CHEMISTRY AND MODELING OF LOWER ATMOSPHERE OF MARS

A THESIS

Submitted for the Award of Ph.D. Degree of PACIFIC ACADEMY OF HIGHER EDUCATION AND RESEARCH UNIVERSITY

By SHAH SIDDHI YOGESHKUMAR

Under the Supervision of

Prof. S. A. HAIDER

Dr. RAKSHIT AMETA



DEPARTMENT OF CHEMISTRY FACULTY OF SCIENCE

PACIFIC ACADEMY OF HIGHER EDUCATION AND RESEARCH UNIVERSITY UDAIPUR

Dedicated to my Family

DEPARTMENT OF CHEMISTRY PAHER UNIVERSITY, UDAIPUR

Prof. S. A. HAIDER Senior Professor

CERTIFICATE

It gives me immense pleasure in certifying that the thesis entitled "CHEMISTRY AND MODELING OF THE LOWER ATMOSPHERE OF MARS" submitted by SHAH SIDDHI YOGESHKUMAR is based on the research work carried out under my guidance. She has completed the following requirements as per Ph.D. regulations of the University.

- (i) Course work as per University rules.
- (ii) Residential requirements of the University.
- (iii) Regularly submitted Half Yearly Progress Report.
- (iv) Published/accepted minimum of two research paper in a refereed research journal.

I recommend the submission of thesis.

Date:

(Prof. S. A. HAIDER)

Ph.D Supervisor Faculty of Science, PAHER University Udaipur

Senior Professor Physical Research Laboratory Ahmedabad

DEPARTMENT OF CHEMISTRY PAHER UNIVERSITY, UDAIPUR

Dr. RAKSHIT AMETA Associate Professor

CERTIFICATE

It gives me immense pleasure in certifying that the thesis entitled "CHEMISTRY AND MODELING OF THE LOWER ATMOSPHERE OF MARS" submitted by SHAH SIDDHI YOGESHKUMAR is based on the research work carried out under my guidance. She has completed the following requirements as per Ph.D. regulations of the University.

- (i) Course work as per University rules.
- (ii) Residential requirements of the University.
- (iii) Regularly submitted Half Yearly Progress Report.
- (iv) Published/accepted minimum of two research paper in a refereed research journal.

I recommend the submission of thesis.

Date:

(Dr. RAKSHIT AMETA)

Co-Supervisor

DECLARATION

I, SHAH SIDDHI YOGESHKUMAR D/o Shri YOGESHKUMAR SHAH

resident of Ahmedabad, Gujarat (India) hereby declare that the research work incorporated in the present thesis entitled " CHEMISTRY AND MODELING OF THE LOWER ATMOSPHERE OF MARS" is my own work and is original. This work (in part or in full) has not been submitted to any University for the award of a Degree or a Diploma. I have properly acknowledged the material collected from secondary sources, wherever required. I solely own the responsibility for the originality of the entire content.

Date: Place: Udaipur (SHAH SIDDHI YOGESHKUMAR) Research Scholar

COPYRIGHT

I, SHAH SIDDHI YOGESHKUMAR, hereby declare that the Pacific Academy of Higher Education and Research University, Udaipur, Rajasthan shall have the rights to preserve, use and disseminate this thesis entitled "CHEMISTRY AND MODELING OF THE LOWER ATMOSPHERE OF MARS" in print or electronic format for academic / research purpose.

Date: Place: Udaipur (SHAH SIDDHI YOGESHKUMAR) Research Scholar

ACKNOWLEDGEMENTS

There are a number of people who deserve to be acknowledged and thanked for their help during my Ph.D. tenure. First of all, I would like to express my sincere and deepest gratitude to my supervisor, **PROF. S. A. HAIDER**, for his meticulous guidance, continued encouragement and moral support all through the pursuance of the research work. I consider myself very fortunate to be associated with **PROF. S. A. HAIDER**. His enthusiasm and integral view on research have made a deep impression on me. He has spent voluminous amount of time with me and helped me in understanding the research issues and improving my presentation skills. He has helped me set milestones and guided me to make steady progress. I have been greatly benefitted from his discussions, remarks and suggestions. His positive attitude towards solving scientific problems teaches me a lot. His supervision helped me throughout my research and writing of this thesis.

I gratefully acknowledge the support of J.C. Bose grant to carry out my thesis work.

I am very much indebted to **DR. RAKSHIT AMETA** my co-supervisor. His suggestions, valuable advices and guidance helped me in many ways.

