Effects of density and temperature variations on the metallicity of Mrk71

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Historically, two indicators of heavy element abundances in ionized nebulae, optical collisionally excited lines (CELs) with an exponential temperature (T_e) dependence and recombination lines (RLs) with less T_e sensitivity, have produced inconsistent results. By using the less T_e dependent infrared (IR) [O III] CELs, Chen et al. [1] argue that the temperature inhomogeneities scenario proposed by Peimbert [2] cannot explain the abundance discrepancy in the star-forming galaxy Mrk 71. We show that this conclusion depends on several assumptions, mainly the absence of biases in electron density (n_e) determinations, a parameter on which IR-CELs depend more than optical CELs. Since multiple n_e indicators in previous and the discussed work on Mrk 71 show significant differences, we

conclude that the existence of temperature inhomogeneities cannot be ruled out.

Chen et al. [1] tested the presence of temperature inhomogeneities in the star forming galaxy Mrk 71. To carry out their analysis, these authors used an optical spectrum from the Keck Cosmic Web Imager (KCWI) at the W. M. Keck Observatory as well as IR spectra from the Far Infrared Field-Imaging Line Spectrometer (FIFI-LS) at the Stratospheric Observatory for Infrared Astronomy (SOFIA) and from the Photodetector Array Camera and Spectrometer (PACS) at the Herschel Space Observatory.

By comparing the different H I line flux ratios with the theoretical predictions, they infer a reddening constant $c(\mathrm{H}\beta) = 0.09 \pm 0.04$, considering the reddening curve of [3] with $R_V = 3.1$. They derive the electron density (n_e) of the gas with three indicators: [O II] $\lambda3726/\lambda3729$, [O III] $\lambda52\mu\mathrm{m}/\lambda88\mu\mathrm{m}$ and the O II V1 RL multiplet. On the other hand, they derive the T_e by considering [O III] $\lambda4363/\lambda4959$ as well as [O III] $\lambda4959/\lambda52\mu\mathrm{m}$ and $\lambda4959/\lambda88\mu\mathrm{m}$. From the comparison of the $\mathrm{O}^{2+}/\mathrm{H}^{+}$ abundance derived both with optical [O III] CELs and O II RLs and assuming that the abundance discrepancy (AD) is produced by temperature variations, they infer a $t^2 \sim 0.1$ (see Eq. (12) from [2]). This result would imply that both the derived temperature from [O III] $\lambda4959/\lambda52\mu\mathrm{m}$ and $\lambda4959/\lambda88\mu\mathrm{m}$ should be ~ 3000 K lower than what is obtained from [O III] $\lambda4363/\lambda4959$. However, Chen et al.[1] found a good consistency between their calculations of T_e based on [O III] $\lambda4959/\lambda52\mu\mathrm{m}$, $\lambda4959/\lambda88\mu\mathrm{m}$ and $\lambda4363/\lambda4959$ and therefore they claim the absence of significant temperature fluctuations in Mrk 71.

The results obtained by Chen et al. [1] are highly dependent on the accuracy of the absolute flux calibration between the three instruments, since there are no H I detections in the IR data that could be used to normalize the spectra. Considering that the KCWI observations were taken under non-photometric conditions, that the FIFI-LS observations present telluric features [4] and that the PACS observations were carried out in the "un-chopped" mode and show detector response variations [5], the absolute flux calibration between the three different kinds of data is not straightforward. In fact, the comparison of [C II] $\lambda158\mu\mathrm{m}$, detected both in FIFI-LS and PACS reveals a difference of $\sim 15\%$ between the flux calibrated data of both instruments even after the PACS detector response variations correction. Possible systematic differences between the optical and IR-spectra are not analyzed or quantified by Chen et al. [1].

The difference between the FIFI-LS and PACS spectra implies the existence of a systematic bias in the flux of at least one of the [O III] IR CELs used. Dividing the flux difference of $\sim 15\%$ quadratically and including it in the uncertainty bars does not properly treat the systematic error, as it impacts differently [O III] $\lambda4959/\lambda52\mu\mathrm{m}$ than [O III] $\lambda4959/\lambda88\mu\mathrm{m}$, given their different n_e-dependence. Considering that both [O III] IR CELs have similar fluxes, a more robust way to reduce the impact of the flux bias is to use the sum of their fluxes instead, comparing T_e derived from [O III] $\lambda4959/\lambda\lambda52+88\mu\mathrm{m}$

with the value obtained using $\lambda4363/\lambda4959$. The flux systematic difference calls into question the density derived from [O III] $\lambda52\mu$m/$\lambda88\mu$m with the reported absolute fluxes.

In Fig. 1 we present the resulting plasma diagnostics considering the line fluxes and uncertainties reported by Chen et al. [1] under three values of $c(\mathrm{H}\beta)$, all consistent within the reported 1σ. In all cases, the reddening curve of [3] with $R_V = 3.1$ was used. The atomic data used were the default ones from PyNeb [6] in its version 1.1.16. As shown in Fig. 1, depending on the $c(\mathrm{H}\beta)$ and the n_e adopted, it is possible to be consistent either with the absence of temperature inhomogeneities or the opposite case, predicted by $t^2 = 0.097^{+0.008}_{-0.009}$.

