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ABSTRACT

Accurate chemical compositions of star-forming regions are a critical diagnostic tool to characterize the star formation history and gas flows which regulate galaxy formation. However, the abundance discrepancy factor (ADF) between measurements from the "direct" optical electron temperature (T_e) method and from the recombination lines (RL) represents ~ 0.2 dex systematic uncertainty in oxygen abundance. The degree of uncertainty for other elements is unknown. We conduct a comprehensive analysis of O⁺⁺ and N⁺ ion abundances using optical and far-infrared spectra of a star-forming region within the nearby dwarf galaxy Haro 3, which exhibits a typical ADF. Assuming homogeneous conditions, the far-IR emission indicates an O abundance which is higher than the T_e method and consistent with the RL value, as would be expected from temperature fluctuations, whereas the N abundance is too large to be explained by temperature fluctuations. Instead a component of highly obscured gas is likely required to explain the high far-IR to optical flux ratios. Accounting for this obscured component reduces both the IR-based metallicities and the inferred magnitude of temperature fluctuations, such that they cannot fully explain the ADF in Haro 3. Additionally, we find potential issues when predicting the RL fluxes from current atomic data. Our findings underscore the critical importance of resolving the cause of abundance discrepancies and understanding the biases between different metallicity methods. This work represents a promising methodology, and we identify further approaches to address the current dominant uncertainties.

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1. INTRODUCTION

The abundance of heavy elements in the interstellar medium (ISM) with respect to hydrogen, i.e., metallicity, serves as a critical diagnostic tool for understanding the astrophysical processes which govern galaxy formation. Metallicity is particularly valuable as a probe of star formation history, gas accretion, feedback mechanisms, and galactic-scale outflows (e.g., Maiolino & Mannucci 2019; Sanders et al. 2021; Davé et al. 2017; Torrey et al. 2019). Oxygen (O) and nitrogen (N) are among the elements most commonly used to assess gas-phase metallicities, and they are more powerful in combination due to their distinct nucleosynthetic origins and subsequent enrichment pathways. Oxygen in the ISM is produced mostly from the cataclysmic termination of massive stars in the form of corecollapse supernovae (CCSNe). In contrast, nitrogen's enrichment is largely facilitated by stellar winds from intermediate-mass Asymptotic Giant Branch (AGB) stars (e.g., Nomoto et al. 2013), resulting in a temporally delayed contribution to the enrichment of the ISM relative to star-forming events. The total nitrogen yield also increases with overall metallicity due to secondary production from the CNO cycle. This dichotomy in enrichment processes renders the ratio of these elements an invaluable metric for tracing the integrated history of star formation and gas flows.

Substantial research has been dedicated to understanding the enrichment patterns of O and N metallicities (e.g., Alloin et al. 1979; Pilyugin et al. 2012; Berg et al. 2012; Izotov et al. 2012; James et al. 2015; Vincenzo et al. 2016; Steidel et al. 2016; Magrini et al. 2018; Annibali & Tosi 2022; Sanders et al. 2023), revealing minimal evolution in the N/O ratio among lowmetallicity galaxies while observing an elevated N/O ratio in high-metallicity galaxies. This trend aligns with the classical CCSNe and AGB enrichment scenarios. Nevertheless, recent findings have uncovered an unexpected increase in the N/O ratio within early galaxies during the epoch of reionization (Bunker et al. 2023; Isobe et al. 2023; Marques-Chaves et al. 2024), possibly linked to settings of supermassive star enrichment processes operating in dense clusters (D'Antona et al. 2023; Nagele & Umeda 2023; Pascale et al. 2023; Belokurov & Kravtsov 2023; Charbonnel et al. 2023; Senchyna et al. 2023; Cameron et al. 2023; Kobayashi & Ferrara 2024; Nandal et al. 2024). Notably, the large N/O abundances found in early galaxies are based on rest-frame ultraviolet emission lines, as opposed to optical diagnostics used at lower redshifts ($z \leq 3$). Such diagnostics are powerful and complementary in probing a vast redshift range, but may introduce different systematic errors (e.g., Topping et al. 2024). This underscores the necessity to accurately determine the chemical abundance patterns in galaxies to better understand their chemical evolution throughout cosmic history.

A standard approach to measure the gas-phase metal content, often referred to as the "direct" T_e method, relies on analyzing the collisionally excited emission lines (CEL). These are produced when ions such as O^{++} or N⁺ undergo radiative transitions from various energy levels, following excitation from collisions with electrons. The flux ratio of emission lines from different collisionally excited energy levels (e.g., [O III] $\lambda 4363$ / [O III] $\lambda 5007$) provides a measurement of the temperature T_e , which in turn allows ion abundances to be determined from line luminosities. However, this T_e sensitivity presents a challenge when multiple ionizing sources contribute to temperature structures and fluctuations within the gas (Pilyugin et al. 2012). Treating the gas as a uniform phase across an entire galaxy - or even within an H II region – can bias the T_e method toward regions of higher temperature, and thus, lower elemental abundance, leading to an underestimation of the true metallicity. This systematic bias is often invoked to explain the so-called abundance discrepancy factor (ADF), where T_e -based oxygen metallicities are consistently lower than those determined through T_{e} insensitive recombination lines (RL; e.g., O II 4650 V1 multiplet, also emitted by O^{++} gas) by ~ 0.25 dex (Peimbert et al. 1993, 2005; Esteban et al. 2009, 2014). As one way to explain this dicrepancy, the amount of bias in the T_e method is directly related to the magnitude of temperature fluctuations, which can be expressed as a dimensionless variance t^2 :

$$t^{2} = \frac{\int n_{X} n_{e} (T_{e} - T_{0})^{2} \,\mathrm{d}V}{\int T_{0}^{2} n_{X} n_{e} \,\mathrm{d}V}$$
(1)

where n_X and n_e are the densities of specific ions and free electrons respectively, T_0 is the mean electron temperature, and V is the integration volume. A key open question is whether temperature fluctuations in ionized nebulae are in fact sufficiently high to explain the ADF (e.g., Peimbert et al. 2017; Maiolino & Mannucci 2019).

In a pilot study by Chen et al. (2023) (hereafter C23), the temperature fluctuation hypothesis was empirically tested within the nearby dwarf galaxy Mrk 71 using

far-IR fine-structure emission lines. While these far-IR emission lines (e.g., [O III] $\lambda\lambda52$, 88 μ m) are the product of collisional excitation, the low energy required for their excitation renders them effectively insensitive to T_e . Therefore, a direct comparison between the far-IRderived metallicity and the optical-CEL (OCEL) metallicity yields a direct gauge of temperature fluctuations without ambiguity caused by different emission mechanisms (Jones et al. 2020), i.e., the metallicity derived from far-IR lines is expected to be nearly identical to the RL method even if t^2 is large. Intriguingly, our findings revealed a t^2 value in Mrk 71 for O⁺⁺ gas that is consistent with zero, and is in tension (~ 2σ) with the ADF derived between the O^{++} RL and OCEL metallicities. This result highlights the power of combining optical and far-IR spectra to address key issues regarding the magnitude of temperature fluctuations t^2 , the origin of the ADF, and the absolute gas-phase abundances. Such methods are especially promising for application at high redshifts, where the relevant optical and far-IR lines are now being detected at z > 8 thanks to the combination of JWST and the Atacama Large Millimeter Array (ALMA; Fujimoto et al. 2023; Jones et al. 2020). It is thus a pivotal time to harmonize metallicity measurements across both low and high-redshift galaxies.

