



Universiteit  
Leiden  
The Netherlands

## Orion's Dragon and other stories: Feedback by massive stars

Pabst, C.H.M.

### Citation

Pabst, C. H. M. (2021, March 18). *Orion's Dragon and other stories: Feedback by massive stars*. Retrieved from <https://hdl.handle.net/1887/3147353>

Version: Publisher's Version

License: [Licence agreement concerning inclusion of doctoral thesis in the Institutional Repository of the University of Leiden](#)

Downloaded from: <https://hdl.handle.net/1887/3147353>

**Note:** To cite this publication please use the final published version (if applicable).

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/3147353> holds various files of this Leiden University dissertation.

**Author:** Pabst, C.H.M.

**Title:** Orion's Dragon and other stories: Feedback by massive stars

**Issue date:** 2021-03-18

# Orion's Dragon and Other Stories

Feedback by massive stars

ISBN: 978-94-6419-144-8

An electronic copy of this thesis can be found at <https://openaccess.leidenuniv.nl>

Cover design: As Orion, the Greek mythological hunter, was passing by the star-forming region of the nebula named in his honor, he beheld, by virtue of his infrared glasses, the funny creature that lived in its midst. The rotated and cropped data cube of the carbon far-infrared emission line came to be called Orion's Dragon. Front cover background image credit: Uwe Kindziorra; dragon drawing credit: Janneke de Jonge. Back cover: [C II] emission in three velocity channels (blue: 4-5 km s<sup>-1</sup>, green: 8-9 km s<sup>-1</sup>, red: 12-13 km s<sup>-1</sup>).

# Orion's Dragon and Other Stories

## Feedback by massive stars

### Proefschrift

ter verkrijging van  
de graad van Doctor aan de Universiteit Leiden,  
op gezag van Rector Magnificus prof. dr. ir. H. Bijl,  
volgens besluit van het College voor Promoties  
te verdedigen op donderdag 18 maart 2021  
klokke 16.15 uur

door

Cornelia Hilke Manuela Pabst

geboren op 18 september 1989  
te Marburg, Duitsland

Promotores: Prof. dr. A. G. G. M. Tielens (Universiteit Leiden)  
Dr. J. R. Goicoechea (Consejo Superior de Investigaciones Científicas)

Promotiecommissie

Voorzitter: Prof. dr. H. J. A. Röttgering (Universiteit Leiden)  
Secretaris: Prof. dr. P. P. van der Werf (Universiteit Leiden)  
Overige leden: Dr. L. D. Anderson (West Virginia University)  
Dr. M. Gerin (École Normale Supérieure)  
Prof. dr. C. R. O'Dell (Vanderbilt University)

*Voor iedereen*

*„Zwei Dinge erfüllen das Gemüt mit immer neuer und zunehmender Bewunderung und Ehrfurcht, je öfter und anhaltender sich das Nachdenken damit beschäftigt: der bestirnte Himmel über mir und das moralische Gesetz in mir. Beide darf ich nicht als in Dunkelheiten verhüllt oder im Überschwenglichen, außer meinem Gesichtskreise suchen und bloß vermuten; ich sehe sie vor mir und verknüpfe sie unmittelbar mit dem Bewusstsein meiner Existenz.“*

– Immanuel Kant („Kritik der praktischen Vernunft“, 1788)

# Contents

---

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Feedback and the evolution of galaxies . . . . .	1
1.2	Ionized gas, PDR structures, and forbidden lines . . . . .	1
1.3	The Orion molecular cloud . . . . .	4
1.4	SOFIA/upGREAT . . . . .	5
1.5	Thesis outline . . . . .	8
1.6	Outlook . . . . .	9
1.7	Epilogue . . . . .	11
<b>2</b>	<b>[C II] emission from L1630 in the Orion B molecular cloud</b>	<b>13</b>
2.1	Introduction . . . . .	14
2.2	Observations . . . . .	16
2.2.1	[C II] Observations . . . . .	16
2.2.2	Dust SED Analysis . . . . .	17
2.2.3	CO(1-0) Observations . . . . .	18
2.2.4	H $\alpha$ Observations . . . . .	19
2.3	Analysis . . . . .	19
2.3.1	Kinematics: velocity channel maps . . . . .	19
2.3.2	Global morphology . . . . .	19
2.3.3	Kinematics: velocity-resolved line spectra . . . . .	22
2.3.4	Edge-on PDR models . . . . .	24
2.3.5	Correlation diagrams . . . . .	26
2.4	Discussion . . . . .	29
2.4.1	[C II] Emission from the PDR . . . . .	29
2.4.2	[C II] Emission from the H II region . . . . .	30
2.4.3	FIR emission and beam-dilution effects . . . . .	31
2.4.4	Column densities, gas temperature, and mass . . . . .	32
2.4.5	Excitation properties from [ $^{13}\text{CII}$ ] . . . . .	35
2.4.6	Photoelectric heating and energy balance . . . . .	36
2.4.7	Line cuts . . . . .	38
2.4.8	Geometry of the L1630 molecular cloud . . . . .	40
2.4.9	Comparison with models . . . . .	41
2.4.10	Comparison with OMC1 in the Orion A molecular cloud . . . . .	43
2.5	Conclusion . . . . .	44
2.A	Calculating [C II] optical depth and excitation temperature . . . . .	47
2.B	Face-on calculation . . . . .	47
<b>3</b>	<b>Disruption of the Orion molecular core 1 by wind from the massive star <math>\theta^1</math> Orionis C</b>	<b>49</b>
3.A	Methods . . . . .	56
3.A.1	SOFIA observations . . . . .	56
3.A.2	Orion . . . . .	61
3.A.3	Kinematics of the gas . . . . .	61
3.A.4	Mass estimates of the Veil . . . . .	64

