Circumgalactic Oxygen Absorption and Feedback

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Abstract

O VI absorption in quasar spectra caused by intervening circumgalactic atmospheres suggests a downturn in the atmospheric column density in sightlines passing beyond about 100 kpc from central star-forming galaxies. This turnover supports the hypothesis that the oxygen originates in the central galaxies. When converted into oxygen space density using an Abel integral inversion, the O VI columns require \( \gtrsim 10^9 M_\odot \) of oxygen concentrated near 100 kpc. Circumgalactic gas within this radius cools in less than 1 Gyr and radiates \( \sim 10^{42.5} \) erg s\(^{-1}\) overall. The feedback power necessary to maintain such oxygen-rich atmospheres for many Gyr cannot be easily supplied by galactic supernovae. However, massive central black holes in star-forming galaxies may generate sufficient accretion power and intermittent shock waves at \( r \sim 100 \) kpc to balance circumgalactic radiation losses in late-type \( L^* \) galaxies. The relative absence of O VI absorption observed in early-type, passive \( L^* \) galaxies may arise from enhanced AGN feedback from their more massive central black holes.

Key words: galaxies: abundances – quasars: absorption lines

1. Introduction

The possibility of high oxygen abundances in hot, virialized gas around normal star-forming galaxies has attracted much attention. Tumlinson et al. (2011) describe strong UV absorption in quasar spectra due to the O VI doublet (1031.9, 1037.6 Å) having redshifts similar to those of \( \sim L^* \) galaxies observed close to quasi-sightlines. Distances between sightlines and the central galaxies, i.e., the impact parameters \( R \), are large, implying that the absorption occurs in extended circumgalactic gaseous atmospheres surrounding star-forming galaxies. Impact parameters of \( 10 \lesssim R \lesssim 150 \) kpc are observed in star-forming galaxies with redshifts \( 0.1 \lesssim z_{\text{gal}} \lesssim 0.4 \) and stellar masses \( 9.5 \lesssim \log(M_* / M_\odot) \lesssim 11.5 \). Large oxygen column densities \( N_{\text{O VI}} \approx 10^{14.5 \pm 0.25} \text{ cm}^{-2} \) suggest large oxygen masses.

Detailed observations of circumgalactic absorption by O\(^{\scriptscriptstyle{5\text{}}}\) and other ions of C, N, O, Mg, Si, and Fe are described in a series of publications: Werk et al. (2012, 2013, 2014, 2016), Johnson et al. (2015)\( \equiv \) JCM, and Borthakur et al. (2016). Broad O VI absorption is detected in essentially all sightlines near star-forming galaxies but in only a small fraction of sightlines near passive, early-type \( L^* \) galaxies. Of interest here are decreasing O VI absorption columns that extend beyond the \( \sim 150 \) kpc survey limit of Tumlinson et al. to at least \( \sim 300 \) kpc around \( L^* \) galaxies (Prochaska et al. 2011, JCM).

Meanwhile, a significant computational effort is underway by cosmological simulators to understand the origin of oxygen in the hot circumgalactic gas: Stinson et al. (2013), Suresh et al. (2015), Liang et al. (2016), Roca-Fabrega et al. (2016), Oppenheimer et al. (2016), Sokolowska et al. (2016), etc. In these studies, most of the circumgalactic oxygen is provided by supernova-driven galactic winds from the central galaxy. Nevertheless, many of these sophisticated computational studies underpredict observed O VI column densities.

Recent theoretical treatments of O VI in the circumgalactic medium include the phenomenological model of Stern et al. (2016), which envisions O VI as low-density, externally photoionized gas surrounding denser ionized gaseous clumps that produce lower ionization absorption lines of C, N, O, Mg, Si, and Fe. This scenario explicitly links the kinematics of the O VI gas with the lower ionization material (as suggested by observations of Werk et al. 2016). Most recently, Faerman et al. (2017) introduced a model for galaxy coronae to reproduce O VI observations together with X-ray observations of higher ionization states of oxygen in the Milky Way. In their phenomenological model, circumgalactic gas is multi-phase with a distribution of densities all in pressure equilibrium.

As with lower ionization absorption lines, some O VI absorption may occur in small, actively cooling regions. However, as seen in Figure 3 of Werk et al. (2013), broad velocity widths of O VI absorption lines extend to velocities unassociated with low-ionization absorption. This suggests that most O VI absorption arises not in thermally perturbed regions but in extended hydrostatic atmospheres—we adopt this assumption here.

