MMTF DISCOVERY OF GIANT IONIZATION CONES IN MR 2251−178: IMPLICATIONS FOR QUASAR RADIATIVE FEEDBACK

KORY KREIMEYER1 AND SYLVAIN VEILLEUX1,2,3
1 Department of Astronomy, University of Maryland, College Park, MD 20742, USA; kory@astro.umd.edu, veilleux@astro.umd.edu
2 Astroparticle Physics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
3 Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany

ABSTRACT

We report the discovery of giant ionization cones in the 140 kpc nebula around quasar MR 2251−178 based on deep [O iii] λ5007/Hβ and [N ii] λ6583/Hα flux ratio maps obtained with the Maryland–Magellan Tunable Filter on the Baade–Magellans 6.5 m Telescope. These cones are aligned with the weak double-lobed radio source observed on smaller scale (<30 kpc). They have an opening angle ~120° ± 10° and subtend ~65%–90% of 4π sr, where the uncertainty takes into account possible projection effects. The material in the outer ionization cones is matter-bounded, indicating that all ionizing photons emitted through the cones escape from the system. The quasar ionizing flux is ~2–3 times fainter outside of these cones, despite the largely symmetric geometry of the nebula in [O iii]. Overall, adding up the contributions from both inside and outside the cones, we find that ~65%–95% of the quasar ionizing radiation makes its way out of the system. These results emphasize the need for line ratio maps to quantify the escape fraction of ionizing radiation from quasars and the importance of quasar radiative feedback on the intergalactic medium.

Key words: diffuse radiation – galaxies: halos – intergalactic medium – quasars: general – quasars: individual (MR 2251−178)

Online-only material: color figures

1. INTRODUCTION

There is growing evidence that feedback from active galactic nuclei (AGNs) plays a significant role in producing the galaxy populations we observe today (e.g., Veilleux et al. 2005; Fabian 2012 and references therein). AGN feedback also seems to be needed to explain the scaling relations between black hole and spheroid masses (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000). This feedback may take two forms: mechanical (winds or jets) or radiative. While observational evidence for powerful AGN-driven outflows has grown in recent years (e.g., Rupke & Veilleux 2003; Goñi et al. 2008; Curran & Whiting 2011), making the interpretation more difficult. An important exception is the giant (140 kpc) photoionized nebula around the type 1 radio-quiet quasar MR 2251−178 (Macchetto et al. 1990; Shopbell et al. 1999). To our knowledge this is the largest emission-line nebula around any radio-quiet AGN (e.g., Husemann et al. 2010; Liu et al. 2013). This nebula is in rotation around the host, unaffected dynamically by the weak, double-lobed radio source observed to extend ~27 kpc centered on the nucleus (Bergeron et al. 1983; Macchetto et al. 1990; Shopbell et al. 1999). The central quasar (LUV ~7 × 1021 W Hz−1, corrected for Galactic extinction) seems solely responsible for the high ionization level of the nebula. At a distance of only 263 Mpc, corresponding to a scale of ~1.3 kpc arcsec−1, this nebula is thus an excellent laboratory to study the effects of radiative feedback.

In this Letter, we map for the first time the ionization structure of the nebula around MR 2251−178 using deep narrowband images centered on key optical emission lines. We describe the observations and methods used to reduce the data in Section 2. The images of MR 2251−178 are presented in Section 3 along with line ratio maps created from these images. In Section 4, these line ratio maps are compared with photoionization models to derive the ionization structure of the nebula around MR 2251−178 and the fraction of ionizing radiation that escapes from the system as a function of azimuth angle. These results are discussed in the context of quasar radiative feedback.

