Spatially Extended Low-ionization Emission Regions (LIERs) at $z \sim 0.9$

Raphael E. Hviding$^{1,2}$, Gabriel B. Brammer$^{1,4}$, Ivelina G. Momcheva$^{3,5}$, Brit Fisher Lundgren$^5$, Danilo Marchesin$^{6,7}$, Norbert Pirzkal$^3$, Russell E. Ryan$^3$, Andrea Vang$^7$, David A. Wake$^5$, Matthew Bourque$^3$, Catherine Martin$^3$, and Kalina V. Nedkova$^6$

1 Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755, USA
2 Department of Astronomy, Steward Observatory, University of Arizona, 933 North Cherry Avenue, Rm N204, Tucson, AZ 85721, USA
3 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
4 Cosmic Dawn Center, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark
5 Department of Physics, University of North Carolina Asheville, One University Heights, Asheville, NC 28804, USA
6 Department of Physics and Astronomy, Tufts University, 574 Boston Avenue, Suite 304, Medford, MA 02155, USA
7 Department of Astronomy, University of Wisconsin-Madison, 475 N. Charter Street, Madison, WI 53706, USA

Abstract

We present spatially resolved emission diagnostics for eight $z \sim 0.9$ galaxies that demonstrate extended low-ionization emission line regions over kpc scales. Eight candidates are selected based on their spatial extent and emission line fluxes from slitless spectroscopic observations with the Hubble Space Telescope/Wide Field Camera 3 G141 and G800L grisms in the well-studied Great Observatories Origins Deep Survey (GOODS) fields. Five of the candidates (62.5%) are matched to X-ray counterparts in the Chandra X-ray Observatory Deep Fields. We modify the traditional Baldwin–Phillips–Terlevich (BPT) emission line diagnostic diagram to use [S II]/(H$\alpha$ + [N II]) instead of [N II]/H$\alpha$ to overcome the blending of [N II] and H$\alpha$ + [N II] in the low-resolution slitless grism spectra. We construct emission line ratio maps and place the individual pixels in the modified BPT. The extended low-ionization nuclear emission line regions (LINER)-like emission present in all of our candidates, coupled with X-ray properties consistent with star-forming galaxies and weak [O III]Å5007 Å detections, is inconsistent with purely nuclear sources (LINERs) driven by active galactic nuclei (AGNs). While recent ground-based integral field unit spectroscopic surveys have revealed significant evidence for diffuse LINER-like emission in galaxies within the local universe ($z \sim 0.04$), this work provides the first evidence for the non-AGN origin of LINER-like emission out to high redshifts.

Key words: galaxies: evolution – galaxies: fundamental parameters – quasars: emission lines

1. Introduction

Introduced in Heckman (1980) as a new class of galactic nuclei, low-ionization nuclear emission line regions (LINERs) exhibit emission line ratios consistent with low-ionization atomic transitions, with strong [N II], [S II], and [O I] and relatively weak [O III]. Originally, LINERs were hypothesized to form a part of a continuum of active galactic nuclei (AGNs) ranging from high-luminosity quasars and Seyfert galaxies toward their low-luminosity counterparts. In recent years, LINERs have been of particular interest due to the mounting evidence that their characteristic emission is not constrained solely to the nucleus, but extends out to kpc scales, as shown by several integral field unit (IFU) surveys (e.g., Sarzi et al. 2006; Singh et al. 2013; Belfiore et al. 2016).

Although LINERs have been identified in many galaxies using a variety of spectral apertures, we adopt the Belfiore et al. (2016) naming convention, which excludes the “N” for nuclear and refers to low-ionization emission line region as LIERs. In the local universe, up to 40% of “normal” galaxies (excluding interacting galaxies, merging galaxies, and active galaxies) may be LIERs in certain stellar mass ranges (Belfiore et al. 2016).

The literature surrounding diffuse LIERs has advanced several hypotheses for the extended emission. First, the “stellar hypothesis” for the extended emission (e.g., Binette et al. 1994; Stasińska et al. 2008; Sarzi et al. 2010; Cid Fernandes et al. 2011; Yan & Blanton 2012) argues that post asymptotic giant branch (post-AGB) stars provide sufficient photoionization to produce observed LIER ratios, a compelling theory as LINER-like emission is predominantly observed in early-type and red galaxies, where evolved stars become the dominant ionizing source (Belfiore et al. 2016). Second, the “starburst hypothesis” for the extended emission (Sharp & Bland-Hawthorn 2010; Yuan et al. 2010; Ho et al. 2014, 2016) argues that a burst of star formation, leading to ionizing outflows and galactic winds, causes the elevated line ratios on extended scales. Third, the “merger hypothesis” for extended emission (e.g., Monreal-Ibero et al. 2006, 2010; Rich et al. 2011; Soto et al. 2012) argues that tidally induced gas flows from galaxy interaction, leading to shock ionization across various spatial extents. Finally, recently Weilbacher et al. (2018) argued that Lyman-continuum leakage was sufficient to explain the photoionization present in the merger Antennae Galaxy.

