Line-driven winds from accretion disks in AGNs

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We investigate here the line-driven winds (LDWs) from accretion disks in active galactic nuclei (AGNs). Rapid mass loss via stellar winds is a phenomenon which has been associated with hot luminous stars. It is generally accepted as well that winds from OB stars, and perhaps from WR stars, are basically driven by radiation pressure in UV lines (Lucy & Soloman 1970; De Loore 1984; Castor, Abbot, & Klein 1975). Radiation driven winds, however, are not just limited to single stars. Cataclysmic binaries can produce LDWs either by radiation coming from the vicinity of the compact object or from its surrounding disk (Drew & Verbunt 1985). While accretion onto a supermassive black hole is believed to power AGNs, it appears also that substantial amounts of matter are accelerated and expelled from the system. Optical observations of relatively cold, $T_e \approx 10^4 - 10^5$ oK, gas in Seyferts and QSOs have been interpreted in favor of accretion disks there (Malkan & Sargent 1982). In our earlier work we have shown that such disks are capable of producing LDWs by scattering and absorption of disk-continuum photons (Shlosman, Vitello, & Shaviv 1985).

In the present work we investigate further the properties of LDWs from the disks. We find that basic differences exist between the stellar and the disk LDWs. The effect of coupling the ionization and thermal balance to the LDW hydrodynamics can hardly be overestimated in the latter case. As the z-component of of the disk gravity increases with height above the disk, a corresponding increase in the radiation line-force must come from changes in the ionization structure of the wind.

The radiation force applied to the LDW results from scattering and absorption of the disk-continuum photons in the Doppler-shifted UV resonance lines. The radiation force due to electron scattering opacity, $\kappa_{es}$, for an optically thin wind is given by

$$g_{es} = \frac{\kappa_{es} F}{c}, \quad (1)$$

where $F$ is the frequency integrated, locally emitted radiation flux from the disk. The line-radiation force per unit mass calculated in the Sobolev approximation and summed over absorption lines is given by:

$$gl = \sum_l \frac{F(\nu_l)}{c} e^{-\kappa_{li} \frac{1-e^{-\tau_l}}{\tau_l}}, \quad (2)$$
where $\nu_l$ is the frequency of the line center, and $\kappa_l$ is the line absorption coefficient normalized by the line-profile function in the absence of stimulated emission:

$$\kappa_l \rho = \frac{\pi c^2}{m_e e} f_l n_l$$

(3)

with $f_l$ and $n_l$ being respectively the line oscillator strength and the number density of absorbing ions in the wind. The optical depth for line absorption, $\tau_l$, depends on the local velocity gradient in the wind and is given by:

$$\tau_l = \frac{\kappa_l \rho c}{\nu_l} \left| \frac{dv_x}{dz} \right|^{-1}.$$  

(4)

We find, that contrary to the stellar LDW, the line force for disk LDW depends upon the ionization state of the absorbing ions in the wind, in addition to being dependent on the velocity gradient. This is taken into account by calculating self-consistently the ionization and thermal balance structure in the wind.

The dynamics of the LDW can be approximated by a set of three equations (Shlosman, Vitello, & Shaviv 1985): the continuity equation,

$$\rho v_x \Omega = \dot{M},$$

(5)

the momentum conservation equation along the streamline which starts at the disk surface at the radius $R$,

$$(v_x^2 - v_s^2) \frac{dv_x}{dz} = v_x \left\{ \frac{2v_x^2}{\Omega R^2} - \frac{dv_x^2}{dz} - \frac{GM_{BH} z}{\Omega^{3/2} R^3} \left( 1 - \Gamma_{ss} \right) + g_l \right\}.$$  

(6)

and the energy conservation equation,

$$\frac{dT}{dz} = \frac{2}{3} \frac{1}{v_x} \left\{ \frac{H - \Lambda}{\kappa_B n} - T \left( \frac{dv_x}{dz} + \frac{2v_x}{\Omega R^2} \right) \right\},$$

(7)

where $\dot{M}$ is the mass-outflow rate per unit disk area; $\Omega = 1 + z^2/R^2$ is the geometrical factor that accounts for the streamline divergence when the flow geometry changes from planar near the disk to spherical far from the disk; $\Gamma_{ss}$ is the ratio of $g_{ss}$ to the $z$-component of gravitational field in the wind; $v_s(z)$ is the thermal sound velocity; and $H$ and $\Lambda$ are respectively the heating and cooling rates per unit volume.

