

Radiolytic Studies of Naphthalene in the Presence of Water

Y. Keheyán · I. L. ten Kate

Received: 16 January 2012 / Accepted: 5 March 2012
© Springer Science+Business Media B.V. 2012

Abstract Naphthalene is an interesting candidate to study in the framework of organic delivery to planetary surfaces as well as in the origin of life. Additionally, naphthalene is of environmental interest, because of its chronic and acute effects on living systems, such as humans and animals (e.g. moths). Naphthalene has been well studied in both fields. In this paper we give an overview of radiolytic studies of naphthalene in the presence of both liquid water and water ice. From our review it appears that OH radicals are formed both in liquid water and in interstellar ices and that these radicals play a considerable role in the degradation of naphthalene. However, it also appears that upon irradiation of naphthalene in liquid water, hydrogen peroxide, a species that accelerates naphthalene degradation, is formed. Based on this review we suggest that the role of hydrogen peroxide in interstellar ices should be further investigated.

Keywords Radiolysis · Astrobiology · PAHs · Hydroxylation

Introduction

Polycyclic aromatic hydrocarbons (PAHs) are widely formed (Tielens and Charnley 1997) and omnipresent in space, comprising 10–20 % of the cosmic carbon (Kaiser et al. 2000; Tielens 2008; Ehrenfreund et al. 2011; and references in all). They are involved in a variety

Paper presented at the 11th European Workshop on Astrobiology—EANA 11, 11th–14th July 2011, Köln, Germany

Y. Keheyán (✉)
ISMN-CNR, INAF, c/o Department of Chemistry, University of Rome “La Sapienza”, p.le A. Moro 5,
Rome 00185, Italy
e-mail: yeghis.keheyán@uniroma1.it

I. L. ten Kate
Centre for Physics of Geological Processes, University of Oslo, Sem Sælandsvei 24, 0316 Oslo, Norway
e-mail: science@ingeloes.com

of phenomena observed throughout the universe, including a range of unidentified infrared bands (e.g., Flickinger and Wdowiak 1990; Cook and Saykally 1998; Cataldo et al. 2004) and some of the diffuse interstellar bands (e.g., Cossart-Magos and Leach 1990; Snow et al. 1998; Maier et al. 2004, 2006). Gaseous PAHs have been observed in a large variety of interstellar environments, for example, protoplanetary and planetary nebulae, reflection nebulae, HII regions, and the diffuse interstellar medium (Léger and Puget 1984; Sandford 1996; Bregman et al. 2000; Bernstein et al. 2001; Allamandola 2011). These detections have been made possible by a tremendous amount of laboratory studies on PAHs in the gas phase, summarized in Tielens (2008). As soon as the temperature is sufficiently low (below 50 K), such as in dense interstellar clouds, PAHs condense onto refractory dust grains and form interstellar ices (Sandford and Allamandola 1993). At these temperatures most species freeze, thus the ice mantles formed around these silicate and carbonaceous grains contain a variety of other compounds, including H₂O, CO, CO₂, CH₃OH and NH₃ (Gibb et al. 2004, and references therein). Laboratory studies on ultraviolet (UV) radiation of PAHs embedded in these ices have shown that the PAHs can oxidize and react with other compounds present in the ices (Bernstein et al. 1996, 2002, 2003, 2007; Bouwman et al. 2010, 2011a, b). In this process a wide range of organics, such as aromatic alcohols, ketones, quinones, and amino acids, can be formed (Bernstein et al. 1999, 2001; Chen et al. 2008). Both the parent PAHs and their derivatives are present in comets, carbonaceous meteorites, and interplanetary dust particles (IDPs) (Cronin and Chang 1993; Moreels et al. 1994; Botta and Bada 2002; Sephton 2002; Sandford et al. 2006; Flynn et al. 2008; Li 2009). It has been suggested that PAHs and their derivatives can also be formed through chemical processing inside meteorites, such as through Fischer-Tropsch type reactions and subsequent processes such as cooling of magmatic and impact-generated gases or alkylation through aqueous exposure (Anders 1996; Zolotov and Shock 1999, 2000; Elsila et al. 2005). The delivery of these extraterrestrial organic molecules to the Earth's surface (e.g. Flynn et al. 2004) may have played a role in the origin of life (Ehrenfreund et al. 2002, 2006).

