GAS EXCITATION IN ULIRGs: MAPS OF DIAGNOSTIC EMISSION-LINE RATIOS IN SPACE AND VELOCITY

KURT T. SOTO AND CRYSTAL L. MARTIN
Physics Department, University of California, Santa Barbara, CA 93106-9530, USA
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ABSTRACT

Emission-line spectra extracted at multiple locations across 39 ultraluminous infrared galaxies have been compiled into a spectrophotometric atlas. Line profiles of Hα, [N ii], [S ii], [O i], Hβ, and [O iii] are resolved and fit jointly with common velocity components. Diagnostic ratios of these line fluxes are presented in a series of plots, showing how the Doppler shift, line width, gas excitation, and surface brightness change with velocity at fixed position and also with distance from the nucleus. One general characteristic of these spectra is the presence of shocked gas extending many kiloparsecs from the nucleus. In some systems, the rotation curves of the emitting gas indicate motions that suggest gas disks, which are most frequent at early merger stages. At these early merger stages, the emission line ratios indicate the presence of shocked gas, which may be triggered by the merger event. We also report the general characteristics of the integrated spectra.

Key words: galaxies: active – galaxies: evolution – galaxies: formation – galaxies: starburst

Online-only material: color figures, figure sets, machine-readable tables

1. INTRODUCTION

The optical emission-line spectrum of a galaxy is a powerful diagnostic of recent star formation (Kennicutt 1998), the gas-phase metallicity (Kewley et al. 2006), and the excitation mechanism (Kewley et al. 2001; Baldwin et al. 1981). Fiber spectra of low-redshift galaxies have provided the first systematic examination of these properties in the central regions of low-redshift galaxies (e.g., Kauffmann et al. 2003a, 2003b; Tremonti et al. 2004). Infrared spectra obtained with the new generation of multi-object spectrographs, including the James Webb Space Telescope, will make it possible to apply these diagnostics over the entire period of galaxy evolution. The interpretation of these spectra, however, is complicated by measurement apertures that subtend a kiloparsec or more.

On scales larger than the narrow-line region of an active galactic nucleus (AGN) or a giant H ii region, the physical process that excites the gas is not necessarily uniform. The contribution to the excitation from shocks or the hard spectrum of an AGN must be properly identified in order to use metallicity and star formation diagnostics constructed under the assumption of photoionization by massive stars.

To address this problem, we obtain spectra that resolve scales of ~1 kpc to map the excitation across a sample of ultraluminous infrared galaxies (ULIRGs). We interpret the emission line ratios used in the standard “BPT diagrams” (Baldwin et al. 1981), using modern diagnostics of gas excitation mechanism (Kewley et al. 2006) and shock ionization grids (Allen et al. 2008). The line ratios used in these diagnostics ([N ii]/Hα, [S ii]/Hα, [O i]/Hα and [O iii]/Hβ) present dust insensitive measures of excitation due to their proximity in wavelength. While the line ratios produced by a power-law spectral energy distribution are largely degenerate with those predicted by shock models (Allen et al. 2008), spatial mapping has proven effective at distinguishing shock excitation from photoionization. The large extranuclear extent of strong forbidden-line emission relative to the Balmer lines (Colina et al. 2005; Monreal-Ibero et al. 2010; Rich et al. 2011) has uniquely identified shocks as the excitation mechanism in some ULIRGs. High forbidden-to-Balmer line ratios also appear to be common in the extranuclear regions of z ~ 2 galaxies mapped with infrared intensity field units (IFUs; Genzel et al. 2011; Law et al. 2007; Wright et al. 2010).

Previous studies have shown that broad line profiles are often associated with shock excitation in mergers (Rich et al. 2011). We improve upon these studies by resolving line profiles, using multiple component fitting, and examining emission-line ratios in velocity space. Since the next generation of optical IFUs such as the Multi-Unit Spectroscopic Explorer (Henault et al. 2003) and Keck Cosmic Web Imager (Martin et al. 2010) will be able to map galaxies in the optical with large fields of view, our approach demonstrates how to analyze these data. We argue that measuring variations in the forbidden-to-Balmer line flux ratio in the velocity coordinates may prove as useful as resolution in the spatial dimension for determining the excitation mechanism.

The main parts of this paper are two sets of figures. The first set illustrates the variation of the forbidden-to-Balmer line flux ratio on scales of approximately 60 km s⁻¹ spatially and 1–2 kpc spatially; it also compares the lines ratios to grids of photoionization models and shock models. The second set displays the emission-line profiles across 39 galaxies, selected from the IRAS 2 Jy survey (Murphy et al. 1996; Strauss et al. 1992, 1990) and known to be undergoing a galaxy merger. Section 2 presents the observations and explains the measurement procedure. The discussion is mostly qualitative, focusing on the trends observed during the progression of the merger. A companion paper (Soto et al. 2012) provides a quantitative analysis of the relationship between the gas excitation and gas kinematics. Throughout the paper we use a cosmology with Ω_m = 0.27, Ω_m = 0.73, and H_0 = 71 km s⁻¹ Mpc⁻¹.

