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Dust Evolution across the Horsehead Nebula (T. Schirmer et al.)

Abstract

Context. Micro-physical processes on interstellar dust surfaces are tightly connected to dust properties (i.e. dust composition, size and shape) and play a key role in numerous phenomena in the interstellar medium (ISM). The large disparity in physical conditions (i.e. density, gas temperature) in the ISM triggers an evolution of dust properties. The analysis of how dust evolves with the physical conditions is a stepping-stone towards a more thorough understanding of interstellar dust.

Aims. The aim of this paper is to highlight dust evolution in the Horsehead Nebula PDR region.

Methods. We use *Spitzer*/IRAC (3.6, 4.5, 5.8 and 8 μm), *Spitzer*/MIPS (24 μm) together with *Herschel*/PACS (70 and 160 μm) and *Herschel*/SPIRE (250, 350 and 500 μm) to map the spatial distribution of dust in the Horsehead over the entire emission spectral range. We model dust emission and scattering using the THEMIS interstellar dust model together with the 3D radiative transfer code SOC.

Results. We find that the nano-grains dust-to-gas ratio in the irradiated outer part of the Horsehead is 6 to 10 times lower than in the diffuse ISM. Their minimum size is 2 to 2.25 times larger than in the diffuse ISM and the power-law exponent of their size distribution, 1.1 to 1.4 times lower than in the diffuse ISM. Regarding the denser part of the Horsehead, it is necessary to use evolved grains (i.e. aggregates, with or without an ice mantle).

Conclusions. It is not possible to explain the observations using grains from the diffuse medium. We therefore propose the following scenario to explain our results. In the outer part of the Horsehead, all the nano-grains have not yet had time to re-form completely through photo-fragmentation of aggregates and the smallest of the nano-grains that are sensitive to the radiation field are photo-destroyed. In the inner part of the Horsehead, grains most likely consist of multi-compositional, mantled aggregates.

Key words. ISM: individual objects: Horsehead Nebula – ISM: photon-dominated regions (PDR) – dust, extinction – evolution

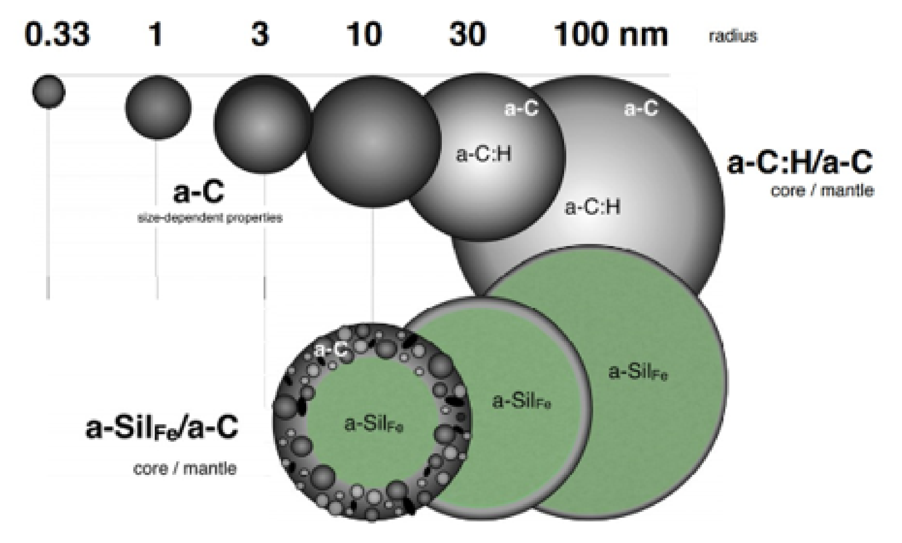


Fig. 1. Model dust populations, as seen in cross-section. In the upper part the a-C:H/a-C grains are shown, where black represents aromatic-rich material and white aliphatic-rich material. In the lower part amorphous silicate grains (green) are shown with a 5 nm thick coagulated/accreted a-C mantle. The particle radii are indicated on a logarithmic scale.