2. OBSERVATIONS AND DATA REDUCTION

Data on MR 2251−178 were obtained in 2011 May and August with the Maryland–Magellan Tunable Filter

4 Based on a redshift z = 0.0640 and a cosmology with H0 = 73 km s−1 Mpc−1, Ωmatter = 0.27, and Ωvacuum = 0.73. The size of the nebula reported here is consistent with previous studies that reported nebular sizes ~200 kpc based on H0 = 50 km s−1 Mpc−1.
Figure 1. MMTF images of MR 2251−178: (a) adaptively smoothed continuum-subtracted [O\textsc{iii}] $\lambda$5007 emission, (b) continuum emission at 5044 Å, (c) adaptively smoothed continuum-subtracted H\alpha emission, (d) continuum emission at 6621 Å, (e) adaptively smoothed continuum-subtracted [N\textsc{ii}] $\lambda$6583 emission, (f) color map derived from the log ratio of (b) and (d). Residuals from the bright central source have been masked. Lighter shade indicates bluer color. The bar at the bottom right corner of each panel indicates 20 kpc. The units in panels (a)–(e) are $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$.

(MMTF; Veilleux et al. 2010) in the Inamori–Magellan Areal Camera and Spectrograph (Dressler et al. 2011) on the 6.5 m Magellan–Baade Telescope. MMTF allows narrowband (FWHM $\sim$ 15 Å) imaging at a wavelength between $\sim$5000 and 9200 Å over a large field of view ($\sim$27' x 27', monochromatic within $\sim$5' of the optical axis). Multiple 20 minute exposures centered on redshifted [O\textsc{iii}] $\lambda$5007, H\alpha, and [N\textsc{ii}] $\lambda$6583 were taken for a total integration time of 60, 100, and 140 minutes, respectively. Additional images centered on 5044 Å and 6621 Å were obtained immediately before or after the line images to map the line-free continuum emission.

All images were reduced using the standard MMTF pipeline software.\(^5\) A photometric calibration was applied to each image, based on observations of a photometric standard star taken on the same night. The continuum images were scaled and subtracted from the line images to obtain the pure emission-line maps.

All images were corrected for foreground Galactic extinction, following the procedure of Cardelli et al. (1989) with extinction parameter $R_V = 3.07$, but no attempt was made to correct for extinction within the host galaxy. The images were smoothed using the adaptsmooth code\(^6\) described by Zibetti (2009). This program replaces each pixel of the image with the median value of all pixels within a variable-sized smoothing radius, chosen as the minimum radius which provides S/N $> 3$. The smoothing enhanced the visibility of the diffuse gas emission while leaving the bright galaxy emission mostly unaffected.

3. RESULTS: GIANT IONIZATION CONES

Figure 1 shows the adaptively smoothed emission-line images of MR 2251−178 as well as the unsmoothed narrowband continuum images. The nebula extends out to $\sim$90 kpc from...

\(^5\) Available from http://www.astro.umd.edu/~veilleux/mmtf/datared.html.

\(^6\) Available at http://arcetri.astro.it/~zibetti/Software/ADAPTSMOOTH.html.
the quasar, elongated along the east–west direction, lopsided to the south, and with a total wing span of ∼140 kpc. Interestingly, these data do not reveal any line emission beyond the extent of the nebula detected by Shopbell et al. (1999), suggesting that we have detected the true edge of the nebula. The superior image quality of the MMTF data over those of Shopbell et al. resolves the nebula into a spectacular complex of clumps and filaments down to scales of ∼1 kpc, primarily distributed into a vast two-armed structure seemingly detached from the central host.

The green (5044 Å) and red (6621 Å) continuum maps are shown in Figures 1(b) and (d), while a color image derived from their ratios is shown in Figure 1(f). This last panel indicates a slight red excess along the north–south direction, passing through the nucleus. While stellar population may contribute to radial color gradients, we favor reddening due to dust to explain this non-axisymmetric color distribution. At a distance of ∼5–10 kpc from the nucleus (i.e., well outside of possible artifacts due to the bright central source), we measure a difference \[ \log (f_{5044}/f_{6621})_{\text{cone}} - \log (f_{5044}/f_{6621})_{\text{anti-cone}} \] ∼ 0.115, corresponding to \( A_V = 1.1 \pm 0.5 \) mag (Cardelli et al. 1989).