The purpose of this work is to extend evidence for the existence of LIERs out to $z \sim 0.9$ and to present methods for their detection using slitless grism spectroscopy. So far, spatially resolved spectroscopic observations of LIERs galaxies have been limited to the local universe. The average redshift of the LIERs confirmed by Belfiore et al. (2016) in the Sloan Digital Sky Survey-IV (SDSS-IV) Mapping Nearby Galaxies at Apache Point Observatory (Bundy et al. 2015, MaNGA survey) is $z \sim 0.04$. We report, for the first time, the detection of eight galaxies at $z \sim 0.9$ with spatially extended LINER-like emission line ratios (i.e., LIERs). In order to detect spatially resolved emission diagnostics of $z \sim 0.9$ galaxies, we make use of the 3D-Hubble Space Telescope (HST) survey (Brammer et al. 2012; Momcheva et al. 2016), a near-infrared slitless
grism survey covering most of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS) Treasury survey area. The 3D-HST Survey carried out two-orbit depth slitless spectroscopy with the G141 grism (1.10 to 1.65 μm) on the HST Wide Field Camera 3 (WFC3) instrument. Additional HST/WFC3 G102 grism spectroscopy (0.8–1.1 μm) is available from the following HST programs: GO-11359 (PI: O’Connell), GO-12190 (PI: Koekemoer), GO-13420 (PI: Barro), GO-13779 (PI: Malhotra), and GO-14227 (PI: Papovich). We focus on the Great Observatories Origins Deep Survey (GOODS) fields, which have both the deepest slitless spectra over a wide area and extensive deep X-ray coverage—7 Ms in CDFs (Luo et al. 2017) and 2 Ms in CDFN (Xue et al. 2016)—allowing for the use of additional X-ray AGN selection criteria.

The discovery of LIERs at z ~ 0.9 is greatly aided by the development of Grizli, a new library for the analysis of space-based slitless spectroscopy (G. B. Brammer et al. 2018, in preparation). The Grizli library presents two significant improvements to the Brammer et al. (2012) and Momcheva et al. (2016) 3D-HST reductions. First, Grizli allows for simultaneous fitting of all available exposures from the G102 and G141 grisms, combining grism spectra obtained at multiple position angles. Second, Grizli provides a mechanism to create drizzled emission line maps, again from combining all available grisms and position angles. We use these emission line maps to create the emission line ratio maps used in this work.

This paper is structured as follows. In Section 2, we describe our modification of traditional LINER diagnostics in order to account for the line blending of low-resolution grism spectroscopy. Section 3 describes the selection of candidates and their extraction using the new Grizli pipeline. Section 4 presents the candidates in detail, including spatially resolved spectroscopic diagnostics that demonstrate signatures consistent with spatially extended LIERs. Section 5 summarizes our findings and discusses future research.

Cosmological calculations are made assuming the ΛCDM model from Wilkinson Microwave Anisotropy Probe (WMAP) measurements with $H_0 = 69.3$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.287$, and $\Omega_\Lambda = 0.713$ (Hinshaw et al. 2013).

## 2. Line Blending in 3D-HST

In order to categorize the emission line ratios of the selected galaxies, we make use of the well-known Baldwin–Phillips–Terlevich (BPT) diagnostic (Baldwin et al. 1981). In order to distinguish between star-forming galaxies and typical LINERs, we employ the BPT diagram that compares the [S II]6717 Å + 6731 Å to Hα and [O III]5007 Å to the [O III]λ5007 Å to Hβ ratio. Between the redshifts of z ~ 0.7 and z ~ 1.5, the Hα and [S II] emission lines fall into the wavelength coverage of the G141 grism, while the Hβ and [O III] lines fall into the coverage of the G102 grism. However, due to the low spectral resolution ($R \sim 150$) of the HST/WFC3 G141 grism, the entire [N II] λ6548 Å, Hα, [O III] λ5007 Å, [N II] λ6584 Å complex of lines is not resolved, but blended into a single line (Brammer et al. 2012).

We develop a modification to the traditional BPT diagnostic in order to account for this line blending in Hα. We use the Oh et al. (2011) improved emission line measurements from the Abazajian et al. (2009) SDSS Data Release 7 (DR7) catalog in order to create a modified BPT diagnostic to select all objects with a signal-to-noise ratio (S/N) > 3 in each aforementioned line. In Figure 1(a), we show all selected objects, color-coded using the Kewley et al. (2006) criteria to separate star-forming galaxies, Seyferts, and LINERs. We then plot the objects after adding in the [N II] contribution into the Hα line, as shown in Figure 1(b). This is our modified BPT diagram. In order to mimic the original selection criteria, we generate two classifications in this modified BPT diagram. To separate Seyferts and LINERs, we use a two class linear discriminant analysis (McLachlan 1992, LDA) to find the linear subspace that minimizes the within-class scatter and maximizes the cross-class scatter. After projecting onto the optimal linear subspace, we choose a cutoff between classes when the fraction of correctly identified LINERs is equal to that of Seyferts.