THEMIS モデルの概念図 (A. Jones+, 2013)
(N. Ysard+, 2016)

Background

星間空間に存在するダストの概念的なモデル

1. (power-law) silicate & graphite + PAH — MRN ダスト / Draine & Lee 1984 など
2. コア-マントル構造を持ったダスト → 著者らはこのタイプのダストモデルを研究している中心的なグループ
3. アグリゲイト構造を持ったダスト

Overview

Horsehead Nebula の赤外線強度プロファイルを PDR code で再現

3.6–500 μm (Spitzer/IRAC & MIPS, Herschel/PACS & SPIRE)

PDR code に入れるダストとして 3つの Cases を比較した

- Case: a シンプルなコアーマントルモデル
- Case: b 高密度環境でダストアグリゲイトが形成
- Case: c 高密度環境で氷をまとったダストアグリゲイトが形成

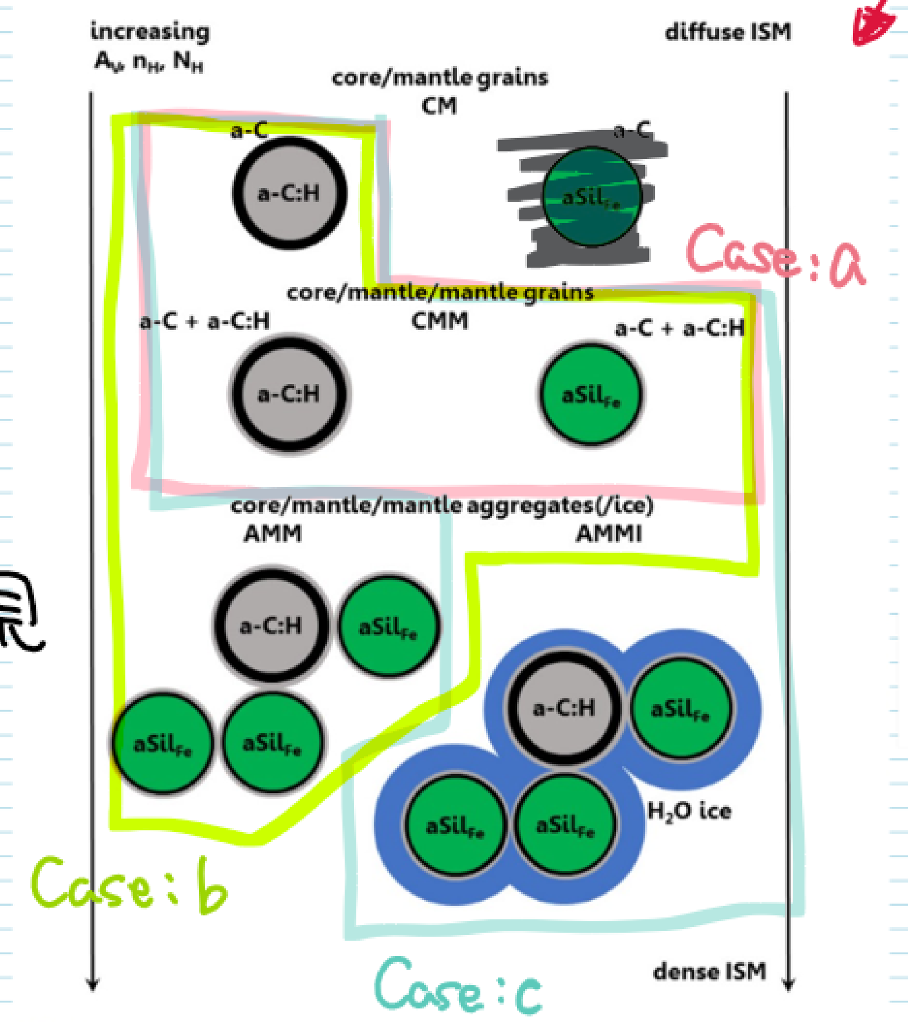


Fig. 1. Schematic view of the dust composition and stratification from the diffuse ISM to dense molecular clouds. The gas density increases from the top to the bottom of the figure.

Result

ISMのダストに比べて a-Cの量が少ない, 最小ダストサイズが大きい, サイズ分布が steep (Caseに依らず) (これは説明されていないような…)

遠赤外線のプロファイルは Case c によって最も良く再現された

分子雲内で icy ダストアグリゲイトの形成

Discussion

2つの dust photo-processing mechanisms が重要だと示唆

- (i) ダストアグリゲイトの部分的な破壊 → ダストサイズの再分配
- (ii) 小さな a-C ダストの破壊 (蒸発)

