Neutral Heating Efficiency in the Dayside Martian Upper Atmosphere

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Abstract

The neutral heating efficiency is commonly defined as the fraction of the solar extreme ultraviolet and X-ray energy absorbed by a planetary atmosphere that ends up as local heat. It is a crucial parameter that determines the upper atmospheric temperature and, consequently, the thermal escape rate on both solar system bodies and exoplanets. Combining the Mars Atmosphere and Volatile Evolution measurements of a variety of atmospheric parameters, we calculate the neutral heating efficiency in the dayside Martian upper atmosphere based on a complicated network of microscopic processes, including photon and photoelectron impact processes, as well as exothermic chemical reactions. Our calculations indicate that neutral heating is mainly contributed by photon impact at low altitudes, of which the bulk occurs via CO2 photodissociation, and exothermic chemistry at high altitudes, of which the bulk occurs via O2 and CO2 dissociative recombination. Collisional quenching of metastable neutrals and ions, which is of great interest in the literature, contributes to local heating by no more than 10% at all altitudes. In the dayside median sense, the neutral heating efficiency remains roughly constant at 20% from 150 to 200 km and increases steadily to 32% near 250 km. The heating efficiency at 150–200 km shows a weak correlation with solar zenith angle, increases modestly with increasing solar activity, and is clearly enhanced over strong crustal magnetic anomalies. Throughout the study, strict local heating is assumed, but nonlocal heating does not affect our results near or below 200 km.

1. Introduction

The solar extreme ultraviolet (EUV) and X-ray radiation deposits a substantial amount of energy in a planetary upper atmosphere via various physical and chemical processes initiated by the photoionization and photodissociation of atmospheric neutrals (Fox et al. 2008, and references therein). Photoelectrons produced by solar EUV/X-ray ionization (e.g., Coates et al. 2011) interact with ambient neutrals via both elastic and inelastic collisions, of which the latter is manifested as a variety of channels, such as collisional excitation, dissociation, and ionization (e.g., Bhardwaj & Micheal 1999; Bhardwaj & Jain 2009; Bhardwaj & Mukundan 2015). Solar radiative inputs also initiate a complicated network of photochemistry in the upper atmosphere, including ion-neutral chemistry, neutral-neutral chemistry, and dissociative recombination (DR; e.g., Fox & Sung 2001; Lavvas et al. 2008a, 2008b).

During the above processes, a fraction of the solar EUV/X-ray energy absorbed by the atmosphere ends up as the local thermal energy causing atmospheric heating (e.g., Stolarski et al. 1975; Stolarski 1976). Such a fraction is frequently termed the neutral heating efficiency (Torr et al. 1980a), a key parameter of broad aeronomical and astronomical interests that determines quantitatively how the atmospheric thermal structure responds to solar EUV/X-ray energy inputs (e.g., Forbes et al. 2008; Krasnopolsky 2010; Jain et al. 2015; Bougher et al. 2017; Zurek et al. 2017). The neutral heating efficiencies in the upper atmospheres of various planetary bodies have been evaluated in numerous previous works. On the Earth, Torr et al. (1980b) found the neutral heating efficiency to vary from 50% near 175 km with maximum solar EUV energy deposition to 10% near 400 km. The first calculation of the neutral heating efficiency in the Martian upper atmosphere was made by Fox & Dalgarno (1979a, 1979b), who obtained values between 16% and 27% depending on the choice of the percentage radiative energy loss. For Venus, Hollenbach et al. (1985) obtained a heating efficiency of 10%–15% including strong eddy cooling, while Dickinson & Bougher (1986) obtained a heating efficiency of 9.5% without eddy cooling. Later studies of the Earth (Roble et al. 1987), Mars (Fox et al. 1996), Venus (Fox 1988; Chassefière 1996), and Titan (Fox & Yelle 1991; De La Haye et al. 2008) led to variable heating efficiencies from 15% to 30%. Waite et al. (2005) estimated a relatively large neutral heating efficiency of 53% for solar EUV energy deposition in the upper atmosphere of Jupiter. Similar studies have also been made on exoplanets, reporting altitude-dependent neutral heating efficiencies of 15%–40% (Yelle 2004; Shematovich et al. 2014). The choice of the heating efficiency is critical for determining the thermal escape rate on solar system bodies (e.g., Watson et al. 1981; Chassefière 1996; Cui et al. 2008; Strobel 2008a, 2008b; Yelle et al. 2008) and exoplanets (e.g., Lammer et al. 2003; Baraffe et al. 2004; Lecavelier des Etangs et al. 2004; Hubbard et al. 2007a, 2007b; Lecavelier des Etangs 2007; Davis & Wheatley 2009; Lissauer et al. 2011; Sanz-Forcada et al. 2011; Kawahara et al. 2013; Lanza 2013; Wu & Lithwick 2013).

This study is intended for a state-of-the-art evaluation of the neutral heating efficiency in the dayside Martian upper atmosphere and its variability. To be distinguished from all previous works that were exclusively based on numerical
calculations, the results presented here are constrained as much as possible by realistic data, which helps to reduce various sources of model uncertainty to minimum levels. Such an effort relies on the simultaneous measurements of a number of controlling parameters required for accurately calculating the neutral heating efficiency, which only become available with the arrival of the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft on the red planet (Jakosky et al. 2015). These controlling parameters include the solar EUV/X-ray irradiance, measured by the Extreme Ultraviolet Monitor (EUVM; Eparvier et al. 2015); the neutral and ion atmospheric densities, measured by the Neutral Gas and Ion Mass Spectrometer (NGIMS; Mahaffy et al. 2015b); the differential energetic electron intensity, measured by the Solar Wind Electron Analyzer (SWEA; Mitchell et al. 2016); and the thermal electron temperature, measured by the Langmuir Probe and Waves (LPW; Andersson et al. 2015).

The layout of the paper is as follows. In Section 2, we describe the methodology used for calculating the neutral heating efficiency in the dayside Martian upper atmosphere, emphasizing our treatments of photon and photoelectron impact processes, exothermic chemistry, and collisional quenching. In Section 3, we apply our methodology to the multi-instrument MAVEN data set accumulated on the dayside of Mars and present the detailed results for one specific MAVEN orbit. This is followed by Section 4 where we present the vertical, solar zenith angle (SZA), and solar cycle variations of the neutral heating efficiency, as well as the possible impact of crustal magnetic fields. Finally, we discuss the results in Section 5 and provide concluding remarks in Section 6. The neutral heating efficiency and its variations inferred from the MAVEN data are important for a proper understanding of the thermal structure in the dayside Martian upper atmosphere (e.g., Forbes et al. 2008; Krasnopolsky 2010; Bouger et al. 2017; Stone et al. 2018).

