Limits to Ionization-parameter Mapping as a Diagnostic of HII Region Optical Depth

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Abstract

We employ ionization-parameter mapping (IPM) to infer the optical depth of H II regions in the northern half of M33. We construct [O III]λ5007/[O II]λ3727 and [O III]λ5007/[S II]λ6724 ratio maps from narrowband images continuum-subtracted in this way, from which we classify the H II regions by optical depth to ionizing radiation, based on their ionization structure. This method works relatively well in the low-metallicity regime, 12 + log(O/H) ≤ 8.4, where [O III]λλ4959, 5007 is strong. However, at higher metallicities, the method breaks down due to the strong dependence of the [O III]λλ4959, 5007 emission lines on the nebular temperature. Thus, although O^++ may be present in metal-rich H II regions, these commonly used emission lines do not serve as a useful indicator of its presence, and hence the O ionization state. In addition, IPM as a diagnostic of optical depth is limited by spatial resolution. We also report a region of highly excited [O III] extending over an area ~1 kpc across and [O III]λ5007 luminosity of 4.9 ± 1.5 × 10^48 erg s^-1, which is several times higher than the ionizing budget of any potential sources in this portion of the galaxy. Finally, this work introduces a new method for continuum subtraction of narrowband images based on the dispersion of pixels around the mode of the diffuse-light flux distribution. In addition to M33, we demonstrate the method on C III]λ1909 imaging of Haro 11, ESO 338-IG004, and Mrk 71.

Unified Astronomy Thesaurus concepts: Disk galaxies (391); Irregular galaxies (864); Starburst galaxies (1570); Emission line galaxies (459); Interstellar line emission (844); Nebulae (1095); Direct imaging (387); Radiative transfer (1335); Young massive clusters (2049); Star formation (1569); Astrostatistics distributions (1884)

Supporting material: animations, machine-readable table

1. Introduction

The nebular ionization parameter describes the ionizing photon density relative to gas density, and it is a fundamental diagnostic of radiation feedback in photoionized H II regions. In recent years, diagnostics of the ionization parameters such as [O III]λλ4959, 5007/[O II]λ3727, [S III]λλ9069, 9531, [O III]/Hβ, and [O III]/[S II] (Pellegrini et al. 2012; Zastrow et al. 2013; Keenan et al. 2017; Wang et al. 2019) have been used to evaluate the nebular optical depth to Lyman continuum (LyC) radiation in both individual H II regions and starburst galaxies. An especially compelling class of objects are the Green Pea galaxies (Cardamone et al. 2009), which are selected on the basis of their extreme ionization parameters in [O III]/Hβ. Confirming predictions (e.g., Jaskot & Oey 2013), the Green Peas have yielded the most consistent detections of LyC-emitting galaxies in the local universe (e.g., Izotov et al. 2016, 2018), and are therefore of vital interest to galaxy evolution and cosmic reionization. However, although we noted above a direct link between ionization parameter and LyC optical depth, the exact relationship between these these quantities is not well understood in these starbursts, due to complicating factors like gas morphology, composition, geometry, and density distributions, and also variations in ionizing spectral energy distributions (SEDs) from various candidate stellar populations and other ionizing sources. Nevertheless, the ionization parameter is an easily observed and widely used diagnostic of the nebular conditions in star-forming regions both near and far.

It is well known that [O III]λλ4959, 5007 emission drops precipitously at oxygen abundances 12 + log(O/H) > 8.4 (e.g., Kewley & Dopita 2002). For example, the well-known abundance diagnostic $R23 \equiv ([O II]λ3727 + [O III]λλ4959, 5007)/Hβ$ increases monotonically to maximum values around this metallicity. This is caused by strong sensitivity of this line to the electron temperature, which decreases at higher oxygen abundance. Therefore, using line ratios that rely on [O III]λλ4959, 5007 as a diagnostic of ionization parameter will be unreliable at metallicities where these lines are weak.

In this work, we use the H II regions of the Local Group galaxy M33 to explore the regime where [O III]λλ4959, 5007 is not, effective as a diagnostic of ionization parameter for the purpose of evaluating radiation feedback and LyC escape. In order to generate the emission-line images required for this analysis, it is necessary to carry out continuum subtraction, and we also further explore this process.

2. Observations of M33

The north half of M33 was observed with the MOSAIC-1.1 imaging camera at the Mayall 4 m telescope, Kitt Peak National Observatory, on 2011 October 28–29. We used the narrowband filters for [O II]λ3727 (“O2” FWHM 50 Å), [O III]λλ5007 (“O3,” FWHM 50 Å), and [S II]λ6724 (“ha16,” FWHM 81 Å) for line imaging. For the continuum, we used broadband filters BATC454 (~4320–4700 Å) and BATC705 (~6950–7920 Å) for continuum subtraction of [O II] and [O III], and of Hα and [S II], respectively. The continuum filters are used with the kind permission of R. Windhorst. We also used archive Hα observations obtained in 2001 with the same setup by Massey et al. (2007). There were 6 × 1400 s, 4 × 600 s, 5 × 600 s + 1 × 900 s, and 5 × 300 s exposures in [O II], [O III], [S II], and Hα, respectively, and 5 × 500 s and...
Notes.