![Figure 1. BPT excitation diagnostic diagrams. Panels (a) and (b) plot the Oh et al. (2011) DR7 emission line fluxes on a traditional BPT and line-blended BPT, respectively. In panel (a), we plot the Kewley et al. (2006) delineations, which inform our modified BPT delineations, as shown in panels (b) and (c). We plot integrated GOODS 3D-HST line measurements for objects with a 3σ detection in each line and the integrated Grizli line measurements for our LIER candidates in panel (c). Median errors are shown in each panel.](image-url)
(approximately 88%). This results in Equation (1),

$$\log_{10} \left( \frac{[O\,\text{iii}]}{H\beta} \right) = 2.34 \cdot \log_{10} \left( \frac{[S\,\text{ii}]}{H\alpha + [N\,\text{ii}]} \right) + 1.65,$$

which provides a distinction between LINERs and Seyferts in the modified BPT. We make use of a linear classifier due to its simplicity and since a higher-order function would not drastically reduce the interclass contamination.

We conduct the same procedure to generate a selection cut between all AGN and star-forming galaxies. Again, we generate two class LDA but instead select our cutoff in order to select AGN purely, without any galaxies lying above the line, resulting in Equation (2):

$$\log_{10} \left( \frac{[O\,\text{iii}]}{H\beta} \right) = -1.32 \cdot \log_{10} \left( \frac{[S\,\text{ii}]}{H\alpha + [N\,\text{ii}]} \right) - 0.29.$$

This results in only correctly identifying 57% of all AGN, a relatively conservative criterion in order to ensure that there is minimal star-forming galaxy contamination. In addition, we add a vertical component to the criterion, categorizing any object with a $\log_{10}([S\,\text{ii}]/(H\alpha + [N\,\text{ii}])) > -0.4$ as an AGN. This was assigned visually and only adds less than 4% contamination to the total AGN sample. We make use of the latter criterion extensively in Section 4 where many objects do not have corresponding $[O\,\text{iii}]/H\beta$ ratios, and we solely rely on the $[S\,\text{ii}]/(H\alpha + [N\,\text{ii}])$ ratio.

In Figure 1(c), we plot all 3D-HST extracted objects in the GOODS fields that have a 3σ detection in all of the contributing lines—86 in total—for comparison.

### 3. Sample Selection and Properties

#### 3.1. Emission Line Flux

We begin by selecting objects from the Momcheva et al. (2016) catalog, which presents reduced data and data products from WFC3 G141 grism spectroscopy from the 3D-HST survey, a 248-orbit HST Treasury program in the CANDELS fields. We use the emission line catalog, including photometry correction scales, to find candidates with high signal-to-noise emission line ratios. We impose a flux limit on both the $H\alpha + [N\,\text{ii}]$ and $[S\,\text{ii}]$ emission lines, requiring a minimum $H\alpha + [N\,\text{ii}]$ flux of $30 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ and a minimum $[S\,\text{ii}]$ flux of $8 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$, which let us consistently detect $H\alpha + [N\,\text{ii}]$ emission out to 9 kpc and $[N\,\text{ii}]$ emission out to 6 kpc in most objects. Following this selection, we are left with 795 sources in the GOODS-South field and 687 in the GOODS-North field. In order to retrieve well-constrained emission line ratios with low uncertainties, we require candidates to have an $H\alpha + [N\,\text{ii}]$ emission S/N $> 10$ and an $[S\,\text{ii}]$ emission S/N $> 2$, resulting in 40 objects in the GOODS-South field and 61 in the GOODS-North field.

#### 3.2. Source Geometry for an Optimal Line Map

We further select objects where the combination of the morphology and the geometry of the dispersed spectra is favorable for determining robust emission line ratio maps. Due to the low resolution of the grism spectra, the $\sim 275$ Å (observed frame) separation between $H\alpha$ and the $[S\,\text{ii}]$ doublet results in a separation between the two features of only 6 pixels in the images. The Grizli pipeline does mask areas where there is contamination from neighboring lines, but then we cannot constrain emission line ratios in these regions. This effect is only significant in the dispersion direction of the image and is exacerbated by the morphology of the galaxy.