タイムスケールの観点でも大きな矛盾はない

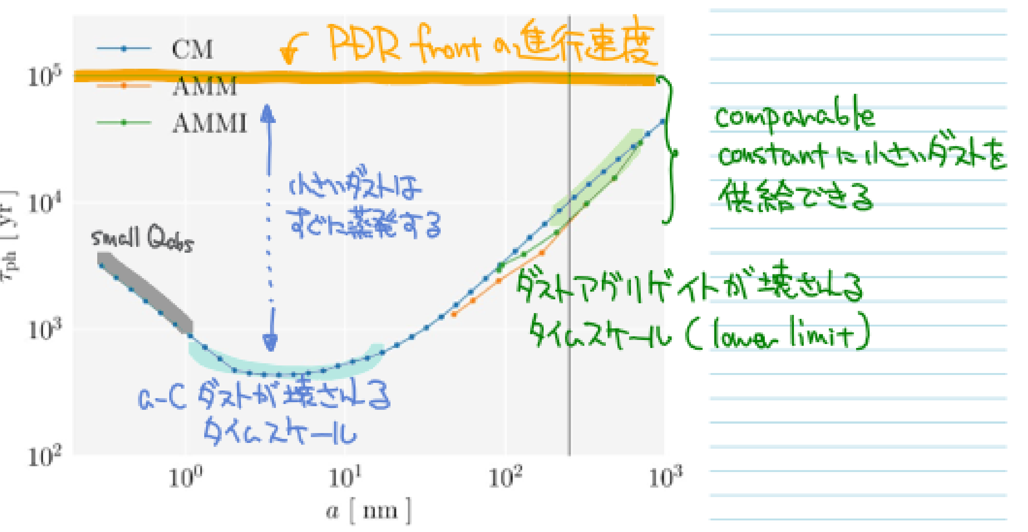


Fig. 12: Photo-fragmentation time-scale at the Horsehead edge as a function of the grain radius, a. Blue line refers to CM grains, orange line to AMM and green line to AMMI. The horizontal black line corresponds to the advection time-scale $\tau_a \sim 10^5$ years in the outer part of the Horsehead. The vertical black line corresponds to the limit at 250 nm beyond which more than 50 % of the AMM(I) dust mass is contained (Ysard et al. 2016).