Characterization of the temperature fluctuations within ionized nebulae can be significantly expanded by using the same methods to measure t^2 between different ion species. A recent study by Méndez-Delgado et al. (2023a) underscores the necessity by unveiling a correlation between $t^2(O^{++})$ and the differential temperature, $T_e(O^{++})-T_e(N^+)$. This suggests that temperature fluctuations might be intrinsically linked to the inherent temperature disparities amongst various gas phases.

In this paper, we apply the optical+far-IR methodology from C23 to measure t^2 from both O⁺⁺ as well as N⁺ for the first time. This study is made possible by the recent availability of comprehensive datasets from integral field unit (IFU) spectrographs spanning the optical and far-IR: the Far Infrared Field-Imaging Line Spectrometer on the Stratospheric Observatory for Infrared Astronomy (SOFIA/FIFI-LS; Fischer et al. 2018), the Photodetector Array Camera and Spectrometer on the Herschel Space Telescope (Herschel/PACS: Poglitsch et al. 2010), and the recent commissioning of the red channel (also known as the Keck Cosmic Reionization Mapper; KCRM) of the Keck Cosmic Web Imager on the W.M. Keck Observatory (Keck/KCWI; Morrissey et al. 2018). Here we focus on a star-forming region within the dwarf galaxy Haro 3 (also known as NGC 3353 or Mrk 35; RA=10:45:22.4; Dec=+55:57:37; z = 0.003208). Based on the fiber spectrum centered on the host galaxy from

the Sloan Digital Sky Survey data release 8 (SDSS DR8), the host galaxy has a stellar mass $\log(M_*/M_{\odot}) \sim 8.5$, star formation rate SFR $\sim 0.1 M_{\odot}/\text{yr}$, and gas-phase metallicity $12 + \log(\text{O/H}) \simeq 8.7$ (Kauffmann et al. 2003; Brinchmann et al. 2004; Tremonti et al. 2004), although we note that metallicities adopted from SDSS are systematically higher than from the T_e method (e.g., Kewley & Ellison 2008). In this work, we focus on the luminous H II region $\simeq 4''_{...2}$ ($\sim 300 \text{ pc}$) northwest of Haro 3's nucleus, often labeled as "Region A" (Steel et al. 1996). This region dominates the host galaxy's total star formation and ionizing photon production (Johnson et al. 2004).

This paper is organized as follows. We describe the observational dataset in §2. Detailed methods leading to the temperature and metallicity measurements are presented in §3. In §4, we discuss our findings. The conclusions are summarized in §5.

2. OBSERVATIONS

The Keck/KCWI data of Haro 3 were collected on the nights of UT 2023-06-19 and 2023-11-11. Both nights were dark, clear, with photometric conditions. The observations involved two distinct observation strategies: firstly, a series of brief snapshots to prevent the saturation of strong emission lines, and secondly, deep exposures aimed at detecting faint emission features including auroral and oxygen recombination lines. All observations used the Medium slicer, with 0.7 slits and a $\sim 16^{\circ} \times 20^{\circ}$ field of view (FoV). For the snapshots, the BL and RL gratings were employed to obtain broad wavelength coverage. The BL grating was centered at 4500 Å (coverage 3580–5580 Å, $R \sim 1800$), with an exposure time of $t_{exp} = 5s \times 8 = 40s$; the RL grating was centered at 8000 Å (6465–9780 Å, $R \sim 2000$) with $t_{\rm exp} = 30s \times 7 = 210s$. The deep exposures utilized the BM and RL gratings. The BM grating was centered at 4400 Å (3985–4865 Å, $R \sim 4000$) to resolve the O II RL multiplet with individual exposure times ranging between 200s, 600s, and 660s, and a total $t_{exp} = 2660s$; the RL grating was centered at 7250 Å (5715–9035 Å, $R \sim 1900$) to cover the faint [N II] auroral emission, with individual exposure times as a mixture of 200s, 300s, and 330s, achieving a total $t_{exp} = 2660s$ as well. Between individual exposures, the FoV was rotated by 45° to enable good spatial sampling.

We performed the KCWI data reduction process following the methodology described in C23, utilizing the upgraded Python version of the Data Reduction



Figure 1. Left: Fields of view of the Keck/KCWI (cyan) and SOFIA/FIFI-LS (magenta) observations, and contours of the [O III] 88 μ m emission map from Herschel/PACS (yellow), overlaid on the color composite image constructed from Sloan Digital Sky Survey images in g, r and i filters. Right: Extracted spectra after continuum subtraction (blue) and the corresponding fitted line profiles (orange) of several important emission features for this work.

Pipeline $(DRP)^1$, which now supports the red channel. As in C23, we altered the DRP, opting for linear resampling over cubic resampling to ensure flux conservation. Sky subtraction was performed by scaling and removing the b-spline sky model generated by the DRP from separately obtained exposures of adjacent blank sky, subsequent to the on-source exposures. Flux calibration was performed using observations of the A-type standard star BD+26 2606, taken immediately after the science exposure sequence. Data cubes from individual exposures were resampled to a uniform grid with a pixel size of $0^{\prime\prime}_{...3} \times 0^{\prime\prime}_{...3}$ prior to their combination using KCWIKIT (Prusinski & Chen 2024). The blue-channel data were averaged with weights according to exposure time. The red-channel detector exhibited a much higher incidence of cosmic rays (CR), which were not entirely eliminated by the DRP. To address this, we employed a sigma-clipping method with $N_{\sigma} = 3$, centered around the median value, prior to the average combination of data cubes. From comparison of flux measurements across different grating configurations, we determined that the relative flux accuracy is within < 2%. Additionally, two pseudo-broad-band images were generated from the RL-7250 and RL-8000 cubes in the i band and compared with images from the SDSS data release 18 (Almeida et al. 2023). A discrepancy of $\sim 4\%$ was identified and subsequently corrected in the data cubes. Following this adjustment, we conservatively adopt a 3%absolute flux accuracy, which is included in the subsequent analyses.

The [O III] $\lambda 88 \ \mu m$ and [N II] $\lambda 122 \ \mu m$ emission lines were observed with the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) aboard the Herschel Space Observatory, as part of the Herschel Dwarf Galaxy Survey (HDGS; Cormier et al. 2015). These reduced data (v14.2.0) were obtained from the Herschel Data Archive². The "chop-nod" mode was employed for these observations, with exposure times of 4068 s for [O III] 88 μ m and 805 s for [N II] 122 μ m. Additionally, reduced data of [O III] 52 μ m emission were acquired from the SOFIA Data Archive³, as reported by Peng et al. (2021). These observations utilized the Field-Imaging Far-Infrared Line Spectrometer (FIFI-LS; Fischer et al. 2018), with a total integration time of 1413 s. The flux-calibration uncertainties of PACS and FIFI-LS individually are $\sim 10\%$, and the relative uncertainty between the two instruments is $\sim 15\%$ (Fadda et al. 2023).

3. METHODS

3.1. Flux Measurements

Accurate temperature and metallicity measurements are based on the ability to reliably compare line fluxes from optical and infrared data. This comparison requires matching the point spread function (PSF) and extraction aperture of the various IFU data sets. We matched the PSF of each instrument by convolving pseudo-narrowband (PNB) images of distinct [O III] or [N II] emission lines with Gaussian spatial profiles. Fig. 2 shows an example of PSF matching between

¹ https://github.com/Keck-DataReductionPipelines/KCWI_DRP

 $^{^{2}}$ https://archives.esac.esa.int/hsa/whsa/

³ https://irsa.ipac.caltech.edu/Missions/sofia.html

KCWI [O III] $\lambda 5007$ and PACS [O III] 88 μ m. For the [O III] $\lambda 5007$ (KCWI) compared to far-IR images, the optimal full width at half maximum (FWHM) values for the Gaussian convolution kernels were determined from the best fit to be 10".03 ± 0".04 for [O III] $\lambda 52 \ \mu$ m (FIFI-LS), 9".45 ± 0".02 for [O III] $\lambda 88 \ \mu$ m (PACS), and 13".5 ± 0".1 for [N II] $\lambda 122 \ \mu$ m (PACS). The residual root mean square (RMS) of the fit is < 10% of the peak intensity of the [O III] and [N II] PNB images. These FWHM values are consistent with expectations from the diffraction limit of the telescopes and wavelengths of the targeted features.

