Summary

Atmospheres of Mars and Venus have been studied extensively by several space missions. The wealth of information acquired by these missions have not only helped in understanding the atmospheric evolution of the two planets, but raised many questions as well. In the present thesis an attempt has been made to understand some of the physical processes that are governed by solar radiation interaction with the upper atmospheres of Mars and Venus. Energetic photons emanating from Sun deposit their energy in planetary upper atmosphere and initiate many physical and chemical processes. Molecular and atomic emissions coming from the sunlit atmosphere (dayglow) are manifestations of such an interaction. These emissions provide useful information about atmospheric structure, composition, temperature, and energetics of the atmosphere. Modelling of dayglow emissions is not only crucial for understanding physical processes governing these emission, also to determine and constrain the input parameters, such as cross sections and model atmosphere. In this thesis, the ultraviolet and visible dayglow emissions (viz., CO Cameron band, CO$_2^+$ ultraviolet doublet, N$_2$ VK band, and OI green (5577 Å), red doublet (6300, 6364 Å), and ultraviolet 2972 Å emissions) in atmospheres of Mars and Venus are modelled. The effect of various input parameters on the dayglow emission intensity is also studied. Modelling of these emissions is also important in context of current observations being carried out by SPICAM/Mars Express (MEx) on Mars and SPICAV/Venus Express (VEx) on Venus. Model calculation of emissions other than those mentioned above will be carried out in future and is discussed in the following section.

Photoelectron—generated due to photoionization—is an important source of upper atmospheric emissions. Degradation of an electron in an atmosphere requires a technique for electron energy apportionment. Since atmospheres of both Mars and Venus are predominately CO$_2$ (95% by volume), a Monte Carlo model is developed in this thesis for electron energy degradation in an atmosphere of CO$_2$. A detailed compilation of cross sections of electron impact on CO$_2$ is presented which is used as an input in the
Monte Carlo model and also used in the modelling of dayglow emissions. The output of Monte Carlo simulation is used to generate the “yield spectra”, which embodied all the information related to electron degradation process, and can be used to calculate the “yield” or (population) for any inelastic process. The numerical yield spectra have been fitted analytically resulting in an “Analytical Yield Spectra (AYS)”. The mean energy per ion pair and efficiencies for different inelastic processes have been calculated using AYS, which compares well with those obtained by using numerical yield spectra. The mean energy per ion pair for neutral CO$_2$ is found to be 37.5 (35.8) eV at input energy of 200 (1000) eV. Ionization is the dominant loss process due to its higher cross section at higher energies. At energies above 100 eV, \(\sim50\%\) energy goes into the ionization loss channel. Among the excitation processes, 13.6 eV and 12.4 eV states are dominant loss processes consuming \(\sim28\%\) energy above 200 eV. The AYS is used to calculate steady state photoelectron fluxes in the atmosphere of Mars and Venus.

The intensity of CO Cameron band and CO$_2^+$ doublet emissions is calculated in the atmospheres of Mars and Venus. The effect of two solar EUV flux model namely, EUV flux model for Aeronomic Calculation (EUVAC) and SOLAR2000 (S2K) on emission intensity is calculated for different solar activity conditions. The emission rates of CO(a$^3\Pi$) and CO$_2^+$($B^2\Sigma_u^+$) are height-integrated to calculate the overhead intensity and along the line of sight to obtain the limb intensities. The intensities of CO(a', d, e) triplet band emissions on Mars and Venus are predicted. Calculated limb intensities on Mars are compared with the SPICAM/MEx and UV spectrometer/Mariner observed intensities. The calculated brightness profiles of CO Cameron band and CO$_2^+$ doublet emissions are in agreement with the SPICAM observation; however, in solar maximum condition the calculated intensities are lower than those observed by Mariner 6 and 7 ultraviolet spectrometers.

On Venus, the calculated brightness of CO Cameron band and CO$_2^+$ doublet emissions is compared with recent SPICAV observation. The calculated intensities of CO Cameron band and CO$_2^+$ doublet emissions at the peak altitude are about 50% and 30%, respectively, higher than the observation. The model calculated peak altitude of CO Cameron band and CO$_2^+$ UV doublet emission profiles is lower by \(\sim3\) km than that observed by SPICAV: indicating lower neutral density in the VTS3 model atmosphere of Venus, which is used in the present calculations. The calculated overhead intensities of CO Cameron and CO$_2^+$ UV doublet band emissions are about a factor of 2 higher in the solar maximum condition than those during the solar minimum condition. This variation in intensity from low to high solar activity depends upon the solar EUV flux model used in the calculation, e.g., when the S2K model is used instead of EUVAC, the emission intensities of CO Cameron band and CO$_2^+$ UV doublet vary by less than a factor of 2. Overall, the effect of solar EUV flux models on the emission intensity is 30-40% in solar minimum condition and \(\sim2-10\%\) in solar maximum condition.
Present study has clearly demonstrated that the cross section of $a^3\Pi$ state in e-CO process is important in modelling CO Cameron band emission on Mars and Venus. The contribution of e-CO process in CO Cameron band also depends on the density of CO in the atmosphere; hence, it is difficult to constrain the former without fixing the later.

