THE PHYSICS OF IONIZED GAS IN AGN: TESTING PREDICTIONS FROM FIRST PRINCIPLES

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Ionized gas in AGN is present on all scales, from few $r_g$ to several kpc. Despite the complex phenomenology, the physics of this gas is governed by a few fundamental principles. The nuclear strong radiation field is likely the only ionization and heating source. Gas dynamics in some regions is almost completely governed by the Black Hole mass.

The consequences of these first principles lead to clear predictions that can be tested experimentally.
The coincidence between the soft X-ray and [O III] emission is striking in most sources observed by Chandra and HST, both in extension and in morphology (e.g. Bianchi+, 2006)

The same gas, photoionized by the AGN continuum, and extended on ~100s pc, produces both the soft X-ray emission lines and the NLR optical emission

➢ Inconsistent with a single-$U$ model → requires high-$U$ and low-$U$ phases
➢ The [O III]/soft X-ray ratio is spatially constant → $n \propto r^{-2}$
➢ The [O III]/soft X-ray ratio is fairly universal among the sources
**Radiation Pressure Compression**

**Assumptions**

✓ Radiation is the dominant force acting on the gas
✓ The ambient pressure is much lower than radiation pressure

**Consequences**

The radiation is absorbed in the surface layer of the gas, both ionizing it and compressing it, thus increasing its pressure

The pressure of the incident radiation itself can confine the ionized layer of the illuminated gas: **the gas is Radiation Pressure Compressed**
At $\tau \gg 1$, all the radiation is absorbed, and there is a transition to neutral gas.

At $\tau \sim 1$, the gas pressure roughly equals the radiation pressure: this layer is called the **ionization front**.

Near the ionization front, at the boundary between the H II and H I layers, the temperature is always $T_f \sim 10^4 \, \text{K}$, and the equality of gas pressure and radiation pressure implies that the ionization parameter is always $\sim 0.03$. 

**Radiation Pressure Compression**

 Courtesy J. Stern
A large range of \( n \) and \( U \) in a single slab: the same gas which emits the low-ionization emission lines has a highly ionized surface which emits X-ray lines.

At the ionization front, the temperature is universal and \( P_{\text{gas}} = P_{\text{rad}} \): since the latter is \( \propto r^{-2} \), then \( n \propto r^{-2} \).

The hydrostatic solution of RPC gas is independent of the boundary values at the illuminated surface \( (U_0, n_0, P_{\text{gas},0}) \): RPC models are universal and have essentially zero free parameters.
Soft X-ray Emission in Obscured AGN

Dominated by strong emission lines with low or no continuum

Most of the ‘soft excess’ is concentrated in very strong lines easily detected even in very low SNR spectra

(e.g. Guainazzi & Bianchi, 2007)

Diagnostic ratios on triplets and higher order series lines point to photoionization, with an important role of photoexcitation

(e.g. Kinkhabwala+ 2002, Guainazzi & Bianchi, 2007)
The bracketed quantity above represents the **differential emission measure (DEM) distribution** (e.g. Liedahl 1999; Sako+ 1999)

In practice, the DEM distribution is the ensemble of weighting factors that determine the contributions of each ionization zone to the total line flux
The usefulness of the DEM is that it can be derived theoretically for a given scenario, and readily compared to what is measured experimentally.

**Constant Density (Liedahl 1999)**

\[
\frac{d \langle EM \rangle}{d \log \xi} \propto \xi^{-3/2}
\]

**RPC (Stern+14, Bianchi 2019a)**

\[
\frac{d}{d \log \xi} \langle EM \rangle = 2.2 \cdot 10^{68} \Omega_{4\pi} L_{45} \xi^{-0.9} \text{ cm}^{-3}
\]

\[
\frac{dL}{d \log \xi} \propto \xi^{-1}
\]
The derived DEM in the case of RPC gas is very characteristic and robust against the specific gas parameters and illuminating SEDs.

In practice, the DEM is basically set by the hydro-static equilibrium which the gas must obey in case of RPC, and does not depend on the other details.
The observed DEM in NGC1068 evidently appears as a power-law distribution: a linear regression gives a slope of $\sim -0.85$.

**The correspondence between the observed DEM and the distribution predicted for a RPC gas is impressive.**

It is important to stress that there are no free parameters in this comparison, apart from the average normalization of the two curves.
The observed DEM distribution of NGC 4151 is very similar to that of NGC 1068, again in extremely good agreement with the RPC predictions (slope $\sim -0.78$).

