Outflows from AGN: their Impact on Spectra and the Environment

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Abstract. We present a brief summary of the main results from our multi-dimensional, time-dependent simulations of gas dynamics in AGN. We focus on two types of outflows powered by radiation emitted from the AGN: disk winds and winds driven from large-scale inflows. We show spectra predicted by the simulations and discuss their relevance to observations of broad- and narrow-line regions of the AGN. We finish with a few remarks on whether these outflows can have a significant impact on their environment and host galaxy.

1. Introduction

While AGN are very strong sources of electromagnetic radiation, they are also sources of outflows of matter and magnetic energy. There is a growing body of evidence that outflows are quite common and are an integral part of AGN (e.g., Crenshaw et al. 2002; Richards & Hall 2004). Moreover, radiation and mass outflows in luminous sources are physically coupled as matter can absorber, scatter and emit radiation and radiation can affect dynamics and ionization of matter. For example, powerful mass outflows in quasars are very likely winds driven by radiation from accretion disks (e.g., reviews by Königl 2006; Proga 2007a). In addition, as we will illustrates here, the same radiation can drive outflows from large scale inflows.

In this paper, we briefly summarize results from numerical simulations of disk winds and large-scale outflows. We review the properties of these outflows and compare them with those observed in AGN. This will allow us to assess the level of our understanding of AGN outflows and their potential role in the AGN feedback.

2. Radiation-Driven Outflows from Accretion Disks

The successes of modelling outflows driven by radiation pressure on spectra lines (line driving) from OB stars (e.g., Castor et al. 1975; Puls et al. 2008) and from accretion disks in cataclysmic variables (CVs; e.g., Proga 2005) motivate applications of a similar physics to model outflows in AGN.

In Proga et al. (2000) and Proga & Kallman (2004), we adopted the approach from Proga et al. (1998, 1999) to calculate axisymmetric time-dependent hydrodynamical models of line-driven winds from accretion disks in AGN. To
apply the line-driven disk wind model developed for CVs to AGN, we took into account, in an approximated way, the difference in the spectral energy distribution between AGN and CVs. In particular, we introduced three major modifications to our previous approach: 1) calculation of the parameters of the line force based on the wind properties, 2) effects of optical depth on the continuum photons, and 3) radiative heating and cooling of the gas.

Our AGN wind calculations follow (i) a hot and low density flow with negative radial velocity in the polar region, (ii) a dense, warm and fast equatorial outflow from the disk, and (iii) a transitional zone in which the disk outflow is hot and struggles to escape the system. Fig. 1 shows an example of a velocity field of a AGN disk wind model.

To make a direct comparison with observations, we calculated synthetic line profiles based on our model for the C IV λ1549 Å line [Proga & Kallman 2004]. The synthetic line profiles show a strong dependence on inclination angle: the absorption forms only when an observer looks at the CE through the fast wind (i.e., $i \geq 60^\circ$ as shown in Fig. 3 of [Proga & Kallman 2004]; see also Fig. 2 here). This $i$ dependence can explain why only 10% of QSO have BALs.

The model also predicts high column densities for the inclination angles at which strong absorption lines form. Schurch et al. (2009) computed broad band spectra for various inclination angles using the simulation from [Proga & Kallman 2004]. Fig. 3 presents some examples and shows that the model is consistent
Figure 2. Theoretical profiles of CIV 1549Å based on the wind model of Proga & Kallman (2004) as a function of inclination angle, $i$ (see bottom right corner of each panel for the value of $i$). The solid lines show the profiles due to the absorption only whereas the dashed lines show the profiles due to the absorption and emission (the line source function includes resonance scattering and thermal emission). Note the sensitivity of the lines on the inclination angle. The zero velocity corresponding to the line center is indicated by the vertical line.

with the observations, i.e., BAL QSO are underluminous in X-rays compared to their non-BAL QSO counterparts (e.g., [Brandt et al. 2000; Giustini et al. 2008]).

3. Radiation-Driven Outflows from Large-Scale Inflows

In the previous section, we showed that the powerful radiation from an AGN can drive a strong wind from an accretion disk, the place where the radiation is produced. In turn, this wind has a significant impact on the radiation. However, the same radiation can also change the dynamics of the material at large distances from the radiation source.