2. DATA

2.1. Sample and Aperture Selection

Moderate-resolution spectra were obtained at the Keck Observatory with the Echellette Spectrograph and Imager (ESI;
Sheinis et al. (2002) under average seeing of 0′′.8. The observations and data reduction are described in Martin (2005, 2006), where the Na i λ5890, 96 interstellar absorption kinematics were measured previously and discussed for the 18 objects with published CO velocities. In the remaining 21 objects in the sample, redshifts were determined from the integrated Hα emission line. We calculated the flux error as a function of wavelength in each aperture by adding the rms error along the continuum away from the emission lines and the sky error in the spatial region outside of the detectable continuum.

The broad spectral bandpass covers recombination lines from H and He and the following strong forbidden lines: [S ii]λ,6717, 31, [N ii]λ,6548, 6584, [O i]λ,6300, 64, [O iii]λ,5007, and sometimes [O ii]λ,3727, 29 at lower signal-to-noise ratio. Dust-insensitive line ratios constructed from a subset of these line flux measurements are presented in this paper for the full sample of 39 galaxies.

Table 1 lists the name, merger stage, infrared luminosity, and redshift of each galaxy. The galaxies have IR luminosities LIR > 6 × 1011 L⊙, which identify them as ULIRGs and 60 μm flux > 1.94 Jy (Murphy et al. 1996). The redshift range from 0.043 to 0.15 corresponds to angular scales from 1.00 to 2.61 kpc arcsec⁻¹. The position angle of the 20″ long slit is also listed for each galaxy.

Figure 1 shows two examples of the spatial placement of apertures for galaxies in the full figure sets in Figures 2 and 3. The left panel shows an r-band image of each ULIRG from Murphy et al. (1996). The slit position and the apertures used to extract spectra are marked. In the middle panel, the same apertures are marked and numbered on a cutout of the two-dimensional (2D) spectrum near Hα and [N ii]. All spectral orders were spatially registered with the order containing Hα by cross correlation of the spatial continuum profile. The location of the brightest continuum emission defines the position of aperture 0; and the apertures are slightly separated (∼0′′1) to reduce correlations between adjacent spectra. Measurements of the Doppler shift, velocity dispersion, and excitation are more subtle but can be seen by comparing an unblended emission line to the diagnostic line ratios is challenging. The line profiles must be broad enough to blend with neighboring lines, coverage of one or more unblended lines like [O i] λ,6300 is essential.

2.2. Emission-line Fitting

In Figure 3, we show the observed emission-line profiles as a function of aperture and of line transition for the full galaxy sample. In this section, we describe example figures for the same two galaxies as in Figure 1. First, Figure 4 shows the Hα+[N ii] line profiles as a function of aperture position along the slit shown in Figure 1. Prominent spatial gradients in the ratio of [N ii] to Hα flux can be easily seen by scanning up and down the first column for each galaxy. Figure 4 illustrates the variation in the relative [N ii] to Hα strength along the slits shown in Figure 1. The ratio is very high in the extended, low surface brightness emission surrounding IRAS11095−0238. IRAS05246+0103 shows similar variation at the various positions coinciding with the few kpc regions around the nuclei. The variations in the velocity coordinate are more subtle but can be seen by comparing an unblended forbidden line, i.e., [O i] λ,6300 or [O iii] λ,5007, with the Hβ profile from the same aperture.

Next, in Figure 5 we show the line profiles for a single aperture as a function of line transition. In the IRAS11095−0238 spectrum, the broad, blue wing on the [O i] λ,6300 profile is clearly stronger (relative to the total line flux) than the wing on the Hβ profile. IRAS05246+0103 shows this broad feature as well in the measured transitions with Hβ being weaker. We note that in the spectral direction, quantifying these variations in the diagnostic line ratios is challenging. The line profiles must be moderately well resolved, e.g., FWHM of 60 km s⁻¹ for these echelle spectra. Because the Hα, [N ii], and [S ii] lines are often broad enough to blend with neighboring lines, coverage of one or more unblended lines like [O i] λ,6300 is essential.

