



**HAL**  
open science

## Photochemistry of C<sub>3</sub>H<sub>p</sub> hydrocarbons in Titan's stratosphere revisited

Eric Hébrard, M. Dobrijevic, Jean-Christophe Loison, A. Bergeat, K. M. Hickson, F. Caralp

► **To cite this version:**

Eric Hébrard, M. Dobrijevic, Jean-Christophe Loison, A. Bergeat, K. M. Hickson, et al.. Photochemistry of C<sub>3</sub>H<sub>p</sub> hydrocarbons in Titan's stratosphere revisited. *Astronomy and Astrophysics - A&A*, 2013, 552, pp.132. 10.1051/0004-6361/201220686 . hal-00833258

**HAL Id: hal-00833258**

**<https://hal.science/hal-00833258>**

Submitted on 1 Dec 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

# Photochemistry of $C_3H_p$ hydrocarbons in Titan's stratosphere revisited

E. Hébrard<sup>1,2</sup>, M. Dobrijevic<sup>1,2</sup>, J. C. Loison<sup>3,4</sup>, A. Bergeat<sup>3,4</sup>, K. M. Hickson<sup>3,4</sup>, and F. Caralp<sup>3,4</sup>

<sup>1</sup> Université de Bordeaux, Laboratoire d'Astrophysique de Bordeaux, UMR 5804, 33270 Floirac, France  
e-mail: hebrard@obs.u-bordeaux1.fr

<sup>2</sup> CNRS, Laboratoire d'Astrophysique de Bordeaux, UMR 5804, 33270 Floirac, France

<sup>3</sup> Université de Bordeaux, Institut des Sciences Moléculaires, UMR 5255, 33400 Talence, France

<sup>4</sup> CNRS, Institut des Sciences Moléculaires, UMR 5255, 33400 Talence, France

Received 1 November 2012 / Accepted 22 January 2013

## ABSTRACT

The description of  $C_3$  hydrocarbon chemistry in current photochemical models of Titan's atmosphere is found to be far from complete. We have carefully investigated the photochemistry involving  $C_3H_p$  compounds in the atmosphere of Titan (considering both photolysis and neutral reactions), which considerably impacts the abundances of many other hydrocarbon species (including  $C_2$  compounds). Model results indicate that three species ( $C_3$ ,  $c-C_3H_2$  and  $C_3H_3$ ) could be abundant enough to be present in the *Cassini*/INMS data. Because the error bars on predicted  $C_3$ -hydrocarbon abundances are considerably larger than those of the observational data, new experimental and theoretical studies targeting the measurement of low-temperature reaction rate constants and product branching ratios are required to reduce current model uncertainties. In particular, we highlight 30 “key reactions”, the uncertainty factors of which should be lowered to improve the quality of photochemical models involving  $C_3H_p$  molecules.

**Key words.** planets and satellites: individual: Titan – planets and satellites: atmospheres – planets and satellites: composition – astrochemistry

## 1. Introduction

The latest results obtained by the *Cassini-Huygens* mission confirmed that the dissociation and ionization of methane of  $CH_4$  and nitrogen  $N_2$  in the high stratosphere of Titan initiates a complex photochemistry of hydrocarbons and nitrogen compounds through molecule-molecule and ion-molecule reactions, which leads to the production of  $C_nH_p$  hydrocarbons (up to  $n = 6$  at least; the heaviest hydrocarbon clearly detected is benzene, see for instance [Brown et al. 2009](#), for a comprehensive review of our current knowledge about Titan). The modeling of such an atmospheric system is limited by the lack of kinetic and photolytic data at low temperature ( $T \in [100, 150]$  K) especially for heavy hydrocarbons. [Hébrard et al. \(2007\)](#) pointed out that a great deal of information regarding the larger species ( $n > 3$ ) is missing from current photochemical models. In particular, only a small fraction of all possible reactions producing or involving  $C_3$ -compounds is included in current photochemical models, from which we conclude that several important processes could be missing. To correctly understand how the  $C_3$ -,  $C_4$ - and  $C_6$ -hydrocarbons previously detected in the atmosphere of Titan ( $CH_3C_2H$ ,  $C_3H_6$ ,  $C_3H_8$ ,  $C_4H_2$  and  $C_6H_6$ ) are produced, it is necessary to complete the chemical scheme for lighter species (i.e.,  $C_2$ - and  $C_3$ -compounds). In a recent study, [Hébrard et al. \(2012\)](#) updated the chemical scheme of  $C_2$ -hydrocarbons to provide a solid basis for the study of HCN and HNC neutral productions. In this previous model, we modified various rate constants and branching ratios for reactions involving C and CH. These changes did not play a major role in the chemistry of HCN/HNC but strongly affected C and  $C_3H_p$  concentrations. One of the main changes concerned the  $C + C_2H_2$  reaction, which was predicted to lead to the formation

of the  $C_3H_2$  adduct (as in all photochemical models of giant planets' and Titan's atmospheres where this reaction is present, [Lebonnois et al. 2001](#); [Wilson & Atreya 2004](#); [Moses et al. 2005](#); [Lavvas et al. 2008](#)) but in fact leads to the formation of  $C_3 + H_2$  and  $C_3H + H$  (see Appendix C). Moreover, [Zhang et al. \(2010\)](#) highlighted the fact that atomic carbon C is likely to be more abundant in Titan's upper atmosphere than previously predicted. Carbon atoms are indeed efficiently produced by both the  $H + CH$  ([van Harrevelt et al. 2002](#)) and the  $N + CN$  ([Daranlot et al. 2012](#)) reactions, whereas they are only very slowly consumed by their reaction with  $N_2$  ([Husain & Kirsch 1971](#)) and do not react at all with  $CH_4$  ([Husain & Kirsch 1971](#); [Kim et al. 2003](#)). As a result, the  $C + C_2H_2$  (along with  $C + C_2H_4$ ) reaction is an efficient source of  $C_3H_p$  species, such as  $C_3$ , a very stable bi-carbene molecule found to be abundant in various interstellar media ([Oka et al. 2003](#); [Mookerjee et al. 2010](#)) and in comets ([Huggins 1881](#); [Rousselot et al. 2001](#)), but absent from any current models of Titan's atmosphere. In the present study, we continue our systematic approach to improve the neutral chemical scheme of Titan's atmosphere, focusing specifically on  $C_3$ -hydrocarbons. This work is also important for the modeling of ion-molecule reactions involving  $C_3H_p$  species in the ionosphere of Titan, and vice versa. Abundances of neutral species (and their uncertainties) and ion species are indeed strongly coupled ([Carrasco et al. 2007](#)). The Ion and Neutral Mass Spectrometer (INMS) instrument onboard *Cassini* moreover revealed a few neutrals with densities that pure neutral photochemical chemistry could not easily reproduce. This is for example the case for benzene  $C_6H_6$ , which has been detected in abundance with the INMS instrument, the production of which is now assumed to involve ion chemistry, and notably dissociative recombinations ([Westlake et al. 2012](#); [Plessis et al. 2012](#)).

Another important question clearly points out the need for a careful study of C<sub>3</sub>-hydrocarbons chemistry. From an uncertainty propagation study and a global sensitivity analysis point of view, Hébrard et al. (2009) found that C<sub>3</sub>H<sub>2</sub> is a key compound in the photochemistry of Titan (i.e., several reactions involving C<sub>3</sub>H<sub>2</sub> are responsible for large uncertainties in the abundances of major compounds). It is therefore crucially important to update and complete the chemical scheme related to this compound. Peng et al. (2010) showed a linear increase of the uncertainty factor of species abundance with increasing molecular mass for the three major hydrocarbon families (alkanes, alkenes and alkynes) and a nonlinear uncertainty growth pattern with increasing mass for C<sub>n</sub> and C<sub>n</sub>H<sub>2</sub> species. Consequently, it is necessary to lower the uncertainties on the current chemical scheme of C<sub>2</sub>- and C<sub>3</sub>-hydrocarbons to improve the precision of model results for heavy hydrocarbons. This requires us to first evaluate the uncertainties on the computed abundances of C<sub>3</sub>-compounds and then to identify the key reactions responsible for the largest of them (following the methodology of Hébrard et al. 2009).

The photochemical model used in the present study is derived from the model of Hébrard et al. (2012): details about the model are given in that paper. Our methodology to improve the chemical scheme for C<sub>3</sub>-compounds is presented in Sect. 2. The abundances of C<sub>3</sub>-hydrocarbons are presented in Sect. 3. In particular, we show the main differences between the present and our previous model (Hébrard et al. 2012) and we present the main reactions that are responsible for the production and loss of the major C<sub>3</sub>-hydrocarbons (for the nominal model only). In Sects. 4 and 5 we perform an uncertainty propagation study and a global sensitivity analysis to determine the key reactions responsible for the model result uncertainties for C<sub>3</sub>-compounds. This new list of key reactions is discussed in detail in Appendix C.

## 2. Chemical scheme

### 2.1. Chemical reactions

Many important photochemical processes involving C<sub>3</sub>H<sub>p</sub> species in Titan's atmosphere are found to retain the C<sub>3</sub> carbon backbone whilst changing the corresponding number of H atoms. For example, photodissociations such as the C<sub>3</sub>H<sub>6</sub> + hν → C<sub>3</sub>H<sub>5</sub> + H reaction lead to lower saturation levels, while the opposite is true for termolecular reactions such as the C<sub>3</sub>H<sub>5</sub> + H + M → C<sub>3</sub>H<sub>6</sub> + M reaction. There are only a few reactions producing C<sub>3</sub>H<sub>p</sub> molecules from smaller carbon containing species. These include bimolecular reactions: C + C<sub>2</sub>H<sub>2</sub>, C + C<sub>2</sub>H<sub>4</sub>, CH + C<sub>2</sub>H<sub>2</sub>, CH + C<sub>2</sub>H<sub>4</sub>, CH + C<sub>2</sub>H<sub>6</sub>, <sup>1</sup>CH<sub>2</sub> + C<sub>2</sub>H<sub>2</sub>, <sup>1</sup>CH<sub>2</sub> + C<sub>2</sub>H<sub>4</sub>, CH<sub>3</sub> + C<sub>2</sub>H and termolecular reactions CH<sub>3</sub> + C<sub>2</sub>H<sub>3</sub> + M and CH<sub>3</sub> + C<sub>2</sub>H<sub>5</sub> + M. The bimolecular reactions dominate at high altitude (above 800 km) and the termolecular reactions dominate at low altitude and higher pressures. In terms of total production flux, the CH<sub>3</sub> + C<sub>2</sub>H<sub>3</sub> + M and CH<sub>3</sub> + C<sub>2</sub>H<sub>5</sub> + M termolecular reactions are the most efficient.

In the present work, several rate constants have been updated and some reactions have been added. Our new chemical scheme, derived from the chemical scheme presented in Hébrard et al. (2006, 2009, 2012), includes 143 compounds and 944 reactions (102 photodissociation processes, 2 dissociation processes of N<sub>2</sub> by cosmic rays, 737 bimolecular reactions and 103 termolecular reactions). A major change in this update is the introduction of radiative association reactions, following the work of Vuitton et al. (2012). The complete list of reactions is available upon request and can be downloaded from the KIDA database

(Wakelam et al. 2012). In the following sections, we explain how we evaluated some unknown rate constants and how we assigned their uncertainty factors in the chemical scheme we propose.

### 2.2. Photolysis processes

To better describe the photochemistry of the C<sub>3</sub>H<sub>p</sub> species, we reviewed the parameters important for their photolysis (cross sections, quantum yields and dissociation limits). The photoabsorption cross sections were calculated from formula (3) of van Hemert & van Dishoeck (2008). We also updated the photolysis parameters for C<sub>2</sub>H<sub>2</sub> and HC<sub>3</sub>N. Table 1 presents the photodissociation limits corresponding to the exit channel exothermicities for barrierless dissociations or to the exit Transition State (TS) energies when the values are known. These values correspond to the product appearance only if photodissociation arises from the unimolecular decay of a molecule in an excited vibrational level of the electronic ground state formed by a non-radiative transition from the electronically excited state. Experimental branching ratio determinations are very scarce. Uncertainties on these branching ratios are therefore very large, particularly below 200 nm where many exit channels are possible. We discuss of the quantum yields and dissociation limits in Appendix A for all species presented in Table 1 along with the absorption cross sections for selected important species.

### 2.3. Methodology for the chemical review

The reactions and rate constants were updated following the same procedure used to complete the photochemistry of HCN and HNC (Hébrard et al. 2012). First, a systematic literature search was performed (particularly for the reactions of C, CH and <sup>1</sup>CH<sub>2</sub> reactions with C<sub>2</sub>H<sub>2</sub> and C<sub>2</sub>H<sub>4</sub>). When no information was found, we performed density functional theory (DFT) calculations at the M06-2X/cc-pVTZ level using the *Gaussian09* software package (Frisch et al. 2009) to evaluate the presence and the values of any energetic barriers to the entrance valley for the important reactions (in terms of production and/or loss rate). For some critical reactions or when DFT results were ambiguous, we also performed MRCI+Q/cc-pVTZ calculations using the *Molpro* software package (Werner et al. 2010). When no energetic barrier was found present, the value of the considered rate constant was estimated using long-range forces, mainly through dispersion interactions (Stoecklin & Clary 1992; Georgievskii & Klippenstein 2005) and by taking into account the electronic degeneracy, γ<sub>el</sub>. We investigated certain association reactions that play a major role in Titan's atmosphere but are not well characterized, particularly in the low-pressure region. We present in Appendix B a semi-empirical model (called “k<sub>association</sub> - ρ”), based on the calculations of Vuitton et al. (2012) and also on various experimental rate constants, which has allowed us to estimate values of the low-pressure limiting rate constant for associations reactions, k<sub>0</sub>, as a function of the vibrational density of states of the adduct, ρ(E<sub>0</sub>). We also applied this model to some radiative association processes addressed by Vuitton et al. (2012) as well as in earlier calculations.

Many of the reactions involved in the atmosphere of Titan are of the type atom/radical + radical or atom/radical + unsaturated compound. For these processes, there is often competition between the formation of bimolecular products and adduct stabilization. Adduct stabilization A + B → C designates the conjugation of the termolecular reaction A + B + M → C + M and the radiative association A + B → C + hν. When bimolecular

**Table 1.** New or modified photodissociation processes included in the model (update of Hébrard et al. 2012).

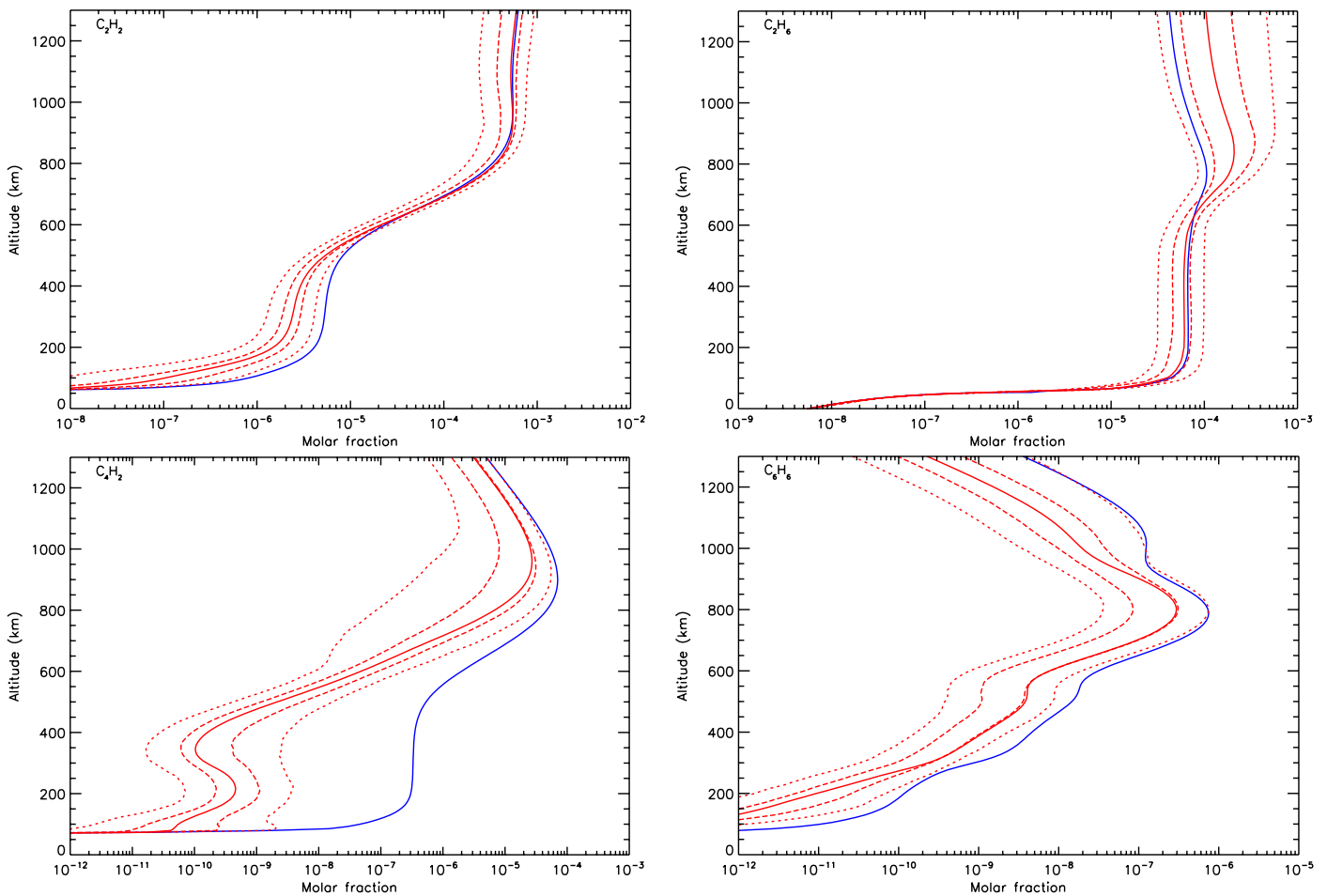
Reaction number	Reaction	Quantum yield $q$ , dissociation limit (nm)
J1	C <sub>2</sub> H <sub>2</sub> + $h\nu$ → C <sub>2</sub> H + H	1.0, 215
J2	C <sub>3</sub> + $h\nu$ → C <sub>2</sub> + C	1.0, 161
J3	c-C <sub>3</sub> H + $h\nu$ → C <sub>3</sub> + H	1.0, 359
J4	l-C <sub>3</sub> H + $h\nu$ → C <sub>3</sub> + H	1.0, 374
J5a	c-C <sub>3</sub> H <sub>2</sub> + $h\nu$ → l-C <sub>3</sub> H + H	0.3, 266
J5b	c-C <sub>3</sub> H <sub>2</sub> + $h\nu$ → c-C <sub>3</sub> H + H	0.3, 274
J5c	c-C <sub>3</sub> H <sub>2</sub> + $h\nu$ → C <sub>3</sub> + H <sub>2</sub>	0.4, 289
J6a	l-C <sub>3</sub> H <sub>2</sub> + $h\nu$ → l-C <sub>3</sub> H + H	0.3, 308
J6b	l-C <sub>3</sub> H <sub>2</sub> + $h\nu$ → c-C <sub>3</sub> H + H	0.3, 318
J6c	l-C <sub>3</sub> H <sub>2</sub> + $h\nu$ → C <sub>3</sub> + H <sub>2</sub>	0.4, 325
J7a	t-C <sub>3</sub> H <sub>2</sub> + $h\nu$ → l-C <sub>3</sub> H + H	0.5, 298
J7b	t-C <sub>3</sub> H <sub>2</sub> + $h\nu$ → c-C <sub>3</sub> H + H	0.5, 307
J8a	C <sub>3</sub> H <sub>3</sub> + $h\nu$ → t-C <sub>3</sub> H <sub>2</sub> + H	0.5, 292
J8b	C <sub>3</sub> H <sub>3</sub> + $h\nu$ → c-C <sub>3</sub> H <sub>2</sub> + H	0.5, 330
J9a	CH <sub>2</sub> CCH <sub>2</sub> + $h\nu$ → C <sub>2</sub> H <sub>2</sub> + <sup>3</sup> CH <sub>2</sub>	0.2, 280
J9b	CH <sub>2</sub> CCH <sub>2</sub> + $h\nu$ → C <sub>3</sub> H <sub>3</sub> + H	0.7, 315
J9c	CH <sub>2</sub> CCH <sub>2</sub> + $h\nu$ → l-C <sub>3</sub> H <sub>2</sub> + H <sub>2</sub>	0.05, 326
J9d	CH <sub>2</sub> CCH <sub>2</sub> + $h\nu$ → c-C <sub>3</sub> H <sub>2</sub> + H <sub>2</sub>	0.05, 390
J10a	CH <sub>3</sub> C <sub>2</sub> H + $h\nu$ → C <sub>2</sub> H + CH <sub>3</sub>	0.07, 227
J10b	CH <sub>3</sub> C <sub>2</sub> H + $h\nu$ → C <sub>2</sub> H <sub>2</sub> + <sup>3</sup> CH <sub>2</sub>	0.03, 276
J10c	CH <sub>3</sub> C <sub>2</sub> H + $h\nu$ → C <sub>3</sub> H <sub>3</sub> + H	0.80, 309
J10d	CH <sub>3</sub> C <sub>2</sub> H + $h\nu$ → l-C <sub>3</sub> H <sub>2</sub> + H <sub>2</sub>	0.05, 320
J10e	CH <sub>3</sub> C <sub>2</sub> H + $h\nu$ → c-C <sub>3</sub> H <sub>2</sub> + H <sub>2</sub>	0.05, 382
J11a	C <sub>3</sub> H <sub>5</sub> + $h\nu$ → C <sub>2</sub> H <sub>2</sub> + CH <sub>3</sub>	0.16, 450
J11b	C <sub>3</sub> H <sub>5</sub> + $h\nu$ → CH <sub>2</sub> CCH <sub>2</sub> + H	0.42, 505
J11c	C <sub>3</sub> H <sub>5</sub> + $h\nu$ → CH <sub>3</sub> C <sub>2</sub> H + H	0.42, 518
J12a	C <sub>3</sub> H <sub>6</sub> + $h\nu$ → CH <sub>2</sub> CCH <sub>2</sub> + H + H	0.05, $\lambda < 160$ 0.05, $\lambda \in [160, 197]$
J12b	C <sub>3</sub> H <sub>6</sub> + $h\nu$ → CH <sub>3</sub> C <sub>2</sub> H + H + H	0.05, $\lambda < 160$ 0.05, $\lambda \in [160, 199]$
J12c	C <sub>3</sub> H <sub>6</sub> + $h\nu$ → C <sub>2</sub> H <sub>2</sub> + CH <sub>3</sub> + H	0.7, $\lambda < 160$ 0.2, $\lambda \in [160, 209]$
J12d	C <sub>3</sub> H <sub>6</sub> + $h\nu$ → C <sub>3</sub> H <sub>3</sub> + H <sub>2</sub> + H	0.2, $\lambda < 160$ 0.2, $\lambda \in [160, 222]$
J12e	C <sub>3</sub> H <sub>6</sub> + $h\nu$ → C <sub>2</sub> H <sub>3</sub> + CH <sub>3</sub>	0.0, $\lambda < 160$ 0.3, $\lambda \in [160, 281]$
J12f	C <sub>3</sub> H <sub>6</sub> + $h\nu$ → C <sub>3</sub> H <sub>5</sub> + H	0.0, $\lambda < 160$ 0.2, $\lambda \in [160, 324]$
J13	C <sub>3</sub> H <sub>7</sub> + $h\nu$ → C <sub>3</sub> H <sub>6</sub> + H	1.0, 867
J14a	HC <sub>3</sub> N + $h\nu$ → CN + C <sub>2</sub> H	0.3, 185
J14b	HC <sub>3</sub> N + $h\nu$ → HCN + C <sub>2</sub>	0.1, 193
J14c	HC <sub>3</sub> N + $h\nu$ → C <sub>3</sub> N + H	0.3, 220