We have begun studying gas dynamics in AGNs on subparsec and parsec scales [Proga 2007b; Proga et al. 2008; Kurosawa & Proga 2008, 2009a,b; Kurosawa et al. 2009]. In the following, we briefly summarize the main results of this work.

In Proga (2007b), we calculated a series of models for non-rotating flows that are under the influence of super massive BH gravity and radiation from an accretion disk surrounding the BH. Generally, we used the numerical methods developed by Proga et al. (2000). Our numerical approach allows for the self-consistent determination of whether the flow is gravitationally captured by the BH or driven away by thermal expansion or radiation pressure.

For a $10^8 M_\odot$ BH with an accretion luminosity of 0.6 of $L_{\text{Edd}}$ (the same parameters as in the disk wind simulations), we found that a non-rotating flow settles quickly into a steady state and has two components (1) an equatorial inflow and (2) a bipolar inflow/outflow with the outflow leaving the system along the pole. The first component is a realization of Bondi-like accretion flow. The second component is an example of a non-radial accretion flow becoming an outflow once it is pushed close to the rotational axis of the disk where thermal expansion and radiation pressure can accelerate the flow outward. The main result of these simplified calculations is that the existence of the above two flow components is robust yet their properties are sensitive to the geometry.
Figure 3. The 0.3-13 keV transmitted X-ray spectra ($E_{\Delta E}$) from five different lines-of-sight, with different inclinations, through the hydrodynamic simulation of an AGN outflow presented in Proga & Kallman (2004). The spectra were calculated with XSCORT (v5.18) using snapshot 800 of the Proga & Kallman simulation to provide self-consistent physical outflow properties. The input ionizing power-law spectrum is shown in black. The spectra correspond to inclinations of $\theta = 50, 57, 62, 65, \& 67^\circ$, (top to bottom). These l.o.s were chosen to highlight the range of spectral shapes that result from the different physical properties throughout the simulated wind. The figure is from Schurch et al. (2009).

SED of the radiation field, and the outer boundaries. In particular, the outflow power and the degree of collimation are higher for the model with radiation dominated by UV/disk emission than for the model with radiation dominated by X-ray/central engine emission. This sensitivity is related to the fact that thermal expansion drives a weaker and wider outflow, compared to the radiation pressure.

Rotation of the inflowing gas changes the geometry of the flow because the centrifugal force prevents gas from reaching the rotational axis (see Fig. 1 in Proga et al. 2008). This, in turn, reduces the mass outflow rate because less gas is pushed toward the polar region. We also found that rotation can lead to fragmentation and time variability of the outflow. As the flow fragments, cold and dense clouds form (Figs. 4 and 12 in Proga et al. 2008).

Three-dimensional effects are also important. In Kurosawa & Proga (2008), we considered effects of radiation due to a precessing accretion disk on a spherical cloud of gas around the disk. On the other hand, in Kurosawa & Proga (2009a), we recalculated some models from papers Proga (2007b) and Proga et al. (2008) in full 3-D. Our 3-D simulations of a nonrotating gas show small yet noticeable nonaxisymmetric small-scale features inside the outflow. However, the outflow as a whole and the inflow do not seem to suffer from any large-scale instability. In the rotating case, the nonaxisymmetric features are very prominent, especially
Three-dimensional hydrodynamical simulations of outflow formation via redirection of accreting gas by the strong radiation from an accretion disk around a super massive black hole with its mass $M_{\text{BH}} = 10^8 M_\odot$. The infalling gas is weakly rotating (sub-Keplerian), and the Eddington ratio of the system is 0.6. The volume rendering representation of the density distributions is shown. The outflow morphology is bi-conical, but the flow contains relatively cold and dense cloud-like structures which resembles those observed in the NRLs of Seyfert galaxies. The figure is from Kurosawa & Proga (2009b).

in the outflow which consists of many cold dense clouds entrained in a smoother hot flow (e.g., see Figs. 4 and 5). The 3-D outflow is nonaxisymmetric due to the shear and thermal instabilities. Effects of gas rotations are similar in 2-D and 3-D. In particular, gas rotation increases the outflow thermal energy flux, but reduces the outflow mass and kinetic energy fluxes. In addition, rotation leads to time variability and fragmentation of the outflow in the radial and latitudinal directions. The collimation of the outflow is reduced in the models with gas rotation. The main difference between the models with rotation in 3-D and 2-D is that the time variability in the mass and energy fluxes is reduced in the 3-D case because of the outflow fragmentation in the azimuthal direction.