Naphthalene

Naphthalene (C₁₀H₈) is the smallest and most stable polycyclic aromatic hydrocarbon. It has a high vapor pressure at room temperature (0.2 mbar), making it relatively easy to study in the gas phase, and it is water-soluble (25–30 mg L⁻¹) in ambient conditions. Naphthalene has been very well studied due to its role in interstellar chemistry and its environmental implications, especially with respect to water pollution. Gaseous naphthyl, C₁₀H₇⁺, the dehydrogenated form of the naphthalene cation, was investigated because such species are likely to be present in the diffuse interstellar medium, as a result of photodissociation of the parent PAH cations (Allamandola et al. 1989). Laboratory studies of the chemical reactivity of naphthalene cations (C₁₀H₆⁺ and C₁₀H₈⁺) in the gas phase by Le Page et al. (1997) showed that the rapid addition of a hydrogen atom to the radical cations C₁₀H₈⁺ and C₁₀H₆⁺, as well as the efficient radiative association of C₁₀H₇⁺ with molecular hydrogen, indicates that protonated naphthalene, C₁₀H₉⁺, will be readily formed from its precursor ions in the interstellar medium (see also Snow et al. 1998). Furthermore, these results indicate that protonated naphthalene will be a terminal ionic species in interstellar environments where the naphthalene cation and its derivatives are able to survive (Le Page et al. 1999). It has been shown that protonated naphthalene displays similar features in the infrared as observed in the unidentified infrared bands (Ricks et al. 2009), and the evidence of the naphthalene cation (C₁₀H₈⁺) in the

interstellar medium in the direction of the star Cernis 52 in the Perseus constellation has also been reported (Iglesias-Groth et al. 2010).

The formation of naphthalene, and PAHs in general, has always been considered to take place in high temperature environments; for example, polycyclic aromatic species can grow in ionized gases by association of smaller building blocks, such as naphthyl and phenyl rings (Ascenzi et al. 2010). However, this cannot explain the PAH abundance in the interstellar medium, considering their short lifetime (Micelotta et al. 2010a, b, 2011). Very recently Parker et al. (2012) showed that naphthalene could be synthesized under low temperature conditions as well. This makes naphthalene an interesting candidate to study in the framework of organic delivery to planetary surfaces as well as the origin of life. In living systems, such as humans and animals, naphthalene has chronic and acute effects, including change or destruction of red blood cells (EPA-1, EPA-2). Naphthalene is a compound in daily life products, such as insect repellents, pesticides, dye intermediates, and tanning agents. Due to its poisonous nature naphthalene has been well studied both the field of air and water pollution. In this paper we give an overview of radiolytic studies of naphthalene in the presence of water, both in liquid and solid state (water ice). The ice studies we describe here were carried out in the field of interstellar chemistry, whereas the liquid water studies were carried out in the field of water pollution studies. We highlight some findings and discuss the effect of radiolysis of water in these reactions. We conclude the paper with some remarks on how both experimental lines could be beneficial to each other.

Radiolytic Experiments Involving Naphthalene

One of the first experiments investigating the effect of radiation on naphthalene in the presence of H₂O was carried out by Keheyan and Perez (1991). In these experiments gaseous naphthalene was subjected to ionizing radiation (in the form of gamma rays) in the presence of H₂O, air, and a mixture of H₂O and air. These experiments were conducted to study the reactions that lead to the formation of small amounts of 2-naphthol and how these reactions could contribute to terrestrial atmospheric smog. It was shown that the conversion rate of naphthalene was low and dominated primarily by the interaction of OH radicals formed by radiolysis of the water. Subsequent experimental investigations can be divided into two categories, naphthalene in ices and naphthalene in water. These categories are further reviewed below.

