

Features of Afterbody Radiative Heating for Jupiter Entry

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In this extended abstract, a preliminary analysis of a trajectory-based heating and ablation study in the afterbody of a Jovian entry probe is presented. The radiative flux in the afterbody impinging on the backshell of the probe is investigated with and without the presence of ablation product gas. The heritage tangent-slab approximation for radiative heating is shown to underpredict the radiative heating by as much as 50% in the afterbody making the high-fidelity, yet computationally expensive, ray-tracing approach necessary to accurately predict the radiative heating predictions. An investigation into the merits of employing the ray-tracing approach for the prediction of the divergence of radiative flux in the afterbody flow field will be presented in the final manuscript. Nonequilibrium effects in the afterbody region will be investigated in the final manuscript including the impact of electron-ion recombination rates. To bound the problem based on the best available knowledge, an uncertainty analysis will be performed. Sources of uncertainty are identified in the ablation modeling, radiation modeling, flowfield kinetics, and thermodynamic properties of select species.

I. Introduction

Entry into the Jovian atmosphere is the most severe environment ever experienced by a planetary probe or vehicle. On 7 December 1995, the Galileo Probe deceleration module entered Jupiter's atmosphere at a relative velocity of 47.4 km/s and experienced a nearly 250 g_e deceleration from Mach 50. The forebody carbon phenolic heatshield experienced an estimated peak heating rate of 30 kW/cm² and a heat load of 300 kJ/cm². During decent, forebody recession was measured and a number of previous studies have made attempts to replicate the flight data [1–3], though many issues still remained. More recently, Erb et al. [4] conducted an in-depth analysis into the forebody, providing the most accurate prediction of heating and recession to-date.

Aside from the forebody heating, another issue is the afterbody heating, which is the focus of the current study. A number of previous studies have investigated the afterbody heating environments for entry into other planets and have found radiative heating to be the dominate factor in this region. Johnston et al. [5] studied the afterbody radiative heating for an Earth entry scenario and found that, among others, simulating the presence of ablation product gas and employing the high-fidelity ray-tracing approach for predicting the radiative flux was necessary for accurately simulating the physics of the problem. Likewise, Brandis et al. [6] showed that radiative heating in the aerothermal environment for a Mars entry scenario can be greater than the convective heating while also warning of the limitations of employing a tangent-slab approach for determining radiative heating. Furthermore, Johnston et al. [7] recently found that shock-layer radiation in the afterbody flow was the dominate heating source on a vehicle backshell during Titan entry. A parametric uncertainty analysis showed that while emission from the shock was sensitive to the chemical kinetics, the afterbody flow had little influence on the radiative heating.

The current study aims to leverage the available data from the study by Erb et al. [4] and analyze the important radiative features in the afterbody of a Jupiter entry probe. An investigation into the radiative emissions from the flowfield chemical composition, with and without ablative product gas, will be conducted to determine the impact of coupling ablation in a Jupiter entry scenario. A comparison of radiative heating predictions using the computationally efficient tangent-slab and the high fidelity ray-tracing will be presented. Other modeling choices, such as using ray-tracing for the calculations of the divergence radiative flux in the flowfield, electron-ion recombination rates, and state-specific H modeling, will be investigated and their relative impact will be quantified. Additionally, the impact of uncertainty in many model parameters on afterbody heating will be quantified and their individual impact assessed to guide future investments in uncertainty reduction. Sources of uncertainty are identified in the ablation modeling, radiation modeling, flowfield kinetics, and thermodynamic properties of select species. The results from this analysis will provide recommended practices for future designs and analyses of Jupiter entry missions.

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The next section outlines the analysis approach used in the current study. Section III provides an overview of the previous work which the current study continues. Section IV presents the preliminary results for the afterbody aerothermal heating response. Finally, section V presents the addition that will be made in the final manuscript.

