

Cover Page



Universiteit Leiden



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<http://hdl.handle.net/1887/74478>

Author: Bacalla, X.

Title: Electronic spectroscopy of molecules of astrophysical interest

Issue Date: 2019-07-02

List of publications

The following papers are included in this thesis:

- **The B²Π – X²Π electronic origin band of ¹³C₆H**
Bacalla, X., Zhao, D., Salumbides, E. J., Haddad, M. A., Linnartz, H., and Ubachs, W.
Journal of Molecular Spectroscopy **308–309** (2015) 41–44.
CHAPTER 3
- **Spectroscopic survey of electronic transitions of C₆H, ¹³C₆H, and C₆D**
Bacalla, X., Salumbides, E. J., Linnartz, H., Ubachs, W., and Zhao D.
The Journal of Physical Chemistry A **120** (2016) 6402–6417.
CHAPTER 4
- **The EDIBLES survey IV. Cosmic ray ionization rates in diffuse clouds from near-ultraviolet observations of interstellar OH⁺**
Bacalla, X. L., Linnartz, H., Cox, N. L. J., Cami, J., Roueff, E., Smoker, J. V., Farhang, A., Bouwman, J., and Zhao, D.
Astronomy and Astrophysics **622** (2019) A31.
CHAPTER 5

The author has also contributed to the writing of:

- **C₆₀⁺ and the diffuse interstellar bands: an independent laboratory check**
Spieler, S., Kuhn, M., Postler, J., Simpson, M., Wester, R., Scheier, P., et al.
The Astrophysical Journal **846** (2017) 168.
- **The ESO Diffuse Interstellar Band Large Exploration Survey (EDIBLES)**
Cami, J., Cox, N. L., Farhang, A., Smoker, J., Elyajouri, M., Lallement, R., et al.
The Messenger **171** (March 2018) 31–36.

Curriculum Vitae

I was born on the 14th day of September, 1989, in the island of Cebu, Philippines. I went to Mabolo Elementary School for my primary education from 1996 to 2002. It was during this time that I had developed an interest in science (which was also reinforced by a visit to a brief and temporary science exhibition / museum in one of the malls in our city). Then I got a scholarship to attend Cebu City National Science High School (2002–2006). Here I did not like mathematics, though I eventually appreciated it by the end of this period and after learning that it cannot be ignored when one decides to take a science or engineering course for university. After graduating, I was awarded a scholarship from our national department of science and technology, which allowed me to pursue a bachelor's degree in applied physics in the University of San Carlos (USC) (2006–2011). For my thesis, I worked with Dr. Raymund Sarmiento on monitoring ethylene gas emissions in climacteric fruits through photoacoustic spectroscopy, which I did together with Dexter Manalili (who is also currently doing his PhD research here in the Netherlands).

A couple of months after graduation, I stayed in our [laser spectroscopy and interferometry / optics] group as a research assistant. Then I applied as a physics instructor in the same department. For the next two and a half years, I taught introductory physics and laboratory courses to undergraduate students. Within my teaching stint, I managed to acquire a scholarship and pursued a master's degree in physics (2012–2014). I had the opportunity to do my thesis research here in the Netherlands for six months with Dr. Edcel Salumbides (my former teacher in USC) and Prof. dr. Wim Ubachs who both work in the LaserLaB at the VU University Amsterdam. My project was on recording the first-ever spectrum of the $^{13}\text{C}_6\text{H}$ isotopologue, which I adopted for my thesis and defended in USC. This introduced me to cavity ring-down spectroscopy (CRDS), with its possible applications to astrochemistry, and also to Prof. dr. Harold Linnartz who would be one of my supervisors for my PhD studies.

Harold and Wim have since had a longstanding collaboration on the spectroscopy of carbon-based molecules in relation to the problem of the diffuse interstellar bands (DIBs). Building on my previous MSc work, I succeeded (in November 2014) the then-candidate Dr. Mohammad Ali Haddad as the PhD student working on the CRDS

setup in the LaserLaB, and worked in Amsterdam for the first year of my PhD. During this time I measured electronic spectra of C_6H using the CRD technique and analyzed them with the PGOPHER software, with the help of Edcel and Dr. Dongfeng Zhao. In the laboratory for astrophysics in Leiden, Dongfeng introduced me to the incoherent broadband cavity-enhanced absorption spectroscopy (IBBCEAS) setup from which I measured spectra of other carbon chains such as C_8H and $C_{10}H$. Thus far, I had quite an experience with operating the pinhole and slit plasma discharge nozzles; I worked with Dr. Jordy Bouwman in employing the electron impact ionization source with IBBCEAS. For a good half of my stay in the Observatory, I was also involved in a large consortium of DIB astronomers (i.e., the EDIBLES team, lead by Dr. Nick Cox and Dr. Jan Cami) where I utilized telescope data for deriving the cosmic-ray ionization rates in diffuse interstellar clouds. I have presented all my work on various (inter)national conferences and meetings, and published them in peer-reviewed journals, which are described in this dissertation.