2 × 1050 s + 3 × 550 s exposures in the blue and red continuum filters, respectively. All observations were dithered to cover the gaps between the eight MOSAIC CCD chips. After being median-combined, the images have a variety of residual defects, including gaps between the eight MOSAIC CCD chips. After being median-

The values in Table 1, columns (6)–(9), are the underreddened fluxes (F_{obs}) that we adopt for calibration.

We apply rectangular apertures corresponding to the reported slit width at the position for each object given in Table 1 of Toribio San Cipriano et al. (2016). We use the photutils aperture photometry routine in astropy to obtain the photometry. To account for positional inaccuracies arising from atmospheric seeing, we offset the slit positions by a normally distributed random variable with standard deviation equal to the seeing in pixels. We average over 20 such randomly offset apertures for the integrated photometry. The computed ratios are then used together with the calibrated flux ratios derived from the data of Toribio San Cipriano et al. (2016) to determine the flux calibration, using the H{\alpha}/H{\beta} ratio of 2.86.

3. Continuum Subtraction

Narrowband imaging data include flux from both line emission and diffuse stellar continuum. To isolate the line flux, an offline image containing only the continuum is usually subtracted. Due to differing filter transmissions and variation in the continuum spectral energy distribution (SED), the continuum image must be scaled before subtraction, and determining the scale factor is nontrivial. Hayes et al. (2009) and James et al. (2016) have utilized stellar population synthesis modeling that computes spatially varying scale factors on a pixel-by-pixel basis. These methods are model dependent, and Hayes et al. (2009) discuss their advantages and pitfalls in detail.

In this work, we focus on empirical methods that compute a single characteristic scale factor for a large region or an entire image. Keenan et al. (2017) describe a method where a single optimal scale factor is found for such a region. They note a slope change in the mode of the pixel values versus scale factor for the continuum-subtracted images. Keenan et al. (2017) show that this transition results when the scale factor induces any oversubtraction. At small values of the scale factor, the mode of the pixel-value histogram is determined by the lowest-value pixels. The change in flux for these pixels is small as the scale factor varies, hence the slope of mode versus scale factor is shallow. At higher values of the scale factor, the mode is dominated by oversubtracted pixels. As the scale factor increases, the first pixels to become oversubtracted are the brightest ones, and their flux has a strong dependence on scale factor. Thus, the slope of the mode versus scale factor is steeper in the oversubtracted regime (see Keenan et al. 2017 for more details).

Hong et al. (2014) present a method that similarly identifies the transition to oversubtraction, but based on the skewness of the pixel-value histogram as a function of the scale factor. The above two methods have been shown to work well for images where there are a significant number of continuum-dominated pixels. However, we still encountered some difficulties in adequately constraining the best scale factors. In particular, the slope transition reported by Keenan et al. (2017) can be hard to discern. There can be multiple slope changes and oscillatory behavior in the mode, as Keenan et al. (2017) indicate. The exact point of transition is therefore uncertain. Similarly, the method used by Hong et al. (2014) relies on computing the second derivative of the skewness with respect to the scale factor.
Estimating this derivative accurately requires a very fine search through the scale factor space. The Appendix demonstrates the functionality of these two methods (Figures 14, 16, and 18). In this paper, we therefore propose a revised method that uses the mode to obtain the optimal scale factor, which can provide a narrower confidence interval while also reducing the computing power needed.

3.1. Revised Mode Method to Identify Scale Factor

The line emission represents an excess signal over the continuum; hence, the pixel-value distributions will have a tail to positive values dominated by the real signal. Since we are interested in identifying the diffuse background to carry out the continuum subtraction, we therefore employ a $3\sigma$ filter from the scipy library on the line image. The routine computes the mean and standard deviation $\sigma$ of the data, then rejects any data points that are $>3\sigma$ from the mean. The mean and standard deviation are recomputed and the filtering is done again. This iterative process is continued until there are no more rejections. At each scale factor, we first subtract the scaled continuum from the line image, then invoke the $3\sigma$ filter on the subtracted image. This removes much of the real signal, leaving a residual histogram that is more dominated by the diffuse continuum signal. The resulting pixel-value distribution is better suited for the purpose of identifying the optimal continuum-image scale factor.

Similar to Hong et al. (2014), we observe a transition in the skewness of the pixel histogram as the scale factor is increased. Figure 1 shows how the shape of the pixel-value distribution changes as the scale factor is varied. At low scale factors (Figure 1(a)), the image is undersubtracted. The distribution for the subtracted image resembles the initial flux distribution, where pixels with high continuum values contribute to high-value bins. As a result, the histogram is skewed to the right.

As the scale factor is increased, the flux distribution in the line image approaches the flux distribution in the scaled offline image.

Ideally, at this point of optimal continuum subtraction, the background flux should be zero. This is characterized by the mode of the pixel histogram being zero. However, this is not always the case, since the sky may have a different SED compared to the diffuse stellar continuum. This issue is particularly relevant for ground-based observations where the sky background is significant. Once the scale factor has been set by subtracting the stellar emission, the residual sky background can be eliminated while performing aperture photometry, as we have done for the flux measurements in Tables 1 and 2.