Naphthalene in Interstellar Ices

Bernstein et al. (2001) subjected naphthalene embedded in H₂O ice at 15 K to vacuum ultraviolet (VUV) radiation from a flowing hydrogen discharge lamp (Ly α radiation at 121.6 nm and a molecular transition centered at 160 nm). These conditions are representative of the UV and temperature conditions in the dense interstellar clouds where the ices are expected to form (Sandford and Allamandola 1993). The main reaction products found were 1- and 2-naphthol 1,4-naphthoquinone as along with smaller amounts of 2,6-dihydroxy and 2,7-dihydroxy naphthalene. Gudipati and Allamandola (2003) expanded upon these experiments and showed that irradiation with similar VUV radiation leads to the formation of naphthalene cations at 15 K. Upon heating above 100 K, these cations formed 1-naphthols. The photo-products formed in both experiments (Bernstein et al. 2001; Gudipati and Allamandola 2003) were most likely the result of multistep reactions between the naphthalene cation and the species formed by photolysis of the ice, such as OH and OH \cdot . Theoretical modeling suggests

that the reactions of OH with naphthalene and the naphthalene cation have no barriers, and that both reactions are expected to favor 1-naphthol over 2-naphthol (Ricca and Bauschlicher 2000), which is indeed observed in Bernstein et al. (2001).

Naphthalene in Water

Due to its possibly carcinogenic effect on humans (IARC 2002) and its acute and chronic effects on human and animal health, naphthalene has been very well documented in pollution control studies (e.g. Cesareo et al. 1986). Glaze et al. (1992) showed that naphthalene dissolved in water is directly photolyzed upon radiation with UV (254 nm). However, in this process naphthalene produces significant amounts of hydrogen peroxide, which substantially accelerates the degradation rate of naphthalene (Glaze et al. 1992). Hydrogen peroxide has been detected in the interstellar medium (Bergman et al. 2011) and could therefore play a role in the irradiation chemistry of interstellar ices. In addition to hydrogen peroxides, reaction products like naphthols, naphthoquinone, benzaldehyde, and phthalic and benzoic acids were formed (Glaze et al. 1992; Tuhkanen and Beltrán 1995). Experiments on naphthalene using only hydrogen peroxide, without any form of irradiation, did not result in naphthalene degradation (Tuhkanen and Beltrán 1995). Irradiation of naphthalene in the presence of added hydrogen peroxides led to the additional formation of aliphatic and lower-molecular-weight carboxylic acids (Tuhkanen and Beltrán 1995).

Effect of OH Radicals

The kinetics of the gas-phase reactions of naphthalene with OH radicals has been studied at 295 ± 1 K in one atmosphere of air (Atkinson and Aschmann 1986). A rate constant of $2.59 \pm 0.24 \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ has been determined for this reaction. This shows that under atmospheric conditions naphthalene will react mainly with the OH radical, with a naphthalene lifetime of approximately 11 h. It is well known (Melton and Neece 1971) that water radiolysis produces highly reactive OH and H radicals. These radicals are much more reactive than the OH^- or H^+ formed by ionic dissociation. The OH radical is a powerful oxidizing agent and is chemically very reactive. Radiolysis of water vapor leads to the formation of OH radicals through the following reaction:



The G value refers to the number of molecules of reactant consumed or product formed per 100 eV of energy absorbed. The reported G-value for reaction (1) is 3.7 (Swallow 1973) and from this the rate of OH radical formation can be calculated. At OH radical concentrations above $10^{11} \text{ radicals cm}^{-3}$, radical-radical reactions such as



must be considered (Dixon-Lewis and Williams 1977) due to the fact that the rate constant of such reaction (2) is $6.5 \times 10^{-11} \text{ radicals cm}^{-3} \text{ s}^{-1}$.

Under γ radiation (as used in Keheyani and Perez 1991) activated forms of oxygen are formed, including excited-state singlet oxygen, allowing a non-radical induced oxidation of aromatic molecules (Clough 1980). In the experiments by Keheyani and Perez (1991) only the β -isomer, 2-naphthol, was formed upon radiation, whereas in the experiments by Bernstein et al. (2001) the α -isomer, 1-naphthol, was also formed and favored over the β -isomer, as predicted by Ricca and Bauschlicher (2000).