The inspiration, support and cooperation that I have received from my friends and seniors are beyond the scope of any acknowledgement. Yet, I would like to express my heartfelt gratitude to them. I am very fortunate to have colleagues like **BHAVIN BHAI**, **THIRU BHAIYA**, **DEEPAK BHAIYA**, **ASHIM BHAIYA**, **TIKU BHAIYA**, **DISHA DIDI**, **SHEFALI** and **MASOOM**. I thank them for their moral support, and for creating a fun-loving working atmosphere. When in need, instant help and support was provided by my colleagues. I am truly indebted to them for their positive support and concerns for me.

I would like to thank the Computer Centre staffs, namely **JIGAR SIR**, **TEJAS SIR**, **MISHRA SIR** and **VAIBHAV** for their help regarding computational problems. I am also thankful to staff members of the library for their continuous support.

I would also like to thank **PROF. ANIL BHARADWAJ**, Director, Physical Research Laboratory (PRL), and **PROF. P. JANARDHAN**, Dean, PRL to allow me to avail the facilities of PRL to complete my thesis work.

I am lifelong grateful to my beloved parents, SHRI YOGESHKUMAR SHAH and SMT. VISHAKHABEN SHAH, who worked hard to educate me. Their hard work inspired me to do hard in my studies. I ever express my immense sense of gratitude to them for their love, care, encouragement and support right from my birth. I will be deeply beholden to them. It is my pleasant duty to recall with gratitude the everlasting affection, encouragement and all support which I have been receiving from my sister. I also dedicate this thesis to my lovely sister **RIDDHI PARIKH** for her constant motivation and love. I also gathered courage from the warm wishes coming from my lovely and cute nieces, **JIYA** and **JUHI**. I am thankful to my jiju **NAINESH PARIKH** for his encouragement. I am also thankful to all my cousins and family members for their love and support. I thank the God for giving me such supportive and lovable family.

Last but not the least, the most important people in my life, my loving husband BHAVAN SHAH and our wonderful daughter YASHVI, deserve a special appreciation for their love, care, patience and unconditional support. They never complained about anything even though they missed my presence a lot.

(SHAH SIDDHI YOGESHKUMAR)

PREFACE

The understanding of the complex behavior of the atmosphere and ionosphere of various planets requires a balanced effort in theoretical modeling, experiments and analysis of the observations. The ability to combine observations with numerical models is critical in predicting atmospheric phenomena. Theoretical models based on fundamental principles in conjunction with data from recent satellites are important to improve our understanding of the physical, chemical and dynamical processes in the atmosphere. Given such importance, modeling of planetary atmospheres has been a major thrust area in India. To help in strengthening this area of research, we have developed various models to study the complex behavior of Martian atmosphere/ionosphere and dust storms. The Martian ionosphere can be divided into D, E, and F region. The Mars ionospheric F- region is formed by EUV radiation with wavelength 90 – 1026 Å at altitude ~125-135 km. Mars ionospheric E-region is produced by X-ray radiation with wavelength of 10-90 Å at altitude ~100-112 km. At night the E-region of Mars disappear because of absence of the primary source of ionization. Most of the radio occultation experiments used radio frequency wave to infer the ionosphere of Mars. The lower ionosphere is made of D region. The D peak of electron density occurs at altitude range from 25 to 35 km. In D layer electron density is less than the positive ion density from which the existence of negative ions can be inferred. The primary sources of ionization of D region are galactic cosmic rays.

The Solar flare response is a key problem in the planetary ionosphere. The solar flares are sudden increases in solar radiation associated with sunspots. The occurrence of solar flares directly depends on sunspot number which in turn depends on solar activity.

The sunspot number increases as the sun progresses in its activity during 11-years solar cycle. The solar flares are broadly classified as X, M, C and B-classes according to their Xray brightness in the wavelength range 1 to 70 Å. The GOES, which operate in geostationary orbit above the earth track the solar flares reaching the earth by measuring the X-ray, flux at shorter wavelengths (0.5-3 Å and 1-8 Å) because these shorter wavelength Xray fluxes are more sensitive to the solar flares. Among various Mars' missions, the MGS was the only mission, which measured a large number of electron density profiles (5600) in the ionosphere of Mars during solar maximum conditions so far. It observed the responses of about 32 solar flare events in the electron density profiles of Martian ionosphere. Therefore, the electron density data of MGS is very useful to understand the implications of solar flares on Mars. We have also carried out modelling of D and E region ionosphere of Mars due to impact of soft X-rays, hard X-rays and GCR radiations during solar flare and non-flare conditions. We have reported hard X-rays as a new source of ionization, which also produced D region ionosphere of Mars. We have studied response of all 32 Solar flare in the E region ionosphere of Mars. The effect of ozone, dust, and Schuman resonance frequencies in D region ionosphere of Mars are also studied. In absence of measurements, our model results will provide a benchmark values that may help to guide the design of future atmospheric/ionospheric payloads of Mars.

