HST/ACS EMISSION LINE IMAGING OF LOW-REDSHIFT 3CR RADIO GALAXIES. I. THE DATA*

GRANT R. TREMBLAY1,3, MARCO CHIABERGE1,2, WILLIAM B. SPARKS1, STEFI A. BAUM3, MARK G. ALLEN4, DAVID J. AXON3, ALESSANDRO CAPETTI5, DAVID J. E. FLOYD5, F. Duccio MACCHETTO1, GEORGE K. MILEY6, JACOB NOEL-STORRE3, CHRISTOPHER P. O’DEA3, ERIC S. PERLMAN8, AND ALICE C. QUILLEN9

1 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA; grant@stsci.edu
2 INAF—Istituto di Radioastronomia, Via P. Gobetti 101, Bologna I-40129, Italy
3 Rochester Institute of Technology, 84 Lomb Memorial Drive, Rochester, NY 14623, USA; grant@astro.rit.edu
4 Centre de Données Astronomiques, 11 Rue de l’Université, 67000 Strasbourg, France
5 INAF—Osservatorio Astronomico di Torino, Strada Osservatorio 20, 10025 Pino Torinese, Italy
6 Las Campanas Observatory, Observatories of the Carnegie Institute of Washington, Casilla 601, La Serena, Chile
7 Leiden Observatory, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands
8 Physics and Space Sciences Department, Florida Institute of Technology, 150 West University Boulevard, Melbourne, FL 32901, USA
9 Department of Physics and Astronomy, University of Rochester, 600 Wilson Boulevard, Rochester, NY 14627, USA

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ABSTRACT

We present 19 nearby (z < 0.3) 3CR radio galaxies imaged at low and high excitation as part of a Cycle 15 Hubble Space Telescope (HST) snapshot survey with the Advanced Camera for Surveys (ACS). These images consist of exposures of the Hα (6563 Å, plus [N II] contamination) and [O III]λ5007 emission lines using narrowband linear ramp filters adjusted according to the redshift of the target. To facilitate continuum subtraction, a single-pointing 60 s line-free exposure was taken with a mediumband filter appropriate for the target’s redshift. We discuss the steps taken to reduce these images independently of the automated recalibration pipeline so as to use more recent ACS flat-field data as well as to better reject cosmic rays. We describe the method used to produce continuum-free (pure line-emission) images, and present these images along with qualitative descriptions of the narrow-line region morphologies we observe. We present Hα+[N II] and [O III] line fluxes from aperture photometry, finding the values to fall exactly on the redshift–luminosity trend from a past HST/WFPC2 emission line study of a larger, generally higher redshift subset of the 3CR. We also find expected trends between emission line luminosity and total radio power, as well as a positive correlation between the size of the emission line region and redshift. We discuss the associated interpretation of these results, and conclude with a summary of future work enabled by this data set.

Key words: galaxies: active – quasars: emission lines – radio continuum: galaxies

Online-only material: color figures

1. INTRODUCTION

Characteristically intense nuclear emission in radio galaxies, along with the highly collimated jets powered by accretion onto their central engines, can influence star formation, excitation, and ionization of the interstellar medium (ISM), as well as provide kinetic stresses on the hot X-ray emitting coronal gas that pervades clusters of galaxies (Quillen & Bower 1999; McNamara et al. 2000; Blanton et al. 2001; Reynolds et al. 2002; Ruszkowski & Begelman 2002). Narrowband imaging surveys of radio galaxies at redshifts z > 0.6 were among the first studies to establish such a connection, having shown the optical line-emitting gas (∼ 104 K) near the nuclei of these objects to spatially align with the radio jet axes on kiloparsec scales (Fosbury 1986; Hansen et al. 1987; Baum et al. 1988; McCarthy 1988; Baum et al. 1990). This so-called “alignment effect” has been attributed to shocks induced by propagation of the radio jet, as well as photoionization from the active galactic nucleus (AGN; e.g., Baum & Heckman 1989a; McCarthy 1993; Best et al. 2000). While these shocks can trigger star formation along the regions of the ISM excited into line emission (Chambers et al. 1987), more recent work has suggested that feedback from the AGN may also play a role in ultimately quenching the star formation rate (SFR) in the late stages of the host galaxy’s evolution, thereby ushering its rapid passage from the “blue cloud” to the “red sequence” (e.g., Cowie et al. 1996; Bell et al. 2004; Faber et al. 2007, and references therein).

Work is ongoing in reconciling the seemingly competing roles of AGN feedback in both inducing, then possibly truncating star formation at successive stages of galactic evolution (e.g., Silk & Rees 1998; Fabian 1999; di Matteo et al. 2005; Hopkins et al. 2005; Silverman et al. 2008). Regardless, it is clear that the AGN and its host galaxy share coevolutionary pathways (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000), and that studies of the ionized nuclear gas in radio galaxies, as unique probes of the early universe, will be key to understanding this relationship on size and timescales small and large.

The Hubble Space Telescope (HST) has undertaken systematic surveys of the 3CR catalog of radio galaxies in the UV (Allen et al. 2002), optical (Martel et al. 1999; de Koff et al. 2000; Privon et al. 2008), and near-infrared (Madrid et al. 2006; Donzelli et al. 2007; Tremblay et al. 2007; Floyd et al. 2008). These programs, in concert with a robust array of ground-based observations of the 3CR in nearly all wavelength regimes, have established a uniform database of cross-spectrum imaging and spectroscopy for a sample that is nearly complete with redshift and flux limit, unbiased with respect to optical/IR wavelengths, and containing galaxies exhibiting a variety of intrinsic characteristics. The completeness and diversity of the sample has

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enabled studies into radio-loud unification models and the dichotomy between relatively low power, edge-darkened Fanaroff and Riley class I radio galaxies (hereafter FR I; Fanaroff & Riley 1974) and higher power, edge-brightened FR II radio galaxies (Chiaberge et al. 2000, 2002). HST observations of the 3CR have also led to discoveries of new optical and IR jets (Floyd et al. 2006), a trend between nuclear dusty disk inclination and host galaxy isphotal shapes (Tremblay et al. 2007) and face on disks with optical jets (Sparks et al. 2000). Jet/disk orientations were studied at unprecedented spatial resolution (e.g., Schmitt et al. 2002; Verdoes Kleijn & de Zeeuw 2005; Tremblay et al. 2006 and references therein). Allen et al. (2002) also found complex UV morphologies unlike those seen in quiescent hosts, indicative of ongoing star formation.

In this paper we present narrowband emission line observations of 19 nearby (z < 0.3) 3CR radio galaxies imaged at low and high excitation with the Advanced Camera for Surveys (ACS) aboard HST. These images of the warm optical line (Hα and [O iii]λ5007) emitting gas present in the nuclei of the radio galaxies in our sample offer the highest sensitivity and spatial resolution yet available in the HST 3CR database. This enables detailed studies of shocked and star-forming regions of the ISM in relation to radio jets, providing the already rich 3CR data set with a larger framework from which to study the various phenomena discussed above.