II. Simulation Parameters and Tools

The flowfield is modeled in this work using the Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) software, which is a finite-volume, Navier-Stokes flow solver [8]. This solver uses a second-order, upwind, discretization scheme with Roe's flux-difference splitting scheme and Yee's Symmetric Total Variation Diminishing (STVD) formulation of the inviscid flux. The flowfield is assumed to be steady state at each simulated trajectory point. The forebody boundary layer is modeled as fully-turbulent, employing the Cebeci-Smith algebraic turbulence model [9]. Both of these assumptions are consistent with previous studies [3, 4, 10, 11]. The wake flow is modeled as laminar as previous studies of backshell heating on planetary entry bodies with similar shape have shown that the primary heating source is radiation to the backshell surface, which is independent of the boundary layer state [5, 12]. The gas properties are modeled with a one temperature chemical nonequilibrium assumption. The Jovian atmosphere is modeled with 13.6% helium and 86.4% hydrogen, by volume.

The coupled ablation flowfield is modeled using the following 21 species: H_2 , H , He , H^+ , He^+ , e^- , C , C_2 , C_3 , C_4 , C_5 , C^+ , CH , C_2H , CH_2 , C_2H_2 , O , O_2 , O^+ , CO , and CO_2 . The rate model used in this study is presented in the appendix in Table A1. The char rate is computed assuming chemical equilibrium between the carbon char and the gas at the wall [8, 13]. Steady-state ablation is assumed to compute the pyrolysis rate and heat conducted into the surface, as discussed further in section III. The elemental mass fractions assumed for the virgin carbon phenolic are 0.92, 0.06, and 0.02 for carbon, oxygen, and hydrogen, respectively. These are consistent with previous studies. Steady-state equilibrium ablation is applied. Further details of this model, including justification for the steady-state approximation, will be provided in the final manuscript.

The radiation is modeled using the High-Temperature Aerothermodynamic Radiation (HARA) code [14, 15]. A ray-tracing approach [16] is applied for computing the radiative heating, while the tangent-slab approach is used to compute the divergence of the radiative flux, unless noted otherwise. The radiation mechanisms activated for the current study are presented in the appendix in Table A2. Coupled radiation is modeled in the flowfield energy equations. The uncertainties in this table will be discussed in the final manuscript.

III. Data Leveraged for Current Study

The current study is a continuation of a detailed investigation of the Galileo probe forebody conducted by Erb et. al. [4]. The forebody shape is an axisymmetric sphere-cone with a 22.2 cm nose radius and a 44.86 degree half angle frustum region while the backshell is 55.2 cm sphere. The thermal protection on the nose cone of the descent module was a chopped-molded carbon phenolic material while the frustum region employed tape-wrapped carbon phenolic; the backshell heat shield was phenolic nylon. The thermal protection system (TPS) material on the nose cone was 14.6 cm thick at the stagnation point and decreased to 5.1 cm at the sphere-cone transition location. From there, the TPS thickness increased to 5.4 cm at the shoulder. The backshell heatshield was approximately 2 cm thick along the probe centerline and tapered down to approximately 1 cm near the shoulder. Due to the narrow margins afforded to the backshell heatshield it is vital to accurately predict the heating this region will experience.

The recession history of the forebody carbon phenolic heatshield was recorded with 10 analog resistance ablation detector (ARAD) sensors embedded in the forebody TPS. Additionally, four resistance thermometers were bonded to the inside of the structure to monitor the internal temperature [17, 18]. Locations of these sensors are shown in Fig. 1b. The ARAD data were successfully transmitted from the Galileo orbiter back to Earth after the planetary entry. Using the flight ARAD measurement data, Milos [17, 18] reconstructed the recession profile of the forebody heatshield. However, the temperature data were overwritten during the peak heating phase of the trajectory. As such, the only way to validate if afterbody flow field physics are accurately being predicted is to match the forebody recession measured by the flight data as accurately as possible.