Given the substantial PSF differences between KCWI (with $\sim 1''$ FWHM) and the far-IR instruments, coupled with the compact nature of Haro 3, the S/N ratio for faint emission lines in the KCWI data significantly deteriorates post-convolution. To ensure a reliable comparison while preserving an acceptable S/N, we extract 1-D spectra from both pre- and post-PSFmatched KCWI data cubes across various apertures. An aperture-correction factor is then derived by comparing the extinction-corrected fluxes (see $\S3.2$) of strong emission lines (including [Ne III] λ 3869, [O III] λ 4363, $\lambda\lambda 4959, 5007, \text{ and } H\beta$) between these spectra. The apertures, centered on the nebular emission peak, have preconvolution radii of 2"25 and post-convolution radii of 3'' (Fig. 2, left). The aperture sizes were selected to optimize the S/N ratio and to minimize the inclusion of flux from other sources. The systematic uncertainty of this aperture correction is estimated to be < 2%, based on the standard deviation of the flux ratios.

The spectral profiles of the optical emission lines are best described by a narrow Gaussian profile with an additional broad component contributing < 1% of the total flux. However, due to undersampling in detector space for SOFIA/FIFI-LS and Herschel/PACS, the far-IR line profiles are instead better described by Voigt profiles. For consistency, fluxes of all [O III] and [N II] optical and far-infrared CELs were measured by fitting Voigt profiles after extracting the 1D spectra, except for the weak features specifically described below. The choice of Voigt versus Gaussian profiles results in < 1% differences in flux for the optical lines. The [N II] $\lambda\lambda 6548$, 6583 doublet, located near H α , is fit concurrently with the intensity ratio constrained to the theoretical value of 1:2.942 (Froese Fischer & Tachiev 2004). The [N II] λ 5755, λ 122 μ m lines, and the O II RL V1 multiplet lines are fitted using only Gaussian profiles due to their relative weakness. Additionally, individual lines within the RL multiplet are fitted simultaneously to account for blending. Fig. 1 shows the best fits to several representative lines. The 1- σ flux uncertainties are derived from the error spectra. However, data cube resampling and PSF convolution inevitably induce pixel covariance, affecting the accuracy of error estimation. To address this, we compare the standard deviation of a featureless section of the spectra with the calculated error spectra, and rescale the error spectra based on the factorial differences before propagating the flux errors. All measured fluxes related to this work, before and after aperture matching and attenuation correction, are presented along with their 1σ uncertainties in Appendix A.

3.2. Attenuation Correction

In this study, dust attenuation correction, including contributions from the Milky Way⁴ and Haro 3, was performed using the Hydrogen Balmer and Paschen lines. Unlike the emission lines from O^{++} and N^{+} , fluxes of the H I lines for attenuation correction are determined by integration over a wavelength range manually selected to accommodate stellar absorption features. This consideration is particularly crucial for the weaker Balmer lines, where stellar absorption has a significant impact. Reliable flux measurements are obtained from $H\beta$ to H10 (or $H\theta$), as well as P10 and P14 lines. However, the H7 (H ϵ) and H8 (H ζ) lines are excluded due to their blending with other spectral features. Other Balmer and Paschen lines are deemed unsuitable for reliable flux measurements, either being too weak or contaminated by telluric OH emission. The ability to measure $H\alpha$, P10, and P14 fluxes from the newly commissioned redchannel of KCWI significantly increases the accuracy of this attenuation correction. With Paschen line attuenuation being $\sim 70\%$ that of the Balmer lines, and the wavelength baseline increasing by $> 4 \times$, the attenuation correction uncertainty is reduced by 40% compared to using Balmer lines alone.

The strength of dust attenuation, $c(\text{H}\beta)$, is derived by modeling the observed fluxes of Balmer and Paschen lines. The model assumes that the intrinsic H line ratios are given by the case B recombination scenario with $T_e = 8,500$ K and an electron density $n_e = 100$ cm⁻³. ⁵ The attenuation of H fluxes is calculated using an extinction curve from Cardelli et al. (1989) with a pa-

⁴ The Milky Way extinction in the direction of Haro 3 contributes only $c(\text{H}\beta) \simeq 0.01$ based on Schlafly & Finkbeiner (2011).

⁵ This assumption is informed by the T_e and n_e values derived from [O III] far-IR emission, as discussed in §3.3. Variations in T_e and n_e have a marginal impact on the results. For example, a scenario with $T_e = 10,000$ K and $n_e = 100$ cm⁻³ alters the P13/H β ratio by < 2%.



Figure 2. Left: An example of PSF matching between the [O III] λ 5007 PNB image from Keck/KCWI (top-left) and the [O III] 88 μ m PNB image from Herschel/PACS (bottom-left). The KCWI PNB image has been convolved with a 2D Gaussian kernel (top-right) to match the PACS PNB image's PSF. The resulting residual is shown in the bottom-right panel. The red dashed circles indicate the apertures from which the 1D spectra were extracted. *Right*: Modeling of dust attenuation based on the observed flux ratios of hydrogen Balmer and Paschen lines. In the top panel, the data points represent the correction factors needed to align the observed flux ratios with those predicted by Case B recombination. The best-fit attenuation models are represented by solid curves, while the shaded areas denote their 1 σ uncertainties. The blue (orange) color indicates the 1D spectra before (after) PSF matching. The steep slope at the lower wavelengths is primarily due to contributions from stellar absorption. The lower panel shows the fractional deviations between the observed and best-fit flux ratios, for the same data points. Data points near unity indicate a good agreement with the attenuation model.

rameter $R_V = 3.1.^6$ The model also accounts for stellar absorption by assuming a fixed equivalent width for the Balmer lines (W_{abs}) , while positing no absorption for the Paschen lines. This assumption is based on stellar population synthesis models. Specifically, for the Binary Population and Spectral Synthesis (BPASS) v2.3 (Stanway & Eldridge 2018) model, the Paschen $W_{\rm abs}$ is $\lesssim 30\%$ of the Balmer ones in the age range of 10^7 – 10^9 years. In the observed spectra, the Paschen lines also have no broad absorption signatures that appear in the high-order Balmer lines. We find that both $c(H\beta)$ and $W_{\rm abs}$ vary significantly between the small unconvolved optical and the large PSF-convolved far-IR apertures. The change is consistent with the $c(H\beta)$ and W_{abs} maps derived from the same method using the unconvolved KCWI data. The maps indicate that the larger aperture includes more contribution from the surrounding host galaxy, with both higher dust attenuation and stronger

effects of stars with Balmer absorption. Consequently, $c(H\beta)$ measurements were made separately both before and after aperture matching, with the aperture correction factor calculated based on the attenuationcorrected fluxes. The best-fit models and $c(H\beta)$ are presented in Fig. 2 and Table 1. Uncertainties in the $c(H\beta)$ measurements are included in the subsequent measurements.

