Dust, Haze and Clouds on Mars and Titan

S N Tripathi and MaryKutty Michael

Department of Civil Engineering, Indian Institute of Technology Kanpur

Abstract

Dust has been observed on the atmospheres of various heavenly bodies beyond the terrestrial atmosphere. We are particularly interested in the atmospheres of Mars and Titan (satellite of Saturn) as the dust, haze and clouds on these heavenly bodies are of great interest to the scientific community due to the distinct characteristics. We have seen an explosion in the amount of data in the past one and a half decade from Mars and Titan due to the successful operation of various spacecrafts at Mars (including the Pathfinder, Mars Global Surveyor, Mars Odyssey, Mars Express, Mars Exploration Rovers, and Mars Reconnaissance Orbiter) and the Cassini-Huygens mission in the Saturn system.

The long term observations of dust in the atmosphere of Mars can explain the seasonal pattern of dust activity on Mars. The main feature of the annual cycle is the intermittent occurrence of regional and global dust storms during the period of maximum insolation (perihelion season) or when the surface and atmosphere are warmest. It takes several months for the dust to settle down after a global dust storm. Regional dust storms occur every Martian year and the planet-encircling or the global dust storms occur once in about three Martian years. The presence of water ice clouds is usually anti-correlated with that of dust. The largest dust storms are observed during the dusty perihelion season, while the clouds are mostly observed during the cooler aphelion season. The appearance of low-latitude clouds repeats every Martin year with very similar amplitude and spatial distribution.

The polycyclic aromatic hydrocarbons (PAH) which is one of the main constituents of the thick haze on the Titan's atmosphere is best known as carcinogens and environmental pollutants on Earth. Except the haze layers close to the surface of Titan, detached haze layers were observed at altitudes 300 - 600 km above the surface. Particles of tens of nm size were also observed even at about 1000 km above the surface. All these can be explained by the complex photochemistry functioning in the atmosphere of Titan. Methane ice clouds were also observed by Cassini instruments on Titan.

Introduction

Dust has been observed on the atmospheres of various heavenly bodies beyond the terrestrial atmosphere. We are particularly interested in the atmospheres of Mars and Titan (a satellite of Saturn) as the dust, haze and clouds on these heavenly bodies are of great interest to the scientific community due to their distinct characteristics. In the past one and half decades, there has been an exponential rise in the amount of data gathered on Mars and Titan. This is due to the successful operations of various spacecrafts on Mars (including the Pathfinder, Mars Global Surveyor (MGS), Mars Odyssey, Mars Express, Mars Exploration Rovers, and Mars Reconnaissance Orbiter), and the highly successful Cassini-Huygens mission in the Saturn system.

Mars

The dust activity on Mars has been known to the scientific community since the early 19th century. Though many dust events were reported from Earth-based observations, the dawn of the "spacecraft era" gave clearer information about the dust devils, dust storms, planet-encircling storms, and so forth. The global dust storms observed by the Mariner 9 and the Viking orbiters have helped to strengthen both our awareness on and the importance of these events in the Martian atmosphere and surface. The fact that many spacecraft observations have been conducted to study the dust activity in the Martian atmosphere, and that hundreds of articles have been published on the same topic, makes us realize the complexities and the importance of dust behaviour over there.

The early investigations of dust on Mars were made through ground-based telescopic observations. Though these measurements were meritorious, their limitations introduced considerable uncertainties with regard to dust storm detection and identification. The difference between the dust in the atmosphere and that on the surface was not very pronounced, the differences in the different layers of the atmosphere of the Earth was not effectively taken care of, albedo changes were not considered important, and many such issues were associated with those observations made from Earth. The earliest space-craft observations were made in the 1960s and 70s. Mariner 4, 6, and 7 made flybys at Mars in 1965 and 1969. Mariner 9 orbited Mars for about 11 months during 1971-72. Viking 1 and 2 entered the Martian orbit in 1976 and orbited around Mars for 4 years and 2 years respectively.