2. Methodology

The solar EUV/X-ray radiative energy is deposited in the dayside Martian upper atmosphere via a number of processes (Fox et al. 2008, and references therein). (1) Solar photons and photoelectrons are able to dissociate or ionize ambient neutrals, releasing a portion of the input energy as kinetic energies of dissociative fragments, which are thermalized rapidly. (2) Photoelectrons excite ambient neutrals electronically, vibrationally, or rotationally through a variety of channels, with the excitation energy released as local heat via processes such as collisional quenching and predissociation. (3) Exothermic chemical reactions serve as an important source of local heating depending on the enthalpy differences between reactants and products. It is noteworthy that processes (1) and (3) also likely involve the production of metastable neutrals or ions (e.g., McNeal et al. 1972; Yee et al. 1990; Gérard et al. 2013), which may strengthen local heating considerably via collisional quenching (e.g., Fox 1988; De La Haye et al. 2008).

In this study, we determine the neutral heating efficiency, denoted as $\epsilon$, in the Martian upper atmosphere as

$$\epsilon = \frac{H_{ph} + H_{phe} + H_{chem}}{H_{sol}}, \quad (1)$$

where $H_{ph}$, $H_{phe}$, and $H_{chem}$ represent the local heating rates via photodissociation and photoionization, photoelectron impact inelastic collisions, and exothermic chemistry, respectively, and $H_{sol}$ is the solar energy deposition rate calculated using the photoabsorption cross-section data of Heays et al. (2017) and a combined CO$_2$ and O background atmosphere (Mahaffy et al. 2015a). The calculations of various heating sources in Equation (1) are detailed below.

2.1. Photon Impact Processes

To evaluate $H_{ph}$ in Equation (1), we need to include the contributions from both photodissociation and photoionization. For the former, we consider only the most dominant dissociative channel, CO$_2$ + $h\nu$ $\rightarrow$ CO + O, assuming both products in their ground states, CO($3S^\pi$) and O($3P$). The CO$_2$ photodissociation cross sections of Heays et al. (2017) are used. The energy released as local heat is set as the incident photon energy in excess of the respective dissociation threshold of 5.453 eV (Shaw et al. 1995). In reality, the fragments of CO$_2$ dissociation could be in various excited states, such as O($3S$) (Lawrence 1972) and CO($3\Pi$) (Phillips et al. 1977), but such a complexity is ignored in our calculation because available information on the yields of different excited states is extremely limited.

The calculation of the neutral heating rate due to photoionization is more complicated, involving both CO$_2$ and O. For CO$_2$, we consider several important channels, including the production of CO$_2^+$ in the ground $X^3\Pi_g$ state, as well as three electronically excited states of $A^3\Pi_u$, $B^3\Sigma^+_u$, and $C^3\Sigma^+_g$ (Masuoka 1994). The production of $X^3\Pi_g$ does not contribute to local heating because the kinetic energy release is carried away by the accompanying photoelectron. The CO$_2^+$ ($A^3\Pi_u$) and CO$_2^+$ ($B^3\Sigma^+_u$) radiatively decay to the ground $X^3\Pi_g$ state very rapidly, with a characteristic lifetime of 10$^{-7}$ s (Schwenzer 1965), thus not contributing to local heating either. An exception is CO$_2^+$ ($C^3\Sigma^+_g$), because it is generally thought to predissociate to O$^+$ and CO in their electronically ground states of $4\Sigma$ and $1\Sigma^+$ (Wauchop & Broida 1971; Tsurubuchi & Iwai 1974), releasing a mean kinetic energy of 0.1 eV stored in dissociative fragments (e.g., Frey et al. 1977). For the other dissociative ionization channels of CO$_2$ as summarized by Masuoka (1994), no experimental data on the kinetic energy release are available, and we assume for simplicity the same kinetic energy release as quoted above. For O, which dominates over CO$_2$ near and above 210–220 km (Mahaffy et al. 2015a), we include the production of O$^+$ in both the ground $4\Sigma$ state and two electronically excited states of $2\Sigma$ and $2\Pi$ (Verner et al. 1996), with local heating evaluated based on the competition between collisional quenching and spontaneous emission (see Section 2.4 for details). Here the appropriate CO$_2$ and O photoionization cross sections are based on Masuoka (1994) and Verner et al. (1996), respectively.

2.2. Photoelectron Impact Processes

Inelastic collisions between photoelectrons and ambient neutrals provide a substantial heat source of the dayside Martian upper atmosphere via either kinetic energy release or collisional quenching of metastable ions or neutrals. For CO$_2$, we include 12 channels of electronic or vibrational excitation and seven channels of (dissociative) ionization (Shematovich et al. 2008; Bhardwaj & Jain 2009), whereas for O, we include two channels of electronic excitation and three channels of ionization (Laheber & Gilmore 1990). The relevant cross sections
compiled by Itikawa (2002) are used. Neutral or ionized products at higher excited states are not considered due to their small cross sections (e.g., Itikawa 2002) and reduced photoelectron intensity at energies appropriate for these processes (e.g., Sakai et al. 2015). All channels leading to multiple dissociation, ionization, and electron attachment are also neglected for the same reasons (e.g., Cicman et al. 1998).

For the two electronically excited states of O, local heating occurs exclusively via collisional quenching, with the energy loss via radiative decay being properly subtracted (see Section 2.4).

For the three modes of CO2 vibrational excitation, (010) (bending), (001) (asymmetric stretching), and (100) (symmetric stretching; e.g., Bhardwaj & Jain 2009), a certain fraction of the respective excitation energy, 0.083 eV for (010), 0.172 eV for (001), and 0.291 eV for (100), could be potentially deposited as local heat. The excitation energy for the (010) bending mode is lost via the associated CO2 emission at 15 μm, which serves as an important cooling mechanism in the Martian upper atmosphere (e.g., Bougher et al. 1999, 2000). Grofulović et al. (2016) showed that the cross sections of Itikawa (2002) were seriously overestimated for the (001) vibrational mode. To accommodate the most recent complication of CO2 cross-section data, this mode is ignored in this study. For the remaining (100) mode, 100% of collisional quenching is assumed, but we show below that this process makes a negligible contribution to neutral heating in the ambient atmosphere.