3.3. Temperature, Density, and Metallicity

Electron temperatures for O⁺⁺ and N⁺ [$T_e(O^{++})$ and $T_e(N^+)$], along with their metallicities (i.e., O⁺⁺/H⁺ and N⁺/H⁺ abundance ratios), were determined using PyNeb (Luridiana et al. 2015). We adopt collisional strengths from Storey et al. (2014); Tayal (2011) and transition probabilities from Storey & Zeippen (2000); Froese Fischer & Tachiev (2004). Our approach is to measure $T_e(IR)$ from the extinction-corrected ratios of far-IR to optical nebular lines (namely [O III] $\lambda\lambda 52 \ \mu m/5007$, [O III] $\lambda\lambda 88 \ \mu m/5007$, and [N II] $\lambda\lambda 122 \ \mu m/6583$), and metallicities from the ratios of far-IR to H I Balmer lines (e.g., [O III] $\lambda 52 \ \mu m/H\alpha$). We compute $T_e(IR)$ and metallicities as a function of electron density n_e . We also measure $n_e(IR)$ directly

⁶ Changing R_V assumptions imposes a small change in the final metallicity measurements, mostly for the far-IR metallicities. Specifically, assuming $R_V = 2.6(4.1)$ increases the far-IR O/H metallicity measurement by $\simeq 0.03(-0.05)$ dex, which does not affect our conclusions.

from the [O III] $\lambda\lambda 52 \ \mu m/88 \ \mu m$ flux ratio. The 1σ uncertainties are estimated using the Markov Chain Monte Carlo (MCMC) method, accounting for systematic uncertainties arising from flux calibration and extinction correction described earlier. The posterior distributions of T_e , n_e , and metallicities are illustrated in Fig. 3 with maximum-likelihood values reported in Table 1.

The T_e and metallicity values derived from far-IR emission lines are notably influenced by n_e (Fig. 3), due to the low critical density $(n_{\rm crit} \sim 10^2 - 10^3 {\rm cm}^{-3})$ of these lines. The [O III] $\lambda\lambda52 \ \mu m/88 \ \mu m$ ratio provides a self-consistent measurement of n_e within the same aperture and from the same [O III] emitting gas. We adopt this $n_e([O \text{ III}])$ for all T_e and metallicity calculations in this work. For reference, in Table 1 and Fig. 3, we also include n_e values measured from the optical [O II] $\lambda\lambda 3726/3729$ and [S II] $\lambda\lambda 6716/6731$ ratios, as well as those derived from the relative intensities of the O II V1 multiplet. For both [O II] and [S II], n_e has been determined from apertures with $r_{\rm ap} = 2''_{.25}$ and 3" before and after PSF-matching. The n_e values measured from the smaller $r_{\rm ap} = 2''.25$ aperture are higher than those from the 3" aperture, aligning with a density gradient in the H II region as reported in previous studies (Binette et al. 2002; Phillips 2007; García-Benito et al. 2010; Jin et al. 2023). The optical measurements of $n_e([O II])$ and $n_e([S II])$ are consistent (within < 1 σ) with the far-IR $n_e([O III])$ measurements. However, even after accounting for aperture differences, the n_e derived from the O II recombination lines remains considerably higher than the other measurements.

The T_e and metallicity are measured from OCELs and RLs in a manner similar to that used for the far-IR analysis. $T_e(\text{OCEL})$ is calculated from the auroral-tonebular flux ratios (i.e., [O III] $\lambda\lambda4363/5007$ and [N II] $\lambda\lambda5755/6583).$ These temperatures are then used to derive CEL-based metallicities from the [O III] $\lambda 5007/H\alpha$ and [N II] $\lambda 6583/\text{H}\alpha$ ratios. We also use $T_e(O^{++})$ obtained from OCELs to calculate the O II RL emissivity. The total flux from the O II lines at 4638.9, 4641.8, 4649.1, 4650.8, 4661.6, and 4676.2 Å in the V1 multiplet is then used to calculate the RL-based O^{++} metallicity. We note that RL emissivity and hence metallicity exhibits a relatively weak dependence on T_e . The T_e and metallicities derived from OCELs and RLs have minimal sensitivity to electron density (n_e) in the low-density regime which applies here (Fig. 3).

In addition to ion abundances, we also calculate the total O/H, N/H, and N/O ratios. The O/H ratio is derived by summing the O^+/H^+ and O^{++}/H^+ ratios,

assuming that all oxygen in the H II regions is singly or doubly ionized. This is expected to be accurate to within a few percent (Izotov et al. 2006; Berg et al. 2018). The O⁺/H⁺ metallicity is measured from the direct- T_e method using the [O II] $\lambda\lambda 3726,29$, and the auroral [O II] $\lambda\lambda 7318,20,30,31$ fluxes. For N, we assume that the ratio of singly and doubly ionized N is the same as O, i.e., N⁺/N⁺⁺ = O⁺/O⁺⁺(OCEL) = 1.92. The N⁺⁺/N⁺ ratio implied from this assumption is in agreement with the [N III] $\lambda\lambda 57 \ \mu m/[N II]$ 122 μm ratio reported in Cormier et al. (2015). It is important to note that the total N and O metallicities presented in this study are intended only as reference values. Our conclusions regarding the ADF and temperature fluctuations, discussed in §4, do not depend on these results.

Fig. 3 summarizes the T_e and ion abundance measurements as functions of n_e . We find a typical abundance discrepancy in Haro 3, with the RL-based abundance of O^{++} higher than OCELs by ~ 0.25 dex. The far-IR [O III] lines suggest a lower T_e and higher abundance than OCELs, and are consistent within 1σ uncertainty of the RL metallicity. This is in contrast with C23, in which we instead found the O/H metallicity derived from the far-IR and OCEL methods to be consistent. Our results for Haro 3 can be explained by temperature fluctuations and suggests $t^2 \sim 0.05$ (Table 1). However, the far-IR [N II] emission does not support a simple temperature fluctuation scenario. A much higher $t^2 \sim 0.5$ and a much lower average temperature T_0 are required to reconcile the optical and far-IR CELs of [N II]. The [O III] and [N II] measurements differ by $\sim 2\sigma$ in t^2 alone, and $> 2\sigma$ in the 2D space of (t^2, T_0) (see §4.1 and Fig. 4). The N^+/O^{++} abundance ratio offers a more powerful test. The far-IR N^+/O^{++} ratio is $\simeq 2\sigma$ higher than that derived from OCELs. However, since the [N II] $\lambda 6583$ emission is less sensitive to T_e than [O III] λ 5007, any temperature fluctuations should result in a "true" N^+/O^{++} ratio that is lower than the value we report from the OCELs; the far-IR value is likewise expected to be lower. Instead, our far-IR N^+/O^{++} ratio is $\sim 3\sigma$ higher than expected from the temperature fluctuation hypothesis (Fig. 3, lower right panel). Notably, while the IR-to-optical comparisons are subject to various sources of uncertainty (e.g., attenuation correction, electron density, flux calibration), the purely IR measurement of N^+/O^{++} is relatively robust. In particular, there is no attenuation correction, minimal aperture matching correction, and minimal n_e dependence thanks to the similar critical densities of [O III] 88 μ m and [N II] 122 μ m (Fig. 3). We thus consider the comparison of N^+/O^{++} from IR-only and optical-only measurements as one of the most reliable tests.





