SF2A 2022
J. Richard, A. Siebert, E. Lagadec, N. Lagarde, O. Venot, J. Malzac, J.-B. Marquette, M. N'Diaye, D. Briot (eds)

DUST EVOLUTION IN PHOTON-DOMINATED REGIONS

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Abstract. Carbonaceous nano-grains play a fundamental role in the physico-chemistry of the interstellar medium (ISM) and especially of photon-dominated regions (PDRs). Their properties vary with the local physical conditions and affect the local chemistry and dynamics. We aim to highlight the evolution of carbonaceous nano-grains in three different PDRs and propose a scenario of dust evolution as a response to the physical conditions. We used Spitzer/IRAC (3.6, 4.5, 5.8, and 8 μm) and Spitzer/MIPS (24 μm) together with Herschel/PACS (70 μm) to map dust emission in IC63 and the Orion Bar. To assess the dust properties, we modelled the dust emission in these regions using the radiative transfer code SOC together with the THEMIS dust model. Regardless of the PDR, we find that nano-grains are depleted and that their minimum size is larger than in the diffuse ISM (DISM). The evolution of the nano-grain dust-to-gas mass ratio with both G_0 and the effective temperature of the illuminating star indicates a competition between the nano-grain formation through the fragmentation of larger grains and nano-grain photo-destruction. We modelled dust collisions driven by radiative pressure with a classical 1D approach to show that this is a viable scenario for explaining nano-grain formation through fragmentation and, thus, the variations observed in nano-grain dust-to-gas mass ratios from one PDR to another. We find a broad variation in the nano-grain dust properties from one PDR to another, along with a general trend of nano-grain depletion in these regions. We propose a viable scenario of nano-grain formation through fragmentation of large grains due to radiative pressure-induced collisions.

Keywords: ISM: individual objects: IC63, Orion Bar – ISM: photon-dominated regions (PDR) – dust, extinction – evolution

1 Introduction

Interstellar dust is ubiquitous in the interstellar medium (ISM) and it is involved into the physical, chemical, and dynamical evolution of numerous environments through different processes such as the gas heating through the photoelectric effect (Bakes & Tielens 1994; Weingartner & Draine 2001) and the H_2 formation on dust surfaces (e.g Le Bourlot et al. 2012; Bron 2014; Jones & Habart 2015). The efficiency of these processes depends crucially on the dust properties (size, composition, and shape). It is therefore crucial to constrain those properties in order to understand better the different environments where dust exists. However, the broad disparity in the physical conditions (density and irradiation) triggers an evolution of these dust properties through grain growth (i.e. accretion and coagulation), grain destruction (i.e. photo-destruction and collisions), and processing (i.e. aromatisation, dehydrogenation), which are not yet fully understood.

The radiative feedback of freshly formed stars irradiating their nearby dense environments leads to the creation of the well-known photon-dominated regions (PDRs). In these regions, physical conditions vary significantly on small spatial scales which is why PDRs are a unique place to study how dust evolves as a response to the physical conditions. The mid-IR spectra of PDRs present a wealth of emission band features due to the smallest grains overlying the continuum of hot dust emission which has been extensively analysed using the Infrared Space Observatory (ISO) and Spitzer data. Strong variations in the spectra have been found across and between PDRs (e.g. Peeters et al. 2002, 2004; Rapacioli et al. 2006; Abergel et al. 2002; Bern et al. 2007). With Herschel data in the far-IR (FIR), it has also become possible to study the emission of large grains in

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thermal equilibrium (e.g. Abergel et al. 2010; Arab et al. 2012). Using the dust model THEMIS (Jones et al. 2013, 2017) together with the 3D radiative transfer code SOC (Juvela 2019), the study from Schirmer et al. (2020) (hereafter called Paper I) reported that the nano-grain dust-to-gas mass ratio in the irradiated outer part of the Horsehead is 6-10 times lower than in the diffuse ISM and that the minimum size of these grains is 2.25 times larger than in the diffuse ISM.

The gas physics and chemistry in PDRs are strongly affected by variations in the dust properties (Schirmer et al. 2021). The aim of this talk is to present the constraints on the nano-grain dust properties in the Orion Bar and in IC63, two PDRs that present very contrasted physical conditions, using *Spitzer* and *Herschel* observations.