In what follows, we pursue the astrophysical implications of the observed O VI column density profile \( N_{\text{O VI}}(R) \), assuming that the oxygen has been expelled from the central star-forming galaxies and now resides in circumgalactic atmospheres in collisional ionization equilibrium. Specifically, we create simple hot gas atmospheres around a fiducial \( L^* \) galaxy with a stellar mass \( M_* = 10^{10.4} M_\odot \) near the center of the sample observed by Tumlinson et al. (2011), having a dark halo mass \( M_h = 10^{12.2} M_\odot \). We begin with a reference atmosphere devoid of feedback distortion in which the gas has an NFW profile reduced by the cosmic baryon fraction. From this, we construct several approximate atmospheres distorted by increasing amounts of feedback heating which must be maintained by continued feedback that balances radiation losses. The radial oxygen abundance profile in each atmosphere is adjusted until the space density profile of O\(^{\scriptscriptstyle{15}}\) ions is consistent with the observed mean column density profile \( N_{\text{O VI}}(R) \). We show that the local O abundance can significantly exceed solar at \( \sim 100 \) kpc with large total oxygen masses \( \gtrsim 10^9 M_\odot \). Radiative cooling time profiles are almost identical for all model atmospheres, but their radiative luminosities require feedback energies in excess of that expected from supernova feedback.
alone. This provides strong evidence that central black holes are the dominant source of feedback energy having black hole accretion rates and masses that match those expected in $L^*$ galaxies.

2. Hydrostatic Circumgalactic Atmospheres

Following Oppenheimer et al. (2016), we adopt a representative $L^*$ central galaxy having stellar mass $M_* = 10^{10.4} M_\odot$ and dark halo mass $M_h = 10^{12.2} M_\odot$. The NFW halo that confines the hot gas is assumed to have concentration $c = 4.86(M_{200}/10^{14} M_\odot)^{-0.11} = 7.67$ (Neto et al. 2007), and virial radius $r_{200} = 240$ kpc where the density is $1/200$ of the critical density. We expect that dark halos in $L^*$ galaxies are no longer accreting dark (or baryonic) matter and may have been quiescent for several Gyr (Prada et al. 2006; Cuesta et al. 2008; Diemer & Kravtsov 2014). Consequently, we adopt an NFW density profile for the dark matter halo and assume that it has not changed substantially since redshifts $z \sim 0.2$ where most circumgalactic O VI absorption is observed.

We now construct several approximate atmospheres in this halo having increasing amounts of distortion due to feedback. The equation of hydrostatic equilibrium $dP/dr = -\rho g_{\text{NFW}}$ can be written

$$dP/dr = -(T/r)(d \log \rho /d \log r) - g_{\text{NFW}}(\mu m_p/k)$$

where $P = (k/\mu m_p)\rho T$, $m_p$ is the proton mass, and $\mu = 0.61$ is the molecular weight. In the absence of feedback, baryons also have an NFW density profile reduced by the cosmic baryon fraction, $f_b = 0.16$. We disregard the stellar mass of the central galaxy because it is only $\sim 10$ percent of the baryonic mass within the virial radius. The gas density profile without feedback is therefore $\rho(r) = f_b \rho_0 y(1 + y)^2$ where $y = c(r/r_{200})$, $\rho_0 = (200 \rho_s/3)c^3/f(c)$, $f(y) = \ln(1 + y) - y/(1 + y)$, and $\rho_s = 9.2 \times 10^{-30}$ gm cm$^{-3}$ is the critical density for Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. The halo mass is $M_h = M_{200} = (4\pi/3) 200 \rho_s r_{200}^3$ and the gravitational acceleration $g_{\text{NFW}} = GM_h(r)/r^2$.

In the presence of feedback, atmospheric gas is heated, its central entropy is increased, and the entire atmosphere is pushed outward. To mimic these feedback effects, we consider density profiles described by

$$\rho = f_b \rho_0 y_0 y^3$$

where $y_0$ is a parameter that increases with the influence of feedback. The central entropy $S = T/n_e^2/3$ has zero slope similar to galaxy group profiles visible in X-rays (Pratt et al. 2010). Because feedback sources are centrally concentrated, these atmospheres are designed to approach the feedback-free density profile at large radius, $\rho(y) \approx f_b \rho_0 y^3$. We therefore disregard any significant density change at large radius, either an enhancement as gas is pushed out by feedback or a gas deficiency if feedback extends to the distant halo. In any case, intermediate radii, $\sim 100$ kpc, are most relevant to our concerns here. Our adoption of Equation (2) does not affect conclusions discussed below.

The solid black contours in Figure 1 show temperature, density, and gas mass profiles for a circumgalactic atmosphere without feedback. Also in Figure 1 are profiles for three atmospheres with increasing feedback:

- blue : red : green :: $y_0 = 1 : 2 : 4$.

