



Universiteit
Leiden
The Netherlands

Laboratory studies of water ice in space : optical and photochemical properties

Kofman, V.

Citation

Kofman, V. (2019, June 19). *Laboratory studies of water ice in space : optical and photochemical properties*. Retrieved from <https://hdl.handle.net/1887/74048>

Version: Not Applicable (or Unknown)

License: [Leiden University Non-exclusive license](#)

Downloaded from: <https://hdl.handle.net/1887/74048>

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

Cover Page



Universiteit Leiden



The handle <http://hdl.handle.net/1887/74048> holds various files of this Leiden University dissertation.

Author: Kofman, V.

Title: Laboratory studies of water ice in space : optical and photochemical properties

Issue Date: 2019-06-19

Bibliography

- Accolla, M., Congiu, E., Dulieu, F., Manicò, G., Chaabouni, H., Matar, E., Mokrane, H., Lemaire, J. L., and Pirronello, V. (2011). "Changes in the morphology of interstellar ice analogues after hydrogen atom exposure". In: *Phys. Chem. Chem. Phys.* 13, p. 8037.
- Alexander, C. M. O., McKeegan, K. D., and Altwegg, K. (2018). "Water Reservoirs in Small Planetary Bodies: Meteorites, Asteroids, and Comets". In: *Space Sci. Rev.* 214:36.
- Allamandola, L. J., Tielens, A. G. G. M., and Barker, J. R. (1989). "Interstellar polycyclic aromatic hydrocarbons - The infrared emission bands, the excitation/emission mechanism, and the astrophysical implications". In: *Astrophys. J. Suppl. Ser.* 71, pp. 733–775.
- Altwegg, K. et al. (2016). "Prebiotic chemicals—amino acid and phosphorus—in the coma of comet 67P/Churyumov-Gerasimenko". In: *Sci. Adv.* 2.5, e1600285–e1600285.
- Andrews, L., Friedman, R. S., and Kelsall, B. J. (1985). "Vibronic absorption spectra of condensed ring aromatic cation systems in solid argon". In: *J. Phys. Chem.* 89.19, pp. 4016–4020.
- Balsiger, H. et al. (2015). "Detection of argon in the coma of comet 67P/Churyumov-Gerasimenko". In: *Sci. Adv.* 1, e1500377–e1500377.
- Banisaukas, J., Szczepanski, J., Eyler, J., Vala, M., Hirata, S., Head-Gordon, M., Oomens, J., Meijer, G., and von Helden, G. (2003). "Vibrational and Electronic Spectroscopy of Acenaphthylene and Its Cation". In: *J. Phys. Chem. A* 107, pp. 782–793.
- Bar-Nun, A., Herman, G., Laufer, D., and Rappaport, M. L. (1985). "Trapping and release of gases by water ice and implications for icy bodies". In: *Icarus* 63.3, pp. 317–332.
- Baragiola, R. A. (2003). "Water ice on outer solar system surfaces: Basic properties and radiation effects". In: *Planet. Space Sci.* 51, pp. 953–961.
- Baratta, G. A. and Palumbo, M. E. (1998). "Infrared optical constants of CO and CO₂ thin icy films". In: *J. Opt. Soc. Am. A* 15, pp. 3076–3085.

- Baratta, G. A., Leto, G., and Palumbo, M. E. (2002). "A comparison of ion irradiation and UV photolysis of CH₄ and CH₃OH". In: *Astron. Astrophys.* 384, pp. 343–349.
- Barnard, E. E. (1919). "On the dark markings of the sky, with a catalogue of 182 such objects." In: *Astrophys. J.* 49, pp. 1–24.
- Bartels-Rausch, T., Bergeron, V., Cartwright, J. H., Escribano, R., Finney, J. L., Grothe, H., Gutiérrez, P. J., Haapala, J., Kuhs, W. F., Pettersson, J. B., et al. (2012). "Ice structures, patterns, and processes: A view across the icelands". In: *Reviews of Modern Physics* 84.2, p. 885.
- Bauschlicher Jr., C. W., Ricca, A., Boersma, C., and Allamandola, L. J. (2018). "The NASA Ames PAH IR Spectroscopic Database: Computational Version 3.00 with Updated Content and the Introduction of Multiple Scaling Factors". In: *Astrophys. J., Suppl. Ser.* 234, p. 32.
- Bennett, C. J., Chen, S.-H., Sun, B.-J., Chang, A. H. H., and Kaiser, R. I. (2007). "Mechanistical Studies on the Irradiation of Methanol in Extraterrestrial Ices". In: *Astrophys. J.* 660, pp. 1588–1608.
- Öberg, K. I. (2016). "Photochemistry and Astrochemistry: Photochemical Pathways to Interstellar Complex Organic Molecules". In: *Chem. Rev.* 116.17. PMID: 27099922, pp. 9631–9663.
- Bergin, E. A. and Tafalla, M. (2007). "Cold Dark Clouds: The Initial Conditions for Star Formation". In: *Annu. Rev. Astron. Astrophys.* 45, pp. 339–396.
- Berné, O., Mulas, G., and Joblin, C. (2013). "Interstellar C₆₀⁺". In: *Astron. Astrophys.* 550, p. L4.
- Bernstein, M. P., Sandford, S. A., and Allamandola, L. J. (1997). "The Infrared Spectra of Nitriles and Related Compounds Frozen in Ar and H₂O". In: *Astrophys. J.* 476, pp. 932–942.
- Bernstein, M. P., Dworkin, J. P., Sandford, S. A., Cooper, G. W., and Allamandola, L. J. (2002). "Racemic amino acids from the ultraviolet photolysis of interstellar ice analogues". In: *Nature* 416, pp. 401–403.
- Bernstein, M. P., Sandford, S. A., and Allamandola, L. J. (2005). "The Mid-Infrared Absorption Spectra of Neutral Polycyclic Aromatic Hydrocarbons in Conditions Relevant to Dense Interstellar Clouds". In: *Astrophys. J. Suppl. Ser.* 161, pp. 53–64.
- Bernstein, M. P., Sandford, S. A., Mattioda, A. L., and Allamandola, L. J. (2007). "Near- and Mid-Infrared Laboratory Spectra of PAH Cations in Solid H₂O". In: *Astrophys. J.* 664, pp. 1264–1272.
- Bertin, M., Romanzin, C., Doronin, M., Philippe, L., Jeseck, P., Ligterink, N. F. W., Linnartz, H., Michaut, X., and Fillion, J.-H. (2016). "UV Photodesorption of Methanol in Pure and CO-rich Ices: Desorption Rates of the Intact Molecule and of the Photofragments". In: *Astrophys. J.* 817.

- Bhatt, N. H. and Cami, J. (2015). "A Sensitive Spectral Survey of Interstellar Features in the Near-UV [3050-3700 Å]". In: *Astrophys. J. Suppl. Ser.* 216, p. 22.
- Bieler, A. et al. (2015). "Abundant molecular oxygen in the coma of comet 67P/Churyumov-Gerasimenko". In: *Nature* 526, pp. 678–681.
- Biennier, L., Salama, F., Allamandola, L. J., and Scherer, J. J. (2003). "Pulsed discharge nozzle cavity ringdown spectroscopy of cold polycyclic aromatic hydrocarbon ions". In: *J. Chem. Phys.* 118, pp. 7863–7872.
- Biennier, L., Salama, F., Gupta, M., and O'Keefe, A. (2004). "Multiplex integrated cavity output spectroscopy of cold PAH cations". In: *Chem. Phys. Lett.* 387, pp. 287–294.
- Bockelée-Morvan, D. et al. (2016). "Evolution of CO₂, CH₄, and OCS abundances relative to H₂O in the coma of comet 67P around perihelion from Rosetta/VIRTIS-H observations". In: *Mon. Not. R. Astron. Soc.* 462, S170–S183.
- Boersma, C., Bauschlicher Jr., C. W., Ricca, A., Mattioda, A. L., Cami, J., Peeters, E., Sánchez de Armas, F., Puerta Saborido, G., Hudgins, D. M., and Allamandola, L. J. (2014). "The NASA Ames PAH IR Spectroscopic Database Version 2.00: Updated Content, Web Site, and On(Off)line Tools". In: *Astrophys. J., Suppl. Ser.* 211, p. 8.
- Bok, B. J. and Reilly, E. F. (1947). "Small Dark Nebulae". In: *Astrophys. J.* 105, pp. 255–257.
- Boogert, A. C. A. et al. (2008). "The c2d Spitzer Spectroscopic Survey of Ices around Low-Mass Young Stellar Objects. I. H₂O and the 5-8 μm Bands". In: *Astrophys. J.* 678, pp. 985–1004.
- Boogert, A. C. A., Gerakines, P. A., and Whittet, D. C. B. (2015). "Observations of the icy universe." In: *Annu. Rev. Astron. Astrophys.* 53, pp. 541–581.
- Boschi, R., Clar, E., and Schmidt, W. (1974). "Photoelectron spectra of polynuclear aromatics. III. The effect of nonplanarity in sterically overcrowded aromatic hydrocarbons". In: *J. Chem. Phys.* 60, pp. 4406–4418.
- Bossa, J. B., Isokoski, K., de Valois, M. S., and Linnartz, H. (2012). "Thermal collapse of porous interstellar ice". In: *Astron. Astrophys.* 545, A82.
- Bossa, J.-B., Isokoski, K., Paardekooper, D. M., Bonnin, M., van der Linden, E. P., Triemstra, T., Cazaux, S., Tielens, A. G. G. M., and Linnartz, H. (2014). "Porosity measurements of interstellar ice mixtures using optical laser interference and extended effective medium approximations". In: *Astron. Astrophys.* 561, A136.
- Bossa, J.-B., Paardekooper, D. M., Isokoski, K., and Linnartz, H. (2015a). "Methane ice photochemistry and kinetic study using laser desorption time-of-flight mass spectrometry at 20 K". In: *Phys. Chem. Chem. Phys.* 17, pp. 17346–17354.