### Table 1

| IRAS Name | Merger Class | \( \log_{10} \left( \frac{L_{IR}}{L_{\odot}} \right) \) | \( z \) | P.A. |
|-----------|-------------|-----------------|-----|-----|
| 001534+5454 | IIIb⁺ | 12.10 | 0.1116 | −22.0 |
| 00188−0856 | V | 12.33 | 0.1285 | −3.3 |
| 00262+4251 | IVa⁺ | 12.08 | 0.0972 | −14.1 |
| 01003−2238 | V⁺ | 12.25 | 0.1177 | 10.0 |
| 01298−0744 | IVb | 12.29 | 0.1362 | −89.3 |
| 03158+4227 | IVa⁺ | 12.55 | 0.1344 | −15.0 |
| 03551+0028 | IIIb | 12.48 | 0.1519 | 76.5 |
| 02546+1013 | IIIa⁺ | 12.05 | 0.0971 | 109.5 |
| 08030+5243 | IVb⁺ | 11.97 | 0.0835 | 0.0 |
| 08311−2459 | IVb⁺ | 12.40 | 0.1006 | 67.5 |
| 09111−1007 | IVa⁺ | 11.98 | 0.0542 | 73.5 |
| 09583+4714 | IIIa⁺ | 11.98 | 0.0859 | 124.0 |
| 10378+1109 | IVb | 12.23 | 0.1362 | 11.3 |
| 10494+4424 | IVb⁺ | 12.15 | 0.0923 | 25.0 |
| 10565+2448 | M⁺ | 11.98 | 0.0431 | 109.0 |
| 11095−0238 | IVb | 12.20 | 0.1065 | 10.0 |
| 11506+1331 | V | 12.27 | 0.1273 | 80.3 |
| 11598−0112 | IVb | 12.40 | 0.1507 | 130.0 |
| 12071−0444 | IVb⁺ | 12.31 | 0.2848 | 0.0 |
| 13451+1232 | IIIb | 12.27 | 0.1212 | 105.7 |
| 15130−1958 | IVb⁺ | 12.03 | 0.1094 | 116.0 |
| 15245+1019 | IIIb⁺ | 11.96 | 0.0755 | 127.8 |
| 15462−0405 | IVb | 12.16 | 0.1003 | 164.6 |
| 16900−0139 | IIIb | 12.48 | 0.1336 | 107.6 |
| 16474+3430 | IIIb | 12.12 | 0.1115 | 161.8 |
| 16487+5447 | IIIb | 12.12 | 0.1038 | 66.2 |
| 17028+5817 | IIIa | 12.11 | 0.1061 | 94.5 |
| 17208−0014 | IIIb⁺ | 12.38 | 0.0428 | 166.7 |
| 17574+0629 | IIIb⁺ | 12.10 | 0.1096 | 51.2 |
| 18368+3549 | IVa⁺ | 12.19 | 0.1162 | −31.0 |
| 18443+7433 | V⁺ | 12.23 | 0.1347 | 29.6 |
| 18470+3233 | IIIa⁺ | 12.02 | 0.0785 | 67.3 |
| 19297−0406 | IVb⁺ | 12.36 | 0.0857 | 149.5 |
| 19458+0944 | IVa⁺ | 12.31 | 0.1000 | 118.1 |
| 20046−0623 | IIIb⁺ | 12.02 | 0.0843 | 72.0 |
| 20087−0508 | IIIb⁺ | 12.39 | 0.1057 | 85.5 |
| 20414−1651 | IVb | 12.19 | 0.0869 | 12.6 |
| 23327+2913 | IIIa | 12.03 | 0.1075 | −4.3 |
| 23365+3604 | IIIb⁺ | 12.13 | 0.0645 | −19.5 |

Notes. Column 1: name. Column 2: merger classification (Veilleux et al. 2002). Column 3: IR luminosity (Murphy et al. 1996). Column 4: Redshift. Column 6: position angle of slit in degrees.

* Classifications estimated from r-band images and Murphy et al. (1996).
Our line-fitting procedure consists of fitting multiple Gaussian components simultaneously to eight transitions (Hα, [N II]λλ6548, 6583, [S II]λλ6717, 31, [O I]λ6300, Hβ, and [O III]λλ5007) with MPFIT in IDL. The fitting method ties the individual kinematic components of the emission-line profiles together, by requiring the same Doppler shift and velocity line width for all transitions. The amplitude of each component can vary independently. These requirements assume that the gas clouds that are identified by each kinematic component emit in all transitions. This method handles differing degrees of line blending by finding a solution suitable for all transitions. For some apertures, Hβ absorption contributed by the underlying stellar population significantly affects the line profile. We therefore include an Hβ absorption component in the fitting as well, but allow it to vary independently from those of the emission components (Soto & Martin 2010).

We determined the number of components to fit by comparing fitting residuals to the flux measurement errors. The fitting for each aperture starts with a single-component fit to all of the lines. If the residual flux exceeds the measurement error over a resolution element (FWHM > 70 km s$^{-1}$), we include another fit component. We maintain spatial continuity in the fits by using the results from adjacent apertures as the initial guess for subsequent apertures.

Two fitting components typically characterized the line profiles of all measured transitions well, but we often see variations in amplitude and line width as a function of aperture and fitting component. The fit of these multiple components allows us to identify separate kinematic components that vary in spatially different ways (Figure 4). The position–velocity diagrams in the right column of Figure 1 and the upper right panels in Figure 2 further illustrate these variations in the cases of IRAS11095−0238 and IRAS05246+0103. All of this suggests that multiple kinematic components at a fixed position often arise from physically distinct components of the galaxy and can be separated by this spatial and spectral deconstruction of the emission-line profiles. We include a full description of the fitted kinematic components in Table 2.

2.3. Integrated Apertures

We extract pseudo-integrated spectra to examine the impact of the spatial and kinematic structure seen in the spectral line ratios on spatially unresolved spectra. The integrated spectra employ a large aperture that encompasses all of the arcsecond scale sub-apertures in order to sum the flux per spectral pixel over the observed sections of the galaxies. We fit the resulting integrated line profiles using the technique described in Section 2.2.
Soto et al. (2012) compare the spectral components identified in these integrated spectra to the components in sub-apertures. Our analysis of the integrated spectra demonstrates when separate physical components, established on the basis of the spatially resolved spectra, can be recognized in velocity space in the integrated spectrum.