Figure 3. T_e and abundance measurements of O⁺⁺/H⁺ (left), N⁺/H⁺ (middle), and N⁺/O⁺⁺ (right) from various methods. The red solid and dashed lines represent the measurements and their 1 σ uncertainties obtained via the OCEL method. The magenta lines denote RL metallicity measurements for O⁺⁺/H⁺ and the inferred "true" mean temperature (T_0) and metallicities for N⁺/H⁺ and N⁺/O⁺⁺, assuming temperature fluctuations as deduced from the [O III] RL vs. OCEL method. The effect of temperature fluctuations, parameterized by t^2 , is such that the mean T_0 is lower than the T_e derived from OCEL, while ion abundances O⁺⁺/H⁺ and N⁺/H⁺ are higher. We expect the ratio N⁺/O⁺⁺ to be lower than OCEL when accounting for temperature fluctuations (as shown in the lower right panel). The measurements and 1 σ uncertainties derived from different far-IR lines are illustrated by the blue and orange lines and the corresponding shaded areas. The green shaded regions and yellow stars show the 1 σ confidence interval and the best-fit value of n_e , derived from the combination of [O III] $\lambda\lambda52 \ \mu m$ and 88 $\ \mu m$ lines. Additionally, n_e measurements obtained from [O II], the O II V1 RL multiplet, and [S II] are depicted with brown errorbars, in which the inner solid range indicates the aperture variation and the outer dotted ranges indicate the 1 σ uncertainty. All density indicators suggest $n_e \lesssim 10^3 \text{ cm}^{-3}$, corresponding to the regime in which [O III] $\lambda52 \ \mu m$ and [O III] $\lambda88 \ \mu m/[N II] \ \lambda122 \ \mu m$ are relatively robust abundance indicators.

4. DISCUSSION

4.1. To t^2 or not to t^2 ?

A key objective of this study is to assess the degree to which temperature fluctuations can account for the ADF, which is ubiquitously observed between OCEL and RL. We find agreement in O^{++}/H^+ abundance between the RL and far-IR measurements, which appears to support the hypothesis that the ADF is caused by temperature fluctuations. However, the N⁺/H⁺ and N⁺/O⁺⁺ ratios derived from far-IR and OCEL observations do not support this simple scenario (Fig. 3).

With the goal to understand whether temperature fluctuations alone can explain the disparity, we convert the differences in metallicity measurements between RL vs. OCEL and far-IR vs. OCEL into pairs of (t^2, T_0) based on Eq. 1. Traditionally, such calculations have been performed analytically, under the assumption that temperature fluctuations are relatively minor compared to T_0 (see Peimbert et al. 2017). However, this assumption proves inadequate for reconciling the [N II] far-IR and OCEL measurements. Consequently, we performed a numerical integration of Eq. 1 and estimated uncertainties in the (t^2, T_0) parameters using MCMC.

In Fig. 4 and Table 1, we present the posterior distributions of (t^2, T_0) calculated from comparisons of [O III] RL vs. OCEL, [O III] far-IR vs. OCEL, and [N II] far-IR vs. OCEL. As expected from the the [O III] RL and far-IR metallicity measurements, the (t^2, T_0) values derived from [O III] analyses are in mutual agreement. The t^2 value obtained from [O III] RL vs. optical CEL aligns with the typical range of t^2 $(\simeq 0.02-0.2)$ reported in similar H II regions (Peimbert et al. 2005; Esteban et al. 2009, 2014). Additionally, our findings are consistent with typical H II regions in $[t^2, T_e([O \text{ III}]) - T_e([N \text{ II}]), \log(O/H)]$ space, which has been presented as evidence for temperature fluctuations (Méndez-Delgado et al. 2023a). The t^2 value derived from far-IR vs. OCEL is consistent within $\sim 1\sigma$ of the RL vs. OCEL value.

However, the [N II] far-IR vs. OCEL comparison presents a more complex picture. The (T_0, t^2) values differ by $> 2\sigma$ from the [O III] values, with an anomalously large t^2 (Table 1). Some degree of difference is expected since N⁺ and O⁺⁺ originate from fundamentally differ-

Table 1. Properties of Haro 3 $r_{\rm ap} = 2''.25$

	$r_{\rm ap} = 2''_{} 25$	r_{a}	$r_{\rm ap} = 3$ "	
Property	(before PSF match	hing) (after P	(after PSF matching)	
$c(\mathrm{H}\beta)$	0.317 ± 0.016	.016 0.253 ± 0.037		
$n_e([O III]) (cm^{-3})$		1	13^{+55}_{-74}	
$n_e([O II]) (cm^{-3})$	163 ± 42	101 ± 23		
$n_e(O \text{ II } \text{RL}) \text{ (cm}^{-3})$	578^{+76}_{-141}			
$n_e([S II]) (cm^{-3})$	228 ± 10	145 ± 8		
$n_e([\text{Cl III}]) \ (\text{cm}^{-3})$	< 880	< 1030		
$n_e([\text{Ar IV}]) \ (\text{cm}^{-3})$	< 1110	< 1059		
	OCEL	RL	Far-IR	
$T_e([O III]) (K)$	$9498^{+95}_{-86}a$	_	8000^{+420}_{-270}	
$T_e([N II]) (K)$	$9770^{+150}_{-140}a$		$6590^{+700}_{-440}a$	
$T_e([O II]) (K)$	11330_{-430}^{+410}			
$12 + \log(O^{++}/H^{+})$	8.202 ± 0.022^{a}	8.440 ± 0.020^{a}	$8.509\substack{+0.054\\-0.087}$	
$12 + \log(\mathrm{O/H})^{b}$	8.309 ± 0.025	8.505 ± 0.020	$8.565^{+0.053}_{-0.069}$	
$12 + \log(\mathrm{N^+/H^+})$	6.632 ± 0.024^{a}		$7.15^{+0.13}_{-0.11}a$	
$12 + \log(N/H)^c$	$7.098^{+0.029}_{-0.031}$		$7.61^{+0.12}_{-0.11}$	
$\log(N^+/O^{++})$	-1.559 ± 0.027^{a}		$-1.348^{+0.063}_{-0.099}$	
$\log(N/O)^{bc}$	-1.014 ± 0.076		$-0.55^{+0.09}_{-0.13}$	
	RL vs. OCEL	IR v	rs. OCEL	
$t^2([O III])$	0.051 ± 0.010	0.078 ± 0.027		
$T_0([O III]) (K)$	8160 ± 130	7620^{+490}_{-370}		
$t^2([N II])$		$0.54^{+1.11}_{-0.26}$		
$T_0([N II]) (K)$		5400^{+1200}_{-1800}		

^{*a*}Assuming $n_e([O \text{ III}] \text{ IR}).$

^b Assuming O/H = O⁺/H⁺ + O⁺⁺/H⁺, where O⁺/H⁺ is measured from [O II] $\lambda\lambda$ 3726,3729, assuming $T_e([N II] OCEL)$.

 $^{c}\operatorname{Assuming}\,\mathrm{N/H}=\mathrm{N^{+}/H^{+}}+\mathrm{N^{++}/H^{+}},$ and $\mathrm{N^{+}/N^{++}}=\mathrm{O^{+}/O^{++}}(\mathrm{OCEL}).$

ent regions within the H II regions, consistent with their distinct ionization energies $(O^{++}: 35.12 \text{ eV}; N^+: 14.53)$ eV) and corroborated by spatially resolved photoionization models (e.g., Sankrit & Hester 2000; Arthur et al. 2011; Yang et al. 2023; Jin et al. 2023). However, the t^2 from [N II] far-IR vs. OCEL corresponds to a temperature standard deviation $\sigma(T_e) = 3930^{+670}_{-490}$ K, or approximately 65–85% of T_0 . Stasińska (2000) noted that traditional photoionization models struggle to account for the degree of temperature fluctuations indicated by the ADF, suggesting that additional factors like cosmic rays (Giammanco & Beckman 2005) may be needed to explain fluctuations on the order of even $\simeq 1000-2000$ K. Given the existing difficulties in explaining temperature fluctuations in the theoretical framework, the extent of temperature fluctuations implied by our measurements of [N II] in Haro 3 imposes a substantial challenge to

temperature fluctuations alone as an explanation of the ADF.

