Quasar Structure Emerges from the Three Forms of Radiation Pressure

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Abstract. All quasar spectra show the same atomic features in the optical, UV, near-IR and soft X-rays over all of cosmic time, luminosity black hole mass and accretion rate. This is a puzzle. Here I show that it is possible that all of these atomic features can be accounted for by gas from an accretion disk driven the three forms of radiation pressure: electron scattering, line driving and dust driving. The locations where they successfully drive an escaping wind, and those where they produce only a failed wind are both needed.

1. The Puzzle of Quasar Spectra

It is remarkable that, to a good approximation, the spectra of all quasars and active galactic nuclei (called quasars hereinafter) are the same over 13 Gyr of cosmic time, 6 orders of magnitude in luminosity, and 3 orders of magnitude in both black hole mass and Eddington ratio. This constancy poses a problem. Whatever structures produce these atomic features they must be formed by some robust physics that does not depend strongly on any of these parameters. Accretion disk winds hint at a solution, but whether this can be realized has not been clear.

The features are these: All show (1) permitted broad (FWHM ~ 5000 km/s) emission lines (BELs); (2) narrow (FWHM ~ 1000 km/s) emission lines (NELs) that often extend into resolved bi-cones; (3) an Fe-K X-ray emission line at 6.4 keV. Half or more show: high ionization (4) UV narrow (FWHM < 200 km/s) absorption lines (NALs) and (5) X-ray narrow (FWHM < 300 km/s) absorption lines (known as "Warm Absorbers, or "WAs"), while about 15% show (6) broad (Δv ~ 10,000 km/s) absorbers, known as Broad Absorption Lines, or "BALs").

There are two exceptions: in both "type 2" quasars and "blazars" some or all of these features are covered up, either by reddening of the central region (type 2s), or by overwhelming them with a beamed continuum from a jet (blazars). But in type 2s the missing BELs can be seen in polarized light, while in blazars a normal quasar spectrum can be glimpsed when the jet is temporarily in a low state. So we believe that, intrinsically, all quasars have the same features in their inner regions.

Here I show that it is possible that these atomic features can be completely accounted for by the three forms of radiation pressure: electron scattering, line driving and dust driving, both in the locations where they are effective in driving an escaping wind, and where they produce only a failed wind.
2. Funnel Wind Model for Quasars

In 2000 I proposed a phenomenological model for quasar structure that could account for all the atomic features in quasars (Elvis 2000, 'E00'). The model determined the geometry and kinematics of the quasar. The model posits gas thrown off the accretion disk vertically in a narrow band of radii. As this wind is hit by the continuum radiation it bends radially outward, forming a funnel-shaped flow. BALs are seen looking along the radial flow, which reaches $\tau_{\text{esc}} \sim 1$ so giving the Fe-K line. NALs and WAs are seen looking almost perpendicularly through the flow, at low angles to the accretion disk; viewed from above the wind no absorption features are seen. The relative numbers of NALs, BALs and no absorption quasars set the angle of the flow to the disk to be $\sim 30^\circ$ [ignoring any possible equatorial obscuration (see Elvis 2012, in prep.)]. The BELs are formed from a cool phase of the wind.

2.1. Funnel Wind Predictions and Tests

A good model makes specific, testable, predictions. Table 1 lists predictions of the E00 model, and the papers which tested them. In each case the model survived the test, though some are still debated.

| Ref # | Prediction |
|-------|------------|
| 1     | WA is in outflow |
| 2     | WA has narrow absorption lines |
| 3     | WAs & NALs have same outflow velocities |
| 4     | WAs & NALs have consistent ionization states & column densities |
| 5     | WAs & NALs occur in the same objects |
| 6     | NAL bi-cones will be hollow and matter bounded outflows |
| 7     | WAs & NALs are common in high luminosity objects |
| 8     | WAs & NALs are common in edge-on AGNs |
| 9     | WA has a few distinct phases |
| 10    | WA phases are in pressure balance |
| 11    | WA is radially thin |
| 12    | NALs arise at accretion disk radii |
| 13    | WAs arise at accretion disk radii |
| 14    | BELs have a large scale height |
| 15    | BELs are dominated by rotation |
| 16    | BAL regions exist in all quasars |
| 17    | BAL region rotates |
| 18    | BAL scattering region creates narrow Fe-K emission |

References for each test: (1) Kaspi & et al. (2000); (2) Collinge & et al. (2001); (3) Gabel & et al. (2005a); (4) Mathur et al. (1994), Hamann et al. (2000), Krongold et al. (2003); (5) Kriss (2001); (6) Crenshaw & Kraemer (2000), Fischer et al. (2011), Piconcelli et al. (2005), Vestergaard (2003); (7) Leighly et al. (1997); (8) Andrade-Velázquez & et al. (2010); (9) Krongold et al. (2005); (10) Krongold et al. (2007); (11) Dunn et al. (2010); (12) Korista & Goad (2000); (13) Smith et al. (2005); (14) Young et al. (1999); (15) Young et al. (2007); (16) Sim et al. (2008).