The adoption of a density value close to n_e([O II] $\lambda3726/\lambda3729$)=160 $\pm$ 10 cm^{-3} instead of the available n_e(O II)=310 $\pm$ 50 cm^{-3} which comes from the O^{2+} ion, was not justified by [1]. Both values are typical within the range of densities found in previous studies of Mrk 71 [ranging from $\sim$ 50 cm^{-3} to $\sim$ 1200 cm^{-3} 7–9]. The most evident problem with the n_e value derived from [O II] $\lambda3726/\lambda3729$ by Chen et al. [1] is that panels (c) and (d) of their Fig. 2 show that the spectral resolution of KCWI is insufficient to have at least a partial separation of the [O II] doublet. Therefore, this density value strongly depends on the assumptions imposed on the Gaussian deblend required to measure the lines separately with uncertainty bars of $\sim$ 0.6%.

In order to reinforce their arguments on the absence of strong density and temperature fluctuations in Mrk 71, Chen et al.[1] mention that in a sample of regions, among which Mrk 71 does not appear, [10] found differences of only $\sim$ 1000 K between [O III] $\lambda1666/\lambda5007$ and [O III] and $\lambda4363/\lambda5007$ and that this is not sufficient for the temperature fluctuations scenario to explain the observed AD factor. However, such an assertion can be proven to be incorrect. Considering Eq. 15 from [2]: $T_e([\mathrm{O\,III}]\lambda1666/\lambda5007) - T_e([\mathrm{O\,III}]\lambda4363/\lambda5007)[\mathrm{K}] = 12330 \times t^2$. For the most common value of $t^2 \sim 0.04$ found for the star forming regions [11, 12], the temperature difference would be of $\sim$ 500 K. A very extreme value of $t^2 = 0.097^{+0.008}_{-0.009}$, would imply a difference of 1200 ± 110 K. This exercise demonstrates that the temperature differences found by [10] can comprise typical and extreme values of t^2.

We conclude that based on the data and the analysis presented by Chen et al. [1], one cannot be conclusive on the presence or absence of temperature inhomogeneities in Mrk 71. It is necessary to consider the possible presence of density variations that could introduce systematic biases on the n_e diagnostics even if the line intensity ratios are well measured as shown by [13]. n_e-biases could affect determinations of O^{2+}/H$^+$ based on [O III] $\lambda\lambda52 + 88\mu$m in a much higher extent than those based on O II V1. Observational evidence of temperature and density inhomogeneities in star-forming regions (including Mrk 71) is presented by [14] and [15], respectively.

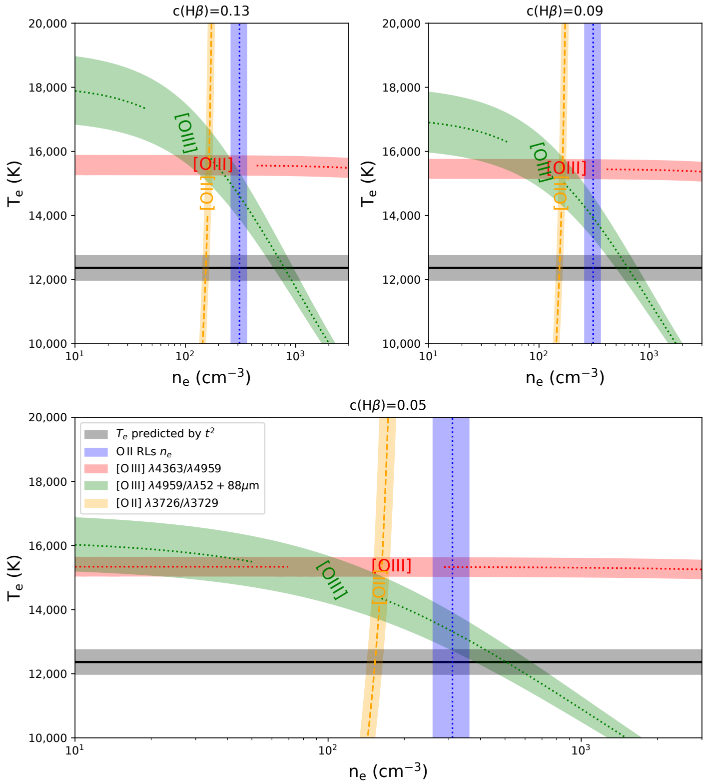

Figure 1: **Using the data presented by Chen et al. [1] it is possible to show either the absence of temperature inhomogeneities or the opposite case.** Each panel shows a plasma diagnostic plot considering a slightly different reddening constant, $c(\mathrm{H}\beta)$, all consistent within the 1σ uncertainties. According to the t^2-paradigm, in the presence of temperature inhomogeneities, [O III] $\lambda 4959/\lambda\lambda 52{+}88\mu$m (green band) should be lower than [O III] $\lambda 4363/\lambda 4959$ (red band), matching the value predicted by the O II RLs (black band). Depending on $c(\mathrm{H}\beta)$ and the adopted electron density (n_e), it is possible to argue either against the existence of temperature fluctuations or the opposite case.

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Conflict of interest/Competing interests. The authors declare no competing interests.

Data availability. All the data discussed here was presented by [1].

Code availability. Our results use the PyNeb code, publicly available on GitHub. https://github.com/Morisset/PyNeb_devel

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