THEMISモデルを用いることで Horsehead nebula における ダストの進化を議論することができた

分子雲内でのアイス+ダストアグリゲイトの形成

photo-processing による small a-C の破壊 / ダストアグリゲイトからの small dust 供給

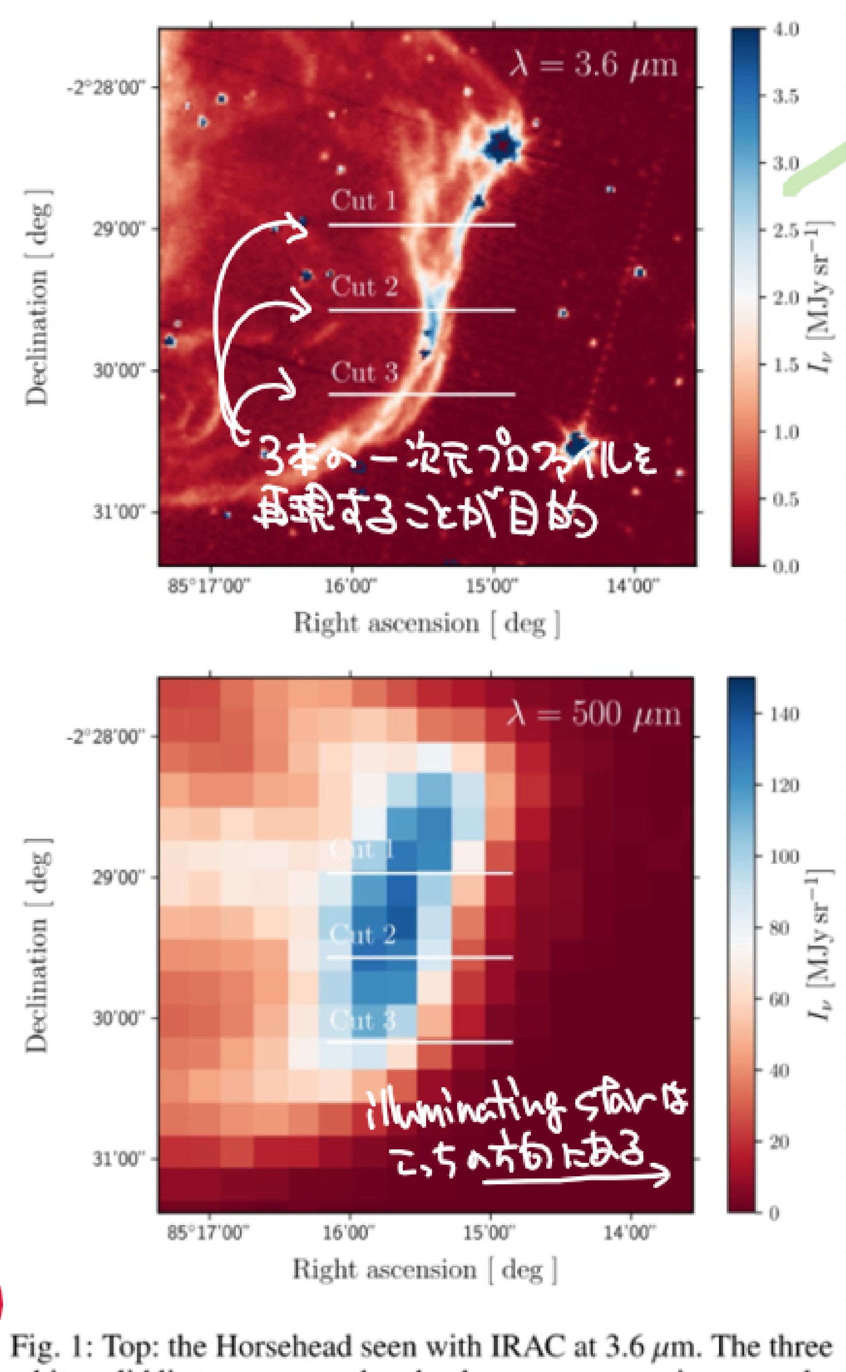


Fig. 1: Top: the Horsehead seen with IRAC at 3.6 μm. The three white solid lines correspond to the three cuts we use in our study. Bottom: the Horsehead seen with SPIRE at 500 μm.

3.6μm & 500μm の撮像結果
分子雲が西からの光源によって照らされている
3つの一次元プロファイル (cut 1–3) が今回の解析の対象になっている

分子雲の構造を単純化
- edge の内側では一定密度
- edge の外側では polynomial
- 奥行き方向には constant
- 分子雲の厚さは変わらない