We use the integrated line fluxes for the individual galaxies in the mergers and classify their overall excitation type using line ratio comparisons (Kewley et al. 2006). Table 3 shows the result of these classifications. The H\textsc{ii} class comprises the largest fraction of the sample (43%) in the shows the classification of these integrated spectra, while LINER and Seyfert classes make up 18% and 12% of the sample. Galaxies with mixed classifications in the different diagnostic diagram make up the remaining 27% of the sample.

3. RESULTS

3.1. Line Ratios

Deblending the line profiles allows us to investigate the underlying excitation mechanism that is relevant for each kinematic component. In the standard BPT diagram, ratios of forbidden transitions to Balmer transitions ([N\textsc{ii}]/H\textalpha, [S\textsc{ii}]/H\textalpha, [O\textsc{i}]/H\textalpha, and [O\textsc{iii}]/H\beta) probe the energy of the associated ionizing radiation (Baldwin et al. 1981). High forbidden to Balmer line ratios exceeding the range possible for star
Figure 3. Line profiles for each measured transition (horizontal axis) as a function of aperture (vertical axis) for each ULIRG in the sample. Each cell is labeled with the transition and aperture number identified in Figure 2. The scales have been adjusted to illustrate the line profile in each transition. The red and blue lines identify the different Gaussian components from the resulting simultaneous fit. The dark green line represents the $H\beta$ absorption component. For the left column, only the components of the $H\alpha$ transition are displayed to minimize confusion; the $[N\,II]$ kinematics are the same as the other transitions, while the amplitudes can vary.

(A color version and the complete figure set (39 images) are available in the online journal.)

formation can imply the presence of either AGN (Kewley et al. 2006) or shocks (Allen et al. 2008).

In the right column of Figure 1 and the upper right panel of Figure 2, we present the kinematic components along with an indicator for the type of excitation that is most likely relevant. The top right panel of Figure 1 is an example of one of the more irregular kinematic patterns for the galaxy IRAS11095−0238. In this case the entire galaxy has shock-like excitation. The lower right panel of Figure 1 shows a different kinematic pattern the narrow $H\,II$-like emission in IRAS05246+0103 and broad shock-like emission closer to the nuclei.

### 3.2. Shock Models

Shock models predict the line ratios created by the shocks for a range of magnetic field strengths, densities, and shock velocities ($v_{sh}$; Allen et al. 2008). Here, we focus on magnetic field ranging from 1 to 100 $\mu$G for starburst galaxies (Thompson et al. 2006). The shock-only model with solar metallicity and electron density $n_e = 10$ cm$^{-3}$, overlapped with a large fraction of the measured line ratios. The line ratios fall into the region of the BPT diagram that more often suggests LINER-like excitation. If these measured line ratios can be attributed to shocks, the models suggest that the precursor to the shock is not a significant contributor to the ionization (Dopita & Sutherland 1995). Some of the measured line ratios fall just below the shock grid, but the effect of averaging over an $\sim 1$ kpc$^2$ can include contributions by $H\,II$ regions as well, moving the line ratio toward the $H\,II$ region of the diagram. The spread in the $[O\,I]/H\alpha$ ratio with $v_{sh}$ in these models (Figure 6) indicates that the $[O\,I]/H\alpha$ versus $[O\,III]/H\beta$ diagram is a more sensitive identifier of shocks and shock velocity. The $[S\,II]/H\alpha$ and $[N\,II]/H\alpha$ gridlines, on the other hand, pile up for gridlines with $v_{sh} > 250$ km s$^{-1}$.

In a different class of objects, line-emitting red galaxies, extended LINER-like emission is detected at extended radii as well, but post-asymptotic giant branch (AGB) stars are the suspected source of ionization (Yan & Blanton 2012). These post-AGB stars would make the largest relative contribution to the ULIRG spectra at large galactocentric radii because there is an increase in stellar age with radius (Soto & Martin 2010); the central regions are dominated by ongoing star formation. However, the ages of the stellar populations necessary to create this excitation are few Gyr, much larger than the $\sim 0.4$ Gyr implied by the measured stellar population ages. Furthermore, the scaling between $H\alpha$ luminosity and stellar mass from this form of excitation (Yan & Blanton 2012) implies an order of magnitude more stellar mass ($2 \times 10^{11} M_\odot$) than is found in these galaxies (Tacconi et al. 2002). We therefore conclude that LINER-like excitation in our ULIRG sample most likely results from shocks.

Having identified components of the emission beyond the range of ionization by $H\,II$ regions, we estimate $v_{sh}$ from the
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Figure 4. For the transitions Hα + [N ii], we show the line profile for all positions in IRAS11095−0238 (above) and IRAS05246+0103 (below). Left: for IRAS11095−0238, the line profile shows a clear variation from aperture to aperture. In the aperture −2.7 kpc from the r-band nucleus, the broad component (dashed) is blueshifted relative to the narrow (dotted) component. On the other side of the nucleus at 2.1 kpc from the center, the broad component is slightly redshifted relative to the narrow component. Right: in IRAS05246+0103 there is more than one nucleus (positions: 0.1 kpc and −10.8 kpc). A broad component can be seen in the line profile in each of them.

position of the component line ratios on the shock grids. We estimate errors in $v_{sh}$ from the position of the end of the error bar in each measurement, and using the difference in these velocities as the $v_{sh}$ error. We present these estimates on a per component basis in Table 4. The error in $v_{sh}$ is dominated by systematic errors from the uncertainty in model selection and the influence of a radiative precursor region on the emitted flux.

