Disk-Driven Outflows in AGNs

Arieh Königl

Department of Astronomy & Astrophysics, University of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637, U.S.A.

Abstract. Analysis of spectral absorption features has led to the identification of several distinct outflow components in AGNs. The outflowing gas is evidently photoionized by the nuclear continuum source and originates in the accretion flow toward the central black hole. The most likely driving mechanisms are continuum and line radiation pressure and magnetic stresses. The theoretical modeling of these outflows involves such issues as: (1) Which of the above mechanisms actually contributes in each case? (2) How is the gas uplifted from the underlying accretion disk? (3) How can the intense central continuum radiation be shielded to allow efficient radiative driving? (4) Is the outflow continuous or clumpy, and, if clumpy, what is the nature and dynamical state of the “clouds”? This review summarizes recent theoretical and observational results that bear on these questions and outlines prospects for further progress.

1. Observational Background

Recent observational work has strengthened the evidence for the common existence of gas outflows from the centers of active galaxies. In the case of Seyfert 1 galaxies, high-resolution UV and X-ray spectroscopy (involving, in particular, HST, FUSE, Chandra, and XMM/Newton) has pointed to the presence of gas outflowing\(^1\) at \(\sim 10^2 - 10^3\) km s\(^{-1}\) and most likely originating on the scale of the broad emission-line region (BELR) — \(R_{\text{BELR}} \approx 0.1L_{45}^{0.7}\) pc (where \(L_{45}\) denotes the optical luminosity in units of \(10^{45}\) ergs s\(^{-1}\); Kaspi et al. 2000).

The outflowing gas in Sy 1 galaxies is often seen in absorption and is inferred to have a global covering factor \(> 0.5\) (e.g., Crenshaw et al. 1999). At high resolution the absorbing gas separates into distinct kinematic components that are characterized by a range of physical properties (such as the value of the ionization parameter \(U \equiv n_\nu/n_H \propto L_{\text{ion}}/n_H r^2\), the ratio of the number densities of ionizing photons and hydrogen nuclei) and of FWHM widths (up to \(\sim 400\) km s\(^{-1}\) in the Crenshaw et al. 1999 sample, indicative of macroscopic motions). Although the strongest absorption components evidently lie completely outside of the BELR, the high line-of-sight covering factors derived in certain

\(^1\)The outflow speeds are inferred from measurements of line blueshifts relative to the systemic velocity of the galaxy, and are typically significantly smaller than the line widths of the BELR gas (\(\lesssim 10^4\) km s\(^{-1}\)). The latter have been attributed to either rotation, turbulence, or the effect of electron scattering.
cases suggest that at least some of the absorbing gas lies close to the nucleus. This conclusion is supported by direct estimates of the density in a number of sources, which indicate that the respective absorbing component must lie at a distance of less than a fraction of a parsec from the continuum source (e.g., Netzer et al. 2002; Gabel et al. 2002). The effect of the partially ionized “warm absorber” gas is manifested in both the UV and X-ray spectra, and there is evidence that at least some of the UV and X-ray components overlap. An important issue, not yet fully resolved in most cases, is the relationship between the different kinematic and ionization components that are identified in a given source: are they best described as a single-phase or a multiphase outflow?

Spectral variability studies can help answer the question of whether the flow is uniform or clumpy. Typical variability time scales are months to years, and, although in some cases the origin of the variability is apparently a change in the irradiating continuum (e.g., Kraemer et al. 2002a), in other cases the preferred explanation is a change in the column density of the absorbing gas (e.g., Crenshaw & Kraemer 1999): this can be attributed to the transit or evolution of density inhomogeneities that intercept our line of sight.

Measurements of variability in P Cygni profiles of UV lines have been interpreted as evidence for a systematic acceleration of the BELR gas in the Sy 1 galaxy NGC 3516 (Hutchings et al. 2001). Inferences from X-ray spectroscopy of an increase in the outflow speed with decreasing degree of ionization in a number of sources (e.g., Sako et al. 2001; Kaastra et al. 2002) are consistent with this picture. Evidence for a systematic acceleration has also been inferred for the narrow emission-line region (NELR) gas in both Sy 1 (Crenshaw et al. 2000) and Sy 2 (Crenshaw & Kraemer 2000) galaxies over distances \( \gtrsim 10^2 \text{pc}. \)

Broad absorption-line QSOs (BALQSOs) are another class of AGNs where there is strong evidence for distinct outflow components. Typical speeds are \( \sim 10^3 - 10^4 \text{km s}^{-1} \), but values of up to \( \sim 0.1 \text{c} \) have been inferred. Similarly to the warm-absorber component in Sy 1 galaxies, at least some of this gas evidently lies outside of the BELR, and the covering factor at the source is \( \gtrsim 0.3 \) (e.g., Goodrich 1997). However, in contrast with Sy 1 galaxies, which are typically viewed at a comparatively small angle to the symmetry axis, BALR outflows may be observed at a relatively large angle to the axis (see \S 2). The so-called “associated” QSO absorption systems (e.g., Richards et al. 1999), which are blueshifted relative to the source by up to \( \sim 0.1 \text{c} \), may potentially originate in the QSO itself just like BALQSO outflows. This possibility has proven hard to verify because of the difficulty in pinning down the distance from the QSO, which might be \( \gg R_{\text{BELR}} \).