2 Data and model

We describe here the previous studies of the Orion Bar and IC63 and we also present the *Spitzer* and *Herschel* observations. We also detail the THEMIS dust model as well as the radiative transfer code used to compute dust emission.

2.1 Selected PDRs

The Orion Bar (see Fig. 1, right panel) is a bright filament of the Orion molecular cloud, a site located at 414 pc (Menten et al. 2007) that is undergoing massive star-formation. The bar is illuminated by the O7-type star θ^1 Ori C, the most massive member of the Trapezium young stellar cluster, at the heart of the Orion Nebula (about $2'$ north east of the Bar, e.g., O'Dell 2001). We follow Arab et al. (2012) and adopt $G_0 = 2.6 \times 10^4$ in this study. Since it was first discovered with the telescope of the Mount Wilson and Palomar Observatories then mentioned in Sharpless (1953), IC63 (see Fig. 1, left panel) has been the subject of various studies (e.g. Fleming et al. 2010; Andersson et al. 2013; Andrews et al. 2018; Dennis 2020; Lai et al. 2020; Soam et al. 2021a,b). As G_0 estimates vary between $G_0 \sim 1000$ (Thi et al. 1999) and $G_0 \sim 1200$ (Witt et al. 1989; Jansen et al. 1994), we chose $G_0 = 1100$.

We use *Spitzer* and *Herschel* observations in six photometric bands (3.6, 4.5, 5.8, 8, 24, and 70 μm) for IC63 and in five photometric bands (3.6, 4.5, 5.8, 8, and 70 μm) for the Orion Bar[*]. The processing of the *Spitzer* maps is detailed in Bowler et al. (2009). We study the observed emission profiles through a cut across both of these PDRs (see solid white lines in Fig. 1).

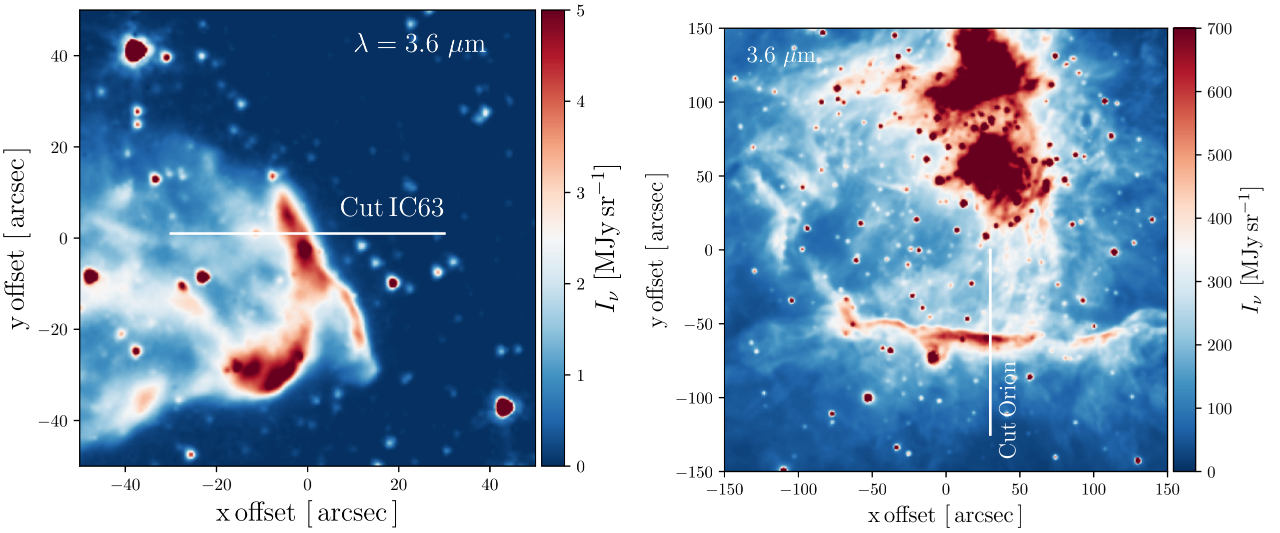

Fig. 1. Selected PDRs seen with Spitzer. Left: IC63 seen at 3.6 μm. Right: the Orion Bar seen at 3.6 μm. The white solid lines correspond to the cuts used in our study.