As with shock-only models, shock + precursor grids with $n_e = 10 \text{ cm}^{-3}$ cover a reasonable fraction of the measured line ratios, but we find that there is a small systematic offset of 25 km s$^{-1}$. Similarly, in models with $n_e = 0.1 \text{ cm}^{-3}$, we find a similar systematic offset with a slightly larger scatter.

### 3.3. Excitation Categories

When trying to characterize the underlying physical processes present in merging galaxies, many mechanisms are at work exciting the gas in the object which leads to the measured optical emission lines. The measured emission-line ratios span a range of values within the diagnostic diagrams making the interpretation difficult. We attempt to simplify the analysis by categorizing the measured components into two categories: “H II-like” and “shock-like.” We make this distinction by comparing a component’s emission-line ratios to the maximum ionization in the extreme starburst case (Kewley et al. 2006). Below this line, we define the line ratio as “H II-like;” above it, we define the line ratio as “shock-like,” since the spectral energy distribution of a star-forming region is not sufficient to create these emission ratios. Figure 6 displays where the shock models and diagnostic diagrams intersect, showing the tendency of these fast shock models to exhibit emission-line ratios in the region of the diagnostic diagram typically associated with photoionization by AGNs.

The clearest cases for grouping a component into “shock-like” or “H II-like” is when all three diagnostic measurements (log([O iii]/Hβ) versus log([N ii]/Hα), log([S ii]/Hα), and log([O i]/Hα)) agree, i.e., are below or above this extreme starburst line. In cases where the measures do not agree, we generally rely upon the sensitivity of the [O i] transition to determine the classification for a particular component. For cases where the errors in flux ratio are consistent with either case, we classify the component as “unclear.” For each galaxy, we present the emission-line ratios for each component on these diagrams in Figure 2.

### 4. LOCATION OF SHOCKED GAS

The categorization of emission into different excitation categories allows the identification of “shock-like” ratios beyond the nuclei of the galaxies. For the 38 galaxies that exhibit “shock-like” emission-line ratios in at least one of the components, the spatial position of the “shock-like” component lies 3 kpc from the nucleus. For 14 of the objects, “shock-like” emission also appears within 2 kpc of the nucleus. Only one galaxy shows exclusively “H II-like” emission—IRAS16474+3430.
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Figure 5. For a single aperture in IRAS11095−0238 (left) and IRAS05246+0103 (right), we present the line profiles for all analyzed transitions. Two components are required to fit the asymmetric line profiles evident in each transition. The two components used in the fits have the same kinematics for each transition.

Figure 6. Shock grids (Allen et al. 2008) are presented for a solar abundance with \( n_e = 10 \ \text{cm}^{-3} \). The yellow–orange lines are contours of constant shock velocity in \( \text{km s}^{-1} \). The cyan–blue lines are lines of constant magnetic field in \( \mu \text{G} \). Also included in the plots are the “extreme starburst lines” and the lines that indicate the distinction between Seyferts and LINERs. Larger forbidden to Balmer line ratios can indicate either a faster shock, or a larger contribution by an AGN. In Figure 2, we present these diagnostics along with the individual line ratios for each component in each galaxy.

The kinematic spatial variations along the slit suggest that some of these galaxies host gas disks, despite disturbance caused by the merger interaction. The smooth transition of Doppler shift from red to blue identifies the candidate disks, while the excitation categories indicate that gas with “shock-like” excitation shares the same kinematics. We define a “disk” in these cases as when the contiguous components with \( \sigma_v < 150 \ \text{km s}^{-1} \) cross the line \( v = 0 \ \text{km s}^{-1} \). We make an exception in the cases where two nuclei are present, as indicated by the presence of a second continuum peak. In these cases, the objects have motions associated with their interaction, so are allowed to have a velocity offset. Using these parameters, we find 12 systems with clear disks, presented in Figure 7 and described in Section 4.1.1. We include the measured rotation gradients in Table 5.

4.1. Evidence for Gas Disks
4.1.1. Individual Objects

IRAS00153+5454. Figure 2 shows two continuum sources, identifying it as a double-nucleus object with a separation of
Figure 7. In the above plot we show position–velocity diagrams for components with \( v_c < 200 \text{ km s}^{-1} \) for 12 objects with profiles most indicative of rotation. We identify nuclei based on the position of continuum sources in the 2D spectra, which are marked above the data points. In IRAS00153+5454, IRAS11095−0238, and IRAS15462−0406, the shocked components appear to be part of a rotating gas disk. IRAS05246+0103, IRAS08030+5243, IRAS09583+4714, and IRAS19297−0406 on the other hand present predominantly H\( \alpha \)-like emission in its gas disk. IRAS17208−0014 and IRAS18470+3233 show a mixture of H\( \alpha \) and shock, with the shock in the outer edges of the disk. IRAS11506+1331, IRAS18470+3233, and IRAS15245+1019 are double-nucleus objects with possibly multiple disks, and a large mixture of H\( \alpha \) and shock excitation.

