Characterizing the UV and X-ray Outflow in Mrk 509

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Abstract. We observed Mrk 509 during the fall of 2009 during a multiwavelength campaign using XMM-Newton, Chandra, HST/COS, SWIFT, and Integral. The 600-ks XMM/RGS spectrum finds two kinematic components and a discrete distribution of ionized absorbers. Our high S/N COS spectrum detects additional complexity in the known UV absorption troughs from a variety of sources in Mrk 509, including the out-
flow from the active nucleus, the ISM and halo of the host galaxy, and infalling clouds or stripped gas from a merger that are illuminated by the AGN. The UV absorption only partially covers the emission from the AGN nucleus with covering fractions lower than those previously seen with STIS, and are comparable to those seen with FUSE. Given the larger apertures of COS and FUSE compared to STIS, we favor scattered light from an extended region near the AGN as the explanation for the partial covering. As observed in prior X-ray and UV spectra, the UV absorption has velocities comparable to the X-ray absorption, but the bulk of the ultraviolet absorption is in a lower ionization state with lower total column density than the gas responsible for the X-ray absorption. Variability compared to prior UV spectra lets us set limits on the location, density, mass flux, and kinetic energy of the outflowing gas. For component 1 at \(-400\ \text{km s}^{-1}\), the kinetic energy flux of both the UV and the X-ray outflow is insufficient to have a significant impact on further evolution of the host galaxy.

1. Introduction

Outflows from active galactic nuclei (AGN) may have a significant impact on the evolution of their host galaxies (Silk & Rees 1998; Scannapieco & Oh 2004; Granato et al. 2004; Di Matteo et al. 2005; Hopkins et al. 2008; Somerville et al. 2008). Generally, to have an impact on the host galaxy’s evolution, models require the kinetic energy flux of the AGN outflow to be >5% of the bolometric luminosity of the AGN (Di Matteo et al. 2005). While some fraction of the outflows in low-luminosity AGN may not escape their host galaxy, at least as measured in the local universe (Das et al. 2005; Ruiz et al. 2005; Das et al. 2007), the impact of the outflow on the host could be sufficient if the kinetic energy flux is even ten times less, or > 0.5% (Hopkins & Elvis 2010).

Nearby AGN provide local analogs that can help us to understand the mechanics, energetics, and chemical enrichment patterns that may play a significant role in cosmic evolution at high redshift. More than half of low-redshift AGN exhibit blue-shifted UV or X-ray absorption features indicative of outflowing gas (Crenshaw et al. 2003; Dunn et al. 2007; Cappi et al. 2009; Tombesi et al. 2010). Understanding the geometry and the location of the outflow relative to the active nucleus is a key to making an accurate assessment of the total mass and the kinetic luminosity of the outflow. Distance determinations are particularly difficult. Using density-sensitive absorption lines to establish the gas density, in combination with photoionization models that reproduce the observed relative column densities can provide precise distance estimates. These measures have ranged from tens of parsecs in NGC 3783 (Gabel et al. 2005) and NGC 4151 (Kraemer et al. 2006), and up to kiloparsec scales in some quasars and AGN (Hamann et al. 2001; Scott et al. 2004; Edmonds et al. 2011).

To improve upon these prior studies, we have conducted a multiwavelength campaign of coordinated X-ray, UV, and optical observations of the nearby luminous Seyfert 1 galaxy Mrk 509 (z=0.034397; Huchra et al. 1993). A complete overview of the campaign is given by Kaastra et al. (2011). Mrk 509 is an ideal object for study due to its high flux, moderate luminosity that rivals that of QSOs (Kopylov et al. 1974), and deep, well structured absorption troughs. Our observations using the Cosmic Origins Spectrograph (COS) (Green et al. 2011) on HST obtained as part of this campaign provide insight into long-term changes in the absorbing gas.
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2. UV Spectra of Mrk 509

The COS spectra of Mrk 509 and their calibration are fully discussed by Kriss et al. (2011). The COS observations were obtained on 2009 December 10 and 11, and we compare these to the STIS echelle spectrum obtained on 2001 April 13 by Kraemer et al. (2003) and the FUSE spectrum obtained by Kriss et al. (2000). Figures 7 and 8 of Kriss et al. (2011) compare the normalized COS and STIS spectra. Kriss et al. (2011) normalized the calibrated spectra by fitting an emission model to the continuum and emission lines and dividing this model into the calibrated spectra. The same emission model was used for both STIS and COS with appropriately fitted adjustments to the intensities of the emission line components and the continuum.

In Fig. 7 of Kriss et al. (2011) one can see that components 1 and 1b in the COS Ly$\alpha$ spectrum are not as deep as in the STIS spectrum. In contrast, component 1 in the N v absorption profile is noticeably shallower in the STIS spectrum compared to the COS spectrum. These changes are consistent with a change in ionization state of the absorbing gas in response to the change in continuum flux. The continuum flux seen in the COS observation is 80% higher than for the STIS observation. An increase in the ionization of the absorbing gas leads to less neutral hydrogen and a lower column density for Ly$\alpha$, and increased ionization and a higher column density for N v.

