

The role of failed accretion disk winds in active galactic nuclei

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Abstract. Both observational and theoretical evidence point at outflows originating from accretion disks as fundamental ingredients of active galactic nuclei (AGN). These outflows can have more than one component, for example an unbound supersonic wind and a failed wind (FW). The latter is a prediction of the simulations of radiation-driven disk outflows which show that the former is accompanied by an inner failed component, where the flow struggles to escape from the strong gravitational pull of the supermassive black hole. This FW component could provide a physical framework to interpret various phenomenological components of AGN. Here we briefly discuss a few of them: the broad line region, the X-ray obscurer, and the X-ray corona.

Keywords. accretion, accretion disks; black hole physics; galaxies: active

1. Introduction

The inner structure of luminous active galactic nuclei (AGN) is shaped by the presence of winds launched on accretion disk scales, as indicated by their large terminal velocities ($v_{\text{out}} \gg 5000 \text{ km s}^{-1}$ and up to several $0.1c$). Such winds cannot be sustained by thermal pressure, but must be driven by either magnetic or radiative forces (e.g., see for a recent review [Giustini & Proga 2019](#)). In the case of radiation-driven accretion disk winds (specifically line-driven, LD), a chaotic, dense, struggling inner component is always accompanying the larger scale successful mass outflow: it is the failed wind (FW; [Proga, Stone & Kallman 2000](#); [Proga & Kallman 2004](#); [Proga 2005](#)). Here “successful” or “failed” means the ability of inability of the gas in reaching the escape velocity v_{esc} . In LD disk wind models, the FW is a fundamental ingredient of the mass flow of luminous AGN as the wind itself. In fact, its formation is more robust than the formation of the wind. Therefore if LD disk wind models hold, observable quantities related to the FW should be identifiable in AGN as well. In the following section, we briefly discuss the possible role of the FW in the inner accretion flow of luminous AGN.

2. Failed line-driven accretion disk winds in the AGN inner structure

Line driving can deposit much more momentum in the gas than pure electron scattering, allowing the launching of material with velocity greater than v_{esc} in sub-Eddington regimes ([Castor, Abbott & Klein 1975](#)). For LD to be effective, the presence of spectral transitions is therefore fundamental. The spectral energy distribution of luminous AGN allows for LD winds to be launched from accretion disk scales pushing on the many UV

transitions available (e.g., Murray *et al.* 1995; Proga, Stone & Kallman 2000; Proga & Kallman 2004). A large X-ray flux is also characteristic of luminous AGN, and while the X-ray photons will push on relatively few available X-ray lines, they will mostly concur to strip the electrons off the UV-absorbing atoms, thus destroying the many UV spectral transitions available and effectively “overionizing” the wind material (e.g., Dannen *et al.* 2019, and references therein). *The term “overionization” is referred to a level of ionization that is too large to produce the observed UV lines and to sustain LD winds above local v_{esc} .* Therefore the ratio between the UV and X-ray radiation flux is crucial for the successful launch and acceleration of LD winds in AGN.

In the first models of LD accretion disk winds in AGN, a layer of dense gas (a *shield*), absorbing the strong ionizing X-ray flux, was assumed to exist between the X-ray continuum source and the UV-absorbing wind. This is the “hitchhiking gas” of Murray *et al.* 1995, which postulated the presence of this gas just in front of the flow that is effectively accelerated out of the system. It was speculated that a gradient in pressure would then cause the hitchhiking gas to accelerate together with the farther out wind (hence the nickname).

Hydrodynamical simulations performed by Proga and collaborators (Proga, Stone & Kallman 2000; Proga & Kallman 2004) showed that for massive (black hole mass $M_{\text{BH}} > 10^8 M_{\odot}$), luminous AGN (Eddington ratio $\dot{m} > 0.5$), the accretion flow settles in a hot polar flow, a fast equatorial outflow, and an inner transitional zone where the material is lifted up by the strong radiation pressure. The gas in the transition zone is exposed to the strong ionizing continuum, loses most or all of its bond electrons, thus losing line driving force. This material is unable to reach v_{esc} before getting overionized, and it falls back toward the disk. *The failure or success of the wind is measured in terms of overcoming or not the local v_{esc} .* The inner FW effectively protects (shields) the material located farther out from the strong ionizing continuum radiation, therefore allowing for the successful launch of the wind at radii larger than where the FW dominates, and where the radiation pressure is large enough to overcome BH gravity (Proga & Kallman 2004; Risaliti & Elvis 2010).