We organize this paper as follows. In Section 2 we describe these HST observations in detail, and in Section 3 we discuss the associated data reduction. In Section 4 we present the Hα+[N ii] (low-excitation) and [O iii] (high-excitation) emission line images, as well as qualitative descriptions of each. We also provide emission line luminosity results and an associated discussion. We summarize this work and discuss future studies enabled by this new data set in Section 5. Throughout this paper we use $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$.

2. SAMPLE SELECTION AND OBSERVATIONS

In this paper we present 19 radio galaxies from the low-redshift (z < 0.3) extragalactic subset of the Revised Third Cambridge Catalog (3CR, Bennett 1962a, 1962b; Spinrad et al. 1985). 3CR sources are selected by radio flux density at 178 MHz, at which extended, unbeamed lobes are detected irrespective of the radio jet’s orientation with respect to the line of sight. The sample is therefore free from orientation bias and is nearly complete with redshift, providing a strong framework for statistical analysis important for studies of, e.g., radio-loud unification models. Moreover, the sample consists of radio galaxies that exhibit a wide variety of characteristics (size, shape, jet morphology, radio luminosity, FR type, dust content, etc.), allowing for physical comparisons to be made among properties intrinsic to various species of radio-loud AGN. We select the low-redshift subset of the 3CR so as to achieve the highest possible spatial resolution, in addition to requiring the Hα line to be within the redshift range of high sensitivity to provide uniform line ratio mapping.

Of the 116 extragalactic 3CR sources with z < 0.3, 98 were awarded for observation in the Cycle 15 ACS snapshot program 10882 (PI: Sparks). The remaining 18 targets that were not requested in our proposal were excluded for various reasons, mainly due to emission line data already being present in the archive for that object. Ultimately, 20 of our awarded targets were observed prior to failure of ACS side two electronics in 2007 January. Of these observations, 19 were successful. Our observation of 3C 371 was carried out but unsuccessful due to failure of guide star acquisition, resulting in unusable data. The sample consists of 4 FR I radio galaxies, 12 FR II radio galaxies, and 3 targets exhibiting compact steep spectrum (CSS) or undiscernible radio morphology.

While only a small subset of our initially proposed sample was observed, the nature of HST’s snapshot mode means that observations were scheduled by convenience with respect to HST’s other programs at the time, and not by any selection effect. Our group of galaxies is therefore as unbiased as the 3CR itself. Moreover, the 19 galaxies successfully observed span nearly the whole redshift range (0.0075 < z < 0.224; see Figure 1) of the underlying sample and, as we will discuss in more detail in Section 4, includes galaxies exhibiting a wide array of emission line characteristics.

Our 19 successful observations consist of ACS Wide Field Channel (WFC) exposures of the Hα+[N ii] and [O iii]λ5007 emission lines using narrowband (2% bandpass) linear ramp filters (LRFs) at wavelengths adjusted according to the redshift of the target (see Table 1). The LRFs aboard ACS feature effective central bandwidths that vary as the filter is rotated across the FOV. While the LRFs are useful in providing the observer narrowband imaging capabilities at a wide variety of central wavelengths, there is a drawback in that the target is imaged monochromatically only over a small region (~40˝ × 80˝) of the instrument’s FOV. In planning the observations for this data set, we ensured that the target galaxy nuclei always corresponded to the very center of this region.

With each target fully observed in one orbit, an exposure time of 2 × 200 s and 2 × 250 s was used for the Hα and [O iii] lines, respectively, with a two-point dither pattern (of line spacing 0˚145) to aide cosmic ray and hot pixel rejection. So as to facilitate continuum subtraction from the emission line images, a 60 s, single-pointing exposure was
Table 1
Observation Log

<table>
<thead>
<tr>
<th>Source (1)</th>
<th>( \epsilon ) (2)</th>
<th>Obs. Date (UT) (3)</th>
<th>( \alpha ) (J2000.0) (4)</th>
<th>( \delta ) (J2000.0) (5)</th>
<th>Filters (6)</th>
<th>Line/Cont. (7)</th>
<th>( \lambda ) (Å) (8)</th>
<th>Exp. Time (s) (9)</th>
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<tr>
<td>3C 33.0</td>
<td>0.0597</td>
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<td>01 08 52.8</td>
<td>+13 20 14</td>
<td>FR647M</td>
<td>Cont.</td>
<td>5824</td>
<td>1 × 60</td>
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<tr>
<td>3C 40.0</td>
<td>0.0180</td>
<td>2006 Sep 17</td>
<td>01 20 34.0</td>
<td>−01 20 34</td>
<td>FR647M</td>
<td>Cont.</td>
<td>5593</td>
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<td>+04 06 39</td>
<td>FR647M</td>
<td>Cont.</td>
<td>5654</td>
<td>1 × 60</td>
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<td>+33 53 15</td>
<td>FR647M</td>
<td>Cont.</td>
<td>6842</td>
<td>1 × 60</td>
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<tr>
<td>3C 129.0</td>
<td>0.0208</td>
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<td>04 49 09.1</td>
<td>+45 00 39</td>
<td>FR647M</td>
<td>Cont.</td>
<td>5615</td>
<td>1 × 60</td>
</tr>
<tr>
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<td>04 56 43.0</td>
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<td>FR647M</td>
<td>Cont.</td>
<td>6677</td>
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<td>07 27 04.5</td>
<td>−02 04 42</td>
<td>FR647M</td>
<td>Cont.</td>
<td>6710</td>
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<td>−03 08 27</td>
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<td>Cont.</td>
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<td>08 21 33.6</td>
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<td>6215</td>
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<td>2006 Dec 5</td>
<td>09 21 08.6</td>
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<td>FR647M</td>
<td>Cont.</td>
<td>6457</td>
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<td>2007 Jan 22</td>
<td>09 47 45.1</td>
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<td>FR647M</td>
<td>Cont.</td>
<td>5973</td>
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<td>Cont.</td>
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<td>1 × 60</td>
</tr>
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<td>12 19 23.2</td>
<td>+05 49 31</td>
<td>FR647M</td>
<td>Cont.</td>
<td>5541</td>
<td>1 × 60</td>
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<td>2007 Jan 11</td>
<td>13 21 17.8</td>
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<td>FR647M</td>
<td>Cont.</td>
<td>5934</td>
<td>1 × 60</td>
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<td>2006 Dec 30</td>
<td>15 10 22.5</td>
<td>+70 45 52</td>
<td>FR647M</td>
<td>Cont.</td>
<td>6154</td>
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<td>15 24 05.5</td>
<td>+54 28 15</td>
<td>FR647M</td>
<td>Cont.</td>
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<td>+45 33 30</td>
<td>FR647M</td>
<td>Cont.</td>
<td>6004</td>
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<td>+79 46 17</td>
<td>FR647M</td>
<td>Cont.</td>
<td>5808</td>
<td>1 × 60</td>
</tr>
</tbody>
</table>