We next constructed maps of MR 2251−178 in two of the classic diagnostic line ratios: [O III] \( \lambda5007/\lambda\beta \) and [N II] \( \lambda6583/\lambda\alpha \) (Figure 2), assuming that \( f(\lambda\beta) = f(\lambda\alpha)/2.85 \), the Case B recombination value (Osterbrock 1989). We have neglected intrinsic dust reddening because it is presumed to be small outside of the nucleus based on our continuum color map (Figure 1(f)) and the published long-slit spectroscopy (e.g., Macchetto et al. 1990). The line ratio maps reveal a previously unknown ionization bicone with an apparent opening angle ∼120° ± 10° roughly aligned along the east–west direction (∼87° west of north). The biconical ionization structure is particularly evident within the inner 30 kpc, but also extends all the way to the edge of the nebula to encompass most of the gas in the large two-armed structure. Interestingly, the double-lobed radio structure reported by Macchetto et al. (1990) is aligned along the same direction (within ∼10°) as the ionization cones and has a total extent of ∼27 kpc (Macchetto et al. 1990, scaled to current cosmology) that is similar to that of the inner cones (see white line in Figure 2). While this radio structure is not believed to be a major source of kinetic energy to the nebula (Bergeron et al. 1983), it is clear that the ionizing radiation from the quasar is preferentially escaping along the radio jet axis.

4. DISCUSSION

4.1. Geometry of the Ionization Cones

The inclination of the bicone axis with respect to our line of sight is challenging to determine. If it coincides with the radio jet axis (Section 3), then the bisymmetry of the radio structure favors a large inclination angle. However, the type 1 classification of this quasar indicates that our line of sight avoids the central obscuring torus. If the geometry of the ionization cones reflects the structure of this inner torus, then the jet axis has to be ≥30° from the plane of the sky to allow our line of sight to lie within one of the cones.

The three-dimensional distribution of the extended gas surrounding MR 2251−178 is an unresolved topic with some favoring a spherical envelope (e.g., Shopbell et al. 1999); however, the spherical gas simulations of Mulchaey et al. (1996), when viewed from an angle within the cones, have difficulties reproducing the V-shaped biconical structure of MR 2251−178. For this reason, we favor a flattened distribution for the extended gas. Given the probability distribution of apparent opening angles from a bicone with a true opening angle of 70° illuminating a thin disk (Figure 8 of Mulchaey et al. 1996), we estimate that the true opening angle of the bicone in MR 2251−178 lies within the range 80°–130°.

4.2. Line Ratio Diagrams

The large [O III] \( \lambda5007/\lambda\beta \) and small [N II] \( \lambda6583/\lambda\alpha \) ratios throughout the nebula of MR 2251−178 suggest photoionization by the quasar. This is confirmed in Figure 3, where these line ratios are plotted in one of the diagnostic diagrams of Baldwin et al. (1981) and Veilleux & Osterbrock (1987). A more quantitative analysis of these data requires comparing the line ratios with detailed AGN photoionization models. This is done in Figures 3(c) and (d), where we plot two photoionization models from Groves et al. (2004). The models assume a density \( n_H = 1000 \) cm\(^{-3}\) and an incident ionizing power-law spectrum \( f_\nu \propto \nu^{\alpha_e} \) with index \( \alpha_e = -1.4 \) in the range 5 eV ≤ \( h\nu \) ≤ 1 keV. Figure 3(c) shows the case for a dusty ISM, while Figure 3(d) presents the
Figure 3. (a) Same as Figure 2(a), but with markers showing the locations of individually examined regions. (b) The [O\textsc{iii}]/H\textbeta vs. [N\textsc{ii}] \(\lambda 6583/\text{H}\alpha\) line ratio diagram for the regions highlighted in panel (a). The size of the crosses indicates their approximate uncertainty, with the largest symbols having an uncertainty of \(\sim 10\%\) and the smallest symbols having an uncertainty of up to \(\sim 30\%\). The solid blue line and brown dashed line are the starburst limits of Kewley et al. (2001) and Kauffmann et al. (2003), respectively. The bottom two panels are the same diagnostic diagram with models from Groves et al. (2004) overlaid for the (c) dusty and (d) dust-free cases. (A color version of this figure is available in the online journal.)