In the work by Erb et. al. [4], convective heating was shown to be a significant contributor to total surface heating away from the stagnation-point, particularly later in the trajectory. Inclusion of a moving wall boundary due to ablation, multi-component diffusion modeling, and ray-tracing significantly improve baseline model accuracy when compared to the flight recession data. The uncertainty analysis provided in this study highlights the impact of variability in many physical modeling parameters, including those related to the flowfield rate model, radiation modeling, and heats of

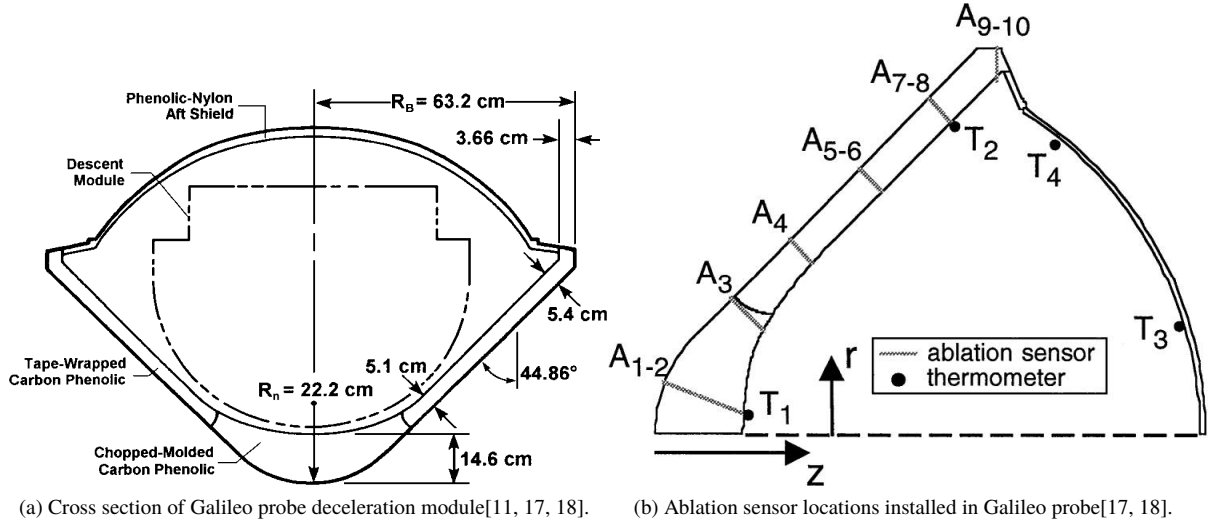


Fig. 1 Galileo probe deceleration module overview[17].

formation of carbon-based species. Overall, the modeling approaches discussed in their paper outline an accurate approach to predicting TPS recession during similar entry conditions. The results of their study are shown in Fig. 2. The current study will leverage the available data generated from the forebody analysis to provide accurate predictions of the afterbody aerothermal environment.

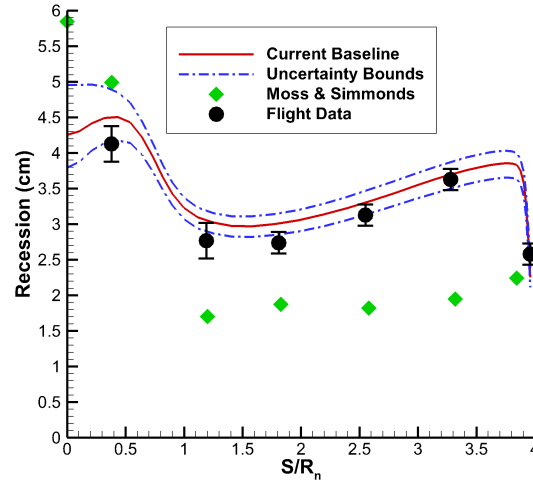


Fig. 2 Predicted recession with uncertainty compared to flight data.