product formation occurs through a distinct mechanism, we can easily separate the bimolecular channel from the adduct formation channel. For example, for H atom abstraction in the reactions of H and CH<sub>3</sub> with some hydrocarbon radicals, there is either a direct pathway or an adduct formation pathway followed by an elimination. However, the TSs for this latter type of system leading from the adduct to H<sub>2</sub> or CH<sub>4</sub> products are generally located above the energy of the separated reagents, as is the case for the H + C<sub>2</sub>H<sub>5</sub> → C<sub>2</sub>H<sub>4</sub> + H<sub>2</sub> (Irlé & Morokuma 2000) and the CH<sub>3</sub> + C<sub>2</sub>H<sub>5</sub> → CH<sub>4</sub> + C<sub>2</sub>H<sub>4</sub> reactions (Zhu et al. 2004). For the H + C<sub>2</sub>H<sub>3</sub> reaction, the TSs leading to H<sub>2</sub> and C<sub>2</sub>H<sub>2</sub> are below the entrance level (Chang et al. 1998) but an experimental study by Monks et al. (1995) strongly indicated that H<sub>2</sub> + C<sub>2</sub>H<sub>2</sub> formation occurs mainly through a direct mechanism. Therefore we considered here that H-atom abstraction is always a direct channel, clearly separated from the other bimolecular product channels that arise from adduct formation. When bimolecular product formation occurs through the same first step as adduct

formation, i.e., through addition, we cannot separate bimolecular product formation from adduct stabilization. A good example is the H + C<sub>2</sub>H<sub>5</sub> → C<sub>2</sub>H<sub>6</sub>/CH<sub>3</sub> + CH<sub>3</sub> reaction. Here, bimolecular product formation competes with adduct stabilization and with redissociation to the reagents. The main effect of the existence of an exit bimolecular channel from the adduct is to reduce the fraction of adduct stabilization at low pressure, which leads to a lower value for the low-pressure limiting rate constant  $k_0$ . For small systems (CH<sub>p</sub>, C<sub>2</sub>H<sub>p</sub>) with an open bimolecular exit channel from the adduct, adduct stabilization is negligible when compared with bimolecular reaction for pressures below 0.1–1 Torr (corresponding to altitudes greater than ~200 km in Titan's atmosphere). In most cases we can therefore neglect adduct stabilization. For large systems or when the bimolecular exit TSs are located close to the entrance level, adduct stabilization cannot be ignored. To deal with such systems we must consider a multiple-well treatment using the master equation for each system, which is beyond the scope of this study. Instead, we used experimental values for the termolecular reaction rate constant (when these were available in the literature) or we estimated them using our semi-empirical “ $k_{\text{association}}-\rho$ ” model, dividing  $k_0$  (and  $k_r$ ) values by factors between 10 and 1000, depending on the size of the system and the position of the exit TS to take into account the effect of the open bimolecular exit channel. When the radiative association was estimated to be very weak ( $<10^{-16}$  cm<sup>3</sup> molecule<sup>-1</sup> s<sup>-1</sup>), it was neglected. When there is a competition between adduct stabilization and bimolecular product formation, we considered that the total rate constant was a constant leading to  $k_{\text{bimolecular}} = k_{\infty} - k_{\text{adduct}}$  (see Appendix B). This competitive behaviour is always considered at the outset, but can be neglected for most reactions. Exceptions include the H + C<sub>2</sub>H<sub>5</sub>, H + C<sub>3</sub>H, H + l,t-C<sub>3</sub>H<sub>2</sub> and H + C<sub>3</sub>H<sub>7</sub> reactions (for which the  $k_0$  values are low) and the H + C<sub>3</sub>H<sub>6</sub>, H + C<sub>4</sub>H<sub>3</sub>, CH<sub>3</sub> + C<sub>2</sub>H<sub>3</sub> and CH<sub>3</sub> + C<sub>3</sub>H<sub>3</sub> reactions (for which the  $k_0$  values are high). This competitive behavior is neglected for all other investigated reactions as our results are relevant only for altitudes above 200 km. However, many association reactions may play a more important role at altitudes lower than 200 km, for example the C<sub>2</sub>H + alkenes reactions (Woon & Park 2009). Details on how rate constants and uncertainty factors were calculated are given in Appendix B.

#### 2.4. Importance of isomers

In reconsidering the chemical network for C<sub>3</sub> hydrocarbon species, we have found it necessary to introduce several isomers of species already present in the chemical scheme for two main reasons. Firstly, if the various isomers are present at sufficiently high densities, they might be distinguished by observations. Secondly, the different isomers may also have different chemical reactivity than the other species present in the model and introducing them might open some new chemical pathways that were absent from the previous model. As a result, some reactions with new isomers could also be key reactions because they could prove to be a significant source of uncertainties in the current photochemical model. In the present study, we have introduced the isomers of two compounds: C<sub>3</sub>H and C<sub>3</sub>H<sub>2</sub>. We did not consider the isomers of the other C<sub>3</sub>-compounds for several reasons. One isomer of C<sub>3</sub>H<sub>3</sub> is considerably more stable than the others. For C<sub>3</sub>H<sub>7</sub>, we considered only one isomer because n-C<sub>3</sub>H<sub>7</sub> and i-C<sub>3</sub>H<sub>7</sub> have been shown to have similar reactivities (Tsang 1988). Nevertheless, reactions involving these isomers as reactants are likely to have different products, so it will be necessary to differentiate between these isomers when



**Fig. 1.** Comparison between the previous model of Hébrard et al. (2012) (blue solid line) with the present work (red solid line) for four representative compounds: acetylene  $C_2H_2$ , ethane  $C_2H_6$ , diacetylene  $C_4H_2$  and benzene  $C_6H_6$ . 5th and 15th 20-quantiles (red long-dashed lines) and 19th 20-quantiles (red short-dashed lines) for the abundances distributions of the present model are also given.

studying heavier hydrocarbons ( $C_n$ -compounds,  $n > 3$ ). It is also important to note that the reactivity of  $N(^4S)$  with the various isomers introduced can give different products. Future studies of the inclusion of nitrogen in complex organic compounds for Titan's atmosphere should therefore pay particular attention to these reactions.

### 3. Photochemical model results

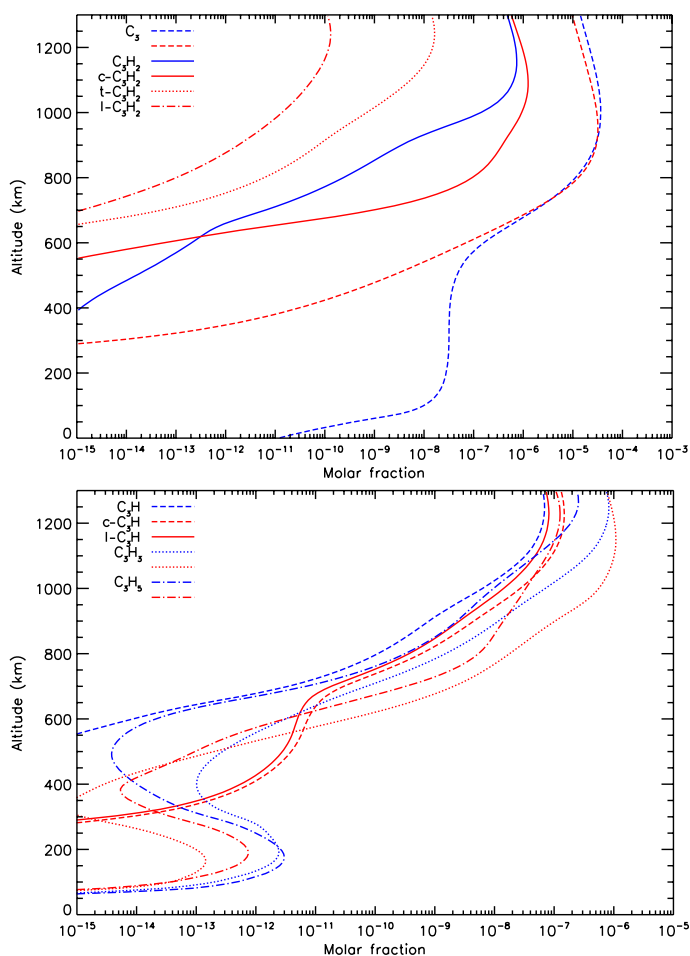
First, we stress the limitations of our model. Microphysics of particles in Titan's lower stratosphere and troposphere as well as the attenuation of solar photons by aerosols and the impact of cosmic rays in the lower atmosphere are not taken in account in our model (except for the dissociation of  $N_2$ ). As a consequence, the results presented here for altitudes below approximately 200 km are not fully relevant. It is also important to note that including aerosols in the model would introduce additional uncertainties in the calculations of the actinic flux and of condensation processes. The propagation of these uncertainties is not treated in the present model. Due to the absence of coupling with ions in the upper atmosphere, the total production and loss of some neutral compounds is only poorly constrained above 800 km (Plessis et al. 2012). The aim of the present work is to improve the neutral photochemistry of Titan's atmosphere (which will serve as a basis for future modeling studies including ion-molecule reactions), not to constrain some physical

parameters (like the eddy diffusion coefficient). The incident solar flux at every level in the atmosphere was calculated as a function of the diurnally averaged unattenuated solar flux at the top of the atmosphere for a medium solar activity (normalized from Thuillier et al. 2004).

#### 3.1. Comparison with the previous model of Hébrard et al. (2012)

To illustrate how the model results have been affected by the improvement of the chemical scheme for  $C_3$ -compounds, we compare our results with the recent model of Hébrard et al. (2012) (quoted as “previous model” in the following). We first checked to what extent the update of the chemical scheme for  $C_3H_p$  compounds affected the abundances of nitrogen compounds,  $C_2$ -hydrocarbons and  $C_n$ -hydrocarbons ( $n > 3$ ). For nitrogen compounds, the difference between the previous and the present model results are small and always within the error bars of the model, whatever the altitude. For hydrocarbons, the situation depends on the compounds (see Fig. 1). For some compounds, the difference is noticeable but still lies within the error bars of the model (like  $C_2H_6$  and  $C_4H_{10}$ ). For other compounds the difference is outside the error bars of the model (like  $C_2H_2$  and  $C_6H_6$ ) and can reach several orders of magnitude (like  $C_4H_2$  and  $C_4H_6$ ).

More evidently, the present update has a noticeable effect on the abundances of many  $C_3$ -compounds, mainly  $C_3$ ,  $C_3H$ ,  $C_3H_2$ ,



**Fig. 2.** Comparison of the previous model of Hébrard et al. (2012) (blue solid lines) with the present work (red solid lines) for the carbon trimer C<sub>3</sub>, 2-cyclopropyn-1-yl c-C<sub>3</sub>H and 2-propynylidyne l-C<sub>3</sub>H, cyclopropenylidene c-C<sub>3</sub>H<sub>2</sub>, propadienylidene l-C<sub>3</sub>H<sub>2</sub> and propynylidene t-C<sub>3</sub>H<sub>2</sub>, propargyl radical C<sub>3</sub>H<sub>3</sub> and allyl radical C<sub>3</sub>H<sub>5</sub>.

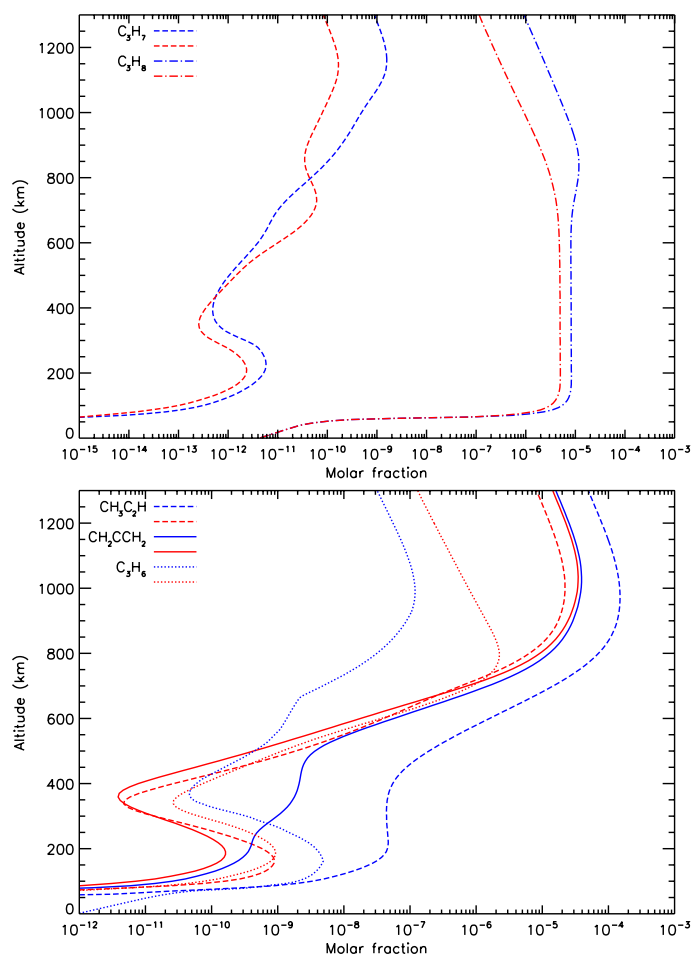
C<sub>3</sub>H<sub>3</sub>, C<sub>3</sub>H<sub>4</sub> and C<sub>3</sub>H<sub>6</sub>. Comparisons between the previous and the present models are presented in Figs. 2 and 3. For the other C<sub>3</sub>-compounds the differences are less pronounced between the two models and are within the error bars of the model (see also Figs. 4–7).

### 3.2. Main production and loss processes

In the following, the main processes that contribute to the production or the loss of a given compound are given at the steady state for the nominal set of rate constants (unperturbed by the Monte-Carlo procedure explained in Sect. 4). Values in parentheses give the relative importance in percentage terms of the total production or loss rates. The emphasis is placed on compounds that show pronounced differences between the previous and the present model. Owing to the uncertainty factors attached to all reactions and all abundances, the relative importance of each reaction to the total production and loss rates might be very different in the Monte-Carlo runs than in the nominal one.

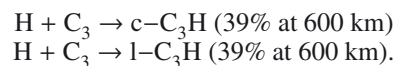
#### 3.2.1. Carbon trimer C<sub>3</sub>

C<sub>3</sub> was introduced in the previous model, but was described by only a limited network of reactions. As shown in Fig. 2, the



**Fig. 3.** Comparison of the previous model of Hébrard et al. (2012) (blue solid lines) with the present work (red solid lines) for methylacetylene CH<sub>3</sub>C<sub>2</sub>H and allene CH<sub>2</sub>CCH<sub>2</sub>, propene C<sub>3</sub>H<sub>6</sub>, propyl radical C<sub>3</sub>H<sub>7</sub> and propane C<sub>3</sub>H<sub>8</sub>.

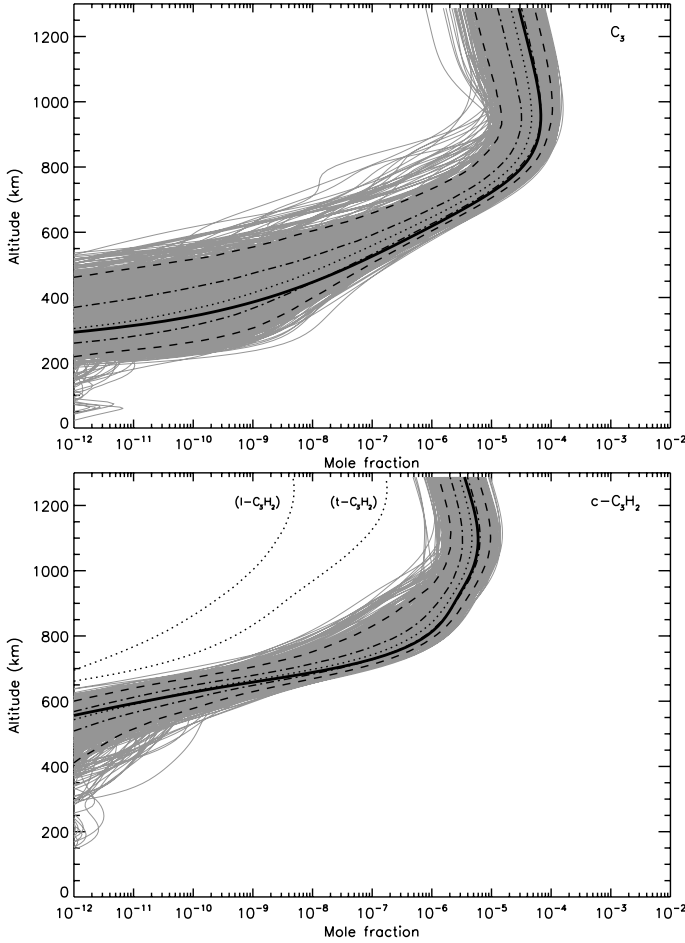
present update of the earlier reaction scheme has a dramatic effect on the abundance of C<sub>3</sub> in the lower atmosphere and C<sub>3</sub> is now the most abundant C<sub>3</sub>H<sub>p</sub> species above 700 km. The main source for C<sub>3</sub> at high altitudes is the C + C<sub>2</sub>H<sub>2</sub> reaction, whereas at lower altitudes, the H + l-C<sub>3</sub>H and, especially, the H + c-C<sub>3</sub>H processes take over gradually. The main processes responsible for the loss of C<sub>3</sub> in the lower atmosphere are the termolecular reactions,



These associations were not present in the previous model. The photolysis of C<sub>3</sub> leading to the formation of C<sub>2</sub> and C represents 18% of the total loss at 600 km.

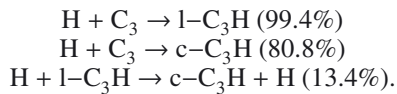
#### 3.2.2. 2-cyclopropyn-1-yl c-C<sub>3</sub>H and 2-propynylidyne l-C<sub>3</sub>H

Cyclic C<sub>3</sub>H (c-C<sub>3</sub>H) and linear C<sub>3</sub>H (l-C<sub>3</sub>H) are predicted to have similar abundances (within a factor 2) but their relatively low densities throughout the atmosphere, as a result of their high reactivity with atomic hydrogen H, probably prevent a differentiation in their putative detection. Their profiles differ noticeably from C<sub>3</sub>H profile (which was considered as a single species in the previous model) below 700 km, where several important



**Fig. 4.** Abundance profiles of the carbon trimer  $C_3$  and cyclopropenylidene  $c-C_3H_2$  obtained after 900 runs. Thick black solid line: initial profile. Black dotted line: median profile obtained from the uncertainty propagation study. Black dashed-dotted lines: 5th and 15th 20-quantiles of the distribution. Black long-dashed lines: 1st and 19th 20-quantiles of the distribution.

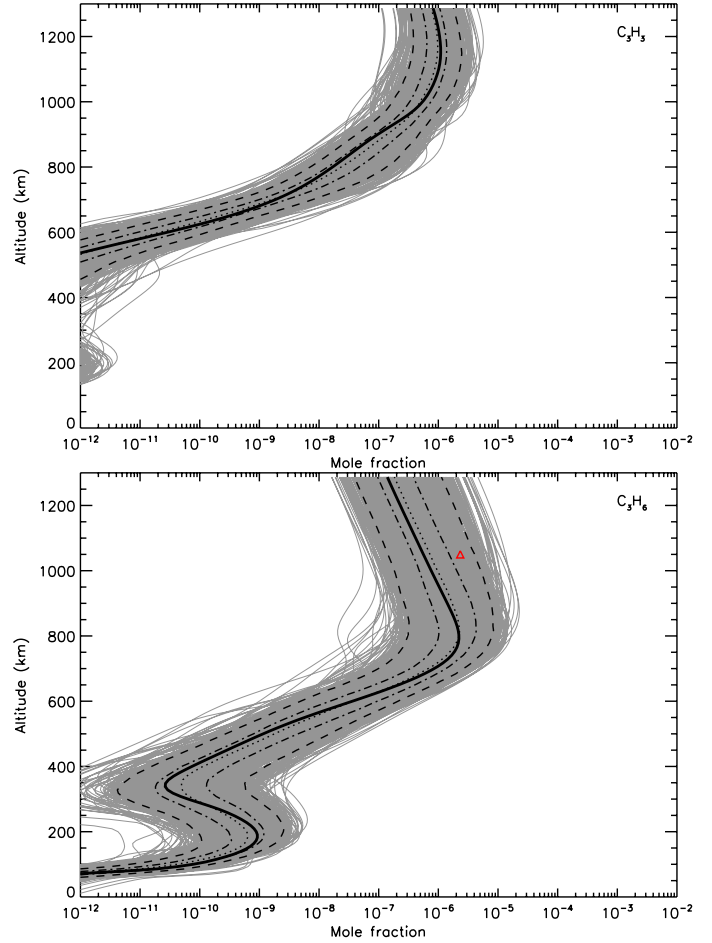
reactions for  $C_3H$  were missing. For instance, at 600 km, the main processes responsible for their production are



None of these reactions were present in our previous model. We found that both  $C_3H$  isomers have a similar reactivity with the other species present in the model. We also note (see Sect. 5) that two reactions involving  $l-C_3H$  are key reactions for the production of the carbon trimer  $C_3$ .

