# 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  $\sim 100s$  pc, produces both the soft X-ray emission lines and the NLR optical emission

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



## **Radiation Pressure Confinement**

Mathews 67; Pier&Voit 95; Dopita+02; Różańska+06; Pellegrini+07,09; Draine 11; Yeh&Matzner 12;Stern+14a,b; Baskin+14a,b



#### 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 Confined

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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  $T_f \sim 10^4 K$ , and the equality of gas pressure and radiation pressure implies that the ionization parameter is always  $\sim 0.03$ 

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- ✓ 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<sub>gas</sub> = P<sub>rad</sub>: since the latter is ∝ r<sup>-2</sup>, then n ∝ r<sup>-2</sup>
- ✓ The hydrostatic solution of RPC gas is independent of the boundary values at the illuminated surface  $(U_0, n_0, P_{gas,0})$ : 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 EMISSION MEASURE DISTRIBUTION



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)

 $d \,(\mathrm{EM}) \,/ d \log \xi \propto \xi^{-3/2}$ 

#### RPC (STERN+14, BIANCHI+IN PREP.)

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





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



Very interesting case of NGC 5548: the archetypal Seyfert I is in an obscured state since (at least) 2012 Its soft X-ray emission is now the same as in Seyfert 2s (slope  $\sim -0.87$ ) 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  $\sim -0.78$ )



## THE DEM IN CHRESOS

#### Catalogue of High REsolution Spectra of Obscured Sources: 239 XMM-Newton RGS observations of 100 X-ray



#### 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

and  $\dot{m}$  and  $L_{bol}$  decrease



Log  $\sigma_*$  (km s<sup>-1</sup>)  $(M_{BH})$ 

The lack of Balmer lines with  $\Delta v > 25\ 000$  km s<sup>-1</sup> 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  $\dot{m} < 10^{-4.3} M_8$ 



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** ( $4 \times 10^{-5} - 3 \times 10^{-4}$ : Bianchi+2008, 2017), **Q2131427** ( $2 - 3 \times 10^{-3}$ : Panessa+ 2009), **NGC3660** ( $4 \times 10^{-3} - 2 \times 10^{-2}$ : 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



 $FWHM_{H\alpha} \simeq 20\ 000 - 40\ 000 \text{ km s}^{-1}$ 

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 extremely broad line emission is now evident!



When the narrow emission lines from the NLR are subtracted, a broad asymmetric and double-peaked profile is left, sometimes observed in lowluminosity AGN, and thought to originate in the outer parts of the accretion disk (e.g. Storchi-Bregmann+ 2017)



The luminosity of the broad  $H\alpha$ component is in perfect agreement with the X-ray luminosity as in Type I objects

Apparently this is a "normal" BLR, i.e. formed by the same mechanism which sets the BLR size in all AGN

This mechanism must be simple and robust, being present in AGN from  $\sim 10^{39}$  to  $\sim 10^{47}$  erg s<sup>-1</sup>, producing a universal  $R_{BLR} = 0.1L_{46}^{1/2}$  pc relation. We now see it works also from  $L/L_{Edd} \sim 1$  down to  $10^{-4}$ 

However, the intrinsic nature of the disk may be also playing a fundamental role: larger BLR radii found in LINERs (e.g. Balmaverde & Capetti 2014), wind component suppressed in LLAGN (Storchi-Bergmann+ 2017)

## MEET THE BEAUTY

## "You put a cloud of gas at some distance from the AGN, and the rest is set by nature." (Ari Laor)