Electronic excitation of CO2 is assumed to be dissociative for all channels (Flaherty et al. 2006), including the 8.6, 9.3, 11.1, 12.4, 13.6, 15.5, 16.3, 17.0, and 17.8 eV states (e.g., Itikawa 2002; Bhardwaj & Jain 2009). The excitation contributes to local heating via kinetic energy release, which is 1.0, 1.0, 1.4, 0.7, and 1.0 eV for the first five states and 0.8 eV for the remaining four states (Fox & Dalgarno 1979a).

These values are in harmony with the available measurements of the kinetic energy distribution of neutral fragments (e.g., Schaione 1979; LeChalr & McConkey 1994) for the electron impact energy of interest here. For the four states above 15 eV, the respective heating rates are multiplied by 50% to account for autoionization (Jackman et al. 1977). Extra excited states may be present, associated with the known O11356, C11329, O11304, C11657, C11561, and C11279 emission features (e.g., Ajello 1971), which are ignored in this study due to their relatively small cross sections (Fox & Dalgarno 1979b). Some of the processes listed above produce dissociative fragments in electronically excited states such as O(S) and O(D) (see Table 8 of Fox & Dalgarno 1979a), and their contributions to local heating via collisional quenching are included.

For electron impact ionization, neutral heating occurs via collisional quenching of the electronically excited states of O1(2D0, 2 P0), with additional contributions from kinetic energy release for the dissociative ionization channels of CO2 (Itikawa 2002). The kinetic energy distributions of various charged fragments have been obtained by time-of-flight spectroscopy (e.g., Velotta et al. 1994; Locht & Davister 1995; Tian & Vidal 1998), but measurements of neutral fragments are not available (McConkey et al. 2008). Without a loss of generality, here a representative kinetic energy of 2 eV is assumed to be released as local heat per dissociative ionization.

2.3. Exothermic Chemistry

The complicated chemical network in the dayside Martian upper atmosphere initiated by photodissociation and photoinization serves as an additional heat source that has been considered in previous studies (e.g., Fox & Dalgarno 1979a; Fox et al. 1996). To evaluate the role of such a heating mechanism, the simplified photochemical reaction list of Martinis et al. (2003) is used, along with their reaction coefficients. The kinetic energy release for each reaction is determined from the difference in enthalpy between reactants and products, assuming that all ions and neutrals involved are in their ground states (see below for two important exceptions).

Existing studies have suggested that Og DR is an important heating mechanism in the Martian upper atmosphere (e.g., Fox et al. 1996). It is therefore necessary to consider this chemical process in greater detail, as done by Fox & Haç (2009) for their evaluation of atomic O escape on Mars also driven by O2 DR. In reality, this reaction may proceed via five different channels, which are

\[
\begin{align*}
O_2^+ + e &\rightarrow O(3P) + O(3P) + 6.99 \text{ eV}, \\
&\rightarrow O(D) + O(P) + 5.02 \text{ eV}, \\
&\rightarrow O(S) + O(P) + 2.80 \text{ eV}, \\
&\rightarrow O(D) + O(D) + 3.06 \text{ eV}, \\
&\rightarrow O(D) + O(S) + 0.83 \text{ eV}, \\
\end{align*}
\]

where the respective exothermicities are also provided. The total O2 DR coefficient of 2.4 × 10⁻⁷(300/T_e)⁰.⁷ in units of cm³ s⁻¹ is used (Peverall et al. 2001), with T_e being the thermal electron temperature in K. The branching ratio for channel (c) has been determined to be effectively zero (e.g., Peverall et al. 2001; Petrigiani et al. 2005), whereas the branching ratios for the other channels are known to vary with the vibrational state of O2. The ion storage ring studies of Petrigiani et al. (2005) have shown that at zero collision energy, the branching ratios for channels (a, b, d, e) are (0.265, 0.473, 0.204, 0.058) at \( v = 0 \), (0.073, 0.278, 0.51, 0.139) at \( v = 1 \), and (0.02, 0.764, 0.025, 0.211) at \( v = 2 \), where \( v \) is the vibrational quantum number. These branching ratios, together with knowledge of the O2 DR vibrational distribution, could be used to determine the weighted mean exothermicity due to O2 DR. Here we adopt the O2 vibrational distribution calculated by Fox & Haç (2009), which varies monotonically from (100%, 0, 0) at 80 km to (47%, 31%, 22%) at 400 km for \( v = (0, 1, 2) \) (see their Figure 6). Higher vibrationally excited states are neglected for simplicity. Furthermore, the collisional quenching of O(D) and O(S) produced via channels (b, d, e) of O2 DR is also treated as a local heat source.

Another potentially important channel of exothermic chemistry is via CO2 DR, which may occur in the form of

\[
\begin{align*}
CO_2^+ + e &\rightarrow CO(\chi \Sigma^\pm) + O(3P) + 8.31 \text{ eV}, \\
&\rightarrow CO(a^3\Pi) + O(3P) + 2.30 \text{ eV}, \\
&\rightarrow CO(a^3\Sigma^+) + O(3P) + 1.26 \text{ eV}, \\
&\rightarrow CO(d^3\Delta) + O(3P) + 0.49 \text{ eV}. \\
\end{align*}
\]

The branching ratios for the latter three channels were reported to be 38%, 18%, and 20%, respectively, by Rosati et al. (2003). The contributions from CO production in other electronically
excited states, such as CO($^4\Pi$) and CO($^3\Sigma^-$), are typically negligible, with branching ratios below 1% (e.g., Tsuji et al. 1995), and accordingly, we attribute the remaining fraction of 24% in Equation (3) to the production of ground-state CO($^2\Sigma^+$). We also implicitly ignore the vibrational excitation of all CO states quoted above.

2.4. Collisional Quenching of Excited O and O$^+$

Photon and photoelectron collisions with ambient neutrals, as well as photochemical reactions, may produce neutrals or ions in the electronically or vibrationally excited states, of which some are metastable and contribute to local heating via collisional quenching (Fox et al. 2008).

