Line-driven winds near compact objects

Dorodnitsyn A.
Space Research Institute
Moscow
Sources of acceleration

• Magnetic driving

  *Jets (collimated) and bipolar (less collimated) outflows.*
  *nuclei of active galaxies*
  *galactic X-ray binaries*
  *Protostars*

  *High Lorentz factors*
  *High degree of collimation*

  *In fact very little is known about actual B in accretion disks*

• Radiation driving

  *“Natural” and almost inevitable mechanism for high luminosity disks*

  *Overionization by the central source raises the problem of confinement*
AGN

- **NALs** –
  - Narrow absorption line region

- **BALs** –
  - Broad absorption line region

- **BELs** –
  - Broad emission region

- *Narrow absorption line region seen in UV and X-ray spectra*  \[ \sim 1000 \ \text{km/s} \]

- The blue-shifted broad absorption lines the most convincing evidence of outflows with \[ V^{\infty} = 0.2c \]

- Broad emission lines, *UV – indicate outflows with velocities several thousand km/s*
Radiationally accelerated winds

- **O-type stars**
  - theory of Castor, Abbott, Klein (1975)
    - pressure in lines
    - Sobolev effect

- **WR-stars - ?**
- **Evolved massive stars**
  - absorption of the radiation flux in continuum
  - all types of opacity
    - true absorption
    - lines
    - Dust

- **Line-driven winds from accretion disks**
  - Murray at al. (1995) (a quasi-1D model)
  - Proga et al. (1998,2000) (the 2D calculations of the accretion disk powered winds)
  - Stevens & Kallman (1990) (winds from massive X-ray binaries , together with ionizing effects of the radiation from the central source)

...
\[ I = I_0 \exp(-\tau_I) \]
\[ \tau_l = \int_r^\infty \psi \rho \kappa_l \, dr \approx \frac{\rho v_{th} \kappa_L}{|dV / dr|} \]

\[ f_l \sim \left( \frac{1}{\frac{dV}{\rho \, dr}} \right)^\alpha \]

\[ v \frac{dv}{dr} = \Phi(v, r) + A(r) \left( \frac{dv}{dr} \right)^\alpha \]

**CAK-theory**

Mutliband Approach to AGN
A photon, emitted elsewhere in the "photosphere, may become resonant with the line transition downstream.

Since the line has a thermal width, the absorption takes place in a resonant layer of the typical size of about Sobolev length.
Gravitationally Exposed Flow

The key ingredient of the standard theory is that the optical depth (measured on the lab. frequency of the line transition) can be expressed as a function of the velocity gradient in the flow.

The same is true in the case when a photon, emitted somewhere deeply in the potential well, will become resonant with the line absorption both due to velocity difference and due to GR effect of redshifting.


*astro-ph/0409363*
• To calculate the radiation pressure force taking into account gravitational redshifting

• What is the relative impact of gravitational redshifting in comparison with standard case

• only very simple input conditions are chosen
  – no ionization,
  – Spherical symmetry
  – CAK parameterization law

We may hope that approximately the same difference will hold between GEF and CAK cases in more realistic calculations
GEF-theory

- Spherically-symmetric
- Background Schwarzschild metric
- Nonrelativistic, v/c terms retained only, Sobolev theory of the radiation transfer in lines
Radiation + Gravity

\[ T^{\alpha\beta} = (P + \rho)u^\alpha u^\beta + P g^{\alpha\beta} \]

- Stress-energy tensor for the perfect gas
  - total mass-energy density
  - barionic rest-mass density
  - internal energy of the perfect gas

\[ \rho = \rho_0 (1 + E_i), \]
\[ \rho_0 = m_b n_b \]

\[ \int \int_{-\Omega} \]

\[ G^{\alpha\beta} = \int_{0}^{\infty} d\nu \int d\Omega (\chi_\nu - \eta_\nu) n^\alpha \]

- Four-force density
  - describes the process of the interaction of the matter with the radiation field