Very interesting case of NGC 5548: the archetypal Seyfert 1 is in an obscured state since (at least) 2012. Its soft X-ray emission is now the same as in Seyfert 2s (slope $\sim -0.87$).
No steeper DEMs than RPC:

- Lower $N_H$ clouds can only flatten it (you must have the ionized layer!)
- No other gas compressing mechanism (i.e. magnetic), which can produce only dense photoionized gas

No apparent correlation between covering factor and luminosity
BLR line widths are driven by the BH gravity

**Keplerian Motion**

\[ M_{BH}(H\beta) = \Delta v^2 R_{BLR}/G \]

\[ M_{BH} = 10^{-21.7} \Delta v^2 L_{bol}^{1/2} M_\odot \]

\[ \dot{m} = 10^{-16.4} \Delta v^{-2} L_{bol}^{1/2} \]

\[ \Delta v = 21.1 M_{BH}^{1/4} \dot{m}^{-1/4} \]

\[ \Delta v = 10^{10.85} M_{BH}^{1/2} L_{bol}^{-1/4} \]

\[ \Delta v \text{ increases as } M_{BH} \text{ increases and } \dot{m} \text{ and } L_{bol} \text{ decrease} \]

**BLR Radius (Dust Sublimation)**

\[ R_{BLR} = 0.086 \left( L_{bol}/10^{46} \right)^{1/2} \]

Laor 2003
The lack of Balmer lines with $\Delta v > 25,000$ km s$^{-1}$ may result from a physical upper limit on the velocity dispersion at which the BLR clouds can survive (Laor 2003)

**No BLR is present when** $L_{bol} < 10^{41.8} M_8^2$, or $m < 10^{-4.3} M_8$

If the BLR is part of a disk wind, it cannot form if its launching radius falls below a critical radius: the innermost orbit of a classic Shakura & Sunyaev disk (Nicastro 2000), or the transition radius to a radiatively inefficient accretion flow (Trump+ 2011)

**No BLR forms for Eddington rates lower than a critical value** ($\sim 2 \times 10^{-3} M_8^{-1/8}$)
If the BLR cannot form in weakly accreting AGN, we expect the existence of “true” Seyfert 2 galaxies: optically Type 2 objects, without obscuration. The best candidates are found with simultaneous optical/X-ray observations:

**NGC3147** \((4 \times 10^{-5} - 3 \times 10^{-4}: \text{Bianchi+2008, 2017})\), **Q2131427** \((2 - 3 \times 10^{-3}: \text{Panessa+ 2009})\), **NGC3660** \((4 \times 10^{-3} - 2 \times 10^{-2}: \text{Bianchi+, 2012})\)
Have the above theoretical predictions, that the BLR disappears at very low luminosities/accretion rates, indeed been vindicated by these objects?

Be careful:

- low $L_{bol}/L_{Edd}$ AGN are heavily dominated by the host galaxy emission
- low $L_{bol}$ – high $M_{BH}$ make the lines extremely broad, even harder to detect

**NGC3147: THE BEST CANDIDATE**

$$3.1 \times 10^8 M_\odot \rightarrow 4 \times 10^{42} \text{ erg s}^{-1}$$

$$\text{FWHM}_{H\alpha} \approx 7088 \left( \frac{M_{BH}}{10^8 M_\odot} \right)^{0.49} \left( \frac{L_{bol}}{10^{44}} \right)^{-0.26} \text{ km s}^{-1}$$

**Stern&Laor 2012, Bianchi+2012**

The only way to definitely exclude the predicted BLR emission is HST spectroscopy

The HST narrow slit ($0.1''$) can exclude the bulk of the host emission, and reveal if the expected very broad H$\alpha$ is indeed present
The small slit width hugely reduces the host contamination.

An H$\alpha$ line with an extremely broad base (FWZI~27 000 km s$^{-1}$) is now evident!

NGC 3147 is not a true type 2 AGN.
The line profile shows a steep cutoff blue wing and an extended red wing, which match the signature of a mildly relativistic thin accretion disk line profile.
It is indeed well fit with a nearly face on thin disk with an inner radius at $77 \pm 15 r_g$, which matches the prediction of $62^{+18}_{-14} r_g$ from the $R_{BLR} \sim L^{1/2}$ relation.

The luminosity of the broad Hα line is consistent with the predicted values from the X-ray and [O III] luminosities (Stern & Laor2012a,b): NGC 3147 appears like a standard type 1 AGN at the very low end of luminosity ranges.

Hα disk line profiles have been observed in a handful of objects: here we find that the BLR forms a thin disk, extending down well below $100 r_g$.

A thin accretion disk at $L/L_{Edd} \sim 10^{-4}$ is in contradiction with the standard paradigm, that at low accretion rates, the accretion configuration becomes optically thin and quasi-spherical (Blandford & Begelman 1999).

**Optical detections of relativistic line profiles may provide a new tool to explore the innermost disk structure**
“You put a cloud of gas at some distance from the AGN, and the rest is set by nature.”

(Ari Laor)

BASIC REFERENCES