Two potentially important metastable species are O($^2\Pi$) and O$^+$(2$^3$D$_0$), with excitation energies of 1.96 and 3.32 eV (Laher & Gilmore 1990; Tayal 2002). The former is produced via photoelectron impact excitation (Section 2.2) and O$_2$ DR (Section 2.3), whereas the latter is produced via photoionization (Section 2.1) and photoelectron impact ionization (Section 2.2). For O($^2\Pi$), the radiative lifetime is 180 s, to be compared with the range of quenching timescales of 10$^3$ s, and for O$^+$(2$^3$D$_0$), the radiative lifetime is at least 10$^3$ s, to be compared with the range of quenching timescales of 0.1–100 s, where the quenching timescales are estimated using the quenching coefficients of 2 × 10$^{-11}$ cm$^3$ s$^{-1}$ for O($^2\Pi$) and 1 × 10$^{-10}$ cm$^3$ s$^{-1}$ for O$^+$(2$^3$D$_0$) (Slanger et al. 2008; see their Table 3), as well as the typical density range in the dayside Martian upper atmosphere at 120–250 km (Mahaffy et al. 2015a). The above comparisons suggest that O($^2\Pi$) more likely loses its excitation energy as local heat at low altitudes and as radiation at high altitudes, whereas O$^+$(2$^3$D$_0$) loses its excitation energy as local heat at all altitudes considered here. All radiative lifetimes quoted above and below are estimated from the transition probabilities compiled by Wiese (1996).

Higher excited states of atomic and ionized O are possible, but they usually decay rapidly to lower metastable states via spontaneous emission (e.g., Slanger et al. 2008). Specifically, O($^5\Sigma$(S)) with an excitation energy of 4.18 eV decays to the O($^2\Pi$) metastable state with a lifetime of 0.8 s and to the O($^3\Pi$) ground state more slowly with a lifetime of 13 s. Both are substantially smaller than the range of quenching timescales longer than 10$^3$ s due to the extremely small quenching coefficient of 5 × 10$^{-15}$ cm$^3$ s$^{-1}$ for O($^5\Sigma$(S)) (Slanger et al. 2008), implying that upon production, about 94% of O($^5\Sigma$) could be assumed to decay immediately to the O($^2\Pi$) metastable state via emission, and local heating occurs via O($^2\Pi$) collisional quenching.

The situation for O$^+$(2$^3$P$_0$), with an excitation energy of 5.02 eV, is more complicated. It decays to the O$^+$(2$^3$D$_0$) metastable state with a lifetime of 10–16 s and the O$^+$(4$^3$S$_0$) ground state more slowly with a lifetime of 47 s. These lifetimes lie in the middle of the respective range of quenching timescales of 0.1–100 s at 120–250 km using a quenching coefficient of 2 × 10$^{-10}$ cm$^3$ s$^{-1}$ for O$^+$(2$^3$P$_0$) (Slanger et al. 2008). Accordingly, local heating associated with O$^+$(2$^3$P$_0$) production includes both O$^+$(2$^3$P$_0$) quenching itself and O$^+$(2$^3$D$_0$) quenching originated from around 78% of O$^+$(2$^3$P$_0$) radiative decay.

3. Application to the MAVEN Data

The methodology described in Section 2 is applied to the multi-instrument data set accumulated during a large number of dayside MAVEN orbits with SZA below 75°, from the beginning of the mission up to 2018 February 14. The data utilized in this study are restricted to the inbound portion of each orbit to avoid possible contamination by adsorption or heterogeneous chemistry occurring on the NGIMS antechamber walls (e.g., Mahaffy et al. 2015b). The LPW electron temperatures, crucial for calculating the DR rates of various ion species in the dayside Martian upper atmosphere (see Section 2.3), have been corrected for overestimates at low altitudes due to surface resistance or capacitance on the instrument sensor (Ergun et al. 2015; Peterson et al. 2018) following the procedure of Cui et al. (2019a). The photoelectron energy spectra, extracted from the dayside SWEA measurements, are corrected for spacecraft charging with the potential measured by the MAVEN Suprathermal and Thermal Ion Composition instrument (McFadden et al. 2015).

An example is presented in Figure 1 for the inbound portion of MAVEN orbit No. 1079 during the second deep-dip (DD) campaign on 2015 April 20 with a periapsis altitude of 130.9 km at SZA = 8.5° near the equator. The total solar EUV/X-ray energy input below 90 nm is estimated to be 1.64 erg cm$^{-2}$ s$^{-1}$ when integrated over the level 3 solar spectral model at Mars, constructed from the Flare Irradiance Spectral Model—Mars and calibrated with the MAVEN EUVM-band irradiance data (Thiemann et al. 2017). In Figure 1, different panels show the CO$_2$ O, N$_2$, CO, and NO neutral densities (a); the O$_2^+$, O$^+$, CO$_2^+$, N$_2^+$/CO$^+$, NO$^+$, and thermal electron (or total ion) densities (b); the neutral and thermal electron temperatures (c); the differential photoelectron intensity (d); the solar energy deposition rate and various neutral heating rates (e); and the heating efficiency defined by Equation (1) and the shape parameter of the photoelectron energy spectrum to be described later (f); all over the altitude range of 130–250 km. We caution that the density profiles of N$_2$, CO, NO, and all ion species quoted above are necessary for calculating the chemical heating rate (see Section 2.3).

In panel (a), the solid dots represent direct NGIMS measurements, and the solid lines represent the logarithmic fittings to these measurements in order to remove small-scale fluctuations likely driven by gravity waves (e.g., England et al. 2017). The NO density profile, which is generally not available from the level 2 NGIMS data products, is constructed assuming diffusive equilibrium with a dayside NO mixing ratio of 7.5 × 10$^{-4}$ at 150 km (Mahaffy et al. 2015a). This is a reasonable procedure, since the homopause on Mars is typically below the altitude range displayed in Figure 1 (e.g., Slipski et al. 2018).

In panel (b), the N$_2^+$ and CO$^+$ densities cannot be distinguished by the NGIMS instrument due to their equality in mass. Since the ion density profiles from some of the MAVEN orbits exhibit strongly varying and irregular features, the measured ion densities are directly used in our calculations.