Table 2

| IRAS        | Ap | Ex | \( r - r_{\text{ap}} \) (kpc) | Ap size (kpc) | \( v \) (kms\(^{-1}\)) | \( \sigma_c \) (kms\(^{-1}\)) | \( F_{\text{H} \alpha} \) (F \times 10\(^{-17}\)) | \( F_{[\text{N} \text{ii}]} \) (F \times 10\(^{-17}\)) | \( F_{[\text{S} \text{ii}]} \) (F \times 10\(^{-17}\)) | \( F_{[\text{O} \text{ii}]} \) (F \times 10\(^{-17}\)) | \( F_{[\text{O} \text{iii}]} \) (F \times 10\(^{-17}\)) |
|-------------|----|----|-------------------------------|--------------|---------------------------|-----------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| IRAS05246+0103 | 0 s | 0.30 | 19.5 ± 2.0 | 216 ± 2.4 | 29.9 ± 0.29 | 26.6 ± 0.29 | 24 ± 0.76 | 5.96 ± 0.27 | 3.7 ± 0.49 | 5 ± 0.6 |

Notes. Column 1: IRAS galaxy. Column 2: aperture number. Column 3: excitation classification; h denotes a component with H\( \alpha \)-like line ratios, s represents components with line ratios indicative of shock, u is an unclear component where the errors in the flux ratio make the measurement consistent with either interpretation. Column 4: distance of sampled region from associated nucleus in kpc. Column 5: size of the selected aperture in arcseconds. Column 6: line-of-sight velocity of fitted spectral component in km s\(^{-1}\). Column 7: velocity dispersion of fitted spectral component in km s\(^{-1}\). Column 8: flux of H\( \alpha \) emission in the fitted spectral component in units of 10\(^{-17}\) erg s\(^{-1}\) cm\(^{-2}\). Column 9: flux of [N\( \text{ii} \)] emission in the fitted spectral component in units of 10\(^{-17}\) erg s\(^{-1}\) cm\(^{-2}\). Column 10: flux of [S\( \text{ii} \)] emission in the fitted spectral component in units of 10\(^{-17}\) erg s\(^{-1}\) cm\(^{-2}\). Column 11: flux of [O\( \text{ii} \)] emission in the fitted spectral component in units of 10\(^{-17}\) erg s\(^{-1}\) cm\(^{-2}\). Column 12: flux of [O\( \text{iii} \)] emission in the fitted spectral component in units of 10\(^{-17}\) erg s\(^{-1}\) cm\(^{-2}\). Column 13: flux of [O\( \text{iii} \)] emission in the fitted spectral component in units of 10\(^{-17}\) erg s\(^{-1}\) cm\(^{-2}\).

\(~10\) kpc. The emission for the northern nucleus is dominated by “shock-like” emission, while a smaller shock region exists in the southern nucleus. The velocities in the northern nucleus may indicate rotation in a disk: IRAS01298−0744. The emission in this object extends to \(~12\) kpc from the continuum source. Rotation is evident in the central and northern regions of the disk (Figure 2), while the emission in the far south presents more of a flat rotation profile. Apertures 4 and 5 in Figure 3 show a peculiar emission component on the red side of the H\( \alpha \)+[N\( \text{ii} \)] line profile. This emission is not fit, since it does not clearly show up in any of the other transitions.

IRAS01358+4227. The narrow components are primarily “shock-like,” and only show a shallow rotation gradient in Figure 2. The morphology of the \( r \)-band image is consistent with a face on disk-like objects, which could explain the flat rotation curve.

IRAS05246+0103. This double-nucleus object is spatially extended by approximately 11 kpc, however they both appear to have extended gas disks. The extended emission is mostly dominated by “H\( \alpha \)-like” emission. The position–velocity plot (Figure 2) shows two disk-like rotation curves with broader emission closer to the nuclei. The narrow emission lines in these cases are more often H\( \alpha \)-like, but some components at the east side of the eastern nucleus have shock-like line ratios. In the line profile plots (Figure 3), apertures 4 and 6 show a good example of the simultaneous fitting decomposing a blended H\( \alpha \)+[N\( \text{ii} \)] profile.

IRAS08030+5243. One of the clearer examples of disk-associated rotation, which includes narrow “shock-like” emission. At the far ends of this rotation curve (Figure 2) in this object the Doppler shift turns around and approaches the systemic velocity. The central aperture in this case shows a double-peaked narrow emission profile (Figure 3).
Table 3
Integrated Spectral Classification