- Bossa, J.-B., Maté, B., Fransen, C., Cazaux, S., Pilling, S., Robson Monteiro Rocha, W., Ortigoso, J., and Linnartz, H. (2015b). "Porosity and Band-strength Measurements of Multi-phase Composite Ices". In: *Astrophys. J.* 814, pp. 47–61.
- Bouilloud, M., Fray, N., Bénilan, Y., Cottin, H., Gazeau, M.-C., and Jolly, A. (2015). "Bibliographic review and new measurements of the infrared band strengths of pure molecules at 25 K: H₂O, CO₂, CO, CH₄, NH₃, CH₃OH, HCOOH and H₂CO". In: *Mon. Not. R. Astron. Soc.* 451, pp. 2145–2160.
- Bouwman, J., Paardekooper, D. M., Cuppen, H. M., Linnartz, H., and Allamandola, L. J. (2009). "Real-Time Optical Spectroscopy of Vacuum Ultraviolet Irradiated Pyrene:H₂O Interstellar Ice". In: *Astrophys. J.* 700, pp. 56–62.
- Bouwman, J., Cuppen, H. M., Bakker, A., Allamandola, L. J., and Linnartz, H. (2010). "Photochemistry of the PAH pyrene in water ice: the case for ion-mediated solid-state astrochemistry". In: *Astron. Astrophys.* 511, A33.
- Bouwman, J., Mattioda, A. L., Linnartz, H., and Allamandola, L. J. (2011). "Photochemistry of polycyclic aromatic hydrocarbons in cosmic water ice. I. Mid-IR spectroscopy and photoproducts". In: *Astron. Astrophys.* 525, A93.
- Brogli, F. and Heilbronner, E. (1972). "Photoelectron spectra of benzenoid hydrocarbons C₁₈H₁₂". In: *Angew. Chem. Int. Ed.* 11, p. 538.
- Browell, E. V. and Anderson, R. C. (1975). "Ultraviolet optical constant of water and ammonia ices." In: *J. Opt. Soc. Am.* 65, pp. 919–926.
- Brown, D. E., George, S. M., Huang, C., Wong, E. K. L., Rider, K. B., Smith, R. S., and Kay, B. D. (1996). "H₂O condensation coefficient and refractive index for vapor-deposited ice from molecular beam and optical interference measurements". In: *J. Phys. Chem.* 100, pp. 4988–4995.
- Brownlee, D. (2014). "The Stardust Mission: Analyzing Samples from the Edge of the Solar System". In: *Annu. Rev. Earth Planet. Sci.* 42, pp. 179–205.
- Butscher, T., Duvernay, F., Rimola, A., Segado-Centellas, M., and Chiavassa, T. (2017). "Radical recombination in interstellar ices, a not so simple mechanism". In: *Phys. Chem. Chem. Phys.* 19, pp. 2857–2866.
- Callahan, M. P., Abo-Riziq, A., Crews, B., Grace, L., and de Vries, M. S. (2008). "Isomer discrimination of polycyclic aromatic hydrocarbons in the Murchison meteorite by resonant ionization". In: *Spectrochim. Acta Mol. Biomol. Spectrosc.* 71, pp. 1492–1495.
- Calvin, W. M., Clark, R. N., Brown, R. H., and Spencer, J. R. (1995). "Spectra of the icy Galilean satellites from 0.2 to 5 μ m: A compilation, new observations, and a recent summary". In: *J. Geophys. Res.* 100, pp. 19041–19048.
- Cami, J., Bernard-Salas, J., Peeters, E., and Malek, S. E. (2010). "Detection of C₆₀ and C₇₀ in a Young Planetary Nebula". In: *Science* 329, p. 1180.

- Campbell, E. K., Holz, M., Gerlich, D., and Maier, J. P. (2015). "Laboratory confirmation of C_{60}^+ as the carrier of two diffuse interstellar bands". In: *Nature* 523, pp. 322–323.
- Campbell, E. K., Holz, M., and Maier, J. P. (2016a). " C_{60}^+ in Diffuse Clouds: Laboratory and Astronomical Comparison". In: *Astrophys.J.L* 826, p. L4.
- Campbell, E. K., Holz, M., Maier, J. P., Gerlich, D., Walker, G. A. H., and Bohlander, D. (2016b). "Gas Phase Absorption Spectroscopy of C_{60}^+ and C_{70}^+ in a Cryogenic Ion Trap: Comparison with Astronomical Measurements". In: *Astrophys.J.* 822, p. 17.
- Candian, A., Sarre, P. J., and Tielens, A. G. G. M. (2014). "Polycyclic Aromatic Hydrocarbons with Armchair Edges and the 12.7 μm Band". In: *Astrophys. J.* 791, p. L10.
- Chen, Y.-J., Chuang, K.-J., Muñoz-Caro, G. M., Nuevo, M., Chu, C.-C., Yih, T.-S., Ip, W.-H., and Wu, C.-Y. R. (2014). "Vacuum Ultraviolet Emission Spectrum Measurement of a Microwave-discharge Hydrogen-flow Lamp in Several Configurations: Application to Photodesorption of CO Ice". In: *Astrophys. J.* 781, p. 15.
- Chuang, K.-J., Fedoseev, G., Ioppolo, S., van Dishoeck, E. F., and Linnartz, H. (2016). "H-atom addition and abstraction reactions in mixed CO, H_2CO and CH_3OH ices - an extended view on complex organic molecule formation". In: *Mon. Not. R. Astron. Soc.* 455, pp. 1702–1712.
- Chuang, K.-J., Fedoseev, G., Qasim, D., Ioppolo, S., van Dishoeck, E. F., and Linnartz, H. (2017). "Production of complex organic molecules: H-atom addition versus UV irradiation". In: *Mon. Not. R. Astron. Soc.* 467, pp. 2552–2565.
- Chyba, C. and Sagan, C. (1992). "Endogenous production, exogenous delivery and impact-shock synthesis of organic molecules: an inventory for the origins of life". In: *Nature* 355, pp. 125–132.
- Clements, A. R., Berk, B., Cooke, I. R., and Garrod, R. T. (2018). "Kinetic Monte Carlo simulations of water ice porosity: extrapolations of deposition parameters from the laboratory to interstellar space". In: *Phys. Chem. Chem. Phys.* 20, pp. 5553–5568.
- Cody, G. D. and Alexander, C. M. O. D. (2005). "NMR studies of chemical structural variation of insoluble organic matter from different carbonaceous chondrite groups". In: *Geochim. Cosmochim. Acta* 69, pp. 1085–1097.
- Cody, G. D., Heying, E., Alexander, C. M. O., Nittler, L. R., Kilcoyne, A. L. D., Sandford, S. A., and Stroud, R. M. (2011). "Cosmochemistry Special Feature: Establishing a molecular relationship between chondritic and cometary organic solids". In: *Proc. Natl. Acad. Sci. U.S.A.* 108, pp. 19171–19176.
- Collings, M. P., Anderson, M. A., Chen, R., Dever, J. W., Viti, S., Williams, D. A., and McCoustra, M. R. S. (2004). "A laboratory survey of the thermal