In panel (c), the neutral temperature profile is derived by downward integrating the hydrostatic balance equation of CO$_2$ analogous to Cui et al. (2018a). A constant neutral temperature of 250 K at the top boundary of 250 km is assumed for all orbits. Both the raw LPW electron temperature profile (solid red) and the corrected profile (dashed red) are indicated. The corrected temperature profile is consistent with the expected strong coupling between neutrals and electrons at the bottom of the figure (e.g., Chen et al. 1978; Choi et al. 1998; Matta et al. 2014; Peterson et al. 2018).
In panel (d), the distinctive signatures of photoelectrons near Mars are clearly manifested as the sharp peaks at 22–27 eV due to CO₂ and O ionization by the strong solar He II emission line at 30.4 nm and the apparent knee at 60–70 eV due to the rapid change in solar flux at wavelengths shorter than 17 nm (e.g., Sakai et al. 2015; Peterson et al. 2016). We caution that an SWEA spectrum measured on the dayside of Mars may also contain the signature of solar wind (SW) electrons, which is recognizable with the aid of the shape parameter introduced by Xu et al. (2017). Since we are interested here in the neutral heating associated with solar radiative energy inputs only, we follow their procedure to determine the shape parameter for each SWEA spectrum and exclude all spectra with shape parameters above 1. For orbit No. 1079, the shape parameter...
shown in panel (f) remains below 1 in most cases, indicative of negligible heating caused by SW electron precipitation. The apparent spike in panel (d) slightly above 200 km, with a shape parameter of ~2 in panel (f), is excluded for the reason addressed above.

In panel (f), the neutral heating efficiency obtained for this particular orbit demonstrates a systematic trend that increases from 20% near 130 km to 32% near 250 km. The local maximum in heating efficiency near 230 km is obviously connected to the maximum in \( O_2^+ \) density at the same altitude in panel (b), more likely reflecting a wave-induced perturbation rather than a common feature (see the median heating efficiency profile in Section 4).

The relative contributions from various heating mechanisms are easily seen in Figure 1(e), revealing that the contributions from photon impact and exothermic chemistry are significant at all altitudes, whereas the contribution from photoelectron impact is of minor importance but still nonnegligible. To achieve a better understanding of the neutral heating scenario, we display in Figure 2 the importance of various channels for local heating, revealing that contributions of these two ion-neutral reactions to the total heating rate for comparison. The \( O_2^2+ \) DR mainly via the two channels producing \( CO \) in the ground \( X^1\Sigma^+ \) state and the first excited \( a^3\Pi \) state (Equations 3(a) and (b)). The next two important channels following DR are the ion-neutral reactions

\[
\begin{align*}
O^+ + CO_2 &\rightarrow O_2^2+ + CO + 1.21 \text{ eV}, \\
O_2^2+ + NO &\rightarrow NO^+ + O_2 + 2.81 \text{ eV},
\end{align*}
\]

of which the former delivers 0.65 eV and the latter 1.40 eV to the respective neutral product in the form of kinetic energy. When averaged over the altitude range of 130–250 km, the contributions of these two ion-neutral reactions to the total chemical heating rate are 11% and 7%, with the sum of the remaining reactions contributing to an additional 6%.

Figure 2. Comparison of various heating rates due to photon impact (a) and photoelectron impact (b) processes, as well as exothermic chemical reactions (c). The photon impact processes include the photodissociation (PD) of \( CO_2 \), as well as the photoionization (PI) of \( CO_2 \) and \( O \). For the photoelectron impact processes, we consider the electron impact (EI) ionization (ion), dissociation (dis), electronic excitation (exc), and vibrational excitation (vib) of either \( CO_2 \) or \( O \), whereas for the \( CO_2 \) EI dissociation, we show the effects of kinetic energy release (K) and collisional quenching (Q) separately. For exothermic chemistry, several important channels are shown individually, including \( O_2^2+ \) and \( CO_2 \) DR, as well as two additional ion-neutral reactions.
both vibrationally excited CO$_2$ and electronically excited O make comparable contributions to local heating up to ~200 km, above which electronically excited O$^+$ becomes more important. This is not surprising because in our calculations, excited O$^+$ is exclusively produced from O by photon impact, whereas excited O and CO$_2$ could be partially produced from CO$_2$ by photon or photoelectron impact, and an enhanced O mixing ratio at high altitudes (Mahaffy et al. 2015a) is reasonably consistent with the relative importance of different channels of collisional quenching. In general, collisional quenching insignificantly accounts for 9% of total heating at all altitudes in Figure 3.

Discussions so far have focused on neutral heating via different mechanisms in the dayside Martian upper atmosphere, taking MAVEN orbit No. 1079 as an example. The relative contributions from photon and photoelectron impact processes, as well as exothermic chemistry, are compared. These contributions surely vary from orbit to orbit, but the general scenario remains well defined. We apply the methodology described in Section 2 to a total of 1293 dayside MAVEN orbits, which allow the variations of the neutral heating efficiency to be thoroughly explored.

4. Variations of Neutral Heating Efficiency

The variation of the neutral heating efficiency over the altitude range of 150–250 km is displayed in Figure 4, in the dayside median sense. The region at lower altitudes is not shown due to its limited sampling during DD campaigns only. To facilitate comparison among different heating mechanisms, we also separately show the neutral heating efficiencies due to photon and photoelectron impact, as well as exothermic chemistry, denoted as $\epsilon_{\text{ph}}$, $\epsilon_{\text{phe}}$, and $\epsilon_{\text{chem}}$, respectively. The error bars in the figure encompass the upper and lower quartiles.

Figure 4 demonstrates clearly that in the median sense, neutral heating is primarily contributed by photon impact and exothermic chemistry. Both processes cause a neutral heating efficiency that remains fairly constant at 150–200 km: 14% for photon impact and 7% for exothermic chemistry. Above 200 km, the effect of the former decreases with increasing altitude, whereas the effect of the latter increases instead. Such a distinction is connected to an increasing plasma–to–neutral density ratio with increasing altitude (e.g., Jakosky et al. 2015). The effect of photoelectron impact on neutral heating is small overall, but its contribution cannot be neglected at low altitudes, where the ionization efficiency, defined as the ratio between the photoelectron impact ionization rate and the photoionization rate, is also enhanced (e.g., Nicholson et al. 2009; Cui et al. 2018b). Both are due to the fact that more energetic photons tend to penetrate deeper into the atmosphere, creating more photoelectrons and thus enhancing the atmospheric response to their collisions with neutrals (e.g., Withers 2009, and references therein). Combining the three mechanisms, the total neutral heating efficiency, $\epsilon = \epsilon_{\text{ph}} + \epsilon_{\text{phe}} + \epsilon_{\text{chem}}$, is roughly constant at 22% up to ~200 km, and nearly 65% of the heating occurs via photon impact. At higher altitudes, $\epsilon$ increases steadily with increasing altitude up to 33% at 250 km, where exothermic chemistry dominates.