Balakrishnan and Reddy (1968) observed a variation in the α - and β -isomers upon γ radiation of naphthalene dissolved in water under pure oxygen. However, in these experiments the amount of β -isomers varied with the sample temperature, indicating a change in the mechanism of hydroxylation and naphthol formation by means other than OH attack. One process could be the radiolysis of the oxygen present in both experiments (Balakrishnan and Reddy 1968; Keheyan and Perez 1991). It is well known that among the active species of oxygen formed during its radiolysis $O(^1D)$ can play a role. The following reaction



can explain the increase of the radicals in an irradiated system containing oxygen (either pure or in air) and water.

Conclusion

The comparison of the ice and liquid water experiments shows that the processes breaking down naphthalene are comparable. A large role in this process is reserved for the interaction with OH radicals, which are formed by irradiation of the water present. However, from the analysis of UV interactions with naphthalene dissolved in water, the formation of large amounts of hydrogen peroxide is observed, a process that considerably accelerates the degradation rate of naphthalene. In this manuscript we discussed only those reactions involving naphthalene, but it can be hypothesized that similar processes will play a role in the case of other PAHs. Hydrogen peroxide has been shown to form in water ice due to VUV photodissociation (Yabushita et al. 2008). No mention of hydrogen peroxides or their influence has been made in the existing literature on experiments with naphthalene in interstellar ices. Considering the role of hydrogen peroxide in the irradiation of naphthalene in liquid water, it may be worthwhile investigating its role in interstellar ices.

Acknowledgments The authors thank A. Bull-Aller for suggestions on the proper use of the English language and three anonymous reviewers for the helpful comments. Y.K. gratefully acknowledges financial support through Italian Space Agency (ASI), Contract n. I/015/07/0.

References

- Allamandola L (2011) PAHs and astrobiology. In: Joblin C, Tielens AGGM (eds) PAHs and the Universe, EAS Publications Series 46:305–317
- Allamandola LJ, Tielens AG, Barker JR (1989) Interstellar polycyclic aromatic hydrocarbons: the infrared emission bands, the excitation/emission mechanism, and the astrophysical implications. *Astrophys J Suppl Ser* 71:733–775. doi:10.1086/191396
- Anders E (1996) Evaluating the evidence for past life on Mars. *Science* 274:2119–2120
- Ascenzi D, Aysina J, Tosi P, Maranzana A, Tonachini G (2010) Growth of polyaromatic molecules via ion-molecule reactions: an experimental and theoretical mechanistic study. *J Chem Phys* 133:184308. doi:10.1063/1.3505553
- Atkinson R, Aschmann S (1986) Kinetics of the reactions of naphthalene, 2-methylnaphthalene, and 2,3-dimethylnaphthalene with OH radicals and with O_3 at 295 ± 1 K. *Int J Chem Kinet* 18:569–573
- Balakrishnan I, Reddy MP (1968) Homolytic hydroxylation of naphthalene in oxygenated aqueous solutions by γ radiolysis at higher temperatures. *J Phys Chem* 72:4609–4613. doi:10.1021/j100859a042
- Bergman P, Parise B, Liseau R, Larsson B, Olofsson H, Menten KM, Güsten R (2011) Detection of interstellar hydrogen peroxide. *Astron Astrophys* 531:L8. doi:10.1051/0004-6361/201117170