Notes. The 19 3CR radio galaxies observed as part of the HST Cycle 15 SNAP program 10882 (PI: Sparks), listed by source name in ascending order: (1) 3CR source name; (2) redshift; (3) observation date; (4) right ascension (J2000.0, in hours, minutes, and seconds); (5) declination (J2000.0, in degrees, arcminutes, and arcseconds); (6) ACS ramp filters used, listed for the 60 s continuum, the 400 s Hα, and the 500 s [O III]5007 observations, respectively; (7) Emission line (or continuum) observed, corresponding to filter configuration; (8) redshift-adjusted wavelength of emission line being observed, corresponding to the wavelength to which the ramp filter has been configured, with 2% bandwidth for the Hα and [O III] exposures, and 9% bandwidth for the continuum exposures; (9) exposure time in seconds. The continuum images are single exposures, while the emission line observations consist of two exposures in a two-point dither pattern. See Section 2 for more details on the sample selection and observations for this program. Also part of this program was 3C 371, the observation of which failed due to failure of guidestar acquisition. It is therefore excluded from presentation and analysis in this paper. See Table 2 for a summary of the optical properties of the above sample, and Table 3 for a summary of its radio properties.
taken with a medium (9%) bandpass ramp filter centered at rest-frame 5500 Å, covering a region of the optical spectrum absent of significant contamination from line emission (see Figure 2 for a representative example of our filter selection strategy). Subarrays were used to increase the efficiency of these observations, allowing four images to be stored in the ACS buffer at once. The WFC on ACS consists of two 2048 × 4096 pixel CCDs (WFC1 and WFC2), each with a plate scale of 0.049 per pixel and a field of view (FOV) of 202″ × 202″ (further details may be found in the ACS Instrument Handbook, Boffi et al. 2007). See Table 1 for an observation log related to this program.

It is important to note that, for all “Hα imaging” presented in this paper, the bandpass used was contaminated by [N ii] emission at 6548 and 6583 Å. References to Hα will therefore read “Hα+[N ii]” throughout this paper. Though it is beyond the scope of this work to subtract this contamination, [N ii] flux does not impact the results presented in this paper in any way as we present all correlations with respect to Hα+[N ii] and never Hα alone. In follow-up papers providing analysis of these data, however, new ground-based optical spectroscopy of the 3CR by Buttiglione et al. (2009) may be used to better quantify the contribution of [N ii] through each Hα bandpass. The Buttiglione spectra, obtained using the Telescopio Nazionale Galileo (TNG), may be convolved with the spectral response of the HST ACS ramp filters, providing a constraint on the relative strength of Hα and [N ii] in the filter throughput. In doing this, one must take into account the fact that the TNG spectra are extracted from a 2″ × 2″ region, while many of our galaxies (e.g., 3C 33) are far more extended. In Figure 3 we plot the de-reddened flux ratios from Buttiglione et al. (2009) of the diagnostic line [N ii]λ6584 to Hα, versus redshift, for each galaxy in our sample (with the exception of 3C 132). The results from Buttiglione et al. (2009), some of which are apparent in Figure 3, show that the relative contributions of [N ii] and Hα vary widely from source to source, and that [N ii] appears to dominate in most high-excitation galaxies (HEGs; see Table 2).

3. DATA REDUCTION

Here we describe the steps taken to produce data that has been calibrated, cleaned of cosmic rays (CRs) and hot pixels, and finally subtracted of contamination from continuum emission.
The *HST* on-the-fly recalibration (OTFR) pipeline utilizes pre-launch (ground) flats in the reduction of ACS LRF images, the use of which can contribute upward of 7% uncertainty to reduced data given the evolution of the instrument in the years since launch. By reducing each image “manually,” we are able to avoid introducing this uncertainty, as well as implement a more proactive approach to cleaning the images of CRs and hot pixels, particularly in the case of the single-pointing continuum images for which automated CR rejection via combination of dithered images is not possible. For these reasons the images presented in this paper have been reduced independently of the OTFR pipeline, in a process we describe below.

### 3.1. Calibration

The calibration stage begins with the raw exposures and corrects for flat-fielding, bias and dark levels, as well as absolute sensitivity. Each of these corrections is performed by the IRAF\(^\text{10}\) routine *calacs* (in *stsdas.hst_calib.acs*). So as to avoid the uncertainty that would otherwise have been introduced by the use of pre-launch flats in the OTFR pipeline, we updated the *PfLFile* header keyword for each raw image to specify that the newest available flat be utilized for each *calacs* run.

In selecting the appropriate new flat to use (in lieu of the old ground flats used by the OTFR pipeline) we employ the same strategy that was used when the original ground flats for the ramp filters were created. That is, LRF flats are interpolated from flats for ACS narrow-, medium-, and broadband (i.e., non-LRF) filters that correspond most closely with the redshift-adjusted wavelength of the emission line (or continuum) being imaged. The minor difference in central wavelength, throughput, and bandwidth of these (non-LRF) filters corresponds to negligible differences in their corresponding flat fields (less than the ∼7% uncertainty introduced in using the old ground LRF flats).

With the replacement flats chosen on a case-by-case basis and the image headers updated to reflect these changes, the *calacs* routine was run for each image, producing calibrated FITS files (one for the continuum exposure, and two each for the Hα+[N\(^{\text{ii}}\)] and [O\(^{\text{iii}}\)] exposures) that have been flat-fielded and corrected for bias, dark current, and absolute sensitivity. It is upon these calibrated images that cosmic ray and hot pixel rejection was performed, as we discuss in the following section.

### 3.2. Cosmic Ray and Hot Pixel Rejection

The NOAO IRAF task *cosmicrays* (noao.imred.crutil) was run on copies of the science frames of each calibrated exposure (one for the continuum image, two each for the Hα+[N\(^{\text{ii}}\)] and [O\(^{\text{iii}}\)] images) to identify CRs and hot pixels. The routine identifies cosmic ray events by a detection algorithm based on a mean flux comparison within a specified detection window. A pixel within this window whose value is higher than a user-specified threshold dependent upon the mean value of its neighbors is considered “bad,” and flagged for cleaning by the routine. Once the list of cosmic ray and hot pixel candidates is established over the whole image, *cosmicrays* replaces flagged pixels with the mean value of its four neighbors. A “cleaned” output file is then generated. We were careful to ensure that *cosmicrays* did not mis-identify real features (particularly galaxy nuclei or other physical, bright features) as CRs or hot pixels. The routine’s parameters were adjusted if this was the case.

The “cleaned” output from *cosmicrays* is insufficient for our needs, as the routine will often simply “dull” the CR rather than truly replace it. This is because *cosmicrays* flags pixels within a detection window that often contains neighboring pixels that are also affected by the CR (and are therefore far brighter than the true background). In the worst instances, depending on the parameters that are chosen, *cosmicrays* can sometimes reconstruct the very CR it was attempting to mask.

