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RADIATIVE FEEDBACK: MULTI-LINE STUDY OF THE PHOTO-DISSOCIATION REGION M17-SW

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Abstract. The radiation from massive stars, photo-dissociating and ionizing their parental molecular cloud, is a significant feedback process regulating star formation. To study it, we mapped the photo-dissociation region (PDR) M17-SW in several fine structure and high-J CO lines with FIFI-LS, the far-infrared integral spectrometer aboard SOFIA. An analysis of the CO and [OI]146 μm line intensities, combined with the far infrared intensity, allows us to create a density and UV intensity map using a one dimensional model. The density map reveals a sudden change in the gas density crossing the PDR. The strengths and limits of the model and the locations of the ionization and photo-dissociation fronts of the edge-on PDR are discussed.

1 Introduction

To study the destruction of molecular clouds by massive stars forming from them, we selected the well-studied edge-on PDR, M17-SW, for observations with FIFI-LS in several important cooling lines, which also can serve as diagnostics. The far-infrared imaging spectrometer FIFI-LS (Fischer et al., 2018) on SOFIA (Temi et al., 2018) allowed us to map a large portion of M17-SW in key far infrared transitions with the goal of modeling the whole mapped area with a simple PDR model. Fig. 1 shows an overview of M17 with the mapped area marked. We mapped the area in [O III] 52 μm and 88 μm, [NIII] 57 μm, [OI] 63 μm and 146 μm, [C II] 158 μm, and CO(16-15) and (14-13). From the continua measured together with the line intensities and available Herschel continuum maps, we created a far infrared intensity map (I_{FIR}) by creating spectral energy distributions (SEDs) at each map pixel and then integrating them.

2 PDR Analysis

The PDR Tool Box (PDRT, Pound and Wolfire, 2022)[1] predicts ratios and some absolute intensities of the main cooling lines of a PDR depending on the density of hydrogen nuclei (H-density), n, and the strength of the UV radiation field, G_{UV}. In addition, the far infrared intensity is predicted assuming that all the UV radiation is absorbed and re-emitted in the far infrared. The comparison between observations and predictions provides us with estimates of n and G_{UV} for each position in the mapped area. We only compare the optically thin [OI]146 μm and CO($14 \to 13$) lines and I_{FIR} to the PDRT model. Since the optically thin emission can escape in any direction, the observed intensities should not depend much on the exact geometry of the PDR like the inclination angle of the PDR surface nor the clumpiness of the medium. Taking the line ratio can further eliminate any systematic effects. The result for the H-density is shown in the *top left panel* of Fig. 2. The H-densities form a bimodal distribution with peaks at $10^{3.8}\mathrm{cm}^{-3}$ and $10^{5.9}\mathrm{cm}^{-3}$ and a distinct jump in density. A contour is drawn as reference to the jump in the two *top panels* of Fig. 2, enclosing densities of more than $10^5\mathrm{cm}^{-3}$ with an uncertainty better than 1 dex. The UV intensity follows

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[1] http://dustem.astro.umd.edu/ The PDR Tool Box (PDRT) was significantly revised in August 2020, when the analysis presented here had already been finished. In terms of the new PDRT, we are using the wk2006 models.

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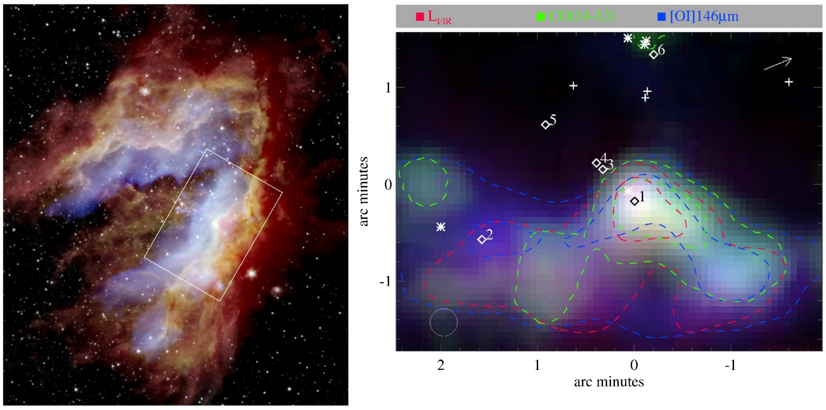

Figure 1: *Left:* M17 (3.6 μm- white, 20 μm- blue, 37 μm- green, 70 μm- red) by Lim et al. (2020); the box shows the approximate location of the FIFI-LS maps. *Right:* The three observed intensities maps used to calculate the input quantities for the PDRT model. The contours are at 1/3 and 2/3 of the peak fluxes. The circle indicates spatial resulution. The white symbols indicate the locations of the O-stars identified by Hoffmeister et al. (2008): stars for types earlier than O9, crosses for types O9 and O9.5. The arrow points north.

closely the I_{FIR} map as can be expected from the model assumption. The UV intensities go up to $10^{4.7}\,G_0$ and have a median of $10^{4.1}\,G_0$, with G_0 being the Habing field ($0.12{\cdot}10^{-3}$erg cm^{-2}s^{-1}sr^{-1}).

2.1 PDR Structure

The *top right panel* of Fig. 2 shows a three-color image of M17-SW in three mid-infrared tracers. There is a color change showing where the conditions change in this layered edge-on PDR. There is the red-blue region with strong 8 μm and [O III]52 μm emission with a quick transition to the green-blue region with strong 37 μm and some 8 μm but vanishing [O III]52 μm emission. The density jump follows the color change fairly well, and thus also the transition from the H II-region to the molecular cloud, except around the clump containing M17-UC1. There, the yellow contour is well in front of the sharp edge of the clump towards the H II-region, which can be seen in the IRAC Band 4 and the FORCAST 37 μm image. Since the PDRT modeling is based on the FIR maps smoothed to a resolution of about 17″, the location of the density jump can easily be pushed out by a good fraction of the maps' resolution around the flux peaks of these maps, which all peak around M17-UC1.