On further increasing the scale factor, the pixels with strong continuum flux now contribute to the negative bins as they are the first ones to become oversubtracted. The spread increases in the negative direction, skewing the histogram to the left (Figure 1(c)). This is a reversal of the behavior seen earlier, and it corresponds to the transition in skewness reported by Hong et al. (2014). It should be noted that the negative tail is less statistically “heavy” compared to the positive tail, due to the continued presence of pixels with emission-line flux. Hong et al. (2014) demonstrate the same effect as a slight positive bias to the skew at the transition point.

At the optimal scale factor, the number of background pixels is therefore maximized in the modal bin, as shown in Figure 2. Due to the background noise, the optimally subtracted histogram will still have some spread around the mode. We therefore also consider the total number of pixels in the bins adjacent to the modal bin. This is also helpful if the mode falls on the boundary between two bins. Using all three bins provides some robustness against such cases. Thus, the optimal scale factor is that which maximizes $\left(f_0 + f_1 + f_2\right)/N$, where $f_0$ is the number of pixels in the modal bin; $f_1$ and $f_2$ are the number of pixels in the pre-modal and post-modal bins, respectively; and $N$ is the total number of pixels in the image, after applying the $3\sigma$ filter. If the modal bin is the first or last bin, then $f_1$ or $f_2$ are accordingly assumed to be zero. The value of $N$ changes with the scale factor due to the $3\sigma$ filter. Initially, the brightest pixels get rejected, but at the correct scale factor, the flux from these correctly subtracted pixels falls within the $3\sigma$ limit. The chosen metric, $\left(f_0 + f_1 + f_2\right)/N$, is computed using only the pixel histogram at the current scale factor. The methods of Keenan et al. (2017) and Hong et al. (2014) require the histograms at adjacent values of the scale factor to compute the slope of the mode, or the second derivative of skewness that requires finer sampling to reduce the error bound.

A jagged or scalloped pattern is apparent in Figure 2 as the scale factor is increased. The pattern arises due to the binning criteria chosen for the modal bin fraction. In particular, it is due to the choice of using only the three modal bins to measure of the peak of the pixel distribution. In the case of highly skewed histograms, the peak is inadequately sampled by only three bins, and small changes in the pixel distribution are amplified, giving rise to the jagged pattern seen. This behavior can be
Table 2

H II Regions in Northern M33

| Object  | R.A. (J2000) | Decl. (J2000) | 12+log(O/H)$^a$ | Opacity$^b$ | Hβ$^c$ | Hβ err$^c$ | [O II]$^d$ | [O II] err$^c$ | [O III]$^d$ | [O III] err$^c$ | [S II]$^d$ | [S II] err$^c$ |
|---------|--------------|--------------|------------------|-------------|--------|-----------|---------|-----------|---------|-----------|---------|-----------|
| BCLMP 616 | 1h32m54.38 s | 30d50m28.8 s | 8.226$^{+0.006}_{-0.005}$ | 1 | 14.6 | 0.22 | 7.61 | 0.20 | 2.03 | 0.46 | 2.97 | 0.40 |
| LHK2017 54 | 1h32m56.28 s | 30d40m36.7 s | 8.383$^{+0.004}_{-0.003}$ | 4 | 23.6 | 3.9 | 13.1 | 1.0 | 5.2 | 2.6 | 13.1 | 4.5 |
| BCLMP 289 | 1h32m57.5 s | 30d44m27 s | 8.209$^{+0.003}_{-0.003}$ | 3 | 57.4 | 19 | 31.4 | 0.83 | 66.4 | 4.6 | 18.1 | 21 |
| CPSDP 67 | 1h32m59.2 s | 30d41m20.8 s | 8.518$^{+0.005}_{-0.005}$ | 1 | 10.1 | 1.4 | 4.91 | 0.16 | 2.65 | 1.4 | 3.64 | 2.0 |
| BCLMP 285 | 1h33m02.8 s | 30d41m08.1 s | 8.238$^{+0.003}_{-0.003}$ | 1 | 13.1 | 0.25 | 5.95 | 0.04 | 4.63 | 0.27 | 2.13 | 0.42 |

Notes.

$^a$ From Lin et al. (2017).

$^b$ 1 = optically thick, 2 = blister, 3 = optically thin, 4 = shock, 5 = indeterminate.

$^c$ Luminosities given in $10^{36}$ erg s$^{-1}$.

Data for first five objects are shown here. The online journal has data for all 108 objects in a machine-readable format.

(This table is available in its entirety in machine-readable form.)
smoothed by modifying the criterion to include more bins, or by finer sampling of the pixel distribution by increasing the number of bins. Finer sampling has an added computational cost. For the purposes of identifying the globally optimal scale factor from a symmetric histogram, the chosen metric works well and is unaffected by the local variations due to skewed histograms. The Appendix demonstrates this method, with comparisons to the Keenan et al. (2017) and Hong et al. (2014) methods (Figures 14, 16, and 18).