The first 3 predictions were quickly confirmed by Chandra and XMM-Newton grating spectra. The 4th required the realization that partial covering applied to the UV lines, while the 5th was demonstrated by explicitly testing if NALs predicted WAs and
vice versa. The 6th was demonstrated by Hubble STIS long slit spectroscopy of narrow line region bi-cones. Number 7 was shown with larger UV and X-ray samples, while # 8 had already been shown, but was not widely known.

Predictions 9 and 10 have been controversial. It is now clear that every good X-ray spectrum can be fitted with a 2-3 phase WA in pressure equilibrium, but more complex solutions are allowed. Higher spectral resolution is needed to be definitive.

Tests 11-13 are closely connected. Initial results showed small radii, but a number of newer observations clearly put certain NAL systems at large, kiloparsec, distances. This is the greatest challenge so far to the funnel wind model. How general this conclusion is remains unknown.

BELs (#14-15) have been less tested. Polarimetry indicates rotation in some bright objects. BALs (#17-18) are also poorly tested. Again, polarimetry shows that BAL velocity gas is present in non-BAL objects and that the BAL region rotates.

These results gave us the confidence to search for a physical understanding based on this structure, one that can explain the more peculiar features in E00: the thin wind region, and a flow neither polar nor equatorial.

3. A Non-hydrodynamic Radiation Driving model

Radiation can transfer momentum to matter in only three ways, via: (1) electron scattering, (2) atomic absorption, (3) molecular/surface physics absorption. Normally we talk of these as Compton scattering, line driving and dust driving. Below the Eddington limit gravity exceeds the Compton scattering force, preventing a Compton scattered wind escaping; but few quasars reach Eddington (Kollmeier & et al. (2006), Steinhardt & Elvis (2010)). Line driving is hundreds of times more effective in O-stars, driving escaping winds well below Eddington. A dust grain effectively absorbs all the incident light, and so a medium with sufficient charged dust can even more effectively accelerate a wind. Which of these mechanisms work in quasars?

3.1. The QWIND Code

We built a non-hydrodynamic code, QWIND (Risaliti & Elvis (2010), 'RE10'). This is justified as the gas is always moving supersonically. NAL/WA blueshifts are \( \sim 1000 \text{ km/s} \) and the gas, at \( T \leq 10^6 \text{ K} \), has a thermal velocity of \( \leq 100 \text{ km/s} \), so this assumption is reasonable. Avoiding hydro let us quickly explore parameter space.

QWIND assumes that packets of gas are ejected at all radii from the disk, a generalization of E00, with some velocity and density, and follows their equation of motion as they are irradiated (as in Icke (1980), Watarai & Fukue (1999)). CLOUDY is used to determine the ionization of the gas packet, and performs the radiative transfer to filter the quasar continuum through the inner gas packets. We used the Castor et al. (1975) 'CAK' formalism to determine \( \alpha(\text{CAK}) \), the multiplier, or gain, of line driving over pure Compton scattering. Importantly, the UV continuum has a \( \cos \theta \) dependence on angle above the disk, while the X-ray continuum is considered isotropic. The UV/X-ray ratio is an input parameter. Only the supermassive black hole gravity was included.

For typical conditions QWIND produced the flow lines in Figure 1. A number of distinct zones form naturally.

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\(^1\)Neglecting pair production.
3.2. Compton Scattering Zone

The innermost zone is overionized, so only Compton scattering is effective, but below L(Edd) the wind cannot escape. Once $\tau_{es} > 1$ this gas preferentially scatters X-rays out of the disk plane, reducing the ionization parameter in the next zone. This is the "hitchhiking gas" of Murray & Chiang (1998). The gas in this region still reaches a few 1000 km/s) before falling back. Such high ionization, turbulent, variable velocity gas has been seen in NGC 1365 (Risaliti & et al (2005)), with $\tau_{es} \sim 1$. Some L(Edd) objects show high velocity winds (Pounds et al. (2003), Chartas et al (2002)).

3.3. Line Driving Zone

The next zone out is where line driving becomes effective and an escaping wind is formed. Line driving has become widely accepted for NALs/WAs, following Murray et al. (1995, Murray et al. (1995)). We find that in this zone $\alpha$(CAK) is only $\sim 10$. The escaping wind still reaches BAL-like speeds exceeding 10,000 km/s, but the low $\alpha$(CAK) allows the wind to make a large angle to the disk, contrary to Murray & Chiang (1995 Murray & Chiang (1995)), and consistent with E00. Once the column density reaches $N_H \sim 10^{22}$ cm$^{-2}$, the line driving UV photons are absorbed, so this zone is physically thin, as in E00. This $N_H$ is characteristic of WAs. High ionization BELs (CIV, OVI, NV, HeII, 'HiBELs') are often considered part of a line-driven wind, and can produce the observed line profiles (Murray & Chiang (1997)). Some multi-phase WA solutions include a $\sim 10^4$K branch, which may produce the HiBELs. This should be explored in detail.