Another potentially important ingredient is dust. The presence of dust within the outflow has been inferred in some warm absorbers and BALQSOs. There is also a direct indication from spectropolarimetry in the Sy galaxy NGC 1622 for dust moving toward us at a speed of \( \sim 10^3 \text{km s}^{-1} \) (Goodrich 1989).

2. Association of Outflows with Disks

The BELR emission is characterized by single-peaked lines and a variability pattern in which a change in the continuum flux produces an earlier response in the red wing of a line like H\( \beta \) than in the blue wing. These characteristics
are most naturally interpreted in terms of a rapidly accelerated outflow from a rotationally supported disk (e.g., Chiang & Murray 1996). This interpretation applies to the two main proposed driving mechanisms of disk outflows: line driving by the disk radiation (e.g., Murray & Chiang 1997) and centrifugal driving along open magnetic field lines that thread the disk (e.g., Bottorff et al. 1997).

A disk-like geometry for the BELR has been inferred from an observed correlation between the peak line width and the radio-axis inclination to the line of sight in radio-loud QSOs (e.g., Vestergaard et al. 2000; Hough et al. 2002). An equatorial disk geometry has also been indicated for BALR outflows by spectropolarimetric observations of BALQSOs (e.g., Goodrich & Miller 1995; Cohen et al. 1995).

3. Theoretical Framework

A broadly consistent picture of the BELR and BALR in terms of disk outflows can be summarized as follows:

- The BELR gas (or at least its high-ionization component) in Seyfert galaxies and QSOs corresponds to a disk-driven outflow that is photoionized by the central continuum radiation.
- The BALR outflow is BALQSOs likely has a dominant contribution from the radiation pressure force exerted by the central continuum, which accelerates the gas along comparatively low-latitude trajectories.
- The photoionized gas at the base of the outflow can naturally account for the X-ray and UV warm-absorber component. The X-rays are typically absorbed by a larger column than the UV radiation. This can be attributed to clumpiness (the UV absorption occurs in low-filling-factor “clouds”) or to the UV absorption occurring predominantly in the outer, less strongly ionized regions of the photoionized nuclear gas.
- The partially ionized gas likely also contributes to the X-ray absorption in BALQSOs. The comparatively rapid upward acceleration of the disk outflow results in a vertical density stratification that gives rise to a systematic decrease in the absorbing column with increasing latitude. This explains why BALQSOs, which are evidently viewed close to the disk plane, have low X-ray fluxes that in most cases can be attributed to a large absorbing column (e.g., Brandt et al. 2000; Green et al. 2001). Part of the absorption in BALQSOs and Sy 2 galaxies may occur in a dusty, molecular “torus” located outside the BELR. This proverbial “torus,” which is the basis of the unification scheme of type 1 and type 2 sources (either Seyferts or QSOs; e.g., Antonucci 1993) can be associated with the dusty outer region (beyond the dust sublimation radius $R_{\text{subl}}$) of the disk outflow (Königl & Kartje 1994). Some dust absorption in Sy 2 galaxies evidently originates on larger scales ($\gtrsim 10^{-2}$ pc), probably in molecular clouds located in the plane of the host galaxy (e.g., Crenshaw & Kraemer 2001; Risaliti

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2The sublimation radius can be naturally identified with the outer boundary of the BELR (Netzer & Laor 1993).
et al. 2002), but the bulk of the absorption in Compton-thick sources likely arises in the more compact “torus” (e.g., Guainazzi et al. 2001).

To flesh out this modeling framework, several key questions need to be addressed:
1) Is the gas uplifted from the disk surface (radiative driving by intrinsic or reprocessed disk radiation, or a hydromagnetic wind)?
2) If radiation pressure on atoms is efficient, what provides the requisite shielding of the central continuum — A “failed” radiation pressure-driven wind? The inner region of a hydromagnetic disk outflow?
3) Is radiation pressure on dust important for the outflow dynamics?
4) Is the BELR/BALR gas composed primarily of “clouds”, as has been traditionally assumed, or can it be attributed to a continuous outflow (Murray et al. 1995)? If clouds are present, are they coherent, long-lived entities, and, if so, how are they confined?

In the following sections I discuss these issues in greater detail.