- desorption of astrophysically relevant molecules". In: *Mon. Not. R. Astron. Soc.* 354, pp. 1133–1140.
- Cook, A. M., Ricca, A., Mattioda, A. L., Bouwman, J., Roser, J., Linnartz, H., Bregman, J., and Allamandola, L. J. (2015). "Photochemistry of Polycyclic Aromatic Hydrocarbons in Cosmic Water Ice: The Role of PAH Ionization and Concentration". In: *Astrophys.J.* 799, p. 14.
- Cottin, H., Moore, M. H., and Bénilan, Y. (2003). "Photodestruction of Relevant Interstellar Molecules in Ice Mixtures". In: *Astrophys.J.* 590, pp. 874–881.
- Cruz-Diaz, G. A., M., M. G., Chen, Y.-J., and Yih, T.-S. (2014). "Vacuum-UV spectroscopy of interstellar ice analogs-I. Absorption cross-sections of polar-ice molecules". In: *Astron. Astrophys.* 562, A119.
- Cruz-Diaz, G. A., Martín-Doménech, R., Moreno, E., Muñoz Caro, G. M., and Chen, Y.-J. (2018). "New measurements on water ice photodesorption and product formation under ultraviolet irradiation". In: *Mon. Not. R. Astron. Soc.* 474, pp. 3080–3089.
- Cuppen, H. M., Ioppolo, S., Romanzin, C., and Linnartz, H. (2010). "Water formation at low temperatures by surface O₂ hydrogenation II: the reaction network". In: *Phys. Chem. Chem. Phys.* 12, p. 12077.
- Cuyllé, S. H., Tenenbaum, E. D., Bouwman, J., Linnartz, H., and Allamandola, L. J. (2012). "Ly α -induced charge effects of polycyclic aromatic hydrocarbons embedded in ammonia and ammonia:water ice". In: *Mon. Not. R. Astron. Soc.* 423, pp. 1825–1830.
- Cuyllé, S. H., Allamandola, L. J., and Linnartz, H. (2014a). "Photochemistry of PAHs in cosmic water ice. The effect of concentration on UV-VIS spectroscopy and ionization efficiency". In: *Astron. Astrophys.* 562, A22.
- Cuyllé, S. H., Allamandola, L. J., and Linnartz, H. (2014b). "Photochemistry of PAHs in cosmic water ice. The effect of concentration on UV-VIS spectroscopy and ionization efficiency". In: *Astron. Astrophys.* 562, A22.
- Dalton, J. B., Cruikshank, D. P., Stephan, K., McCord, T. B., Coustenis, A., Carlson, R. W., and Coradini, A. (2010). "Chemical Composition of Icy Satellite Surfaces". In: *Space Sci. Rev.* 153, pp. 113–154.
- Danger, G., Fresneau, A., Abou Mrad, N., de Marcellus, P., Orthous-Daunay, F.-R., Duvernay, F., Vuitton, V., d'Hendecourt, L. L. S., Thissen, R., and Chiavassa, T. (2016). "Insight into the molecular composition of laboratory organic residues produced from interstellar/pre-cometary ice analogues using very high resolution mass spectrometry". In: *Geochim. Cosmochim. Acta.* 189, pp. 184–196.
- Danylewych, L. L. and Nicholls, R. W. (1978). "Intensity measurements and transition probabilities for bands of the CN violet (B₂ Σ —X₂ Σ) band system". In: *Proc. R. Soc. Lond. A.* Vol. 360. The Royal Society, pp. 557–573.

- Dartois, E. et al. (1998). "Detection of the "44 MU m" band of water ice in absorption in combined ISO SWS-LWS spectra". In: *Astron. Astrophys.* 338, pp. L21–L24.
- Dawson, R. I. and Johnson, J. A. (2018). "Origins of Hot Jupiters". In: *Annu. Rev. Astron. Astrophys.* 56, pp. 175–221.
- de Barros, A. L. F., Domaracka, A., Andrade, D. P. P., Boduch, P., Rothard, H., and da Silveira, E. F. (2011). "Radiolysis of frozen methanol by heavy cosmic ray and energetic solar particle analogues". In: *Mon. Not. R. Astron. Soc.* 418, pp. 1363–1374.
- de Marcellus, P., Meinert, C., Myrgorodska, I., Nahon, L., Buhse, T., d'Hendecourt, L. L. S., and Meierhenrich, U. J. (2015a). "Aldehydes and sugars from evolved precometary ice analogs: Importance of ices in astrochemical and prebiotic evolution". In: *Proc. Natl. Acad. Sci. U.S.A.* 112, pp. 965–970.
- de Marcellus, P., Meinert, C., Myrgorodska, I., Nahon, L., Buhse, T., d'Hendecourt, L. L. S., and Meierhenrich, U. J. (2015b). "Aldehydes and sugars from evolved precometary ice analogs: Importance of ices in astrochemical and prebiotic evolution". In: *Proc. Natl. Acad. Sci. U.S.A.* 112, pp. 965–970.
- Deleuze, M. S. (2002). "Valence one-electron and shake-up ionization bands of polycyclic aromatic hydrocarbons. II. Azulene, phenanthrene, pyrene, chrysene, triphenylene, and perylene". In: *J. Chem. Phys.* 116, pp. 7012–7026.
- Dello Russo, N., Kawakita, H., Vervack, R. J., and Weaver, H. A. (2016). "Emerging trends and a comet taxonomy based on the volatile chemistry measured in thirty comets with high-resolution infrared spectroscopy between 1997 and 2013". In: *Icarus* 278, pp. 301–332.
- Dohnálek, Z., Kimmel, G. A., Ayotte, P., Smith, R. S., and Kay, B. D. (2003). "The deposition angle-dependent density of amorphous solid water films". In: *J. Chem. Phys.* 118, pp. 364–372.
- Draine, B. T. and Li, A. (2007). "Infrared Emission from Interstellar Dust. IV. The Silicate-Graphite-PAH Model in the Post-Spitzer Era". In: *Astrophys. J.* 657.2, pp. 810–837.
- Dulieu, F., Amiaud, L., Congiu, E., Fillion, J. H., Matar, E., Momeni, A., Pirronello, V., and Lemaire, J. L. (2010). "Experimental evidence for water formation on interstellar dust grains by hydrogen and oxygen atoms". In: *Astron. Astrophys.* 512, A30.
- Ehrenfreund, P., Bernstein, M. P., Dworkin, J. P., Sandford, S. A., and Allamandola, L. J. (2001). "The Photostability of Amino Acids in Space". In: *Astrophys. J.* 550, pp. L95–L99.
- Ehrenfreund, P. et al. (2002). "Astrophysical and astrochemical insights into the origin of life". In: *Rep. Prog. Phys.* 65, pp. 1427–1487.

- Eistrup, C., Walsh, C., and van Dishoeck, E. F. (2016). "Setting the volatile composition of (exo)planet-building material. Does chemical evolution in disk midplanes matter?" In: *Astron. Astrophys.* 595, A83, A83.
- Elsila, J. E., Aponte, J. C., Blackmond, D. G., Burton, A. S., Dworkin, J. P., and Glavin, D. P. (2016). "Meteoritic Amino Acids: Diversity in Compositions Reflects Parent Body Histories". In: *ACS Cent. Sci.* 2.6, pp. 370–379.
- Es-sebbar, E. T., Bénilan, Y., Fray, N., Cottin, H., Jolly, A., and Gazeau, M.-C. (2015). "Optimization of a Solar Simulator for Planetary-photochemical Studies". In: *Astrophys. J., Suppl. Ser.* 218, p. 19.
- Evans Neal J., I. et al. (2009). "The Spitzer c2d Legacy Results: Star-Formation Rates and Efficiencies; Evolution and Lifetimes". In: *Astrophys. J., Suppl. Ser.* 181.2, pp. 321–350.
- Fayolle, E. C., Bertin, M., Romanzin, C., Michaut, X., Öberg, K. I., Linnartz, H., and Fillion, J.-H. (2011). "CO Ice Photodesorption: A Wavelength-dependent Study". In: *Astrophys. J.* 739, p. L36.
- Fayolle, E. C., Bertin, M., Romanzin, C., Poderoso, H. A. M., Philippe, L., Michaut, X., Jeseck, P., Linnartz, H., Öberg, K. I., and Fillion, J. H. (2013). "Wavelength-dependent UV photodesorption of pure N₂ and O₂ ices". In: *Astron. Astrophys.* 556, A122.
- Fedoseev, G., Chuang, K.-J., Ioppolo, S., Qasim, D., van Dishoeck, E. F., and Linnartz, H. (2017). "Formation of Glycerol through Hydrogenation of CO Ice under Prestellar Core Conditions". In: *Astrophys. J.* 842, pp. 52–61.
- Foing, B. H. and Ehrenfreund, P. (1994). "Detection of two interstellar absorption bands coincident with spectral features of C₆₀⁺". In: *Nature* 369, pp. 296–298.
- Frantseva, F., Mueller, M., ten Kate, I., van der Tak, F. F. S., and Greenstreet, S. (2018). "Delivery of organics to Mars through asteroid and comet impacts". In: *Icarus* 309, pp. 125–133. ISSN: 0019-1035.
- Fuchs, G. W., Cuppen, H. M., Ioppolo, S., Romanzin, C., Bisschop, S. E., Andersson, S., van Dishoeck, E. F., and Linnartz, H. (2009). "Hydrogenation reactions in interstellar CO ice analogues. A combined experimental/theoretical approach". In: *Astron. Astrophys.* 505, pp. 629–639.
- Fulara, J., Jakobi, M., and Maier, J. P. (1993). "Electronic and infrared spectra of C₆₀⁺ and C₆₀⁻ in neon and argon matrices". In: *Chem. Phys. Lett.* 211, pp. 227–234.
- Fulvio, D., Sivaraman, B., Baratta, G. A., Palumbo, M. E., and Mason, N. J. (2009). "Novel measurements of refractive index, density and mid-infrared integrated band strengths for solid O₂, N₂O and NO₂ : N₂O₄ mixtures". In: *Spectrochim. Acta A* 72, pp. 1007–1013.