We caution that the modal bin maximization works to subtract the dominant background component in the image, regardless of whether it is diffuse starlight, sky emission, or diffuse nebular emission. Thus, if the goal is to subtract diffuse starlight, then that component should constitute a significant fraction of the total pixel population. For example, if sky pixels dominate the variance, then the algorithm produces an undersubtracted image relative to diffuse starlight. This can be caused by two effects. First, if sky emission dominates the flux of the background pixels, then the algorithm identifies the optimal scale factor for the sky background. This is illustrated in the Appendix. Similarly, if the random variance of the sky pixels is high in images with low signal to noise, then the large variance makes the reduced spread of the stellar continuum pixels harder to detect. This can be explained as follows: the unsubtracted line image has a certain variance arising from the true signal, which is gradually subtracted out by increasing the scale factor. At the same time, we introduce additional variance through the random noise of the sky pixels, which increases on increasing the scale factor. If the signal-to-noise ratio (S/N) is low, the reduction in variance of diffuse starlight is drowned out by the noise that we introduce. The spread is minimized at a lower scale factor, resulting in an undersubtracted image. We address this issue in Section 3.2 and the Appendix.

On the other hand, the presence of widespread diffuse line emission will also bias the pixel-value histogram and the spread toward higher values. Contamination of pure continuum pixels with diffuse line emission therefore also inflates the variance of continuum pixels. The algorithm proposed above overcompensates for the larger spread, resulting in a scale factor greater than optimum. This is mitigated by ensuring the presence of pure continuum pixels in the image. Therefore, prior knowledge about the emission region characteristics is required. In short, the background must be dominated by diffuse starlight pixels in order for these statistical methods to identify the optimal scale factor to subtract this background component. See Hong et al. (2014) for a discussion on how the various background compositions affect these continuum-subtraction methods.

3.2. Application of the Method

Like most spiral galaxies, M33 has a strong color gradient in its diffuse starlight, implying that the scale factor for subtracting this component will vary spatially. We therefore define five regions using elliptical isophotes (Figure 3), which are are chosen by visual inspection of the approximate stellar surface brightness. Region 0, the galactic center, is dominated by resolved sources and does not have many background pixels. When presented with an image like this, our algorithm tends to produce oversubtracted images since there is not enough background to determine the correct scale factor. The opposite holds for Region 4, which is dominated by sky pixels and relatively lacking in diffuse starlight. Sky-dominated images tend to undersubtract diffuse starlight when we apply our method, as described in Section 3.1. Regions 1, 2, and 3 have a good mix of emission, continuum, and background pixels, so our method works well for such regions.

Due to the different characteristics of the pixel populations of Regions 0 and 4, we assign the scale factors for Regions 0 and 4 by setting the modes of their continuum-subtracted pixel values equal to the modes for Regions 1 and 3, respectively.

In our pipeline, we first employ the 3σ filtering described above to the emission-line image. The pixels with the strongest fluxes are rejected by the filter. Next, we generate the pixel-value histogram of the continuum-subtracted image. The bin width is chosen following Sturges (1926): the number of bins \( n \approx 1 + \log_2 N \), where \( N \) is the total number of pixels. For our images, this value is 22–25 bins, depending on the region. The modal bin is identified, and the modal bin fraction is calculated as described earlier in Section 3.1. The exact value of mode \( M \) can be calculated by taking the intersection of two lines that linearly interpolate the data in the modal bin:

\[
M = L + \frac{f_0 - f_1}{2f_0 - f_1 - f_2} \times h, \tag{2}
\]

where \( L \) is the lower limit of the modal bin, and \( h \) is the bin width. This exact value is needed to set the scale factors for Regions 0 and 4. An animation of the continuum-subtraction process (Figure 4) is available. Table 2 gives our narrowband fluxes for the objects, with errors estimated by computing the median background around each object during aperture photometry. We confirmed the H\(\alpha\) luminosities of three giant H II regions: NGC 604, NGC 595, and IC 131 with the values given by Relaño & Kennicutt (2009).

To further test our new method of continuum subtraction, we also apply it to C III \( \lambda 1909 \) narrowband imaging of three starburst galaxies, Haro 11 (Micheva et al. 2020), ESO338-IG04, and Mrk 71. Whereas M33 has a strong color gradient and many resolved individual stars, these more distant galaxies are dominated by more uniform, diffuse starlight. These examples also have very faint line emission compared to the M33 data. We find that our new continuum-subtraction methods...
technique works well on these galaxies. The results are shown in the Appendix.

4. Ionization-parameter Mapping

We generate line ratio maps for \([\text{O III}] / \text{[O II]}\) and \([\text{O III}] / \text{[S II]}\) as described by Keenan et al. (2017) and Pellegrini et al. (2012) to evaluate the optical depth of photoionized H II regions by ionization-parameter mapping (IPM). IPM is most directly applied to distinct objects, and significant diffuse continuum can mask the signal from individual H II regions. Unsharp masking allows us to locally remove the average diffuse ionized gas emission over a given length scale. This allows for an amplification in the signal for optically thin nebulae, where the low-ionization emission may be dominated by diffuse ambient emission. The residual presence of field stars affects the median smoothing, so we first carry out a bilinear interpolation over these across regions 3 times the stellar point spread function (PSF). We then mask any emission with intensity greater than 30 counts \((5.8 \times 10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \text{px}^{-1})\). This is approximately the saturation level of the detector. We median filter the remaining emission over a length scale 30× the stellar PSF, corresponding to 83.1 pixels. Finally, we subtract that medianed image from the original data, smoothed to the seeing to improve S/N.