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[*] Observations at 24 μm of the Orion Bar exist but are saturated.

2.2 Dust modelling

Photon-dominated regions are optically thick and radiative transfer is therefore required to properly model dust emission. We used the 3D radiative transfer code SOC (Juvela 2019), together with the THEMIS dust model (described hereafter).

The Heterogeneous dust Evolution Model for Interstellar Solids, THEMIS[†] (e.g., Jones et al. 2013; Khler et al. 2014; Jones et al. 2017) is based on observational constraints and laboratory measurements on interstellar dust analogues that are amorphous hydrocarbons, a-C(:H) (e.g., Jones 2012a,b,c), and amorphous silicates, a-Sil. This model includes dust evolution through processes such as photo-processing, fragmentation, and coagulation resulting from wide variations in the physical condition of the ISM. The THEMIS model for the diffuse ISM is therefore composed of three dust populations that are i) a-C(:H) dust population whose size distribution follows a power-law with an exponential cut-off. Since about 80 % of the mass of this population is found in grains smaller than 20 nm, and thus mostly aromatic-rich, we refer to it as a-C grains or nano-grains indifferently in the following. ii) a-C(:H) dust population whose size distribution follows a log-normal law. As this population is essentially composed of a-C:H/a-C core-mantle grains (99 % of mass), we refer to it as a-C:H/a-C grains, although a few a-C are included. iii) a-Sil/a-C dust population whose size distribution follows a log-normal law.

3 Constraints on dust properties

Nano-grain properties are contrained through three parameters associated with their size distribution: 1) the abundance, that is, the a-C mass to gas ratio, $\mathrm{M_{a-C}/M_H}$; 2) the minimum size, $a_{\mathrm{min,\,a-C}}$; and 3) the slope of the power-law size distribution, α. The influence of variations in these parameters on both the dust size distribution and the associated spectra in the optically thin limit are shown in Schirmer et al. (2020) (Fig. 4, first line for the dust size distributions and second line for the associated spectra).

We use the 3D radiative transfer code SOC together with THEMIS to model dust emission in IC63 and the Orion Bar. We explore the 3D-space ($\mathrm{M_{a-C}/M_H}$, $a_{\mathrm{min,\,a-C}}$, α) to assess dust properties in IC63 and in the Orion Bar (more details about the 3D-exploration in Schirmer et al. (2022)). The main results are:

1. Whether in IC63 or in the Orion Bar, the nano-grain dust-to-gas mass ratio, $\mathrm{M_{a-C}/M_H}$, is lower than in the diffuse ISM. In IC63, $\mathrm{M_{a-C}/M_H}$ is roughly twice as low as in the diffuse ISM. In the Orion Bar, $\mathrm{M_{a-C}/M_H}$ is 60-100 times lower than in the diffuse ISM. The uncertainty on this last value is due to the degeneracy between $a_{\mathrm{min,\,a-C}}$ and α.

2. The nano-grain minimum size, $a_{\mathrm{min,\,a-C}}$, in IC63 is 1.75 times larger than in the diffuse ISM. In the Orion Bar, the degeneracy between $a_{\mathrm{min,\,a-C}}$ and α does not allow us to draw a conclusion on the nano-grain minimum size.

3. The power-law exponent of the nano-grain size distribution, α, is the same in IC63 and in the diffuse ISM. Regarding the Orion Bar, α is at least 1.2 times lower than in the diffuse ISM.

We find a good agreement between our modelled dust emission and the observations of *Spitzer* and *Herschel* in IC63 (see Fig. 2) and the Orion Bar (see Fig. 8 in Schirmer et al. (2022)). In IC63, it is possible to simultaneously fit the observations in all the photometric bands only if we remove the one at 4.5 μm. This problem has already been encountered in the Horsehead Nebula (see Schirmer et al. (2020)) and explained therein. These results confirm what was found for the Horsehead, namely, an increase in the nano-grain minimum size together with a decrease in the nano-grain dust-to-gas mass.