4. Radiative Driving

Various observations have pointed to a potentially central role for radiation pressure in driving the observed outflows. In particular, the detection of a “ghost of Lyα” (a signature of the radiative acceleration of the N V ion by Lyα flux imprinted on the C IV BAL profile) has provided direct evidence for radiative acceleration in BALQSOs (e.g., Arav 1996). In the case of the warm-absorber component in Sy 1 galaxies, the inferred outflow speeds were shown to be consistent with radiative driving involving the O VII and O VIII absorption edges (e.g., Reynolds & Fabian 1995).3 In fact, the size of the warm-absorber region has been deduced by comparing observed flux variability time scales to the recombination times of the relevant oxygen ions (e.g., Netzer et al. 2002).4

Explicit models of radiatively driven disk winds in AGNs have been constructed semianalytically (Murray et al. 1995) and numerically (Proga et al. 2000). These models account for the requisite shielding of the radiatively driven gas in terms of a “failed” inner outflow. The numerical simulations suggest that time-dependent dynamical effects could give rise to strong localized density enhancements and to apparently distinct outflow components. These results are, however, subject to the following potential caveats:

• The ability of the disk to radiatively uplift the postulated outflow as a result of either external or internal heating has not yet been self-consistently calculated.

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3 Some of the edge identifications have, however, been questioned in view of new Chandra and XMM/Newton observations (e.g., Branduardi-Raymont et al. 2001).

4 Note in this connection that, if a given ion can be identified as dominating the acceleration $g_{\text{rad}}$, then an independent measure of the characteristic gas-injection radius $r_0$ can be obtained from the inferred terminal speed $V_\infty$ in view of the fact that radiative acceleration typically occurs over a scale $\Delta r \ll r_0$ (e.g., Arav et al. 1994). Thus $V_\infty \approx [2g_{\text{rad}}(r_0) r_0]^{1/2}$, $g_{\text{rad}} \propto L_{\text{ion}}/r^2$, $\Rightarrow V_\infty \propto r_0^{-1/2}$. 
In view of the sensitive dependence of radiative acceleration on the irradiating spectrum, radiative transfer effects beyond simple attenuation need to be incorporated into the numerical models (Everett 2002 and these Proceedings). The radiatively driven disk outflow model has recently been tested by HST observations of two high-state cataclysmic variables (Hartley et al. 2002): the strong positive correlation between UV brightness and wind activity predicted by these models was found to be disobeyed by both binaries, indicating that nonradiative factors may control the mass-loss rate in these systems.

5. Magnetic Driving

Magnetically mediated disk outflows (specifically, centrifugally driven winds; e.g., Blandford & Payne 1982) are commonly invoked in low-luminosity astrophysical systems such as low-mass protostars (e.g., Königl & Pudritz 2000). Magnetic driving is also believed to underlie AGN jets (e.g., Blandford 2000). An open field configuration that is compatible with this picture has been inferred from polarization measurements in the Galactic center circumnuclear disk (Hildebrand et al. 1993).

Magnetic driving can produce high-speed, high-momentum-discharge disk outflows; such outflows transport angular momentum efficiently and hence may arise naturally in accretion disks. AGN outflows of this type would have a strongly stratified vertical density profile and would be photoionized in their inner regions and dusty in their outer parts. As was demonstrated by Königl & Kartje (1994), these winds could naturally account for the visual obscuration and UV/X-ray attenuation inferred in Type 2 AGNs. Such winds, in fact, give rise to effective obscuring tori that are “fuzzy,” as has been inferred in objects like NGC 4151 (Crenshaw et al. 2000). The comparatively high opacity of the dusty regions results in the “flattening” (by radiation pressure) of the “torus” in high-luminosity sources (a trend that has been inferred observationally), and the reprocessing of the central continuum radiation by the wind and disk in the dusty outer regions by and large reproduces the measured near/mid-infrared spectra of Seyfert galaxies. The predicted electron and dust distributions can also account for the distinct optical/UV continuum polarization properties of Sy 1 and Sy 2 galaxies (Kartje 1995). Furthermore, the magnetic pressure of these outflows provides an effective confining agent for embedded clouds, and internal MHD turbulence can contribute to the line broadening exhibited by the BELR gas (Bottorff & Ferland 2000).