IV. Preliminary Results

This section presents the preliminary results for the aerothermal analysis at nine trajectory points from the reconstructed Jovian atmosphere [17] seen in Table 1. First, a comparison between the heating for an ablating and non-ablating surface is made. And secondly, a comparison between tangent-slab and ray-tracing is presented. The preliminary backshell radiation results are presented for both cases.

Table 1 Reconstructed Jovian atmosphere and trajectory data.

Time (s)	Altitude (km)	Velocity (m/sec)	Density (kg/m ³)	Pressure (bars)	Temperature (K)
40.35	190	46951.0	3.16e-5	1.84e-4	165.0
43.79	170	46256.0	7.03e-5	4.12e-4	165.8
47.36	150	44813.0	1.49e-4	8.90e-4	168.9
49.21	140	43531.0	2.27e-4	1.32e-3	164.3
51.16	130	41591.0	3.49e-4	1.99e-3	160.8
53.23	120	38617.0	5.56e-4	3.02e-3	153.6
55.52	110	34296.0	8.36e-4	4.62e-3	156.6
58.19	100	28440.0	1.23e-3	7.00e-3	160.6
61.57	90	21342.0	1.85e-3	1.05e-2	160.1

A. Effects of Ablation

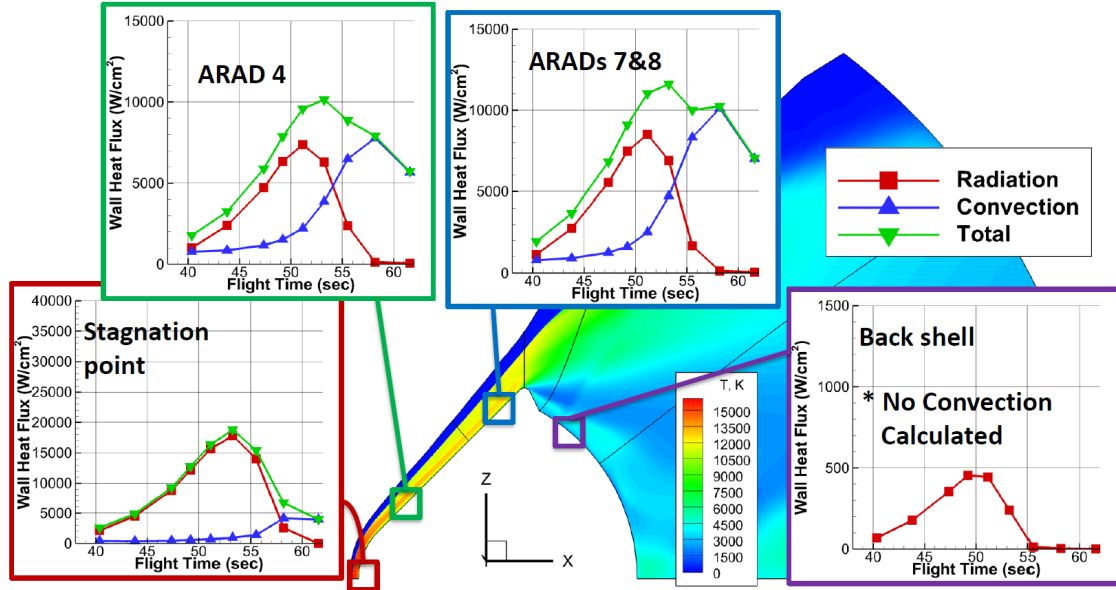
To investigate the impact of ablation on Galileo probe heating, Figures 3a and 3b compare the heating for an ablating and non-ablating surface, respectively. These figures show that ablation significantly reduces the forebody heating through the trajectory, with a reduction of nearly 50% for the peak heating case at 53.23 s. This difference is less prominent on the conical frustum region, where the ablation reduces the heating by less than 20%. While the effect of ablation on convective heating is considered for most reentry systems, the impact of ablation products on radiation is often not considered.