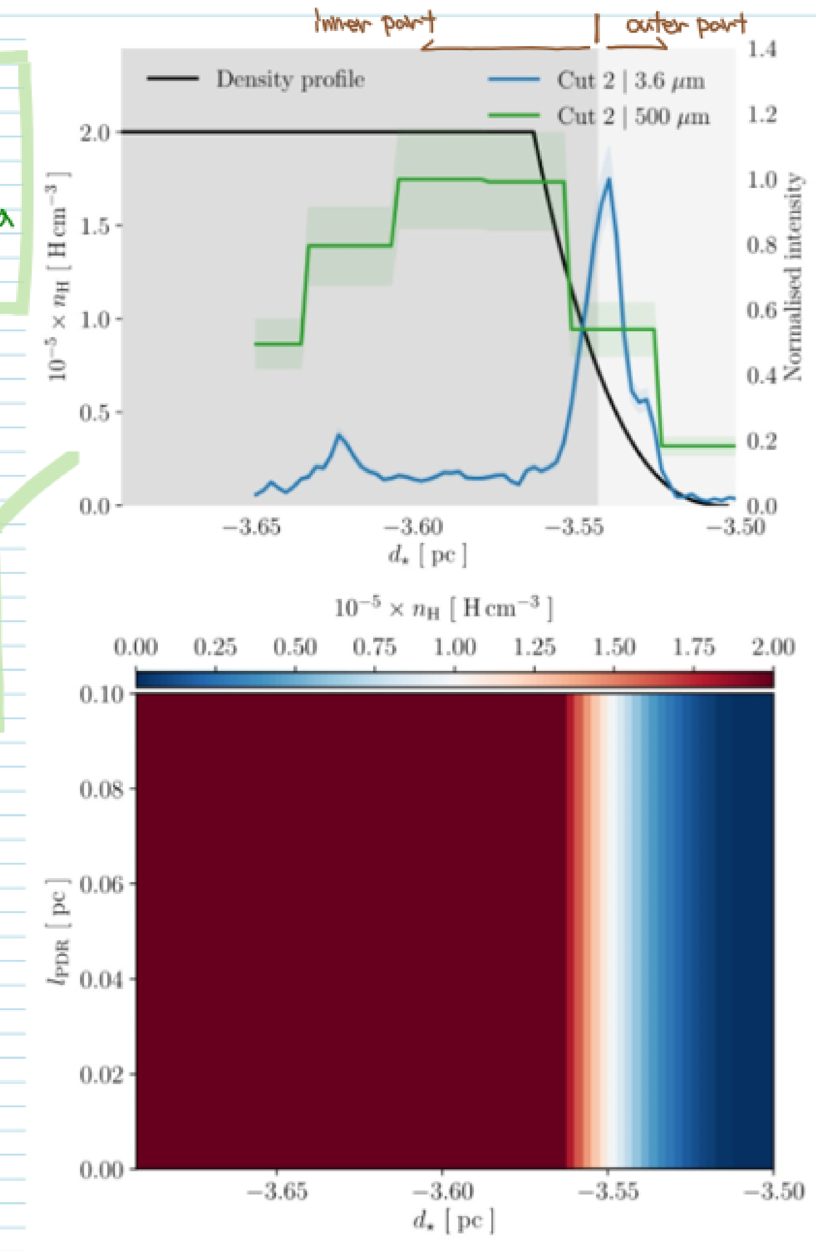
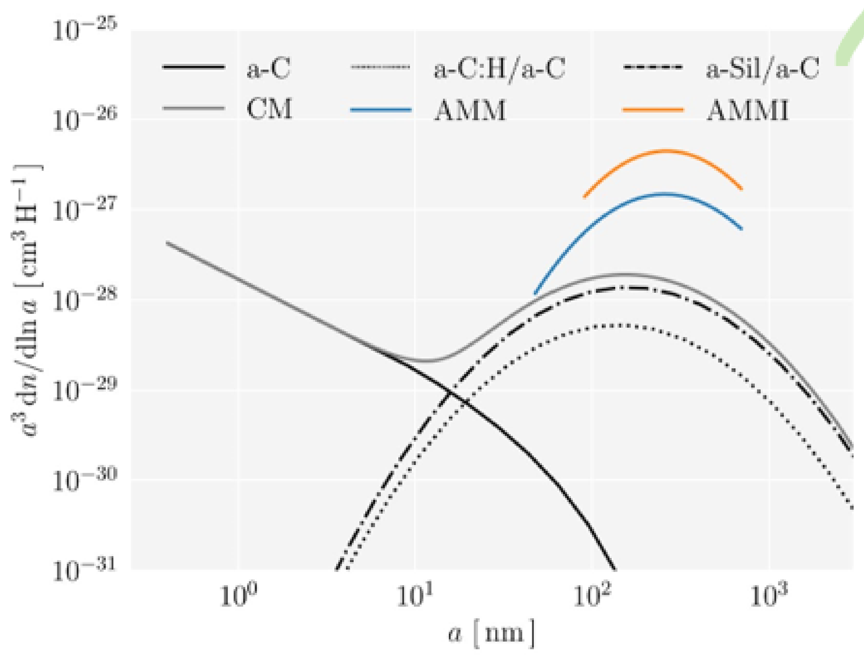


Fig. 2: Top: assumed density profile across the Horsehead (black line, see Sect. 2.3). Normalised observed dust emission (blue line) in IRAC$_{3.6}$ (see Fig. 1) and observed dust emission (green line) in SPIRE$_{500}$. The grey part corresponds to the inner part of the Horsehead, defined in Sect. 4.4. Bottom: density profile in the 2D-space defined by the distance to the star, $d_\star$, and the length of the Horsehead along the line of sight, l_{PDR}.

THEMIS モデルでのダストサイズ分布
a-C だけ truncated power-law
マントルのついたダストは log-normal



Name	size	α	a_{min} [nm]	a_{max} [nm]	a_c [nm]	a_t [nm]	a_0 [nm]
Core Mantle grains (CM)							
a-C	p-law	5	0.4	4900	10	50	-
a-C:H/a-C	log-n	-	0.5	4900	-	-	7
a-Sil/a-C	log-n	-	1	4900	-	-	8
Aggregated Mantle Mantle grains (AMM)							
AMM	log-n	-	47.9	700	-	-	479
Aggregated Mantle Mantle Ice grains (AMMI)							
AMMI	log-n	-	91.2	700	-	-	610

fitting のパラメタは以下
- a-C/ガス 質量比
- a-C 最小サイズ
- a-C power-law index
- 分子雲の厚さ

どの Case でもそれなりに説明できる結果を得たが
Cut 1–3 のいずれにおいても Case c のアイスアグリゲイトが最良の fit 結果

	Case a cut 1	Case a cut 2	Case a cut 3	Case b cut 1	Case b cut 2	Case b cut 3	Case c cut 1	Case c cut 2	Case c cut 3
$10^2 \times M_{a-C}/M_H$	0.009	0.011	0.011	0.011	0.017	0.013	0.013	0.021	0.017
$a_{min,a-C}$ [nm]	0.825	0.825	0.925	0.825	0.8	0.925	0.825	0.8	0.9
α	-7.0	-6.0	-7.5	-6.5	-5.5	-7.5	-6.5	-5.5	-6.5
l_{PDR} [pc]	0.283	0.297	0.273	0.290	0.267	0.282	0.275	0.254	0.265
χ^2_{min}	49.6	45.1	36.0	51.0	33.9	36.9	41.3	30.5	30.7

