A Cool Mist in a Warm Wind:
A Physical Origin for the Broad Emission Line Region

Martin Elvis
Harvard-Smithsonian Center for Astrophysics

Fog Waterfall, Iceland (Kjartan Gunnsteinsson c/o Daily Mail, 8 July 2015)
Broad Emission **Lines**: Invariant with Redshift, Luminosity

The Physics must be robust and inevitable. Not a function of host galaxy

Highest Redshift Quasar $z=7.1$ (from UKIDSS, Mortlock et al., 2011)

*With large CIV blueshifts*
All of the complex quasar phenomenology must fall out of a simple theory

The Black Hole + Disk + Jet Paradigm has no atomic features

So Where do all the emission and absorption lines come from?

Especially the Broad Emission Line Region
What do we know about the Broad Emission Line Region?

Basics - 1:
- High densities: $10^9 - 10^{12}$ cm$^{-3}$
- FWHM $\sim 1\% - 3\% \, c \rightarrow \sim 10^3 - 10^4 \, R_g$
- Wide range of ionization: FeII, MgII $\rightarrow$ CIV, OVI
Broad Emission Line Region Basics - 2

- Spans factor 10 in radius
- Keplerian $\rightarrow$ black hole masses
- Stratified higher mean ionization parameter at small radii

$$v^2 r = GM$$, i.e. Keplerian
Broad Emission Line Region - Geometry

• Covering factor ~10% ("textbook result")
• Reverberation mapping shape: thick disk (Pancoast et al., 2014)
Broad Emission Line Region Kinematics: mostly Rotation

Wills & Browne, 1986

Continuous 40° PA swing with velocity

Hα

Direct (unpolarized) light
Scattered (polarized) light

E-vectors of scattered rays

Equatorial scattering element (part of an entire ring of scatterers)

Rotating broad-line emitting disc

Mrk 985, James Smith+2002

James Smith et al. 2005

Mrk 985, James Smith+2002

Continuous 40° PA swing with velocity

polarization PA

Wills & Browne, 1986

Log R

$H_\alpha$ FWHM (km/s)

$H_\alpha$

Wavelength (Å)

James Smith et al. 2005

AGN Winds on the Georgia Coast, Jekyll Island, 26 – 29 June 2017  arXiv:1703.02956  Martin Elvis, elvis@cfa.harvard.edu
Broad Emission Line Region Kinematics: also Inflows

- Velocity Resolved Reverberation Mapping
- Redshifts at zero lag
  \( \rightarrow \text{Infall} \)

- Isodelay Surfaces
  Peterson 2003

AGN Winds on the Georgia Coast, Jekyll Island, 26 – 29 June 2017  
arXiv:1703.02956  
Martin Elvis, elvis@cfa.harvard.edu
Scaling Relations for Broad Emission Lines

Hβ Broad Emission Line Region size grows as $L^{1/2}$
Object to object relation
Hβ cloud density ~ constant

Scaling Relations for Broad Emission Lines

Bentz et al. 2006

This work

$\alpha = 0.52 \pm 0.04$
"Breathing" Broad Emission Line Region

Radius of Hβ BELR grows as $L^{1/2}$ in year-on-year changes
Single object relation
Hβ Cloud density $\sim$ constant

---


---

Radius (light-days)

Continuum luminosity $(10^{-15}$ erg s$^{-1}$ cm$^{-2}$ A$^{-1})$
Baldwin Effect

Broad emission line EW lower at high $L_{UV}$  Baldwin 1977

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{baldwin_effect.png}
\caption{Baldwin Effect}
\end{figure}
The Broad Emission Line Region

...is a heavily constrained system
Any model must explain all the observed phenomenology
Quite a challenge!
Standard view of Broad Emission Line Clouds
Locally Optimally Emitting Clouds (LOC) Model

Clouds have a random distribution of density and input ionizing flux \([n(H), \varphi(H)]\). Clouds at the optimum conditions for each line emit most strongly.

Works...
But frustrating:
No physical insight into origin of BELR.

Many LOC papers, including:
Baldwin et al. 1995; Korista et al. 1997;
Korista & Goad, 2000, 2004;
Goad & Korista, 2015.
We need a Physical Origin for the Broad Emission Line Region

Somehow this comes out of the Standard Model

What are we missing?
Disk Winds are the new piece of the Standard AGN Model

Radiation Line Driven Winds arise naturally from an accretion disk


My suggestion:
Physics of Disk Winds produce the Broad Emission Line Clouds

Accelerating hollow bi-conical disk wind
Elvis, 2000

Supermassive black hole
Accretion disk
X-ray/UV ionizing continuum
Disk Winds can explain many Quasar Atomic Features

- Bi-conical Narrow Line Region
  - Broad Absorption Lines
  - Reflection features
  - Narrow absorption lines
  - X-ray `warm' absorbers

Origin of the Broad Emission Line Region?
Gas Illuminated by a Quasar Continuum is unstable

- Makes 2 - 3 co-existing stable phases
  Krolik et al. 1981, Chakravorty+08,09, 12
- Warm phase is X-ray/UV Warm Absorber
- Cool phase is at BELR temperatures

“A cool mist in a warm wind”

Physics:
- Clouds condense out of the wind
  - in ~days << escape time
- Driven to stable (P,T) regions
  - by UV/X-ray variability
  - changes force multiplier in line driven wind
  - rapidly changing acceleration i.e. a “jerk”
Cool clouds cannot accelerate & fall back, making “Quasar Rain”

Force multiplier due to radiation line driving drops to 1 in cool clouds. Clouds become ballistic.