There are several reasons the large difference between ablating and non-ablating heating for Galileo. For example, the non-ablating simulations lack the strongly absorbing carbonaceous species produced from the ablating surface. Matsuyama et al. [10] shows that a decrease in the cross section of C₃ increases the radiative heat flux. The lack of ablative gases impacts the convective heating as the energy that would otherwise facilitate dissociation reactions near the wall is permitted to transport into the probe surface. This increases the convective heat flux through to the peak heating trajectory point.

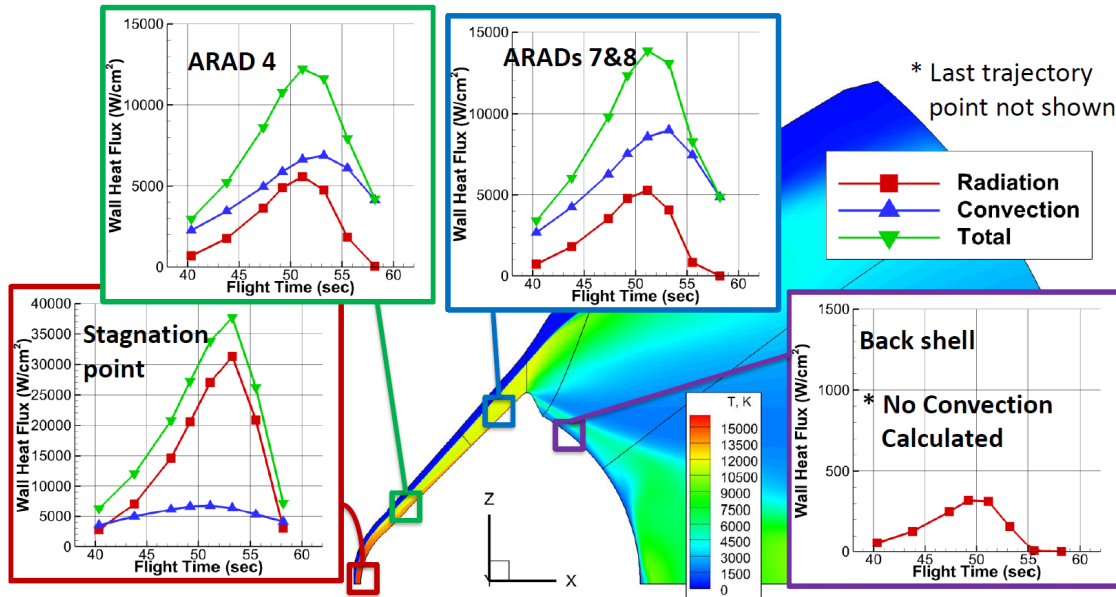
The preliminary backshell radiation results can be seen in these figures as well. A point was chosen on the backshell to apply the ray tracing technique in both the ablative and non-ablative cases. As is seen in the figures, the radiative heating is roughly 25% greater for the ablating case, which is the direct result of increased radiative emission from ablation gases. This conclusion that ablation products impact the radiative heating on the backshell surface is consistent with previous work regarding super orbital entry velocity into Earth's atmospheres [5]. A more detailed investigation into the effects of ablation on afterbody heating will be presented in the final manuscript. Spectrum plots will show that emissions from ablation products contribute greatly to the radiative heating and thus cannot be neglected for a Jupiter entry scenario.

B. Ray-Tracing vs. Tangent-Slab Approximation

The radiation code, HARA, uses a tangent-slab approximation [19] for computing the radiative flux and its divergence; however, Johnston and Brandis [5] showed that the tangent-slab approximation can cause the afterbody radiation to be over predicted in the afterbody region. Figure 4 shows the difference in radiative heating profile at select points on the vehicle for the tangent-slab approach versus a full ray-tracing approach [16]. In the forebody, the tangent-slab approach only slightly over predicts the radiative heating. However, in the afterbody, the radiative heat flux is significantly under predicted with tangent-slab by more than a factor of two at peak heating. While the tangent-slab approach is less computationally demanding, the approach in this study will be to use the coupled ray-tracing procedure, as performed by Erb et al.[4], to improve the accuracy of the analysis. By utilizing the heating predictions from the high fidelity ray-tracing, the heating response, including re-radiation, can be more accurately predicted.