Therefore, we utilized the “cleaned” output from *cosmicrays* only as an intermediate step toward the creation of a bad pixel mask for each exposure. To that end, we divided the original, uncleaned copy of the calibrated science frame with the “cleaned” output from *cosmicrays*. The divided image was then examined by eye, and blinked with the uncleaned frame so as to qualitatively assess the success of *cosmicrays* in identifying offending pixels. The bad pixel mask was then created from the divided image, in which pixels whose values were above a specified threshold dictated those that were to be masked in the uncleaned image. This threshold was decided qualitatively for each image based on our assessment of the success of *cosmicrays* in distinguishing truly bad pixels from real features. Often, accepting every flagged pixel from the divided image into the final mask would result in masking healthy pixels on the galaxy itself. If this appeared to be the case, the “allowance threshold” was set above the values of the incorrectly flagged pixels in the divided image, so that they were not made part of the final mask. We paid particular attention to flagged pixels within the immediate vicinity of the target galaxy, and ensured on a case-by-case basis that the pixels being masked were indeed CR events or hot pixels and not real features in the galaxy. This was accomplished through blinking individual exposures or by comparing the continuum image to archival *HST* data from, e.g., WFC2 in the few cases where the correct choice was not obvious.

The mask was then used with the *fixpix* task to linearly interpolate values for masked pixels based on those of their nearest unmasked neighbors. While this is in effect similar to the procedure employed by *cosmicrays*, it is more robust in that *fixpix* is better able to replace a CR event with pixels generally consistent with that of the true background. *cosmicrays*, on the other hand, will often simply “dull” the CR rather than truly replace it, as it flags pixels within a detection window that often contains neighboring pixels affected by the CR (and are therefore far brighter than the true background). Moreover, the masking process allows the user to check at each step that no real feature on the galaxy is erroneously altered. This process was repeated several times (typically three times) for each calibrated science frame (one continuum exposure, two Hα+[N\(^{\text{ii}}\)] frames, and two [O\(^{\text{iii}}\)] frames). At each iteration in the process we varied the detection thresholds in *cosmicrays*, as well as the parameters associated with creating the subsequent mask, in order to ensure that all CRs and hot pixels were ultimately identified and cleaned. In Figure 4 we provide a representative example of the steps in our cosmic ray and hot pixel rejection strategy. The upper left and lower right panels in the figure serve as a “before and after” comparison.

In two cases (3C 33 and 3C 78) a large CR event landed directly on or near to the target galaxy image in the single-pointing continuum exposure. In these cases we masked the CR while taking care to affect the galaxy light distribution as little as possible. Inevitably, some error due to pixel value interpolation remains on the final reduced images (as the continuum

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\(^{10}\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
exposure is used for both Hα+[N ii] and [O iii] in the continuum subtraction process, described in Section 3.4). However, while this error is difficult to characterize it is unlikely that it has a significant effect on the ultimate science value of the data, both for morphological studies of the emission line region and for, e.g., flux measurements.

3.3. Multidrizzle

The calibrated, cleaned data were passed through the multidrizzle routine with the default parameters. The task calculates and subtracts a background sky value for each exposure, searches for additional bad pixels not already flagged in the data quality array, and drizzles the two exposures into outputs that are shifted and registered with respect to one another. From these drizzled exposures a median image is created, which is then compared with original input images so as to reject the (very few) CRs not already cleaned in our previous CR rejection process, as we describe in the section above. More information on the specifics of multidrizzle can be found in Koekemoer et al. (2002). Final output images were left unrotated with respect to north to avoid pixel interpolation errors that might add uncertainty to our continuum subtraction and flux estimation strategies, which we describe in the sections below.

3.4. Image Alignment

To facilitate continuum subtraction it was first necessary to align the continuum exposures with their corresponding drizzled emission line images to ensure registration down to a fraction of a pixel. A first pass registration was made by the world coordinate system (WCS) to achieve rough alignment of the continuum image with its companion line emission data. Subsequently, fractional shifts and rotations were manually applied using foreground stars and features on the galaxy as alignment aides (with the added help of the task imalign). Initial image registration was already well established for 8 of the 19 galaxies in our sample as their observations were carried out using the same guide stars in all (continuum, Hα+[N ii], and [O iii]) exposures. The remaining 11 observations included small slews of HST to allow for proper placement of the galaxy image on the WFC chip (necessary to image at the desired LRF wavelength). In these cases guide star acquisition was required between exposures. Registration for these 11 targets was therefore not initially ideal, and great care was taken to ensure proper alignment through manually applied shifts and rotations. After the appropriate shifts and rotations were applied, the WCS systems on the images were registered with respect to one another so as to enable proper WCS alignment when viewing the images.

3.5. Continuum Subtraction

Here we describe the steps taken to produce Hα+[N ii] and [O iii] line emission images that are effectively free from contamination by continuum light from the galaxy. The aligned images were multiplied by their exposure times to set pixel values (in electrons per second for drizzled ACS images) to total electrons. The continuum image was then scaled by a factor determined for each image on a case-by-case basis. Initially, this factor was roughly estimated using the synthphot synthetic photometry package (specifically calcphot) in IRAF. The calcphot models served as a qualitative guide in roughly establishing the scaling factor, which was later refined iteratively through a trial and error process that involved scaling and subtracting the continuum image from the line emission image, and examining residual pixel values on the resultant image in regions
known to be dominated by continuum emission on the original unsubtracted data. The process was repeated until these regions possessed a mode pixel value very close to the background level (which was effectively zero, after the multidrizzle process). Ultimately, the above strategies were employed in both qualitative and quantitative ways on a case-by-case basis for each image, ensuring that the final subtracted image could be confidently considered as “pure” line emission within the error established by the absolute photometry for this data set. In Figure 5 we provide a representative “before and after” comparison in the case of continuum subtraction for 3C 33.

3.6. Emission Line Luminosity Measurements

For each Hα+[N II] and [O III] image we have measured the total flux from all detected line emission in the galaxy’s central regions. Emission line fluxes were measured from the continuum-subtracted images using the apphot routines in IRAF. We adopted an “all the flux you see” approach when establishing the size of the aperture with which the photometric measurement was performed. In this way, we measure “total” flux as opposed to flux through an aperture that is the same across the entire data set.

For consistency, we defined a “source region” by heavily smoothing a copy of each emission line image with a Gaussian kernel set to an arbitrarily large sigma. The aperture for the measurement was then set to the radius corresponding to a reasonable contour in the smoothed image enclosing all detected line emission from the galaxy. We also defined an outer boundary beyond which the image may be non-monochromatic (due to the ramp filters; see Section 2 for an explanation). The region between the “source region” and the outer boundary defined the area in which the Hα+[N II] and [O III] background level was measured.