Hollenbach and Tielens (1999) report in their section on "Time-dependent and nonstationary PDRs" that for relatively high gas densities ($\approx 10^6$cm^{-3}) and UV intensities ($10^{4.5}G_0$), as derived here for the PDR region, the ionization and dissociation fronts can even merge as H_2 flows fast enough towards the H II region. Therefore, in M17-SW, the ionization and photo-dissociation fronts may even be merged. Even with a clumpy structure and projection effects, the density jump in the model and the layered appearance of the various tracers indicate that both fronts should be where the red and yellow contours drawn in the *top right panel* of Fig. 2.

2.2 Predictions for the [C II] and [OI] 63 μm lines

Using the derived densities and UV intensities, the PDRT can predict e.g., the line ratios of the [C II] and [OI] 63 μm lines to the [OI] 146 μm line. Overall, there is about a factor of 3 less [C II] emission relative to [OI] 146 μm predicted by the PDRT than we observe, even if we subtracted a foreground [C II] emission. A clumpy PDR model (see, e.g., Stutzki and Guesten, 1990) would predict a stronger [C II] emission from the PDR, but that cannot be the whole explanation. A clumpy PDR model would not explain the higher [C II]/[OI] 146 μm ratio in the H II-region. A combination of a widespread foreground [C II], under-predicted [C II] due to a non-clumpy model, and [C II] coming from other local phases not included in the simple model may all contribute to the discrepancy to the observed [C II] emission.

The *lower panel* of Fig. 2 shows the predicted and observed [OI] line ratio. Taking the large uncertainties into account, the observations and predictions of the [OI]-line ratio agree with each other in the H II-region. However, going from the H II-region into the molecular cloud, the observed ratio clearly drops from the high

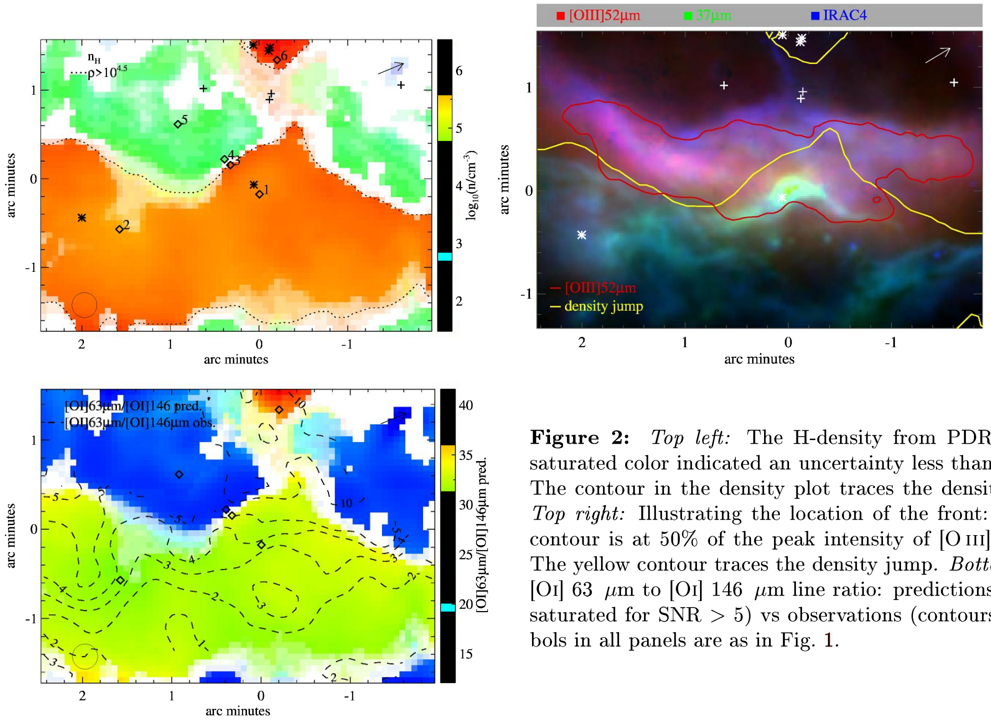

Figure 2: *Top left:* The H-density from PDRT. Fully saturated color indicated an uncertainty less than 0.2 dex. The contour in the density plot traces the density jump. *Top right:* Illustrating the location of the front: the red contour is at 50% of the peak intensity of [O III] 52 μm. The yellow contour traces the density jump. *Bottom:* The [OI] 63 μm to [OI] 146 μm line ratio: predictions (colors; saturated for SNR > 5) vs observations (contours). Symbols in all panels are as in Fig. 1.

values in the H II-region down to less than two and even to unity in some places deep into the cloud. The increasing self-absorption of the [OI] 63 μm line deeper into this edge-on PDR is exactly what we expected to see in this edge-on geometry.

3 Conclusions

The PDR known as M17-SW has been mapped with SOFIA/FIFI-LS in several fine-structure lines and high-J CO lines. The line ratio maps of the optically thin PDR-lines and the continuum maps, in form of the infrared intensity, were used to model the conditions across the mapped area using the PDRT tool, yielding a hydrogen nuclei density map with a distinct jump and UV radiation map. The high H-densities and derived UV field point to the ionization and photo-dissociation fronts being nearly merged. Using a relatively simple PDR model with optically thin tracers allowed us to derive maps for the parameters of the model and to make predictions for the optically thick lines producing a consistent picture of the physical conditions in the PDR. The density jump approximates the area where the atomic layer in the edge-on PDR should be expected.

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