(a) Coupled radiation and ablation.



(b) Coupled radiation (no ablation).

Fig. 3 Galileo entry trajectory heating profile.

V. Additions to Final Manuscript

There are several additions intended for the final manuscript. Backshell radiation predictions resulting from a ray tracing technique over the entire surface will be presented and discussed in great detail with regards to the source of the backshell radiation and the impact of ablation products. New insights into the heat loads experienced on the aft structure can be interpreted from these results and can be used for future TPS design. The shape change of the forebody heat shield could potentially alter the flow structure and effect the resultant heat load in the afterbody. As such, the final manuscript will include results of modifying the forebody heat shield geometry based on the predicted recession profile. Other modeling approaches, such as using ray-tracing for the calculations of the divergence radiative flux in the flowfield, nonequilibrium effects in the afterbody region such as electron-ion recombination rates, and state-specific H modeling, will be investigated and their relative impact will be quantified. Finally, sources of uncertainty are identified

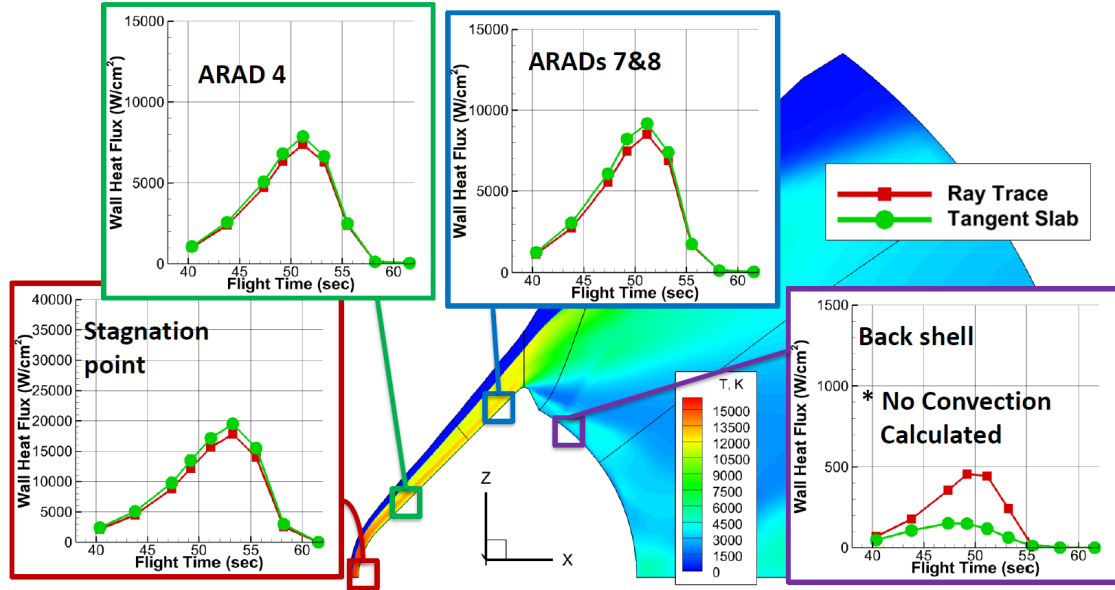


Fig. 4 Comparison of ray-tracing and tangent-slab backshell radiative heat flux calculations.

in the ablation modeling, radiation modeling, flowfield kinetics, and thermodynamic properties of select species. As such, to provide a robust prediction of the afterbody heating response, a detailed uncertainty quantification study similar to those performed in previous works [12, 20, 21] will be included in the final manuscript.