| IRAS Name | [NII]/Hα | [SII]/Hα | [OIII]/Hβ | Total |
|-----------|----------|----------|-----------|-------|
| 00153+5454 | C        | H/S      | L/S       | M     |
| 00153+5454 | C        | L        | L         |      |
| 00188+0856 | A        | T        | S         | S     |
| 00262+4251 | A        | T        | L         | T     |
| 01003+2238 | A        | S        | S         | S     |
| 01298−0744 | C        | T        | L         | L     |
| 03158+4227 | A        | T        | H         |      |
| 03521+0028 | X        | X        | X         | X     |
| 05246+0103 | C/A      | H        | T         | H     |
| 05246+0103 | C        | L        | T         | L     |
| 08030+5243 | C        | H        | H         | H     |
| 08311−2459 | X        | X        | X         | X     |
| 09111−1007 | C        | H        | H         | H     |
| 09583+4714 | A        | S        | S         | S     |
| 09583+4714 | H        | H        | H         | H     |
| 10378+1109 | A        | T        | L         | L     |
| 10494+4424 | C/A      | H        | S/L       | M     |
| 10565+2448 | C        | H        | H         | H     |
| 11095−0238 | C        | L        | L         | L     |
| 11506+1331 | C        | H        | H/S       | S     |
| 11506+1331 | C        | H        | H/S       | S     |
| 11598−0112 | C        | H        | H         | H     |
| 12071−0444 | A        | T        | S         | S     |
| 13451+1232 | A        | S        | S         | S     |
| 15130−1958 | A        | S        | S         | S     |
| 15245+1019 | C        | H        | H         | H     |
| 15245+1019 | A        | H        | S/L       | M     |
| 15462−0405 | C        | H        | T         | H     |
| 16090−0139 | C/A      | T        | L         | L     |
| 16474+3430 | C        | H        | H         | H     |
| 16474+3430 | C        | H        | H         | H     |
| 16487+5447 | C        | H        | S/L       | M     |
| 16487+5447 | A        | S/L      | S/L       | M     |
| 17028+5817 | H        | H        | H         | H     |
| 17028+5817 | C        | S/L      | S/L       | S/L   |
| 17208−0014 | C        | H        | H         | H     |
| 17574+0629 | H        | H        | H         | H     |
| 18368+3549 | A        | S/L      | S/L       | S/L   |
| 18443+7433 | A        | T        | L         | L     |
| 18470+3233 | C        | H        | H         | H     |
| 18470+3233 | C        | H        | L         | H/L   |
| 18470+3233 | C        | H        | H         | H     |
| 19297−0406 | C        | H        | H         | H     |
| 19458+0944 | C        | H        | L         | H/L   |
| 20046−0623 | C        | H        | H         | H     |
| 20087−0308 | A        | S/L      | S/L       | S/L   |
| 20414−1651 | C        | H        | H/S       | H     |
| 23327+2913 | A        | S/L      | S/L       | S/L   |
| 23365+3604 | C        | H        | H         | H     |

Notes. Column 1: IRAS name. Column 2: spectral classifications as defined in Kewley et al. (2006) with fluxes from the sum of both kinematic components in the spatially integrated measurements along the ESI long slit. These diagnostics come from the comparison of [NII]/Hα vs. [OIII]/Hβ. A refers to galaxies that exceed the maximum excitation possible from star formation alone suggesting a possible AGN. H refers to the regions below the empirical limit to the excitation by HII regions (Kauffmann et al. 2003a), and C refers to the region between these, where the integrated emission-line ratio is expected to be a combination of HII and AGN contributions. Column 3: spectral classifications as defined in Kewley et al. (2006) for the line ratios [SII]/Hα vs. [OIII]/Hβ. L refers to line ratios indicating LINER, and S refers to line ratios indicating a Seyfert galaxy. Column 4: spectral classifications as defined in Kewley et al. (2006) for the line ratios [OIII]/Hβ vs. [OII]/Hα. Column 5: the total classification determined by combination of the three diagnostic diagrams. The additional classification of M is included where a mix of all three classifications makes the class designation ambiguous.
indication that the merging disks may be nearly orthogonal or a multiple merger. The emission in this collision is dominated by "H\textsc{ii}-like" emission.

**IRAS18470+3233.** This object is a multiple merger. In Figure 2 the western galaxy in this merger hosts two emission features that present "disk-like" line profiles separated by a 150 km s$^{-1}$ offset. The eastern galaxy has a spatially large rotation profile, which includes shock ionization in the central 4 kpc.

**IRAS19297−0406.** This object presents rotation profiles in Figure 6 that extend to ±5 kpc and are mostly "H\textsc{ii}-like" in ionization. The whole rotation curve is offset from systemic, implying that there is a possible slight error in the used redshift.

**IRAS20046−0623.** The continuum profile in this object is flat along the spatial axis and extended over 8 kpc as can be seen in the 2D spectrum of Figure 2. There are no clear peaks in the continuum profile. The $r$-band image indicates that the two intersecting galaxies are nearly perpendicular. A rotation gradient is evident along the major axis of the sampled objects, while the minor axis shows little rotation.

### 4.1.2. Conclusions

Out of the entire sample of 39 ULIRGs, the 20 objects in Section 4.1.1 exhibit kinematics that suggest gas disks. Though in many cases the orientation of the gas disk with respect to the line of sight is not clear, these candidate gas disks have narrow emission lines with $\sigma \lesssim 150$ km s$^{-1}$ that vary smoothly in Doppler shift along the slit. Twelve objects with the clearest rotation profiles presented Figure 7 show strong gradients in Doppler shift along the slit. Those disks with shallow rotation gradient may simply be close to face-on, thereby decreasing the line of sight velocity. The remaining objects in the sample have either little evidence of an extended gas disk, broader emission features, or unclear spatial trends in the gas kinematics. Four objects out of the full sample (IRAS03521+0028, IRAS10378+1109, IRAS16090-0139, IRAS18368+3549) exhibit only less ordered motion that is not clearly part of a disk. We note that our selection of disks is incomplete due to the spatial coverage by the long slit. The slit position angle was selected to either sample multiple nuclei or sample an elongation in the $r$ band image of the object, so a misalignment with the major axis would interfere with the detection of a disk.