- Fulvio, D., Brieva, A. C., Cuyllé, S. H., Linnartz, H., Jäger, C., and Henning, T. (2014). "A straightforward method for Vacuum-Ultraviolet flux measurements: The case of the hydrogen discharge lamp and implications for solid-phase actinometry". In: *Appl. Phys. Lett.* 105.1, p. 014105.
- Garrod, R. T., Widicus Weaver, S. L., and Herbst, E. (2008). "Complex Chemistry in Star-forming Regions: An Expanded Gas-Grain Warm-up Chemical Model". In: *Astrophys. J.* 682, pp. 283–302.
- Gerakines, P. A., Schutte, W. A., Greenberg, J. M., and van Dishoeck, E. F. (1995). "The infrared band strengths of H₂O, CO and CO₂ in laboratory simulations of astrophysical ice mixtures." In: *Astron. Astrophys.* 296, p. 810.
- Gerakines, P. A., Schutte, W. A., and Ehrenfreund, P. (1996). "Ultraviolet processing of interstellar ice analogs. I. Pure ices." In: *Astron. Astrophys.* 312, pp. 289–305.
- Gerakines, P. A., Moore, M. H., and Hudson, R. L. (2004). "Ultraviolet photolysis and proton irradiation of astrophysical ice analogs containing hydrogen cyanide". In: *Icarus* 170, pp. 202–213.
- Gerakines, P. A., Hudson, R. L., Moore, M. H., and Bell, J.-L. (2012). "In situ measurements of the radiation stability of amino acids at 15-140 K". In: *Icarus* 220, pp. 647–659.
- Gibb, E. L. and Whittet, D. C. B. (2002). "The 6 Micron Feature in Protostars: Evidence for Organic Refractory Material". In: *Astrophys. J.* 566, pp. L113–L116.
- Gibb, E. L., Whittet, D. C. B., Boogert, A. C. A., and Tielens, A. G. G. M. (2004). "Interstellar Ice: The Infrared Space Observatory Legacy". In: *Astrophys. J. Suppl. Ser.* 151, pp. 35–73.
- Gillett, F. C. and Forrest, W. J. (1973). "Spectra of the Becklin-Neugebauer point source and the Kleinmann-Low nebula from 2.8 to 13.5 microns." In: *Astrophys. J.* 179, pp. 483–491.
- Goesmann, F. et al. (2015). "Organic compounds on comet 67P/Churyumov-Gerasimenko revealed by COSAC mass spectrometry". In: *Science* 349.2.
- Goodman, A. M. (1978). "Optical interference method for the approximate determination of refractive index and thickness of a transparent layer". In: *Appl. Opt.* 17, pp. 2779–2787.
- Gredel, R., Carpentier, Y., Rouillé, G., Steglich, M., Huisken, F., and Henning, T. (2011). "Abundances of PAHs in the ISM: confronting observations with experimental results". In: *Astron. Astrophys.* 530, A26.
- Grim, R. J. A., Baas, F., Geballe, T. R., Greenberg, J. M., and Schutte, W. A. (1991). "Detection of solid methanol toward W 33A." In: *Astron. Astrophys.* 243, pp. 473–477.

- Gudipati, M. S. and Allamandola, L. J. (2003). "Facile Generation and Storage of Polycyclic Aromatic Hydrocarbon Ions in Astrophysical Ices". In: *Astrophys.J.* 596, pp. L195–L198.
- Gudipati, M. S. and Allamandola, L. J. (2004). "Polycyclic Aromatic Hydrocarbon Ionization Energy Lowering in Water Ices". In: *Astrophys.J.* 615, pp. L177–L180.
- Gudipati, M. S. and Allamandola, L. J. (2006). "Unusual Stability of Polycyclic Aromatic Hydrocarbon Radical Cations in Amorphous Water Ices up to 120 K: Astronomical Implications". In: *Astrophys.J.* 638, pp. 286–292.
- Guennoun, Z., Aupetit, C., and Mascetti, J. (2011). "Photochemistry of coronene with water at 10 K: first tentative identification by infrared spectroscopy of oxygen containing coronene products". In: *Phys. Chem. Chem. Phys.* 13.16, pp. 7340–7347.
- Hagen, W., Allamandola, L. J., and Greenberg, J. M. (1979). "Interstellar molecule formation in grain mantles - The laboratory analog experiments, results and implications". In: *Astrophys. and Space Sci.* 65, pp. 215–240.
- Hama, T. and Watanabe, N. (2013). "Surface Processes on Interstellar Amorphous Solid Water: Adsorption, Diffusion, Tunneling Reactions, and Nuclear Spin Conversion". In: *Chem. Rev.* 113, pp. 8783–8839.
- Hardegree-Ullman, E. E., Gudipati, M. S., Boogert, A. C. A., Lignell, H., Allamandola, L. J., Stapelfeldt, K. R., and Werner, M. (2014). "Laboratory Determination of the Infrared Band Strengths of Pyrene Frozen in Water Ice: Implications for the Composition of Interstellar Ices". In: *Astrophys. J.* 784, pp. 172–182.
- Hardy, F.-X., Rice, C. A., and Maier, J. P. (2017). "Gas-phase Electronic Spectra of Coronene and Corannulene Cations". In: *Astrophys.J.* 836, p. 37.
- Harvey, A. H., Gallagher, J. S., and Levelt Sengers, J. M. H. (1998). "Revised Formulation for the Refractive Index of Water and Steam as a Function of Wavelength, Temperature and Density". In: *J. Phys. Chem. Ref. Data* 27, pp. 761–774.
- Heays, A. N., Bosman, A. D., and van Dishoeck, E. F. (2017). "Photodissociation and photoionisation of atoms and molecules of astrophysical interest". In: *Astron. Astrophys.* 602, A105.
- Henderson, B. L. and Gudipati, M. S. (2015). "Direct Detection of Complex Organic Products in Ultraviolet ($Ly\alpha$) and Electron-irradiated Astrophysical and Cometary Ice Analogs Using Two-step Laser Ablation and Ionization Mass Spectrometry". In: *Astrophys. J.* 800, pp. 66–82.
- Herbig, G. H. (1995). "The Diffuse Interstellar Bands". In: *Annu. Rev. Astron. Astrophys.* 33, pp. 19–74.
- Herbst, E. and van Dishoeck, E. F. (2009). "Complex Organic Interstellar Molecules". In: *Annu. Rev. Astron. Astrophys.* 47, pp. 427–480.