With these regions defined using the smoothed image, the corresponding regions on the original continuum-subtracted images were identified. The image was then examined to establish the standard deviation of background, and the pixel values were thresholded to a value of order one sigma above the background level, corresponding to \( \sim 0.01 \) electrons per second. Counts above this threshold were considered signal and were counted in the photometric summation of flux values, while pixels below this threshold were read as zero and were not counted.

We summed counts above the pre-defined threshold within the source region (aperture), and then subtracted the estimated background measured similarly within the intermediate region (exterior to the source region but interior to the outer boundary). Photometric conversion was then applied by scaling the residual (source minus background) value by the inverse sensitivity (the PHOTFLAM keyword), converting the value from electrons per second to flux units in erg cm\(^{-2}\) s\(^{-1}\) \(\Delta\)\(^{-1}\). Flux measurements were made on unrotated images to avoid pixel interpolation errors. Emission line flux values were converted to luminosities via the luminosity distance. Non-rotated images were used for flux calibration to minimize pixel interpolation errors. Ultimately, the calibrations allow us to measure emission line flux with an uncertainty of \(~ 15\%\).

4. RESULTS AND DISCUSSION

In Figures 6–8 we present the continuum-free line emission images listed by ascending 3C number. Hα+[N II] images are shown to the left and are presented in orange and [O III] images are shown to the right in blue. Where possible we have estimated the projected orientation of the radio jet axis on the sky from high spatial resolution archival Very Large Array (VLA) radio maps retrieved from the NASA/IPAC Extragalactic Database (NED\(^{11}\)), indicated by an arrow in the top right corner of the galaxy’s [O III] image. This orientation was qualitatively estimated from the apparent inner jet axis for FR I radio galaxies, and along the hotspot-to-hotspot axis for FR II radio galaxies. See Table 3 for a summary of the radio properties for objects in the sample. In instances where the figure does not display an estimate for the radio jet orientation, data were either not readily available, were of insufficient resolution to make a confident estimate, or were cospatial with the source on galactic scales (i.e., morphologically similar to CSS sources).

4.1. Description of Individual Sources

In the subsections below we discuss the observed morphology of the high surface brightness Hα+[N II] and [O III] line emission detected in each galaxy. Objects are listed in ascending order by the name of the source. For information relating to the observations of each of the below galaxies, see Table 1. For quantitative data regarding the optical and radio properties of each object, see Tables 2 and 3, respectively. All images discussed below are presented in Figures 6, 7, and 8.

\(^{11}\) http://nedwww.ipac.caltech.edu/
4.1.1. 3C 33; $z = 0.059$

Extended regions of high surface brightness line emission are seen in both the Hα+[N ii] and [O iii] images. The low- and high-excitation regions trace a general “integral sign” shape extending $\sim 5$ kpc and oriented NE to SW. In both images a fainter, detached shell of low- and high-excitation emission is observed NE of the main “integral sign” feature. The [O iii] features more obviously clumpy, brighter hotspots along the lane of emission and near the nucleus than does the Hα+[N ii] image. Long slit spectroscopy of the extended line emission obtained by Simkin (1979) and Heckman et al. (1985) suggested that the line emitting gas is rotating along an axis oriented at a position angle (P.A.) of $\sim 19^\circ$ with respect to the FR II radio jet axis. (Figure 6).

4.1.2. 3C 40; $z = 0.017$

A dusty disk on 100 pc scales is seen in both Hα+[N ii] and [O iii] images, marked by the absence of emission along a circumnuclear rim that is more prominent in the [O iii] image than it is in Hα+[N ii]. Low- and high-excitation line emission is seen tracing the edges of the disk on the southern side, while [O iii] emission on the northern side of the disk appears less extensively distributed. The band marking the disk is not continuous, rather in both images it is interrupted by low-surface brightness line emission apparently connecting the southern and northern sides of the disk in the same general location. Note that the apparent major axis of the disk appears roughly orthogonally oriented with respect to the FR II radio jet axis. (Figure 6).

4.1.3. 3C 78; $z = 0.028$

An optical jet is seen in both Hα+[N ii] and [O iii] emission to extend from the core in a northeastely direction (projected on the sky). The bright, unresolved nucleus in both images is surrounded by a generally isotropic region of narrow-line emitting gas in both Hα+[N ii] and [O iii]. Sparks et al. (2000) noted the presence of a face-on dusty nuclear disk in this FR I radio galaxy. Both distributions appear slightly more extended in the plane perpendicular to the optical synchrotron radio jet axis described by Sparks et al. (1995). Perlman et al. (2006) note the presence of an emission line knot cospatial with the radio jet axis. That we apparently detect both high- and low-excitation emission along the jet axis may be an important result, and is worthy of future study (Figure 6).
4.1.4. 3C 93.1; $z = 0.244$

A compact distribution of narrow-line emitting gas is seen surrounding the nucleus and extended $\sim 3.8$ kpc primarily toward the NE. The lopsided morphology observed in both the H$\alpha$+[N ii] and [O iii] emitting gas is evidence of the presence of an anisotropic nuclear ionizing radiation field. 3C 93.1 is a CSS source (Figure 6).

4.1.5. 3C 129; $z = 0.021$

Narrow-line emission associated with 3C 129 is only marginally detected in both filter configurations. Compact H$\alpha$+[N ii] emission with very low surface brightness is observed to be cospatial with the nucleus. Conversely, the nucleus is not detected in the [O iii] image, where instead only very faint extended emission that appears to be associated with the nucleus extends $1''$ to the north and south. 3C 129 is one of the four FR I radio galaxies in our sample (Figure 6).

4.1.6. 3C 132; $z = 0.214$

A bright nucleus surrounded by fainter, more diffuse emission is observed in both H$\alpha$+[N ii] and [O iii] images. The nucleus appears fainter in [O iii] and what appears to be a faint "hotspot" is located directly to the north of the nucleus (Figure 6).

4.1.7. 3C 136.1; $z = 0.064$

In H$\alpha$+[N ii], an elongated nucleus is seen with major axis oriented north–south on the sky. Faint, disjoint distributions of narrow-line gas surround the nucleus in two filamentary plumes extending from the core along a N–S axis roughly perpendicular to the FR II radio jet axis. Clumpy patches of disparate, low-surface brightness emission are observed at radii of $\sim 1''$. In [O iii] there is an apparent double nucleus with hotspots more clearly separated than in the H$\alpha$+[N ii] image. The north–south filaments seen in H$\alpha$+[N ii] are not detected in [O iii] (Figure 7).

4.1.8. 3C 180; $z = 0.220$

A bi-conical series of shells is observed in both H$\alpha$+[N ii] and [O iii], reminiscent of other bi-conical NLR morphologies observed in some Seyfert II galaxies (e.g., Mrk 3, Mrk 573, NGC 5252, Capetti et al. 1999). At both low- and high-excitation we observe a bright, lopsided emission region cospatial with the nucleus. Fainter "plume-like" features extend from both the northern and southern extremities of the extended core of emission. The bi-conical series of shells of emission extends $\sim 8$ kpc to both the NE and SW of the core. The abundance of optical line emitting gas along a preferred axis suggests the presence of a highly anisotropic ionizing radiation field. 3C 180 lacks a Fanaroff–Riley classification, and we are unable
No. 2, 2009  

**HST EMISSION LINE IMAGING OF RADIO GALAXIES**  

**Figure 8.** Same as Figure 6. East is left, north is up. Note that panels labeled “Hα” actually show Hα+[N ii] emission.  
(A color version of this figure is available in the online journal.)

to characterize the morphology of its radio source in any meaningful way given the available data. McCarthy et al. (1995) note that 3C 180 resides in a cluster (Figure 7).