Spatially resolved emission line diagnostics allow us to examine the relationship between the presence of rotation and the spatial distribution of gas excitation. In the subsample of galaxies with the clearest evidence for a disk (Figure 7), two disks appear in some of the double nuclei objects, increasing the number of disks to consider to 15. IRAS05246+0103, IRAS19297−0406, IRAS09583+4714, IRAS15245+1019 and IRAS18470+3233 show disks that are strongly dominated by H\textsc{ii}-like excitation. In IRAS11095−0238, IRAS11506+1331 (both disks), IRAS15462−0405, and IRAS00153+5454 the rotating gas is dominated by shock-like excitation. The distribution of excitation in these objects places the H\textsc{ii}-like regions closer to nuclei, with shock-like excitation in the outer few kpc, with an exception for IRAS18470+3233. This H\textsc{ii}-centered distribution also appears in the shock-dominated disks, where just the central aperture is H\textsc{ii}-like, but the rest of the disk is dominated by shock-like excitation.

The sample included in this study chooses galaxies at various merger phases, which we can compare to the presence of a rotation profile in the position velocity diagrams. In the 12 clearest cases of rotation (Figure 7), 7 are in binaries, 1 is a multiple merger, and the remaining 4 are at a later single nucleus phase with extended diffuse emission. The number of early merger phase objects with clear disks suggest that a gas disk appears at early stages of the merger, and is then removed as the galaxies coalesce. This observation supports the interpretation that some shocks are triggered by the initial merger interaction.

There are at least 4 different possible origins of narrow shocked components of the emission line profiles. (1) In merger models (Cox et al. 2004), shocks occur as the gas disks collide. (2) Shocks also occur as gas that was previously removed via tidal stripping falls back into the galaxies. (3) Shocks can also be produced by the dissipation of energy injected by massive stars.
created in the burst of star formation. (4) Shock-like emission can also be produced by photoionization via aging post-AGB stars. The gas disks in this study appear more frequently in the earlier, binary stages of the merger, many of which present shock excitation in the disk. The presence of shocks in the early stages suggests that the merger interaction at this phase can trigger shocks, rather than only appearing after the galaxies have coalesced. Since we have identified more shocks in gas disks at the early merger stages, we suspect that further mapping of the kinematics will identify more gas disks. Future observations that employ integral field spectroscopy will allow a better analysis of the gas kinematics and excitation in concert with its spatial distribution along the merger sequence. By mapping the emission lines and the kinematics, we can better estimate the merger phase which leads to better understanding of the processes that create shocked gas disks.

5. SUMMARY

In this analysis of long-slit ESI data, we observed complex line profiles in the various line species used for the examination of emission-line excitation. The spectral resolution and signal to noise obtained with ESI allow detailed investigation of the underlying emission mechanisms. Spatial resolution along the long slit allows us to further understand the extended structure of these sources. By performing a simultaneous multicomponent fits to the Balmer and forbidden lines, we were able to identify shocked gas disks at early merger stages. These data are relevant for many investigative purposes such as informing model creation and examination of gas processes in the merging galaxies and strong star formation environments.

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Facility: Keck:II (ESI), Nickel

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Table 5

| IRAS Name | Edge Positions (kpc) | Rotation Grad (km s⁻¹ kpc⁻¹) |
|-----------|---------------------|-----------------------------|
| 00153+5454(a) | 10.3 | 2.1 |
| 00153+5454(b) | 11.9 | 10.5 |
| 01298+0744 | 10.6 | 3.1 |
| 03158+4227 | 6.7 | 2.0 |
| 05246+0103(a) | 5.8 | 5.6 |
| 05246+0103(b) | 13.1 | 1.0 |
| 08030+5243 | 3.6 | 73.8 |
| 08311+2459 | 4.1 | 24.9 |
| 09111+1007 | 4.2 | 11.6 |
| 09583+4714 | 5.3 | 22.6 |
| 10565+2448 | 4.4 | 0.7 |
| 11095+0238 | 5.2 | 11.3 |
| 11506+1331(a) | 8.5 | 9.1 |
| 11506+1331(b) | 4.8 | 15.6 |
| 11598+0112 | 5.2 | 23.6 |
| 15245+1019 | 6.6 | 11.3 |
| 15462+0405 | 5.6 | 12.5 |
| 16487+5447 | 8.3 | 15.8 |
| 17208+0014 | 4.6 | 32.4 |
| 18470+3232(a) | 4.8 | 11.1 |
| 18470+3232(b) | 15.7 | 12.8 |
| 19287+0406 | 6.4 | 19.8 |

Notes. Column 1: IRAS name. Columns 2 and 3: distance of the rotation profile edge from the continuum source in kpc. Columns 4 and 5: minimum and maximum velocities of rotation profile in km s⁻¹. Column 6: rotation gradient in km s⁻¹ kpc⁻¹.

a 08311+2459, 09583+4714, and 11598+0112 have a highly displaced Hα region not included in the description of the possible disk.