Mutiliband Approach to AGN
\[ T^{\alpha\beta}_{\beta} - G^\alpha = 0 \]

**Equation of motion**

(Euler equation)

Mihalas & Mihalas (1984)
and references therein

\[ (n_b \ u^\alpha)_{;\alpha} = 0 \]

**Continuity equation**

Such a simple split of radiation and matter is possible only if radiation and outflowing matter have no “weight”. It is justified by our assumption of the background Schwarzschild metric.
Basic equations

\[ \frac{P + \rho}{h} \left( V h \frac{dV}{dr} + \frac{M}{r^2} \right) + \frac{dP}{dr} - \frac{1}{h} G^1 = 0 \]

Continuity equation

\[ \rho_0 V r^2 \sqrt{h} = \frac{\dot{M}}{4\pi} \]
Optical depth with gravitational + Doppler redshifting

\[ \tau_1 = \chi l_{GEF}, \quad \text{- Modified Sobolev scale} \]

\[ l_{GEF} = \frac{V_{th}}{\sqrt{h} \frac{dV}{dr} + c w} \approx \frac{V_{th}}{\frac{dV}{dr} + \frac{1}{c} \frac{d\phi}{dr}} \]

\[ w = \frac{d}{dr} \sqrt{h} \]

\( \sim \) acceleration of the particle that was initially at rest

Mutliband Approach to AGN
A nonlinear character of the equation of motion

\[ F = \mathbf{v} \left( \frac{dv}{dr} + \frac{1}{\rho} \frac{dP}{dr} + \frac{d\phi}{dr} - \frac{L\sigma_e}{4\pi r^2 c} - \frac{L\sigma_e k}{4\pi r^2 c} \left( \frac{4\pi}{\dot{M}} \right) \right) \left[ vr^2 \left( \frac{dv}{dr} + \frac{1}{c} \frac{d\phi}{dr} \right) \right]^\alpha \]

\( 0 < \alpha < 1 \)
Towards a solution

\[ F(p, v', r) = 0 \quad \text{Equation of motion} \]

\[ \left( \frac{\partial F}{\partial r} \right)_{cr} = 0 \quad \text{Singularity condition} \]

\[ \left( \frac{\partial F}{\partial r} \right)_{cr} + v'_cr \left( \frac{\partial F}{\partial v'} \right)_{cr} = 0 \quad \text{Regularity condition} \]
2 boundary value problem

- Shooting methods
  - Relaxation methods (Heney-type)
  - Always shoot first and only then relax
Gravitationally Exposed Line-driven Flow
<table>
<thead>
<tr>
<th>Model</th>
<th>$x_{c,GEF}$</th>
<th>$x_{c,CAK} - x_{c,GEF}$</th>
<th>$\frac{V^\infty_{GEF} - V^\infty_{CAK}}{V^\infty_{CAK}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>15</td>
<td>7.47</td>
<td>0.57</td>
</tr>
<tr>
<td>S2</td>
<td>20</td>
<td>9.95</td>
<td>0.51</td>
</tr>
<tr>
<td>S3</td>
<td>50</td>
<td>25</td>
<td>0.37</td>
</tr>
<tr>
<td>S4</td>
<td>100</td>
<td>50</td>
<td>0.2</td>
</tr>
</tbody>
</table>

$x_e = \frac{r_c}{r_g}$ - position of the critical point

Mutliband Approach to AGN
Continuous transition of the solution from GEF case (s=1) to CAK case (s=0)

Multiparam Approach to AGN
Density distribution in the wind.

Mutliband Approach to AGN
Solid line indicates GEF solution for the Newtonian potential, dashed line – GEF solution for Paczynski-Wiita potential

Mutliband Approach to AGN
Concluding Remarks

• A theory of winds that takes into account effects of strong gravitational fields has been developed.

• It is demonstrated that a regime of the "GRAVITATIONALLY EXPOSED FLOW" rather than a standard line-driven wind (CAK-theory) is developed.

• The comparison of both regimes shows that it is of up to 40% increase of the efficiency of acceleration may be obtained.