Atmospheric structural distortion by feedback is stabilized when the time-averaged feedback power maintains atmospheric profiles against radiation losses. If feedback drops below this maintenance level, large masses of gas can cool toward the central galaxy, resulting in an unphysical mass accumulation, similar to the overcooling problem encountered in cosmological simulations. Structural and maintenance feedback can be provided by the same physical mechanisms.

The green atmosphere in Figure 1 is designed to match a hot gas density of $10^{-4}$ cm$^{-3}$ at radius $\sim 50-60$ kpc in the Milky Way as suggested by Fang et al. (2013) from XMM surface brightness observations and by Sokolowska et al. (2016) from O VII and O VIII observations. This density is marked with a green circle in Figure 1(b).

3. O$^{+5}$ Column and Space Densities

Blue squares in Figure 2(a) are COS-Halos detections of O VI column densities $N_{OVI}$ in circumgalactic atmospheres of $L^*$ galaxies (Tumlinson et al. 2011) at sightline offsets $R$ in kpc. While most columns are clustered about $N_{OVI} \sim 10^{14.7}$ cm$^{-2}$, there is evidence of decreasing columns beyond $R \sim 100$ kpc. This decrease is confirmed by additional O VI observations by JCM, many having larger $R$. In Figure 2(a), we plot JCM data for star-forming $L^*$ galaxies having impact offsets $R > 75$ kpc and stellar masses within $10.1 < \log(M_*/M_\odot) < 10.7$. While only two galaxies are detected (green squares in Figure 2), a large number of upper limits (inverted red triangles) provides convincing evidence of a rather sharp decrease in O VI columns beyond $\sim 100$ kpc. Such a decrease strongly supports the prevailing interpretation that very large oxygen masses have been ejected from $L^*$ galaxies and/or their progenitors. Decreasing $N_{OVI}(R)$ profiles also constrain the atmospheric O/H abundance and the feedback mechanism that maintains it.

Although data are sparse, we fashion a magenta line in Figure 2 showing a likely column density profile for $L^*$ galaxies. The magenta line is described by

$$N_{OVI}(R) = N_0 [1 + (R/R_0)^{-q}]^{-1} (R/R_0)^{q}$$

where $N_0 = 5.2 \times 10^{14}$ cm$^{-2}$, $R_1 = 40$ kpc, $q = -1/3$, $R_0 = 140$ kpc and $p = 3$.

The corresponding empirical space density of O$^{+5}$ ions $n_{O^{+5}}(r)$, can be found from an Abel integral inversion,

$$n_{O^{+5}}(r) = -\frac{1}{\pi} \int_{r}^{\infty} \frac{dN}{dR} \frac{dR}{(R^2 - r^2)^{1/2}}$$

which is plotted as a magenta line in Figure 2(b). The inner, dotted part of the $n_{O^{+5}}(r)$ profile is unconstrained by current $N_{OVI}$ data. For comparison, dashed lines in Figure 2(b) shows O$^{+5}$ space density profiles $n_5(r)$ for each atmosphere in Figure 1, assuming uniform solar abundance $A_{O^{+5}} = 5 \times 10^{-4}$ and employing ionic fractions for collisional ionization equilibrium (Gnat & Sternberg 2007).

The juxtaposition of $n_5$ and $n_{O^{+5}}$ profiles in Figure 2(b) allows an instant determination of atmospheric O abundance profiles $Z_{O^5}(r)$ in solar units required to match the mean profile $n_{O^{+5}}(r)$ and, when projected, the adopted mean column density profile.
For example, the oxygen abundance in solar units for the red atmosphere is simply $Z_{\text{O,red}} = \frac{\n_{\text{O, red}}}{\n_{\text{H, red}}}$ at every radius.

Oxygen abundance profiles derived in this manner for each atmosphere are illustrated in Figure 3(a). Maximum abundances are expected near $r \sim 100$ kpc where the slope $dN_{\text{OVI}}/dR$ changes. Oxygen abundances $Z_0$ are large, particularly in the high feedback, low-density green atmosphere. At $r = 100$ kpc, $O$ abundances in the blue, red, and green atmospheres are
Large bolometric X-ray luminosity profiles in Figure 4(b), \( \log L_x \approx 42.2 \pm 0.4 \) erg s\(^{-1}\), attest to the powerful cooling effect of \( \sim 10^9 \, M_\odot \) of oxygen extending to \( r \approx 100 \) kpc. To explore the destiny of pure cooling without feedback, we computed spherical time-dependent cooling flows allowing blue, red, and green (b, r, g) atmospheres initially at rest to evolve for the lookback time 2.4 Gyr at redshift 0.2 with abundances from Figure 3(a). These straightforward calculations, not discussed in detail here, verify that gas masses of \( \log (M/M_\odot) \approx (11.2, 10.9 \) and 10.5), all in excess of \( M_\odot \), cool at the origin in (b, r, g) atmospheres during this relatively short time. All oxygen-rich gas within \( \sim 210 \) kpc cools. Such an atmospheric collapse is not supported by the recent star formation history of the Milky Way (Gonzalez Delgado et al. 2017) or by observations of extended circumgalactic O VI absorption in star-forming \( L^* \) galaxies. Clearly, a strong time-averaged maintenance feedback power comparable to \( L_x \) must be provided by supernovae or central black holes. Our concern here is not the energetics of the outflows that previously carried O-rich gas out to \( \sim 100 \) kpc, but how this gas is maintained during more recent times.