In order to select galaxies with the least contamination, we use the structural parameters measured for 3D-HST (van der Wel et al. 2014b) to select candidates where the grism spectral dispersion axis is not aligned to the morphological position angle. Round objects (i.e., with an axis ratio $q = (a/b) \sim 1$) are unaffected by the relative directions of the dispersion and position angles. We therefore only select objects with a $q < 0.8$ in order to enhance the separation of the emission lines, reducing our sample to 33 sources in the GOODS-South field and 50 in the GOODS-North field. Finally, we impose a condition on the alignment between the dispersion axis and the morphological position angle, requiring at least a 10° separation between the two. Together, our morphological and spatial cuts ensure that our $H\alpha$ and $[S\,\text{ii}]$ emission are separated by at least 6 pixels. For objects with multiple grism angles, we use the angle that maximizes the separation parameter. Our final sample is comprised of 67 sources: 28 in the GOODS-South field and 39 in the GOODS-North field.

### 3.3. Final Sample

For all objects that satisfy the flux, S/N, morphology, and position angle cuts, we extract spatially resolved emission line maps for each line in the modified BPT diagnostic using Grizli. We further divide the $[S\,\text{ii}]$ map by the $H\alpha + [N\,\text{ii}]$ map and the $[O\,\text{iii}]$ map by the $H\beta$ map to create the emission line ratio maps discussed in Section 4. Given the few number of objects, we examined all ratio maps individually by eye and determined those with high visual evidence for extended LINER-like emission if there was consistent detection of elevated line ratios, i.e., similar adjacent pixels, out to kpc scales. The final sample we selected consists of the eight objects listed in Table 1 alongside the Grizli derived redshifts, the $J$-band magnitude, the stellar mass (Skelton et al. 2014), determined from spectral energy distributions (SEDs) and space-based infrared photometry, the star formation rate (UV+IR based, see Whitaker et al. (2014) for details), and X-ray data (Xue et al. 2016; Luo et al. 2017).

Figures 1(c) and 2 show our final sample with respect to the full 3D-HST catalog. Figure 2 additionally plots objects that satisfy our flux, S/N, and morphological selection criteria, “i.e.,” cuts corresponding to physical properties. Figure 1(c) shows the integrated emission line ratios of the modified BPT diagram with our final sample of eight object shown with large symbols. Most fall within a region that, while denoted as star-forming with our modified diagnostic, contain significant overlap with LINERs, and may potentially be identified as LINER AGN if followed up with high-resolution spectroscopy that is not limited by $H\alpha$ line blending.

Figure 2(a) plots our objects according to their Grizli redshifts and 3D-HST $J_{\mu}$ magnitudes. Our candidates occupy a fairly narrow redshift range (0.66–1.52), a result of our requirement that the emission features fall within the wavelength coverage of the grisms. Furthermore, at any given redshift, our objects are located on the brighter end of the magnitude distribution due to our flux constraints on the candidates, along with the majority of our selected objects. Figure 2(b) shows our candidates relative to objects in a similar
### Table 1
**LIER Candidates**

| ID  | 3D-HST | R.A. J2000  | Decl.  | z   | JH | AB | M$^a_\odot$ | sSFR$^a$ | $L_{0.5-7\text{ keV}}$$^{ab}$ | ID | CDF | $L_{0.5-7\text{ keV}}$ | $\Gamma_{\text{eff}}$ | $f_X^a$ | $f_X^b$ | $L_{1.4\text{ GHz}}$ | $f_X^c$ |
|-----|----------------|-------------|--------|-----|----|----|------------|---------|-----------------|-----|------|----------------|-------------|---------|---------|----------------|--------|
|     | GOOD-S                 |             |        |     |    |    |            |         |                 |     |      |                |             |         |        |              |        |
| 983 | 03$^{h}32^m29^s44^{.4}$ | $-27^\circ55'38''20$ | 0.660  | 0.660 | 19.84 | 10.27 | $-8.66$ | 41.4  | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $\ldots$ |
| 15738 | 03$^{h}32^m25^s18^{.6}$ | $-27^\circ50'19''71$ | 1.095  | 1.095 | 21.04 | 10.31 | $-8.65$ | 41.6  | 466             | 1.95  | $-2.55$ | $\ldots$      | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $-3.03$ |
| 26087 | 03$^{h}32^m39^s18^{.8}$ | $-27^\circ47'15''04$ | 1.097  | 1.095 | 20.90 | 10.33 | $-8.66$ | 41.6  | 749             | 41.52 | 2.52   | $\ldots$      | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $\ldots$ |
| 36653 | 03$^{h}32^m36^s03^{.0}$ | $-27^\circ44'23''76$ | 1.038  | 1.044 | 21.55 | 10.08 | $-8.64$ | 41.3  | 677             | 41.66 | 1.43   | $-2.10$      | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $-2.58$ |
|     | GOOD-S                 |             |        |     |    |    |            |         |                 |     |      |                |             |         |        |              |        |
| 18043 | 12$^{h}37^m22^s57^{.5}$ | $+62^\circ13'56''74$ | 1.022  | 1.023 | 20.81 | 10.49 | $-8.72$ | 41.7  | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $\ldots$ |
| 21285 | 12$^{h}36^m59^s92^{.2}$ | $+62^\circ14'49''06$ | 0.761  | 0.761 | 20.50 | 10.31 | $-8.69$ | 41.5  | 416             | 41.40 | 1.40   | $-2.31$      | 18.08          | $\ldots$ | $\ldots$ | $\ldots$      | $-2.79$ |
| 22593 | 12$^{h}37^m01^s94^{.6}$ | $+62^\circ15'10''43$ | 0.938  | 0.946 | 21.42 | 10.04 | $-8.84$ | 41.1  | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $\ldots$ |
| 22815 | 12$^{h}37^m08^s37^{.3}$ | $+62^\circ15'14''66$ | 0.839  | 0.842 | 20.98 | 10.02 | $-8.62$ | 41.3  | 471             | 41.79 | 1.40   | $-2.04$      | $\ldots$        | $\ldots$ | $\ldots$ | $\ldots$      | $-2.51$ |