The importance of ionization changes in the disk LDW can be shown both analytically and numerically. Introducing a new velocity variable $w \equiv v_x^2/2$, a new spatial variable, $u$, such that $d/du \equiv R^2 \Omega (d/dz)$, we can re-write the momentum equation (6) in the form

$$F(u, w, \frac{dw}{du}) \equiv \left( 1 - \frac{v_x^2}{2w} \right) \frac{dw}{du} - h(u) - g_l(u, w, \frac{dw}{du}) = 0,$$

(8)

where $h(u)$ containing the terms from the gravitational attraction, electron scattering radiation pressure, and the gas thermal pressure is only a function of the spatial variable $u$. In terms of the variables $(u, w, dw/du)$, $g_l$ depends on $w$ and $u$. 

only through variations in the ionization fractions. Critical points were found to occur close to the disk surface (i.e. $\Omega \approx 1$). At the critical point of equation (8) one finds a quadratic equation for $(dw/du)/w$

$$\frac{v^2}{2} \left( \frac{1}{w} \frac{dw}{du} \right)^2 = w \left( \frac{1}{2w} \frac{\partial v^2}{\partial u} + \frac{\partial g_l}{\partial w} \right) \left( \frac{1}{w} \frac{dw}{du} \right) - \left( \frac{\partial h}{\partial u} + \frac{\partial g_l}{\partial u} \right) = 0. \quad (9)$$

We observe that the $\partial v^2/\partial u$ term is very small as the LDW is essentially kept isothermal due to the wind being in near thermal equilibrium with the radiation field. Similarly, for $\Omega \approx 1$, the term $\partial g_l/\partial u$ also is negligible. We note the fact that $\partial h/\partial u < 0$ due to the the gravity field in a disk geometry. Finally, $g_l$ is found to vary with the variables $u$ and $w$ only due to changes in the ionization fractions. For there to be a positive solution for $(dw/du)/w$ at the critical point the relations

$$\frac{\partial g_l}{\partial w} > 0, \quad \left( w \frac{\partial g_l}{\partial w} \right)^2 + 2v^2 \left( \frac{\partial h}{\partial u} \right) \geq 0 \quad (10)$$

must be satisfied. For the disk LDW, a changing ionization balance is therefore required for the existence of a critical point in the flow. The dependence of the line force on the spatial coordinate affects the LDW through the variation of the total density in the wind, i.e. through the continuity equation (5), providing the radiation flux $F(\nu)$ is unchanged. Beyond the critical point, for continuous LDW solutions to exist from the disk the momentum equation (8) gives us the necessary condition that the increasing gravitational field must be overcome by the similarly increasing radiation line-force acceleration which results changes in the ionization structure in the wind.

Solutions for disk LDWs were only found where the line-force continued to increase beyond the critical point to where the wind reaches escape velocity. In Figures 1 and 2 are shown for comparison solutions for disk and stellar (spherical) geometries. Figure 1 shows velocity profiles, while Figure 2 gives the profiles of the ratio of line-force to gravitational force. For the stellar wind, the line-force peaks near the critical point and decays. The disk wind as expected gives a continuous increase in the line-force well after the critical point has been reached. We find that the increasing gravitational field near the disk surface leads to a dramatic modification in the wind velocity profile and the mass loss rate per unit area.

REFERENCES

Figure 1: Velocity Profiles

Figure 2: Line Force Profiles