In the scenario proposed by Giustini & Proga (2019), for $M_{\text{BH}} \gtrsim 10^8 M_{\odot}$ and $\dot{m} \gtrsim 0.01$, the AGN inner structure is dominated by the presence of a LD disk wind and its inner FW component. A LD wind is launched at all radii where the local radiation pressure overcomes gravity; in the inner portions of disk the wind is unable to escape because of overionization, and therefore forms a FW. The AGN appearance will be more or less dominated by the FW (and thus have slower or faster LD winds), depending on how large is the X-ray/UV flux ratio as seen by the gas. Although the Giustini & Proga (2019) scenario is still qualitative, it already makes some predictions. We discuss in the following three phenomenological components of AGN that might be explained by the FW in AGN, in order of decreasing distances from the central supermassive black hole (SMBH): the (high-ionization) broad line region in Section 2.1, the X-ray obscurer in Section 2.2, and the X-ray corona(e) in Section 2.3.

2.1. The FW as BLR

The broad line region (BLR) is a fundamental ingredient of luminous AGN: it consists of gas photoionized by the AGN continuum and whose motion responds to the gravitational potential of the central SMBH (e.g., Peterson *et al.* 2004). The BLR is phenomenologically divided into a low-ionization (e.g., Mg II, H β) and a high-ionization (e.g., C IV, Ly α) component which show distinct kinematics (e.g., Marziani *et al.* 1996). In particular, a difference in peak position between low-ionization and high-ionization emission lines is indicative of strong radial motions of the gas producing the latter (Gaskell 1982).

The high-ionization emission lines in luminous AGN can in fact be blueshifted by several hundreds (up to thousands) km s^{-1} with respect to the low-ionization emission lines and the host galaxy (e.g., Richards *et al.* 2011): part of the high-ionization BLR must be a wind. Most of the low-ionization BLR likely originates at large scales, close to the dust sublimation radius, where radiation pressure on dust grains can form an outer wind and a FW (Czerny & Hryniewicz 2011). Radiation pressure on UV lines, that forms a LD accretion disk wind and an inner FW, can explain instead the bulk of the high-ionization emission lines (Proga & Kallman 2004). Part of the low-ionization emission lines can also be produced within dense clumps at the base of the wind, and would then also be blueshifted (Waters *et al.* 2016).

Blueshifted broad absorption lines in high-ionization UV transitions[†] are also observed in a large number of luminous AGN (up to 40%, Allen *et al.* 2011). These are the so-called broad absorption line quasars (BAL QSOs), and display the most direct evidence for the presence along the line of sight of strong winds, which can reach velocities of several $0.1c$. Such high velocities must be produced close to the SMBH, on accretion disk scales. The presence of the broad absorption troughs alone indicates that a lot of momentum has been deposited in the gas by radiation. Remarkably, the most recent observations of large samples of AGN have demonstrated that high-ionization BAL QSOs correspond to quasars in general (Rankine *et al.* 2020), thus supporting accretion disk wind scenarios for luminous AGN in general. If driven by radiation, a disk wind will be accompanied by the inner FW, and this will also contribute to the emission of the BLR. But how?

As summarised in Giustini & Proga (2019), in LD disk winds scenarios the BLR appears in luminous AGN at $\dot{m} \gtrsim 0.01$, when the inner accretion and ejection flow consists of a disk, LD wind, FW, and inner X-ray source; the LD wind + FW then produce the high-ionization BLR. In particular, the production of the symmetric portion of the high-ionization BLR is associated to the FW, while its blueshifted and blue-skewed portion, to the wind itself.

The strongest (fastest, densest) LD disk winds are those produced in AGN with a low X-ray/UV flux ratio (*X-ray weak*), either because of high \dot{m} and/or a large M_{BH} . These have a vast radial zone of the inner flow dominated by winds, and only a small inner region where the wind fails. Thus they produce winds with a large range of velocities, including large terminal velocities $\gg 5,000 \text{ km s}^{-1}$ and up to several $0.1c$ when launched in the innermost regions of the disk. On the contrary, in the case of AGN with a large X-ray/UV flux ratio (*X-ray bright*), a larger inner region of the accretion flow is dominated by the FW. In these AGN, successful winds are only launched at larger scales, thus reaching lower terminal velocities.