- Bernstein MP, Sandford SA, Allamandola LJ (1996) Hydrogenated polycyclic aromatic hydrocarbons (Hn-PAHs) and the 2940 and 2850 wavenumber (3.40 and 3.51 Micron) infrared emission features. *Astrophys J* 472:L127–L130
- Bernstein MP, Sandford SA, Allamandola LJ, Gillette JSB, Clemett SJ, Zare RN (1999) UV irradiation of polycyclic aromatic hydrocarbons in ices: production of alcohols, quinones, and ethers. *Science* 283:1135–1138. doi:10.1126/science.283.5405.1135
- Bernstein MP, Dworkin JP, Sandford S, Allamandola L (2001) Ultraviolet irradiation of naphthalene in H₂O Ice: implications for meteorites and biogenesis. *Meteorit Planet Sci* 36:351–358
- Bernstein MP, Elsila JE, Dworkin JP, Sandford SA, Allamandola LJ, Zare RN (2002) Side group addition to the PAH coronene by UV photolysis in cosmic ice analogs. *Astrophys J* 576:1115–1120
- Bernstein MP, Moore MH, Elsila JE, Sandford SA, Allamandola LJ, Zare RN (2003) Side group addition to the polycyclic aromatic hydrocarbon coronene by proton irradiation in cosmic ice analogs. *Astrophys J* 582:L25–L29. doi:10.1086/345941
- Bernstein MP, Sandford SA, Mattioda AL, Allamandola LJ (2007) Near- and mid-infrared laboratory spectra of PAH cations in solid H₂O. *Astrophys J* 664:1264–1272
- Botta O, Bada JL (2002) Extraterrestrial organic compounds in meteorites. *Surv Geophys* 23:411–467. doi:10.1023/A:1020139302770
- Bouwman J, Cuppen HM, Bakker A, Allamandola LJ, Linnartz H (2010) Photochemistry of the PAH pyrene in water ice: the case for ion-mediated solid-state astrochemistry. *Astron Astrophys* 511:A33
- Bouwman J, Cuppen HM, Steglich M, Allamandola LJ, Linnartz H (2011a) Photochemistry of polycyclic aromatic hydrocarbons in cosmic water ice: II. Near UV/VIS spectroscopy and ionization rates. *Astron Astrophys* 529:A46
- Bouwman J, Mattioda AL, Linnartz H, Allamandola LJ (2011b) Photochemistry of polycyclic aromatic hydrocarbons in cosmic water ice: I. Mid-IR spectroscopy and photoproducts. *Astron Astrophys* 525:A93
- Bregman JD, Hayward TL, Sloan GC (2000) Discovery of the 11.2 micron polycyclic aromatic hydrocarbon band in absorption toward Monoceros R2 IRS3. *Astrophys J* 544:L75–L78
- Cataldo F, Keheyán Y, Heyman D (2004) Complex organic matter in space: about the chemical composition of carriers of the unidentified infrared bands (UIBs and protoplanetary emission spectra recorded from certain astrophysical objects). *Origins Life Evol Biosp* 34:13–24
- Cesareo D, di Domenico A, Marchini S, Passerini L, Tosato ML (1986) Environmental photochemistry of chlorinated aromatics in aqueous media. A review of data. In: Pelizzetti E, Serpone N (eds) *Homogeneous and heterogeneous photocatalysis*. D. Reidel Publishing Comp, Dordrecht, pp 593–627
- Chen YJ, Nuevo M, Yih TS, Ip W-H, Fung HS, Cheng CY, Tsai HR et al (2008) Amino acids produced from the ultraviolet/extreme-ultraviolet irradiation of naphthalene in a H₂O+NH₃ ice mixture. *Mon Not R Astron Soc* 384:605–610. doi:10.1111/j.1365-2966.2007.12687.x
- Clough RL (1980) γ -Radiation-oxidation of polycyclic aromatic hydrocarbons: involvement of singlet oxygen. *J Am Chem Soc* 102:5242–5245. doi:10.1021/ja00536a021
- Cook DJ, Saykally RJ (1998) Simulated infrared emission spectra of highly excited polyatomic molecules: a detailed model of the PAH-UIR hypothesis. *Astrophys J* 493:793–802
- Cossart-Magos C, Leach S (1990) Polycyclic aromatic hydrocarbons as carriers of the diffuse interstellar bands: rotational band contour tests. *Astron Astrophys* 233:559–569
- Cronin JR, Chang S (1993) Organic matter in meteorites: Molecular and isotopic analysis of the Murchison meteorite. In: Greenberg JM, Mendoza CX, Pirronello V (eds) *The chemistry of life's origins*, vol. 416. Kluwer, the Netherlands, pp 209–258
- Dixon-Lewis G, Williams DJ (1977) Chapter 1. The oxidation of hydrogen and carbon monoxide. In: Bamford CH, Tipper CFH (eds) *Comprehensive chemical kinetics*, volume 17. Elsevier, the Netherlands, pp 1–248
- Ehrenfreund P, Irvine W, Becker L, Blank J, Brucato J, Colangeli L, Derenne S, Despois D, Dutrey A, Fraaije H, Lazcano A, Owen T, Robert F (2002) Astrophysical and astrochemical insights into the origin of life. *Rep Prog Phys* 65:1427–1487
- Ehrenfreund P, Rasmussen S, Cleaves J, Chen L (2006) Experimentally tracing the key steps in the origin of life: the aromatic world. *Astrobiology* 6:490–520. doi:10.1089/ast.2006.6.490
- Ehrenfreund P, Spaans M, Holm NG (2011) The evolution of organic matter in space. *Philos T R Soc A* 369:538–554. doi:10.1098/rsta.2010.0231
- Elsila J, de Leon N, Buseck P, Zare R (2005) Alkylation of polycyclic aromatic hydrocarbons in carbonaceous chondrites. *Geochim Cosmochim Acta* 69:1349–1357. doi:10.1016/j.gca.2004.09.009
- EPA-1: <http://www.epa.gov/ttn/atw/hlthef/naphthal.html#ref1> (last visited March 5, 2012)
- EPA-2: <http://www.epa.gov/iris/subst/0436.htm> (last visited March 5, 2012)
- Flickinger GC, Wdowiak TJ (1990) Spectra of polycyclic aromatic hydrocarbon molecules at elevated temperature and the interstellar unidentified infrared bands. *Astrophys J* 362:L71–L74