As a first step toward investigating the combined effect of magnetic and radiative driving, Everett (2002 and these Proceedings) constructed a semianalytic model in which magnetic stresses uplift the gas from the disk surface and the central continuum contributes radial radiative driving further up (after the gas rises to a height where the inner portions of the stratified outflow provide an optimal shielding of the nuclear continuum). His model also incorporates clouds (uplifted by the ram pressure of the continuous wind and confined by the wind magnetic pressure) and dust. In a complementary approach, Proga (2002) carried out exploratory numerical simulations of magnetically/radiatively driven disk winds under a variety of (sometimes strong) simplifications.
6. Multiphase Outflows

As was noted in §1, high-resolution UV and X-ray observations of the warm absorber gas in Sy 1 galaxies have identified several velocity and ionization-parameter components in each source. In the case of NGC 3783, for example, photoionization modeling has implied a correspondence of two distinct ionization components to a single kinematic component (Kraemer et al. 2001), which provides strong support for the presence of a multiphase outflow. This conclusion is supported by the inferred smooth variation of the continuum covering factor in the wings of the individual kinematic absorption components in this source, which was interpreted as pointing to a (cloud?) substructure (Gabel et al. 2002). Although the existing data are not yet sufficient for drawing general conclusions, there have been indications for the coexistence of at least two distinct ionization components also in other sources (e.g., Mrk 509; Kraemer et al. 2002b). The presence of a two-component gas has also been suggested for the NELR of certain Seyfert galaxies (e.g., Ogle et al. 2000; Komossa 2001).

There is also growing evidence for the existence of multiphase outflows in BALQSOs. For example, in the case of FBQS 1044, absorption features that, when interpreted in the context of a single-phase model imply a distance from the central continuum source of \( \sim 0.7 \) kpc, yield a much smaller, physically more reasonable scale of \( \sim 4 \) pc when reinterpreted in terms of a shielded, continuous, low-density wind with embedded dense clouds (Everett et al. 2002 and these Proceedings). Similar apparent difficulties in other sources (e.g., the radio-loud galaxy 3C 191; Hamann et al. 2001) might be resolved in the same way. The inference that an obscuring cloud is responsible for the X-ray absorption in the lensed BALQSO UM 425 (Aldcroft & Green, these Proceedings) is consistent with this picture.

The notion of discrete clouds in the BELR has been challenged by cross-correlation spectral analyses (e.g., Arav et al. 1998; Dietrich et al. 1999), which indicate that an implausibly high number of clouds may be required to account for the smoothness of the measured line profiles. This conclusion could, however, be mitigated if MHD turbulence, and not just thermal motions, contributes to the intrinsic line widths (Bottorff & Ferland 2000). Discrete clouds could be entrained into the continuous disk outflow at the disk surface (in analogy with coronal mass ejections in the Sun). Such clouds could be subsequently confined by the wind magnetic field (e.g., Everett et al. 2002; Everett 2002). An alternative possibility is that the clouds represent transient condensations (which need not be confined) in a turbulent medium (e.g., Bottorff & Ferland 2001) — these two possibilities would have similar spectral signatures and thus may be hard to distinguish observationally.\(^5\)

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\(^5\)Note, however, that a strong magnetic contribution to the line widths (which implies \( P_{\text{magnetic}} \gg P_{\text{thermal}} \) in the emitting gas) likely corresponds to transient density enhancements rather than to long-lived clouds (which require pressure confinement), since magnetic confinement of clouds is optimized when \( P_{\text{magnetic, cloud}} \ll P_{\text{thermal, cloud}} \) and \( P_{\text{magnetic, confining}} \approx P_{\text{thermal, cloud}} \).
7. Further Progress

Theory

• Semianalytic models have reached the level where the basic qualitative aspects of the interplay between magnetic and radiative driving, and the dynamics of a multiphase outflow, can be studied. Incorporating the effect of a disk radiation field (in addition to a central continuum) is the next step in this effort.
• 2D numerical simulations, which have revealed several suggestive features, need to be combined with a photoionization code and generalized to 3D. The most important questions that need to be answered are: Can the full observed range of outflow speeds be reproduced with this mechanism? Can radiative driving alone account for the requisite uplifting, shielding, and acceleration for realistic AGN radiation fields and disk models? Can the nonsteady effects identified in the simulations account for the observed spectral characteristics?
• 2D and 3D MHD simulations of centrifugally driven disk outflows have already been carried out, but their observational implications to AGN spectra have not yet been studied. Ultimately, a comprehensive radiative/magnetic driving model should be simulated with a single code.

Observations

• Use high-resolution optical/UV/X-ray spectroscopy to relate the distinct kinematic and ionization components identified in warm-absorber and BALQSO outflows; in particular, can a general case be made for a multiphase outflow?
• Continue to refine the tool of spectropolarimetry in AGN research; in particular, can the results derived in BALQSOs be obtained also in Seyfert galaxies, and can more evidence be uncovered for high-velocity dust?
• Attempt to carry out detailed searches for a correlation between UV brightness and wind activity to test radiatively driven outflow models (as has recently been done for CVs).
• Search for spectral signatures of high-velocity outflows in low-\(L_{\text{ion}}\) sources (e.g., BL Lac objects) in an effort to discriminate between magnetic and radiative disk-outflow models.

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