4.2. Non-thermal effects

Another hypothesis proposed to explain the ADF involves the deviation from thermal equilibrium of electrons, leading to a distribution of electron energies that diverges from the classical Maxwell-Boltzmann framework. Nicholls et al. (2012, 2013); Dopita et al. (2013) investigated the concept of a κ -distribution, a generalized Lorentzian model characterized by an extended high-energy tail, as a potential mechanism underlying the ADF observed in H II regions and planetary nebulae. The κ -distribution has been documented within the solar system, primarily attributed to the influx of high-energy plasma from the solar wind. This mechanism suggests that a higher proportion of high-energy



Figure 4. The posterior distributions of temperature fluctuations (expressed as t^2 , left; or $\sigma(T_e)$, right) and the average temperatures (T_0) , as deduced from the ADFs between various methods under the assumption that ADFs are solely caused by temperature fluctuations. Symbols show the best-fit values, while shaded regions denote the 1σ and 2σ confidence intervals. The two methods based on [O III] emission demonstrate consistency within a 1σ range. However, in the case of [N II], the inferred T_0 is significantly lower (> 2σ) compared to the T_0 values obtained from [O III], and the implied temperature fluctuations are considerably larger, with $\sigma(T_e)$ comparable to T_0 .

electrons could enhance the population of ions in excited states, leading to an overestimation of T_e when derived from the auroral to nebular line ratios through the "direct- T_e " method.

We can test whether this offers a satisfactory explanation thanks to the difference in T_e -sensitivity of the [O III] $\lambda\lambda 4363/5007$ and [N II] $\lambda\lambda 5755/6583$ ratios, which likewise respond differently to the κ -distribution. Specifically, to explain the ADF, the $T_e([O III])$ of Haro 3 requires a less pronouced κ -distribution ($\kappa \geq$ $(50)^7$, while $T_e([N \text{ II}])$ suggests a significant modulation from the high-energy tail ($\kappa \sim 10$). Since N⁺ and O⁺⁺ ions are not strictly co-spatial, it is, again, reasonable to expect different κ -distributions derived from the N^+ and O^{++} gas. However, the implication that N^+ requires more high-energy injection (based on its lower associated κ value) is contradictory to the naive picture that gas closer to the ionizing energy source is more highly ionized. Therefore, we conclude that a nonthermal κ -distribution of electron energies is unlikely to be the cause of the ADF.

4.3. Density fluctuations

In addition to temperature fluctuations, Méndez-Delgado et al. (2023b) and Rickards Vaught et al. (2023) have recently discussed the effects of density (n_e) fluctuations in H II regions. In the presence of fluctuations, the measured n_e values are biased towards the critical densities for collisional de-excitation of the n_e diagnostics. Specifically, n_e values derived from [O II] and [S II] nebular emission are reported to be approximately 300 cm^{-3} lower than those obtained from auroral or UV lines (also see Mingozzi et al. 2022). However, auroral line-based n_e diagnostics (e.g., the ratio of [O II] $\lambda\lambda7319 + 20 + 30 + 31$ to $\lambda\lambda3726 + 29$; Méndez-Delgado et al. 2023b) are notably sensitive to T_e . Given the broad range of $T_e([N \text{ II}])$ deduced from our OCEL and far-IR analyses, these auroral-line-based n_e diagnostics offer limited constraints. We also examined constraints on n_e using optical diagnostics with higher critical densities, but these primarily yielded upper limits. Specifically, measurements of [Cl III] $\lambda\lambda5518, 5538$ and [Ar IV] $\lambda\lambda 4711, 4740$ give n_e upper limits (1σ) of < 880 cm⁻³ and $< 1110 \text{ cm}^{-3}$, respectively, consistent with other n_e determinations. Therefore, these indicators cannot confirm or quantify the strength of n_e fluctuations in Haro 3.

Within the framework of density fluctuations, the observed underestimation of n_e by $\sim 300 \text{ cm}^{-3}$ aligns with estimates derived from O II RLs, as reported in Table 1. However, we find that the recombination coefficients

⁷ The parameter κ is defined such that a lower value of κ has a more pronouced high-energy tail, while $\kappa = \infty$ is equivalent to the Maxwell-Boltzmann distribution.

for O II from Storey et al. (2017) cannot fit the observed fluxes of individual lines well (Appendix A). The $n_e(O \text{ II })$ value provided in Table 1 reflects the most likely solution from MCMC based on current atomic data, yet this best-fit scenario (Fig. 5) overestimates the fluxes of O II 4649.13 and 4650.84 by $\sim 40\%$ (Fig. 6). This finding contrasts with the studies by C23 on Mrk 71 and Storey et al. (2017) on various nearby H II regions, where adjusting n_e yielded reasonable fits to the O II RL line ratios. As shown in Fig. 5, a few O II RL lines are blended with other spectral features, potentially increasing their systematic uncertainties. As a sanity check, we reconducted the same analysis with only a subset of the O II emission of 4638.86, 4641.81, and 4676.23 which are relatively robust. This subset suggests an $n_e = 440^{+230}_{-130} \text{ cm}^{-3}$ and increases the ADF between [O III] OCEL and RL by $\simeq 0.1$ dex. While the O/H metallicity from this subset is closer to the far-IR metallicity, the new n_e is still inconsistent with other n_e measurements. In another attempt to reconcile this discrepancy, we developed models incorporating both T_e and n_e fluctuations to simulate the O II RL flux ratios. Nonetheless, these models generally favored minimal n_e fluctuations and were unable to achieve a more accurate fit. Such findings highlight potential challenges in utilizing O II RL fluxes for metallicity measurements in conditions where the O II fluxes are not measured individually. While probing the accuracy of atomic data and the emission mechanisms of O II RLs falls outside the scope of this investigation, it represents an important avenue for future research.

The observed differences in n_e across two extraction apertures for Haro 3, as documented in Table 1, indicate the presence of a moderate n_e gradient (~ 70 cm⁻³, or $\simeq 0.2$ dex in $\simeq 1$ "). If we consider log-normal density distributions, such a standard deviation of $\simeq 0.3$ dex can lead to an overestimation of T_e by ~ 100 K and an underestimation of the O^{++}/H^+ ratio by ~ 0.02 dex for the far-IR lines. This effect is negligible compared to the ADF, and is in the *opposite direction* of the observed discrepancy between far-IR and optical measurements. Similarly, the accuracy of our metallicity measurements could also be affected by contributions from the diffused ionized gas (DIG) of the host galaxies. However, the H II region dominates the host galaxy in nebular and ionizing radiation. By comparing the $H\alpha$ fluxes in the extraction aperture and a region on the opposite side of the host galaxy, the contribution of DIG is estimated to be < 1% of the line fluxes.

4.4. A complex gaseous environment



Figure 5. Optimal model fit from MCMC analysis for the O II V1 RL multiplet. The top panel presents the observed continuum-subtracted spectra in black, and the model sum that consists of multiple Gaussian components in red. The middle panel illustrates the decomposition of the total model into its constituent Gaussian components: those associated with the O II multiplet are highlighted in color, while those corresponding to other spectral features are shown in gray. The unidenfied absorption feature at rest-frame vacuum wavelength of $\lambda_0 = 4648.7$ Å also appeared in C23 as an emission line. We suspect that it originates either from Fe I or C III. The bottom panel displays the residuals of the fit. The residual is low (standard deviation × pixel size is < 1% of the total O II RL flux), indicating a good fit.