- Flynn GJ, Keller LP, Jacobsen C, Wirick S (2004) An assessment of the amount and types of organic matter contributed to the Earth by interplanetary dust. *Adv Space Res* 33:57–66. doi:10.1016/j.asr.2003.09.036
- Flynn GJ, Keller LP, Wirick S, Jacobsen C (2008) Organic matter in interplanetary dust particles. In: Kwok S, Sandford S (eds) *Proceedings IAU symposium No. 251.*, pp 267–275. doi:10.1017/S174392130802173X
- Gibb E, Whittet D, Boogert A, Tielens A (2004) Interstellar ice: the infrared space observatory legacy. *Astrophys J Suppl S* 151:35–73
- Glaze WH, Beltrán F, Thukanen T, Kang J-W (1992) Chemical models of advanced oxidation processes. *Water Poll Res J Can* 27:23–42
- Gudipati M, Allamandola L (2003) Facile generation and storage of polycyclic aromatic hydrocarbon ions in astrophysical ices. *Astrophys J* 596:L195–L198
- IARC (2002) Some traditional herbal medicines, some mycotoxins, naphthalene, and styrene. IARC monographs on the evaluation of carcinogenic risks to humans (Vol. 82, pp. 1–601). World Health Organization
- Iglesias-Groth S, Manchado A, García Hernández A, González Hernández JI, Lambert DL (2010) Evidence for the naphthalene cation in a region of the interstellar medium with anomalous microwave emission. *Astrophys J Let* 685:L55–L58
- Kaiser R, Asvany O, Lee Y (2000) Crossed beam investigation of elementary reactions relevant to the formation of polycyclic aromatic hydrocarbon (PAH)-like molecules in extraterrestrial environments. *Planet Space Sci* 48:483–492
- Keheyan Y, Perez G (1991) Radiation induced gas phase naphthalene hydroxylation. *Chemosphere* 23:627–632
- Le Page V, Keheyan Y, Bierbaum V, Snow T (1997) Chemical constraints on organic cations in the interstellar medium. *J Am Chem Soc* 119:8373–8374
- Le Page V, Keheyan Y, Snow T, Bierbaum V (1999) Reactions of cations derived from naphthalene with molecules and atoms of interstellar interest. *J Am Chem Soc* 121:9435–9446
- Léger A, Puget JL (1984) Identification of the “Unidentified IR Emission Features” of interstellar dust. *Astron Astrophys* 137:L5–L8
- Li A (2009) PAHs in comets: an overview. In: *Deep impact as a world observatory event: synergies in space, time, and wavelength. ESO Astrophysics Symposia, 2009.* pp. 161–175. doi:10.1007/978-3-540-76959-0_21
- Maier JP, Walker GAH, Bohlender DA (2004) On the possible role of carbon chains as carriers of diffuse interstellar bands. *Astrophys J* 602:286
- Maier JP, Boguslavskiy AE, Ding H, Walker GAH, Bohlender DA (2006) The gas phase spectrum of cyclic C₁₈ and the diffuse interstellar bands. *Astrophys J* 640:369–372
- Melton CE, Neece GA (1971) Rate constants and cross-sections for the production of OH⁻ from O⁻ and H⁻ in water. *J Am Chem Soc* 93:6757–6759
- Micelotta ER, Jones AP, Tielens AGGM (2010a) Polycyclic aromatic hydrocarbon processing in a hot gas. *Astron Astrophys* 510(A37):1–14