- Herbst, E. (2014). "Three milieux for interstellar chemistry: gas, dust, and ice". In: *Phys. Chem. Chem. Phys.* 16, pp. 3344–3359.
- Herschel, W. (1785). In: *Philos. Trans. Ser. 1*, 75:213.
- Hibbins, R. E. (1996). PhD thesis. The University of Nottingham.
- Hibbins, R. E., Miles, J. R., Sarre, P. J., and Herbig, G. H. (1994). "Diffuse interstellar bands between 3900 Å and 4200 Å". In: *The Diffuse Interstellar Bands*. Ed. by A. G. G. M. Tielens, p. 31.
- Hiraoka, K., Ohashi, N., Kihara, Y., Yamamoto, K., Sato, T., and Yamashita, A. (1994). "Formation of formaldehyde and methanol from the reactions of H atoms with solid CO at 10–20 K". In: *Chemical Physics Letters* 229, pp. 408–414.
- Hirata, S., Head-Gordon, M., Szczepanski, J., and Vala, M. (2003). "Time-Dependent Density Functional Study of the Electronic Excited States of Polycyclic Aromatic Hydrocarbon Radical Ions". In: *J. Phys. Chem. A* 107, pp. 4940–4951.
- Hobbs, L. M. et al. (2008). "A Catalog of Diffuse Interstellar Bands in the Spectrum of HD 204827". In: *Astrophys. J.* 680, pp. 1256–1270.
- Hobbs, L. M. et al. (2009). "Studies of the Diffuse Interstellar Bands. III. HD 183143". In: *Astrophys. J.* 705, pp. 32–45.
- Honeycutt, R. K. (1972). "Structure in the interstellar reddening law: 3450 - 5800 Å." In: *Astron. J.* 77, pp. 24–28.
- Hudgins, D. M., Sandford, S. A., Allamandola, L. J., and Tielens, A. G. G. M. (1993). "Mid- and far-infrared spectroscopy of ices - Optical constants and integrated absorbances". In: *Astrophys. J. Suppl. Ser.* 86, pp. 713–870.
- Huisken, F., Rouillé, G., Steglich, M., Carpentier, Y., Jäger, C., and Henning, T. (2014). "Laboratory Studies on the Role of PAHs as DIB Carriers". In: *The Diffuse Interstellar Bands*. Ed. by J. Cami and N. L. J. Cox. Vol. 297. IAU Symposium, pp. 265–275.
- Ioppolo, S., Cuppen, H. M., Romanzin, C., van Dishoeck, E. F., and Linnartz, H. (2008). "Laboratory Evidence for Efficient Water Formation in Interstellar Ices". In: *Astrophys. J.* 686, pp. 1474–1479.
- Ioppolo, S., Cuppen, H. M., Romanzin, C., van Dishoeck, E. F., and Linnartz, H. (2010). "Water formation at low temperatures by surface O₂ hydrogenation I: characterization of ice penetration". In: *Phys. Chem. Chem. Phys.* 12, p. 12065.
- Ioppolo, S., van Boheemen, Y., Cuppen, H. M., van Dishoeck, E. F., and Linnartz, H. (2011). "Surface formation of CO₂ ice at low temperatures". In: *Mon. Not. R. Astron. Soc.* 413, pp. 2281–2287.
- Jenniskens, P. and Blake, D. F. (1996). "Crystallization of Amorphous Water Ice in the Solar System". In: *Astrophys. J.* 473, p. 1104.

- Jenniskens, P. and Desert, F.-X. (1994). "A survey of diffuse interstellar bands (3800-8680 Å)". In: *Astron. Astrophys. Suppl Ser.* 106.
- Jing, D., He, J., Brucato, J., De Sio, A., Tozzetti, L., and Vidali, G. (2011). "On Water Formation in the Interstellar Medium: Laboratory Study of the O+D Reaction on Surfaces". In: *Astrophys. J.* 741, p. L9.
- Jochims, H. W., Baumgärtel, H., and Leach, S. (1999). "Structure-dependent Photostability of Polycyclic Aromatic Hydrocarbon Cations: Laboratory Studies and Astrophysical Implications". In: *Astrophys. J.* 512, pp. 500–510.
- Johnson, P. V., Hodyss, R., Chernow, V. F., Lipscomb, D. M., and Goguen, J. D. (2012). "Ultraviolet photolysis of amino acids on the surface of icy Solar System bodies". In: *Icarus* 221, pp. 800–805.
- Kato, T. and Yamabe, T. (2005). "Jahn-Teller effects and charge transfer in the positively charged triphenylene and coronene". In: *Chem. Phys. Lett.* 403, pp. 113–118.
- Keane, J. V., Boogert, A. C. A., Tielens, A. G. G. M., Ehrenfreund, P., and Schutte, W. A. (2001). "Bands of solid CO₂ in the 2-3 μm spectrum of S 140:IRS1". In: *Astron. Astrophys.* 375, pp. L43–L46.
- Keszthelyi, T., Balakrishnan, G., Wilbrandt, R., Yee, W. A., and Negri, F. (2000). "Evidence of Dynamical Jahn-Teller Effect on Triphenylene Radical Cation: Resonance Raman Spectrum and ab Initio Quantum-Chemical Calculations". In: *J. Phys. Chem. A* 104, pp. 9121–9129.
- Khan, Z. (1978). "Experimental and theoretical studies on electronic-spectra of tetracyclic aromatic hydrocarbon cation radicals". In: *Can. J. Spectrosc.* 23, pp. 8–15.
- Khan, Z. (1992). "Electronic Spectra of Radical Cations and their Correlation with Photoelectron Spectra. VI. A Reinvestigation of Two-, Three-, and Four-Ring Condensed Aromatics". In: *Acta. Phys. Pol. A* 82.6, pp. 937–955.
- Kjaergaard, H. G., Robinson, T. W., and Brooking, K. A. (2000). "Calculated CH-Stretching Overtone Spectra of Naphthalene, Anthracene and Their Cations". In: *J. Phys. Chem. A* 104, pp. 11297–11303.
- Kofman, V., Sarre, P. J., Hibbins, R. E., ten Kate, I. L., and Linnartz, H. (2017). "Laboratory spectroscopy and astronomical significance of the fully-benzenoid PAH triphenylene and its cation". In: *Mol. Astrophys.* 7, pp. 19–26.
- Kofman, V., Witlox, M. J. A., Bouwman, J., ten Kate, I., and Linnartz, H. (2018). "A Multifunctional Setup to record FTIR and UV-vis Spectra of Organic Molecules and their Photoproducts in Astronomical Ices". In: *Rev. Sci. Instrum.* 89.5, p. 053111.
- Kokkin, D. L., Reilly, N. J., Troy, T. P., Nauta, K., and Schmidt, T. W. (2007). "Gas phase spectra of all-benzenoid polycyclic aromatic hydrocarbons: Triphenylene". In: *J. Chem. Phys.* 126.8, pp. 084304–084304.

- Krijt, S., Ormel, C. W., Dominik, C., and Tielens, A. G. G. M. (2016). "A panoptic model for planetesimal formation and pebble delivery". In: *Astron. Astrophys.* 586, A20, A20.
- Kuhn, M. et al. (2016). "Atomically resolved phase transition of fullerene cations solvated in helium droplets". In: *Nat. Commun.* 7, p. 13550.
- Lacy, J. H., Baas, F., Allamandola, L. J., Persson, S. E., McGregor, P. J., Lonsdale, C. J., Geballe, T. R., and van de Bult, C. E. P. (1984). "4.6 micron absorption features due to solid phase CO and cyano group molecules toward compact infrared sources." In: *Astrophys. J.* 276, pp. 533–543.
- Lada, C. J. and Wilking, B. A. (1984). "The nature of the embedded population in the rho Ophiuchi dark cloud : mid-infrared observations." In: *Astrophys. J.* 287, pp. 610–621.
- Lamberts, T., Cuppen, H. M., Ioppolo, S., and Linnartz, H. (2013). "Water formation at low temperatures by surface O₂ hydrogenation III: Monte Carlo simulation". In: *Phys. Chem. Chem. Phys.* 15, p. 8287.
- Langhoff, S. R. (1996). "Theoretical infrared spectra for polycyclic aromatic hydrocarbon neutrals, cations, and anions". In: *J. Chem. Phys.* 100.8, pp. 2819–2841.
- Levell, J. W., Ruseckas, A., Henry, J. B., Wang, Y., Stretton, A. D., Mount, A. R., Galow, T. H., and Samuel, I. D. W. (2010). "Fluorescence Enhancement by Symmetry Breaking in a Twisted Triphenylene Derivative". In: *J. Phys. Chem. A* 114, pp. 13291–13295.
- Lignell, A. and Gudipati, M. S. (2015). "Mixing of the Immiscible: Hydrocarbons in Water-Ice near the Ice Crystallization Temperature". In: *J. Chem. Phys. A* 119, pp. 2607–2613.
- Ligterink, N. F. W., Paardekooper, D. M., Chuang, K.-J., Both, M. L., Cruz-Diaz, G. A., van Helden, J. H., and Linnartz, H. (2015). "Controlling the emission profile of an H₂ discharge lamp to simulate interstellar radiation fields". In: *Astron. Astrophys.* 584, A56.
- Ligterink, N. F. W., Coutens, A., Kofman, V., Müller, H. S. P., Garrod, R. T., Calcutt, H., Wampfler, S. F., Jørgensen, J. K., Linnartz, H., and van Dishoeck, E. F. (2017). "The ALMA-PILS survey: detection of CH₃NCO towards the low-mass protostar IRAS 16293-2422 and laboratory constraints on its formation". In: *Mon. Not. R. Astron. Soc.* 469, pp. 2219–2229.
- Ligterink, N. F. W., Terwisscha van Scheltinga, J., Taquet, V., Jørgensen, J. K., Cazaux, S., van Dishoeck, E. F., and Linnartz, H. (2018). "The formation of peptide-like molecules on interstellar dust grains". In: *Mon. Not. R. Astron. Soc.* 480, pp. 3628–3643.
- Linnartz, H. (2014). "Solid State DIBs". In: *The Diffuse Interstellar Bands*. Ed. by J. Cami and N. L. J. Cox. Vol. 297. IAU Symposium, pp. 359–363.