4 Conclusion

We use *Spitzer* and *Herschel* data to map dust emission in two PDRs: IC63 and the Orion Bar. We modelled dust emission across those two PDRs using the THEMIS dust model together with the radiative transfer code SOC. We show that dust similar to that of the diffuse ISM cannot explain the observations and, thus, the dust size distribution has to be modified.

The nano-grain dust-to-gas mass ratio is roughly half that of IC63 and almost 100 times lower in the Orion Bar than in the diffuse ISM. The nano-grain minimum size is about 0.7 nm in IC63 and no more than 0.8 nm

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[†] THEMIS is available here : https://www.ias.u-psud.fr/themis/

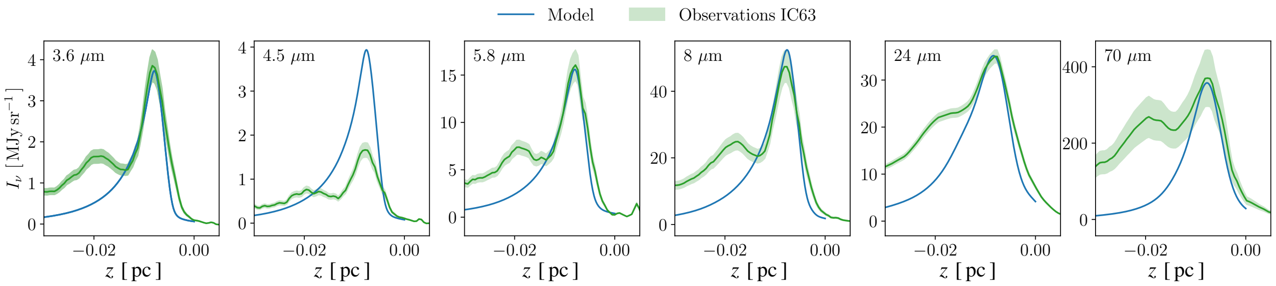

Fig. 2. Comparison between the observed dust emission and the modelled dust emission in IC63 using the best set of dust parameters ($M_{\mathrm{a-C}}/M_{\mathrm{H}}$ = 0.10 $\times 10^{-2}$, $a_{\mathrm{min,\,a-C}}$ = 0.70 nm, and α = -5) in six photometric bands (3.6, 4.5, 5.8, 8, 24, and 70 μm). The dust modelled (observed) emission is shown in blue (green) line. The cut considered across IC63 is shown in Fig. 1.

in the Orion Bar. The slope of the size distribution in IC63 is almost the same as in the diffuse ISM whereas it is steeper in the Orion Bar. This suggests that the mechanism at the origin of the nano-grain destruction is more efficient than the one of nano-grain formation in the Orion Bar compared to IC63.

To this end, we estimate formation timescales assuming that nano-grains are mainly formed through collisions between larger grains driven by radiative pressure from the star (see Schirmer et al. (2022)). We also estimate destruction timescales assuming that nano-grains are destroyed by energetic photons. Based on this timescale analysis, we find that the nano-grain destruction-to-formation ratio increases from IC63 to the Orion Bar, through the Horsehead, which explains the decrease in the nano-grain abundance from IC63 to the Orion Bar. As the photo-destruction efficiency is quite low in IC63 compared to the Orion Bar and Horsehead, whereas the formation of nano-grains in IC63 is efficient, this explains why the presence of dust in IC63 is more similar to what we would find in the diffuse ISM – as compared to what we would find in the Orion Bar and the Horsehead. The fact that the nano-grain minimum size scarcely varies from one PDR to another, but is still twice as large as than in the diffuse ISM suggests that there is a critical size above which dust grains are resilient to photo-destruction, regardless of irradiation. Based on our constraints on the nano-grain minimum size, we find that this critical size is around 0.7-0.8 nm.

This work was supported by the Programme National Physique et Chimie du Milieu Interstellaire (PCMI) of CNRS/INSU with INC/INP co-funded by CEA and CNES. We would like to thanks Olivier Bern for stimulating discussions on dust photo-dissociation. T.S. acknowledges support from the Knut and Alice Wallenberg Foundation (grant no. 2020.0081).

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