For my next career step, I will go back to the Philippines and help reestablish our optics laboratory in USC, and continue to teach physics.

Acknowledgments

If you found yourself reading this part of the thesis first, then you are excused. After all, this is where you can find the important characters that helped forge this memoir of scientific research and who have contributed immensely to my PhD life (which brought me to defend my thesis—successfully, I hope). Also, I may have forgotten to include your name in the list; please feel free to approach me and I will give you a handshake and/or a hug.

My utmost gratitude goes first to the people of the Netherlands and of the Philippines for enabling me to pursue my studies in physics and astronomy which, otherwise, would not be possible without their hard-earned taxes.

To Harold and Wim, thank you for your guidance and encouragement. Treating me as a colleague who can contribute something to the academic field in which you have both long played an important part is humbling and empowering.

To my direct supervisors, Edcel, Dongfeng, and Jordy, I am grateful for the wisdom you have imparted to me, especially in our musings on spectroscopy and in our experiments in the laboratory.

Many thanks to the staff in both Leiden and Amsterdam who, without hesitation, have always helped me solve my pressing administrative requirements and technical needs: Marjan Balkestein, Evelijn Gerstel, Alexandra Schouten-Voskamp, Yvonne Kluijt, Marja Herronen, Martijn Witlox, Aart Vos, Raymond Koehler, Rob Kortekaas. And to everyone in the FMD, ELD, SCIS, the Observatory Secretariat and Computer Group, thank you all for your support!

Special thanks to Dia Eek, Tugçe Özyurt, and Gerrit Kuik who were instrumental in getting me to the Netherlands for the first time.

I would also like to thank the thesis reading committee for taking the time to review my manuscript (on such a tight schedule), as well as the anonymous reviewers of our publications reproduced in this booklet.

To the group of astronomers who I have worked closely in the production of the OH⁺ paper, and to the whole EDIBLES team, my sincerest thanks for being patient with teaching me and guiding me through the process.

Being a member of two research groups with different focus can sometimes be a challenge and may invoke a feeling of being out of place. When I am in the LaserLaB in Amsterdam, I see myself as an astrophysicist surrounded by physicists. On the other hand, in the Laboratory for Astrophysics in Leiden, I am a spectroscopist surrounded by chemists and astronomers. However, this meant that I got to talk to and hear the perspectives of my colleagues from seemingly diverse fields which only enriched my learning experience. For this I am grateful for my fellow PhD students and postdocs who have shared their thoughts and their time with me. The same goes for my colleagues especially in the field of spectroscopy who I've met in various (inter)national conferences, I thank you all for the interesting discussions and fun times. And to those that I have worked with in my experiments in both the CRDS and BB-DIB setups, thank you! (I won't mention all their names for there are quite a lot of them that have since come and gone all throughout my PhD life.)

To the small group of friends that I have accumulated here in Leiden, from the music and art clubs, from the physics department, and my neighbors, I thank you for the camaraderie, and may our paths cross again.

Living alone in a foreign land has never been too hard of an ordeal, thanks to all of my friends from home who never missed a chance to keep in touch. To JC, Sam, and Mike (and to all of my online chat-mates) and to those who had the opportunity to visit personally, thank you very much for spending your time with me. To Therese, thank you for your patience and understanding.

I am especially indebted to my surrogate family here in the Netherlands who took good care of me. *Daghang salamat* to the Bisdaks: Adonis, Jane, Edcel, Marian, Albert, and Dexter. Here's to more board game nights, cycling tours, and boating expeditions along the Amstel! And to all members of our Filipino community who have always been warm and accommodating, I cannot thank you enough.

To my niece, Lea, and to all of my nibblings (Patiting, Boknoy, Keno, Shai-shai, and Sky) who never fail to entertain (and sometimes, bug) their uncle during short vacations back home, thank you.

Lastly, and most importantly, to Panfilo, Antonette, Gladys, and Gracie, many thanks for supporting me all the way despite knowing that I will be away from home for quite some time. You will always be a part of what I do and what good I will accomplish. I will always love you.