Following Pellegrini et al. (2012), we classify the M33 H II regions into five classes: (0) indeterminate, (1) optically thick, (2) blister, (3) optically thin, and (4) shocked, based on the ionization structure in the halos of individual regions. Objects are considered optically thick if \([\text{O II]}\) and/or \([\text{S II]}\) dominates over at least two-thirds of the circumference in projection. Blister and optically thin H II regions are those with the low-ionization species dominating over one-third to two-thirds; and less than one-third of the circumference, respectively. Shocked nebulae show an ionization structure that is unlikely to have
resulted from photoionization alone, with a pocket of low-ionization species on the interior surrounded by [O III] on the outside. Objects are categorized as “indeterminate” due to poor S/N, incomplete data, or abnormal ionization morphology.

Our classifications are given in Table 2 for our sample of 108 objects, and are based on consideration of both [O III]/[S II] and [O III]/[O II] ratio maps. The object locations in the disk of M33 are shown in Figure 5. We present examples of categories 1–4 in Figures 6 to 9. These figures show the [O III]/[S II] and [O III]/[O II] ratio map for these representative objects. Similar images for all the objects in our sample are provided in the interactive version of Figure 10 below.

Figure 6 shows ratio maps for BCLMP 668, an optically thick nebula. As evidenced by Figures 6(b) and (c), this object shows a classic, Strömgren sphere structure, with the low-ionization envelope completely surrounding the highly ionized core. The emission from [O III] is relatively low throughout.

Figure 7 shows ratio maps for BCLMP 650, a blister object. In Figures 7(b) and (c), we see that the envelope of the low-ionization species [O II] and [S II] extends about halfway around the H II region in projection. There is a break to the west (upper portion in the image), where [O III] dominates, allowing the escape of ionizing radiation.

IC 132 (Figure 8) is an optically thin H II region that is extremely bright in [O III]. Figure 8(b) shows that the ratio of [O III]/[S II]3727 is > 1 over the entire visible extent of the object. The ionization structure in Figure 8(b) is similar to that found by López-Hernández et al. (2013) for this object. Comparing Figure 8(c) with other objects demonstrates how the [O III]/[S II]6724 morphology changes dramatically for optically thick versus thin regions.

The morphology of BCLMP 667 (Figure 9) shows the lower-ionization species dominating along the inside curve of this object, which is the opposite of what is expected for photoionization from a source driving the shell-like nebular morphology. We therefore classify this as a shock-ionized object.

4.1. Metallicity Dependence of IPM

Figure 10(a) shows [O III]/[O II] excitation vs. 12 + log(O/H), with optical depth class shown by the symbol colors. We have used data from Lin et al. (2017) for the values of 12 + log(O/H) for the H II regions in our sample (Table 2). As expected, Figure 10(a) shows a strong anticorrelation between optical depth and [O III]/[O II] ratio. However, there is also a clear trend with metallicity, and there are no objects classified as optically thin (as opposed to blister) having 12 + log(O/H) > 8.25.

The strength of the [O III]λ5007 line exhibits a strong, nonlinear relationship with the O abundance: it gets stronger with increasing metallicity in the metal-poor regime, but at higher metallicities, the greater abundance of metals cools the nebula, rendering it unable to collisionally excite [O III] in the visible-wavelength transitions. Thus, fine-structure lines in the infrared dominate the [O III] emission at higher 12 + log(O/H). Bright-line abundance indices such as $R_{23} = ([\text{O III}]\lambda3727 + [\text{O III}]\lambda4959, 5007)/\lambda3300$ and O3N2 = log($[\text{O III}]\lambda5007/\lambda3300$) are based on this principle, and are thus maximized in the interval 12 + log(O/H) = 8.0 to 8.5, dropping off steeply at higher values (e.g., Yip et al. 2007; Kewley & Dopita 2002). For our sample, Lin et al. (2017) derive the values of 12 + log(O/H) using the bright-line indices O3N2, N2 = log([N II]6583/HO) (e.g., Marino et al. 2013) as well as direct modeling of the electron temperature $T_e$ with a majority derived using methods reliant on the [O III]λ5007 emission line. We caution that H II structural evolution effects can shift strong line ratios like N2 by more than an order of magnitude (Pellegrini et al. 2020); however, the dominant trends with metallicity are well established.

Since we utilize the [O III]/[O II] and [O III]/[S II] ratios as a tracer for degree of ionization, the method of IPM used here is therefore also sensitive to the metallicity. The optical [O III] lines are weak at higher metallicity even though the O$^+$ ion may still be prevalent, and therefore the efficacy of IPM is reduced in this regime. Thus, some of the optically thick objects may be misclassified on account of [O III]/[S II] and [O III]/[O II] being reduced at higher abundances.

As seen in the Large and Small Magellanic Clouds (LMC and SMC), the most luminous H II regions are also the most likely to be optically thin, including blister objects (Pellegrini et al. 2012). This trend is also seen in our sample in Figure 11, which shows the frequency of optically thin and blister H II regions as a function of H o luminosity for objects having 12 + log(O/H) < 8.4. In Figure 10(b), we see that the most optically thin objects are tightly clustered at the lowest metallicities. Luminous H II regions with $L(H_o) > 10^{38}$ erg s$^{-1}$ at moderate metallicities of 12 + log(O/H) = 8.3 or 8.4 are mostly classified as optically thick, while the opposite is true at lower metallicity. This further supports the likelihood that some of the higher-metallicity, high-luminosity objects classified as optically thick are actually optically thin.