**Notes.**

$^a$ Values quoted are the log$_{10}$ of the measurement.

$^b$ Predicted X-ray luminosity derived from the star formation rates and stellar masses following Lehmer et al. (2016).

$^c$ Spectroscopic.
redshift range \((0.5 < z < 1.5)\) and mass range \((\log_{10}(M_*/M_\odot) > 9)\), plotting their total stellar masses against their specific star formation rates. While the sample objects are distributed fairly similarly to the entire sample over specific star formation rates, they are constrained to the high end of the stellar mass distribution, between \(10^{10.0}\) and \(10^{10.5} M_\odot\), which is again likely attributed to our flux cuts. We find that our LIER candidates do not differ from the set of all objects that satisfy our selection criteria, as demonstrated by Figure 2, reinforcing the idea that the sample properties are dominated by our cuts. Compared to the local sample presented by Belfiore et al. (2016), the candidates occupy a stellar mass range where, in the local universe, 20% of galaxies, excluding merging, interacting, or active galaxies, may be LIERs.

We match the sample of eight candidates against the X-ray catalogs in the two fields (Xue et al. 2016; Luo et al. 2017) with a match tolerance of three arcseconds. All our objects fall within the Chandra footprint. Five of our candidates are matched with an X-ray source: GOODS-S 15738, GOODS-S 26087, GOODS-S 36653, GOODS-N 21285, and GOODS-N 22815. Objects are classified as AGNs following the criteria outlined in Luo et al. (2017) as follows: (1) \(L_{\text{X, int}} > 3 \times 10^{32} \text{erg s}^{-1}\) (luminous X-ray sources), (2) \(\Gamma_{\text{eff}} < 1.0\) (hard X-ray sources), (3) \(\log(f_X/f_R) > -1\) (\(f_X\) is the, in order of priority, the full-band, soft-band, or hard-band detected flux; \(f_R\) is the \(R\)-band flux), (4) \(L_{\text{X, int}}/L_{1.4 \text{ GHz}} > 2.4 \times 10^{18}\), and (5) \(\log(f_X/f_K) > -1.2\) (\(f_K\) is the \(K_s\)-band flux). The X-ray luminosity, \(\Gamma_{\text{eff}}, \log(f_X/f_R), L_{\text{X, int}}/L_{1.4 \text{ GHz}}, \) and \(\log(f_X/f_K)\) for the five X-ray detected sources are listed in Table 1. None of the five candidates satisfy any of the applicable Luo et al. (2017) AGN criteria, i.e., in all five, the X-ray flux is likely due to stellar origins.

In addition, we estimate the expected X-ray luminosity due to low- and high-mass black hole binaries to compare to the Chandra observations. Our estimates do not include the contribution due to hot gas, but still likely capture the majority of the luminosity, given that galactic X-ray flux above 1.5 keV is dominated by black hole binaries (Hornschemeier et al. 2005; Lehmer et al. 2010, 2016; Fragos et al. 2013). We use the Lehmer et al. (2016) scaling relationships given by

\[
\begin{align*}
L_{\alpha, \text{LMXB}}(z) &= \alpha_0 (1 + z)^\gamma M_*, \\
L_{\alpha, \text{HMXB}}(z) &= \beta_0 (1 + z)^d \text{SFR},
\end{align*}
\]

where \(\log_{10}(\alpha_0) = 29.30 \pm 0.28\), \(\gamma = 2.19 \pm 0.99\) and \(\log_{10}(\beta_0) = 39.40 \pm 0.08\), \(\delta = 1.02 \pm 0.22\). We assume a hardness ratio of \(\gamma = 1.8\) to convert between 2–10 keV and 0.5–7 keV luminosities.

4. LIER Candidates

In this section, we examine the eight LIER candidates in detail based on their morphologies, Hα + [N II] emission line maps, emission line ratio maps, and distribution of pixels in the modified BPT.