4.1.9. 3C 196.1; z = 0.198

A high surface brightness lane of Hα+[N ii] emission “snakes” NE from the bright elongated core, reminiscent of a “tadpole” shape. Hα+[N ii] emission is also observed extending from the core along an axis perpendicular to the axis of elongation of the “tadpole”-shaped distribution of ionized gas. In the [O iii], high-excitation emission is observed in two localized hotspots cospatial with the elongated bright core seen in Hα+[N ii], and the “tadpole” structure is not detected, nor is the emission along the perpendicular axis (Figure 7).

4.1.10. 3C 197.1; z = 0.13

Bright, unresolved nuclei are seen in both images, surrounded on all sides by a fainter distribution of line-emitting gas. The nucleus appears larger in Hα+[N ii] than it does in [O iii] (Figure 7).

4.1.11. 3C 219; z = 0.174

Compact emission is seen in both bands, as is faint, diffuse emission surrounding the unresolved source at the center (Figure 7).

4.1.12. 3C 227; z = 0.086

Compact emission cospatial with the galaxy’s nucleus is seen at both low- and high excitation. In [O iii] we observe an extremely large arm of emission extending ∼20 kpc, representing
by far the largest distribution of line-emitting gas in our sample. The large structure is oriented along an axis roughly perpendicular to that of the FR II radio jet. Prieto (1993) studies this object in great detail (Figure 7).

### 4.1.13. 3C 234; z = 0.184

The prominent tidal arm described by Carleton et al. (1984) is seen in high surface brightness Hα+[N II] and [O III] emission. To the east is the bright quasar-like nucleus of the galaxy, and in both images a bright feature is seen extending 0.5 from its northwestern edge. The overall elongation of the emission line region, including the tidal arm, is in a projected orientation that is roughly parallel with that of the radio jet axis on large scales (Figure 8).

### 4.1.14. 3C 270; z = 0.0077

The ∼ 120 pc dusty disk originally studied by Jaffe et al. (1993) is notably absent of emission in both Hα+[N II] and [O III], though there remains some Hα+[N II] emission along the inner regions of the disk. The disk is largely edge-on with respect to the line of sight though is inclined such that the western side of the disk “faces” the observer slightly. Note that the western half of the galaxy is noticeably brighter than the eastern half. Cones of high surface brightness Hα+[N II] emission are seen extending from the unresolved nucleus from both sides of the disk, and are elongated along the direction of the jet (east–west on the sky, and nearly perpendicular to the major axis of the dusty disk). Nuclear [O III] emission is also seen extending from both sides of the disk, though seems to be largely absent on the disk itself (Figure 8).

### Table 2

**Optical Properties**

<table>
<thead>
<tr>
<th>Source</th>
<th>Hα Line Flux ($\times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$)</th>
<th>[O III] Line Flux ($\times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$)</th>
<th>$\log L_{H\alpha}$ (erg s$^{-1}$)</th>
<th>$\log L_{[O III]}$ (erg s$^{-1}$)</th>
<th>Ionization Class$^{a,b}$</th>
<th>LAS$_{H\alpha}$ (kpc)</th>
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<td>40.4398</td>
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**Notes.** (1) 3CR source name; (2) measured Hα (6563 Å) line flux in erg s$^{-1}$ cm$^{-2}$; (3) total measured [O III] (5007 Å) line flux in erg s$^{-1}$ cm$^{-2}$; (4) total Hα luminosity in erg s$^{-1}$ cm$^{-2}$ and (5) total [O III] luminosity in erg s$^{-1}$ (fluxes converted to luminosity using $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_L = 0.73$); (6) source classification of host (FR I = Fanaroff-Riley class I radio galaxy, QSO = quasar, BLMG = broad-line radio galaxy, HEG = high-excitation FR II galaxy, LEG = low-excitation FR II galaxy, per the conventions in Jackson & Rawlings (1997)); (7) largest measured angular size of line-emitting region (noted emission line in parentheses note the line for which the observed NLR appears largest, both lines will be listed if the NLRs cover approximately the same physical extent in both lines).

$^a$ Jackson & Rawlings (1997).

$^b$ Buttiglione et al. (2009).

$^c$ Prieto (1993).

### Table 3

**Radio Properties**

<table>
<thead>
<tr>
<th>Source</th>
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<th>$\log P_{178}$ MHz (erg s$^{-1}$ Hz$^{-1}$)</th>
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</table>

**Notes.** (1) Source name; (2) Fanaroff-Riley classification; (3) 178 MHz flux density in Jy; (4) Log$_{10}$ of radio power at 178 MHz, in erg s$^{-1}$

**References.** Fanaroff & Riley 1974; Spinrad et al. 1985.
4.1.15. 3C 285; z = 0.079

A complex, filamentary system of dust lanes bisects the nuclear region of the galaxy in a northeasterly direction and perpendicular to the line of sight. The extinction associated with the predominant lane in this system is seen in the Hα+[N II], where we observe an extended region of high surface brightness emission with complex morphology. A bright, dense column of line emission extends ∼ 1″ northward from the nucleus at the center of the image. Slightly to the southeast a small, bright “integral sign” feature is seen in general alignment with the large dense column. Both of these features are surrounded by fainter narrow-line emitting gas arranged in filamentary plumes as well as clumpy patches. In the [O III] image we observe a dramatically different morphology than is apparent from the Hα+[N II]. A high surface brightness lane of emission “snakes” westward from the center of the galaxy to form a disjoint “W” shape. The nucleus of the galaxy, such as it is, is not discernible from the image. Bright patches of emission populate the nuclear region of the galaxy in a northeasterly direction and slightly toward the southwest (Figure 8).

4.1.16. 3C 314.1; z = 0.119

Diffuse Hα+[N II] emission is distributed in a complex morphology, while the [O III] emission is decidedly more compact, albeit with faint, wispy plumes extending from the nucleus and slightly toward the southwest (Figure 8).

4.1.17. 3C 319; z = 0.192

Very faint line emission is detected in both images, distributed in a diffuse, complex morphology at extended distances from the nucleus. The [O III] is decidedly more compact than is the Hα+[N II] (Figure 8).

4.1.18. 3C 388; z = 0.092

A bright unresolved nucleus is seen in both images. Small, low surface brightness “plumes” can be seen extending toward a northeasterly direction in the Hα+[N II], while a more prominent conical feature is seen on the southwestern side of the nucleus in the [O III] image (Figure 8).