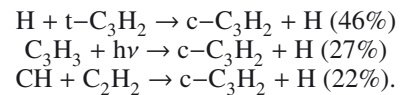
### 3.2.3. Cyclopropenylidene $c-C_3H_2$

Cyclic  $C_3H_2$  ( $c-C_3H_2$ ) is by far the most abundant  $C_3H_2$  isomer. Nevertheless, the importance of the propadienylidene  $l-C_3H_2$  and propynylidene  $t-C_3H_2$  isomers lies in their different reactivity with many compounds. As an example,  $N(^4S)$  is supposed to react only with  $t-C_3H_2$  to produce  $HC_3N$ . Also, the three isomers react differently with  $CH_3$  to produce  $C_2H_3$ , which is involved in many subsequent reactions. Figure 2 clearly shows that  $c-C_3H_2$  is even more abundant in the present work than total  $C_3H_2$  in the previous model (which was considered as a single species previously). Many reactions participate in the production



**Fig. 5.** Abundance profiles of the propargyl radical  $C_3H_3$  and propene  $C_3H_6$  obtained after 900 runs. Thick black solid line: initial profile. Black dotted line: median profile obtained from the uncertainty propagation study. Black dashed-dotted lines: 5th and 15th 20-quantiles of the distribution. Black long-dashed lines: 1st and 19th 20-quantiles of the distribution. The red open triangle refers to *Cassini*/INMS observations from Magee et al. (2009).

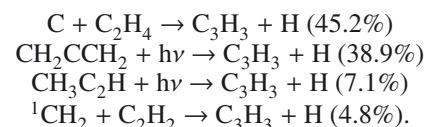
of  $c-C_3H_2$  in the upper atmosphere of Titan (above 800 km, which corresponds to the altitude where the total production rate of  $c-C_3H_2$  is at its maximum), including

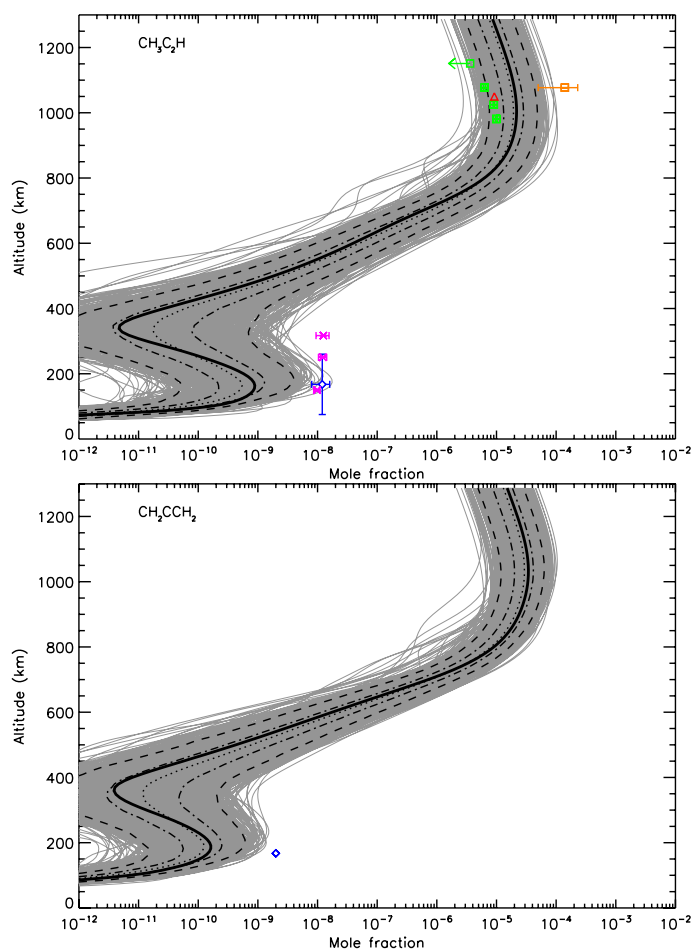


This production is counterbalanced by the photolysis of  $c-C_3H_2$ , which represents 93% of its total loss around 1000 km. None of these reactions were present in our previous model.

### 3.2.4. Propargyl radical $C_3H_3$

$C_3H_3$  is much more abundant in the upper atmosphere in the present model than in the previous one. However, the main reactions that contribute to the total production rate are similar in the two models. For instance, at 1000 km, these are:



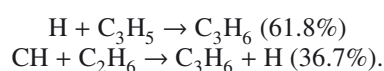


**Fig. 6.** Abundance profiles of methylacetylene CH<sub>3</sub>C<sub>2</sub>H and allene CH<sub>2</sub>CCH<sub>2</sub> obtained after 900 runs. Black solid line: initial profile. Black dotted line: median profile obtained from the uncertainty propagation study. Black dashed-dotted lines: 5th and 15th 20-quantiles of the distribution. Black long-dashed lines: 1st and 19th 20-quantiles of the distribution. The blue open diamond refers to ISO observations from Coustenis et al. (2003), the red open triangle to Cassini/INMS observations from Magee et al. (2009), the green crosses to Cassini/INMS observations from Cui et al. (2009), the orange squares to the corrected Cassini/INMS observations from Cui et al. (2009), the pink crosses to the Cassini/CIRS observations at 3.5°N from Vinatier et al. (2010).

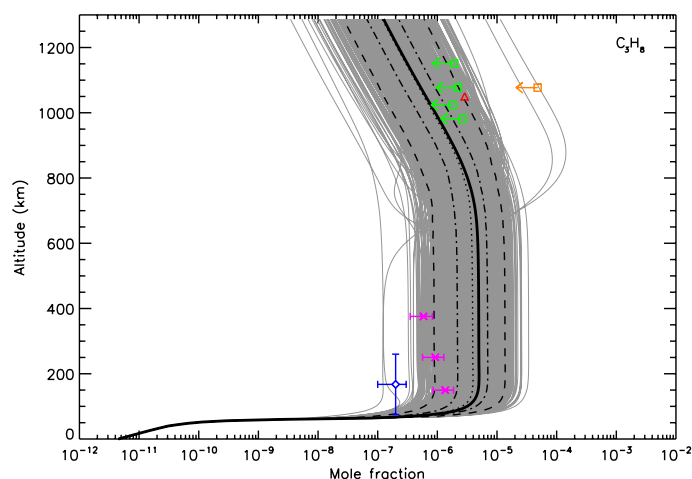
The increase in the abundance of C<sub>3</sub>H<sub>3</sub> comes from a nonlinear competition between reactions involving atomic hydrogen H (H + c-C<sub>3</sub>H<sub>2</sub>, H + C<sub>3</sub>H<sub>3</sub>) and C<sub>3</sub>H<sub>4</sub> isomers photodissociation.

### 3.2.5. Propene C<sub>3</sub>H<sub>6</sub>

C<sub>3</sub>H<sub>6</sub> is found to be much more abundant in the present model compared to the previous one. At 1000 km, the main reactions that contribute to the production of this molecule are



The rate constant of the first addition reaction has been updated since the previous model to include radiative association. Whilst termolecular reaction is negligible at this altitude, radiative association is seen to be important even if the rate is predicted to be relatively slow.



**Fig. 7.** Abundance profiles of propane C<sub>3</sub>H<sub>8</sub> obtained after 900 runs. Black solid line: initial profile. Black dotted line: median profile obtained from the uncertainty propagation study. Black dashed-dotted lines: 5th and 15th 20-quantiles of the distribution. Black long-dashed lines: 1st and 19th 20-quantiles of the distribution. The blue open diamond refers to ISO observations from Coustenis et al. (2003), the red open triangle to Cassini/INMS observations from Magee et al. (2009), the green crosses to Cassini/INMS observations from Cui et al. (2009), the orange square to the corrected Cassini/INMS observations from Cui et al. (2009), the pink crosses to Cassini/CIRS observations at 3.5°N from Vinatier et al. (2010).

## 4. Uncertainty propagation study

### 4.1. Method

The methodology used to study the propagation of uncertainties in the model is described in Hébrard et al. (2007, 2009). In this study, we performed 900 Monte-Carlo runs to obtain statistically significant results. The integration time for each run was set to 10<sup>12</sup> s for simplicity and to limit the computation time. This time is sufficient to reach a steady state for each run. The uncertainty factor was set to 1.2 for all photodissociation rates for simplicity (see Peng et al. (2012) for a valuable discussion about uncertainties on photodissociation rates). A detailed investigation of all sources of uncertainties in these photodissociation rates (arising mainly from uncertainties in absorption cross sections and quantum yields) is beyond the scope of the present paper but should be performed in the future to improve the present model.

### 4.2. Results

Abundance distribution types depend on the compound and can vary with altitudes: distributions are not always normal or log-normal for a given altitude. In this case, quantiles are useful measures to represent the distributions. Consequently, Figs. 4–6 display both the 5th and 15th 20-quantiles and the 1st and 19th 20-quantiles, which represent the intervals containing respectively 50% and 90% of the abundance profiles for several important species in Titan's atmosphere.

The main conclusion of these results is that although the agreement in terms of abundance is good, the current accuracy of photochemical models is quite poor for C<sub>3</sub>H<sub>p</sub> compounds (compared to uncertainties on observations when available), especially below 800 km. Theoretical and experimental studies are clearly required to improve the situation. We see in the next section that global sensitivity analysis can pinpoint the key reactions that are responsible for these large uncertainties.



**Table 2.** Key reactions responsible for the uncertainties on major  $C_3H_p$  compounds at an altitude of 1300, 1000, 600, and 200 km.

Carbon trimer $C_3$				
Reaction	RCCs			
	at 1300 km	at 1000 km	at 600 km	at 200 km
$H + CH \rightarrow C + H_2$	0.21	0.24	0.24	
$C_2H + C_3 \rightarrow C_5 + H$			-0.24	
$N(^2D) + C_3 \rightarrow CN + C_2$	-0.64	-0.52		
$N(^2D) + HCN \rightarrow CH + N_2$	0.37	0.35		
$H + C_2N \rightarrow HCN + C$	0.20			
$H + C_2H_2 + M \rightarrow C_2H_3 + M$				0.74
$H + C_3 \rightarrow l-C_3H$			-0.48	-0.40
$H + c-C_3H_2 \rightarrow C_3H_3$			-0.25	-0.28
$H + l-C_3H \rightarrow C_3 + H_2$			0.25	
$H + l-C_3H \rightarrow c-C_3H + H$			0.25	
Cyclopropenylidene $c-C_3H_2$				
Reaction	RCCs			
	at 1300 km	at 1000 km	at 600 km	at 200 km
$CH + CH_4 \rightarrow C_2H_4 + H$	-0.24	-0.25		
$CH + C_2H_2 \rightarrow t-C_3H_2 + H$	0.23	0.33		
$N(^4S) + C_3H_3 \rightarrow H_2C_3N + H$	-0.22			
$N(^4S) + CN_2 \rightarrow CN + N_2$	-0.25			
$N(^2D) + HCN \rightarrow CH + N_2$	0.53	0.48		
$H + C_2H_2 + M \rightarrow C_2H_3 + M$				0.79
$H + c-C_3H_2 \rightarrow C_3H_3$			-0.88	-0.45
Propargyl radical $C_3H_3$				
Reaction	RCCs			
	at 1300 km	at 1000 km	at 600 km	at 200 km
$H + CH \rightarrow C + H_2$	0.37	0.20		
$N(^4S) + C_3H_3 \rightarrow H_2C_3N + H$	-0.40	-0.45		
$C_2N + H \rightarrow HCN + C$	0.34	0.28		
$C_2N + C_2H_4 \rightarrow C_3H_3CN + H$	-0.25	-0.21		
$H + C_2H_2 + M \rightarrow C_2H_3 + M$				0.82
$H + c-C_3H_2 \rightarrow C_3H_3$		0.30		
$H + C_3H_3 \rightarrow CH_3C_2H$			-0.69	-0.30
$H + CH_2CCH_2 \rightarrow C_3H_5$			-0.22	
$CH_3 + C_3H_3 \rightarrow C_2H_4 + C_2H_2$		-0.25		
Allene $CH_2CCH_2$				
Reaction	RCCs			
	at 1300 km	at 1000 km	at 600 km	at 200 km
$H + C_3H_5 \rightarrow CH_2CCH_2 + H_2$			0.20	0.35
$CH + CH_4 \rightarrow C_2H_4 + H$	-0.23	-0.23		
$CH + C_2H_4 \rightarrow CH_2CCH_2 + H$	0.68	0.72	0.24	
$N(^2D) + HCN \rightarrow CH + N_2$	0.51	0.41		
$H + C_2H_2 + M \rightarrow C_2H_3 + M$				0.72
$H + C_3H_3 \rightarrow CH_2CCH_2$			0.31	
$H + CH_2CCH_2 \rightarrow C_3H_5$			-0.63	-0.22
$H + C_3H_5 \rightarrow C_3H_6$			-0.30	

**Notes.** Only the reactions with absolute values of RCCs greater than 0.2 are displayed. A blank value means that the RCC value is lower than 0.2 and is not given for clarity.

Observational data are presented to give an idea of the agreement between our photochemical model (using a mean eddy diffusion coefficient  $K(z)$ , Hörst et al. 2008) and available

observations for  $C_3$ -compounds. We did not try to better constrain  $K(z)$  because of the current limitations of our model and uncertainties on the model results.

**Table 3.** Key reactions responsible to uncertainties on major C<sub>3</sub>H<sub>p</sub> compounds at an altitude of 1300, 1000, 600, and 200 km.

Methylacetylene CH <sub>3</sub> C <sub>2</sub> H				
Reaction	RCCs			
	at 1300 km	at 1000 km	at 600 km	at 200 km
CH + CH <sub>4</sub> → C <sub>2</sub> H <sub>4</sub> + H			-0.22	
CH + C <sub>2</sub> H <sub>4</sub> → CH <sub>3</sub> C <sub>2</sub> H + H	0.70	0.71	0.22	
N( <sup>2</sup> D) + HCN → CH + N <sub>2</sub>	0.51	0.43		
H + C <sub>2</sub> H <sub>2</sub> + M → C <sub>2</sub> H <sub>3</sub> + M				0.83
H + C <sub>3</sub> H <sub>3</sub> → CH <sub>3</sub> C <sub>2</sub> H		0.26	0.56	
H + CH <sub>3</sub> C <sub>2</sub> H → C <sub>3</sub> H <sub>5</sub>			-0.47	-0.23
Propene C <sub>3</sub> H <sub>6</sub>				
Reaction	RCCs			
	at 1300 km	at 1000 km	at 600 km	at 200 km
H + C <sub>2</sub> H <sub>2</sub> + M → C <sub>2</sub> H <sub>3</sub> + M				0.80
H + C <sub>3</sub> H <sub>6</sub> + M → C <sub>3</sub> H <sub>7</sub> + M			-0.87	-0.33
H + C <sub>3</sub> H <sub>3</sub> → CH <sub>3</sub> C <sub>2</sub> H			0.21	
H + C <sub>3</sub> H <sub>5</sub> → C <sub>3</sub> H <sub>6</sub>	0.64	0.70		
CH <sub>3</sub> + C <sub>3</sub> H <sub>5</sub> → C <sub>4</sub> H <sub>8</sub>	-0.22	-0.28		
Propane C <sub>3</sub> H <sub>8</sub>				
Reaction	RCCs			
	at 1300 km	at 1000 km	at 600 km	at 200 km
C <sub>2</sub> H + C <sub>2</sub> H <sub>6</sub> → C <sub>2</sub> H <sub>5</sub> + C <sub>2</sub> H <sub>2</sub>			0.20	0.20
C <sub>2</sub> H + C <sub>3</sub> H <sub>8</sub> → C <sub>3</sub> H <sub>7</sub> + C <sub>2</sub> H <sub>2</sub>	-0.24	-0.26	-0.32	-0.30
CH <sub>3</sub> + C <sub>2</sub> H <sub>5</sub> → C <sub>3</sub> H <sub>8</sub>	0.44	0.39	0.56	0.69
H + C <sub>2</sub> H <sub>5</sub> → CH <sub>3</sub> + CH <sub>3</sub>	-0.25	-0.26	-0.21	

**Notes.** Only reactions with absolute values of RCCs greater than 0.2 are given. A blank means that the absolute value of RCC is lower than 0.2 and it is not given for clarity.

## 5. Global sensitivity analysis: determination of key reactions

The technique we used to determine the key reactions is based on the computation of Rank Correlation Coefficients (RCCs) between reaction rate constants and mole fractions at different altitudes. It has been previously used and described in Carrasco et al. (2007), Dobrijevic et al. (2008) and Hébrard et al. (2009). The greater the absolute value of the RCC, the more significant the contribution of a given reaction rate to the uncertainty on the mole fraction of a given species. Consequently, all reactions with a high RCC absolute value should be targeted to improve the accuracy of the model. The power of this technique to improve photochemical models has already been demonstrated for Titan by Hébrard et al. (2009) and for Neptune by Dobrijevic et al. (2010).

Tables 2 and 3 give RCCs for the main C<sub>3</sub>-species. The RCC threshold has been arbitrarily set to 0.2. This choice gives for each compound a reasonable set of reactions allowing us to pinpoint only the most significant ones. Thirty key reactions were identified for four representative altitudes. We see that association reactions in general are predicted to be significant in all parts of the atmosphere. The termolecular reaction H + C<sub>2</sub>H<sub>2</sub> → C<sub>2</sub>H<sub>3</sub> in particular is a key reaction for all but one of the C<sub>3</sub>-compounds, listed in Tables 2 and 3. Comments on some of these reactions are given in Appendix C.

The reaction N(<sup>2</sup>D) + HCN → CH + N<sub>2</sub> is also a main key reaction for HCN (see Hébrard et al. 2012). A discussion about the reaction H + CH → C + H<sub>2</sub> can be found as a datasheet in

the KIDA database (Wakelam et al. 2012). Details about these two reactions are therefore not repeated here.

## 6. Conclusion

We have performed a systematic study of all potentially important processes that produce or consume C<sub>3</sub>H<sub>p</sub> compounds. This extensive review has led us to make recommendations for a large number of reaction rates and therefore to improve significantly the chemical schemes published so far for Titan's atmosphere. Several photolysis processes were updated and the rate constants and branching ratios for many bimolecular reactions between neutral species were updated/reinvestigated. A new semi-empirical model based on previous calculations and various experimental data was implemented to allow us to predict the rates of the most important termolecular reactions and radiative associations for Titan's atmosphere. Our update of the chemical network relating to C<sub>3</sub>H<sub>p</sub> substantially modified the overall chemical scheme of Titan's atmosphere. We showed that several important reactions were indeed missing from our previous model (Hébrard et al. 2012) and also from other current photochemical models. This improvement of the C<sub>3</sub>H<sub>p</sub> chemistry has noticeable effects on the abundances of C<sub>2</sub>- and C<sub>n</sub>-compounds ( $n > 3$ ), which are more or less pronounced, depending on the compound. For some species the differences brought about by the update stay within the error bars of the previous model (such as for C<sub>2</sub>H<sub>6</sub>), whereas for other compounds the differences lead to predicted abundances outside the error bars of the previous model (such as for C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>6</sub>H<sub>6</sub>). In some cases, the update has resulted in a change in predicted abundance of several

orders of magnitude (for example,  $C_4H_2$  is over two orders of magnitude less abundant at low altitudes in the updated model). We showed in particular that a careful update of the chemical scheme for a given family of compounds can have a drastic effect (or no effect at all) for other seemingly unrelated compounds. It is therefore important to complete the chemical scheme as far as possible before creating a reduced scheme that can be able to correctly predict the abundance of all the atmospheric constituents.

We found that many of the main processes involving the  $C_3H_p$  species in Titan's atmosphere recycle  $C_3H_p$  species (which essentially changes the degree of saturation of the  $C_3$  backbone), either through photodissociations or through reactions with H atoms. There are only a few reactions that produce  $C_3H_p$  species: bimolecular reactions such as  $C + C_2H_2$ ,  $C + C_2H_4$ ,  $CH + C_2H_2$ ,  $CH + C_2H_4$ ,  $CH + C_2H_6$ ,  ${}^1CH_2 + C_2H_2$ ,  ${}^1CH_2 + C_2H_4$  and  $CH_3 + C_2H_3$  and association reactions like  $CH_3 + C_2H_3$  and  $CH_3 + C_2H_5$ .

We found that some  $C_3$ -molecules such as the carbon trimer  $C_3$ , the cyclopropenylidene radical  $c-C_3H_2$  and the propargyl radical  $C_3H_3$  present predicted abundances high enough to be potentially present in the *Cassini*/INMS data and should therefore be considered in models that aim to interpret these spectra.

The present work confirms previous studies Hébrard et al. (2007, 2009, 2012) that demonstrated that the uncertainties in the results of current photochemical models of Titan's atmosphere could be very important and that the theoretical/experimental determination of rate constants and branching ratios at low temperature is crucial to better constrain *in fine* some physical parameters.

Among all the new processes introduced in the present chemical scheme, some are important reactions for the production and loss of  $C_3$ -compounds and/or are also identified as key reactions (reactions for which the uncertainty factors need to be lowered to improve the predictivity of photochemical models) by uncertainty propagation and global sensitivity analysis. We showed in this study only the most significant key reactions for  $C_3$ -compounds. The complete list of all main key reactions for Titan's atmosphere (concerning all species for which observational data are available) will be available from the KIDA database.

Our model does not take into account ionic chemistry, which is known to have a noticeable impact on the abundances of neutral species (see Plessis et al. 2012). As a consequence, it is important to keep in mind that the abundances of some compounds presented in our study might be significantly affected by the coupling of our neutral chemical scheme with a ionospheric model. This is the case in particular for  $C_3$ . Considering the Proton Affinity of  $C_3$  (767 kJ mol<sup>-1</sup>, Hunter & Lias 1998) and because exothermic proton transfer reactions generally do not present a barrier,  $C_3$  will react with the most abundant ions in Titan's ionosphere ( $HCNH^+$ ,  $CH_5^+$ ,  $C_2H_3^+$ ,  $C_2H_5^+$ ), which will lead to  $C_3H^+$  formation. Ionic chemistry is likely to be a strong sink for  $C_3$  because  $C_3H^+$  loss will be dominated by its reaction with  $CH_4$  (Raksit & Bohme 1983).