We show color images of our candidates in Figure 3. All objects appear to have a red core surrounded by blue spiral arms, indicating enhanced star formation. Figure 4 shows the spatially resolved Hα + [N II] emission line maps produced by the Grizli pipeline, highlighting the areas of strong emission in the galaxy in addition to showcasing the well-resolved Hα emission. For all objects, the emission line maps are extended, and they usually trace the blue spiral arms. Finally, in Figures 5 and 6, we present the diagnostic emission line figures used to verify LIER candidacy for all eight objects. Emission line ratio maps for the Hα + [N II] are presented in Figure 5. For a pixel's emission ratio to be plotted, we require a 2σ detection in [S II] emission. However, if the Hα + [N II] flux is less than a 1σ detection, we plot the lower limit of the emission ratio instead. Ellipses (green) indicate 3, 6, and 9 kpc at the galaxy redshift using the ellipticity and position angle from van der Wel et al. (2014a) that were generated using stacked F125W, F140W, and F160W mosaics. The 1σ Chandra positions are marked in red.

In Figure 6, we plot the emission line ratios on our modified BPT diagram for each object along with the integrated emission line ratio. For a pixel's emission ratio to be plotted, we require a 2σ detection in [S II] and [O III] emission. However, if the corresponding Hα + [N II] or Hβ flux is less than a 1σ detection, we plot the lower limit of the emission ratio instead.
Three of our objects have no available $[\text{O III}]/H\beta$ ratio at all, (GOODS-S 983, GOODS-S 15738, and GOODS-N 21285) due to a nondetection in one or both lines. Another three (GOODS-S 26087, GOODS-N 18043, and GOODS-N 22593) have no individual pixels that satisfy the $[\text{O III}]/H\beta$ S/N requirement as described above for both modified BPT emission line ratios. For these, we plot the $[\text{S II}]/H\alpha + [\text{N II}]$ detections as a histogram along the $x$-axis. Only two of our objects (GOODS-S 36653 and GOODS-N 22815) have $[\text{O III}]/H\beta$ detections per pixel that satisfy our S/N requirements. Each pixel with detections for both ratios for these objects are shown. Given that the $[\text{O III}]/H\beta$ ratio is a strong indicator of...
AGN activity, its low values or nondetection in most of the objects in our sample is an indicator of the non-AGN origin of the LINER-like emission.

1. GOODS-S 983 presents significant extended LINER-like emission out to 6 kpc (Figure 5), mostly centered around the red core visible in Figure 3. This reinforces the notion that an evolved stellar population is providing the source of the ionization. Most of the pixels satisfy our criterion of $\frac{[S\,\text{II}]}{[\text{O\,III}]+[\text{N\,II}]} > -0.4$, placing them in the AGN regime of the modified BPT diagram. However, given the
lack of detection in [O III]/Hβ or a matching Chandra source, it is unlikely that an active super-massive black hole is the source of LINER-like emission.

2. GOODS-S 15738 exhibits strong diffuse emission out to 3 kpc in addition to a strand that extends out to 9 kpc (Figure 5). The latter emission appears to track strongly with a blue knot (Figure 3), which may indicate that this specific emission comes from a region of active star formation that is in line with the “starburst hypothesis” of extended emission. The large spatial extent of the emission, most of which satisfies the [S II]/Hα + [N II] criterion (Figure 6), along with the lack of an [O III]/Hβ ratio detection, suggests a non-AGN origin for the LINER-like emission. In addition, the corresponding Chandra detection for the object satisfies none of the Luo et al. (2017) AGN criteria and can be accounted for by black hole binary emission alone, further supporting the non-AGN hypothesis for the ionization.

3. GOODS-S 26087 presents robust detections out to ~6 kpc in almost every direction, most of which satisfy the requirement of [S II]/Hα + [N II] > −0.4 (Figure 6). Despite a lack of corresponding R- or Ks-band information, the pure X-ray AGN criteria are not satisfied, and the X-ray emission can be accounted for by black hole binaries. Coupled with a low [O III]/Hβ ratio, the areas of LINER-like emission are likely not excited due to AGN activity.

4. GOODS-S 36653 presents a region of LINER-like emission up to ~6 kpc in the northeast portion of the galaxy (Figure 5). This corresponds to the edge of the visible core in Figure 3, which is an area that may be dominated by evolved stars. For this object, there are corresponding [O III] to Hβ detections that place all pixels confidently within the LINER regime. Furthermore, the overall Grizli emission measurements place the object as a whole in the LINER region of the modified BPT diagram, presenting an object that would likely be classified as an AGN in a typical spectroscopic survey. The discrepancy between the Chandra X-ray luminosity and the estimated black hole binary contribution, a factor of about 2.3, is likely due to a contribution from hot gas or large uncertainties in the SED-modeled stellar mass. Like all the other candidates, GOODS-S 36653 does not satisfy any Chandra X-ray criteria, again reinforcing the notion of the non-AGN origin for the ionization.