We further compare in Figure 4 the MAVEN-derived neutral heating efficiency with three model results from Fox & Dalgarno (1979a). These models were constructed based on the Viking 1 upper atmospheric mass spectrometer measurements of the background Martian atmosphere (Nier & McElroy 1976), appropriate for the low solar activity condition and SZA = 45°. The three models are to be distinguished in terms of the presumed radiative energy loss. According to Fox & Dalgarno (1979a), they assumed for both their models A and B that 10% of the kinetic energy release from CO$_2$ photodissociation was stored as the vibrational energy of CO, and that such energy was fully radiated away for model A, but only 50% was radiated away for model B. In both models, heating via the quenching of metastable O$(^3P)$ by CO$_2$ collision was not taken into account; therefore, for an additional model C, Fox & Dalgarno (1979a) further assumed 100% collisional quenching of O$(^3P)$ in addition to the assumption of 50% radiative energy loss from CO vibrational excitation, as in model B. Based on Figure 4, the neutral heating efficiency...
below 200 km implied by the multi-instrument MAVEN data set lies between those from models B and C but substantially higher than the model A result by nearly 40%. Another important difference revealed by Figure 4 is a steady increase in neutral heating efficiency above 200 km, according to our calculations, to be distinguished from a steady decrease according to Fox & Dalgarno (1979a).

Compared to the three models of Fox & Dalgarno (1979a), different treatments of CO vibrational excitation and $O(1D)$ collisional quenching are implemented in our study. On the one hand, neutral heating due to vibrationally excited CO from CO$_2$ photodissociation (e.g., Phillips et al. 1977) is not included in this study because information on the respective cross-section data is not currently available (see Section 2.1). On the other hand, the effect of $O(1D)$ collisional quenching is evaluated much more carefully in this study (see Section 2.4) and is estimated to decline from 97% at 150 km to 26% at 200 km, to be distinguished from the assumption of 100% quenching at all altitudes in Fox & Dalgarno (1979a).

However, we do not expect the difference in $O(1D)$ collisional quenching to be responsible for the difference in heating efficiency between the two studies because the contribution from collisional quenching to neutral heating is typically low (see Figure 3). The neglect of CO vibrational excitation in our study should lead to a noticeably lower heating efficiency than that of Fox & Dalgarno (1979a) due to considerable neutral heating caused by CO$_2$ photodissociation (see Figure 2(a)), but we speculate that a more appropriate scheme of chemical heating implemented here is more than enough to raise the heating efficiency at 150–200 km to a value above those from models A and B of Fox & Dalgarno (1979a).

Due to the importance of O$_3$ and CO$_2$ DR (see Figure 2(c)), we expect the difference in chemical heating between the two studies to be, at least partly, associated with the different O$_3$ and CO$_2$ density profiles used. For instance, the O$_3$ and CO$_2$ densities used by Fox & Dalgarno (1979a) were $1.8 \times 10^3$ and 68 cm$^{-3}$ at 240 km, in agreement with the Viking I RETARDATION POTENTIAL ANALYZER measurements (Hanson et al. 1977), but the more recent MAVEN NGIMS densities that we use are $2.5 \times 10^3$ and $3.0 \times 10^2$ cm$^{-3}$ at the same altitude (Wu et al. 2019). Obviously, the different treatments of chemical heating are also responsible for the different vertical trends above 200 km between the two studies, since enhanced heating efficiency at high altitudes is exclusively driven by chemistry, according to our calculations.

The neutral heating efficiency in the dayside upper atmosphere of Venus, another planet with a CO$_2$-dominated atmosphere, was predicted by Fox (1988) to be 10%, 20%, and 25% at 130–180 km for three models with similar assumptions of radiative energy loss as in Fox & Dalgarno (1979a). For Titan’s atmosphere, which is mainly composed of N$_2$ and CH$_4$, a variable neutral heating efficiency from 22% to 30% at 1000–1500 km was obtained by De La Haye et al. (2008) approximate for the first encounter of Cassini with Titan and assuming solar EUV/X-ray energy inputs only. Therefore, a comparable neutral heating efficiency of 20%–30% is achieved on terrestrial planets in general, despite the large difference in atmospheric composition and structure.

We further investigate the SZA variations of different heating efficiencies, $\epsilon_{\text{ph}}$, $\epsilon_{\text{phe}}$, $\epsilon_{\text{chem}}$ and total $\epsilon$, in the dayside Martian upper atmosphere, as displayed in Figure 5. Here we focus on the median efficiencies at 150–200 km, and the error bars in the figure encompass the upper and lower quartiles. Note that $\epsilon_{\text{phe}}$ is multiplied by 10 to improve visibility.
affected. In practice, solar cycle variation is most distinctive at shorter wavelengths, which should lead to more pronounced enhancement in photoionization than photoabsorption. Consequently, both \( \epsilon_{\text{phe}} \) and \( \epsilon_{\text{chem}} \) are elevated due to more pronounced enhancement in \( H_{\text{phe}} \) and \( H_{\text{chem}} \) than in \( H_{\text{sol}} \) (see Equation (1)). A reduced variation of \( \epsilon_{\text{ph}} \) seen in Figure 6, effectively consistent with no solar cycle variation, could be interpreted following a similar line of reasoning.

Finally, it is instructive to evaluate the impact of crustal magnetic fields on the neutral heating efficiency in the dayside Martian upper atmosphere. For such a purpose, we divide the entire surface of Mars into 48 sectors, each with a size of 30° in latitude and 40° in longitude. The respective median heating efficiencies at 150–200 km are color-coded in Figure 7, superimposed on the crustal magnetic field model of Morschhauser et al. (2014) appropriate for an altitude of 400 km. A hemispheric difference is seen in the figure in that the neutral heating efficiencies over the southern hemisphere, where strong magnetic anomalies tend to cluster (e.g., Acuna et al. 1999; Connerney et al. 1999), are higher than the northern hemisphere values. Except for \( \epsilon_{\text{ph}} \) (see below), a prominent region with particularly high neutral heating efficiencies in Figure 7 is nearly colocated with the strongest crustal magnetic anomaly near Terra Cimmeria (e.g., Morschhauser et al. 2014). These characteristics are indicative of the strong modulation of neutral heating by the ambient magnetic fields.