The next step of the present study should be the improvement of  $C_4H_p$  chemistry (photolysis and neutral reactions). Considering the results we present here, we may expect that such an update of the chemical scheme could have a significant impact on the abundances of many compounds (even lighter ones).

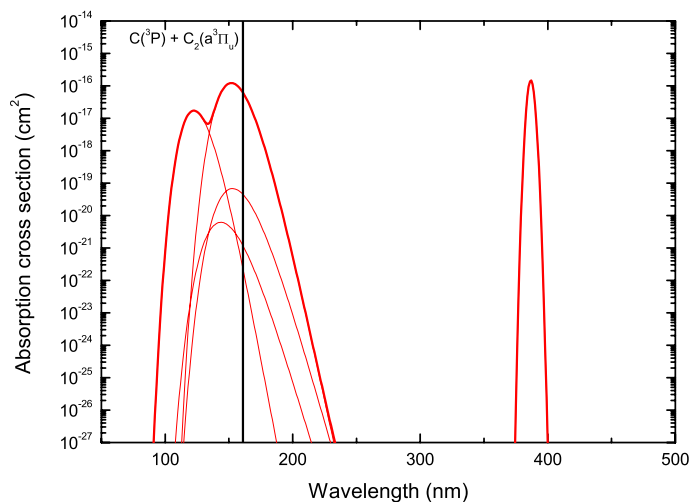
This study might also help us to better understand the complexification of organic compounds in Titan's atmosphere.

**Table A.1.** Branching ratios (in %) for  $C_3H_6$  photolysis.

Channels	$\lambda < 160$ nm	$\lambda \in [160-190]$ nm
$C_3H_5 + H$	0	20
$C_3H_4 + H + H$	10	10
$C_3H_3 + H_2 + H$	20	20
$C_2H_3 + CH_3$	0	30
$C_2H_2 + H + CH_3$	70	20

**Table A.2.** Branching ratios (in %) for  $HC_3N$  photolysis.

Channels	121.6 nm	157 nm	193 nm	212 nm
${}^2C_3N + {}^2H$	57	57	100	100
${}^2C_2H + {}^2CN$	43	43	0	0



**Fig. A.1.** Photoabsorption cross sections for  $C_3$  along with the dissociation limits for the various channels considered.

*Acknowledgements.* E.H. acknowledges support from the European Research Council (ERC Starting Grant 209622: E3ARTHS).

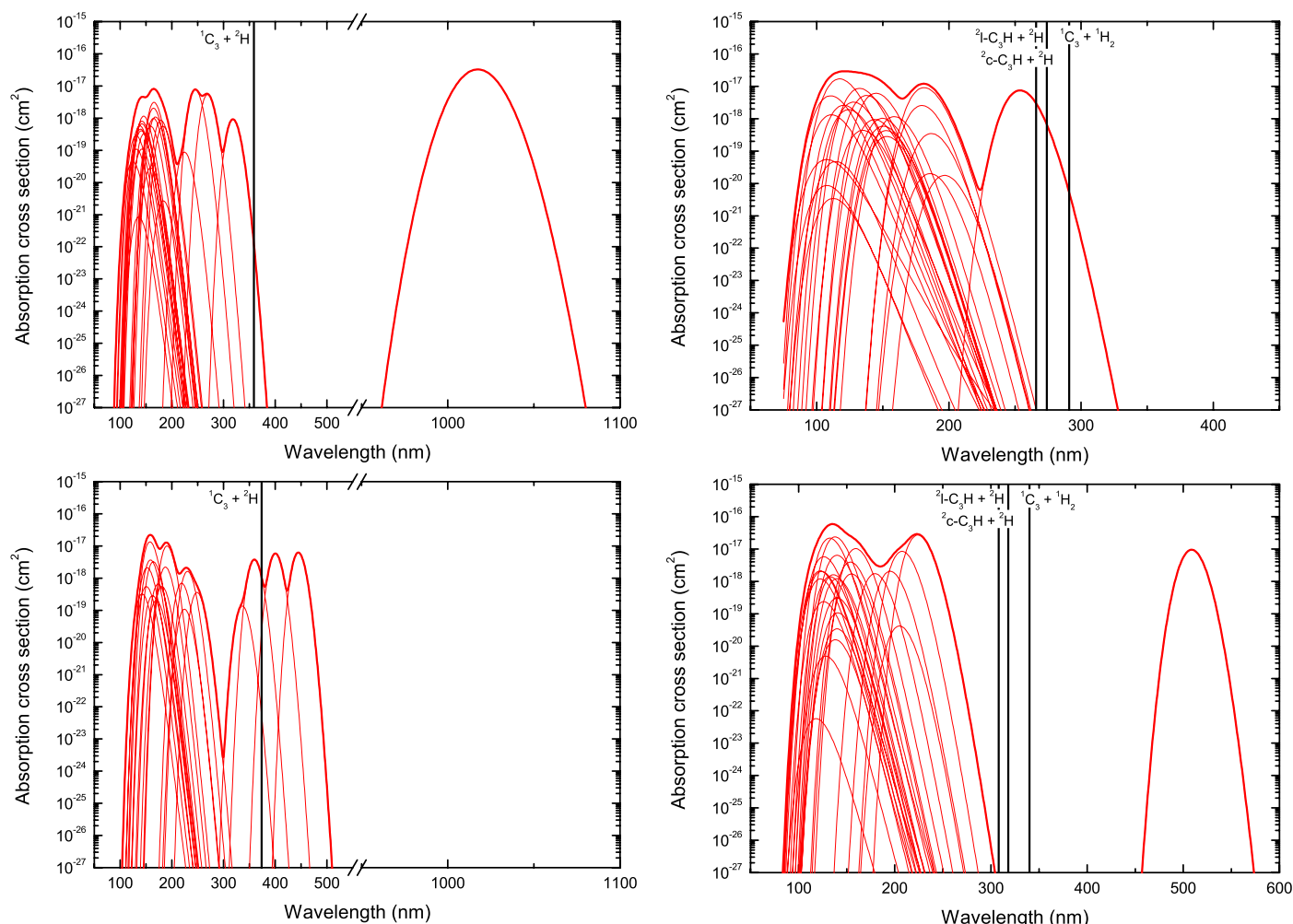
## Appendix A: Cross sections and quantum yield of several compounds

### A.1. Photolysis of $C_2H_2$

$C_2H_2$  photodissociation was reconsidered using the latest measurements, which lead exclusively to the formation of  $C_2H + H$  between 121.6 and 193 nm (Kovács et al. 2010; Läuter et al. 2002).

### A.2. Photolysis of $C_3$

$C_3({}^1\Sigma_g^+)$  has two main transitions, the  ${}^1\Pi_u \leftarrow {}^1\Sigma_g^+$  transition around 405 nm and the  ${}^1\Sigma_u^+ \leftarrow {}^1\Sigma_g^+$  transition around 165 nm (Monninger et al. 2002; van Hemert & van Dishoeck 2008; Chang & Graham 1982). Because the dissociation limit is equal to 7.62 eV (162.7 nm) (Baulch et al. 2005; Martin & Taylor 1995; Gingerich et al. 1994), only the  ${}^1\Sigma_u^+ \leftarrow {}^1\Sigma_g^+$  transition leads to photodissociation. The photodissociation cross section was calculated using the oscillator strengths calculated by van Hemert & van Dishoeck (2008) with a constant width at half maximum  $\Delta\lambda = 20$  nm and taking into account the dissociation energy equal to 735.22 kJ mol<sup>-1</sup>.



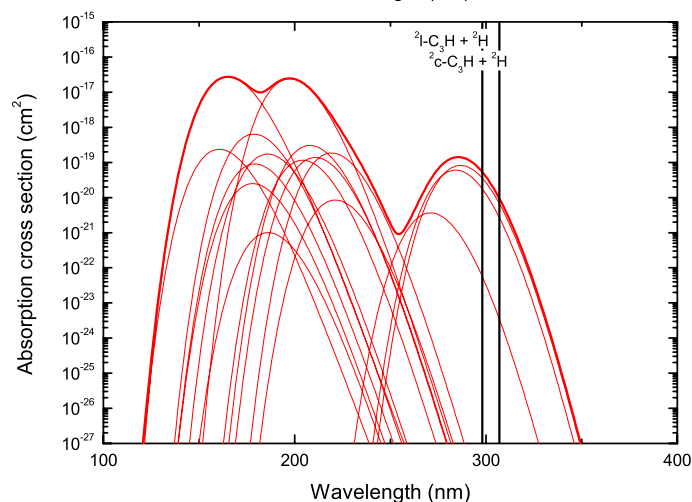
**Fig. A.2.** Photoabsorption cross sections for *c*-C<sub>3</sub>H (top) and *l*-C<sub>3</sub>H (bottom) along with the dissociation limits for the various channels considered.

### A.3. Photolysis of C<sub>3</sub>H and C<sub>3</sub>H<sub>2</sub>

*c*-C<sub>3</sub>H, *l*-C<sub>3</sub>H, *c*-C<sub>3</sub>H<sub>2</sub>, *l*-C<sub>3</sub>H<sub>2</sub> and *t*-C<sub>3</sub>H<sub>2</sub> photodissociation cross sections were calculated using the oscillator strengths calculated by van Hemert & van Dishoeck (2008) with a constant width at half maximum  $\Delta\lambda = 20$  nm. These five radicals absorb in the UV and visible part of the spectrum where the solar flux is highest. Therefore the photodissociation will be dominated by these absorptions, which mainly lead to C-H bond rupture. The photodissociations of *c*-C<sub>3</sub>H and *l*-C<sub>3</sub>H are dominated by the visible and near-UV regions and should yield only C<sub>3</sub> + H. The products of *c*-C<sub>3</sub>H<sub>2</sub> and *l*-C<sub>3</sub>H<sub>2</sub> photodissociation were derived from Mebel et al. (1998), Park et al. (2006) and Großet al. (2008) and were set to *l*-C<sub>3</sub>H + H (30%), *c*-C<sub>3</sub>H + H (30%), and C<sub>3</sub> + H<sub>2</sub> (40%). The C<sub>3</sub> + H<sub>2</sub> exit channel shows a notable exit barrier (Mebel et al. 1998; Park et al. 2006). The products of *t*-C<sub>3</sub>H<sub>2</sub> photodissociation were also derived from Mebel et al. (1998) and Park et al. (2006) and were set to *l*-C<sub>3</sub>H + H (50%) and *c*-C<sub>3</sub>H + H (50%), although the spin-allowed <sup>3</sup>C + C<sub>2</sub>H<sub>2</sub> exit channel may not be negligible. The absorption cross sections of C<sub>3</sub>H and C<sub>3</sub>H<sub>2</sub> are given in Figs. A.1, A.2 and A.3.

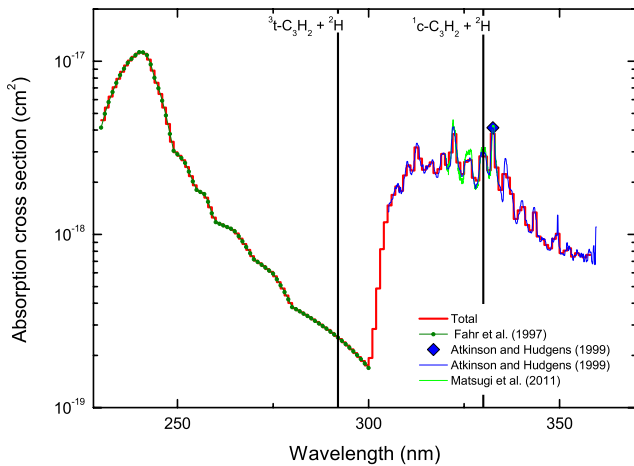
### A.4. Photolysis of C<sub>3</sub>H<sub>3</sub>

The lowest energy electronic absorption spectrum of the C<sub>3</sub>H<sub>3</sub> radical between 290 and 345 nm shows diffuse bands

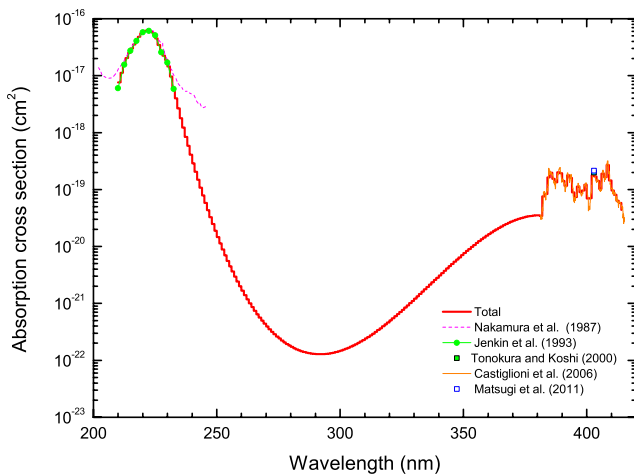


**Fig. A.3.** Photoabsorption cross sections for *c*-C<sub>3</sub>H<sub>2</sub> (top), *l*-C<sub>3</sub>H<sub>2</sub> (middle) and *t*-C<sub>3</sub>H<sub>2</sub> (bottom) along with the dissociation limits for the various channels considered.

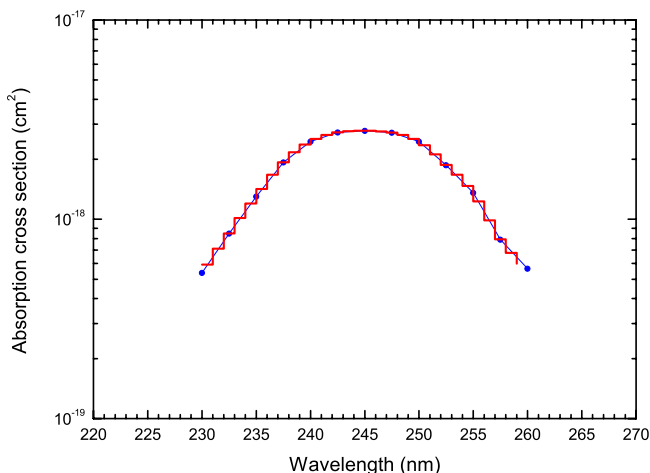
(Atkinson & Hudgens 1999; Eisfeld 2006; Matsugi et al. 2011), attributed to predissociation in the excited state. This leads to an upper limit of 360.1 kcal mol<sup>-1</sup> for the bond dissociation energy, which corresponds to 346 nm and yields *c*-C<sub>3</sub>H<sub>2</sub> + H. The second (strongest) absorption near 240 nm has been confirmed by Deyerl et al. (1999) by H-atom photofragment yield spectra. The main products after photodissociation at 248 nm are also C<sub>3</sub>H<sub>2</sub> + H with a ratio H/H<sub>2</sub> = (97.6/2.4) ± 1.2. We



**Fig. A.4.** Photoabsorption cross sections for  $C_3H_3$  along with the dissociation limits for the various channels considered.



**Fig. A.5.** Photoabsorption cross sections for  $C_3H_5$  along with the dissociation limits for the various channels considered.



**Fig. A.6.** Photoabsorption cross sections for  $C_3H_7$  along with the dissociation limits for the various channels considered.

then assumed that  $C_3H_2$  is the only product in the UV wavelength range. Identifying the different  $C_3H_2$  isomers is more delicate. Deyerl et al. (1999) attributed the measured fragments to  $c-C_3H_2 + H$ , while an Rice–Ramsperger–Kassel–Marcus (RRKM) analysis (Nguyen et al. 2001b) found  $t-C_3H_2 + H$  to be the dominant channel. Goncher et al. (2008) have shown that

some  $c-C_3H_2$  is produced. To a first approximation, we estimated the products to be 50%  $c-C_3H_2$  and 50%  $t-C_3H_2$ . The absorption cross section of  $C_3H_3$  is given in Fig. A.4.

#### A.5. Photolysis of $C_3H_4$ isomers

The photoabsorption cross sections of  $CH_3C_2H$  and  $CH_2CCH_2$  are well known (Ho et al. 1998; Chen et al. 2000). Photolysis studies of these molecules have been performed at 193 nm (Seki & Okabe 1992; Ni et al. 1999) and at 155 nm (Harich et al. 2000a,b). There are some differences. For the  $CH_2CCH_2$  photolysis, the main production channels are H and  $C_3H_3$  (70%) followed by  $CH_2 + C_2H_2$  (20%) with small yields of  $H_2 + c-C_3H_2$  (5%) and  $H_2 + t-C_3H_2$  (5%). For the  $CH_3C_2H$  photolysis, the main production channels are also H and  $C_3H_3$  (80%) followed by  $CH_3 + C_2H$  ( $\approx 7\%$ ),  $CH_2 + C_2H_2$  ( $\approx 3\%$ ) and then  $H_2 + c-C_3H_2$  (5%) and  $H_2 + t-C_3H_2$  (5%). Photodissociation of  $CH_3C_2H$  at 193 nm mainly leads to  $CH_3CC$  production and not to  $CH_2CCH$  (Satyapal & Bersohn 1991; Seki & Okabe 1992).

#### A.6. Photolysis of $C_3H_5$

In Titan's atmosphere, photodissociation of the allyl radical  $H_2C=CH-\dot{C}H_2$  will be dominated by absorption near 403 nm (Tonokura & Koshi 2000; Matsugi et al. 2011) and by the strongest absorption in the 220–240 nm range (Selby et al. 2008; Nakashima & Yoshihara 1987). The absorption cross section of  $C_3H_5$  is given in Fig. A.5. Photodissociation in the 403 nm band leads to H-atom loss only (Stranges et al. 1998), and mainly to  $CH_2CCH_2 + H$  formation (Castiglioni et al. 2006; Szpunar et al. 2002). At 248 nm the H atom loss channel has been found to be equal to 84% with the  $CH_3 + C_2H_2$  channel equal to 16% (corrected to 5% subsequently Stranges et al. 2008). The ratio of  $CH_2CCH_2$  to  $CH_3C_2H$  formation in the 240–250 nm region may be estimated from Minsek & Chen (1993) and leads to a ratio between 2:1 and 3:1. RRKM calculations of the ground state dissociation (Stranges et al. 1998) favor  $CH_3C_2H$  formation and also lead to 31% of  $CH_3 + C_2H_2$  products at 351 nm in contrast to experimental results. Recent trajectory calculations (Chen et al. 2011) better agree with experimental results and mainly lead to  $CH_2CCH_2 + H$  formation. The recommended branching ratios for each absorption band are presented in Table 1.

#### A.7. Photolysis of $C_3H_6$

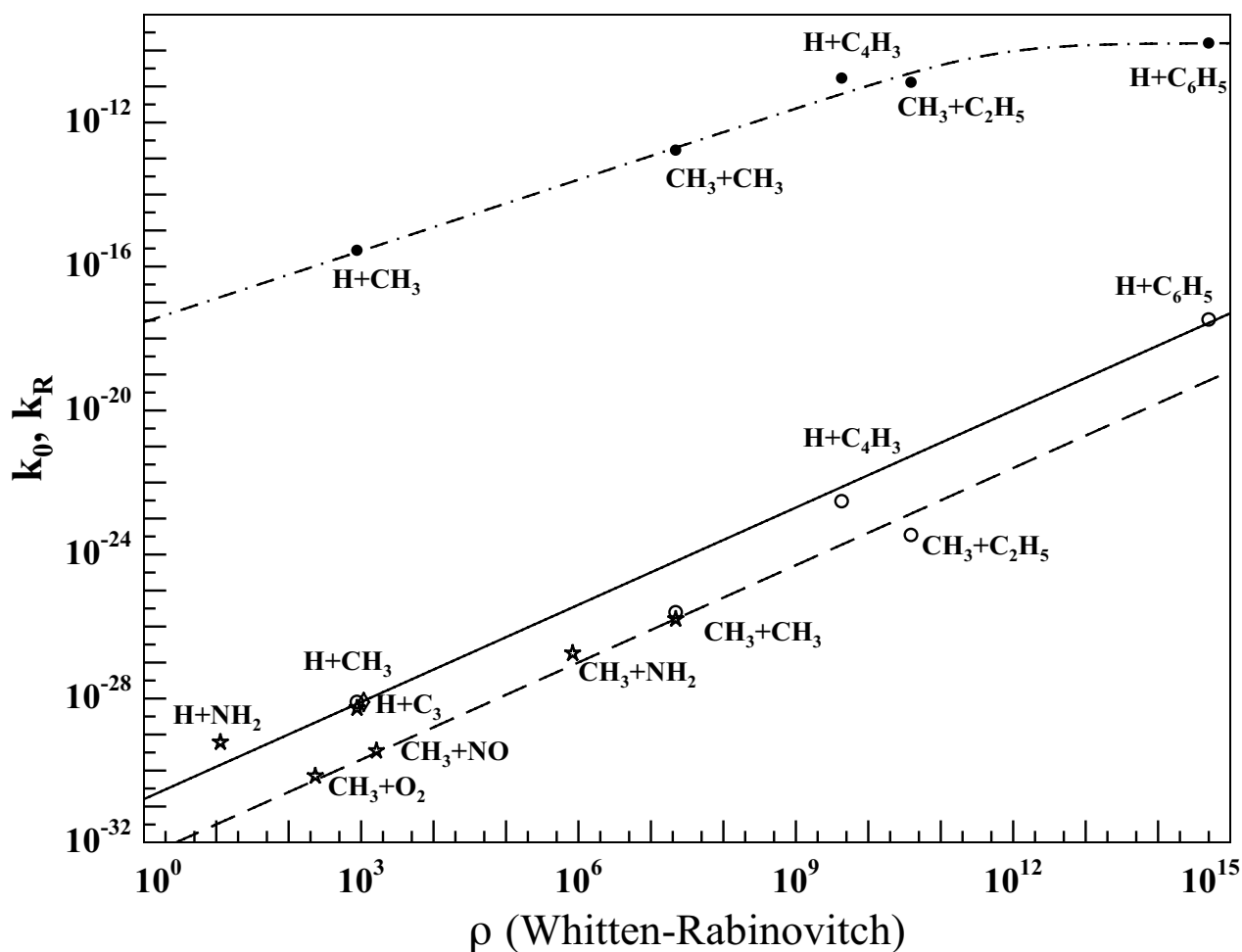
The photofragmentation of propene ( $C_3H_6$ ) is complex and wavelength-dependent. Considering the studies of Borrell et al. (1971) at 184 nm, of Lee et al. (2003) at 157 nm as well as the theoretical study of Qu et al. (2010), we considered the product yields to be those given in Table A.1.