On the other hand, a real trend in increased frequencies of optically thin nebulae must also exist for metal-poor environments. Dust content decreases with metallicity, thereby decreasing the opacity to the Lyman continuum. Also, larger star clusters generating luminous H II regions tend to be more prevalent at lower metallicity, increasing the likelihood of powering objects with the earliest O stars, and enhancing the likelihood of optically thin H II regions. Metal-poor OB atmospheres also tend to be hotter than at solar metallicity (e.g., Maeder & Meynet 2001; Martins & Palacios 2021), driving higher nebular ionization parameters. Thus, without detailed modeling of the individual objects, it is impossible to clarify the locus of optically thin objects in Figure 10, but the IPM classifications in Table 2 likely significantly underestimate the frequency of optically thin nebulae.
The classifications are also dependent on the spatial resolution and depth of the ratio maps. Comparing Figure 11 with the results of Pellegrini et al. (2012) for the LMC and SMC, the frequency of optically thin objects is much lower, about a factor of 2 at \( L(\text{H}\alpha) \sim 10^{38} \text{ erg s}^{-1} \). There is no reason to believe that the properties of the interstellar medium (ISM) of M33 are substantially different than in these galaxies, and so most likely our classifications are affected by the lower spatial resolution of the M33 imaging data (22 pc in the smoothed images) relative to the imaging of the Magellanic Clouds (1.4 pc). Given the qualitative similarity of the results from these two studies, the systematic errors generated by the resolution effects do not substantively change the observed trend in Figure 11. However, we caution that absolute interpretation of optical depths is much less reliable.

We therefore conclude that IPM based on \([\text{O III}]/[\text{O II}]\) or \([\text{O III}]/[\text{S II}]\) is useful only at lower metallicities, \(12 + \log(O/\text{H}) \lesssim 8.4\), and it is also dependent on spatial resolution. Other
Figure 10. [O III]λ5007/[O II]λ3727 (a) and Hα luminosity (b) vs. oxygen abundance. Symbol type and color show optical depth classifications. Objects classified as optically thin and blister have higher [O III]/[O II] values, which is a function of metallicity. Median measurement errors for [O III]/[O II], log L(Hα), and 12 + log(O/H) are 0.06 dex, 0.018 dex, and 0.004 dex. Systematic errors are on the order of 20% for [O III]/[O II] and L(Hα), and 0.18 dex for 12 + log(O/H). An interactive version of panel (b) is available. Users can: (i) Filter the objects by log([O III]/[O II]) by means of a slider. (ii) Select an object by clicking on the symbols or in a dropdown list to view the corresponding ratio maps used for classification as shown in Figures 6–9. Both monochrome and color images are available. (iii) Select the different optical depth categories in the legend to plot only objects in the selected categories. (iv) Hover with a mouse pointer on the symbols to view the ID, metallicity, and [O III]/[O II] value for each object.

Figure 11. Fraction of optically thin H II regions as a function of luminosity for 12 + log(O/H) < 8.4. Luminosities of the sample objects range from log L(Hα) = 36.7 to 39.7; thus, the frequencies in bins with log L(Hα) < 37.5 = 0. There are no objects in our sample that have log L(Hα) in the range 38.8 to 39.2.

Figure 12. Unsmoothed [O III]/[O II] ratio map. The kiloparsec-sized patch is marked. The location of unusually bright GMCs reported by Bigiel et al. (2010) is marked with a red X.
Figure 13. Histograms showing undersubtracted, optimally subtracted, and oversubtracted images of Haro 11. Knots A, B, and C are labeled in the top panel. These illustrate the transition in skewness and the tails of the histograms. An animated version of the continuum-subtraction process, showing a step-by-step increase in the scale factor from 0 to 2, is available. The video duration is 20 s.

(An animation of this figure is available.)
diagnostic lines can extend the use of IPM. For example, Zastrow et al. (2013) have similarly used [S III]λ9069/[S II]λ6724 ratio maps to identify Lyman continuum escape. In general, the underlying principle remains the same: to reveal the nebular ionization structure by differentiating the high- versus low-ionization zones.

4.2. A Kiloparsec-sized Patch of Elevated [O III]

In general, the [O III]λ5007/[O II]λ3727 ratio in the diffuse ISM is low, <0.4, and largely invariant. However, in a region bounded approximately by R.A. ∼1°33′40″ to 1°34′20″ and decl. ∼−30°53′ to 30°59′, we observe a large-scale, bilobed patch of diffuse emission where the [O III]λ5007/[O II]λ3727 ratio is ∼0.6, significantly greater than the background (Figure 12). This patch corresponds to an area ∼9′ × 3.5′, implying a structure with dimensions on the order of ∼1 kpc for the M33 distance of 840 kpc (Freedman et al. 1991). The integrated [O III]λ5007 luminosity of the diffuse patch, excluding other H II regions in the vicinity, is (∼4.9 ± 1.5) × 10^38 erg s^−1. Such a large-scale region of elevated ionization is unusual and difficult to explain.

There is an optically thin H II region, BCLMP 637, at the center of this patch of excited gas. BCLMP 637 is one of the most highly ionized objects in our sample, with an [O III] λ5007/[O II]λ3727 ratio of ∼−4. Its ionization is apparently dominated by [NM2011] J013350.71+305636.7 (Neugent & Massey 2011), a WN3 star. We evaluate whether this WN3 star is responsible for photoionizing the large, excited patch in what follows.