Cool clouds now sub-Eddington. Can’t reach escape velocity.

Nothing to hold clouds up against gravity

“raindrops” fall back on dynamical timescale

Fits the rotating, infalling kinematics of the Broad Emission Line Region

Large scale height likely [TBC]
“Quasar Rain” model predicts many BELR properties
Infalling “raindrops” are Supersonic in the Wind

Mach ≥ 20: Clouds are ripped to shreds

Cloud crushing timescale, $\tau_{cc} = 2\chi^{1/2} \tau_c / M c_s = 10 - 120$ days ~ months

Rayleigh-Taylor unstable

Kelvin-Helmholtz waves at edges

Common situation in astrophysics. e.g. Hopkins & Elvis (2010)
Ablating “raindrops” are seen in X-ray Eclipses


arXiv:1703.02956

© Harry Morosz

- NGC1365 X-ray eclipsing clouds
- $N_H$ rises fast at low covering factor, $f_c$
- Then $N_H$ drops as $f_c$ increases
- “Cometary” tail – non-radial
- Broad emission line velocities
- Few degree opening angle
- Lifetime ~60 days ~months

Maiolino et al. 2012

AGN Winds on the Georgia Coast, Jekyll Island, 26 – 29 June 2017

Martin Elvis, elvis@cfa.harvard.edu

arXiv:1703.02956
Explains Baldwin Effect?

Escape time, $\tau_{\text{esc}}$ shorter for larger Force Multiplier, $\mathcal{M}$

Larger $\mathcal{M}$ if X-rays are weak. Murray et al. 1985

X-rays are weaker at high $L_{\text{UV}}$. Lusso & Risaliti 2016

→ Less time for broad line clouds to form
→ Lower EW broad emission lines = Baldwin Effect?

Lusso & Risaliti 2016

Log $L_X$

Log $L_{\text{UV}}$

$slope = 1$

X-rays grow slower than UV

© Harry Morosz

AGN Winds on the Georgia Coast, Jekyll Island, 26 – 29 June 2017
arXiv:1703.02956
Martin Elvis, elvis@cfa.harvard.edu
Explains constant density broad line clouds?

Constant density clouds due to narrow multi-phase zone?

Constant T, P $\rightarrow$ Constant $n_e$

\[ \alpha_{ox} = 1.2 \]
\[ \alpha = 0.8 \]

Stable branches

2-3 co-existing phases

Thermal equilibrium
The polar opposite of the Locally Optimally Emitting Clouds model

- Prediction of the quasar rain model
- A physical consequence of line-driven accretion disk winds
- Occam’s quasar™ prefers the simpler approach

---

**Hβ Broad Emission Line Region size grows as L^{1/2}**

- Bentz et al. 2006

**r (Hβ) grows as L^{1/2} in year-on-year changes**


---

The constant density broad emission line clouds fit the scaling relations.


arXiv:1703.02956

© Harry Morosz

James Matthews
Quasar Rain: Closer to Solving Quasars?

- Physics-based
  - Treats wind more realistically
  - Fits BELR geometry, kinematics
- Unifies:
  - Broad Line Region clouds
  - Low Ionization X-ray Warm Absorber
  - X-ray eclipsing clouds
- Explains more than previous:
  - Cometary tails on X-ray clouds
  - Constant density clouds
  - Baldwin effect?
- Appealing:
  - Complex phenomenology largely explained
  - No arbitrary new “region”

**Disk winds are all you need**

- Satisfies “Occam’s Quasar” ©James Matthews
A Cool Mist in a Warm Wind
There is much to be done:

1. How is $\tau_{\text{cool}}$ changed in a photoionized gas?
2. Can X-ray/UV variability drive WA gas to stable branches on the S-curves?
3. How are the S-curves altered when $\tau_X \sim \tau_{\text{cool}}$?
4. Can large clouds reach $v_{\text{esc}}$ and so form the narrow emission line region?
5. Can the Baldwin effect be explained by the larger $\tau_{\text{esc}} / \tau_{\text{cool}}$ ratio in high luminosity quasars?
6. What will be the scale height of different lines? (Eq. of motion approach?)
7. Do some lines (e.g. OVI) originate in the warm phase?
8. Hydrodynamic line-driven wind simulation – does it validate model?

But not by me. I don’t have the skills.

And I am busy mining asteroids ☺

Thank You Again
arXiv:1703.02956

Fog Waterfall, Iceland (Kjartan Gunnsteinsson c/o Daily Mail, 8 July 2015)