#### A.8. Photolysis of $C_3H_7$

For the  $C_3H_7$  photodissociation we considered only absorption in the 220–260 nm range from Adachi & Basco (1981), which leads to  $C_3H_6 + H$  (see Fig. A.6).

#### A.9. Photolysis of $HC_3N$

$HC_3N$  photochemistry has been studied between 185 and 254 nm. The main channel seems to be  $HC_3N^{**}$  metastable product (Clarke & Ferris 1995; Seki et al. 1996; Halpern et al. 1988) with a quantum yield as high as 70% at 193 nm (Seki et al. 1996).



**Fig. B.1.** Low-pressure limiting and radiative association rate constants  $k_0$ ,  $k_r$  as a function of the vibrational density of states of the adduct,  $\rho(E_0)$ . The stars are the experimental  $k_0$  values at 300 K, the open circles are the calculated  $k_0$  values at 300 K from Vuitton et al. (2012), the diamond is the calculated  $k_0$  value at 300 K performed for this study and the solid circles are the  $k_r$  calculations at 150 K from Vuitton et al. (2012). Units on the left axis are in  $\text{cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$  for  $k_0$  and  $\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  for  $k_r$ . Experimental data are taken from: H + NH<sub>2</sub> (Gordon et al. 1971), H + CH<sub>3</sub> (Brouard et al. 1989), CH<sub>3</sub> + O<sub>2</sub> (Fernandes et al. 2006), CH<sub>3</sub> + NO (Kaiser 1993), CH<sub>3</sub> + NH<sub>2</sub> (Jodkowski et al. 1995), CH<sub>3</sub> + CH<sub>3</sub> (Slagle et al. 1988; Cody et al. 2002). The solid and dashed lines correspond to the general expression we derived for the low-pressure limiting rate constants  $k_0$  for H addition and CH<sub>3</sub> addition, respectively. The dashed-dotted line corresponds to the general expression we derived for the radiative association rate constants  $k_r$ .

The main bimolecular exit channel is H + C<sub>3</sub>N formation with a quantum yield of approximately 30% at 193 nm, whereas the C<sub>2</sub>H + CN exit channel is very minor (Seki et al. 1996). Recent experimental and ab-initio calculations (Silva et al. 2009) agree well with theoretical work from Luo et al. (2008) and lead to the branching ratios (for bimolecular products only) given in Table A.2. The possible minor production of C<sub>2</sub> + HCN (less than 10%) as well as the production of metastable HC<sub>3</sub>N\*\* were neglected in this study.

#### Appendix B: “ $k_{\text{association}} - \rho$ ” model to determine $k_0$

Statistical theories allow us to calculate the temperature-dependent low-pressure limiting rate constants  $k_0(T)$  (Holbrook et al. 1996) but specific calculations are required for each reaction. Vuitton et al. (2012) performed a master-equation analysis to determine  $k_0$  for various reactions and proposed a general formula ( $k_0 = 8 \times 10^{-30} \times \exp(4.7 \times N)$ , where  $N$  is the number of adduct carbon atoms) for saturated molecule formation (C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>8</sub>, etc.). As stated by Vuitton et al. (2012), this relation, obtained from a fit of their calculations, is valid only if the number of H atoms is equal or close to  $2N + 2$ . For unsaturated

molecule formation, the rate constant is lower because of the reduced number of vibrational modes. As many important reactions involve the formation of highly unsaturated species, such as the C<sub>3</sub> + H → C<sub>3</sub>H reaction, we propose a new semi-empirical model based in part on a fit of the  $k_0$  calculations from Vuitton et al. (2012) and also on various experimental data for barrierless addition as a function of a power of the vibrational density of states of the adduct,  $\rho(E_0)$ , with  $E_0$  corresponding to the exothermicity of the addition.  $\rho(E_0)$  was calculated using the Whitten-Rabinovitch formula (Whitten & Rabinovitch 1963; Holbrook et al. 1996):

$$\rho(E_0) = \frac{(E_0 + aE_z)^{s-1}}{(s-1)! \prod_{i=1}^s h\nu_i}, \quad (\text{B.1})$$

where  $s$  is the number of vibrators,  $E_0$  is the enthalpy of addition,  $E_z$  is the zero-point vibrational energy, and  $a$  is a semi-empirical parameter to account for the level of quantization (a  $a$  value ranging between 0.80 and 0.95 is typical), which varies as a function of molecular size and also as a function of the relative  $E_0/E_z$  value (Holbrook et al. 1996). The vibrational frequencies are calculated using Gaussian 2009 at the M06/aug-pVTZ level (see Fig. B.1).

Radiative association rate constants,  $k_r$ , are complex to calculate accurately (Herbst 1982).  $k_r$  values are highly dependent on the size of the system, of the exothermicity of the addition process, and on the radiative emission rate constant,  $k_{\text{IR}}$ . For high  $k_r$  values, very long adduct lifetimes are required, close to the  $1/k_{\text{IR}}$  value ( $10^{-3}$  to  $10^{-2}$  s), so that radiative associations are important only for large molecule formation. In a similar manner to the molecular association reactions, we performed a fit of the Vuitton et al. (2012) radiative association rate constants with the  $k_r = k_{\text{capture}} \times [k_{\text{IR}} / (k_{\text{dissociation}} + k_{\text{IR}})]$  expression, where  $k_{\text{dissociation}}$  varies as a function of  $\rho(E_0)$  considering similar IR emission probabilities for all adducts.

For a reaction between two chemical species  $A$  and  $B$ , the temperature dependences of  $k_0$  and  $k_r$  can be approximated to  $T^{-(r_A+r_B+1)/2}$ , where  $r$  refers to the number of rotational degrees of freedom for a reactant:  $r = 2$  for a linear species and  $r = 3$  for a spherical top (Herbst et al. 2010). As a result and also taking into account the various experimental dependencies of H and  $\text{CH}_3$  association reactions with  $\text{CH}_3$ , NO and  $\text{O}_2$  as well as the Vuitton et al. (2012) calculations, we used a  $T^{-1.8}$  dependence for H reactions and  $T^{-3.5}$  for  $\text{CH}_3$  reactions in the 100–300 K range. The temperature dependence for radiative association is more complex because the radiative rate constants saturate at  $k_{\text{capture}}$  if no stabilization by collision occurs.

Our “ $k_{\text{association}} - \rho$ ” semi-empirical model leads to

$$\text{For H addition: } k_0 = 1.6 \times 10^{-31} \times (T/300)^{-1.8} \times \rho^{0.9}.$$

$$\text{For } \text{CH}_3 \text{ addition: } k_0 = 4.0 \times 10^{-33} \times (T/300)^{-3.5} \times \rho^{0.9}.$$

$$\text{For radiative association: } k_r = 1.0 \times 10^{-18} \times (T/300)^{-1.5} \times \rho^{0.66} \times k_{\text{capture}} / (1.0 \times 10^{-18} \times (T/300)^{-1.5} \times \rho^{0.66} + k_{\text{capture}}).$$

To estimate the association rate constant it is difficult to use a unique formula for all the cases because radiative association must compete with termolecular reaction. For the  $\text{C}_3\text{H}_p$  system, the radiative association rate constants  $k_r$  are in general small with respect to  $k_{\text{capture}}$ . For barrierless reactions,  $k_{\text{capture}} = k_{\infty}$  and the overall kinetics are described by a modified Troe formula:

$$k_{\text{adduct}} = \frac{(k_0[M]F + k_r)k_{\infty}}{k_0[M] + k_{\infty}} \quad (\text{B.2})$$

with  $\log(F) = \frac{\log(F_c)}{1 + \left[ \frac{\log(k_0[M] + k_{\text{capture}})}{N} \right]^2}$ ,  $F_c = 0.60$  and  $N = 1$ . When

the radiative association rate constants  $k_r$  become comparable to  $k_{\infty}$ , it may be more realistic for intermediate pressure behavior to use  $k_{\text{association}} = \min(k_{\infty}, k_r + \frac{k_0 k_{\infty} [M] F}{k_0 [M] + k_{\infty}})$ , but the differences are however much smaller than the uncertainties.

## Appendix C: Comments on selected reactions

These reactions were identified as the key reactions following our global sensitivity analysis (see Sect. 5). For each reaction, we recommend a value for its rate constant and its uncertainty factors along with a justification for these recommendations.

Reaction	Rate constant $k$	$F_0$	$g$
----------	-------------------	-------	-----

$F_0$  is the uncertainty in the rate constant  $k(T)$  at  $T = 300$  K and  $g$  is the “uncertainty-extrapolating” coefficient defined for use with  $F_0$  to obtain the rate constant uncertainty  $F(T)$  at different temperatures following the expression adapted from KIDA (Wakelam et al. 2012).  $k_{\infty}(T)$  and  $k_r(T)$  are expressed in  $\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  and  $k_0(T)$  in  $\text{cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$ .

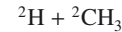
All following  $\Delta H_R$  were calculated using  $\Delta H_f^{298}$  taken from Baulch et al. (2005) except for

$$\begin{aligned} \Delta H_f^{298}(\text{C}_3(\text{X}^1\Sigma^+)) &= 830 \pm 10 \text{ kJ mol}^{-1} \text{ (Gingerich et al. 1994)} \\ \Delta H_f^{298}(\text{c-C}_3\text{H}(\text{X}^2\text{B}_2)) &= 715 \pm 8 \text{ kJ mol}^{-1} \text{ (Costes et al. 2009)} \\ \Delta H_f^{298}(\text{l-C}_3\text{H}(\text{X}^2\text{A}_1)) &= 728 \pm 8 \text{ kJ mol}^{-1} \text{ (Costes et al. 2009)} \\ \Delta H_f^{298}(\text{c-C}_3\text{H}_2(\text{X}^1\text{B}_1)) &= 497 \pm 4 \text{ kJ mol}^{-1} \text{ (Vazquez et al. 2009)} \\ \Delta H_f^{298}(\text{t-C}_3\text{H}_2(\text{X}^3\text{B})) &= 543 \pm 8 \text{ kJ mol}^{-1} \text{ (Aguilera-Iparraguirre et al. 2008)} \\ \Delta H_f^{298}(\text{l-C}_3\text{H}_2(\text{X}^1\text{A}_1)) &= 557 \pm 4 \text{ kJ mol}^{-1} \text{ (Vazquez et al. 2009)} \\ \Delta H_f^{298}(\text{C}_3\text{H}_3(\text{X}^2\text{B}_1)) &= 352 \pm 4 \text{ kJ mol}^{-1} \text{ (Vazquez et al. 2009)}. \end{aligned}$$

### C.1. $\text{H} + \text{CH}_3$

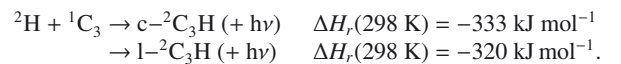


Brouard et al. (1989) have performed a detailed experimental study of this reaction. Forst (1991) performed RRKM calculations scaled to the experimental data in the 300–1000 K range, leading to the expressions  $k_0(T) = 2.63 \times 10^{-28} \times (T/300)^{-2.98} \times \exp(-635/T) \text{ cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$  for He as the bath gas with  $k_{\infty}(T) = 4.57 \times 10^{-10} \times (T/300)^{-0.20} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . The  $k_0$  expression seems reliable, but only above 300 K. Baulch et al. (1994) proposed  $k_0(T) = 6.20 \times 10^{-29} \times (T/300)^{-1.80} \text{ cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$  with He as the bath gas in the 300–1000 K range and  $k_{\infty}(T) = 3.5 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . Smith (2003) performed RRKM simulations in the 65–300 K range, leading to  $k_0(T) = 5.1 \times 10^{-29} \times (T/300)^{-1.06} \times \exp(+17/T) \text{ cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$  ( $F_c = 0.56$ ) in He and  $k_{\infty}(T) = 3.5 \times 10^{-10} \times (T/300)^{-0.09} \times \exp(+12/T) \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . Vuitton et al. (2012) have performed new calculations between 50 and 300 K. There is a relatively good agreement between the calculations (Baulch et al. 1994; Smith 2003; Vuitton et al. 2012) and the experimental data (Brouard et al. 1989), even if the results of Vuitton et al. (2012) seem to be slightly overestimated. However, is not possible to fit the entire temperature and pressure range with only one expression, and the results of Vuitton et al. (2012) are likely to be the more precise ones at low temperature and low density. We recommend their values with  $k_0$  scaled to the available experimental data at 300 K using the Troe expression in  $\text{N}_2$  with  $F_c = 0.60$ ,  $N = 1$ . The radiative association rate constant given by Vuitton et al. (2012) at 150 K,  $k_r(150 \text{ H}) = 2.8 \times 10^{-16} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ , agrees relatively well with Smith (1989), who used a similar methodology, that led to a value of  $7.0 \times 10^{-16} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  without tunneling.



${}^2\text{H} + {}^2\text{CH}_3 \rightarrow {}^1\text{CH}_4 (+ \text{hv})$		
$k_0(T) = 8.9 \times 10^{-29} \times (T/300)^{-1.8} \times \exp(-31.8/T)$	2	0
$k_{\infty}(T) = 3.2 \times 10^{-10} \times (T/300)^{0.133} \times \exp(-2.54/T)$	1.4	0
$k_r(T) = 1.31 \times 10^{-16} \times (T/300)^{-1.29} \times \exp(-19.6/T)$	10	0

### C.2. $\text{H} + \text{C}_3$



There is no bimolecular exit channel for this reaction. Mebel & Kaiser (2002) performed ab initio calculations that showed no barrier at the CCSD(T)/6-311+G(3df,2p)//B3LYP/6-311G(d,p) level. Because this reaction is a very important sink for  $\text{C}_3$ , we also performed DFT (M06-2X/aug-cc-pVTZ) calculations, which showed no barrier, and ab-initio calculations (MRCI+Q/aug-cc-pVTZ), that showed a very small barrier ( $1 \text{ kJ mol}^{-1}$ ) for this reaction. Therefore we recommend a

slightly lower value for  $k_{\infty}$  than  $k_{\text{capture}}$  to take into account the possible presence of an activation barrier. (Mebel & Kaiser 2002) also showed that the isomerization barrier between both C<sub>3</sub>H isomers is considerably lower than the entrance valley. Therefore we considered to a first approximation an equal production of both isomers for termolecular reaction and also for radiative association. We estimated  $k_0$  and  $k_r$  using our “ $k_{\text{association}} - \rho$ ” semi-empirical model. We also performed RRKM calculations in the same way for the two reactions  $\text{H} + \text{C}_3 \rightarrow \text{C}_3\text{H}$  and the well-known  $\text{H} + \text{CH}_3 \rightarrow \text{CH}_4$ , and obtained  $k_0(\text{H} + \text{C}_3) = 2.5 k_0(\text{H} + \text{CH}_3)$ , in good agreement with our “ $k_{\text{association}} - \rho$ ” semi-empirical model.

${}^2\text{H} + {}^1\text{C}_3$		
${}^2\text{H} + {}^1\text{C}_3 \rightarrow \text{c},\text{l-}{}^2\text{C}_3\text{H} (+\text{h}\nu)$		
$k_0(T) = 1.0 \times 10^{-28} \times (T/300)^{-1.8}$	3	0
$k_{\infty}(T) = 6.0 \times 10^{-11}$	2	0
$k_r(T) = 1.0 \times 10^{-16} \times (T/300)^{-1.5}$	10	0

With 50% of c-C<sub>3</sub>H and 50% of l-C<sub>3</sub>H production.

### C.3. H + C<sub>3</sub>H

${}^2\text{H} + \text{c-}{}^2\text{C}_3\text{H} \rightarrow {}^1\text{C}_3 + {}^1\text{H}_2$	$\Delta H_r(298 \text{ K}) = -103 \text{ kJ mol}^{-1}$
$\rightarrow \text{c-}{}^1\text{C}_3\text{H}_2 (+\text{h}\nu)$	$\Delta H_r(298 \text{ K}) = -436 \text{ kJ mol}^{-1}$
${}^2\text{H} + \text{l-}{}^2\text{C}_3\text{H} \rightarrow \text{c-}{}^2\text{C}_3\text{H} + {}^2\text{H}$	$\Delta H_r(298 \text{ K}) = -13 \text{ kJ mol}^{-1}$
$\rightarrow {}^1\text{C}_3 + {}^1\text{H}_2$	$\Delta H_r(298 \text{ K}) = -116 \text{ kJ mol}^{-1}$
$\rightarrow \text{l-}{}^1\text{C}_3\text{H}_2 (+\text{h}\nu)$	$\Delta H_r(298 \text{ K}) = -389 \text{ kJ mol}^{-1}$
$\rightarrow \text{t-}{}^3\text{C}_3\text{H}_2 (+\text{h}\nu)$	$\Delta H_r(298 \text{ K}) = -403 \text{ kJ mol}^{-1}$
$\rightarrow \text{c-}{}^1\text{C}_3\text{H}_2 (+\text{h}\nu)$	$\Delta H_r(298 \text{ K}) = -449 \text{ kJ mol}^{-1}$

These reactions have been studied theoretically in great detail during studies of the  ${}^3\text{C} + \text{C}_2\text{H}_2$  and  ${}^1\text{C} + \text{C}_2\text{H}_2$  reactions (Mebel et al. 2007; Takayanagi 2006; Takahashi & Yamashita 1996; Park et al. 2006). They have no barrier on the singlet surface and on one of the triplet surfaces, which leads to various  ${}^{1,3}\text{C}_3\text{H}_2$  isomers. The main exit channel leads to C<sub>3</sub> + H<sub>2</sub> formation on the singlet surface with a notable barrier on the exit channel located only  $-10 \text{ kJ mol}^{-1}$  below the reactants. Recent calculations coupled with low-temperature experiments (Costes et al. 2009) indicate that the exit channel  $\text{C}({}^3\text{P}) + \text{C}_2\text{H}_2$  might be thermoneutral or even slightly exothermic with respect to  $\text{H} + \text{l-C}_3\text{H}$ . Nevertheless, once the cyclic  ${}^3\text{C}_3\text{H}_2$  intermediate has been formed, both exit channels  $\text{H} + \text{c-C}_3\text{H}$  and  $\text{C} + \text{C}_2\text{H}_2$  can be reached without barrier; the former being lower in energy. As a result, the formation of  $\text{C}({}^3\text{P}) + \text{C}_2\text{H}_2$  products is likely to be very low, whilst isomerization to  $\text{H} + \text{c-C}_3\text{H}$  is also likely to be low with respect to C<sub>3</sub> + H<sub>2</sub> formation given the lower exit barriers. As shown experimentally (Costes et al. 2009; Bergeat & Loison 2001) and theoretically (Mebel et al. 2007), intersystem crossing is efficient enough to quickly convert  ${}^3\text{C}_3\text{H}_2$  into  ${}^1\text{C}_3\text{H}_2$ . The electronic degeneracy factor is then high and the rate constant should be close to the capture rate constant. Taking into consideration the various uncertainties the global rate constant for  $\text{H} + \text{c-C}_3\text{H}$  and  $\text{H} + \text{l-C}_3\text{H}$  reactions is estimated to be equal to  $2.0 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . Stabilization of the c-C<sub>3</sub>H<sub>2</sub> adduct (we neglect the other l,t-C<sub>3</sub>H<sub>2</sub> adducts) may play a non-negligible role at high pressure because the complex has a long lifetime (Park et al. 2006). Because there is one bimolecular exit channel, we considered that these association reactions had rates close to the  $\text{H} + \text{C}_3$  one, neglecting the possibility of radiative stabilization through electronic emission.

$\text{H} + \text{c},\text{l-C}_3\text{H}$		
$\text{H} + \text{c},\text{l-C}_3\text{H} \rightarrow \text{c-C}_3\text{H}_2$		
$k_0(T) = 1.0 \times 10^{-28} \times (T/300)^{-1.8}$	30	0
$k_{\infty}(T) = 2.0 \times 10^{-10}$	3	0
$k_r(T) = 1.0 \times 10^{-16} \times (T/300)^{-1.5}$	100	0
$\text{H} + \text{l-C}_3\text{H} \rightarrow \text{C}_3 + \text{H}_2$		
$k(T) = 0.8 \times (k_{\infty}(T) - k_{\text{H} + \text{c},\text{l-C}_3\text{H} \rightarrow \text{c-C}_3\text{H}_2}(T))$		
$\text{H} + \text{l-C}_3\text{H} \rightarrow \text{c-C}_3\text{H} + \text{H}$		
$k(T) = 0.2 \times (k_{\infty}(T) - k_{\text{H} + \text{c},\text{l-C}_3\text{H} \rightarrow \text{c-C}_3\text{H}_2}(T))$		
$\text{H} + \text{c-C}_3\text{H} \rightarrow \text{C}_3 + \text{H}_2$		
$k_{\infty}(T) - k_{\text{H} + \text{c},\text{l-C}_3\text{H} \rightarrow \text{c-C}_3\text{H}_2}(T)$		

### C.4. H + t-C<sub>3</sub>H<sub>2</sub>

${}^2\text{H} + \text{t-}{}^3\text{C}_3\text{H}_2 \rightarrow \text{l-}{}^2\text{C}_3\text{H} + {}^1\text{H}_2$	$\Delta H_r(298 \text{ K}) = -33 \text{ kJ mol}^{-1}$
$\rightarrow \text{c-}{}^1\text{C}_3\text{H}_2 + {}^2\text{H}$	$\Delta H_r(298 \text{ K}) = -46 \text{ kJ mol}^{-1}$
$\rightarrow \text{c-}{}^2\text{C}_3\text{H} + {}^1\text{H}_2$	$\Delta H_r(298 \text{ K}) = -46 \text{ kJ mol}^{-1}$
$\rightarrow {}^2\text{C}_3\text{H}_3 (+\text{h}\nu)$	$\Delta H_r(298 \text{ K}) = -409 \text{ kJ mol}^{-1}$

The reaction  ${}^2\text{H} + \text{t-}{}^3\text{C}_3\text{H}_2$  can proceed through direct abstraction or through addition. Ab initio calculations (Nguyen et al. 2001a; Goulay et al. 2009; Harding et al. 2007; Vereecken et al. 1998) showed no barrier for addition, which leads to an excited  $\text{C}_3\text{H}_3^{**}$  adduct. Subsequent evolution of  $\text{C}_3\text{H}_3^{**}$  leads either to stabilization at high pressure or to  $\text{H} + \text{c-}{}^2\text{C}_3\text{H}_2$ . The l-C<sub>3</sub>H + H<sub>2</sub> exit channel is thermodynamically accessible but involves a high exit barrier ( $40 \text{ kJ mol}^{-1}$ ) above the exit level and close to the entrance channel. The stabilization cannot be neglected because the only exit channel ( $\text{c-C}_3\text{H}_2 + \text{H}$ ) is not very exothermic and involves a complex rearrangement, which leads to a long  $\text{C}_3\text{H}_3$  adduct lifetime. We neglected however the  ${}^2\text{H} + \text{l-}{}^1\text{C}_3\text{H}_2 \rightarrow {}^2\text{H} + \text{t-}{}^3\text{C}_3\text{H}_2$  reaction as well as the  $\text{C}_3\text{H} + \text{H}_2$  production from the adduct and also the direct  $\text{C}_3\text{H} + \text{H}_2$  formation. The  ${}^2\text{H} + \text{t-}{}^3\text{C}_3\text{H}_2$  reagents correlate with doublet and quadruplet states but the products  ${}^2\text{H} + \text{l},\text{c-C}_3\text{H}_2$  only correlate with doublet states. There is then a  $2/6 = 1/3$  electronic degeneracy factor for this reaction, but not for the  ${}^2\text{H} + \text{l-}{}^1\text{C}_3\text{H}_2$  reaction. Harding et al. (2007) performed variable reaction coordinate transition state theory calculations (VRC-TST) that led to a high value for  $k_{\text{H} + \text{t-C}_3\text{H}_2 \rightarrow \text{C}_3\text{H}_3} = 4.42 \times 10^{-10} \times (T/298)^{0.22} \times \exp(+43.7/T) \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . Because there is one bimolecular exit channel, we considered that the association reactions were similar to those of  $\text{H} + \text{C}_3$ , neglecting the possibility of radiative stabilization through electronic emission.