5. GOODS-N 18043 shows extended LINER-like emission in the core along with a strip along the southeast spiral arm (Figures 3 and 5). In addition, most of the pixels satisfy our [S II]/Hα + [N II] AGN selection (Figure 6). While the integrated [O III]/Hβ ratio can be measured, there are no individual pixels with sufficient S/N for detection. The weak [O III]/Hβ, coupled with the lack of a matched Chandra detection, point toward a non-AGN origin for LINER-like emission, whether from the red core or from the bluer spiral arm.

6. GOODS-N 21285 shows large spatial extent of LINER [S II]/Hα + [N II] ratios past the core out to 6 kpc. This emission tracks with the bluer regions seen in Figure 3, but is also present in the redder core. Most of the individual pixels that satisfy our S/N cuts do satisfy our [S II]/Hα + [N II] AGN selection threshold (Figure 6). GOODS-N 21285 is our only candidate with matching observations across every band used in the Luo et al. (2017) Chandra X-ray criteria. Again, we find no evidence to suggest that the object is an AGN based on these detections and it has X-ray emission consistent with black hole binaries.

7. GOODS-N 22593 shows the most compact emission of all of our sources; however, it still extends out to ~3 kpc. Furthermore, given the lack of an X-ray detection and emission line ratios that place almost all pixels on the modified BPT in an area dominated by LINERs (Figure 6), it is likely that the ionization is not due to an active nucleus.

8. GOODS-N 22815 presents emission consistent with LINER-like ratios out to ≥4 kpc. This is the second object, along with GOODS-S 36653, where we have measurements of the [O III]/Hβ ratios for individual pixels (Figure 6). While the majority of the detected pixels lie below the [S II]/Hα + [N II] cut, the diffuse nature of the emission and the low [O III]/Hβ measurements do not support an active nucleus as the source of the ionizing radiation. The discrepancy between the measured X-ray luminosity and the estimated galactic contribution, a factor of about 2.5, is likely due to a contribution from hot gas or large uncertainties in the SED-modeled stellar mass. Furthermore, the matching Chandra observations do not satisfy any AGN criteria by themselves or when compared to observations in other bands.

5. Summary and Conclusions

In this paper, we have presented the identification of eight candidates for high-redshift, z ~ 0.9, LIERs through spatially resolved emission line diagnostics with Hubble and supported by corresponding Chandra X-ray measurements and multiwavelength photometry. All eight of our candidates present ionized regions consistent with LINER-like emission lines, which are spatially extended, and therefore, inconsistent with the purely nuclear understanding of an AGN. Additionally, we find either weak or no detections for [O III]/Hβ ratios in six (75%) of our objects, an emission diagnostic that is usually a strong indicator for AGN activity. Those objects with spatially resolved [O III]/Hβ serve to place the objects confidently in the LINER regime on our modified BPT diagram. Furthermore, most objects have X-ray luminosities consistent with galactic black hole binary emission, and none of our objects satisfy the AGN X-ray selection criteria outlined in Luo et al. (2017), once again reinforcing the hypothesis for the non-AGN origin for the ionizing radiation.

In a few of our LIER candidates, we find that the extended emission tracks in mainly in either the redder (GOODS-S 983) or bluer parts (GOODS-S 15783) of the optical image, consistent with both the “stellar” and “starburst” hypothesis for the ionization sources, but, in general, most of our objects have extended emission that overlaps both areas of the optical image. While the relatively high rates of specific star formation may suggest the “starburst hypothesis,” we are unable to conclusively constrain the origin of the ionizing source.

This work serves to provide the first evidence for the existence of LIERs out to high redshift. This detection is made possible by the advancement in spatially resolved spectroscopy, allowing for the detection of diffuse emission throughout the candidates. This work was made possible by the Grizli grism reduction package and its ability to create drizzled emission line maps from multiple grism observations with an
arbitrary number of position angles. Furthermore, we developed a modified BPT diagram, allowing for the separation between star formation and AGN emission of objects where the [NII]/Hα diagnostic is not available due to low spectral resolution. Despite the conservative nature of our cuts in our diagram, we are still able to find the clear examples of high-redshift LIERs in the GOODS fields.

There are several projects that follow naturally from our work. Given that we cannot distinguish the ionizing source, it would be of interest to follow up these candidates to not only confirm the elevated line ratios but to gather diagnostics to test the various hypotheses of extended LINER emission. This could be attempted with higher-resolution grism spectroscopy with the James Webb Space Telescope (JWST). It would be of interest to perform follow-up X-ray observations of the objects, especially those in the GOODS-North field, which have shallower Chandra observations. Observations would be well suited to current observational facilities, such as the Nuclear Spectroscopic Telescope Array, or upcoming missions, such as the European Space Agency space observatory, Advanced Telescope for High-ENergy Astrophysics (Barret et al. 2013, ATHENA), or the proposed NASA space observatory, Lynx (Weisskopf et al. 2015).