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Appendix

Table A1 Flowfield rate model.

#	Reaction	$A_{f,i} \left(\frac{cm^3}{mol-s} \right)$	$n_{f,i}$	$D_{f,i}(K)$	$T_{f,i}$	Third Body, M	Uncertainty Multiplier
Dissociation Reactions							
1	$C_2 + M \leftrightarrow 2C + M$	4.500e+18	-1.00	7.1500e+04	T_a	All	0.1, 10.0
2	$C_2H + M \leftrightarrow C_2 + H + M$	1.700e+35	-5.16	5.7400e+04	T_a	All	0.1, 10.0
3	$C_2H_2 + M \leftrightarrow C_2H + H + M$	4.000e+16	0.00	5.4000e+04	T_a	All	0.1, 10.0
4	$C_3 + M \leftrightarrow C_2 + C + M$	1.680e+21	-1.50	8.7740e+04	T_a	H, C, N, O	0.1, 10.0
		8.400e+20	-1.50	8.7740e+04	T_a	others	0.1, 10.0
5	$C_5 + M \leftrightarrow C_3 + C_2 + M$	4.000e+14	0.00	8.1549e+04	T_{ir}	All	0.1, 10.0
6	$CH + M \leftrightarrow C + H + M$	1.900e+14	0.00	3.3717e+04	T_a	All	0.5, 2.0
7	$CO + M \leftrightarrow C + O + M$	1.800e+21	-1.00	1.2900e+05	T_a	H, C, N, O	0.25, 1.5
		1.200e+21	-1.00	1.2900e+05	T_a	others	0.25, 1.5
8	$CO_2 + M \leftrightarrow CO + O + M$	1.380e+22	-1.50	6.3275e+04	T_a	H, C, N, O	0.1, 1.0
		6.900e+21	-1.50	6.3275e+04	T_a	others	0.1, 1.0
9	$H_2 + M \leftrightarrow 2H + M$	8.500e+19	-1.10	5.2335e+04	T_a	H	0.1, 10.0
		9.000e+14	0.00	4.8400e+04	T_a	others	0.5, 2.0
10	$O_2 + M \leftrightarrow 2O + M$	1.000e+22	-1.50	5.9360e+04	T_a	H, C, O, N	0.5, 1.5
		2.000e+21	-1.50	5.9360e+04	T_a	others	0.5, 1.5
11	$CH_2 + M \leftrightarrow C + H_2 + M$	1.300e+14	0.00	2.9700e+04	T_a	All	0.5, 2.0
12	$CH_2 + M \leftrightarrow CH + H + M$	4.000e+15	0.00	4.1800e+04	T_a	All	0.5, 2.0
13	$He + M \leftrightarrow He^+ + e^- + M$	1.330e+13	0.50	2.8516e+05	T_a	All	0.1, 10.0
Exchange Reactions							
14	$C_2 + C_2H_2 \leftrightarrow 2C_2H$	1.100e+14	-0.38	6.8700e+03	T_{ir}		0.1, 10.0
15	$C_2H + H \leftrightarrow C_2 + H_2$	1.600e+13	0.15	1.4600e+04	T_{ir}		0.1, 10.0
16	$C_3 + C \leftrightarrow C_2 + C_2$	6.000e+11	1.07	1.6500e+04	T_{ir}		0.1, 10.0
17	$CH + C \leftrightarrow C_2 + H$	2.000e+14	0.00	0.0000	T_{ir}		0.1, 10.0
18	$CH + CO \leftrightarrow C_2H + O$	2.500e+10	0.67	3.9000e+04	T_{ir}		0.1, 10.0
19	$CO + C \leftrightarrow C_2 + O$	2.000e+17	-1.00	5.8000e+04	T_{ir}		0.1, 10.0
20	$CO + C_2 \leftrightarrow C_3 + O$	1.000e+12	0.00	4.1200e+04	T_{ir}		0.1, 10.0
21	$CO + O \leftrightarrow O_2 + C$	3.900e+13	-0.18	6.9200e+04	T_{ir}		1.0, 10.0
22	$CO_2 + O \leftrightarrow O_2 + CO$	2.710e+14	0.00	3.3797e+04	T_{ir}		0.1, 10.0
23	$H + C_2H_2 \leftrightarrow C_2H + H_2$	1.000e+16	-0.50	1.5500e+04	T_{ir}		0.1, 10.0
24	$H + CO \leftrightarrow CH + O$	6.700e+14	0.15	8.8470e+04	T_{ir}		0.1, 10.0
25	$H_2 + C \leftrightarrow CH + H$	4.000e+14	0.00	1.1700e+04	T_{ir}		0.1, 10.0
26	$CH_2 + H \leftrightarrow CH + H_2$	6.030e+12	-0.00	-900	T_{ir}		0.1, 10.0
Ionization Reactions							
27	$C + e^- \leftrightarrow C^+ + e^- + e^-$	3.900e+33	-3.78	1.3070e+05	T_{ve}		0.5, 10.0
28	$H + e^- \leftrightarrow H^+ + e^- + e^-$	2.200e+30	-2.80	1.5780e+05	T_{ve}		0.05, 10.0
29	$O + e^- \leftrightarrow O^+ + e^- + e^-$	3.900e+33	-3.78	1.5850e+05	T_{ve}		0.1, 10.0

