm cont} = \frac{S_{\rm cl}}{c}\left(\int \Phi(\nu)h\nu\,{\rm d}\nu\bigg|_{\rm before} - \int \Phi(\nu)h\nu\,{\rm d}\nu\bigg|_{\rm after}\right).$$

We use the Gaussian profiles in the line-transfer equation (21) and, when solving the full equation system numerically, we take a care for the cloud velocity differences from step to step be less than one fifth of the linewidths; this condition is necessary for the correct calculation of the line-locking effect.

The drag force depends on the square of the velocity difference between the cloud and the hot gas: $F_{\rm drag} = \rho_{\rm hg}S_{\rm cl}[v(r) - V(r)]|v(r) - V(r)|$. For spherical clouds, confined by the hot-gas pressure, $S_{\rm cl} = \pi\{m_{\rm cl}/[\frac{4}{3}\pi\rho_{\rm hg}(T_{\rm hg}\mu_{\rm cl}/T_{\rm cl}\mu_{\rm hg}]\}^{2/3}$ from the pressure balance condition $(\rho_{\rm cl}/\mu_{\rm cl})T_{\rm cl} = (\rho_{\rm hg}/\mu_{\rm hg})T_{\rm hg}$; here $\rho_{\rm cl}$, $T_{\rm cl}$, $\mu_{\rm cl}$ and $\rho_{\rm hg}$, $T_{\rm hg}$, $\mu_{\rm hg}$ are mass density, temperature and molecular weight of the cloud's gas and the hot gas respectively.

The numerical solutions of the full equation system described above were obtained under the following assumptions.

(i) The incoming spectrum (before the absorption) is a typical QSO spectrum, including the broad emission lines.

(ii) We assume conservation of the mass outflow, which consist of the sum of the flows of the hot-gas and the clouds, but the flows can exchange masses (evaporation and disruption of the clouds in particular). Usually we assume several types (from one to five) of spherical cloud, using the addition equations of the disruption and evaporation rates for mass transfer between the types. The disruption condition was that the higher-mass cloud is disrupted most intensively to low-mass clouds when the former is compressed by the drag pressure more than by the confining pressure.

(iii) We tested both inner and outer locations of the transonic point of the hot-gas flow equation solutions, and we found that the inner point solution results are inconsistent with the observed BAL QSO spectra. So we used the outer point solutions for the BAL

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QSO modelling. We suppose that the absorbing clouds are generated at the distance $R_0$ owing to disruption of much more massive clouds from the obscuring torus.

(iv) At every step of the numerical solution we calculate the gas dynamics and the spectrum of the radiation flow. We took into account 114 resonance lines of the most important ions (using the atomic data from the work of Morton *et al.* (1988) and Morton (1991).

The results of the BAL QSOs model calculations have been given by Vilkoviskij *et al.* (1999). In that work it was shown that the line-locking effect is simulated in the BAL QSO spectra because of the 'quantization' of the cloud acceleration and the velocity on the hundred parsecs scale, but the mechanism of the line-locking here is different from that described by Milne (1926). We show that the main role is played by the absorption of many paths in the system of clouds in the case when the total acceleration is small enough. Then a non-leaner process develops; the absorption decreases the acceleration, which increases the absorption, which in turn leads to zero total acceleration and constant velocity. In fact the acceleration can even be slightly negative owing to strong absorption. However, we would like to stress that in the region of nonlinearity the cloud's dynamics become extremely sensitive to the line-overlapping influence (owing to the assistance of drag force deceleration), and this explains why even a single line overlapping can lead to the locking of acceleration in this case. The stability of the line-locking effect in the variable BAL QSO q1303+308 was analysed by Vilkoviskij and Irwin (2001).

The conditions which promote the line-locking effect are as follows.

The acceleration due to the line-scattered radiation must exceed the continuum absorption acceleration; so the masses of the clouds must be rather small, typically about $(10^{-12}$–$10^{-13})M_\odot$. The mass flow of the clouds must be limited also, typically $\Phi_{cl} = q(10^{-1}$–$10^{-3})M_\odot$ year$^{-1}$, where $q$ is the 'global' covering factor (as seen from the CO).

If these conditions are not satisfied, line locking does not appear. If the mass flow in the clouds is large, there are too many clouds in every velocity interval, and continuous absorption troughs are created, which are seen in the most BAL QSO spectra.

The most natural source of small clouds is their constant creation due to disruption of more massive clouds by the stream, when they are deformed and disrupted by the drag force. These massive clouds are assumed to exist in the obscuring torus (OT), where they have masses of about $(10^{-8}$–$10^{-7})M_\odot$. We suppose that such clouds are cut from the internal surface of the OT by the stream of the hot gas and then are disrupted into smaller and smaller cloudlets down to a stream.

From this 'unified model' we can derive the following explanation of 'high-ionization' and 'low-ionization' types of BAL QSO; if the observer's line of sight only touches the internal surface of the OT, small, high-ionization clouds dominate and one sees high-ionization BALs; however, if the line of sight is embedded in the OT more deeply, it crosses a large amount of large clouds, which provide more continuum absorption and the low-ionization clouds dominate. Owing to strong absorption (by H I and by dust in particular), the largest optical depths produce the lowest ionization. It was shown (Wampler *et al.*, 1995) that in the case of the low-ionization BAL Q0059-2735, at least two different cloud systems exist.

The model simulations based on our theory reproduce many important features of the observed spectra, and this proves the validity of the main propositions of the theory. So some preliminary conclusions on BAL QSO physics may be made.

First of all, we would like to stress once again that our attempts to reproduce the BAL spectra, when we use the 'inner critical point' solutions for the hot-gas flow do not lead us to success, but the 'outer critical point' solutions do. This means that the BAL QSOs have massive and compact stellar kernels, because the 'outer' critical point is typically realized under the condition $M_k \geqslant 10M_{co}$ and $R_k \approx 1$–$3$ pc. This conclusion is extremely important

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in the light of the hypothesis that all (or most of) the radio-quiet QSOs are 'intrinsic' BAL QSOs (Morris, 1988); that is, they all have BAL systems which are mostly invisible owing to the geometry. If this is really the case, our results allow us to suggest an explanation for the absence of strong radio-jets in radio-quiet QSOs: there is too much hot gas inside the massive kernels and it prevents the jets from coming out of the kernel interior. A similar explanation of the radio loud–quiet dichotomy was considered by Kuncic (1999), but without any physical explanation of the differences is the strong and weak jet cases.

The consequences of the presence of the compact stellar cluster for properties of the BELR, the AGN variability and evolution were considered by Vilkoviskij and Czerny (2002). Also, it was shown (Vilkoviskij, 1998, 2001), that absorptions in both Seyfert galaxies and QSOs can be explained in the framework of a common 'universal unification' scheme.

## 4 CONCLUSIONS

We have presented a brief review of the work devoted to dynamic effects produced by the RP in luminous astrophysical objects, which was performed at the Fessenkov Astrophysical Institute in the last decade. The most interesting problems, such as the structure, variability, dynamic and kinetic instabilities in stellar winds, and the line-locking effect and radio loudness–quietness dichotomy in BAL QSOs, are still far from being completely understood, and investigations on these problems are continuing.

### *Acknowledgment*

We would like to express our great respect for and gratitude to the memory of Academician V. G. Fessenkov, who founded our Institute in 1950, and who initiated the many directions of astrophysical investigations (including mass loss from hot stars) carried out at our Institute today, as well as the spirit of wide and free scientific search.

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