From aperture photometry, we find that the observed [O III] λ5007 luminosity of BCLMP 637 is ∼(1.38 ± 0.08) × 10^38 erg s^−1, about 4× less than that of the large patch. The Hα luminosity of BCLMP 637 is (6.75 ± 0.62) × 10^37 erg s^−1, corresponding to Q(Hα) ∼ 5 × 10^39 s^−1. We compare this to the PoWR WNE stellar models at LMC metallicity by Todt et al. (2015) and find that this value is roughly an order of magnitude higher than that predicted by the brightest models. In particular, the LMC WNE PoWR models 10–17, 09–16, and 13–21 predict M_V in the range −4.8 to −5.0 for an early-type Wolf-Rayet (WR) star, which agrees with M_V of −4.9 for [NM2011] J013350.71+305636.7 (Neugent & Massey 2011). The ionizing photon flux predicted by these models is in the range 1.1–1.3 × 10^50 photons s^−1, which is much less than the Q(Hα) required to ionize even BCLMP 637. Thus, additional ionizing OB stars are likely present in the nebula. However, there is no further evidence suggesting an unusual stellar population in this object that can be responsible for also ionizing the large, extended patch of elevated ionization.

Thus we also consider candidate high-mass X-ray binaries (HMXBs) within the patch from the X-ray survey of M33 by Pietsch et al. (2004). We examine two sources: [PMH2004] 192 and [PMH2004] 229. Extrapolating the reported X-ray fluxes in the 0.2–4.5 keV band from Pietsch et al. (2004) with typical HMXB power-law indices of 1.5–2.5 results in ionizing photon emission rates Q(Hα) on the order of 10^46 s^−1. Again, this value of Q(Hα) is orders of magnitude below the required 10^39 s^−1 to explain the origin of the elevated excitation.

Interestingly, Bigiel et al. (2010) report the existence of unusually hot and bright giant molecular clouds (GMCs) adjacent to this high-ionization patch, with a lower inferred CO-to-H_2 conversion factor. These GMCs are located between the two lobes, slightly south of center (Figure 12). This suggests that the elevated ionization is indeed real and physically associated with M33, and that the source responsible for exciting the diffuse [O III] is also heating up the GMCs. The identity and nature of this source remains unknown.

5. Conclusion

To summarize, we have used narrowband imaging of M33 to generate ratio maps in [O III]λ5007/[S II]λ6724 and [O III] λ5007/[O II]λ3727 to explore the limits of ionization-parameter mapping as a probe of H II region optical depth to ionizing UV radiation. We employ a revised empirical method for continuum subtraction building on methods by Keenan et al. (2017) and Hong et al. (2014). This method uses the pixel histogram distribution for diffuse emission after filtering out bright, resolved emission, and exploits the dispersion around the mode.

We show that, due to the metallicity dependence of the [O III] λ5007 emission line, the [O III]λ5007/[S II]λ6724 and [O III] λ5007/[O II]λ3727 ratios can only be effective as optical depth diagnostics in the low-metallicity regime (2 + log(O/H) < 8.4), which is roughly <0.5Z_☉. Most likely, we are unable to identify a number of optically thin H II regions at higher metallicities due to the weakness of [O III]λ5007 emission in this regime. Other emission lines should be used to trace higher-ionization species in these conditions.

We report the presence of a peculiar large-scale (≥1 kpc) structure in northern M33 that is excited in [O III]λ5007 and conspicuously absent in other bands. The known WR star and HMXBs in the vicinity of this patch cannot provide the required radiation to account for its ionization. Further observations are needed to understand its origin.

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Data processing was performed using the open-source Python libraries AstroPy, (Astropy Collaboration et al. 2013, 2018), Photutils (Bradley et al. 2019), NumPy (Harris et al. 2020), and SciPy (Virtanen et al. 2020). Animations of the continuum-subtraction process (Figures 3, 13, 15, and 17) were prepared by generating individual frames in Matplotlib (Hunter 2007) and then combined using FFmpeg (Tomar 2006). Static and interactive versions of Figures 10 and 11 were created using the data visualization libraries Altair (VanderPlas et al. 2018) and Vega (Satyanarayan et al. 2017). Facilities: Mayall(MOSAIC-I), HST(STIS).

Appendix

Application to C III] Imaging of Starburst Galaxies

In Section 4, we demonstrate the continuum-subtraction method based on the modal bin fraction for the M33 data. Given the proximity of M33, a Local Group galaxy, individual stars are resolved, as well as a strong color gradient in the diffuse stellar background. Applying the method to more distant galaxies with more diffuse starlight and more uniform color can provide a cleaner subtraction. Here we demonstrate the method for continuum subtraction of faint C III]λ9099 imaging of three starburst galaxies, ESO 338-IG004, Haro 11, and Mrk 71, using observations from the Hubble Space Telescope (HST; program GO-15088, PI: Micheva). The imaging was obtained with STIS,
using the F25CIII filter for the line image; and F25QTZ (Haro 11 and ESO 338) and F25CN182 (Mrk 71) for the continuum.