3. Discussion

The changes in the absorption seen between the STIS and the COS spectra enable us to infer the density of the absorbing gas, and hence its distance, if we assume that the variations are ionization changes in response to the changes in ionizing flux. Recombination times for hydrogen are too slow to permit us to set any interesting limits on the density. However, N v recombines nearly two orders of magnitude faster, and it provides greater leverage in sensing the density of the absorbing medium. Following Krolik & Kriss (1995) and Nicastro et al. (1999), recombination and ionization time scales depend not only on the density, but also on the relative populations of the ionization states involved: $t_{\text{rec}} = (n_i / n_{i+1}) / (n_e a_{\text{rec}})$. Using the photoionization model for the Mrk 509 absorbers from Kraemer et al. (2003), component 1 has an ionization parameter log $\xi = 0.67$ (where $\xi = L_{\text{ion}} / (nr^2)$). At this level, the ionization fraction for N v is $\sim 0.4$, and the relative equality of populations among the neighboring ionization states of nitrogen makes ionization and recombination timescales similar (Nicastro et al. 1999). For $a_{\text{rec}} = 8.96 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ (Nahar 2006) at a temperature of 20,000 K, and a time between the STIS and COS observations of $2.733 \times 10^8$ s, we get a lower limit on the density of $n_e > 160 \text{ cm}^{-3}$. Since we are using the photoionization models of Kraemer et al. (2003), we use an ionizing luminosity from their SED in Yaqoob et al. (2003), $L_{\text{ion}} = 7.0 \times 10^{44} \text{ erg s}^{-1}$. Together with the ionization parameter log $\xi = 0.67$, this gives an upper limit on the distance of $r < 250$ pc.

Just as limits on the variability timescale can give us lower limits on the density and upper limits on the distance, the lack of variability in Components 2–7 give us an upper limit on the density and a lower limit on the distance. The paper by Edmonds et al. (2012) in this volume shows in detail how the lack of variability in the other UV absorption components results in a lower limit on their distance of $>100–200$ pc.

Overall, these results suggest that the UV absorption seen in our spectra of Mrk 509 arise from a variety of locations in this active galaxy. The high ionization and kin-
matic correspondence of Components 1–3 suggest that they are associated with the X-ray outflow, although the UV gas is lower in ionization than the X-ray. Similarly, Components 4a, 5–6 are associated with the lower-velocity portion of the X-ray outflow, but again, lower ionization than the X-ray gas. The at-rest systemic velocity of Component 4 and its very low ionization suggest that it is the ISM+Halo of the host galaxy. Component 7, at a positive velocity of 200 km s$^{-1}$, is infalling to Mrk 509. We suggest that it might be similar to high-velocity clouds seen in the halo of our own galaxy. Thom et al. (2008) find that HVC Complex C in the Milky Way has log n $\sim -2.5$, dimensions 3 $\times$ 15 kpc, distance of 10 kpc, and a total mass of 8.2 $\times$ 10$^6$ M$_\sun$. For Component 7 in Mrk 509, for solar abundances, the total hydrogen column is $\sim 4 \times 10^{18}$ cm$^{-2}$. If this is similar to Complex C, its size is 1.3 kpc, and its distance from the center of Mrk 509 is 19 kpc.

The density and distance limits for Component 1 allow us to evaluate the mass flux and kinetic luminosity:

$$\dot{M}_{\text{out}} = 4\pi \Delta \Omega r N_H \mu m_p v_{\text{out}} = 3\pi (r/250 \text{pc})(N_H/1.0 \times 10^{19} \text{ cm}^{-2})(v/400 \text{ km s}^{-1})$$

$$\dot{M}_{\text{out}} < 0.12 M_\sun \text{ yr}^{-1}, \text{ so}$$

$$L_k = 1/2 \dot{M}_{\text{out}} v_{\text{out}}^2 < 6.4 \times 10^{39} \text{ erg s}^{-1}$$

We measure $L_{\text{bol}} = 6.4 \times 10^{45}$ erg s$^{-1}$ (which requires $\dot{M}_{\text{acc}} \sim 1.1 M_\sun \text{ yr}^{-1}$), so $L_k/L_{\text{bol}} < 1 \times 10^{-6}$.

We note that even though the column density of the X-ray outflow is two orders of magnitude higher (Detmers et al. 2011), at the same velocity and distance it would have a kinetic luminosity relative to bolometric of $< 10^{-4}$, still more than an order of magnitude lower than needed to have a significant impact on the host galaxy, even in the optimistic models of Hopkins & Elvis (2010).

What would constitute a significant outflow? We need sufficient mass flux and velocity so that $L_k = 1/2 \dot{M}_{\text{out}} v_{\text{out}}^2 > 5\% L_{\text{rad}} = 5\% \eta \dot{M}_{\text{acc}} c^2$, where $\eta$ is the accretion efficiency. If $\dot{M}_{\text{out}} \sim \dot{M}_{\text{acc}}$, then $v_{\text{out}}^2 > 2 \times 5\% \eta c^2$. Since $\eta \sim 0.1$, $v_{\text{out}} > 0.1c$. Thus, even for a massive outflow in which the outflow rate is equal to the accretion rate, outflow velocities would have to exceed 30,000 km s$^{-1}$, in order for the outflow to significantly influence the evolution of the host galaxy. Even at a reduced efficiency of 0.5% (Hopkins & Elvis 2010), velocities would have to be in excess of 10,000 km s$^{-1}$. Such velocities are never seen in local AGN, only in more distant broad absorption line quasars. Allowing for an even more extreme case of the mass outflow exceeding the accretion rate by an order of magnitude, outflow velocities would have to be greater than 3,000 km s$^{-1}$ for $L_k/L_{\text{bol}} > 0.5\%$. Velocities this high are very rare in local AGN.

In conclusion, we find that limits on the density and distance of the absorbers show that their kinetic luminosity is insufficient to cause significant feedback affecting the evolution of the host galaxy. Given that the crucial era for the effects of feedback, however, is during the epoch of galaxy formation, the fact that we do find such significant influence occurring at zero redshift is not a problem. Nothing rules out the possible existence of stronger winds and outflows during the earlier lifetime of the Mrk 509 host.

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