$\text{H} + \text{t-C}_3\text{H}_2$		
$\text{H} + \text{t-C}_3\text{H}_2 \rightarrow \text{C}_3\text{H}_3$		
$k_0(T) = 1.0 \times 10^{-28} \times (T/300)^{-1.8}$	30	0
$k_{\infty}(T) = 4.42 \times 10^{-10} \times (T/300)^{0.22} \times \exp(+43.7/T)$	2	0
$k_r(T) = 1.0 \times 10^{-16} \times (T/300)^{-1.5}$	100	0
$\text{H} + \text{t-C}_3\text{H}_2 \rightarrow \text{c-C}_3\text{H}_2 + \text{H}$		
$k(T) = k_{\infty}(T) - k_{\text{H} + \text{c-C}_3\text{H}_2 \rightarrow \text{C}_3\text{H}_3}(T)$		

### C.5. H + l-C<sub>3</sub>H<sub>2</sub>

${}^2\text{H} + \text{l-}{}^1\text{C}_3\text{H}_2 \rightarrow \text{l-}{}^2\text{C}_3\text{H} + {}^1\text{H}_2$	$\Delta H_r(298 \text{ K}) = -47 \text{ kJ mol}^{-1}$
$\rightarrow \text{c-}{}^1\text{C}_3\text{H}_2 + {}^2\text{H}$	$\Delta H_r(298 \text{ K}) = -60 \text{ kJ mol}^{-1}$
$\rightarrow \text{c-}{}^2\text{C}_3\text{H} + {}^1\text{H}_2$	$\Delta H_r(298 \text{ K}) = -60 \text{ kJ mol}^{-1}$
$\rightarrow {}^2\text{C}_3\text{H}_3 (+\text{h}\nu)$	$\Delta H_r(298 \text{ K}) = -423 \text{ kJ mol}^{-1}$

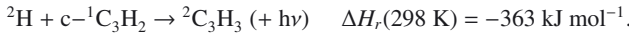
This reaction can also proceed through direct abstraction or addition. We neglected direct  $\text{C}_3\text{H} + \text{H}_2$  production from H atom abstraction. Ab initio calculations (Nguyen et al. 2001a; Goulay et al. 2009; Vereecken et al. 1998) showed no barrier for addition, which leads to  $\text{C}_3\text{H}_3^{**}$ . The subsequent evolution of  $\text{C}_3\text{H}_3^{**}$  leads either to stabilization at high pressure or to  $\text{H} + \text{c-C}_3\text{H}_2$ ,



neglecting the  ${}^2\text{H} + 1^{-1}\text{C}_3\text{H}_2 \rightarrow {}^2\text{H} + \text{t}^{-3}\text{C}_3\text{H}_2$  reaction and the  $\text{C}_3\text{H} + \text{H}_2$  production. The  ${}^2\text{H} + 1^{-1}\text{C}_3\text{H}_2$  reagents correlate with doublet states, as the  ${}^2\text{H} + \text{c}^{-1}\text{C}_3\text{H}_2$  products do. As a result, there is no electronic degeneracy factor for this reaction, which leads to a very high total rate constant. However, the potential curve is likely to be less attractive than the potential energy curve for the  ${}^2\text{H} + \text{t}^{-3}\text{C}_3\text{H}_2$  reaction, a reaction between two open shell radical species. As a result, the variational TS (Georgievskii & Klippenstein 2005) should occur at high energy, slowing down the corresponding rate constant. Taking into account the higher electronic degeneracy factor for  $1^{-1}\text{C}_3\text{H}_2$ , we recommend using the same value for both reactions, with a global rate constant equal to  $4.0 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . Because there is one bimolecular exit channel we considered that the association reactions are similar to the  $\text{H} + \text{C}_3$  ones, neglecting the possibility of radiative stabilization through electronic emission.

$\text{H} + 1^{-1}\text{C}_3\text{H}_2$		
$\text{H} + 1^{-1}\text{C}_3\text{H}_2 \rightarrow \text{C}_3\text{H}_3$		
$k_0(T) = 1.0 \times 10^{-28} \times (T/300)^{-1.8}$	30	0
$k_\infty(T) = 4.0 \times 10^{-10} \times (T/300)^{0.15}$	2	0
$k_r(T) = 1.0 \times 10^{-16} \times (T/300)^{-1.5}$	100	0
$\text{H} + 1^{-1}\text{C}_3\text{H}_2 \rightarrow \text{c}^{-1}\text{C}_3\text{H}_2 + \text{H}$		
$k(T) = k_\infty(T) - k_{\text{H}+1^{-1}\text{C}_3\text{H}_2 \rightarrow \text{C}_3\text{H}_3}(T)$		

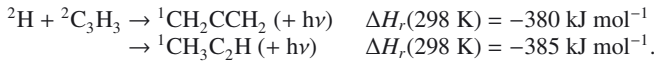
### C.6. $\text{H} + \text{c}^{-1}\text{C}_3\text{H}_2$



The only exothermic reaction is association. There are several ab initio calculations (Nguyen et al. 2001a; Goulay et al. 2009; Vereecken et al. 1998) on the  $\text{H} + \text{c}^{-1}\text{C}_3\text{H}_2$  reactions (related to unimolecular dissociation of the propargyl radical and the  $\text{CH} + \text{C}_2\text{H}_2$  reaction). All calculations lead to the absence of a barrier, or a very small one ( $0.4 \text{ kJ mol}^{-1}$ ), which will have a minor effect in the 150–200 K range and lead to relatively high value for addition rate constant in this temperature range, fixed at  $2.0 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . We estimated  $k_0$  and  $k_r$  using our “ $k_{\text{association}} - \rho$ ” semi-empirical model, neglecting the possibility of radiative stabilization through electronic emission.

$\text{H} + \text{c}^{-1}\text{C}_3\text{H}_2$		
$\text{H} + \text{c}^{-1}\text{C}_3\text{H}_2 \rightarrow \text{C}_3\text{H}_3$		
$k_0(T) = 8.1 \times 10^{-26} \times (T/300)^{-1.8}$	10	0
$k_\infty(T) = 2.0 \times 10^{-10}$	3	0
$k_r(T) = 1.5 \times 10^{-14} \times (T/300)^{-1.5}$	30	0.

### C.7. $\text{H} + \text{C}_3\text{H}_3$



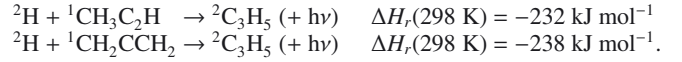
The only possible reaction is the association found to happen without a barrier with  $k_\infty(T) = 2.88 \times 10^{-10} \times (T/300)^{0.15} \times \exp(+46.30/T) \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  (Harding et al. 2007; Miller & Klippenstein 2003). The high-pressure limit should be reached at relatively low pressures compared with the  $\text{H} + \text{C}_3\text{H}_5$  reaction (Hanning-Lee & Pilling 1992) (no clear pressure-dependence between 98 and 400 Torr). Branching ratio calculations have been performed by Miller & Klippenstein (2003), leading to 25% of allene and 75% of methylacetylene, but the calculations have been performed only above 500 K and the rate was found to be pressure-dependent. We estimated  $k_0$  and  $k_r$  using our “ $k_{\text{association}} - \rho$ ” semi-empirical model, neglecting the possibility of radiative stabilization through electronic emission.

### $\text{H} + \text{C}_3\text{H}_3$

$\text{H} + \text{C}_3\text{H}_3 \rightarrow \text{C}_3\text{H}_4$		
$k_0(T) = 4.0 \times 10^{-25} \times (T/300)^{-1.8}$	10	0
$k_\infty(T) = 2.88 \times 10^{-10} \times (T/300)^{0.15} \times \exp(+46.3/T)$	2	0
$k_r(T) = 5.0 \times 10^{-14} \times (T/300)^{-1.5}$	30	0.

We estimated the branching ratios to be 80% of  $\text{CH}_3\text{C}_2\text{H}$  and 20% of  $\text{CH}_2\text{CCH}_2$  below 300 K.

### C.8. $\text{H} + \text{C}_3\text{H}_4$

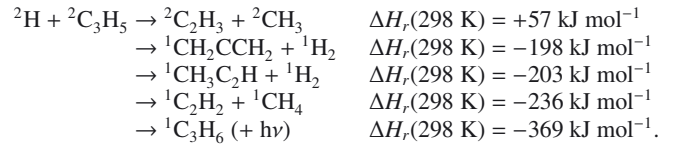


The rate constant values for the  $\text{H} + \text{methylacetylene} (\text{CH}_3\text{C}_2\text{H})$  and  $\text{H} + \text{allene} (\text{CH}_2\text{CCH}_2)$  reactions were taken from various experimental measurements, particularly from Whytock et al. (1976) and Faravelli et al. (2000) for  $\text{H} + \text{CH}_3\text{C}_2\text{H}$  and from Wagner & Zellner (1972) and Aleksandrov et al. (1980) for  $\text{H} + \text{CH}_2\text{CCH}_2$ . We also used the recent theoretical work by Miller et al. (2008). The  $\text{CH}_3 + \text{C}_2\text{H}_2$  production channel is always very minor and was neglected. We also neglected  $\text{H} + \text{CH}_2\text{CCH}_2 \rightarrow \text{H} + \text{CH}_3\text{C}_2\text{H}$  because it is a minor channel and  $\text{CH}_3\text{C}_2\text{H}$  reacts mainly with H atoms to produce the  $\text{C}_3\text{H}_5$  radical. We recommend to use the experimental  $k_\infty(T)$  values and the calculated  $k_0$  and  $k_r$  values (Vuitton et al. 2012) for the  $\text{H} + \text{CH}_3\text{C}_2\text{H}$  and  $\text{H} + \text{CH}_2\text{CCH}_2$  reactions.

### $\text{H} + \text{C}_3\text{H}_4$

$\text{H} + \text{CH}_2\text{CCH}_2 \rightarrow \text{C}_3\text{H}_5$		
$k_0(T) = 1.0 \times 10^{-25} \times (T/300)^{-2.48} \times \exp(-191/T)$	4	0
$k_\infty(T) = 1.4 \times 10^{-11} \times \exp(-1010/T)$	2	50
$k_r(T) = 3.9 \times 10^{-15} \times (T/300)^{2.63} \times \exp(-63/T)$	10	0
$\text{H} + \text{CH}_3\text{C}_2\text{H} \rightarrow \text{C}_3\text{H}_5$		
$k_0(T) = 1.0 \times 10^{-25} \times (T/300)^{-2.48} \times \exp(-191/T)$	4	0
$k_\infty(T) = 6.0 \times 10^{-11} \times \exp(-1233/T)$	1.4	50
$k_r(T) = 3.9 \times 10^{-15} \times (T/300)^{2.63} \times \exp(-63/T)$	10	0.

### C.9. $\text{H} + \text{C}_3\text{H}_5$

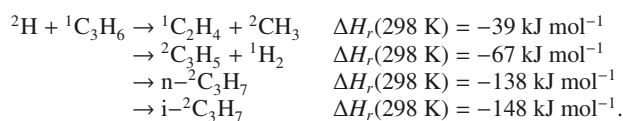


There are three  $\text{C}_3\text{H}_5$  isomers:  $\text{H}_2\text{C}=\text{CH}-\bullet\text{CH}_2$  (allyl),  $\text{H}_3\text{C}-\bullet\text{C}=\text{CH}_2$  and  $\text{H}_3\text{C}-\text{CH}=\bullet\text{CH}$ , the allyl being by far the most stable one and the only isomer considered here. There is one experimental determination of the rate constant for this reaction by Hanning-Lee & Pilling (1992). They measured the room temperature rate constants at four pressures in the range 98–400 Torr, which showed no clear pressure-dependence in this range with the mean rate constant equal to  $(2.8 \pm 1.0) \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . Calculations based on the Troe factorization method confirm that this reaction is near its high-pressure limit under their experimental conditions. Theoretical results (Qu et al. 2010; Zhao et al. 2007) clearly show that there are no bimolecular exit channels. These calculations agree well with Zhao et al. (2007) for the roaming channel (leading to  $\text{C}_2\text{H}_2 + \text{CH}_4$ ) with the TS calculated to be at  $+11 \text{ kJ mol}^{-1}$  with respect to the reactant energies. The high-pressure rate constants have been determined theoretically (Harding et al. 2007), leading to a good agreement with experiments (Hanning-Lee & Pilling 1992). The  $\text{C}_2\text{H}_3 + \text{CH}_3$  exit channel is endothermic. Davis et al. (1999a) proposed a global kinetic mechanism for propene pyrolysis that

does not fully agree with the ab initio calculations. There are no bimolecular exit channels, which leads to a high rate constant for the association reaction. We estimated  $k_0$  and  $k_r$  using our “ $k_{\text{association}} - \rho$ ” semi-empirical model, neglecting the possibility of radiative stabilization through electronic emission.

H + C <sub>3</sub> H <sub>5</sub>		
H + C <sub>3</sub> H <sub>5</sub> → C <sub>3</sub> H <sub>6</sub>		
$k_0(T) = 2.2 \times 10^{-23} \times (T/300)^{-1.8}$	10	0
$k_{\infty}(T) = 2.64 \times 10^{-10} \times (T/300)^{0.18} \times \exp(+63/T)$	1.6	0
$k_r(T) = 9.2 \times 10^{-13} \times (T/300)^{-1.5}$	30	0
H + C <sub>3</sub> H <sub>5</sub> → CH <sub>2</sub> CCH <sub>2</sub> + H <sub>2</sub>		
$k(T) = 1.0 \times 10^{-11}$ (direct abstraction)	3	0.

### C.10. H + C<sub>3</sub>H<sub>6</sub>



There have been various experimental measurements over a wide temperature range (Tsang 1991; Seakins et al. 1993). The H atom can add at two positions, which leads to i,n-<sup>2</sup>C<sub>3</sub>H<sub>7</sub> formation (Galland et al. 2003). The n-<sup>2</sup>C<sub>3</sub>H<sub>7</sub> isomer can evolve towards CH<sub>3</sub> + C<sub>2</sub>H<sub>4</sub>, which is a pressure-dependent channel, but the bimolecular exit channels do not compete with i-C<sub>3</sub>H<sub>7</sub> formation but only with n-C<sub>3</sub>H<sub>7</sub> formation. In this study we considered only one C<sub>3</sub>H<sub>7</sub> isomer. Because the main pathway of this reaction in the low-pressure limit of the addition is dominated by i-C<sub>3</sub>H<sub>7</sub> production, the rate constant should be close to the low-pressure-limiting rate constant  $k_0$  of the H + C<sub>3</sub>H<sub>4</sub> reaction (Vuitton et al. 2012).

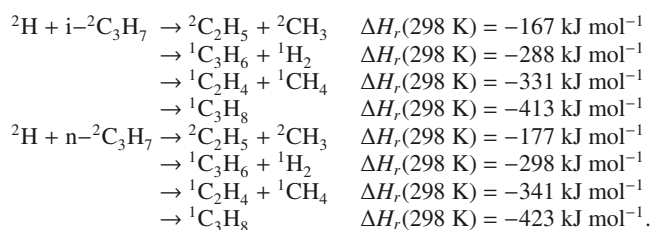
Considering only one C<sub>3</sub>H<sub>7</sub> isomer:

H + C <sub>3</sub> H <sub>6</sub>		
H + C <sub>3</sub> H <sub>6</sub> → C <sub>3</sub> H <sub>7</sub>		
$k_0(T) = 1.4 \times 10^{-25} \times (T/300)^{2.48} \times \exp(-191/T)$	10	100
$k_{\infty}(T) = 7.02 \times 10^{-12} \times (T/300)^{1.16} \times \exp(-440/T)$	1.6	0
H + C <sub>3</sub> H <sub>6</sub> → C <sub>3</sub> H <sub>5</sub> + H <sub>2</sub>		
$k(T) = 4.33 \times 10^{-13} \times (T/300)^{2.5} \times \exp(-1250/T)$	1.8	21
H + C <sub>3</sub> H <sub>6</sub> → C <sub>2</sub> H <sub>4</sub> + CH <sub>3</sub>		
$k(T) = 2.19 \times 10^{-11} \times \exp(-1640/T)$	2	21.

Considering i-C<sub>3</sub>H<sub>7</sub> and n-C<sub>3</sub>H<sub>7</sub> isomers:

H + C <sub>3</sub> H <sub>6</sub>		
H + C <sub>3</sub> H <sub>6</sub> → i-C <sub>3</sub> H <sub>7</sub>		
$k_0(T) = 1.4 \times 10^{-25} \times (T/300)^{2.48} \times \exp(-191/T)$	10	100
$k_{\infty}(T) = 7.02 \times 10^{-12} \times (T/300)^{1.16} \times \exp(-440/T)$	1.6	0
H + C <sub>3</sub> H <sub>6</sub> → n-C <sub>3</sub> H <sub>7</sub>		
$k_0(T) = 1.4 \times 10^{-25} \times (T/300)^{2.48} \times \exp(-191/T)$	10	100
$k_{\infty}(T) = 2.19 \times 10^{-11} \times \exp(-1640/T)$	1.6	21
H + C <sub>3</sub> H <sub>6</sub> → C <sub>3</sub> H <sub>5</sub> + H <sub>2</sub>		
$k(T) = 4.33 \times 10^{-13} \times (T/300)^{2.5} \times \exp(-1250/T)$	1.8	21
H + C <sub>3</sub> H <sub>6</sub> → C <sub>2</sub> H <sub>4</sub> + CH <sub>3</sub>		
$k(T) = k_{\infty, \text{H} + \text{C}_3\text{H}_6 \rightarrow \text{n-C}_3\text{H}_7}(T) - k_{\text{H} + \text{C}_3\text{H}_6 \rightarrow \text{i-C}_3\text{H}_7}(T)$		

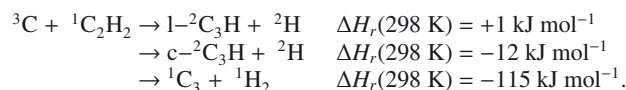
### C.11. H + C<sub>3</sub>H<sub>7</sub>



To a first approximation we considered only one C<sub>3</sub>H<sub>7</sub> isomer. This system is very similar to that of H + C<sub>2</sub>H<sub>5</sub> (Baulch et al. 2005). Direct H atom abstraction may happen without a barrier but is considered to be a minor channel compared with the H + C<sub>2</sub>H<sub>5</sub> reaction (Camilleri et al. 1974). Therefore the rate constant is estimated to be equal to  $3.0 \times 10^{-12} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  and independent of temperature (Tsang 1991). There is very likely no barrier for the addition leading to propane. The various exit channels have been calculated by Zhu et al. (2004), showing a high barrier for the H<sub>2</sub> + C<sub>3</sub>H<sub>6</sub> exit channel but no barrier for the CH<sub>3</sub> + C<sub>2</sub>H<sub>5</sub> exit channel. New calculations (Sivaramakrishnan et al. 2011) show an accessible tight TS for CH<sub>4</sub> + C<sub>2</sub>H<sub>4</sub> formation (roaming channel). The various calculations led us to conclude that the main exit channel at low pressure is the formation of CH<sub>3</sub> + C<sub>2</sub>H<sub>5</sub>. The total rate constants (excluding direct H atom abstraction) have been calculated by Harding et al. (2005), leading to  $k_{(\text{H} + \text{C}_3\text{H}_6)} = 9.68 \times 10^{-11} \times (T/300)^{0.22} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . Because there is one bimolecular exit channel without an exit barrier and with high exothermicity, the addition rate constant at low pressure will be low. The  $k_0$ , value for the H + C<sub>3</sub>H<sub>7</sub> → C<sub>3</sub>H<sub>8</sub> reaction is taken from Teng & Jones (1972).

H + C <sub>3</sub> H <sub>7</sub>		
H + C <sub>3</sub> H <sub>7</sub> → C <sub>3</sub> H <sub>8</sub>		
$k_0(T) = 6.11 \times 10^{-28} \times (T/300)^{-2} \times \exp(-1040/T)$	10	21
$k_{\infty}(T) = 9.68 \times 10^{-11} \times (T/300)^{0.22}$	2	0
H + C <sub>3</sub> H <sub>7</sub> → CH <sub>3</sub> + C <sub>2</sub> H <sub>5</sub>		
$k(T) = k_{\infty, \text{H} + \text{C}_3\text{H}_7 \rightarrow \text{CH}_3 + \text{C}_2\text{H}_5}(T) - k_{\text{H} + \text{C}_3\text{H}_7 \rightarrow \text{C}_3\text{H}_8}(T)$		
H + C <sub>3</sub> H <sub>7</sub> → H <sub>2</sub> + C <sub>3</sub> H <sub>6</sub>		
$k(T) = 3.0 \times 10^{-12}$	3	0.