In the figures presented in this paper, we assume that oxygen is completely mixed on atomic scales, but the degree of mixing remains uncertain. It is likely that circumgalactic oxygen is inhomogeneous, which would decrease the radiative cooling time below that in Figure 4(a), causing small, O-rich regions to cool locally, perhaps even in the presence of maintenance feedback. Such local cooling is supported by low-ionization circumgalactic absorption lines in quasar spectra.

Core-collapse supernovae in late-type \( L^* \) galaxies occur at a rate of 1–3 per century, but generate only \( \sim 0.6 \times 10^{42} \) erg s\(^{-1}\), most of which is dissipated locally in strong shocks in the galactic disk. Successful \( L^* \) feedback requires intermittent shocks propagating through gas at \( r \sim 100 \) kpc at some mean interval \( \Delta t \). The rate that entropy is radiated away by gas at \( r = 100 \) kpc (where \( n \approx 10^{-4} \) cm\(^{-3}\), \( T \approx 10^6 \) K and \( Z \approx Z_\odot \)) can be restored by shocks every log \( \Delta t = (7, 8, 9) \) years with large Mach numbers (1.25, 1.7, 3.9), roughly similar to feedback shock strengths in galaxy group atmospheres. Even if supernova power were sufficient, neither stochastic variations in the galactic supernova rate nor slowly moving (forward and reverse) shocks expected in sustained supernova-driven winds are sufficiently intermittent.

Consequently, massive central black holes may be the most promising source of distant, intermittent feedback shocks. Following King & Pounds (2015), fast-wind feedback from AGNs having luminous accretion disks generate mechanical luminosities \( \sim 0.05 L_x \) where \( L_F = 1.26 \times 10^{38} (M/M_\odot) \) erg s\(^{-1}\) is the Eddington luminosity. Because central black holes in \( L^* \) galaxies with \( M = 10^{10.4} \) M\(_\odot\) have masses \( M_\odot \) similar to that in the Milky Way, \( 4.5 \times 10^{40} \) erg s\(^{-1}\), the expected mechanical power of \( L^* \) winds is \( \sim 30 \times 10^{40} \) to \( 30 \times L_x \) erg s\(^{-1}\). This is sufficient to balance X-ray luminosities in Figure 4(b) with central AGNs that are intermittently active only 3 percent of the time. This duty cycle is \( \lesssim 10 \) percent as required by Oppenheimer et al. (2017) to enhance O VI-absorbing ions in atmospheres of \( L^* \) galaxies.

More collimated feedback modes may also be present. In galaxy groups having black holes and dark halo masses roughly ten times larger than in \( L^* \) galaxies, the accretion power of central black holes maintains atmospheric temperatures \( T \sim 10^7 \) K with no evidence of recent star formation or...
luminous accretion disks. In addition, the Fermi bubbles in the Milky Way reveal that its central black hole is currently delivering an (albeit uncertain) energy of $\sim 10^{59}$ erg to the circum-Galactic atmosphere (Guo & Mathews 2012; Guo et al. 2012), equivalent to the total Galactic supernova energy generated in 10$^8$ years. As outward propagating shocks in atmospheres with $d \log \rho / d \log r > -2$ naturally weaken, shocks formed at large radii by collimated black hole outflows provide more efficient feedback. The non-thermal content of the Fermi Bubbles and extragalactic jets may also suggest feedback modes stronger than disk winds.

Further evidence that central black holes may energize circumgalactic gas are the much lower O VI absorption columns observed in non-star-forming passive $L^*$ galaxies (Tumlinson et al. 2011). Because central black holes in passive $L^*$ galaxies are on average $\sim 40$ times more massive than those in star-forming $L^*$ galaxies (Reines & Volonteri 2015), the accretion feedback in passive galaxies may heat and drive most of the O VI-absorbing circumgalactic gas far out in the galactic potential. Upper limits of four star-forming $L^*$ galaxies in Figure 2(a) also lie far below the magenta profile. Perhaps unusually large feedback events with energy $\gtrsim (GM_\odot M_\odot / r)|_{100 \text{kpc}} \sim 10^{58.7}$ ergs have dramatically reduced the atmospheric density of O$^{+5}$ ions.

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