To be able to compare these new simulations with observations, we are in a process of computing synthetic line profiles, broad band spectra and maps. However, even without these diagnostics we can check if the models are consistent with the data. For example, we can compare the kinematics study of NGC 4151 Das et al. (2005) with the velocity of the cold clouds (cf. Fig. 5) projected ($v_{\text{proj}}$) toward an observer at the inclination angle $i = 45^\circ$, which is the inclination of NGC 4151. Das et al. (2005) used the kinematics model of the outflows with a bi-conic radial velocity law, and found a good fit to their observations when the opening angle of the cone is $\sim 33^\circ$. Interestingly, we find the opening angle of the outflows in our is also about $30^\circ$ (cf. Figs. 5).
Figure 5. Spatial distributions of the “cold clouds” in the model shown in Fig. 4. The grayscale image shows the density map of the cold clouds in logarithmic scale (in cgs unit) on the z–x plane. The cold clouds here are defined as the gas with its density higher than $\rho_{\text{min}} = 1.6 \times 10^{-20}$ g cm$^{-3}$ and its temperature less than $T_{\text{max}} = 1.6 \times 10^5$ K. The clouds are not spherically distributed, but located near the bi-conic surface (which appears as an X-shaped pattern here) defined by the outflowing gas. Note that the length scale are in units of pc. The figure is from Kurosawa & Proga (2009b).

Figure 6 shows $v_{\text{proj}}$ of the clouds plotted as a function of the projected vertical distance, which is the distance along the z-axis in Fig. 5 projected onto the plane of the sky for an observer viewing the system with $i = 45^\circ$. The figure shows that the clouds are accelerated up to 250 km s$^{-1}$ until the projected distance reaches $\sim 4$ pc, but the velocity curve starts to flatten beyond this point. Towards the outer edges (near the outer boundaries), the curve begins to show a sign of deceleration, but not so clearly. We note that the hot outflowing gas, on the other hand, does show deceleration at the larger radii in our models (cf. Fig. 9 in Kurosawa & Proga 2009a). Although the physical size of the long slit observation of NGC 4151 by Das et al. (2005) is much larger scale ($\sim 50$ times larger) than that of our model, their radial velocities as a function of the position along the slit (see their Figs. 5 and 6) show a similar pattern as in our model (Fig. 6). The range of $v_{\text{proj}}$ in our model is about $-250$ to $300$ km s$^{-1}$ while the range of the observed radial velocities in Das et al. (2005) is about $-800$ to $800$ km s$^{-1}$, which is comparable to ours.

4. Concluding Remarks

The models presented here, which numerically simulate the outflows driven by radiation from AGN, are in many respects consistent with observations. Clearly more work is needed to test the models and improve them. However, the first
Figure 6. The velocities of the cold cloud elements (as in Fig. 5) projected toward an observer located at the inclination angle $i = 45^\circ$ are shown as a function of the projected vertical distance (the distance along the z-axis in Fig. 5, but projected on to the plane of the sky for the observer viewing the system with $i = 45^\circ$). The negative projected distance indicates the clouds are found in the lower half of the projection plane. The figure is from Kurosawa & Proga (2009b).

few steps toward the development a self-consistent physical model of the AGN outflows has been taken.

Applications of the model are not limited to AGN because other astrophysical objects – such as X-ray binaries, in particular micro-quasars – have a similar geometry and can be understood within a similar physical framework. In addition, having a physical model of the AGN outflows we can apply it to the so-called AGN feedback problem.

Some results from the outflow models have been already incorporated to galaxy evolution calculations. In particular, Ciotti et al. (2009), improved and extended the accretion and feedback physics explored in their previous papers (e.g., Ciotti & Ostriker 1997, 2001, 2007). By using a high-resolution one-dimensional hydrodynamical code, Ciotti et al. (2009) studied, the evolution of an isolated elliptical galaxy, where the cooling and heating functions include photoionization and Compton effects, and restricting to models which include only radiative or only mechanical feedback (the latter, in the form of disk winds properties of which were adopted from Proga et al. 2000, Proga & Kallman 2004).