In LD disk winds scenarios, the BLR of X-ray weak AGN is dynamically dominated by the wind: the emission lines of e.g. C IV are strongly blueshifted and blue-skewed. Their equivalent width is lower than the one of the same emission lines produced in X-ray bright AGN: here the dynamics of the BLR is dominated by the FW, that does not reach v_{esc} . The emission lines have a larger equivalent width, a more symmetric profile, and little or no blueshift with respect to the redshift of the host galaxy. In other words, the FW extent regulates the extent of the symmetric, non-shifted BLR at the expense of the skewed, blueshifted BLR produced in the wind. When the disk is observed through the wind, X-ray weak AGN will display deeper, broader, and more blueshifted absorption troughs compared to X-ray bright AGN. Broadly speaking, the first type of AGN would correspond to the population A of quasars along their main sequence, while the second type of AGN to their population B (Sulentic *et al.* 2000; Sulentic & Marziani 2015).

[†] Low-ionization broad absorption lines are observed in a small fraction (about 5–10%) of broad absorption line quasars, the low-ionization BAL QSOs; those who do not display them are called high-ionization broad absorption line quasars.

2.2. The FW as the obscurer

The presence of dense, variable layers of X-ray absorbing gas on BLR-scales has been recently inferred by high-quality observations of local Seyfert 1 galaxies (Kaastra *et al.* 2014; Ebrero *et al.* 2016; Mehdipour *et al.* 2015; Kriss *et al.* 2019). This gas is called “obscurer”, as it absorbs the X-ray continuum flux and obscures the view of the strong ionizing X-ray continuum to the material located further out. This further out material, in fact, responds to the changes in X-ray ionizing flux, as strong UV absorption lines are observed emerging in concomitance with the appearance of strong X-ray absorption.

In LD accretion disk wind scenarios, the FW is the material located close to the source of X-rays, that gets all the ionizing continuum, and thus fails reaching v_{esc} and falls back toward the disk. The FW motion is complex: highly dynamical, with locally variable motion made of upward and downward components, and dense filaments and knots embedded in a much hotter medium (Proga 2005). The FW absorbs the X-ray continuum photons, effectively shielding the gas located farther out that can be then accelerated by radiation pressure on UV spectral lines. The FW has therefore all the characteristics to be identified with the “obscurer” of local Seyfert galaxies.

2.3. The FW as the X-ray warm corona(e)

Much closer to the central SMBH than the wind, but maybe partially co-spatial with the inner FW, lies the source of X-ray photons. The X-ray radiation is the clearest signature of accreting BHs, yet its physical origin is still unclear. We know that some compact and hot region must be responsible for the bulk of the intense and variable X-ray emission of AGN, and we call it X-ray “hot corona”. The X-ray hot corona has become a synonym for a low-density (optical depth $\tau \ll 1$) medium full of hot (temperature $kT_e > 100$ keV) electrons, that by interacting with the much slower UV photons emerging from the thermalized accretion disk, increase their energy through inverse Compton scattering (e.g., Haardt & Maraschi 1993). This hot coronal emission is able to overionize the wind material, therefore concurring in destroying the wind, i.e., creating a FW. In recent years, the presence in the inner regions of luminous AGN of material also able to Compton-upscatter UV photons, but with much lower temperature and much higher optical depth ($kT_e \sim 100 - 300$ eV, $\tau \sim 10$), has emerged: this is called the X-ray “warm corona” (Done *et al.* 2012; Mehdipour *et al.* 2015; Petrucci *et al.* 2018). These general physical properties of the X-ray warm corona look similar to those of the FW. An exchange of energy is expected between the source of hard X-ray photons (the hot corona) and the FW, with dense knots within the FW able to emit X-ray bremsstrahlung and thus, in the most extreme cases, switching the main cooling mechanism for the X-ray emitting plasma (Proga 2005). In these cases the warm corona can dominate over the hot corona in terms of density and hence matter cooling/radiation emission, and produce genuinely hard X-ray weak AGN where most of the flux of photons at $E \gtrsim 2$ keV is suppressed: the FW would then become the X-ray corona itself.

3. Conclusions

Accretion disk winds have been recognized as fundamental ingredients of the inner regions of luminous AGN. In the case of LD disk winds, the inner FW component might help interpreting in a physical framework phenomenological features of AGN such as the high-ionization BLR, the obscurer, and the X-ray coronae. The FW solutions of the inner accretion and ejection flow of AGN deserve further attention, in order to assess whether they can change significantly the physical and geometrical structure of the very inner accretion flow around highly accreting SMBHs.

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