Exploring Quasar Disk Winds with *QWIND2*

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Why *QWIND2*?

We are developing a new version of the QWIND code, QWIND2. Our goal is to **predict AGN wind properties** versus gas density, black hole mass, Eddington ratio and other parameters, i.e.: wind terminal velocity, mass and momentum flux, and opening angle.

QWIND2:
- Reformulates disk wind radiative acceleration so the solution is independent of black hole mass with appropriate scaling.
- Improves the physics: force multiplier description, conservation laws,
- Improves numerical stability.

QWIND:
- is a non-hydrodynamical model for the acceleration of line-driven winds from the accretion disks of AGNs, Risaliti & Elvis 2010, RE10).
- successfully explained the origin of the winds commonly detected in AGNs
- produces wind features consistent with Elvis (2000).
- focuses (for now) only on *radiative acceleration*.
- is optimized for a simplified, rapid calculation to allow us to explore the global properties of the outflow for a wide variety of model conditions.

AGN WINDS:
Most, perhaps all, active galactic nuclei (AGNs), have fast winds (~1000 km s^{-1} - ~20,000 km s^{-1}). Detailed hydrodyamical models (e.g. Proga et al 2000, ApJ 543, 686) show that AGN can launch disk winds and accelerate them.

QWIND Details: Material is lifted off the disk and then accelerated by line driving from the disk radiation. The acceleration in units of the gravitational radius (and setting c=1) is

$$a = -\frac{1}{R^2} + \frac{3(1+F)f_{Edd}}{8\pi\eta} z \int\int dr d\phi \frac{1-\sqrt{6/r}}{r^2} \frac{\mathbf{R}-\mathbf{r}}{|\mathbf{R}-\mathbf{r}|^4} e^{-\tau_{uv}}$$

where R = (R,0,z) is the position of the gas streamline, r and phi are coordinates in the disk, F is the force multiplier, η is the accretion efficiency, and we integrate the contribution of the Shakura-Sunyaev (1973) α-disk over radius and azimuth. The first term is just the form taken by Newtonian gravitation in these units. The integral depends on the model parameters only through the optical depth.

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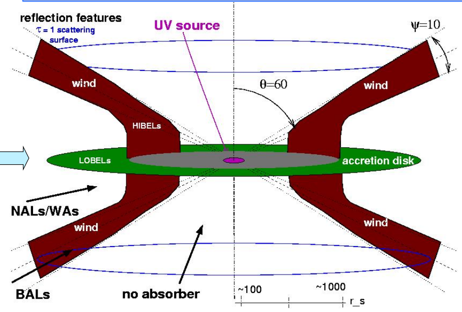
Can we predict wind strength vs $M_\bullet$, $\dot{m}/\dot{m}_{Edd}$?



Phenomenological "funnel wind" model for quasar accretion disk winds (Elvis 2000, Elvis 2001).
QWIND (RE10) model reproduces:
✔ **a thin wind (dr/R<<1),**
BAL terminal velocities (>10,000 km s-1),
large angles to the disk,
ionization matching X-ray warm absorbers

→ Worth taking further?

Reformulation of QWIND

The RE2010 model assumes that gas has been lifted just above the disk around a Schwarzschild black hole by an unspecified mechanism and is then exposed to radiation from: (1) a central X-ray point source and (2) the spatially extended UV radiation from a Shakura-Sunyaev (1973) α-disk. The ionization state of the gas is determined by the X-ray flux at a given radius; we assume that above a critical ionization parameter $\xi = L_{ion}/nr^2 = 10^5 \mathrm{erg\ cm\ s^{-1}}$

the X-ray opacity is pure electron scattering and below it the opacity is set to a constant higher value to represent absorbers. The gas is accelerated due to UV line opacity, which is modelled using the CAK force multiplier formalism described below. The gas is initially distributed parallel to the disk plane with a power law density between inner and outer radii r1 and r2, normalized with density n1 at radius r1.
The black hole mass M and the gas density n1 turn out to be linked parameters: the solution depends on them only through the combination

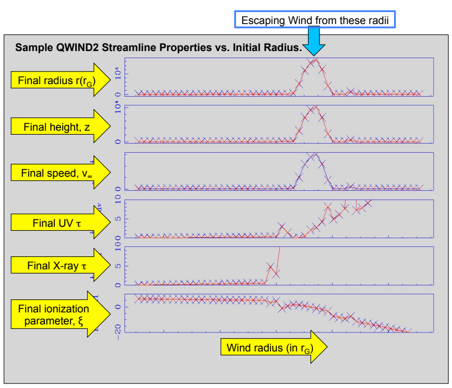
$$\tau = n_1 \sigma_T r_G$$

i.e. τ is the characteristic electron scattering optical depth over the gravitational radius length scale, r_G: $r_G = GM/c^2$

