Ultra fast outflows, and their connection to accretion and ejection processes in AGNs

Anna Lia Longinotti

CONACyT–Instituto Nacional de Astrofísica, Óptica y Electrónica
Luis E. Erro 1, Sta María Tonantzintla, Puebla, C.P. 72840, Mexico
email: annalia@inaoep.mx

Abstract. The growing evidence for energy-conserving outflows in powerful and luminous AGNs supports the idea that high-velocity winds launched from the accretion disc evolve systematically after undergoing a shock with the ambient medium and that they are capable of expelling enough mass and energy so as to produce feedback. This talk will give an overview of recent results on AGN ultra fast outflows, with focus on grating X-ray spectra of bright sources. I will review how UFO work, their observational properties and their relation with AGN outflows in other bands, what is their impact on the host galaxies and their role in feedback processes.

Keywords. galaxies: active, hydrodynamics, atomic processes

1. Introduction

Feedback from Active Galactic Nuclei (AGN) is generally thought to be an important ingredient for galaxies evolution. After large amount of gas is accreted during the earliest stage of a quasar life time, the accumulated energy can be released via ejection of powerful outflows driven by the AGN. If the outflow is as strong as 0.5–5% of the Eddington luminosity of the AGN, it has a profound impact on the development of the host galaxy itself. The effect of these winds is to eventually expel the gas that would otherwise be available for forming new stars in the host galaxy therefore providing an effective mechanism of quenching star formation. It is in this sense that we refer to AGN feedback as a mechanism able to regulate the growth of the galaxy and the growth of the central black hole as well (Di Matteo et al. 2005, Hopkins et al. 2010).

A widely accepted scenario for explaining AGN feedback postulates that a fast wind observable in the X-ray band is launched at accretion disk scale (Fauver-Giguère & Quataert 2012). This highly ionized X-ray gas is currently observed in the form of Ultra Fast Outflows in some AGN spectra (Tombesi et al. 2012, Gofford et al. 2013). While traveling outward, the impact of the wind with the ISM (inter-stellar medium) gives rise to shock processes (King 2010). After shocking with the gas, deceleration and cooling processes lead to the production of a slower outflow with less ionized lines observable in the optical band and to the formation of a bubble of hot, tenuous gas (e.g. Zubovas & King 2012). As a result of the cooling, the presence of molecular gas outflowing at a much lower velocity is expected. This latest phase is frequently observed in several ULIRGS and Quasars (Cicone et al. 2014, Feruglio et al. 2010, 2015).

To date, only two cases of ULIRGS are reported where the observed X-ray and molecular phases of the outflow are physically related, IRAS F11119+3257 (Tombesi et al. 2015) and Mrk 231 (Feruglio et al. 2015). Both results remarkably fit in with the prediction of the energy-conserving outflow model outlined above.

This fascinating picture, among several other variables, relies on the existence and the
properties of the nuclear wind, the so-called “Ultra Fast Outflow”. The X-ray spectra of some AGNs show signature of gas outflowing at high speed \((v \gtrsim 0.1 \, c)\). This gas is so highly ionized by the nuclear radiation that the only dominant ions left are He-like and Hydrogen-like ionic species. These systems were christened as “Ultra-Fast Outflows” (UFOs) (Tombesi et al. 2010) and at the beginning they were observed mainly in the Fe K band at \(E \gtrsim 7\) keV. Several papers reported on UFOs hosted in individual AGNs (Pounds et al. 2003, 2011, 2014, Chartas et al. 2009, Lanzuisi et al. 2012, Nardini et al. 2015), and statistical studies show that they are detected in 30-40% of nearby AGN (Tombesi et al. 2010, 2012, Gofford et al. 2013). The approximate ranges of mass outflow rate \((0.01-1\,M_\odot\, yr^{-1})\) and kinetic energy \((10^{42-45}\,\text{erg s}^{-1})\) are in good agreement with theoretical predictions for black hole winds (King 2010).

Two launching mechanisms are envisaged for the production of such rapid outflows, and both locate the region of action in the accretion disk of the AGN. One way to produce a fast outflow is through radiation driving (Proga and Kallman 2004, Sim et al. 2010), and another one is via magnetic fields in radio-loud sources ("magnetically driven outflows", Fukumura et al. 2015).