Table 1: Best set of parameters (M_{a-C}/M_H, $a_{min,a-C}$, α and l_{PDR}) and the χ^2_{min} associated with all cuts and cases.

4.5 μm, 70 μm はどの Cases も fit せず
⇒ 使っているダストの光学特性のせい?

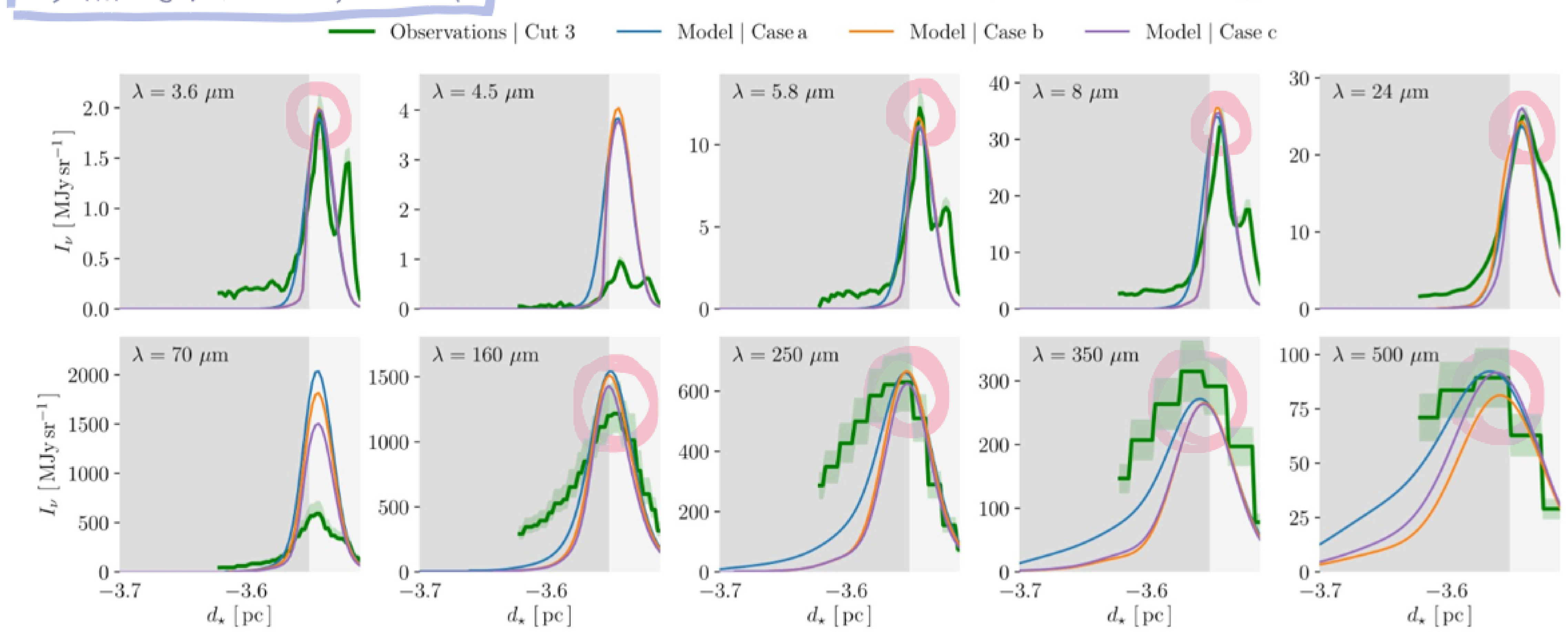


Fig. 10: Top : Comparison between observed emission profiles for cut 1 (green line) with modelled emission profiles obtained with the best set of parameters (see Tab. 1) for case a (blue line), case b (orange line), case c (purple line). Middle : same for cut 2. Bottom : same for cut 3. The grey parts correspond to the inner Horsehead where AMM and AMMI are used in case b and case c, respectively.