The ionization level of the gas in the outer anti-cone (the green crosses in Figure 3) drops considerably. At these lower [O\textsc{iii}]/H\textbeta ratios, we must consider the possibility that some gas is un-ionized, possibly due to dust. The nebula seems matter-bounded with no evidence of ionization edges (which would be characterized by a sudden drop in \(U\)). There is also a hint that the outer gas has slightly lower metallicity than the gas in the inner region, suggesting either an external origin to this gas or a smooth radial metallicity gradient (consistent with the most plausible origins for this gas: tidal debris from a recent galaxy interaction and giant H\textsc{i} envelope ionized by, and gravitationally bound to, the quasar; see Shopbell et al. 1999).

The ionization level of the gas in the outer anti-cone (the green crosses in Figure 3) drops considerably. At these lower [O\textsc{iii}]/H\textbeta ratios, we must consider the possibility that some gas is un-ionized, possibly due to dust. The nebula seems matter-bounded with no evidence of ionization edges (which would be characterized by a sudden drop in \(U\)). There is also a hint that the outer gas has slightly lower metallicity than the gas in the inner region, suggesting either an external origin to this gas or a smooth radial metallicity gradient (consistent with the most plausible origins for this gas: tidal debris from a recent galaxy interaction and giant H\textsc{i} envelope ionized by, and gravitationally bound to, the quasar; see Shopbell et al. 1999).

The ionization level of the gas in the outer anti-cone (the green crosses in Figure 3) drops considerably. At these lower [O\textsc{iii}]/H\textbeta ratios, we must consider the possibility that some gas is un-ionized, possibly due to dust. The nebula seems matter-bounded with no evidence of ionization edges (which would be characterized by a sudden drop in \(U\)). There is also a hint that the outer gas has slightly lower metallicity than the gas in the inner region, suggesting either an external origin to this gas or a smooth radial metallicity gradient (consistent with the most plausible origins for this gas: tidal debris from a recent galaxy interaction and giant H\textsc{i} envelope ionized by, and gravitationally bound to, the quasar; see Shopbell et al. 1999).

The ionization level of the gas in the outer anti-cone (the green crosses in Figure 3) drops considerably. At these lower [O\textsc{iii}]/H\textbeta ratios, we must consider the possibility that some gas is un-ionized, possibly due to dust. The nebula seems matter-bounded with no evidence of ionization edges (which would be characterized by a sudden drop in \(U\)). There is also a hint that the outer gas has slightly lower metallicity than the gas in the inner region, suggesting either an external origin to this gas or a smooth radial metallicity gradient (consistent with the most plausible origins for this gas: tidal debris from a recent galaxy interaction and giant H\textsc{i} envelope ionized by, and gravitationally bound to, the quasar; see Shopbell et al. 1999).

The ionization level of the gas in the outer anti-cone (the green crosses in Figure 3) drops considerably. At these lower [O\textsc{iii}]/H\textbeta ratios, we must consider the possibility that some gas is un-ionized, possibly due to dust. The nebula seems matter-bounded with no evidence of ionization edges (which would be characterized by a sudden drop in \(U\)). There is also a hint that the outer gas has slightly lower metallicity than the gas in the inner region, suggesting either an external origin to this gas or a smooth radial metallicity gradient (consistent with the most plausible origins for this gas: tidal debris from a recent galaxy interaction and giant H\textsc{i} envelope ionized by, and gravitationally bound to, the quasar; see Shopbell et al. 1999).

The ionization level of the gas in the outer anti-cone (the green crosses in Figure 3) drops considerably. At these lower [O\textsc{iii}]/H\textbeta ratios, we must consider the possibility that some gas is un-ionized, possibly due to dust. The nebula seems matter-bounded with no evidence of ionization edges (which would be characterized by a sudden drop in \(U\)). There is also a hint that the outer gas has slightly lower metallicity than the gas in the inner region, suggesting either an external origin to this gas or a smooth radial metallicity gradient (consistent with the most plausible origins for this gas: tidal debris from a recent galaxy interaction and giant H\textsc{i} envelope ionized by, and gravitationally bound to, the quasar; see Shopbell et al. 1999).
of the ionizing radiation arises from star formation. Using the dilution curves of Yuan et al. (2010), we estimate that dilution by star formation is \( \sim 50\% \), so the AGN contribution to the ionizing radiation in this region may be underestimated by a factor of up to two.