4.1.19. 3C 390.3; z = 0.056

Very bright Hα+[N II] emission dominates the image from the unresolved nucleus. The noticeably rhomboidal shape of the nucleus in the [O III] is likely a result of the diffraction spikes seen in both images (Figure 8).

4.2. Discussion: Correlations

Below we discuss significant correlations, consistent with the results of previous related studies, that are apparent in our data. In Section 4.3 we discuss the physical interpretation of these observed trends, and compare our results to past literature.

4.2.1. Emission Line Luminosities Versus Redshift

In Figures 9(a) and 9(b) (top left and top right, respectively) we plot the measured Hα+[N II] and [O III] luminosities (L_Hα and L_OIII) versus redshift for the galaxies in our sample. FR I radio galaxies are plotted in red squares, while FR IIs are plotted in blue circles and the three galaxies whose radio morphologies are unclassified are plotted in green triangles (this convention holds throughout this paper). As expected, the emission line luminosities follow a positive redshift–luminosity trend, albeit with a greater degree of scatter than that found in the canonical K–z relation for radio galaxies (where K is the NIR K-band magnitude of the elliptical radio galaxy host, see Willott et al. 2003 for a detailed study of this correlation). This higher degree of scatter is not necessarily surprising for a number of reasons, some of which we summarize below:

1. Warm optical line emitting gas in radio galaxies is naturally expected to inhabit a greater range in luminosity space than are the NIR starlight distributions of their elliptical hosts. As the stellar component of radio galaxies is believed to have formed at high redshift and evolved passively in the time since (barring other effects), a tight clustering of K-band magnitudes is expected. The amount, ionization state, and detectability of gas in the nuclei of radio galaxies, however, are subject to a number of factors that greatly influence overall emission line luminosities.

2. Our sample includes low-power FR I radio galaxies, characterized by narrow-line emission, and FR II radio galaxies and QSO characterized by broad optical line emission. Broad-line radio galaxies (BLRGs) generally have an optical excess, resulting in a larger contribution to emission line flux. Not surprisingly, the BLRGs in our sample (3C 33, 197.1, 219, 285, 234, and 390.3) generally inhabit the upper regions of Figures 9(a) and 9(b), contributing to the overall scatter.

3. These galaxies range in redshift from 0.0075 < z < 0.224 and were observed with a variety of LRF filter configurations (see Table 2). This results in varying amounts of emission line flux loss beyond the edge of the passband, as well as contamination from [N II].

In Figure 9(c) we plot our Hα+[N II] luminosities in blue squares versus redshift, overplotted with the measured and extrapolated Hα+[N II] luminosities for the sample of 3CR radio galaxies from Privon et al. (2008). The slightly larger scatter observed in the Privon data reflects the fact that roughly 50% of their Hα+[N II] luminosities have been estimated from measured [O III] luminosities using ratios found in the literature. In general, however, our galaxies follow a redshift–luminosity trend roughly consistent with that found for the (generally) higher redshift subset of the 3CR studied in Privon et al. (2008). See Figure 10 for a representative and qualitative comparison of WFPC2 and ACS data quality from the Privon observations and this paper, respectively.

4.2.2. Emission Line Ratios

In Figure 9(d) (bottom right) we plot the measured [O III] luminosities versus the measured Hα+[N II] luminosities for the objects in our sample. Those galaxies lying above the black diagonal line (tracing L_OIII/L_Hα = 1) possess [O III] luminosities greater than their Hα+[N II] luminosities (and vice versa). Note that, in general, L_Hα and L_OIII are roughly similar across the sample, with some notable exceptions whose names we have indicated in the figure.

In future papers it will be necessary to investigate emission line ratio maps, which may carry important implications with regard to the orientation-based unification scheme of radio-loud AGNs (e.g., Padovani & Urry 1992; Chiaberge 2004 and references therein). It is expected that low-excitation lines (like Hα+[N II]) are emitted further from the AGN than are higher excitation lines like [O III], as the fraction of highly excited gas will depend on the proximity of that gas to the ionizing
source, in this case the AGN (e.g., Jackson & Rawlings 1997, and references therein). This spatial dependence of $L_{[\text{O}\text{III}]}/L_{\text{H}\alpha}$ also leads to a dependence upon the sources of obscuration present in the galaxy. In the unification model for radio galaxies, wherein FR Is are unified with BL-Lacs and FR IIs are unified as the parent population of steep spectrum QSO, we expect low-excitation gas to lie further from the obscuring torus, while the fraction of high-excitation gas observed will follow a tighter dependence upon the angle at which the observer views the obscuring torus. We may therefore expect that intrinsically similar radio-loud AGNs viewed at a variety of angles will have unequal [O III] luminosities but roughly equal Hα+[N II] luminosities (Baum & Heckman 1989b; Jackson & Browne 1990).

It will also be important to investigate whether [O III]/Hα ratios of order unity are indicative of Seyfert-like nebular activity. We note that, in general, the majority of objects in our sample with $L_{[\text{O}\text{III}]}/L_{\text{H}\alpha} \neq 1$ in (i.e., those galaxies significantly offset from the diagonal line in Figure 9(d)) are BLRGs, with the exception of one FR I. Though we are unable to make statistically significant inferences with respect to these issues (as our sample consists of only 19 galaxies), further investigation into these line ratios and associated line ratio maps may yield important results.

4.2.3. Emission Line Luminosities Versus Total Radio Power

In Figures 11(a) and 11(b) we plot emission line luminosity versus total radio power at 178 MHz for Hα+[N II] and [O III],
respectively. We note a clear upward trend in both figures, consistent with the results of the comprehensive study by Wilott et al. (1999), which also found a tight correlation between emission line and radio luminosity in flux limited samples of radio galaxies.

We discuss interpretations of this result in Section 4.3, but it is first important to frame the results of the above emission line luminosity comparisons in the context of ionized gas distribution morphologies.

4.2.4. Morphology of the Extended Narrow-line Regions

The low- and high-excitation narrow-line regions we observe in our sample, overall, exhibit extended and complex morphologies characterized by, e.g., clumpy regions of emission (e.g., 3C 33), wispy tendrils (3C 136.1, 3C 319), extended filaments and lanes (3C 196.1, 3C 234), and bi-conical series of shells (3C 180). In general, the morphologies observed in [O III] mirror those in Hα+[N II] with some important exceptions (e.g., 3C 136.1, 3C 196.1, 3C 227, 3C 285). We also note the presence of bright unresolved nuclear emission in the cores of every object with the exception of 3C 129 in [O III] and 3C 285 in Hα+[N II] and [O III] (no clearly “point source-like” nucleus is apparent in our images for that object).