For the first time, the SPICAM/MEx observed $N_2$ Vegard-Kaplan band emission on Mars. Since $N_2$ is the second most abundant gas on Venus, the $N_2$ triplet band features are expected on Venus also. In this context, the application of AYS to the calculation of $N_2$ triplet band dayglow emissions on Mars and Venus has been carried out in the present work. The impact of solar activity, solar EUV flux model, and $N_2$ triplet state cross sections on the $N_2$ triplet band emissions are studied. On Mars, the calculated brightness profile is about a factor of 3 smaller than the SPICAM observation. Constraining the $N_2$/CO$_2$ ratio on Mars by SPICAM observations, the present calculations suggest that the $N_2$/CO$_2$ ratio on Mars would be in the range of 1.1 to 1.4% at 120 km, 1.8 to 3.2% at 140 km, and 4 to 7% at 170 km. The present study also suggests that most of the atmospheric models of Mars have $N_2$ abundances that are larger than the model-derived values, based on the present calculation, by a factors of 2 to 4. Clearly, there is a need for improved understanding of the Martian atmosphere, and the SPICAM observations help to constrain the $N_2$ relative abundance.

On Venus, the calculated intensities of VK bands are an order of magnitude larger than those on Mars. Hence, the intensities are quite large and can be detected by the SPICAV experiment on board the Venus Express. The $N_2$ VK band intensities are also calculated on Titan to explain the recent observations by Cassini spacecraft and to validate the model calculations by applying it to a $N_2$-dominated atmosphere. A good agreement is found between observed and modelled intensity of $N_2$ VK band on Titan.

The effects of important model input parameters, viz., electron impact $N_2$ triplet state excitation cross sections, solar activity, and model atmosphere, on the $N_2$ triplet band emissions have been studied. Changes in the cross section of $N_2$ triplet states can alter the calculated intensity by a factor of $\sim$2. During high solar activity, the calculated intensities are about a factor of 2.5 larger than those calculated for the low solar activity conditions.

Recently, the OI 2972 Å emission has been observed on Mars by SPICAM. The presence of this emission on Mars indicates that the OI 5577 Å (green) must also be present on Mars. In view of this a model of atomic oxygen visible emissions on Mars has been developed in this thesis. Since similar atomic oxygen emissions are expected on Venus, this model is also applied to Venus.

The present calculation showed that photodissociation of CO$_2$ is the major source of O($1S$) production on Mars and Venus. Contrary to the recent suggestion of Huestis et al. [2010], the present calculation showed that dissociative recombination of O$_2^+$ is not the main mechanism of O($1S$) production in the 80–170 km region on Mars. Thus,
the O($^1$S) emission cannot be used as a monitor of Martian ionosphere, unlike that recommended by Huestis et al. [2010]. On Mars and Venus, the main production source of O($^1$D) is photodissociation of CO$_2$, while at higher altitudes dissociative recombination of O$_2^+$, O($^1$S) radiative decay, and photodissociation of CO$_2$ are the major sources. The calculated brightness profile of OI 2972 Å on Mars is in good agreement with the SPICAM observation. Calculations carried out in the present study would lead to a better understanding of the photochemical processes governing the O($^1$S) and O($^1$D) production in the atmospheres of Mars and Venus. Based on the model calculated limb intensity profiles of OI emissions and ratio of 6300 and 5577 Å, it is suggested that in future Mars mission the search for red doublet emissions should focus at altitudes above 160 km, whereas for observing of OI 2972 and 5577 Å emissions the altitude region below 150 km is more suitable.

The information derived from the present work is useful for dayglow observations on Mars and Venus currently being carried out by Mars Express and Venus Express, respectively, and will be helpful for future planetary missions e.g, MAVEN and Indian Mars orbiter mission.

**Scope for future work**

The work presented in this thesis demonstrated the importance of modelling studies on Mars and Venus. Some important results are brought out in this work, based on which more in depth studies would be carried out in near future.

The Monte Carlo model developed for electron degradation in a CO$_2$ atmosphere in this thesis, does not include spatial information of electron degradation. However, based on the present technique, a model for altitudinal degradation of electrons in CO$_2$ atmosphere can be developed, which would be useful in understanding the electron energy deposition over the magnetic anomalies on Mars, thus help in modelling the aurora processes on Mars.

One of the important results presented in this thesis showed the importance of e-CO process in Cameron band emissions in the atmospheres of Mars and Venus. On Venus, the present study showed that CO Cameron band intensity calculated by using VTS3 model is inadequate in explaining the very recent measurement by SPICAV. In this context, it becomes important to further study the production of CO Cameron band on Venus with different model atmosphere such as Venus Thermospheric General Circulation Model (VTGCM).

The model of N$_2$ triplet band emissions has been successfully applied to calculated these emissions on Titan. There is further scope for application of this model to calculate N$_2$ triplet band emissions on Triton, biggest moon of planet Neptune, and Pluto. This study would provide useful for future missions and on-route New Horizons mission.

In this thesis, CO Cameron band, CO$_2^+$ (B$^2$Σ$_u^+$) doublet, N$_2$ triplet band, and atomic
oxygen visible (5577, 6300, and 6364 Å) and UV (2972 Å) emissions on Mars and Venus have been studied. There is scope for further studies of other emissions (e.g., CO Fourth Positive, atomic Carbon emission lines, OI 1356 Å etc.) emanating from sunlit atmospheres of Mars and Venus by modifying the existing dayglow model.