In the present thesis, we have described eight chapters. In chapter 1, we have introduced Martian atmosphere and ionosphere. In the second chapter, we have described three theoretical models, (1) Energy loss method, (2) Analytical yield spectrum, and (3) Continuity equation. In the third chapter, we have studied effect of solar flares in D region ionosphere of Mars.

In the fourth chapter, we have discussed the response to solar X-ray flares in the E region ionosphere of Mars. In the fifth chapter, we have studied seasonal variability of the ozone in lower ionosphere of Mars. In the sixth chapter, we have described the electrical conductivity and SR frequencies in the lower ionosphere of Mars. In the seventh Chapter, we have discussed the summary and conclusions on the work carried out in the present investigation. Finally, in eighth Chapter, we described the future work.

Contents	
Chapter I	
Introduction	1-12
References	13-15
Chapter 2	
A literature Survey and Numerical	
Methodology used	16-29
References	30-33
Chapter 3	
Effect of solar X-ray flares in the D region ionosphere	
of Mars	34-51
References	52-53
Chapter 4	
Photochemistry of E region ionosphere of Mars	54-78
References	79-81
Chapter 5	
Effect of dust storm on ozone column density	82-10
References	101-10
Chapter 6	
Schumann Resonance and conductivity	104-11
References	120-12
Chapter 7	
Executive Summary	124-12
Chapter 8	
Euture Work	107.10
References	12/-12
Publications	130-13
1 ubicutoits	150 15
Presentations in Conference/Symposium	13

List of Figures

Figure Description	
Figure 1.1 Schematic representation of D, E, and F region ionosphere of Mars	2
Figure 1.2 Schematic representations of ion-aerosol and ion-neutral chemistry in the lower atmosphere of Mars.	
Figure 1.3 Schematic representation of the chemistry in the upper ionosphere of Mars	6
Figure 1.4 Neutral model atmosphere in the lower atmosphere of Mars (taken from Molina-Cuberos et al., 2002)	9
Figure 1.5 Neutral model atmosphere in the upper atmosphere of Mars (taken from Millour et al., 2014)	10
Figure 3.1 Schematic diagram and lifetime of secondary cosmic rays.	36
Figure 3.2 Time series of GOES flux plotted at wavelength (0.5-3Å) for 6 April, 2001 and 17 March, 2003.	39
Figure 3.3 Time series of minimum plasma frequency fmin in D region of Earth's ionosphere (figures 3.3a and 3.3b) and Time series of estimated IEC in D region of Mars' ionosphere (figures 3.3c and 3.3d) for 6 April, 2001 and 17 March, 2003.	42
Figure 3.4 The estimated non-flare electron density profiles due to impact of hard X-rays (0.5-3 Å) on 6 April, 2001 and 17 March, 2003 are shown in figure (see red triangle and blue square). The estimated flare electron density profiles due to impact of hard X-rays (0.5-3 Å) on 6 April, 2001 and 17 March, 2003 are also shown (see red star and blue circle). The estimated electron density profile due to impact of GCR is shown by green crossed line.	45
Figure 3.5 The flare induced density profiles of positive ions $(H_30^+(H_20)_4, H_30^+(H_20)_3, H_30^+(H_20)_2, H_30^+H_20, H_30^+, C0_2^+, 0_2^+C0_2, N0^+, and 0_2^+)$ and negative ions $(CO_3^-(H_20)_2, CO_3^-H_20, CO_3^-, CO_4^-, NO_2^-H_20, NO_2^-(H_20)_2, NO_3^-H_20, and NO_3^-(H_20)_2)$ for 6 April, 2001 are shown in figures a and b respectively. The flare induced density profiles of these positive and negative ions for 17 March, 2003 are plotted in figures c and d respectively. The estimated altitude profile of electron density at flare time is also shown in Figures 3.5 a-d.	
Figure 3.6 Non-flare density profiles of positive ions $(H_3O^+(H_2O)_4, H_3O^+(H_2O)_3, H_3O^+(H_2O)_2, H_3O^+H_2O, H_3O^+, CO_2^+, O_2^+CO_2, NO^+, and O_2^+)$ and negative ions $(CO_3^-(H_2O)_2, CO_3^-H_2O, CO_3^-, CO_4^-, NO_2^-H_2O, NO_2^-(H_2O)_2, NO_3^-H_2O, and NO_3^-(H_2O)_2)$ for 6 April, 2001 are plotted in figures a and b respectively. The non-flare density profiles of these positive and negative ions for 17 March, 2003 are plotted in figures c and d respectively. The non-flare	49