4.3. Electron Densities, Ionizing Fluxes, and Escape Fractions

The ionization parameters derived in Section 4.2 can be used to constrain the fraction of the quasar ionizing flux that is escaping the nebula and contributing to the ionization of the IGM. Given Equation (1), we first need to know the electron density in the nebula. For this, we examine discrete clumps in the nebula and use

\[
L(\text{H}\alpha) = 2.85 \times n_e n_p \alpha_{\text{eff}}^{\text{H}/\beta} h v_{\text{H}/\beta} V \epsilon,
\]

(2)

where \( \alpha_{\text{eff}}^{\text{H}/\beta} \) is the effective H\( \beta \) recombination coefficient (3.03 \( \times 10^{-14} \) cm\(^3\) s\(^{-1}\) for \( T = 10^4 \) K; Osterbrock 1989), \( V \) is the volume of each clump (assumed to be spherical with size corrected in quadrature for the seeing (\( \sim 0.7 \) FWHM)), and \( \epsilon \) is the volume filling factor (assumed to be unity in these clumps). For this exercise, we use clumps that are approximately circular on the sky so our assumption of spherical symmetry is reasonable. The seeing-corrected clump diameters range from \( \sim 1.0 \) to 5.0 kpc and the densities are \( n_e \sim 0.1\text{--}1.0 \) cm\(^{-3}\) (top panel of Figure 4), showing a distinct enhancement within the inner \( \sim 15 \) kpc. These values for \( n_e \) fall within the range derived by Macchetto et al. (1990). These densities are well below the value assumed in the Groves et al. models, but we believe the ionization parameters derived from these models are reliable (e.g., the critical density for collisional de-excitation is \( 8 \times 10^4 \) and \( 7 \times 10^5 \) cm\(^{-3}\) for [N\( \text{II} \)] \( \lambda 6583 \) and [O\( \text{III} \)] \( \lambda 5007 \), respectively).

Combining these electron densities with the ionization parameters derived in Section 4.2, we calculate the flux of ionizing photons, \( \Phi_{\text{measured}} \) (photons s\(^{-1}\) cm\(^{-2}\)), at various radii in the bicone. For comparison, we estimate a predicted ionizing photon flux, \( \Phi_{\text{predicted}} \), integrating from 1 to 10 Rydbergs the power-law fit (\( \alpha_\nu = -1.5 \)) to the far-UV nuclear spectral energy of MR 2251–178 reported in Scott et al. (2004). In deriving the predicted flux, we do not account for UV absorption along our line of sight, even though strong Ly\( \alpha \) absorption is present (Monier et al. 2001); \( \Phi_{\text{predicted}} \) is thus likely a lower limit.

The values of \( \Phi_{\text{predicted}} \), \( \Phi_{\text{measured}} \), and \( \Phi_{\text{measured}} / \Phi_{\text{predicted}} \) in the ionization cones are plotted in Figure 4. We see no trend for this ratio to decrease with increasing distance from the quasar. The ionizing radiation from the quasar thus propagates through the nebula with negligible attenuation. Since our deeper observations did not reveal line-emitting material beyond what was already known by Shopbell et al. (1999), we conclude that the nebula is matter-bounded, i.e., all of the ionizing radiation emitted along the ionization cones escapes the nebula.

There is only one well-defined clump in the outer anti-cone region. The inferred ionizing flux at that position is distinctly lower than in the cone region (Figure 4). While this result may indicate that the nebula is radiation-bounded in the anti-cone direction, dilution by star formation may also be responsible for this apparent drop in \( \Phi_{\text{measured}} \), as discussed in Section 4.2.