Due to the near absence of sky emission in these HST images, the variance of background pixels is very low, and we therefore use a 4σ clip, to isolate the diffuse emission instead of 3σ as used for M33. As noted earlier, if sky pixels dominate the pixel population, then our method tends to produce undersubtracted images relative to diffuse background starlight. We therefore crop the region of interest to exclude empty sky regions. This amplifies the small changes to the modal bin fraction from the diffuse starlight and makes the transition from undersubtraction to oversubtraction easier to discern. Figures 13, 15, and 17 present the image subtraction at different scale factors and the pixel histograms of the continuum-subtracted images. Figures 14, 16, and 18 show the fraction of pixels in the modal bins as function of scale factor for these galaxies, respectively. These figures also demonstrate the differences in the diagnostics between our method and those of Keenan et al. (2017) and Hong et al. (2014). We see that our mode-based method provides a simpler and more accurate diagnostic than either of the other two methods. The three methods do agree within the errors for the quantitative example in Figure 13.

In Figures 13, 15, and 17, we can see how the central peak shows hardly any change in shape. This is a consequence of the almost zero sky value in HST images. The tails of the histogram are well defined in the top and bottom panels, but contain less than 10% of the total pixels. Therefore, the aperture size must be carefully chosen to avoid large swaths of empty sky. The pixels that hold the signal for the transition from undersubtraction to oversubtraction would otherwise be drowned out.

For Haro 11 (Figure 13), Keenan et al. (2017) note that the scale factors for the three main starburst knots differ in the continuum subtraction of narrowband emission-line imaging, due to different-age stellar populations, so performing a smaller crop on the individual regions would be necessary for optimal continuum subtraction. Figure 14(c) shows that the algorithm predicts an overall scale factor for the entire galaxy in the interval (1.2, 1.4). The exact scale factor for each knot can be seen in the interactive version of Figure 13. It is 1.38 for Knot A, and 1.26 for Knot C, both of which show residual emission at the respective scale factors, whereas Knot B subtracts out completely at the predicted scale factor of 1.28. In Knot C, the central star cluster has bright C III] line emission. Since the line and offline images are not PSF equalized and the MAMA detector PSF is known to have large wings, what appears as a circular region of diffuse emission around Knot C is an artifact of the subtraction process. The radius of the observed 0′′75 circular halo is consistent with the extent of the PSF wings in the narrowband filter, given the measured S/N in the image (Figure 13(b)). The emission in Knot A is more likely to be real, since it has fainter clusters. This interpretation of our results for Haro 11 is consistent with the findings of Micheva et al. (2020), who carried out a careful, spatially resolved analysis of the C III] line versus continuum emission from this data set.

For ESO 338 (Figure 15), the analysis yields similar results. The peak due to background and sky pixels is broad and shows little variation with scale factor. The line and continuum pixels produce a noticeable transition in the tails of the histogram. Figure 16(c) shows that the modal bin fraction changes only by 0.06, but the peak is well defined. The metric chosen is sensitive to small variations and can determine the optimum scale factor correctly. The apparent diffuse emission near the strong point source in the central starburst region again may be due to the PSF wings.

Mrk 71 (Figure 17) contains two super star clusters, referred to as Knot A (west) and Knot B (east) (e.g., Micheva et al. 2017). The results of our continuum subtraction reveal that Knot A shows some faint, diffuse C III] emission that is extended and therefore real. Knot B shows at least one unresolved point source, which is likely stellar C III] emission from a known WC star (Drissen et al. 2000). No diffuse emission appears to be present in Knot B. Choosing the aperture so that the faint residual emission pixels are not outnumbered by background pixels is key. In Figure 18(c), we see for the chosen aperture size that the algorithm detects the correct scaling without producing oversubtraction.

The C III] emission in Haro 11-A and Mrk 71-A are both associated with the highest-ionization-parameter regions in these two galaxies. Gray et al. (2019) suggest that enhanced C III] may be associated with the suppression of adiabatic mechanical feedback by strongly cooling outflows. We note that Mrk 71-A has been suggested to show evidence of such suppressed superwinds (Oey et al. 2017).

Thus, the new continuum-subtraction method based on the modal bin fraction can be applied to a variety of situations as long as there is a continuous distribution of pixels and a healthy mix of emission, continuum, and sky pixels. Empirical methods work best when there are $\gtrsim 10^4$ pixels where the majority are
Figure 15. Histograms showing undersubtracted, optimally subtracted, and oversubtracted images of ESO 338. An animated version of the continuum-subtraction process, showing a step-by-step increase in the scale factor from 0 to 0.03, is available in the online version of this paper. The video duration is 15 s.

(An animation of this figure is available.)
Figure 16. Mode, skewness, and modal bin fraction vs. scale factor for ESO 338 continuum subtraction. Similar to Figure 14, it is easy to locate the correct scale factor and uncertainty using the new metric.
Figure 17. Histograms showing undersubtracted, optimally subtracted, and oversubtracted images of Mrk 71. An animated version of the continuum-subtraction process, showing a step-by-step increase in the scale factor from 0 to 0.3, is available. The video duration is 15 s. (An animation of this figure is available.)
dominated by stellar continuum and not contaminated by line emission.

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Figure 18. Mode, skewness, and modal bin fraction vs. scale factor for Mrk 71 continuum subtraction.