electron density profiles are also plotted in figures 3.6 a-d.	
Figure 3.7 The density profiles due to impact of GCR of positive ions $(H_30^+(H_20)_4, H_30^+(H_20)_3, H_30^+(H_20)_2, H_30^+H_20, H_30^+, CO_2^+, O_2^+CO_2, NO^+, and O_2^+)$ and negative ions $(CO_3^-(H_20)_2, CO_3^-H_20, CO_3^-, CO_4^-, NO_2^-H_20, NO_2^-(H_20)_2, NO_3^-H_20, and NO_3^-(H_20)_2)$ for 6 April, 2001 are shown in figures a and b respectively. The estimated altitude profile of electron density at flare time is also shown in Figures 3.7 a-b.	51
Figure 4.1 10 X-class (a_1 - a_{10}) flare electron density profiles observed by MGS on 10 respective flare days. The flare profiles are plotted by red lines. Latitude, LT and SZA refer to the flare time profile only.	59
Figure 4.2 Same as in figure 4.1 but for M-class (b ₁ -b ₁₂) flare electron density profiles observed by MGS	60
Figure 4.3 Same as in figure 4.1 but for C-class (c ₁ -c ₁₀) flare electron density profiles observed by MGS	61
Figure 4.4 Relationship between $\log_{10} (N_f/N_o)$ and $\log_{10} (F_f/F_o)$ with standard deviation for 10 X-class (a), 12 M-class (b) and 10 C-class (c) flares. SZA are shown by different colors for different flare profiles. The solid lines are fitted by linear regression for 10 X-class, 12 M-class and 10 C class flares.	64
Figure 4.5 Left panel: The % increase in IEC at different UT for 10 X-class (a), 12 M-class (b) and 10 C-class (c) flare profiles as observed by MGS. Right panel: The % increase in corresponding solar X-ray fluxes at different UT for 10 X-class (d), 12 M-class (e) and 10 C-class (f) flares as observed by GOES 10 at peak flare time.	66
Figure 4.6 Variation of peak electron production rates with Ls for 10 X-class (a), 12 M-class (b) and 10 C-class (c) flare profiles as given in Table 1. These are fitted by sinusoidal function with standard deviation. Figure 4.6(d) shows the heliocentric distance of Mars as a function of Ls.	69
Figure 4.7 (a) Comparison between the modeled and observed electron density profiles on 6 April, 2001 and (b) 17 March, 2003. MGS observed these profiles. The electron densities are calculated on both days due to impact of X-rays (1-8 Å).	73
Figure 4.8 (a, b) Model calculation of ion densities of CO_2^+ , N_2^+ , O_2^+ , O_2^-	75
Figure 4.9 Comparison between the electron density profiles of our model result of 6 April 2001(blue triangle), Lollo et al. 2012 model result of 15 April, 2001 (red cross) and MGS observation during flare period from 80 to 200 km (pink star).	77
Figure 5.1 . The zonally average UV dust optical depth as observed by SPICAM in MY 28 and MY 29 at southern latitude (25°S-35°S).	85
Figure 5.2 Ozone column density from MCD model at 25° S latitude between Ls = 250° to 350° for MY 28 and MY 29.	88