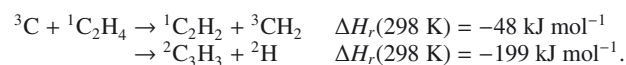
### C.12. C + C<sub>2</sub>H<sub>2</sub>



A considerable amount of work has been performed on this reaction; see for example Costes et al. (2009) and the references therein. The carbon atom in its triplet electronic state can add either to a single carbon of the acetylene molecule to form triplet t-C<sub>3</sub>H<sub>2</sub>, or to the triple bond to produce triplet c-C<sub>3</sub>H<sub>2</sub>, both additions occurring without a barrier. The exit channels on the triplet surface lead to c-C<sub>3</sub>H + H and i-C<sub>3</sub>H + H. Because these channels are not very exothermic, the lifetime of the triplet adduct is long enough (Guadagnini et al. 1998; Mebel et al. 2007) to allow intersystem crossing to the singlet surface and then production of C<sub>3</sub> + H<sub>2</sub>, which is the main exit channel below 300 K (85% between 150 and 200 K, Costes et al. 2009). As a result of this exit channel, the pressure dependence of the rate constants should be weak for  $P < 100$  Torr (Guadagnini et al. 1998) and C<sub>3</sub>H<sub>2</sub> stabilisation should not occur.

C + C <sub>2</sub> H <sub>2</sub>		
C + C <sub>2</sub> H <sub>2</sub> → C <sub>3</sub> + H <sub>2</sub>		
$k(T) = 2.60 \times 10^{-10} \times (T/300)^{-0.07}$	1.2	0.9
C + C <sub>2</sub> H <sub>2</sub> → c-C <sub>3</sub> H + H		
$k(T) = 4.10 \times 10^{-11} \times (T/300)^{-0.39} \times \exp(-2/T)$	1.4	0.8
C + C <sub>2</sub> H <sub>2</sub> → i-C <sub>3</sub> H + H		
$k(T) = 7.8 \times 10^{-12} \times (T/300)^{1.08}$	1.8	2.

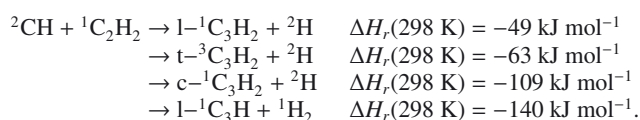
### C.13. C + C<sub>2</sub>H<sub>4</sub>



The rate constant for this reaction has been measured in the 15–300 K range by various groups (Haider & Husain 1993a,b; Chastaing et al. 1999, 2001; Bergeat & Loison 2001). The recommended value is an average of the room temperature rate with the temperature dependence of the Chastaing et al. (2001) experiment. The H atom branching ratio has been determined at 300 K (Bergeat & Loison 2001) to be equal to  $0.92 \pm 0.04$  and co-products and other branching ratios have been determined using ab initio calculations (Le et al. 2001). Adduct stabilization is negligible.

C + C <sub>2</sub> H <sub>4</sub>		
C + C <sub>2</sub> H <sub>4</sub> → C <sub>3</sub> H <sub>3</sub> + H $k(T) = 2.10 \times 10^{-10} \times (T/300)^{-0.11}$	1.4	0
C + C <sub>2</sub> H <sub>4</sub> → C <sub>2</sub> H <sub>2</sub> + CH <sub>2</sub> $k(T) = 2 \times 10^{-11} \times (T/300)^{-0.11}$	2	0.

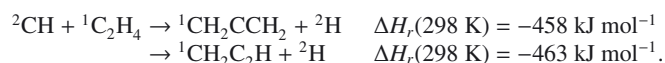
#### C.14. CH + C<sub>2</sub>H<sub>2</sub>



The reaction kinetics of CH with C<sub>2</sub>H<sub>2</sub> has been widely studied (Butler et al. 1981; Berman et al. 1982; Canosa et al. 1997; Thiesemann et al. 1997) for temperatures ranging from 23 K (Canosa et al. 1997) to 710 K (Thiesemann et al. 1997). The experimental temperature dependence of the total rate constant is given by the expression  $1.59 \times 10^{-9} \times T^{-0.233} \times \exp(-16/T) \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  between 23 K and 295 K, suggesting that this reaction proceeds without a barrier. The absence of any pressure dependence for the rate constant shows that stabilization is not competitive with dissociation of the intermediates. There have been five experimental branching ratio determinations for the CH + C<sub>2</sub>H<sub>2</sub> reaction (Boullart et al. 1996; McKee et al. 2003; Goulay et al. 2009; Loison & Bergeat 2009; Maksyutenko et al. 2010) in addition to various theoretical studies (Walch 1995; Vereecken et al. 1998; Vereecken & Peeters 1999; Guadagnini et al. 1998; Nguyen et al. 2001b; Mebel et al. 2007; Goulay et al. 2009). The ab-initio/RRKM calculations give scattered results on this system (Vereecken & Peeters 1999; Mebel et al. 2007; Goulay et al. 2009). A review of the various studies is given by Maksyutenko et al. (2010). There is a general agreement for a branching ratio of  $91 \pm 4\%$  for H atom production and  $9 \pm 2\%$  for H<sub>2</sub> production. The co-product isomers of the H atom have been determined by Maksyutenko et al. (2010) in a single collision experiment but at relatively high collisional energy ( $16.8 \text{ kJ mol}^{-1}$ ):  $31 \pm 5\%$  of c-C<sub>3</sub>H<sub>2</sub> + H and  $60 \pm 5\%$  of t-C<sub>3</sub>H<sub>2</sub>/l-C<sub>3</sub>H<sub>2</sub> + H and by Goulay et al. (2009): 90% of c-C<sub>3</sub>H<sub>2</sub> + H in a slow-flow reactor at 4 Torr and 293 K. The apparent disagreement may be explained by H-atom-assisted isomerization of the nascent C<sub>3</sub>H<sub>2</sub> product to the cyclic c-C<sub>3</sub>H<sub>2</sub> isomer through  $\text{l,t-C}_3\text{H}_2 + \text{H} \rightarrow \text{C}_3\text{H}_3 \rightarrow \text{c-C}_3\text{H}_2 + \text{H}$  (Mebel et al. 2007; Goulay et al. 2009). Considering that the branching ratio does not depend on the collision energy, we can reasonably use the value of Maksyutenko et al. (2010). Given the scatter of the various RRKM calculations, we considered that only t-C<sub>3</sub>H<sub>2</sub> is formed in the t-C<sub>3</sub>H<sub>2</sub>/l-C<sub>3</sub>H<sub>2</sub> + H pathway.

CH + C <sub>2</sub> H <sub>2</sub>		
CH + C <sub>2</sub> H <sub>2</sub> → l-C <sub>3</sub> H + H <sub>2</sub> $k(T) = 3.7 \times 10^{-11} \times (T/300)^{-0.23} \times \exp(-16/T)$	1.6	7
CH + C <sub>2</sub> H <sub>2</sub> → c-C <sub>3</sub> H <sub>2</sub> + H $k(T) = 1.3 \times 10^{-10} \times (T/300)^{-0.23} \times \exp(-16/T)$	1.6	7
CH + C <sub>2</sub> H <sub>2</sub> → t-C <sub>3</sub> H <sub>2</sub> + H $k(T) = 2.5 \times 10^{-10} \times (T/300)^{-0.23} \times \exp(-16/T)$	1.6	7.

#### C.15. CH + C<sub>2</sub>H<sub>4</sub>



The reaction kinetics of CH with C<sub>2</sub>H<sub>4</sub> has been widely studied (Butler et al. 1981; Berman et al. 1982; Canosa et al. 1997; Thiesemann et al. 1997, 2001) for temperatures ranging from 23 K (Canosa et al. 1997) to 726 K (Thiesemann et al. 2001). There are three experimental branching ratio determinations for the CH + C<sub>2</sub>H<sub>4</sub> reaction (McKee et al. 2003; Goulay et al. 2009; Loison & Bergeat 2009) and also theoretical studies (Gosavi et al. 1985; Wang & Huang 1998) as well as coupled ab initio/RRKM studies of this reaction (McKee et al. 2003) or studies on the evolution of the excited allyl radical C<sub>3</sub>H<sub>5</sub> (Davis et al. 1999b; Stranges et al. 2008), which is thought to be the main reaction intermediate. The experimental temperature dependence of the global rate constant of the CH + C<sub>2</sub>H<sub>4</sub> reaction,  $7.74 \times 10^{-9} \times T^{-0.546} \times \exp(-29.6/T) \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  between 23 K and 295 K, suggests that this reaction proceeds without a barrier. There is a good agreement with the various experimental results as well as with the ab initio/RRKM calculations, leading to  $70 \pm 8\%$  of CH<sub>2</sub>CCH<sub>2</sub> + H,  $30 \pm 8\%$  of CH<sub>3</sub>C<sub>2</sub>H + H.

CH + C <sub>2</sub> H <sub>4</sub>		
CH + C <sub>2</sub> H <sub>4</sub> → CH <sub>3</sub> C <sub>2</sub> H + H $k(T) = 1.0 \times 10^{-10} \times (T/300)^{-0.546} \times \exp(-29.6/T)$	1.6	7
CH + C <sub>2</sub> H <sub>4</sub> → CH <sub>2</sub> CCH <sub>2</sub> + H $k(T) = 2.4 \times 10^{-10} \times (T/300)^{-0.546} \times \exp(-29.6/T)$	1.6	7.

#### C.16. <sup>1</sup>CH<sub>2</sub> + C<sub>2</sub>H<sub>2</sub>



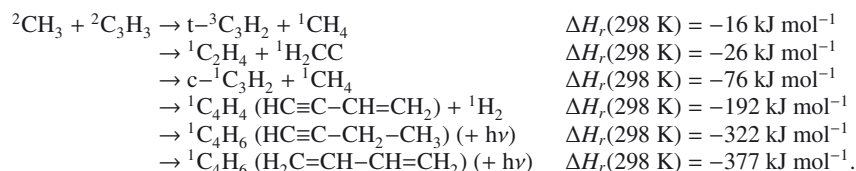
This reaction has been studied experimentally between 195 and 798 K by Gannon et al. (2010a,b). They measured the H atom branching ratio between 298 and 398 K and calculated that adduct stabilization was negligible below 100 Torr. Because there are no models to describe the H atom production increase between 195 K and 298 K and because the rate constant is almost constant in the 195–300 K range, we recommend to use the 195 K value in the 150–200 K range.

<sup>1</sup> CH <sub>2</sub> + C <sub>2</sub> H <sub>2</sub>		
<sup>1</sup> CH <sub>2</sub> + C <sub>2</sub> H <sub>2</sub> → C <sub>3</sub> H <sub>3</sub> + H $k(T) = 7.6 \times 10^{-11}$	1.8	21
<sup>1</sup> CH <sub>2</sub> + C <sub>2</sub> H <sub>2</sub> → C <sub>2</sub> H <sub>2</sub> + <sup>3</sup> CH <sub>2</sub> $k(T) = 2.3 \times 10^{-10}$	1.8	21.

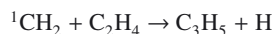
#### C.17. <sup>1</sup>CH<sub>2</sub> + C<sub>2</sub>H<sub>4</sub>



This reaction has been studied experimentally at low pressure (1 Torr) between 195 and 798 K by Gannon et al. (2010a,b). They measured the H atom branching ratio between 298 and 398 K but calculated neither adduct stabilization, nor the exit channels. An earlier experiment by Canosa-Mas et al. (1985) showed that cyclopropane formation is the main exit channel at 400 Torr. The first step of this reaction is likely to be cyclopropane formation resulting from the addition of <sup>1</sup>CH<sub>2</sub> to the double bond (with  $427 \text{ kJ mol}^{-1}$  in internal energy), so much more than the cyclopropane isomerization barrier toward propene equal to  $276 \pm 10 \text{ kJ mol}^{-1}$  (Dubnikova & Lifshitz 1998) or propene formation resulting in <sup>1</sup>CH<sub>2</sub> insertion into one C-H bond (with  $460 \text{ kJ mol}^{-1}$  in internal energy).



The bi-radical H<sub>2</sub>C<sup>•</sup>-CH<sub>2</sub>-<sup>•</sup>CH<sub>2</sub> formation is either endothermic or is only a local minimum. Because the formation of allyl H<sub>2</sub>C=CH-<sup>•</sup>CH<sub>2</sub> + H is exothermic (-91 kJ mol<sup>-1</sup>) without an exit barrier (Harding et al. 2007), this will be the main exit channel at low pressure, and adduct stabilization plays a role only at high pressure (Canosa-Mas et al. 1985). Because there are no models to describe the H atom production increase between 195 K and 298 K and the rate constant is almost constant in the 195–300 K range, we recommend to use the 195 K values in the 150–200 K range. We also neglected adduct stabilization.

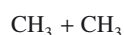


${}^1\text{CH}_2 + \text{C}_2\text{H}_4 \rightarrow \text{C}_3\text{H}_5 + \text{H}$ $k(T) = 6.3 \times 10^{-11}$	1.8	21
${}^1\text{CH}_2 + \text{C}_2\text{H}_4 \rightarrow \text{C}_2\text{H}_4 + {}^3\text{CH}_2$ $k(T) = 1.4 \times 10^{-10}$	1.8	21.

### C.18. CH<sub>3</sub> + CH<sub>3</sub>

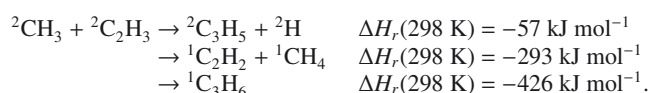


This reaction has been widely studied (Slagle et al. 1988; Cody et al. 2002, 2003). Wang et al. (2003) have fitted various experimental data between 202 and 900 K, leading to  $k_0(T) = 1.14 \times 10^{-25} \times (T/300)^{-3.75} \times \exp(-494/T) \text{ cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$  and  $k_\infty(T) = 7.4 \times 10^{-11} \times (T/300)^{-0.69} \times \exp(-88/T) \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . The  $k_0$  value at low temperature from the fit is not precise due to the lack of experimental data; the measured rate constants at 155 K are already approaching the high pressure limit. Smith (2003) performed RRKM simulations in the 65–300 K range, that led to  $k_0(T) = 8.3 \times 10^{-26} \times (T/300)^{-4.28} \times \exp(-131/T) \text{ cm}^6 \text{ molecule}^{-2} \text{ s}^{-1}$  ( $F_c = 0.3$ ) with H<sub>2</sub> bath gas ( $k_0(\text{N}_2) = 0.7 \times k_0(\text{H}_2)$  Smith 2003) and  $k_\infty(T) = 8.1 \times 10^{-11} \times (T/300)^{-0.262} \times \exp(-37/T) \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ . Vuitton et al. (2012) have performed new calculations between 50 and 300 K, but their results are slightly overestimated with regard to the available experimental data. However, it is not possible to fit the entire temperature and pressure range with only one expression, and the results of Vuitton et al. (2012) are likely to be the most precise at low temperature and low density. We recommend their values with  $k_0$  scaled to fit the experimental data (using Troe expression in N<sub>2</sub> with  $F_c = 0.60$ ,  $N = 1$ ).

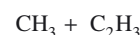


$\text{CH}_3 + \text{CH}_3 \rightarrow \text{C}_2\text{H}_6$ $k_0(T) = 2.4 \times 10^{-26} \times (T/300)^{-3.77} \times \exp(-61.6/T)$	2	0
$k_\infty(T) = 6.8 \times 10^{-11} \times (T/300)^{-0.359} \times \exp(-30.2/T)$	1.4	0
$k_r(T) = 2.96 \times 10^{-14} \times (T/300)^{-3.23} \times \exp(-74.5/T)$	10	0.

### C.19. CH<sub>3</sub> + C<sub>2</sub>H<sub>3</sub>



There is no barrier on the singlet surface, leading to the C<sub>3</sub>H<sub>6</sub> adduct (Thorn et al. 2000; Qu et al. 2010), and this reaction has been studied experimentally by Fahr et al. (1999), Thorn et al. (2000) and Stoliarov et al. (2000) between 1 and 200 Torr. The H atom abstraction reaction by CH<sub>3</sub> is likely to be a separate channel with a rate constant that has been measured on several previous occasions (Fahr et al. 1999; Stoliarov et al. 2000). The C<sub>3</sub>H<sub>6</sub> adduct can lead to C<sub>3</sub>H<sub>5</sub> + H formation, which means that adduct stabilization and bimolecular product formation compete. The results of Stoliarov et al. (2000) and Fahr et al. (1999) as a function of pressure lead to lower  $k_0$  values than  $k_{0,\text{CH}_3} + \text{CH}_3 \rightarrow \text{C}_2\text{H}_6(T)$ . We estimate  $k_{0,\text{CH}_3} + \text{C}_2\text{H}_3 \rightarrow \text{C}_3\text{H}_6(T) = 0.1 \times k_{0,\text{CH}_3} + \text{CH}_3 \rightarrow \text{C}_2\text{H}_6(T)$ . The open-exit channels from the adduct also prevent efficient radiative association, therefore we neglected radiative association in this case.

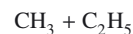


$\text{CH}_3 + \text{C}_2\text{H}_3 \rightarrow \text{C}_3\text{H}_6$ $k_0(T) = 2.4 \times 10^{-27} \times (T/300)^{-3.77} \times \exp(-61.6/T)$	10	100
$k_\infty(T) = 1.2 \times 10^{-10}$	2	100
$\text{CH}_3 + \text{C}_2\text{H}_3 \rightarrow \text{C}_2\text{H}_2 + \text{CH}_4$ $k(T) = 3.3 \times 10^{-11}$	1.4	100
$\text{CH}_3 + \text{C}_2\text{H}_3 \rightarrow \text{C}_3\text{H}_5 + \text{H}$ $k(T) = k_{\infty,\text{CH}_3} + \text{C}_2\text{H}_3 \rightarrow \text{C}_3\text{H}_6(T) - k_{\text{CH}_3} + \text{C}_2\text{H}_3 \rightarrow \text{C}_3\text{H}_6(T)$		

### C.20. CH<sub>3</sub> + C<sub>2</sub>H<sub>5</sub>



We recommend the Vuitton et al. (2012) values scaled to the Troe formula with  $F_c = 0.60$  and  $N = 1$ . We adopted the Baulch et al. (1992) value for the H atom abstraction channel by CH<sub>3</sub>.



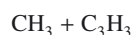
$\text{CH}_3 + \text{C}_2\text{H}_5 \rightarrow \text{C}_3\text{H}_8$ $k_0(T) = 4 \times 10^{-24} \times (T/300)^{-4.47} \times \exp(-95/T)$	4	0
$k_\infty(T) = 8.8 \times 10^{-11} \times (T/300)^{-0.61} \times \exp(-44.8/T)$	3	0
$k_r(T) = 3.8 \times 10^{-12} \times (T/300)^{-3.2} \times \exp(-148/T)$	10	0
$\text{CH}_3 + \text{C}_2\text{H}_5 \rightarrow \text{CH}_4 + \text{C}_2\text{H}_4$ $k(T) = 1.91 \times 10^{-12}$	2.5	100.

### C.21. CH<sub>3</sub> + C<sub>3</sub>H<sub>3</sub>

See equation above.

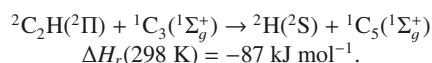
The H atom abstraction channel by CH<sub>3</sub> is very likely to have a barrier in the entrance valley, because the C-H bond strength in C<sub>3</sub>H<sub>3</sub> is high. Adduct formation occurs without a barrier with  $k_\infty(T) = 6.8 \times 10^{-11} \times \exp(+130/T) \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  (Knyazev & Slagle 2001). Fahr & Nayak (2000) studied this reaction at room temperature at 50 Torr using laser photolysis

of the precursors, GC/MS product analysis, and kinetic modelling. They identified the main products as approximately 60% of 1-butyne and 40% of 1,2-butadiene, which shows that at 50 Torr adduct stabilization is the main channel. Lee et al. (2003) found that the  $\text{H}_2\text{CC} + \text{C}_2\text{H}_4$  product channel is accessible through a TS localized 22 kJ mol<sup>-1</sup> below the reactants, leading to these bimolecular products at low pressure. Lee et al. (2003) also found that the other bimolecular exit channels involve TSs located above the entrance level. We estimated  $k_0$  and  $k_r$  using our “ $k_{\text{association}} - \rho$ ” semi-empirical model,  $k_0$  and  $k_r$  being then divided by 100 to take into account the open bimolecular exit channel. The  $\text{H}_2\text{CC}$  produced should isomerize quickly to  $\text{C}_2\text{H}_2$ .



$\text{CH}_3 + \text{C}_3\text{H}_3 \rightarrow \text{C}_4\text{H}_6$		
$k_0(T) = 8.1 \times 10^{-24} \times (T/300)^{-3.5}$	10	0
$k_{\infty}(T) = 6.8 \times 10^{-11} \times \exp(+130/T)$	2	0
$k_r(T) = 6.5 \times 10^{-14} \times (T/300)^{-1}$	30	0
$\text{CH}_3 + \text{C}_3\text{H}_3 \rightarrow \text{C}_2\text{H}_4 + \text{C}_2\text{H}_2$		
$k(T) = k_{\infty, \text{CH}_3 + \text{C}_3\text{H}_3 \rightarrow \text{C}_4\text{H}_6}(T) - k_{\text{CH}_3 + \text{C}_3\text{H}_3 \rightarrow \text{C}_4\text{H}_6}(T)$		

### C.22. $\text{C}_2\text{H} + \text{C}_3$

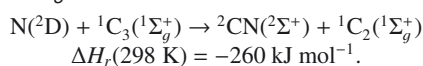


The  $\text{C}_2\text{H}$  radical is highly reactive, particularly with unsaturated hydrocarbons (Chastaing et al. 1998). There is therefore little doubt that the  $\text{C}_2\text{H} + \text{C}_3 \rightarrow \text{H} + \text{C}_5$  reaction has no barrier in the entrance valley. In the  $\text{C}_3$  geometry, the reactants correlate with  $2(\text{A}' + \text{A}'') \otimes 1\text{A}' = 2\text{A}' + 2\text{A}''$  states and the products correlate with  $2\text{A}' \otimes 1\text{A}' = 2\text{A}'$  states, i.e., there is an electronic degeneracy factor of  $\frac{1}{2}$ . Applying classical capture theory (Georgievskii & Klippenstein 2005) and considering only the isotropic dispersion term for long-range interaction, the capture rate constant is close to  $6 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  at 300 K, leading to a rate constant value of  $3 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$  taking into account the electronic degeneracy. This value is close to the rate constant of  $\text{C}_2\text{H} + \text{alkene}$  reactions (Chastaing et al. 1998). Considering the small variation of the rate constant for these reactions, we recommend a constant value in the 150–300 K range.