As motivated by Cui et al. (2018b), we suggest that the impact of crustal magnetic fields on \( \epsilon_{\text{phe}} \) could be explained by the preferred vertical orientation of field lines near strong magnetic anomalies (e.g., Xu et al. 2017), which facilitates photoelectron transport and enhances neutral heating via photoelectron impact above the altitude of peak photoelectron production. Similarly, the impact of crustal magnetic fields on \( \epsilon_{\text{chem}} \) is likely explained by the enhanced thermal plasma content also observed near strong magnetic anomalies (e.g., Ness et al. 2000; Nielsen et al. 2007; Safaeinili et al. 2007; Andrews et al. 2014, 2015; Diéval et al. 2018; Withers et al. 2019; Wu et al. 2019), which in turn acts to enhance neutral heating via both DR and ion-neutral reactions. Since no obvious impact could be exerted on \( \text{CO}_2 \) photodissociation by the magnetic fields, we speculate that the geographic distribution of \( \epsilon_{\text{ph}} \), which is itself less correlated with the magnetic field model of Morschhauser et al. (2014) than the distributions of \( \epsilon_{\text{phe}} \) and \( \epsilon_{\text{chem}} \), is likely unreal and due to limited sampling.

5. Discussions

One important advantage of this study as compared to previous works is the extensive use of MAVEN data such as the solar EUV/X-ray energy flux and the differential photoelectron intensity. For the former, previous calculations were exclusively based on the extrapolation of the terrestrial measurements to Mars, whereas for the latter, kinetic model results were frequently used (Xu & Liemohn 2015, and references therein). The direct use of the MAVEN data in this study reduces the model uncertainty to a level below the combined instrument uncertainty, but now the photon or photoelectron energy range covered by the respective instrument is likely insufficient. The maximum wavelength of 189.5 nm for the EUV solar spectrum corresponds to a minimum photon energy of 6.5 eV. Meanwhile, the SWEA energy spectra used for evaluating photoelectron impact processes have been corrected for spacecraft charging with the simultaneously measured STATIC potential, and this means that the exact photoelectron energy range incorporated in our calculations is nonuniform and varies from spectrum to spectrum. Occasionally, the minimum photoelectron energy could be as large as 18 eV when the spacecraft is strongly negatively charged.

To evaluate these effects, we show in Figure 8 the percentages of \( H_{\text{sol}} \), \( H_{\text{ph}} \) and \( H_{\text{phe}} \) all as a function of wavelength or photoelectron energy. For \( H_{\text{sol}} \) and \( H_{\text{ph}} \), we divide the entire wavelength range into consecutive bins, each covering a 1 nm interval, and for \( H_{\text{phe}} \), an equivalent set of photoelectron energy bins is constructed. Despite the fact that these heating and solar energy deposition rates vary substantially with altitude, their percentage contributions remain fairly constant, and the median results are presented accordingly in the figure appropriate for the altitude range of 200–300 km. The figure clearly reveals that the majorities of \( H_{\text{sol}} \) and \( H_{\text{ph}} \) occur over the wavelength range below 180 nm, which is exclusively covered by the EUVM level 3 solar spectral model (Thiemann et al. 2017). For \( H_{\text{phe}} \), fair contributions to neutral heating may occur at relatively low energies not adequately sampled by the SWEA instrument, but this should not affect our main conclusions because \( \epsilon_{\text{phe}} \) makes up a small part of the total \( \epsilon \).

The calculations presented so far are based on the assumption of local heating only, which is valid at low altitudes, with the mean free path of hot molecules or atoms being small. In reality, the mean free path tends to increase exponentially with increasing altitude, ultimately rendering local heating as a poor approximation in the Martian upper atmosphere. To evaluate the effect of nonlocal heating at a given altitude, \( z \), we implement a simplified heat transport model for which we allocate the heat release evenly over a vertical extent centered at that altitude. Such a vertical extent could be reasonably parameterized by the local mean free path via elastic collisions with ambient neutrals. To account for the altitude variation of the ambient atmosphere, collisions above and below the given altitude are treated separately. To be more specific, we obtain the vertical extent below \( z \), denoted as \( \Delta L_- \), from the condition of \( \int_{z-L}^{z} (\sigma_{\text{CO}_2} N_{\text{CO}_2} + \sigma_{\text{N}_2} N_{\text{N}_2}) dz = 1 \) and the vertical extent above \( z \), denoted as \( \Delta L_+ \), from a similar
condition of \( \int_{z}^{z+\Delta z} (\sigma_{\text{CO}_2}N_{\text{CO}_2} + \sigma_{\text{O}}N_{\text{O}})dz = 1 \). In the above expressions, \( N_{\text{CO}_2} \) and \( N_{\text{O}} \) are the background \( \text{CO}_2 \) and \( \text{O} \) number densities, and \( \sigma_{\text{CO}_2} \) and \( \sigma_{\text{O}} \) are the respective collision cross sections that, in principle, depend on the type of hot molecules or atoms involved. Without loss of generality, we assume the hard sphere collision cross sections of \( 2 \times 10^{-14} \text{ cm}^2 \) (Fox & Hać 2014) and \( 6.4 \times 10^{-15} \text{ cm}^2 \) (Kharchenko et al. 2000) to be common to all neutrals when colliding with \( \text{CO}_2 \) and \( \text{O} \), respectively. Clearly, \( \Delta L_+ \) is larger than \( \Delta L_- \), implying that local heat release more easily diffuses toward higher altitudes.

Based on the procedure outlined above, the total heating rate and efficiency corrected for the nonlocal effect are presented in Figure 9 for MAVEN orbit No. 1079, as in Figure 1. The same quantities without such a correction are superimposed for comparison. The figure suggests that the nonlocal effect is negligible below 200 km but likely becomes important at higher altitudes. Near 250 km, which is well above the traditional exobase of Mars (e.g., Chaffin et al. 2015), the net effect of heat transport is to reduce the heating rate and efficiency by roughly 20% from the respective values assuming strict local heating. We expect a portion of the upward heat transport to be associated with dayside atmospheric escape on Mars, mainly in the form of atomic \( \text{O} \) escape (e.g., Lillis et al. 2017; Jakosky et al. 2018; Cui et al. 2019b). In the dayside median sense, the column-integrated total heating rate above the exobase altitude of 200 km is \( 1.1 \times 10^9 \text{ eV cm}^{-2} \text{ s}^{-1} \) referred to the surface of Mars, of which 15% is likely carried
away by atomic O escape. Here we have adopted an O escaping energy flux of $1.7 \times 10^6$ eV cm$^{-2}$ s$^{-1}$, estimated from the dayside median O escape flux of $6 \times 10^6$ eV cm$^{-2}$ s$^{-1}$ (Lillis et al. 2017) when multiplied by the weighted mean kinetic energy release of 2.86 eV for escaping O atoms.