Figure 5.3 Zonally averaged ozone column densities with error bars as observed by SPICAM in MY 28 at low, mid and high latitude. These observations are compared with zonally averaged ozone column densities obtained from MCD model in MY 28 in the daytime ionosphere of Mars.	90
Figure 5.4 Same as in figure 5.3 but for MY 29.	92
Figure 5.5 The zonal mean production rates of O_3^+ on the surface of Mars at latitudes 2°N (a), 25°N (b), 45°N (c), 70°N (d), 2°S (e), 25°S (f), 45°S (g) and 70°S (h) in MY 28 and MY 29.	95
Figure 5.6 The vertical profiles of $, 0_3^+$ production rate in MY 28 at latitudes 2°N (a), 2°S (b), 25°N (c) and 25°S (d) for Ls = 7.5°, 47.5°, 87.5°, 127.5°, 167.5°, 207.5°, 247.5°, 287.5° and 327.5°	96
Figure 5.7 same as in figure 5.6 but for latitudes $45^{\circ}N$ (a), $45^{\circ}S$ (b) $70^{\circ}N$ (c) and $70^{\circ}S$ (d)	98
Figure 6.1 Schematic diagram of ELF and VLF propagation and SR in planetary surface-ionosphere cavity (Simoes et al., 2012)	106
Figure 6.2 Comparison of ionospheric conductivities between present and other model calculations carried by Molina-Cuberos et al., 2006 and Cardnell et al., 2016.	112
Figure 6.3 Altitude profiles of Schumann Resonance frequency in the night time ionosphere of Mars in MY 25 during high dust storm ($\tau = 1.7$) at low latitude region (25°-35°S).	
Figure 6.4 Block diagram of LEMa experiment for proposed Mars mission to detect lightning	118



Krasnopolsky, V. A (2012), Search for methane and upper limits to ethane and SO2 on Mars. Icarus, **217**, 144-152.

McAdam, A., Franz, H., Archer Jr, P., Freissinet, C., Sutter, B., Glavin, D, et al. (2013), Insights into the Sulfur Mineralogy of Martian Soil at Rocknest, Gale Crater, Enabled by Evolved Gas Analyses.

Venkateswara Rao, N., Leelavathi, V., Mohanamanasa, P., Haider, S. A., and Rao, S. V. B (2019), Enhanced ionization in magnetic anomaly regions of the Martian lower ionosphere associated with dust storms. J. Geophys. Res., Space Physics, **124**, 3007-3020.



Effect of Dust Storm and GCR Impact on the Production Rate of O₃⁺ in MY 28 and MY 29: Modeling and SPICAM Observation

S. A. Haider¹, Y. S. Siddhi^{1,2}, J. Masoom^{1,2}, S. Bougher³

¹Planetary Sciences Division, Physical research Laboratory, Ahmedabad, India
²Research Scholar, Faculty of Science, Pacific Academy of Higher Education of ResearchUniversity, Udaipur, India

³Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, USA

ABSTRACT

We have developed a seasonally dependent energy loss model to calculate the zonally averaged production rates of O_3^+ due to impact of galactic cosmic rays in the dayside troposphere of Mars between solar longitudes (Ls) ~0° and 360° at low latitudes (2°N, 2°S, 25°N, and 25°S), mid-latitudes (45°N and 45°S), and high latitudes (70°N and 70°S) in the Martian Year (MY) 28 and MY 29. We also represent the seasonal variability of zonally averaged ozone column density obtained from Mars Climate Database (MCD; Millour et al., 2014, https://hal.archives-ouvertes.fr/hal-01139592) during the daytime. These results are compared with the daytime observations of column ozone made by Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars onboard Mars Express (MEX). At mid-to-high latitudes ozone column density is maximum in northern winter and minimum in southern summer. At low-to-middle latitudes (2°N–S, 25°N–S, and 45°N–S), the production rates of 0^+_3 represent a broad peak between altitudes 26 and 45 km in both hemispheres. The peak production rates are increasing up to Ls = 47.5° and then stabilized at about 2.5×10^{-8} cm⁻³/s. At Ls $\ge 47.5^{\circ}$ the peak production rate of O_3^+ starts decreasing until it disappeared after Ls = 127.5°. A major dust storm occurred in MY 28 at Ls~280° in southern latitudes (~25°-35°S). During the dust storm period, dust opacity, ozone column density, and 0^+_3 production rate on the surface of Mars were increased by a factor of ~3.

Published in: Journal of Geophysical Research: Space Physics, **124**, 2271–2282(2019), ISSN: 2169-9402

Schumann resonance frequency and conductivity in the nighttime ionosphere of Mars: A source for lightning

S. A. Haider¹, Jayesh P. Pabari¹, J. Masoom^{1,2} and Siddhi Y. Shah^{1,2}

¹Planetary Science Division, Physical Research Laboratory, Ahmedabad, India

²Research Scholar, Faculty of Science, Pacific Academy of Higher Education and

Research

University, Udaipur, India

ABSTRACT

We have solved the Maxwellian equations of electromagnetic waves which oscillate within the cavity formed in the lower ionosphere of Mars between 0 and 70 km. The electrical conductivity and Schumann Resonance (SR) frequencies are calculated in the lower ionosphere of Mars, in the presence of a major dust storm that occurred in Martian Year (MY) 25 at low latitude region $(25^{\circ}-35^{\circ}S)$. It is found that the atmospheric conductivity reduced by one to two orders of magnitude in the presence of a dust storm. It represents a small dust layer at about 25–30 km altitudes where lightning can occur. We also found that the SR frequencies peak at ~18 km with values 19.9, 34.5 and 48.8 Hz for the modes 1 = 1, 2 and 3, respectively, in the non-homogeneous medium. Our results indicate that practical or measurable values of SR are dependent on the altitudes.