Table A2 Radiation mechanisms.

Species	Mechanism	Spectral range (eV)	Uncertainty
C	Lines	0-18	+/- 20%
	Photoionization	0-18	+/- 20%
H	Lines	0-18	+/- 1%
	Photoionization	0-18	+/- 20%
CO	$4 + (A^1\Pi - X^1\Sigma)$	6.0-10.0	+/- 40%
	$3 + (b^3\Sigma - a^3\Pi)$	3.0-5.0	+/- 50%
	$B^1\Sigma - X^1\Sigma+$	10.2-11.4	+/- 50%
	$C^1\Sigma - X^1\Sigma$	10.0-12.2	+/- 50%
	$E^1\Pi - X^1\Sigma$	11.2-11.9	+/- 50%
	Angstrom ($B^1\Sigma - A^1\Pi$)	0.5-3.2	+/- 50%
	Asundi ($a^3\Sigma - a^3\Pi$)	0.1-3.5	+/- 50%
	Triplet ($d^3\Delta - a^3\Pi$)	0.1-4.0	+/- 50%
	Infrared ($X^1\Sigma - X^1\Sigma$)	0.1-1.0	+/- 50%
	Swan ($d^3\Pi_g - a^3\Pi_u$)	1.2-3.2	+/- 50%
C ₂	Ballik-Ramsay ($b^3\Sigma_g^- - a^3\Pi_u$)	0.4-2.5	+/- 50%
	Phillips ($A^1\Pi_u - X^1\Sigma_g^+$)	1.0-3.5	+/- 50%
	Mulliken ($D^1\Sigma_u^+ - X^1\Sigma_g^+$)	5.0-6.2	+/- 50%
	Des.-D'Aram. ($C^1\Pi_g - A^1\Pi_u$)	1.8-4.4	+/- 50%
	Fox-Herzberg ($e^3\Pi_g - a^3\Pi_u$)	2.5-6.2	+/- 50%
H ₂	Lyman ($B^1\Sigma_u^+ - X^1\Sigma_g^+$)	10.0-14.0	+/- 10%
H ₂	Werner ($C^1\Pi_u - X^1\Sigma_g^+$)	8.1-12.3	+/- 20%
C ₃	Swings ($d^3\Pi_g - a^3\Pi_u$)	2.5-4.1	-1 om
	UV ()	7.3-10.0	-1 om
C ₂ H	Continuum	4.6-6.5	+/- 1 om