6. Concluding Remarks

The neutral heating efficiency, defined as the fraction of the solar EUV/X-ray energy absorbed by a planetary atmosphere that ends up as local heat (e.g., Stolarski et al. 1975; Stolarski 1976), is a key parameter of both aeronomical and astronomical interests. This parameter is crucial to a proper understanding of the thermal structure in the dayside planetary atmosphere, which in turn determines the thermal escape rate, as well as the long-term climate evolution (e.g., Lammer et al. 2013; Jakosky et al. 2018). This study is devoted to a thorough investigation of the neutral heating efficiency at 150–250 km in the dayside upper atmosphere of Mars by virtue of the extensive measurements made by a number of instruments on board MAVEN (Jakosky et al. 2015), including the NGIMS neutral and ion densities, the EUVM solar energy flux, the SWEP differential photoelectron intensity, and the LPW thermal electron temperature, accumulated during a total of 1293 MAVEN orbits with periastron SZA below 75°. We calculate the profile of neutral heating efficiency along the inbound portion of each orbit, which allows, on the one hand, the roles of various heating mechanisms to be separated and, on the other hand, the variations of atmospheric heating to be explored.

A complicated network of microscopic processes is taken into account in this study, which could be summarized in three categories: (1) photon impact processes, (2) photoelectron impact processes, and (3) exothermic chemical reactions (Fox et al. 2008, and references therein). The first category contains the photodissociation of CO$_2$, as well as the photoionization of both CO$_2$ and O (Heays et al. 2017), of which we find CO$_2$ photodissociation to be dominant. For the second category, we consider 12 channels of electronic or vibrational excitation and seven channels of (dissociative) ionization of CO$_2$ (Bhardwaj & Jain 2009), as well as two channels of electronic excitation and three channels of ionization of O (Laher & Gilmore 1990). According to our calculations, neutral heating due to photoelectron impact primarily occurs via CO$_2$ vibrational and electronic excitation. The third category contains both ion-neutral and DR reactions (e.g., Fox & Sung 2001; Martinis et al. 2003), and we find O$^+_2$ and CO$_2$ DR to be the two most important reactions causing local heating. All of the above processes likely produce metastable neutrals such as O($^2D$) or ions such as O$^+$($^2D_0$) (e.g., Fox & Dalgarno 1979a), and their contributions to local heating are carefully evaluated based on a timescale comparison between radiative decay and collisional quenching (Slanger et al. 2008). In practice, the fractional heating due to collisional quenching is estimated to be less than 10% of total heating at all altitudes.

Combining the entire available MAVEN data set, we are able to construct a dayside median profile of neutral heating efficiency that remains roughly constant at 20% over the altitude range of 150–200 km, above which it increases steadily to 32% near 250 km. A comparison of different heating mechanisms suggests that neutral heating is mainly contributed by photon impact above 210–220 km and exothermic chemistry at higher altitudes. The contribution from photoelectron impact is of minor importance overall, except at altitudes well below 150 km, where the contributions from all three categories of heating process are comparable. Such low-altitude regions were restrictively sampled by the MAVEN instruments during DD campaigns only. The MAVEN-derived heating efficiency profile is in general agreement with the model results of Fox & Dalgarno (1979a), with modest differences due to different treatments of CO$_2$ photodissociation and O($^2D$) collisional quenching, as well as different ion density profiles utilized in evaluating the chemical heating rate.

We further investigate the variations of the neutral heating efficiency at 150–200 km, and several interesting characteristics are revealed by the data. (1) No strong SZA variation of the heating efficiency is observed, since the CO$_2$ photodissociation rate is not sensitive to the change in SZA above 150 km; meanwhile, the available NGIMS measurements reveal no clear SZA variations of the O$^+_2$ and CO$_2^+$ densities from subsolar up to SZA $\sim 70°$ at similar altitudes (Benna et al. 2015). (2) The heating efficiency shows a modest increase with increasing solar EUV/X-ray energy flux, which could be explained by the fact that solar cycle variation is most distinctive at shorter wavelengths and should lead to more pronounced enhancement in photoionization than photoabsorption. (3) An enhanced heating efficiency is seen over the southern hemisphere, indicative of the strong modulation of neutral heating by the ambient magnetic fields, and this is likely related to the preferred vertical transport of both photoelectrons (e.g., Xu et al. 2017; Cui et al. 2019a) and thermal ions/electrons (e.g., Matta et al. 2015; Diévèl et al. 2018; Withers et al. 2019; Wu et al. 2019) over strong magnetic anomalies.

Our calculations of the neutral heating rate and efficiency in the dayside Martian upper atmosphere are data-driven and thus superior to previous works in that model uncertainties such as those involved in determining the photoelectron intensity are reduced as much as possible. Despite this, a few caveats need to be emphasized, reflecting the limitations of the present study. First, CO$_2$ photodissociation, which is an important part of neutral heating, is assumed to produce CO fragments in the ground state only; including the collisional quenching of vibrationally excited CO (Phillips et al. 1977) should improve our calculations, but such an improvement is only meaningful when knowledge of the respective cross sections becomes available. Second, the considerable contribution from exothermic chemistry to neutral heating calls for improved treatment of both ion-neutral and DR reactions in the dayside Martian upper atmosphere, which is currently very limited, since all products (except for O$^+_2$ and CO$_2$ DR products) are assumed to be in the ground states. Third, we ignore the effect of nonlocal heating throughout this study, and a simplified heat transport model is constructed to evaluate the validity of our results, showing that the heating rate and efficiency obtained under the assumption of strict local heating are accurate up to at least 200 km.

Minding the above limitations, we propose that the results shown here, along with our knowledge of the upper atmospheres of other solar system bodies, such as Venus (Fox 1988) and Titan (De La Haye et al. 2008), suggest a common heating efficiency of 20%–30% on terrestrial planets in general (despite the large difference in atmospheric composition and structure) and highlight the importance of photochemistry in atmospheric heating.
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