Published in: Advances in Space Research, **63**, 2260-2266 (2019), ISSN: 0273-1177

Characteristics of solar X-ray flares and their effects on the ionosphere and human exploration to Mars: MGS radio science observations

P. Thirupathaiah^{a,1}, Siddhi Y. Shah^{a,b}, S.A. Haider^{a,*}

^aPlanetary Sciences Division, Physical Research Laboratory, Ahmedabad, India

^bFaculty of Science, Pacific Academy of Higher Education and Research

University, Udaipur, India

ABSTRACT

Responses of solar X-ray flares were observed in a layer of the Martian ionosphere at altitudes of ~110 km from 32 electron density profiles obtained by radio science experiment onboard Mars Global Surveyor (MGS) during solar cycle 23. Of the 32 profiles recorded during flare periods, 10 were associated with X-class flares, 12 with M class and 10 with C class flares. The flare E-peak densities vary with solar X-ray flux, Solar Zenith Angle (SZA), Solar Longitude (Ls) and latitudes. Ionospheric Electron Content (IEC) and E-peak electron production rates of these flare profiles are estimated in the E region ionosphere. We found a maximum increase of ~200%, ~140% and ~90% in the time series of IEC for X, M and C class flares respectively. The dependence of flare E-peak electron production rate with Ls is fitted by a sinusoidal function. We have also calculated biological doses ~0.1-1.0×10⁻¹, $1-8\times10^{-3}$ and $1-6\times10^{-4}$ Gy for X, M, C class flares X1 is a strong solar flare that gives highest dose, which is potentially lethal for human risk in Mars' space.

Published in: Icarus, **330**, 60-74 (2019), ISSN: 0019-1035

Presentations in Conference/Symposium

1 Model calculation of production rate of H₂O and O₃ on lower atmosphere of Mars: Seasonal Variability

Siddhi Y. Shah, S. A. Haider

Date: 9-12 February, 2016

Organizer: 19th National Space Science Symposium held at Space Physics Laboratory, Vikram Sarabhai Space Center, Thiruvananthapuram.

2 Effect of Solar flares on ionosphere of Mars

Siddhi Y. Shah, S. A. Haider

Date: 8-10 November, 2017

Organizer: Brain Storming Session on Vision and Explorations for Planetary Sciences in Decades 2020-2060, Physical Research Laboratory, Ahmedabad.

3 Calculated electron density due to impact of hard X-rays in D region ionosphere of Mars: First model result

Siddhi Y. Shah, S. A. Haider

Date: 29-31 January, 2019

Organizer: 20th National Space Science Symposium to be held at Savitribai Phule Pune University, Pune.

List of Publications

- Haider, S. A., Batista, I. S., Abdu, M. A., Muralikrishna, P., Shah, S. Y., and Kuroda, T (2015), Dust storm and electron density in the equatorial D region ionosphere of Mars: Comparison with Earth's ionosphere from rocket measurements in Brazil. J. Geophys. Res., 120, 8968-8977.
- Haider, S. A., Batista, I. S., Abdu, M. A., Santos, A. M., Shah, S. Y, et al. (2016),Flare X-ray photochemistry of the E region ionosphere of Mars. J. Geophys.Res., Space Physics, 121, 6870-6888.
- Siddhi Y. S, Haider,S.A., Molina-Cuberos, G. J,Abdu, M.A., Batista, I (2019), A coupled model of the D and E regions of Mars' ionosphere for flare and non-flare electron density profiles: Comparison with Earth's ionosphere, Icarus. (Under review).
- Haider, S. A., Siddhi Y. S, Masoom, J., Sheel, V., and Kuroda, T (2019), Dust loading on ozone, winds and heating rates in the tropics of southern atmosphere of Mars: Seasonal variability, climatology and SPICAM observations. Q J R MeteorolSoc, (Under review).