- Micelotta ER, Jones AP, Tielens AGGM (2010b) Polycyclic aromatic hydrocarbon processing in interstellar shocks. *Astron Astrophys* 510(A36):1–14
- Micelotta ER, Jones AP, Tielens AGGM (2011) Polycyclic aromatic hydrocarbon processing by cosmic rays. *Astron Astrophys* 526(A52):1–17
- Moreels G, Clairemidi J, Hermine P, Brechignac P, Rousselot P (1994) Detection of a polycyclic aromatic molecule in comet P/Halley. *Astron Astrophys* 282:643–656
- Parker DSN, Zhang F, Kim YS, Kaiser RI, Lander A, Kislov VV, Mebel AM et al (2012) Low temperature formation of naphthalene and its role in the synthesis of PAHs (Polycyclic Aromatic Hydrocarbons) in the interstellar medium. *P Nat Acad Sci USA* 109:53–58. doi:10.1073/pnas.1113827108
- Ricca A, Bauschlicher C (2000) The reactions of polycyclic aromatic hydrocarbons with OH. *Chem Phys Lett* 328:396–402
- Ricks AM, Doublerly GE, Duncan MA (2009) The infrared spectrum of protonated naphthalene and its relevance for the unidentified infrared bands. *Astrophys J* 702:301–306. doi:10.1088/0004-637X/702/1/301
- Sandford S (1996) The inventory of interstellar materials available for the formation of the solar system. *Meteorit Planet Sci* 31:449–476
- Sandford S, Allamandola L (1993) Condensation and vaporization studies of CH₃OH and NH₃ ices: major implications for astrochemistry. *Astrophys J* 417:815–825
- Sandford SA, Aleon J, Alexander CMO, Araki T, Bajt S, Baratta GA, Borg J et al (2006) Organics captured from comet 81P/Wild 2 by the Stardust spacecraft. *Science* 314:1720–1724. doi:10.1126/science.1135841
- Septon M (2002) Organic compounds in carbonaceous meteorites. *Nat Prod Rep* 19:292–311. doi:10.1039/b103775g
- Snow T, Le Page V, Keheyan Y, Bierbaum V (1998) The interstellar chemistry of PAH cations. *Nature* 391:259–260
- Swallow A (1973) *Radiation chemistry, an introduction.* Longman Group Ltd., London, p 122

- Tielens AGGM (2008) Interstellar polycyclic aromatic hydrocarbon molecules. *Ann Rev Astron Astrophys* 46:289–337
- Tielens A, Charnley S (1997) Circumstellar and interstellar synthesis of organic molecules. *Origins Life Evol B* 27:23–51
- Tuhkanen TA, Beltrán FJ (1995) Intermediates of the oxidation of naphthalene in water with the combination of hydrogen-peroxide and UV-radiation. *Chemosphere* 30:1463–1475
- Yabushita A, Hama T, Iida D, Kawasaki M (2008) Hydrogen peroxide formation following the vacuum ultraviolet photodissociation of water ice films at 90 K. *J Chem Phys* 129:014709. doi:[10.1063/1.2950093](https://doi.org/10.1063/1.2950093)
- Zolotov MY, Shock E (1999) Abiotic synthesis of polycyclic aromatic hydrocarbons on Mars. *J Geophys Res (Planets)* 104:14033–14049
- Zolotov MY, Shock E (2000) An abiotic origin for hydrocarbons in the Allan Hills 84001 Martian meteorite through cooling of magmatic and impact-generated gases. *Meteorit Planet Sci* 35:629–638