In our analysis, we have established that neither T_e nor n_e fluctuations alone can adequately account for the observed discrepancies in the optical and far-IR flux ratios of [O III] and [N II]. Notably, the consistent disparities observed in the O^{++}/H^+ and N^+/H^+ metallicities, as measured by the OCEL and far-IR methods, suggest that optical photons are fractionally underrepresented. This scenario is consistent with the phenomenon that a portion of the gas is obscured by dust. Although we corrected for dust extinction using the Balmer and Paschen lines, these corrections are biased toward regions of lower dust extinction and thus underestimate the correction factor. Therefore, in regions heavily enshrouded by dust, where even Paschen photons may be absorbed, accurately compensating for their obscured contribution proves to be a formidable challenge.

Assuming that the chemical composition of obscured gas mirrors the gas observed in optical and near-IR, i.e., the far-IR metallicity estimations are inflated due to unaccounted H Balmer and Paschen fluxes, the discrepancies between OCEL and far-IR measurements imply that $\sim 50\%$ of photons are not accounted for in



Figure 6. Observed fluxes and their 1σ uncertainties for the O II RL V1 multiplet (scattered points with error bars) are compared to theoretical predictions of line fluxes as a function of n_e (curves). The colors match the individual components in Fig. 5. The best-fit n_e value and its 1σ uncertainty, as determined by MCMC, are highlighted by vertical lines and a gray shaded area. To enhance clarity, the scattered points are deliberately displaced from the best-fit n_e along the x-axis by increments of 0.03 dex. Arrows pointing from the measured fluxes indicate the necessary adjustments in n_e to reconcile observed values with theoretical expectations. The theoretical curves are based on Storey et al. (2017) and are normalized to ensure the total flux at each n_e aligns with the observed flux. The theoretical model fails to accurately predict the observed fluxes.

the extinction-corrected optical measurements (Fig. 7). However, this estimate of the missing-photon fraction is likely exaggerated. The elevated N⁺/O⁺⁺ ratio identified from far-IR emission relative to the OCEL emission points to a higher abundance, resulting from higher N/O, and/or lower ionization in the obscured gas. This picture can naturally explain the large discrepancy in the N⁺/H⁺ ratio between the far-IR and the OCEL method without invoking an unrealistic degree of temperature fluctuations, and is also consistent with the results from Mrk 71 reported by C23, where we found no significant difference between the far-IR and OCEL O⁺⁺/H⁺ ratio. The major difference between Mrk 71 and Haro 3 is that Haro 3 exhibits substantially ($\gtrsim 3\times$) higher dust attenuation, while Mrk 71 has significantly less dust ($c(H\beta) = 0.09 \pm 0.04$) with much lower metallicity ($12 + \log(O/H) = 7.89^{+0.06}_{-0.10}$ from far-IR), and hence is less likely to contain a large fraction of dust-obscured gas.

This inference regarding dust-obscured gas is further supported by the significant range in dust content estimations reported across various studies. Notably, Johnson et al. (2004) and Hunt et al. (2006) have documented that visual extinction (A_V) values can vary extensively, ranging from 0.5 to 8, depending on the method of measurement and the spectral region analyzed. Furthermore, Hunt et al. (2006) employed photoionization modeling of mid-infrared (mid-IR) emission lines and found evidence supporting the concurrent presence of a low-dust optical emitting component alongside a dustobscured component that is optically invisible. This broad range of inferred dust content highlights the profound influence that obscured gas can exert on our understanding of the chemical composition of H II regions.

Models incorporating two distinct phases of gas with distinct temperatures have also been posited as an alternative explanation for the ADF compared to models based on a continuous temperature distribution (e.g., Liu et al. 2000; Stasińska 2002; Tsamis et al. 2003). In these models, Zhang et al. (2007) have noted that the inclusion of even a minor fraction (~ 10%) of lowtemperature gas ($\sim 1000 \text{ K}$) could replicate the observed \sim 0.2-dex ADF. Meanwhile, it is plausible to consider that these cooler, denser clumps are in pressure equilibrium with their surroundings and possess a higher dust content, as Stasińska et al. (2007) proposed that these dense clumps could be notably metal-rich, adding another layer of complexity to the understanding of H II regions. To disentangle the effects of temperature, density, and dust on the observed ADF and to accurately gauge gas-phase abundances, a promising approach involves the utilization of fine-structure emission lines in the mid-IR. These lines are relatively unaffected by fluctuations in either T_e or n_e , offering a more reliable method for metallicity measurements. Additionally, leveraging mid-IR H Humphreys emission lines circumvents the complications of dust attenuation. Our group is actively exploring this avenue in future work.

5. SUMMARY

In this study, we conducted a detailed examination of T_e and metallicity from O⁺⁺ and N⁺ ions using optical and far-IR spectra of Haro 3, a nearby H II region. The analysis incorporated data from Herschel/PACS, SOFIA/FIFI-LS, and the recently commissioned red channel of Keck/KCWI. The combined capabilities of these three IFU instruments, covering optical and far-



Figure 7. A schematic diagram (*left*) illustrates how gas pockets obscured by dust could explain the observed discrepancies between the optical (OCEL) and far-IR line fluxes. Green arrows show the effect if 50% of emission line luminosities are unaccounted for at optical wavelengths due to regions of high dust obscuration (e.g., Hunt et al. 2006). In this case, the O^{++}/H^+ abundance from far-IR measurements would align with the OCEL method (*center*), while the N^+/H^+ discrepancy between far-IR and OCEL data narrows to ~ 1.5σ (*right*). Such a scenario is thus consistent with modest or zero temperature fluctuations, with t^2 smaller than required to explain the discrepancy between OCEL and RL. The higher N^+/O^{++} from far-IR relative to optical lines in this scenario is not highly significant, but can also be naturally explained by a lower ionizaton state (favoring N^+ and O^+) and/or higher N/O ratio in the highly obscured gas. In any case, a substantial amount of highly obscured emission is needed to explain the far-IR [N II] 122 μ m flux (right panel), and the effect of such correction is to lower the value of t^2 inferred from the comparison of far-IR and OCEL lines.

IR spectra, enabled precise aperture matching and robust comparisons of absolute fluxes. Our approach has yielded the first abundance discrepancy factor (ADF) measurements for both O^{++} and N^+ in a single astronomical object. The principal findings of this research include:

- To explain the ADF measured from the [N II] far-IR vs. OCEL method, temperature fluctuations would have to be unphysically large. The similar N^+/O^{++} ratios observed between the far-IR and OCEL lines indicate that dust obscuration is the main cause of the disparity. This is supported by previous work indicating the presence of infrared emission from heavily obscured regions.
- Assuming identical properties for both obscured and unobscured gas, the estimated fraction of obscured gas is ~ 50%. Nonetheless, the actual proportion of obscured gas could be lower, as suggested by the elevated N⁺/O⁺⁺ ratios measured in far-IR lines, which imply that the obscured gas may have higher N/O abundance and/or lower ionization levels.
- The [O III] far-IR vs. OCEL and RL vs. OCEL methods yield consistent t^2 measurements that align with typical values inferred from RL abundances in H II regions. However, the presence of heavily dust-obscured gas would imply a smaller t^2 value, and that temperature fluctuations alone do not fully account for the observed ADF.

- Non-thermal effects, i.e., a κ distribution, fail to reconcile the differences between far-IR and OCEL emissions. This model would require a disproportionate injection of high-energy plasma for N⁺ compared to O⁺⁺, which contradicts their respective ionization levels.
- Spatial variations of n_e are present in Haro 3. However, the amount of fluctuations is insufficient to significantly modulate the metallicity measurements.
- The relative ratios in the O II V1 RL multiplet are mutually inconsistent, and suggest a higher n_e compared to other density measurements. These inconsistencies necessitate a reevaluation of the RL emission mechanism and/or the atomic data for O II . However, the extent of this discrepancy in n_e does not significantly impact the conclusions.