Finally, the methods used in this work will also be applicable in the era of JWST. JWST is equipped with grism capabilities comparable to those of the HST, and the data analysis will benefit from employing the techniques outlined in this paper in the search for higher-redshift LIERs. Slitless grism observations over large fields, which can be analyzed using Grizli, will serve as excellent tools to search for objects with follow-up potential using higher-resolution spectroscopy, while also providing details about the total LIER population in the high-redshift universe.

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References
Abazajian, K. N., Adelman-McCarthy, J. K., Agnier, M. A., et al. 2009, ApJS, 182, 563
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Barret, D., Nandra, K., Barcons, X., et al. 2013, in S2F2A-2013: Proc. of the Annual Meeting of the French Society of Astronomy and Astrophysics, ed. L. Cam breevy et al., 447
Belfiore, F., Maiolino, R., Maraston, C., et al. 2016, MNRAS, 461, 3111
Binette, L., Magris, C. G., Stasińska, G., & Bruzual, A. G. 1994, A&A, 292, 13
Brammer, G. B., van Dokkum, P. G., Franx, M., et al. 2012, ApJS, 200, 13
Bundy, K., Bershady, M. A., Law, D. R., et al. 2015, ApJ, 798, 7
Cid Fernandes, R., Stasińska, G., Mateus, A., & Vale Asari, N. 2011, MNRAS, 413, 1687
Fragos, T., Lehmer, B., Tremmel, M., et al. 2013, ApJ, 764, 41
Green, D. A. 2011, BASI, 39, 289
Heckman, T. M. 1980, A&A, 87, 152
Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, ApJS, 208, 19
Ho, I.-T., Kewley, L. J., Dopita, M. A., et al. 2014, MNRAS, 444, 3894
Ho, I.-T., Medling, A. M., Bland-Hawthorn, J., et al. 2016, MNRAS, 457, 1257
Hornschemeier, A. E., Heckman, T. M., Prak, A. F., Tremonti, C. A., & Colbert, E. J. M. 2005, AJ, 129, 86
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961
Lehmer, B. D., Alexander, D. M., Bauer, F. E., et al. 2010, ApJ, 724, 559
Lehmer, B. D., Basu-Zych, A. R.,Mineo, S., et al. 2016, ApJ, 825, 7
Luo, B., Brandt, W. N., Xue, Y. Q., et al. 2017, ApJS, 228, 2
Lupton, R., Blanton, M. R., Fekete, G., et al. 2004, PASP, 116, 133
Machlachlan, G. J. 1992, Discriminant Analysis and Statistical Pattern Recognition (New York: Wiley)
Momcheva, I. G., Brammer, G. B., van Dokkum, P. G., et al. 2016, ApJS, 225, 27
Monreal-ibero, A., Arribas, S., & Colina, L. 2006, ApJ, 637, 138
Momreal-Ibero, A., Arribas, S., Colina, L., et al. 2010, A&A, 517, A28
Oh, K., Sarzi, M., Schawinski, K., & Yi, S. K. 2011, ApJS, 195, 13
Rich, J. A., Kewley, L. J., & Dopita, M. A. 2011, ApJ, 734, 87
Sarzi, M., Falcón-Barroso, J., Davies, R. L., et al. 2006, MNRAS, 366, 1151
Sarzi, M., Shields, J. C., Schawinski, K., et al. 2010, MNRAS, 402, 2187
Sharp, R. G., & Bland-Hawthorn, J. 2010, ApJ, 711, 818
Singh, R., van den Ven, G., Jahnke, K., et al. 2013, A&A, 558, A43
Skelton, R. E., Whitaker, K. E., Momcheva, I. G., et al. 2014, ApJS, 214, 24
Soto, K. T., Martin, C. L., Prescott, M. K. M., & Armus, L. 2012, ApJ, 757, 86
Stasińska, G., Vale Asari, N., Cid Fernandes, R., et al. 2008, MNRAS, 391, L29
van der Wel, A., Chang, Y.-Y., Bell, E. F., et al. 2014a, ApJL, 792, L6
van der Wel, A., Franx, M., van Dokkum, P. G., et al. 2014b, ApJ, 788, 28
Weilbacher, P. M., Monreal-Ibero, A., Verhamme, A., et al. 2018, A&A, 611, A95
Weisskopf, M. C., & Bruzual, A. G. 1994, A&A, 292, 13
Whitaker, K. E., Franx, M., Leja, J., et al. 2014, ApJ, 795, 104
Xue, Y. Q., Luo, B., Brandt, W. N., et al. 2016, ApJS, 224, 15
Yan, R., & Blanton, M. R. 2012, ApJ, 747, 61
Yuan, T.-T., Kewley, L. J., & Sanders, D. B. 2010, ApJ, 709, 884