- Linnartz, H., Ioppolo, S., and Fedoseev, G. (2015). "Atom addition reactions in interstellar ice analogues". In: *Int. Rev. Phys. Chem.* 34.2, pp. 205–237.
- Maíz Apellániz, J. (2015). "The ISM in O-star spectroscopic surveys: GOSSS, OWN, IACOB, NoMaDS, and CAFÉ-BEANS". In: *Mem. Soc. Astron. Ital.* 86, p. 553.
- Malkin, J. (1992). *Photophysical and photochemical properties of aromatic compounds*. CRC press.
- Markwick, A. J., Ilgner, M., Millar, T. J., and Henning, T. (2002). "Molecular distributions in the inner regions of protostellar disks". In: *Astron. Astrophys.* 385, pp. 632–646.
- Marty, B. et al. (2017). "Xenon isotopes in 67P/Churyumov-Gerasimenko show that comets contributed to Earth's atmosphere". In: *Science* 356, pp. 1069–1072.
- Mason, N. J., Dawes, A., Holtom, P. D., Mukerji, R. J., Davis, M. P., Sivaraman, B., Kaiser, R. I., Hoffmann, S. V., and Shaw, D. A. (2006). "VUV spectroscopy and photo-processing of astrochemical ices: an experimental study". In: *Faraday Discuss.* 133, p. 311.
- Maté, B., Rodríguez-Lazcano, Y., and Herrero, V. J. (2012). "Morphology and crystallization kinetics of compact (HGW) and porous (ASW) amorphous water ice". In: *Phys. Chem. Chem. Phys.* 14, p. 10595.
- Maté, B., Tanarro, I., Escribano, R., Moreno, M. A., and Herrero, V. J. (2015). "Stability of Extraterrestrial Glycine under Energetic Particle Radiation Estimated from 2 keV Electron Bombardment Experiments". In: *Astrophys. J.* 806, p. 151.
- Maté, B., Rodríguez-Lazcano, Y., Gálvez, Ó., Tanarro, I., and Escribano, R. (2011). "An infrared study of solid glycine in environments of astrophysical relevance". In: *Phys. Chem. Chem. Phys.* 13, p. 12268.
- McClure, M. K., Manoj, P., Calvet, N., Adame, L., Espaillet, C., Watson, D. M., Sargent, B., Forrest, W. J., and D'Alessio, P. (2012). "Probing Dynamical Processes in the Planet-forming Region with Dust Mineralogy". In: *Astrophys. J.* 759.1, L10, p. L10.
- McGuire, B. A. (2018). "2018 Census of Interstellar, Circumstellar, Extragalactic, Protoplanetary Disk, and Exoplanetary Molecules". In: *Astrophys. J., Suppl. Ser.* 239, pp. 17–60.
- Meinert, C., Myrgorodska, I., de Marcellus, P., Buhse, T., Nahon, L., Hoffmann, S. V., d'Hendecourt, L. L. S., and Meierhenrich, U. J. (2016). "Ribose and related sugars from ultraviolet irradiation of interstellar ice analogs". In: *Science* 352, pp. 208–212.
- Miller, S. L. (1953). "A Production of Amino Acids under Possible Primitive Earth Conditions". In: *Science* 117, pp. 528–529.

- Min, M. et al. (2016). "The abundance and thermal history of water ice in the disk surrounding HD 142527 from the DIGIT Herschel Key Program". In: *Astron. Astrophys.* 593, A11, A11.
- Miyauchi, N., Hidaka, H., Chigai, T., Nagaoka, A., Watanabe, N., and Kouchi, A. (2008). "Formation of hydrogen peroxide and water from the reaction of cold hydrogen atoms with solid oxygen at 10 K". In: *Chem. Phys. Lett.* 456, pp. 27–30.
- Morbidelli, A., Lunine, J. I., O'Brien, D. P., Raymond, S. N., and Walsh, K. J. (2012). "Building Terrestrial Planets". In: *Annu. Rev. Earth Planet. Sci.* 40, pp. 251–275.
- Muñoz-Caro, G. M. and Schutte, W. A. (2003). "UV-photoprocessing of interstellar ice analogs: New infrared spectroscopic results". In: *Astron. Astrophys.* 412, pp. 121–132.
- Muñoz-Caro, G. M., Meierhenrich, U. J., Schutte, W. A., Barbier, B., Arcones Segovia, A., Rosenbauer, H., Thiemann, W. H.-P., Brack, A., and Greenberg, J. M. (2002). "Amino acids from ultraviolet irradiation of interstellar ice analogues". In: *Nature* 416, pp. 403–406.
- Muñoz Caro, G. M., Chen, Y. J., Aparicio, S., Jiménez-Escobar, A., Rosu-Finsen, A., Lasne, J., and McCoustra, M. R. S. (2016). "Photodesorption and physical properties of CO ice as a function of temperature". In: *Astron. Astrophys.* 589, A19.
- Mumma, M. J. and Charnley, S. B. (2011). "The Chemical Composition of Comets—Emerging Taxonomies and Natal Heritage". In: *Annu. Rev. Astron. Astrophys.* 49, pp. 471–524.
- Noble, J. A., Theule, P., Borget, F., Danger, G., Chomat, M., Duvernay, F., Mispelaer, F., and Chiavassa, T. (2013). "The thermal reactivity of HCN and NH₃ in interstellar ice analogues". In: *Mon. Not. R. Astron. Soc.* 428, pp. 3262–3273.
- Nuevo, M., Bredehöft, J. H., Meierhenrich, U. J., d'Hendecourt, L. L. S., and Thiemann, W. H.-P. (2010). "Urea, Glycolic Acid, and Glycerol in an Organic Residue Produced by Ultraviolet Irradiation of Interstellar/Pre-Cometary Ice Analogs". In: *Astrobiology* 10, pp. 245–256.
- Nuevo, M., Materese, C. K., and Sandford, S. A. (2014). "The Photochemistry of Pyrimidine in Realistic Astrophysical Ices and the Production of Nucleobases". In: *Astrophys. J.* 793.2, 125, p. 125.
- Öberg, K. I., Garrod, R. T., van Dishoeck, E. F., and Linnartz, H. (2009a). "Formation rates of complex organics in UV irradiated CH₃OH-rich ices. I. Experiments". In: *Astron. Astrophys.* 504, pp. 891–913.
- Öberg, K. I., van Dishoeck, E. F., and Linnartz, H. (2009b). "Photodesorption of ices I: CO, N₂, and CO₂". In: *Astron. Astrophys.* 496, pp. 281–293.

- Öberg, K. I., Boogert, A. C. A., Pontoppidan, K. M., van den Broek, S., van Dishoeck, E. F., Bottinelli, S., Blake, G. A., and Evans II, N. J. (2011). "The Spitzer Ice Legacy: Ice Evolution from Cores to Protostars". In: *Astrophys. J.* 740, p. 109.
- Öberg, K. I., van Dishoeck, E. F., Linnartz, H., and Andersson, S. (2010). "The Effect of H₂O on Ice Photochemistry". In: *Astrophys. J.* 718, pp. 832–840.
- Oomens, J., Sartakov, B. G., Meijer, G., and von Helden, G. (2006). "Gas-phase infrared multiple photon dissociation spectroscopy of mass-selected molecular ions". In: *Int.. J. Mass Spectrom.* 254, pp. 1–19.
- Ormel, C. W., Paszun, D., Dominik, C., and Tielens, A. G. G. M. (2009). "Dust coagulation and fragmentation in molecular clouds. I. How collisions between dust aggregates alter the dust size distribution". In: *Astron. Astrophys.* 502.3, pp. 845–869.
- Orzechowska, G. E., Goguen, J. D., Johnson, P. V., Tsapin, A., and Kanik, I. (2007). "Ultraviolet photolysis of amino acids in a 100 K water ice matrix: Application to the outer Solar System bodies". In: *Icarus* 187, pp. 584–591.
- Paardekooper, D. M., Bossa, J.-B., Isokoski, K., and Linnartz, H. (2014). "Laser desorption time-of-flight mass spectrometry of ultraviolet photo-processed ices". In: *Rev. Sci. Instrum.* 85.10, p. 104501.
- Paardekooper, D. M., Bossa, J.-B., and Linnartz, H. (2016). "Laser desorption time-of-flight mass spectrometry of vacuum UV photo-processed methanol ice". In: *Astron. Astrophys.* 592, A67.
- Palumbo, M. E. (2006). "Formation of compact solid water after ion irradiation at 15 K". In: *Astron. Astrophys.* 453, pp. 903–909.
- Pernet, A., Pilmé, J., Pauzat, F., Ellinger, Y., Sirotti, F., Silly, M., Parent, P., and Laffon, C. (2013). "Possible survival of simple amino acids to X-ray irradiation in ice: the case of glycine". In: *Astron. Astrophys.* 552, A100.
- Pino, T., Boudin, N., and Bréchnignac, P. (1999). "Electronic absorption spectrum of cold naphthalene cation in the gas phase by photodissociation of its van der Waals complexes". In: *J. Chem. Phys.* 111, pp. 7337–7347.
- Pollack, J. B., Hollenbach, D., Beckwith, S., Simonelli, D. P., Roush, T., and Fong, W. (1994). "Composition and Radiative Properties of Grains in Molecular Clouds and Accretion Disks". In: *Astrophys. J.* 421, p. 615.
- Pontoppidan, K. M., Boogert, A. C. A., Fraser, H. J., van Dishoeck, E. F., Blake, G. A., Lahuis, F., Öberg, K. I., Evans Neal J., I., and Salyk, C. (2008). "The c2d Spitzer Spectroscopic Survey of Ices around Low-Mass Young Stellar Objects. II. CO₂". In: *Astrophys. J.* 678, pp. 1005–1031.
- Porco, C. C. et al. (2006). "Cassini Observes the Active South Pole of Enceladus". In: *Science* 311, pp. 1393–1401.
- Portugal, W., Pilling, S., Boduch, P., Rothard, H., and Andrade, D. P. P. (2014). "Radiolysis of amino acids by heavy and energetic cosmic ray analogues in