In Figures 12(a) and 12(b) we compare the projected linear sizes of the line-emitting regions with both redshift and elliptical host galaxy effective radius, respectively. We have estimated the gas distribution sizes, in kpc, from the largest angular size (LAS) subtended by the high surface brightness emission (as projected on the sky). While this is a rough estimate, it provides important insights as evidenced by the weak upward trend of LAS with redshift (Figure 12(a)), implying that larger distributions of optical line emitting gas are found at higher redshifts.
Values for the effective radii $R_{\text{eff}}$ in Figure 12(b) are from Floyd et al. (2008) and Donzelli et al. (2007), and were derived from surface brightness profile fitting to HST/NICMOS H-band images (and some NIR imaging from Telescopio Nazionale Galileo in the case of Donzelli et al. 2007). While the methods employed by these two studies differ, their results are generally consistent, and any uncertainty introduced in plotting results from both papers is reflected in the characteristic error bars we have indicated in the figure. In light of these added uncertainties, however, we are unable to make any significant inferences, though LAS and $R_{\text{eff}}$ do appear weakly correlated for galaxies with $R_{\text{eff}} < 4$ kpc, while no such correlation is evident for those objects with $R_{\text{eff}} > 4$.

4.3. Physical Interpretation of the Trends Observed

We have discussed three trends apparent in our data:

1. Emission line luminosity (both for H$_\alpha$+[N II] and [O III]) appears positively correlated with the redshift of the host galaxy.
2. The H$_\alpha$+[N II] and [O III] luminosities are also tightly correlated with total radio power at 178 MHz.
3. Projected sizes of the ionized gas distributions in our sample are positively correlated with host galaxy redshifts. That is, we observe larger line-emitting regions at greater distances.

The above results are consistent with those of, e.g., Willott et al. (1999, 2003), Privon et al. (2008) (and references therein), as well as many other past studies of emission line gas in radio galaxies. The tight redshift–luminosity correlation in flux-limited samples results in the selection of intrinsically brighter objects at higher redshifts. In radio flux density selected samples such as the 3CR, this is manifest in more powerful radio galaxies (FR IIIs) inhabiting a higher redshift range than do their intrinsically lower-power counterparts (FR Is). Moreover, the alignment effect discussed in Section 1 suggests that propagation of the radio jet plays a role in the excitation of the ISM into line emission (Baum & Heckman 1989a; McCarthy 1993; Best et al. 2000). It is therefore unsurprising that more powerful radio galaxies appear associated with higher emission line luminosities, as they are able to collisionally excite and photoionize greater amounts of gas than are lower-power (and therefore lower-redshift) AGNs (Baum & Heckman 1989a, 1989b; Rawlings & Saunders 1991; Inskip et al. 2002a, 2002b). As accretion disk radiative luminosity appears related to the jet kinetic energy flux (Baum & Heckman 1989b; Rawlings & Saunders 1991), this can be used to place constraints on the physics of the AGN. The greater mechanical energy input and number of ionizing photons provided by more powerful radio sources also explains the dependence of emission line region size on redshift: we expect the more powerful radio galaxies at higher redshifts to be capable of exciting gas at greater distances from the central engine, contributing to the upward trend we observe.

It should also be noted that dense clouds of gas are observed on increasingly larger scales at higher redshifts, ultimately forming the vast Ly-$\alpha$ halos that surround the most powerful radio galaxies (van Ojik et al. 1997; Reuland et al. 2003). While this dependence of gas cloud density and extent on redshift is important for objects with $z > 0.6$ (the point near which the alignment effect precipitously tightens), it is not likely to contribute in any meaningful way to our comparatively low-redshift sample at $z < 0.3$.

Figure 12. Comparison of the projected linear sizes of the extended high surface brightness H$_\alpha$+[N II] emission line regions with both (a) redshift and (b) effective radii $R_{\text{eff}}$ of the host galaxies. The size estimates represent the LAS of the narrow-line regions detected in our H$_\alpha$-[N II] imaging. We do not plot the LAS of the [O III] regions as their sizes generally mirror those of the H$_\alpha$+[N II] regions, with some important exceptions (see Section 4.2). Characteristic error bars appear in the upper right corner of each plot. The effective radii, in kpc, are from Floyd et al. (2008) and Donzelli et al. (2007) and were derived from surface brightness profile fitting to HST/NICMOS H-band images (and some NIR imaging from Telescopio Nazionale Galileo in the case of Donzelli et al. 2007). While the methods employed by these two studies differ, their results are generally consistent, and any uncertainty introduced in plotting results from both papers is reflected in the characteristic error bars we have indicated in the figure. In light of these added uncertainties, however, we are unable to make any significant inferences, though LAS and $R_{\text{eff}}$ do appear weakly correlated for galaxies with $R_{\text{eff}} < 4$ kpc, while no such correlation is evident for those objects with $R_{\text{eff}} > 4$.

(A color version of this figure is available in the online journal.)
5. SUMMARY AND CONCLUDING REMARKS

In this paper we have presented HST/ACS narrowband imaging of [O \text{III}] λ5007 line emission in the central regions of 19 low-redshift radio galaxies from the 3CR catalog. We have chosen the 3CR as the basis for our sample as it is radio flux density selected at a frequency dominated by unbeamed radio lobes, and is therefore free from orientation bias with respect to all HST wavelengths. Moreover, the 3CR has been extensively covered by past ground- and space-based imaging and spectroscopy programs, yielding a robust, cross-spectrum database containing galaxies exhibiting a wide variety of intrinsic characteristics. We limit our sample to the low-redshift subset (z < 0.3) of the 3CR to maximize spatial resolution, as well as to ensure that the emission lines fall within the redshift range of high sensitivity. The ACS observations were carried out during HST Cycle 15, and in total, 19 galaxies were observed prior to failure of the instrument in 2007 January. Reduction of these data was performed independently of the automated OTFR pipeline so as to improve on flat-fielding and to more proactively clean the images of cosmic rays and hot pixels. In addition, contribution from continuum was subtracted to yield effectively pure emission line images.

We have compared the resulting emission line luminosities with both redshift and total radio power, finding weak positive correlations for each. We have also noted an upward trend between the projected size of the emission line gas distributions and redshift. These results are consistent with those from past studies, and we have interpreted the apparent trends to be a result of higher power radio galaxies, preferentially found at greater distances, which can shock and photoionize greater amounts of the ISM further away from the nucleus, thus resulting in brighter and more extended emission line regions.

Regardless of the interpretation, recombination times for warm gas (T \approx 10^4 K) are of order 10^3 years (Osterbrock & Ferland 2006), while lifetimes of radio sources are of order 10^9 years. The process by which the gas is ionized should therefore be ongoing throughout the lifetime of the source, implying a strong connection between AGN activity and observed emission line properties. The sensitive, high spatial resolution images presented in this paper may therefore enrich future works studying jets propagating through the ISM, and their relationship with extended and compact star formation regions as well as X-ray coronal halos. Future emission line studies of larger samples of radio galaxies may also deepen understanding of radio-loud unification schemes, as warm optical line emitting gas traces fundamental energy transport processes coupled to feedback at the interface of the AGN and its surrounding medium.

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