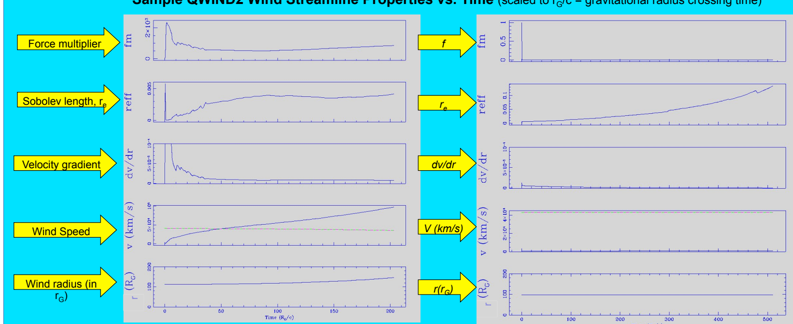
Other model parameters are r1,r2, Eddington fraction, ratio of X-ray to UV luminosity, wind temperature, and radial density power-law slope.

Improvements include:
-**Numerical**:
- calculate analytical optical depth at the base of the streamlines (z = 0) instead of approximating the density as constant for each radial step
- analytic expansion of kinematic step (calculating new velocity, acceleration and velocity gradient) to avoid rounding errors.
- use fitted function to the force multiplier calculation (see below, figure X).

-**Physics:**
- a new approach to calculating the accumulated UV optical depth ensuring consistency between gas acceleration and photon field absorption.
- optical depth is stored as a function of the latitude of the gas element, on the line of sight to the center of the disk (but ignoring relativistic effects).



Sample QWIND2 Wind Streamline Properties vs. Time (scaled to r_G/c = gravitational radius crossing time)



Escaping wind streamline – radiation pressure wins.
R(initial) = 112 r_G

Failed wind streamline – gravity wins.
Same model parameters as the figure to the left, but streamline originates at R=90 r_G, and the ionization is too high to permit efficient acceleration

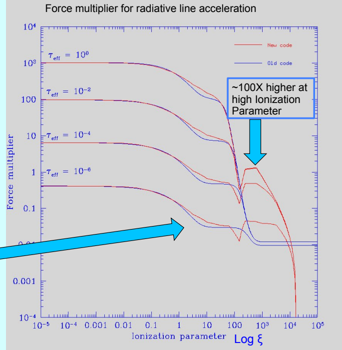
Improved Force multiplier, *f*

RE2010 follows Castor, Abbott and Klein (1975) in approximating the radiative acceleration due to UV line absorption by a wavelength-averaged quantity called the force multiplier, *f*. Stevens and Kallman (1990) determined *f* as a function of the ionization parameter, ξ, and the effective line optical depth $\tau_e = n\sigma_T r_e$
r_e is the *Sobolev length* (Sobolev 1957 the ratio of the thermal velocity width and the velocity gradient: $r_e = \frac{v_{th}}{\left|\frac{dv}{dr}\right|}$

For a stronger velocity gradient, a given amount of radiation is absorbed by a smaller mass of gas, leading to a higher acceleration.

RE2010 implemented the force multiplier using the analytic fitting functions given in Stevens and Kallman (1990), but these only apply below an ionization parameter log ξ = 2. They are up to ***100x larger at higher ξ***. For the new code we interpolate in a tabular representation of their Fig. 5; we also improved the handling of a region of parameter space where subtraction errors were causing inaccuracies. The figure to the right shows the difference in the accelerating force function between the old (blue) and new (red) implementations for the range of ionization parameter and optical depth encountered in our runs of the code.

Force multiplier for radiative line acceleration



CONCLUSIONS

- We are building QWIND2, an improved version of the Risaliti and Elvis 2010 quasar wind model with:
  - fewer free parameters,
  - improved modelling of the physics, and
  - improved numerical stability.
- In particular, the behavior of the solution is *independent of black hole mass* when an appropriate density scaling is introduced.
- Our preliminary experiments with the new code confirm the general conclusions of the earlier paper, but with some adjustments to the region of parameter space in which winds occur.
- The AAS is always sooner than you think. Due to bugs in the code discovered between submitting the abstract and the present time, this poster reports work-in-progress rather than final results. Sorry!

References:
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