- simulated space environments: α -glycine zwitterion form". In: *Mon. Not. R. Astron. Soc.* 441, pp. 3209–3225.
- Prasad, S. S. and Tarafdar, S. P. (1983). "UV radiation field inside dense clouds - Its possible existence and chemical implications". In: *Astrophys. J.* 267, pp. 603–609.
- Raponi, A. et al. (2016). "The temporal evolution of exposed water ice-rich areas on the surface of 67P/Churyumov-Gerasimenko: spectral analysis". In: *Mon. Not. R. Astron. Soc.* 462, S476–S490.
- Raponi, A. et al. (2018). "Variations in the amount of water ice on Ceres' surface suggest a seasonal water cycle". In: *Sci. Adv.* 4, eaao3757.
- Raut, U., Teolis, B. D., Loeffler, M. J., Vidal, R. A., Famá, M., and Baragiola, R. A. (2007). "Compaction of microporous amorphous solid water by ion irradiation". In: *J. Chem. Phys.* 126, pp. 244511–244511.
- Romanescu, C., Marschall, J., Kim, D., Khatiwada, A., and Kalogerakis, K. S. (2010). "Refractive index measurements of ammonia and hydrocarbon ices at 632.8 nm". In: *Icarus* 205, pp. 695–701.
- Romanini, D., Biennier, L., Salama, F., Kachanov, A., Allamandola, L. J., and Stoeckel, F. (1999). "Jet-discharge cavity ring-down spectroscopy of ionized polycyclic aromatic hydrocarbons: progress in testing the PAH hypothesis for the diffuse interstellar band problem". In: *Chem. Phys. Lett.* 303, pp. 165–170.
- Rubin, M. et al. (2015). "Molecular nitrogen in comet 67P/Churyumov-Gerasimenko indicates a low formation temperature". In: *Science* 348.6231, pp. 232–235.
- Sagstuen, E., Sanderud, A., and Hole, E. O. (2004). "The Solid-State Radiation Chemistry of Simple Amino Acids, Revisited". In: *Radiat. Res.* 162, pp. 112–119.
- Salama, F. (2008). "PAHs in Astronomy - A Review". In: *Organic Matter in Space*. Ed. by S. Kwok and S. Sanford. Vol. 251. IAU Symposium, pp. 357–366.
- Salama, F. and Allamandola, L. J. (1991). "Electronic absorption spectroscopy of matrix-isolated polycyclic aromatic hydrocarbon cations. I - The naphthalene cation ($C_{10}H_8^+$)". In: *J. Chem. Phys.* 94, pp. 6964–6977.
- Salama, F. and Allamandola, L. J. (1992). "Is a pyrene-like molecular ion the cause of the 4,430-Å diffuse interstellar absorption band?" In: *Nature* 358, p. 42.
- Salama, F. and Ehrenfreund, P. (2014). "A Critical Review of PAHs as DIB Carriers - Progress and Open Questions". In: *The Diffuse Interstellar Bands*. Ed. by J. Cami and N. L. J. Cox. Vol. 297. IAU Symposium, pp. 364–369.
- Salama, F., Galazutdinov, G., Krelowski, J., Biennier, L., Beletsky, Y., and Song, I. O. (2011). "Polycyclic Aromatic Hydrocarbons and the Diffuse Interstellar Bands. A Survey". In: *The Molecular Universe*. Ed. by J. Cernicharo and R. Bachiller. Vol. 280. IAU Symposium.

- Sandford, S. A., Bernstein, M. P., and Allamandola, L. J. (2004). "The Mid-Infrared Laboratory Spectra of Naphthalene ($C_{10}H_8$) in Solid H_2O ". In: *Astrophys. J.* 607, pp. 346–360.
- Sandford, S. A. et al. (2006). "Organics Captured from Comet 81P/Wild 2 by the Stardust Spacecraft". In: *Science* 314, p. 1720.
- Schiebener, P., Straub, J., Levelt Sengers, J. M. H., and Gallagher, J. S. (1990). "Refractive index of water and steam as function of wavelength, temperature and density". In: *Journal of Physical and Chemical Reference Data* 19, pp. 677–717.
- Schmidt, W. (1977). "Photoelectron spectra of polynuclear aromatics. V. Correlations with ultraviolet absorption spectra in the catacondensed series". In: *J. Chem. Phys.* 66, pp. 828–845.
- Schmitt-Kopplin, P., Gabelica, Z., Gougeon, R. D., Fekete, A., Kanawati, B., Harir, M., Gebefuegi, I., Eckel, G., and Hertkorn, N. (2010). "High molecular diversity of extraterrestrial organic matter in Murchison meteorite revealed 40 years after its fall". In: *Proc. Natl. Acad. Sci. U.S.A* 107.7, pp. 2763–2768.
- Schutte, W. A. and Khanna, R. K. (2003). "Origin of the $6.85 \mu m$ band near young stellar objects: The ammonium ion (NH_4^+) revisited". In: *Astron. Astrophys.* 398, pp. 1049–1062.
- Schutte, W. A., Tielens, A. G. G. M., Whittet, D. C. B., Boogert, A., Ehrenfreund, P., de Graauw, T., Prusti, T., van Dishoeck, E. F., and Wesselius, P. (1996). "The 6.0 and $6.8 \mu m$ absorption features in the spectrum of NGC 7538: IRS9". In: *Astron. Astrophys.* 315, pp. L333–L336.
- Schutte, W. A., Boogert, A. C. A., Tielens, A. G. G. M., Whittet, D. C. B., Gerakines, P. A., Chiar, J. E., Ehrenfreund, P., Greenberg, J. M., van Dishoeck, E. F., and de Graauw, T. (1999). "Weak ice absorption features at 7.24 and $7.41 \mu m$ in the spectrum of the obscured young stellar object W 33A". In: *Astron. Astrophys.* 343, pp. 966–976.
- Sellgren, K., Smith, R. G., and Brooke, T. Y. (1994). "The 3.2 – $3.6 \mu m$ Spectra of Monoceros R2/IRS-3 and Elias 16". In: *Astrophys. J.* 433, p. 179.
- Sellgren, K., Werner, M. W., Ingalls, J. G., Smith, J. D. T., Carleton, T. M., and Joblin, C. (2010). " C_{60} in Reflection Nebulae". In: *Astrophys. J.* 722, pp. L54–L57.
- Sellmeier, W. (1871). "Zur Erkarung der abnormen Farbenfolge im Spectrum einiger Substanzen". In: *Ann. Phys.* 219, pp. 272–282.
- Shen, C. J., Greenberg, J. M., Schutte, W. A., and van Dishoeck, E. F. (2004). "Cosmic ray induced explosive chemical desorption in dense clouds". In: *Astron. Astrophys.* 415, pp. 203–215.
- Shida, T. (1988). *Electronic absorption spectra of radical ions*. Physical sciences data. Elsevier. ISBN: 9780444430359.