4.4. Implications

Our results have important implications on the issue of AGN radiative feedback. First, we have shown that the ionizing radiation field of MR 2251–178 is collimated along the east–west radio axis, producing a bicone with opening angle \( \sim 80^\circ \text{--} 130^\circ \) that covers \( \sim 65\% \text{--} 90\% \) of 4\( \pi \) sr (these numbers take into account the projection effects). Ionizing photons are leaking along directions outside these cones at a rate that is \( \sim 2\text{--}3 \) times lower than along the cones. The nebula around MR 2251–178 appears to be matter-bounded (except perhaps in the anti-cone direction, where we have poor constraints; Section 4.3), indicating that the ionizing radiation that makes it out of the quasar host galaxy also makes it out of the nebula and contributes to ionizing the IGM. A similar situation was observed in HE 1029–1401, a luminous radio-quiet quasar with a photoionized biconical nebula that extends out to 16 kpc (Husemann et al. 2010). In MR 2251–178, however, the walls at the base of the biconical structure are porous, allowing an additional \( \sim 5\% \text{--} 15\% \) of the total ionizing flux from the quasar to escape outside of the ionization cones. Overall, considering the contributions from both inside and outside the cones, and the possibility that the nebula is ionization-bounded outside the cones, we find that \( \sim 65\% \text{--} 95\% \) of the quasar ionizing radiation makes its way out of the system.

The situation may be different at higher redshift where galaxy hosts have larger gas fractions on average than their local counterparts (e.g., Tacconi et al. 2010; Daddi et al. 2010). Dependences on AGN luminosity likely also become important.
Flux-limited AGN surveys preferentially select luminous quasars which are more likely to ionize the host ISM (e.g., Curran & Whiting 2012), create giant halos (e.g., Francis & McDonnell 2006; Cantalupo et al. 2007; Willott et al. 2011; North et al. 2012; Cantalupo et al. 2012), and ionize the surrounding IGM out to Mpc scales (e.g., Gonzalves et al. 2008). The relatively small fraction of type 2 quasars at high redshifts in current surveys suggests that the opening angles of quasar ionization cones increase with increasing quasar luminosities (e.g., Lawrence 1991), raising the efficiency of quasars to ionize the IGM. A similar effect may be taking place in high-redshift star-forming galaxies where giant Lyα halos have been detected (Steidel et al. 2011) and galactic winds poke holes through the ISM where Lyman continuum emission can escape (Nestor et al. 2013 and references therein; cf. nearby dwarf galaxies; Zastrow et al. 2011). A recent study by Liu et al. (2013) finds multiple cases of smoothly distributed ionized envelopes around luminous radio-quiet quasars at $z \sim 0.5$. Line ratio maps similar to those presented in this Letter would help refine our understanding of the geometry and escape fraction of the ionizing radiation fields in these objects, hence the role these luminous quasars play in ionizing the IGM.

We thank M. McDonald for help with data acquisition and reduction, and the referee, M. Villar-Martin, for a thoughtful report. This work was funded through NSF grant AST-10009583 (K.K. and S.V.), a Senior NASA Postdoctoral Program award (S.V.), and the Alexander von Humboldt Foundation (S.V.).

REFERENCES

Bajtlik, S., Duncan, R. C., & Ostriker, J. P. 1988, ApJ, 327, 570
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Becker, R. H., Fan, X., White, R. L., et al. 2001, AJ, 122, 2850
Bergeron, J., Boksenberg, A., Dennefeld, M., & Tarenghi, M. 1983, MNRAS, 202, 125
Bruns, L. R., Wyithe, J. S. B., Bland-Hawthorn, J., & Dijkstra, M. 2012, MNRAS, 421, 2543
Cantalupo, S., Lilly, S. J., & Huchta, M. G. 2012, MNRAS, 425, 1992
Cantalupo, S., Lilly, S. J., & Porciani, C. 2007, ApJ, 657, 135
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Curran, S. J., & Whiting, M. T. 2012, ApJ, 759, 117
Daddi, E., Bournaud, F., Walter, F., et al. 2010, ApJ, 713, 686