Our findings underscore the importance of resolving the origin of the ADF and establishing an accurate metallicity scale. The far-IR fine-structure emission used in this study presents a powerful tool for evaluating the impact of temperature fluctuations in H II regions, and for cross-validating the results with multiple ions. The combination of far-IR and optical spectra, as utilized here, is especially relevant in light of the strong and auroral line measurements obtained at high redshifts with ALMA and JWST, now reaching z > 8. Furthermore, recent ALMA observations have found spatial offsets for the dust continuum and far-IR line emission relative to the UV stellar continuum at z > 4, suggesting a complex dust geometry (e.g., Hodge et al. 2012; Laporte et al. 2017; Matthee et al. 2019; Fujimoto et al. 2022; Killi et al. 2024). Our analysis of Haro 3 exemplifies the potential of such measurements to understand the biases inherent in different metallicity measurement techniques, highlighting both their potential and the associated challenges.

However, this study of Haro 3, along with Mrk 71 in C23, covers only a limited portion of the parameter space of H II regions. These cases underline the necessity for a broader investigation to understand the implications for all H II regions across cosmic history. A comprehensive dataset of H II regions, characterized by similarly detailed metallicity measurements under a variety of physical conditions, will be essential to this endeavor. Furthermore, spatially resolved measurements in both optical and IR spectra, including mid-IR observations via JWST, provide crucial opportunities to analyze and address the heterogeneity within H II regions. Notably, mid-IR features such as the H Humphrey lines and the [S III] and [Ne III] lines are relatively unaffected by variations in temperature, density, and dust content, offering more reliable diagnostic capabilities. Leveraging archival far-IR data combined with JWST mid-IR spectroscopy of nearby H II regions offers tremendous potential to unravel the underlying causes of the ADF and to refine our understanding of the true metallicity scale, as well as the complex properties of gaseous nebulae. Our team is committed to driving these investigations forward in future studies.

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Facilities: Keck(KCWI), SOFIA(FIFI-LS), Herschel(PACS)

Software: astropy (Astropy Collaboration et al. 2013, 2018, 2022), emcee (Foreman-Mackey et al. 2013), PyNeb (Luridiana et al. 2015), KCWI DRP (https://github.com/Keck-DataReductionPipelines/KcwiDRP), SOSPEX (https://github.com/darioflute/sospex), CWITools (O'Sullivan & Chen 2020), KcwiKit (https://github.com/yuguangchen1/KcwiKit.git), and Scientific Colour Maps (Crameri 2018).

APPENDIX

A. LINE FLUXES

Here, we provide a summary (Table 2) of the line flux measurements. The fluxes are measured from 1D spectra extracted from Keck/KCWI, SOFIA/FIFI-LS, and Herschel/PACS from two apertures: 1) $r_{\rm ap} = 2''_{.25}$ for the KCWI PSF, 2) $r_{\rm ap} = 3''_{.25}$ after the PSF is matched to the SOFIA/FIFI-LS [O III] $\lambda 52 \ \mu m$ data cube, and 3) the aperturematched and attenuation-corrected line instensities. The errors quoted in this table are from pure Poisson noise from observations, and do not include systematic uncertainties from flux calibration and attenuation correction. For details on how 1D spectra are extracted and fluxes are measured, see §3.1.

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Line	$_{\lambda_0}a$	$F(r_{\rm ap} = 2''_{\cdot}25)$	$F(r_{\rm ap}=3")$	$I(r_{\rm ap}=2.25)^b$
	(Å)	(10^{-16} erg s)	$s^{-1} cm^{-2}$)	$(I(H\beta) = 100)$
[O II]	3726.03	2006 ± 48	909 ± 14	124.3 ± 3.0
[O II]	3728.82	2546 ± 52	1224 ± 15	157.7 ± 3.2
$H\theta$	3797.90	90.3 ± 2.4	19.9 ± 1.7	5.47 ± 0.15
${ m H}\eta$	3835.39	151.9 ± 2.4	43.9 ± 1.7	9.10 ± 0.14
$H\delta$	3889.05	599.8 ± 2.4	208.5 ± 1.5	35.27 ± 0.14
$ m H\gamma$	4340.47	1152.6 ± 2.7	424.1 ± 1.5	56.05 ± 0.13
[O III]	4363.21	52.38 ± 0.66	19.51 ± 0.82	2.521 ± 0.032
O II	4638.86	1.76 ± 0.14		0.0747 ± 0.0059
O II	4641.81	2.45 ± 0.15		0.1039 ± 0.0064
O II	4649.13	0.82 ± 0.22		0.0347 ± 0.0093
O II	4650.84	1.17 ± 0.17		0.0494 ± 0.0072
O II	4661.63	2.36 ± 0.14		0.0992 ± 0.0059
O II	4676.23	0.78 ± 0.15		0.0326 ± 0.0063
[Ar IV]	4711.37	4.02 ± 0.12	1.92 ± 0.14	0.1654 ± 0.0049
[Ar IV]	4740.16	3.06 ± 0.13	1.02 ± 0.31	0.1243 ± 0.0053
${ m H}eta$	4861.33	2585.8 ± 3.1	1004.8 ± 1.6	100.00 ± 0.12
[O III]	4958.91	3651.7 ± 3.7	1186.5 ± 1.7	136.02 ± 0.14
[O III]	5006.84	10973.8 ± 6.3	3572.7 ± 2.7	401.61 ± 0.23
[Cl III]	5517.71	15.29 ± 0.96	8.69 ± 0.81	0.478 ± 0.030
[Cl III]	5537.88	11.4 ± 1.1	6.75 ± 0.85	0.355 ± 0.034
[N II]	5754.64	8.90 ± 0.23	2.57 ± 0.47	0.2627 ± 0.0068
[N II] c	6548.03	232.8 ± 2.6	103.7 ± 1.1	5.842 ± 0.065
$H\alpha$	6562.82	10122 ± 30	3606 ± 10	253.27 ± 0.75
[N II] c	6583.41	685.0 ± 7.7	305.0 ± 3.3	17.07 ± 0.19
[S II]	6716.47	601.6 ± 2.4	304.5 ± 1.0	14.611 ± 0.058
[S II]	6730.85	484.0 ± 2.2	232.59 ± 0.93	11.722 ± 0.053
[O II]	$auroral^d$	181.82 ± 0.24	59.45 ± 0.22	3.9213 ± 0.0052
P14	8598.39	29.44 ± 0.47	11.25 ± 0.16	0.5062 ± 0.0081
P10	9014.91	80.34 ± 0.46	22.03 ± 0.34	1.3107 ± 0.0075
[O III]	51.8145 $\mu \mathrm{m}$		3460 ± 270	95.1 ± 7.4
[O III]	88.3564 $\mu \rm{m}$		4150 ± 56	114.1 ± 1.5
[N II]	121.769 $\mu \mathrm{m}$		205 ± 16	2.27 ± 0.18

Table 2. Summary of Haro 3 line fluxes

^aRest-frame air wavelengths.

 $^b\,\mathrm{Dust-corrected}$ aperture-matched intensity.

 $^{c}\,\mathrm{Measured}$ simulta enously with fixed [N II] $~\lambda\lambda6583/6548$ ratio of 2.942.

 $[^]d$ Total flux of the [O II] $~\lambda\lambda7318.39,~7319.99,~7329.66,$ and 7330.73 auroral emission lines.

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