- Shida, T. and Iwata, S. (1973). "Electronic spectra of ion radicals and their molecular orbital interpretation. III. Aromatic hydrocarbons". In: *J. Am. Chem. Soc.* 95, p. 3473.
- Smith, I. W. M., Herbst, E., and Chang, Q. (2004). "Rapid neutral-neutral reactions at low temperatures: a new network and first results for TMC-1". In: *Mon. Not. R. Astron. Soc.* 350, pp. 323–330.
- Smith, R. G., Sellgren, K., and Tokunaga, A. T. (1989). "Absorption Features in the 3 Micron Spectra of Protostars". In: *Astrophys. J.* 344, pp. 413–426.
- Sonnentrucker, P. (2014). "Modern DIB Surveys and DIB Environmental Behavior". In: *The Diffuse Interstellar Bands*. Ed. by J. Cami and N. L. J. Cox. Vol. 297. IAU Symposium, pp. 13–22.
- Starkey, N. A., Franchi, I. A., and Alexander, C. M. O. (2013). "A Raman spectroscopic study of organic matter in interplanetary dust particles and meteorites using multiple wavelength laser excitation". In: *Meteoritics and Planetary Science* 48, pp. 1800–1822.
- Steglich, M., Bouwman, J., Huisken, F., and Henning, T. (2011). "Can Neutral and Ionized Polycyclic Aromatic Hydrocarbons Be Carriers of the Ultraviolet Extinction Bump and the Diffuse Interstellar Bands?" In: *Astrophys. J.* 742, p. 2.
- Stein, S. E. (2018). "Mass Spectra". In: *NIST Chemistry WebBook, NIST Standard Reference Database Number 69*. Ed. by P. J. Lindstrom and W. G. Mallard.
- Stern, S. A. et al. (2015). "The Pluto system: Initial results from its exploration by New Horizons". In: *Science* 350, aad1815.
- Sukhorukov, O., Staicu, A., Diegel, E., Rouillé, G., Henning, T., and Huisken, F. (2004). " $D_2 \leftarrow D_0$ transition of the anthracene cation observed by cavity ring-down absorption spectroscopy in a supersonic jet". In: *Chem. Phys. Lett.* 386, pp. 259–264.
- Szczepanski, J. and Vala, M. (1993). "Infrared frequencies and intensities for astrophysically important polycyclic aromatic hydrocarbon cations". In: *Astrophys. J.* 414, pp. 646–655.
- Szczepanski, J., Vala, M., Talbi, D., Parisel, O., and Ellinger, Y. (1993). "Electronic and vibrational spectra of matrix isolated anthracene radical cations - Experimental and theoretical aspects". In: *J. Chem. Phys.* 98, pp. 4494–4511.
- ten Kate, I. L., Garry, J. R. C., Peeters, Z., Quinn, R., Foing, B., and Ehrenfreund, P. (2005). "Amino acid photostability on the Martian surface". In: *Meteorit. Planet. Sci.* 40, p. 1185.
- Terada, H. and Tokunaga, A. T. (2012). "Discovery of Crystallized Water Ice in a Silhouette Disk in the M43 Region". In: *Astrophys. J.* 753, p. 19.
- Terwisscha van Scheltinga, J., Ligterink, N. F. W., Boogert, A. C. A., van Dishoeck, E. F., and Linnartz, H. (2018). "Infrared spectra of complex

- organic molecules in astronomically relevant ice matrices. I. Acetaldehyde, ethanol, and dimethyl ether". In: *Astron. Astrophys.* 611, A35.
- Theulé, P., Duvernay, F., Danger, G., Borget, F., Bossa, J. B., Vinogradoff, V., Mispelaer, F., and Chiavassa, T. (2013). "Thermal reactions in interstellar ice: A step towards molecular complexity in the interstellar medium". In: *Adv. Space Res.* 52, pp. 1567–1579.
- Tielens, A. G. G. M. (2008). "Interstellar polycyclic aromatic hydrocarbon molecules." In: *Annual Review of Astronomy and Astrophysics* 46, pp. 289–337.
- Tielens, A. G. G. M. (2013). "The molecular universe". In: *Rev. Mod. Phys.* 85, pp. 1021–1081.
- Tielens, A. G. G. M. and Hagen, W. (1982). "Model calculations of the molecular composition of interstellar grain mantles". In: *Astron. Astrophys.* 114, pp. 245–260.
- Tilling, I. et al. (2012). "Gas modelling in the disc of HD 163296". In: *Astron. Astrophys.* 538, A20.
- Tuairisg, S. Ó., Cami, J., Foing, B. H., Sonnentrucker, P., and Ehrenfreund, P. (2000). "A deep echelle survey and new analysis of diffuse interstellar bands". In: *Astron. Astrophys. Suppl Ser.* 142, pp. 225–238.
- van Broekhuizen, F. A., Pontoppidan, K. M., Fraser, H. J., and van Dishoeck, E. F. (2005). "A 3–5 μm VLT spectroscopic survey of embedded young low mass stars II. Solid OCN⁻". In: *Astron. Astrophys.* 441, pp. 249–260.
- van de Hulst, H. C. (1946). "The solid particles in interstellar space". In: *Recherches Astronomiques de l'Observatoire d'Utrecht* 11, pp. 2.i–2.
- van Dishoeck, E. F., Herbst, E., and Neufeld, D. A. (2013). "Interstellar Water Chemistry: From Laboratory to Observations". In: *Chem. Rev.* 113, pp. 9043–9085.
- van Dishoeck, E. F. (2014). "Astrochemistry of dust, ice and gas: introduction and overview". In: *Faraday Discuss.* 168, p. 9.
- van Paridon, M. W., Koning, R. E., and Zandstra, P. J. (1979). "MCD spectra of the triphenylene positive ion. A test of the pairing theorem for highly symmetrical hydrocarbons". In: *Chem. Phys. Lett.* 61, pp. 258–261.
- Visser, R., van Dishoeck, E. F., Doty, S. D., and Dullemond, C. P. (2009). "The chemical history of molecules in circumstellar disks. I. Ices". In: *Astron. Astrophys.* 495.3, pp. 881–897.
- Wakelam, V. et al. (2010). "Reaction Networks for Interstellar Chemical Modelling: Improvements and Challenges". In: *Space Sci. Rev.* 156, pp. 13–72.
- Walker, G. A. H., Bohlender, D. A., Maier, J. P., and Campbell, E. K. (2015). "Identification of More Interstellar C₆₀⁺ Bands". In: *Astrophys. J.* 812, p. L8.
- Warneck, P. (1962). "A microwave-powered hydrogen lamp for vacuum ultraviolet photochemical research". In: *Appl. Opt.* 1, pp. 721–726.

- Warren, S. G. and Brandt, R. E. (2008). "Optical constants of ice from the ultraviolet to the microwave: A revised compilation". In: *J. Geophys. Res.-Atmos.* 113.D14, p. D14220.
- Warren, S. G. (1984). "Optical constants of ice from the ultraviolet to the microwave". In: *Appl. Opt.* 23.8, pp. 1206–1225.
- Westley, M. S., Baratta, G. A., and Baragiola, R. A. (1998). "Density and index of refraction of water ice films vapor deposited at low temperatures". In: *J. Chem. Phys.* 108, pp. 3321–3326.
- Williams, J. P. and Cieza, L. A. (2011). "Protoplanetary Disks and Their Evolution". In: *Annu. Rev. Astron. Astrophys.* 49, pp. 67–117.
- Yabushita, A., Hama, T., and Kawasaki, M. (2013). "Photochemical reaction processes during vacuum-ultraviolet irradiation of water ice". In: *J. Photochem. Photobiol., C* 16, pp. 46–61.
- York, B., Sonnentrucker, P., Hobbs, L. M., York, D. G., Friedman, S. D., Dahlstrom, J., Welty, D. E., Snow, T. P., and Rachford, B. L. (2014). "Behaviour of the Broadest DIBs as a Function of E(B-V)". In: *The Diffuse Interstellar Bands*. Ed. by J. Cami and N. L. J. Cox. Vol. 297. IAU Symposium, pp. 138–140.
- Zhen, J., Paardekooper, D. M., Candian, A., Linnartz, H., and Tielens, A. G. G. M. (2014a). "Quadrupole ion trap/time-of-flight photo-fragmentation spectrometry of the hexa-peri-hexabenzocoronene (HBC) cation". In: *Chem. Phys. Lett.* 592, pp. 211–216.
- Zhen, J., Castellanos, P., Paardekooper, D. M., Linnartz, H., and Tielens, A. G. G. M. (2014b). "Laboratory Formation of Fullerenes from PAHs: Top-down Interstellar Chemistry". In: *Astrophys. J.* 797, p. L30.
- Zhen, J., Castellanos, P., Paardekooper, D. M., Ligterink, N. F. W., Linnartz, H., Nahon, L., Joblin, C., and Tielens, A. G. G. M. (2015). "Laboratory Photochemistry of PAHs: Ionization versus Fragmentation". In: *Astrophys. J.* 804, p. L7.
- Zhitnikov, R. A. and Dmitriev, Y. A. (2002). "Detection of free radicals in low-temperature gas-grain reactions of astrophysical interest". In: *Astron. Astrophys.* 386, pp. 1129–1138.