Decarli, R., Walter, F., Yang, Y., et al. 2012, ApJ, 756, 150
Dressler, A., Bigelow, B., Hare, T., et al. 2011, PASP, 123, 288
Fabian, A. C. 2012, ARA&A, 50, 455
Fan, X., Narayanan, V. K., Strauss, M. A., et al. 2001, AJ, 123, 1247
Ferrarese, L., & Merritt, D. 2000, ApJL, 539, L9
Francis, P. J., & Bland-Hawthorn, J. 2004, MNRAS, 353, 301
Francis, P. J., & McDonnell, S. 2006, MNRAS, 370, 1372
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJL, 539, L13
González, J. F., Steidel, C. C., & Pettini, M. 2008, ApJ, 676, 816
Greene, J. E., Zakamska, N. L., Ho, L. C., & Barth, A. J. 2011, ApJ, 732, 9
Groves, B. A., Dopita, M. A., & Sutherland, R. S. 2004, ApJS, 153, 9
Husemann, B., Sanchez, S. F., Wisotzki, L., et al. 2010, A&A, 519, A115
Kauffmann, G., Heckman, T. M., Tremonti, C., et al. 2003, MNRAS, 346, 1055
Kewley, L. J., Heisler, C. E., Dopita, M. A., & Lumsden, S. 2001, ApJS, 132, 37
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Lawrence, A. 1991, MNRAS, 252, 586
Liu, G., Zakamska, N. L., Greene, J. E., Nesvadba, N. P., & Liu, X. 2013, MNRAS, 430, 2327
Loeb, A., & Barkana, R. 2001, ARA&A, 39, 19
Macchetto, F., Colina, L., Golombek, D., Perryman, M. A. C., & di Serego Alighieri, S. 1990, ApJ, 356, 389
Mennier, E. M., Mathur, S., Wilkes, B., & Elvis, M. 2001, ApJ, 559, 675
Mulchaey, J. S., Wilson, A. S., & Tsvetanov, Z. 1996, ApJ, 467, 197
Nestor, D. B., Shapley, A. E., Kornei, K. A., Steidel, C. C., & Siana, B. 2013, ApJ, 765, 47
North, P. L., Courbin, F., Eigenbrot, A., & Chelouche, D. 2012, A&A, 542, A91
Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley, CA: University Science Books)
Rupke, D. S. N., & Veilleux, S. 2013, ApJ, 768, 75
Scott, J. E., Kriss, G. A., Brotherton, M., et al. 2004, ApJ, 615, 135
Shopbell, P. L., Veilleux, S., & Bland-Hawthorn, J. 1999, ApJL, 524, L83
Steidel, C. C., Bogosavljević, M., Shapley, A. E., et al. 2011, ApJ, 736, 160
Swinbank, J., Baker, J., Barr, J., Hook, I., & Bland-Hawthorn, J. 2012, MNRAS, 422, 2980
Tacconi, L. J., Genzel, R., Neri, R., et al. 2010, Natur, 463, 781
Veilleux, S., Cecil, G., & Bland-Hawthorn, J. 2005, ARA&A, 43, 769
Veilleux, S., & Osterbrock, D. E. 1987, ApJS, 63, 295
Veilleux, S., Shopbell, P. L., Rupke, D. S., Bland-Hawthorn, J., & Cecil, G. 2003, AJ, 126, 2185
Veilleux, S., Weiner, B. J., Rupke, D. S. N., & Veilleux, S. 2010, AJ, 139, 145
Villar-Martin, M., Humphrey, A., Delgado, R. G., Colina, L., & Arribas, S. 2011, MNRAS, 418, 2032
Willott, C. J., Chet, S., Bergeron, J., & Hutchings, J. B. 2011, AJ, 142, 186
Yuan, T.-T., Kewley, L. J., & Sanders, D. B. 2010, ApJ, 709, 884
Zastrow, J., Oey, M. S., Veilleux, S., McDonald, M., & Martin, C. L. 2011, ApJL, 741, L17
Zheng, W., Kriss, G. A., Deharveng, J.-M., et al. 2004, ApJ, 605, 631
Zibetti, S. 2009, arXiv:0911.4956