![Figure 1](image_url)

**Figure 1.** *XMM-Newton-RGS* spectrum of the NLSy1 Galaxy Mrk 1044 fitted by four components of ultra fast outflows (Krongold et al. submitted). The fastest component (blue labels) of this system reaches an outflow velocity of \(\sim 48,000\,\text{km s}^{-1}\) and column density of \(N_H \sim 10^{23.32}\,\text{cm}^{-2}\), while the other three are outflowing at \(25,000\,\text{km s}^{-1}\).
2. Ultra Fast Outflows in Narrow Line Seyfert 1 Galaxies

In the very recent years, the discovery of fast outflows in the soft X-ray grating spectra of bright Seyfert Galaxies has opened a complementary path to explore the properties of AGN fast winds. Compared to the results based on CCD spectra, the higher detail provided by grating spectroscopy has revealed that soft X-ray fast winds can be made by multiple components of distinct outflowing velocity, ionization state and column density and that they can be massive enough to produce feedback in the host galaxy, e.g. IRAS 17020+4544 (Longinotti et al. 2015, L15 throughout) and Mrk 1044 (see Fig 1, Krongold et al. submitted). When luminosity variations takes place, the combination of timing and spectroscopy techniques shows that fast X-ray winds respond to flux variations revealing a tight connection between continuum photons emitted in the very inner accretion disc with highly ionized outflowing gas (IRAS 13224-3809 Parker et al. 2017; PDS 456 Matzeu et al. 2017). With the exception of the luminous QSO PDS 456 (Reeves et al. 2016), if we consider the other few cases of fast winds observed in gratings spectra (PG1211+143, Reeves et al. 2018; Akn 564, Gupta et al. 2013), it is clear that the sources where this phenomenon is detected share the same classification: they are all Narrow Line Seyfert 1 (NLSy1).

This AGN class represents an extreme form of Seyfert activity that is manifested in their peculiar continuum and emission-line properties in almost all bands (see Gallo 2006), their small black hole masses ($M_{BH} \sim 10^6-7 M_{\odot}$), high Eddington ratios and often, high degree of X-ray variability (Komossa & Xu 2007).

The recent findings of fast X-ray winds in an increasing number of NLSy1 seem to hint to a common behavior of these sources with objects of much higher luminosity (e.g. Chartas et al. 2002, Tombesi et al. 2015, Nardini et al. 2015). Increasing evidence that the velocity of the wind correlates with the source luminosity (i.e. winds are faster at...
higher luminosities, Pinto et al. 2018) strongly favours radiation driving as the launching mechanism for the outflows, leading therefore to the hypothesis that a high accretion rate is the likely driver of fast winds (Matzeu et al. 2017).

3. Stratification of the fast outflow: a shocked outflow origin?

We now focus on the peculiar case of the NLSy1 IRAS17020+4544. This source presents the simultaneous presence of a stratified fast outflow (L15) and a multi-layered slower absorber. Fine quality multi-epoch spectroscopic information available from two XMM-Newton observations (obtained in the years 2004 and 2014) and a long look with Chandra LETG (obtained in 2017) confirm a surprisingly steady continuum flux and a complex pattern of absorption features (see Fig. 2). While no significant variations are observed in the properties of the fast wind along the 10 years elapsed in between the two XMM-Newton observations, the peculiar evolution of the 4 components of the slow absorber (Sanfrutos et al. submitted) reveals gas flowing inward ($v_{\text{inflow}} \sim 1800-3000$ km s$^{-1}$) and outward ($v_{\text{outflow}} \sim 2000-3400$ km s$^{-1}$), thus suggesting a different nature of this wind compared to “standard” warm absorber.

To explain this complex pattern of absorbers we postulate that the coincidence of the fast outflow with slower winds moving in opposite directions may be explained in terms of a “shocked outflow”. This model predicts that an initial fast outflow radiatively launched at accretion disc scale with outflow velocity $v_{\text{out}} \geq 10^4$ km s$^{-1}$ shocks with the ambient medium (see King & Pounds 2015 for a review). The two shock fronts (reverse and forward) produced by the impact of the wind with gas at an escape velocity lower than the outflow velocity, are separated by a contact discontinuity and whereas the shocked ambient gas could decelerate to velocity of the order of $10^2$ km s$^{-1}$, the wind shock...
(forward) maintains its high velocity while entraining the ambient gas and pushing it further out (Faucher-Giguère & Quataert 2012).