3.4. Failed Wind Zone

Beyond the line driving zone the gas packets no longer reach escape velocity, but do achieve a significant scale height. Gas in this region could be responsible for the low ionization BELs (FeII, MgII, 'LoBELs'), a modification of E00. The LoBELs have long been located in the accretion disk (Collin-Souffrin et al. 1988). This needs inves-
tigating using the LOC formalism \(\text{(Baldwin et al. (1995))}\). X-ray \(N_H\) changes in days are increasingly common \(\text{(Elvis et al. (2004), Puccetti et al. (2007))}\), and have radii and densities suggestive of LoBEL clouds.

4. Dust Driven Zone

RE10 do not include dust driving, as dust should be absent within the dust sublimation radius, \(r_{\text{sub}}\). However, \(\text{Czerny & Hryniewicz (2011)}\) point out that the pressure and temperature conditions at which AGB star winds produce dust are also found on quasar disk surfaces, from a few 1000 Schwartzchild radii outward. Interior to \(r_{\text{sub}}\) these clouds will initially be accelerated, but their dust will soon evaporate, and they will cease to accelerate, probably forming a failed wind. There are changes in X-ray \(N_H\) on timescales of years \(\text{(e.g. Marinucci et al. in prep.)}\), which might be caused by dusty clouds at these radii crossing the line of sight. Beyond \(r_{\text{sub}}\) these clouds will form a wind, which may be one form of the obscuring “torus” needed to explain type 1 and type 2 quasars \(\text{(Elvis 2012, in prep.)}\).

5. Line-Driven Wind Parameter Space

Varying the parameters in QWIND lets us map out the conditions under which an escaping wind forms. Clouds with BEL densities and temperatures make a winds hard to drive at high black hole mass; while an X-ray quiet continuum produces winds over a much wider range of conditions, as expected \(\text{(Murray & Chiang(1995))}\).

Interestingly high \(L/L(\text{Edd})\) does not, as often assumed, imply faster winds. At higher \(L/L(\text{Edd})\) the wind begins further out, and the \(1/r^2\) weakening of the continuum lowers the final speed of the wind.

6. Is Matter Launched at All Disk Radii?

RE10 explicitly separate the problem of accelerating the clouds, which is treated by QWIND, from the initial launching of clouds, by assuming that launching occurs at all radii. There is no necessary connection between the two processes. In fact, it seems unlikely that radiation driving alone can launch material at all disk radii.

There is evidence that the disk supplies gas at many radii. In NGC 5548, the H\(\beta\) BEL radius ‘breathes’ in and out by a factor \(\sim 3\) as the \(<3500\text{Å}\) luminosity changes by a factor \(>6\) \(\text{(Peterson & et al. (1999))}\). The few year timescale is much shorter than the viscous timescale, but comparable to the dynamical time. Plausibly there is pre-existing gas at all these radii, and the continuum luminosity picks out the radius where the H\(\beta\) emissivity is a maximum, as in the LOC model, but now applied to a disk geometry. BELs form a layered sequence from high ionization at small radii out to low ionization at factor \(\sim 20\) larger radii \(\text{(Peterson & Wandel (1999))}\), again as though the gas is pre-existing and emitting whatever BEL is optimal.

The X-ray ‘eclipses’ by (probable) BEL clouds seen in NGC 1365, have a comet-like form: small, dense heads with larger, lower density and higher ionization, tails \(\text{(Maiolino & et al. (2010))}\). The head lifetimes are \(\sim 2\) months, substantially shorter than the orbital timescale. The clouds must then be constantly replenished. The disk is the only plausible source.
Magnetic reconnection could launch gas at all radii. Solar Coronal mass ejections reach $\sim 1000 \text{ km/s}$, more than adequate for quasars. The magneto-rotational instability (MRI), likely responsible for the viscosity in quasar disks, can produce reconnection events. However, there may be a ‘dead zone’ where the gas is too neutral to support MRI, as in proto-planetary disks (Martin & Lubow (2011)). Would there be a corresponding gap in the gas supply for acceleration? MHD winds in general are another means of accelerating quasar winds (Nenkova et al. (2008)). Different acceleration processes may act in different quasars. Tests are needed to discriminate between them.

7. Conclusions

There is an elegance to this view of quasar structure. To form so many observed phenomena from such simple underlying physics is economical. That initially strange features of the funnel wind model are natural consequences of the onset and failure of the three forms of radiation driving is particularly appealing.

This physics is robust to changes in parameters, including $L/L(\text{Edd})$ and black hole mass, as boundary conditions are not important. Anything beyond the immediate environs of the black hole does not change the wind physics, so cosmic time is not important. Hence the puzzle of quasar spectra, with which I began, can be understood: all quasars are much the same because radiative acceleration in a disk setting is always the same.

It will now be important to build on this success by seeing if the model can produce second-order effects, such as eigenvector 1 (Boroson & Green (1992)), and whether a predictive model for the energy and momentum carried by the wind can be produced, in order to have a physical model of quasar feedback.

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