<b>4 Expanding bubbles in Orion A: [C II] observations of M42, M43, and NGC 1977</b>	<b>69</b>
4.1 Introduction . . . . .	70
4.2 Observations . . . . .	73
4.2.1 [C II] observations . . . . .	73
4.2.2 CO observations . . . . .	73
4.2.3 Dust maps . . . . .	73
4.2.4 H $\alpha$ observations . . . . .	75
4.3 Analysis . . . . .	75
4.3.1 Global morphology . . . . .	75
4.3.2 The expanding Veil shell – M42 . . . . .	76
4.3.3 M43 . . . . .	83
4.3.4 NGC 1977 . . . . .	86
4.4 Discussion . . . . .	89
4.4.1 The pressure balance . . . . .	92
4.4.2 Rayleigh-Taylor instability of the Veil shell . . . . .	95
4.4.3 The structure of M43 . . . . .	97
4.4.4 The Veil stellar-wind bubble . . . . .	98
4.4.5 The expanding bubble of $\theta^2$ Ori A . . . . .	101
4.4.6 The thermal bubbles of M43 and NGC 1977 . . . . .	102
4.4.7 Stellar wind versus thermal expansion of bubbles . . . . .	103
4.5 Conclusion . . . . .	106
4.A SED results . . . . .	108
4.B The expanding Rim . . . . .	108
4.C PV diagrams . . . . .	111
<b>5 [C II] 158 <math>\mu</math>m line emission from Orion A. I. A template for extra-galactic studies?</b>	<b>115</b>
5.1 Introduction . . . . .	116
5.2 Observations . . . . .	118
5.2.1 [C II] observations . . . . .	118
5.2.2 CO(2-1) observations . . . . .	118
5.2.3 Dust SEDs . . . . .	118
5.2.4 Ancillary photometric data . . . . .	119
5.3 Analysis . . . . .	120
5.3.1 Global morphology of the emission . . . . .	120
5.3.2 Correlation plots of gas and dust tracers . . . . .	121
5.4 Discussion . . . . .	124
5.4.1 Comparison with Orion B . . . . .	125
5.4.2 The [C II] deficit . . . . .	126
5.4.3 The photoelectric heating efficiency . . . . .	131
5.4.4 The origin of [C II] emission . . . . .	132
5.4.5 Tracers of the star-formation rate . . . . .	132
5.5 Conclusion . . . . .	138
5.A Calculation of the ionization parameter $\gamma$ . . . . .	140

---

<b>6 [C II] 158 <math>\mu</math>m line emission from Orion A. II. PDR physics</b>	<b>141</b>
6.1 Introduction . . . . .	142
6.2 Observations . . . . .	144
6.3 Analysis . . . . .	145
6.3.1 Global morphology and channel maps . . . . .	145
6.3.2 Definition of regions . . . . .	148
6.3.3 Edge-on PDR models . . . . .	149
6.3.4 FIR versus distance . . . . .	150
6.3.5 [C II] versus 70 $\mu$ m . . . . .	152
6.3.6 [C II] versus FIR . . . . .	154
6.3.7 [C II] versus 8 $\mu$ m . . . . .	156
6.3.8 FIR versus 8 $\mu$ m . . . . .	158
6.3.9 [C II] versus CO(2-1) . . . . .	160
6.3.10 Summary of the correlation studies . . . . .	161
6.4 Discussion . . . . .	162
6.4.1 Comparison of PDR models with observations . . . . .	162
6.4.2 The $G_0$ - $p_{\text{th}}$ relationship . . . . .	167
6.4.3 The origin of [C II] emission and CO-dark gas . . . . .	169
6.4.4 Photoelectric heating efficiency . . . . .	172
6.5 Conclusion . . . . .	178
6.A Comparison with Lombardi SED fits . . . . .	179
6.B Correlation plots from free- $\beta$ SED fit . . . . .	181
6.C SED fits to single points . . . . .	183
6.D Spectral line fits . . . . .	183
6.D.1 M42 . . . . .	183
6.D.2 M43 . . . . .	186
6.D.3 NGC 1977 . . . . .	186
6.D.4 Spectra behind the Bar . . . . .	189
<b>Samenvatting</b>	<b>203</b>
<b>Zusammenfassung</b>	<b>213</b>
<b>Publications</b>	<b>223</b>
<b>Curriculum Vitae</b>	<b>225</b>
<b>Acknowledgements</b>	<b>227</b>