Analogously to Supernova Remnants (Velazquez et al. 1998), fluid instabilities (e.g. Rayleigh-Taylor) are likely to develop at the discontinuity between the two shock fronts due to the difference between the densities of the impacting wind and of the impacted medium. A condition for the Rayleigh-Taylor instability to grow is that the mass of the ISM that is pushed by the discontinuity is higher than the mass of the ejecta (Velazquez et al. 1998), which undergoes to a deceleration process that is able to trigger instabilities in the fluid (see Fig. 3). Such instabilities would easily alter the dynamics of the shocked outflow and they may give rise to a re-distribution of the overall velocity field in which slower (and faster) components of the wind may simultaneously cross our line of sight. The effect of the turbulence would then provide a replenishment mechanism that continuously supply new sections/blobs of gas that might as well fall backwards with an opposite direction with respect to the bulk of the outflow.

We have developed a toy model for simulating this behavior and testing the viability of this idea. The simulation is based on the GUACHO code (Esquivel & Raga 2013) and a preliminary output is displayed in Fig. 3. An expanding shock is pushed within a turbulent medium by an inner wind with $v_{\text{out}} = 20,000 \text{ km s}^{-1}$. The expansion time is set to 20 yr, the mass of the central object is $10^6 \, M_\odot$ (i.e. the mass of IRAS17020+4544 and in general of the order of black hole masses in NLSy1 galaxies).

Fig. 3 shows the pattern of velocities developed at the shock front with and without instability. The right panel shows that “plumes” or “fingers” of gas with different velocities are formed as a result of the introduction of instabilities process in the expansion of the shocked outflow. Depending on which “fingers” are intercepted by our line of sight, it is evident that the resulting absorption line spectrum is likely to show a stratified wind consistent with the spectrum observed in IRAS17020+4544 (see Fig. 2). This scenario can easily apply to other NLSy1 sources with the same observational properties.

4. A truly multi-phase outflow in IRAS17020+4544?

Further hints to the presence of a shocked outflow in this source come from radio observations (see Fig. 1) that have revealed an elongated structure on a scale of 10 pc in VLBI images (Giroletti et al. 2017). The appealing possibility that such compact jet, which is produced by synchrotron emission, may represent the signature left by the shock of the inner X-ray outflow with the ambient gas has been postulated by several models of galactic outflows (e.g. Zakamska & Greene 2014; Nims et al. 2015) in an attempt to link synchrotron emission in radio-quiet sources with galaxy scale molecular outflows.

IRAS17020+4544 is hosted by a barred spiral galaxy with IR luminosity typical of LIRG ($L_{\text{FIR}} = 1.05 \times 10^{11} L_\odot$) therefore likely to be rich in molecular gas. We have obtained millimetric observations with the Large Millimetric Telescope (LMT, Hughes et al. 2010) and found tentative evidence for a galaxy scale outflow traced by CO gas (Fig. 1, Longinotti et al. submitted).

Assuming a dynamical timescale of few×$10^6$ years for the outflow to propagate out of the nucleus at the observed bulk velocity of $\sim 600 \text{ km s}^{-1}$, the spatial scale of the wind is approximately $\sim 0.5-3 \text{ kpc}$. The CO mass in the wind is of the order of $10^8 \, M_\odot$ and following Feruglio et al. 2015, we find an approximate estimate of the molecular outflow rate of $\sim 100 \, M_\odot \text{ yr}^{-1}$, which is consistent with recent findings reported for Active Galaxies with comparable CO properties (Cicone et al. 2014).

The relative proportion of momentum load for the X-ray and molecular outflows in IRAS17020+4544 would provide an additional evidence for the existence of energy con-
Figure 4. Left: Simultaneous 5-8 GHz spectral index VLBA image of IRAS17020+4544 observed in 2014. Contours show total intensity at 8 GHz and colours show the spectral index values (Giroletti et al. 2017). Right: Spectrum of the CO(1-0) line in IRAS17020+4544 obtained with the LMT telescope in 2017. The double peaked structure is fitted by two narrow Gaussian components (blue and green), and the line wings are fitted by broad Gaussian line (red line). The molecular gas mass is estimated assuming a CO-to-H$_2$ conversion factor appropriate for ULIRGs (Solomon et al. 1997). The molecular gas masses estimated in each narrow component are very similar, which is compatible with the presence of a ring of molecular material in the galaxy, while the blue wing of the line is consistent with the presence of molecular gas outflowing at $\sim$660 km s$^{-1}$ (Longinotti et al. submitted).

serving winds that propagate through the galaxy after undergoing a momentum boost, supporting the feedback scenario as proposed in earlier works (Feruglio et al. 2015).

Admittedly, these numbers suffer from the large uncertainties in the estimates of the mass outflow rate and of the wind spatial extent, therefore we are currently awaiting the outcome of an already performed interferometry observation to constrain the size of the molecular outflow region and its physical properties.

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