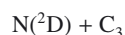


$\text{C}_2\text{H} + \text{C}_3 \rightarrow \text{H} + \text{C}_5$		
$k(150\text{--}300 \text{ K}) = 3.0 \times 10^{-10}$	3	0.

### C.23. $\text{N}({}^2\text{D}) + \text{C}_3$



There are no measurements of this reaction, but we considered the  $\text{N}({}^2\text{D}) + \text{C}_3$  reaction to be slightly faster than the  $\text{N}({}^2\text{D}) + \text{C}_2\text{H}_2$  reaction.  $\text{N}({}^2\text{D})$  reactions with closed-shell molecules, for which only scattered information exists, are particularly important for modeling Titan’s atmosphere and need to be studied in more detail.



$\text{N}({}^2\text{D}) + \text{C}_3 \rightarrow \text{CN} + \text{C}_2$		
$k(150\text{--}300 \text{ K}) = 5.0 \times 10^{-11}$	4	0.

## References

Adachi, H., & Basco, N. 1981, *Int. J. Chem. Kinet.*, 13, 367  
 Aguilera-Iparraguirre, J., Daniel Boese, A., Klopper, W., & Ruscic, B. 2008, *Chem. Phys.*, 346, 56

Aleksandrov, E., Arutyunov, V., Dubrovina, I., & Kozlov, S. 1980, *Kinet. Catal. Engl. Trans.*, 21, 1323  
 Atkinson, D. B., & Hudgens, J. W. 1999, *J. Phys. Chem. A*, 103, 4242  
 Baulch, D., Cobos, C., Cox, R., et al. 1992, *J. Phys. Chem. Ref. Data*, 21, 411  
 Baulch, D., Cobos, C., Cox, R., et al. 1994, *J. Phys. Chem. Ref. Data*, 23, 847  
 Baulch, D. L., Bowman, C. T., Cobos, C. J., et al. 2005, *J. Phys. Chem. Ref. Data*, 34, 757  
 Bergeat, A., & Loison, J.-C. 2001, *Phys. Chem. Chem. Phys.*, 3, 2038  
 Berman, M., Fleming, J., Harvey, A., & Lin, M. 1982, *Chem. Phys.*, 73, 27  
 Borrell, P., Cervenka, A., & Turner, J. W. 1971, *J. Chem. Soc. B*, 2293  
 Boullart, W., Devriendt, T., Borms, R., & Peeters, J. 1996, *J. Phys. Chem.*, 100, 998  
 Brouard, M., Macpherson, M. T., & Pilling, M. J. 1989, *J. Phys. Chem.*, 93, 4047  
 Brown, R., Lebreton, J.-P., & Waite, H. 2009, *Titan from Cassini-Huygens* (New York: Springer)  
 Butler, J., Fleming, J., Goss, L., & Lin, M. 1981, *Chem. Phys.*, 56, 355  
 Camilleri, P., Marshall, R., & Purnell, J. 1974, *J. Chem. Soc., Faraday Trans. 1*, 70, 1434  
 Canosa, A., Sims, I., Travers, D., Smith, I., & Rowe, B. 1997, *A&A*, 323, 644  
 Canosa-Mas, C. E., Frey, H. M., & Walsh, R. 1985, *J. Chem. Soc., Faraday Trans. 2: Mol. Chem. Phys.*, 81, 283  
 Carrasco, N., Hébrard, E., Banaszekiewicz, M., Dobrijevic, M., & Pernot, P. 2007, *Icarus*, 192, 519  
 Castiglioni, L., Bach, A., & Chen, P. 2006, *Phys. Chem. Chem. Phys.*, 8, 2591  
 Chang, K. W., & Graham, W. R. M. 1982, *J. Chem. Phys.*, 77, 4300  
 Chang, A. H. H., Mebel, A. M., Yang, X. M., Lin, S. H., & Lee, Y. T. 1998, *Chem. Phys. Lett.*, 287, 301  
 Chastaing, D., James, P., Sims, I., & Smith, I. 1998, *Faraday Discuss.*, 109, 169  
 Chastaing, D., James, P., Sims, I., & Smith, I. 1999, *Phys. Chem. Chem. Phys.*, 1, 2247  
 Chastaing, D., Picard, S. D. L., Sims, I. R., & Smith, I. W. M. 2001, *A&A*, 365, 241  
 Chen, F., Judge, D., & Wu, C. 2000, *Chem. Phys.*, 260, 215  
 Chen, C., Braams, B., Lee, D. Y., et al. 2011, *J. Phys. Chem. A*, 115, 6797  
 Clarke, D. W., & Ferris, J. P. 1995, *Icarus*, 115, 119  
 Cody, R. J., Payne, W. A., Thorn, R. P., et al. 2002, *J. Phys. Chem. A*, 106, 6060  
 Cody, R. J., Romani, P. N., Nesbitt, F. L., et al. 2003, *J. Geophys. Res.*, 108, 5119  
 Costes, M., Halvick, P., Hickson, K. M., Daugey, N., & Naulin, C. 2009, *ApJ*, 703, 1179  
 Coustenis, A., Salama, A., Schulz, B., et al. 2003, *Icarus*, 161, 383  
 Cui, J., Yelle, R., Vuitton, V., et al. 2009, *Icarus*, 200, 581  
 Daranlot, J., Hincelin, U., Bergeat, A., et al. 2012, *Proc. Natl. Acad. Sci. U. S. A.*, 109, 10233  
 Davis, S. G., Law, C. K., & Wang, H. 1999a, *Comb. Flame*, 119, 375  
 Davis, S. G., Law, C. K., & Wang, H. 1999b, *J. Phys. Chem. A*, 103, 5889  
 Deyerl, H.-J., Fischer, I., & Chen, P. 1999, *J. Chem. Phys.*, 111, 3441  
 Dobrijevic, M., Carrasco, N., Hébrard, E., & Pernot, P. 2008, *Planet. Space Sci.*, 56, 1630  
 Dobrijevic, M., Cavalié, T., Hébrard, E., et al. 2010, *Planet. Space Sci.*, 58, 1555  
 Dubnikova, F., & Lifshitz, A. 1998, *J. Phys. Chem. A*, 102, 3299  
 Eisfeld, W. 2006, *J. Phys. Chem. A*, 110, 3903  
 Fahr, A., & Nayak, A. 2000, *Int. J. Chem. Kinet.*, 32, 118  
 Fahr, A., Laufer, A., & Tardy, D. 1999, *J. Phys. Chem. A*, 103, 8433  
 Faravelli, T., Goldaniga, A., Zappella, L., et al. 2000, *Proc. Combust. Inst.*, 2601  
 Fernandes, R., Luther, K., & Troe, J. 2006, *J. Phys. Chem. A*, 110, 4442  
 Forst, W. 1991, *J. Phys. Chem.*, 95, 3612  
 Frisch, M. J., Trucks, G. W., Schlegel, H. B., et al. 2009, *Gaussian 09 Revision A.1*, Gaussian Inc. Wallingford CT  
 Galland, N., Caralp, F., Hannachi, Y., Bergeat, A., & Loison, J.-C. 2003, *J. Phys. Chem. A*, 107, 5419  
 Gannon, K., Blitz, M., Liang, C.-H., et al. 2010a, *Faraday Discuss.*, 147, 1  
 Gannon, K. L., Blitz, M. A., Liang, C. H., et al. 2010b, *J. Phys. Chem. A*, 114, 9413  
 Georgievskii, Y., & Klippenstein, S. J. 2005, *J. Chem. Phys.*, 122, 194103  
 Gingerich, K. A., Finkbeiner, H. C., & Schmude, R. W. 1994, *J. Am. Chem. Soc.*, 116, 3884  
 Goncher, S. J., Moore, D. T., Sveum, N. E., & Neumark, D. M. 2008, *J. Chem. Phys.*, 128, 114303  
 Gordon, S., Mulac, W., & Nangia, P. 1971, *J. Phys. Chem.*, 75, 2087  
 Gosavi, R. K., Safarik, I., & Strausz, O. P. 1985, *Can. J. Chem.*, 63, 1689  
 Goulay, F., Trevitt, A. J., Meloni, G., et al. 2009, *J. Am. Chem. Soc.*, 131, 993  
 Groß, C., Noller, B., & Fischer, I. 2008, *Phys. Chem. Chem. Phys.*, 10, 5196  
 Guadagnini, R., Schatz, G. C., & Walch, S. P. 1998, *J. Phys. Chem. A*, 102, 5857  
 Haider, N., & Husain, D. 1993a, *J. Chem. Soc., Faraday Trans.*, 89, 7  
 Haider, N., & Husain, D. 1993b, *J. Photochem. Photobiol. A – Chem.*, 70, 119  
 Halpern, J. A., Miller, G. E., Okabe, H., & Nottingham, W. 1988, *J. Photochem. Photobiol. A – Chem.*, 42, 63  
 Hanning-Lee, M. A., & Pilling, M. J. 1992, *Int. J. Chem. Kinet.*, 24, 271

- Harding, L. B., Georgievskii, Y., & Klippenstein, S. J. 2005, *J. Phys. Chem. A*, 109, 4646
- Harding, L., Klippenstein, S., & Georgievskii, Y. 2007, *J. Phys. Chem. A*, 111, 3789
- Harich, S., Lee, Y. T., & Yang, X. 2000a, *Phys. Chem. Chem. Phys.*, 2, 1187
- Harich, S., Lin, J. J., Lee, Y. T., & Yang, X. 2000b, *J. Chem. Phys.*, 112, 6656
- Hébrard, E., Dobrijevic, M., Bénilan, Y., & Raulin, F. 2006, *J. Photochem. Photobiol. C – Photochem. Rev.*, 7, 211
- Hébrard, E., Dobrijevic, M., Bénilan, Y., & Raulin, F. 2007, *Planet. Space Sci.*, 55, 1470
- Hébrard, E., Dobrijevic, M., Pernot, P., et al. 2009, *J. Phys. Chem. A*, 113, 11227
- Hébrard, E., Dobrijevic, M., Loison, J. C., Bergeat, A., & Hickson, K. M. 2012, *A&A*, 541, A21
- Herbst, E. 1982, *Chem. Phys.*, 65, 185
- Herbst, E., Roueff, E., & Talbi, D. 2010, *Mol. Phys.*, 108, 2171
- Ho, G. H., Lin, M. S., Wang, Y. L., & Chang, T. W. 1998, *J. Chem. Phys.*, 109, 5868
- Holbrook, K. A., Pilling, M. J., & Roberston, S. H. 1996, *Unimolecular reactions*, 2nd edn. (Chichester: John Wiley & Sons Ltd.)
- Hörst, S. M., Vuitton, V., & Yelle, R. V. 2008, *J. Geophys. Res. – Planet.*, 113, 10006
- Huggins, W. 1881, *Proc. R. Soc. Lond.*, 33, 1
- Hunter, E. P. L., & Lias, S. G. 1998, *J. Phys. Chem. Ref. Data*, 27, 413
- Husain, D., & Kirsch, L. 1971, *Trans. Faraday Soc.*, 67, 2025
- Irle, S., & Morokuma, K. 2000, *J. Chem. Phys.*, 113, 6139
- Jodkowski, J. T., Ratajczak, E., Fagerstrom, K., et al. 1995, *Chem. Phys. Lett.*, 240, 63
- Kaiser, E. W. 1993, *J. Phys. Chem.*, 97, 11681
- Kim, G.-S., Nguyen, T., Mebel, A., Lin, S., & Nguyen, M. 2003, *J. Phys. Chem. A*, 107, 1788
- Knyazev, V. D., & Slagle, I. R. 2001, *J. Phys. Chem. A*, 105, 3196
- Kovács, T., Blitz, M. A., & Seakins, P. W. 2010, *J. Phys. Chem. A*, 114, 4735
- Läuter, A., Lee, K., Jung, K., et al. 2002, *Chem. Phys. Lett.*, 358, 314
- Lavvas, P. P., Coustenis, A., & Vardavas, I. M. 2008, *Planet. Space Sci.*, 56, 27
- Le, T. N., Lee, H., Mebel, A. M., & Kaiser, R. I. 2001, *J. Phys. Chem. A*, 105, 1847
- Lebonnois, S., Toubian, D., Hourdin, F., & Rannou, P. 2001, *Icarus*, 152, 384
- Lee, S.-H., Lee, Y.-Y., Lee, Y. T., & Yang, X. 2003, *J. Chem. Phys.*, 119, 827
- Loison, J.-C., & Bergeat, A. 2009, *Phys. Chem. Chem. Phys.*, 11, 655
- Luo, C., Du, W.-N., Duan, X.-M., & Li, Z.-S. 2008, *ApJ*, 687, 726
- Magee, B. A., Waite, J. H., Mandt, K. E., et al. 2009, *Planet. Space Sci.*, 57, 1895
- Maksyutenko, P., Zhang, F., Gu, X., & Kaiser, R. I. 2010, *Phys. Chem. Chem. Phys.*, 13, 240
- Martin, J. M. L., & Taylor, P. R. 1995, *J. Chem. Phys.*, 102, 8270
- Matsugi, A., Suma, K., & Miyoshi, A. 2011, *J. Phys. Chem. A*, 115, 7610
- McKee, K., Blitz, M. A., Hughes, K. J., et al. 2003, *J. Phys. Chem.*, 107, 5710
- Mebel, A. M., & Kaiser, R. I. 2002, *Chem. Phys. Lett.*, 360, 139
- Mebel, A. M., Jackson, W. M., Chang, A. H. H., & Lin, S. H. 1998, *J. Am. Chem. Soc.*, 120, 5751
- Mebel, A. M., Kislov, V. V., & Hayashi, M. 2007, *J. Chem. Phys.*, 126, 204310
- Miller, J. A., & Klippenstein, S. J. 2003, *J. Phys. Chem. A*, 107, 2680
- Miller, J. A., Senosiain, J. P., Klippenstein, S. J., & Georgievskii, Y. 2008, *J. Phys. Chem. A*, 112, 9429
- Minsek, D. W., & Chen, P. 1993, *J. Phys. Chem.*, 97, 13375
- Monks, P. S., Nesbitt, F. L., Payne, W. A., et al. 1995, *J. Phys. Chem.*, 99, 17151
- Moninger, G., Förderer, M., Gürtler, P., et al. 2002, *J. Phys. Chem. A*, 106, 5779
- Moore, B., Giesen, T., Stutzki, J., et al. 2010, *A&A*, 521, L13
- Moses, J., Fouchet, T., Bézard, B., et al. 2005, *J. Geophys. Res. - Planet.*, 110, E08001
- Nakashima, N., & Yoshihara, K. 1987, *Laser Chemistry*, 7, 177
- Nguyen, T. L., Mebel, A. M., & Kaiser, R. I. 2001a, *J. Phys. Chem. A*, 105, 3284
- Nguyen, T. L., Mebel, A. M., Lin, S. H., & Kaiser, R. I. 2001b, *J. Phys. Chem. A*, 105, 11549
- Ni, C.-K., Huang, J. D., Chen, Y. T., Kung, A. H., & Jackson, W. M. 1999, *J. Chem. Phys.*, 110, 3320
- Oka, T., Thorburn, J. A., McCall, B. J., et al. 2003, *ApJ*, 582, 823
- Park, W. K., Park, J., Park, S. C., et al. 2006, *J. Chem. Phys.*, 125, 081101
- Peng, Z., Dobrijevic, M., Hébrard, E., Carrasco, N., & Pernot, P. 2010, *Faraday discussions*, 147, 137
- Peng, Z., Cailliez, F., Dobrijevic, M., & Pernot, P. 2012, *Icarus*, 218, 950
- Plessis, S., Carrasco, N., Dobrijevic, M., & Pernot, P. 2012, *Icarus*
- Qu, Y., Su, K., Wang, X., et al. 2010, *J. Comput. Chem.*, 31, 1421
- Raksit, A. B., & Bohme, D. K. 1983, *Int. J. Mass Spectrom. Ion Proc.*, 55, 69
- Rousselot, P., Arpigny, C., Rauer, H., et al. 2001, *A&A*, 368, 689
- Satyapal, S., & Bersohn, R. 1991, *J. Phys. Chem.*, 95, 8004
- Seakins, P., Robertson, S., Pilling, M., et al. 1993, *J. Phys. Chem.*, 97
- Seki, K., & Okabe, H. 1992, *J. Phys. Chem.*, 96, 3345
- Seki, K., He, M., Liu, R., & Okabe, H. 1996, *J. Phys. Chem.*, 100, 5349
- Selby, T. M., Meloni, G., Goulay, F., et al. 2008, *J. Phys. Chem. A*, 112, 9366
- Silva, R., Gichuhi, W. K., Kislov, V. V., et al. 2009, *J. Phys. Chem. A*, 113, 11182
- Sivaramakrishnan, R., Su, M. C., Michael, J. V., et al. 2011, *J. Phys. Chem. A*, 115, 3366
- Slagle, I. R., Gutman, D., Davies, J. W., & Pilling, M. J. 1988, *J. Phys. Chem.*, 92, 2455
- Smith, I. W. M. 1989, *Chem. Phys.*, 131, 391
- Smith, G. P. 2003, *Chem. Phys. Lett.*, 376, 381
- Stoecklin, T., & Clary, D. C. 1992, *J. Phys. Chem.*, 96, 7346
- Stoliarov, S. I., Knyazev, V. D., & Slagle, I. R. 2000, *J. Phys. Chem. A*, 104, 9687
- Stranges, D., Stemmler, M., Yang, X., et al. 1998, *J. Chem. Phys.*, 109, 5372
- Stranges, D., O'Keeffe, P., Scotti, G., Santo, R. D., & Houston, P. L. 2008, *J. Chem. Phys.*, 128, 151101
- Szpunar, D. E., Morton, M. L., Butler, L. J., & Regan, P. M. 2002, *J. Phys. Chem. B*, 106, 8086
- Takayanagi, T. 2006, *J. Phys. Chem. A*, 110, 361
- Takahashi, J., & Yamashita, K. 1996, *J. Chem. Phys.*, 104, 6613
- Teng, L., & Jones, W. E. 1972, *J. Chem. Soc., Faraday Trans. 1: Phys. Chem. Cond. Phases*, 68, 1267
- Thiesemann, H., MacNamara, J., & Taatjes, C. 1997, *J. Phys. Chem. A*, 101, 1881
- Thiesemann, H., Clifford, E. P., Taatjes, C. A., & Klippenstein, S. J. 2001, *J. Phys. Chem. A*, 105, 5393
- Thorn, R. P., Payne, W. A., Chillier, X. D. F., et al. 2000, *Int. J. Chem. Kin.*, 32, 304
- Thuillier, G., Floyd, L., Woods, T. D., et al. 2004, *Adv. Space Res.*, 34, 256
- Tonokura, K., & Koshi, M. 2000, *J. Phys. Chem. A*, 104, 8456
- Tsang, W. 1988, *J. Phys. Chem. Ref. Data*, 17, 887
- Tsang, W. 1991, *J. Phys. Chem. Ref. Data*, 20, 221
- van Harreveld, R., van Hemert, M. C., & Schatz, G. C. 2002, *J. Chem. Phys.*, 116, 6002
- van Hemert, M., & van Dishoeck, E. 2008, *Chem. Phys.*, 343, 292
- Vazquez, J., Harding, M. E., Gauss, J., & Stanton, J. F. 2009, *J. Phys. Chem. A*, 113, 12447
- Vereecken, L., & Peeters, J. 1999, *J. Phys. Chem. A*, 103, 5523
- Vereecken, L., Pierloot, K., & Peeters, J. 1998, *J. Chem. Phys.*, 108, 1068
- Vinatier, S., Bézard, B., Nixon, C. A., et al. 2010, *Icarus*, 205, 559
- Vuitton, V., Yelle, R. V., Lavvas, P., & Klippenstein, S. J. 2012, *ApJ*, 744, 11
- Wagner, H., & Zellner, R. 1972, *Ber. Bunsenges. Phys. Chem.*, 667
- Wakelam, V., Herbst, E., Loison, J.-C., et al. 2012, *ApJSS*, 199, 21
- Walch, S. P. 1995, *J. Chem. Phys.*, 103, 7064
- Wang, Z.-X., & Huang, M.-B. 1998, *Chem. Phys. Lett.*, 291, 381
- Wang, B., Hou, H., Yoder, L. M., Muckerman, J. T., & Fockenberg, C. 2003, *J. Phys. Chem. A*, 107, 11414
- Werner, H.-J., Knowles, P. J., Knizia, G., et al. 2010, *MOLPRO*, version 2010.1, a package of ab initio programs, see <http://www.molpro.net>
- Westlake, J. H., Waite, Jr., J. H., Mandt, K. E., et al. 2012, *J. Geophys. Res. - Planet.*, 117, 1003
- Whitten, G. Z., & Rabinovitch, B. S. 1963, *J. Chem. Phys.*, 38, 2466
- Whytock, D. A., Payne, W. A., & Stief, L. J. 1976, *J. Chem. Phys.*, 65, 191
- Wilson, E. H., & Atreya, S. K. 2004, *J. Geophys. Res. - Planet.*, 109, E06002
- Woon, D. E., & Park, J.-Y. 2009, *Icarus*, 202, 642
- Zhang, X., Ajello, J. M., & Yung, Y. L. 2010, *ApJ*, 708, L18
- Zhao, Y.-L., Laufer, A. H., Halpern, J. B., & Fahr, A. 2007, *J. Phys. Chem. A*, 111, 8330
- Zhu, R., Xu, Z., & Lin, M. 2004, *J. Chem. Phys.*, 120, 6566