These recent calculations confirmed that for Eddington ratios above 0.01, both accretion and radiative outputs are forced by feedback effects to be in burst mode, so that strong intermittencies are expected at early times, while at low redshift the explored models are characterized by smooth, very sub-Eddington mass accretion rates punctuated by rare outbursts. However, the explored models always fail some observational tests. For the high mechanical efficiency of $10^{-2.3}$ as adopted by some investigators, it was found that most of the gas is ejected from the galaxy, the resulting X-ray luminosity is less than a value typically observed and little super massive black hole growth occurs. However, models with low enough mechanical efficiency to accommodate satisfactory black
hole growth tend to allow too strong cooling flows and leave galaxies at $z = 0$ with E+A spectra more frequently than is observed. Surprisingly, it was also found that both types of feedback are required. Radiative heating over the inner few kilo parsecs is needed to prevent calamitous cooling flows, and mechanical feedback from active galactic nucleus winds, which affects primarily the inner few hundred parsecs, is needed to moderate the luminosity and growth of the central black hole. Models with combined feedback pass more observational tests (Ciotti et al., in preparation). Thus it emerges from these simulations that to solve the AGN feedback problem/explain all aspects of the galaxy evolution, more than one form of feedback is needed.

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References

Brandt, W. N., Laor, A., & Wills, B. J. 2000, ApJ, 528, 637
Castor, J. I., Abbott, D. C., & Klein, R. I. 1975, ApJ, 195, 157
Ciotti, L. & Ostriker, J. P. 1997, ApJ, 487, L105
——. 2001, ApJ, 551, 131
——. 2007, ApJ, 665, 1038
Ciotti, L., Ostriker, J. P., & Proga, D. 2009, ApJ, 699, 89
Crenshaw, D. M., Kraemer, S. B., & George I. M. Mass Outflow in Active Galactic Nuclei: New Perspectives, ASP Conference Proceedings, Vol. 255. Edited by D. M. Crenshaw, S. B. Kraemer, and I. M. George, San Francisco: Astronomical Society of the Pacific, 2002
Das, V. et al. 2005, AJ, 130, 945
Giustini, M., Cappi, M., & Vignali, C. 2008, A&A, 491, 425
Königl A. 2006, MmSAI, 77, 598
Kurosawa, R. & Proga, D. 2008, ApJ, 674, 97
——. 2009a, ApJ, 693, 1929
——. 2009b, MNRAS, 397, 1791
Kurosawa, R., Proga, D., & Nagamine K. 2009, ApJ, 707, 823
Proga, D. 1999, MNRAS, 304, 938
Proga, D. 2005, in ASP Conf. Ser. 330, The Astrophysics of Cataclysmic Variables and Related Objects, ed. J.-M. Hameury & J.-P. Lasota (San Francisco: ASP), 103
Proga, D. 2007a, in The Central Engine of Active Galactic Nuclei, ed. L. C. Ho, & J.-M. Wang, ASP Conf. Ser., 373, 267
Proga, D. 2007b, ApJ, 661, 693
Proga, D. & Kallman, T. R. 2004, ApJ, 616, 688
Proga, D., Ostriker, J. P., & Kurosawa, R. 2008, ApJ, 676, 101
Proga, D., Stone, J. M., & Drew, J. E. 1998, MNRAS, 295, 595
Proga, D., Stone, J. M., & Drew, J. E. 1999, MNRAS, 310, 476
Proga, D., Stone, J. M., & Kallman, T. R. 2000, ApJ, 543, 686
Puls, J., Vink, J. S., & Najarro, F. 2008, A&AR, 16, 209
Richards, G.T. & Hall, P.B 2004, AGN Physics with the Sloan Digital Sky Survey, ASP Conference Series, Volume 311, Edited by Gordon T. Richards and Patrick B. Hall, San Francisco: Astronomical Society of the Pacific, 2004
Schurch, N. J., Done, C., & Proga, D. 2009, ApJ, 694, 1