In the last decade and a half, we have seen an explosion of data on Mars due to several spacecraft missions and good quality microwave observations from the Earth. The new era of spacecraft observations began with the launching of MGS (Mars Global Surveyor) in 1997, and in just a matter of one and a half decades, the information gathered about other planetary atmospheres has increased multifold as compared to the hundreds of years of ground-based observations and modeling.

One of the key physical parameters used to quantify the presence of dust in the atmosphere is the column optical depth (optical thickness or opacity). It is a measure of the fraction of radiation at a specific wavelength that would be removed from the vertical component of a beam during its path through the atmosphere by extinction (absorption and scattering) because of the presence of airborne dust. The optical depth of the background dust is usually in the range of 0.3 - 0.5, while the opacity becomes greater than 1 during dust storms. Cantor (2007) reported that the opacity reached 5 during the global dust storm of 2001. It is now believed that in about one to three Martian cycles, there is at least one global dust storm that occurs during maximum insolation, Ls = 180° - 310°(The solar longitude (Ls) is the Mars-Sun angle measured from the Northern Hemisphere spring equinox where Ls = 0. Ls = 90 corresponds to the summer solstice, Ls = 180 is the autumn equinox and Ls = 270 is the winter solstice).

Dust enters the atmosphere of Mars mainly by wind-driven emissions, a process termed as the aeolian process. On Earth, aeolian processes mainly occur in the deserts. With sufficient wind speed, sand particles of ~ 100 μm are moved by fluid drag, and then these particles hop along

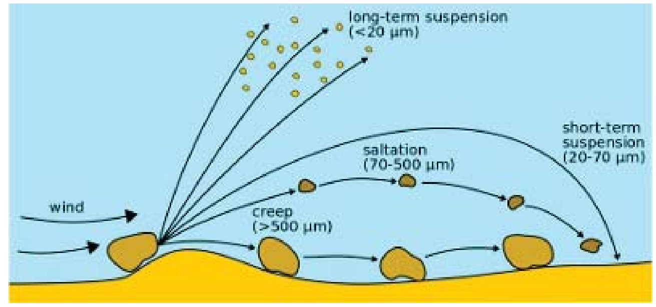

Figure 1. Schematic of the different modes of aeolian transportation. Creep: The largest particles are moving by rolling motion. Saltation: Particles in the size range from 70-500 μm are moving by hopping motion. Suspension: The smallest particles are wafting due to turbulent diffusion. (http://www.wmo.int/pages/prog/arep/wwrp/new/source.html

the surface in a process known as saltation. Dust particles are not generally lifted directly by wind, but are ejected from the soil by the saltating particles. Figure 1 shows a schematic of such processes. The airborne dusts thus generated can be transported to thousands of kilometers from their source regions. (More details about this process can be found in the following article and references therein; Kok et al., 2012).

The dust storms on Mars can be classified into three types according to their sizes. The largest type is the planet-encircling storm, which engulfs all longitudes of the planet. These storms are also known as global or planet-wide storms. The second type is the regional storm with an affected area of more than 2000 km, and the third type is the local storm with an affected area of less than 2000 km. In general, most of the dust storms, irrespective of their size, originate in the southern hemisphere. Most global storms have been observed during the southern spring and summer seasons. Though regional dust storms occur in nearly all seasons, they tend to occur most frequently in the southern spring and summer seasons, known as the dust storm season. This period is nearly centered on the perihelion (Ls = 250°), which is the time of maximum insolation on Mars. The probability of occurrence of regional and local storms during a dust storm season is approximately 80%, while the planet-encircling storms occur once in approximately 2-3 Mars years. (More details about the types of storms and their seasonal and interannual variability can be obtained from the following articles and references therein; Fernandez, 1998; Smith, 2008; Montabone et al., 2015). Figure 2 shows one of the biggest dust storms observed by Hubble Space Telescope. The image on the left side was taken before the onset of the dust storm and the one on the right

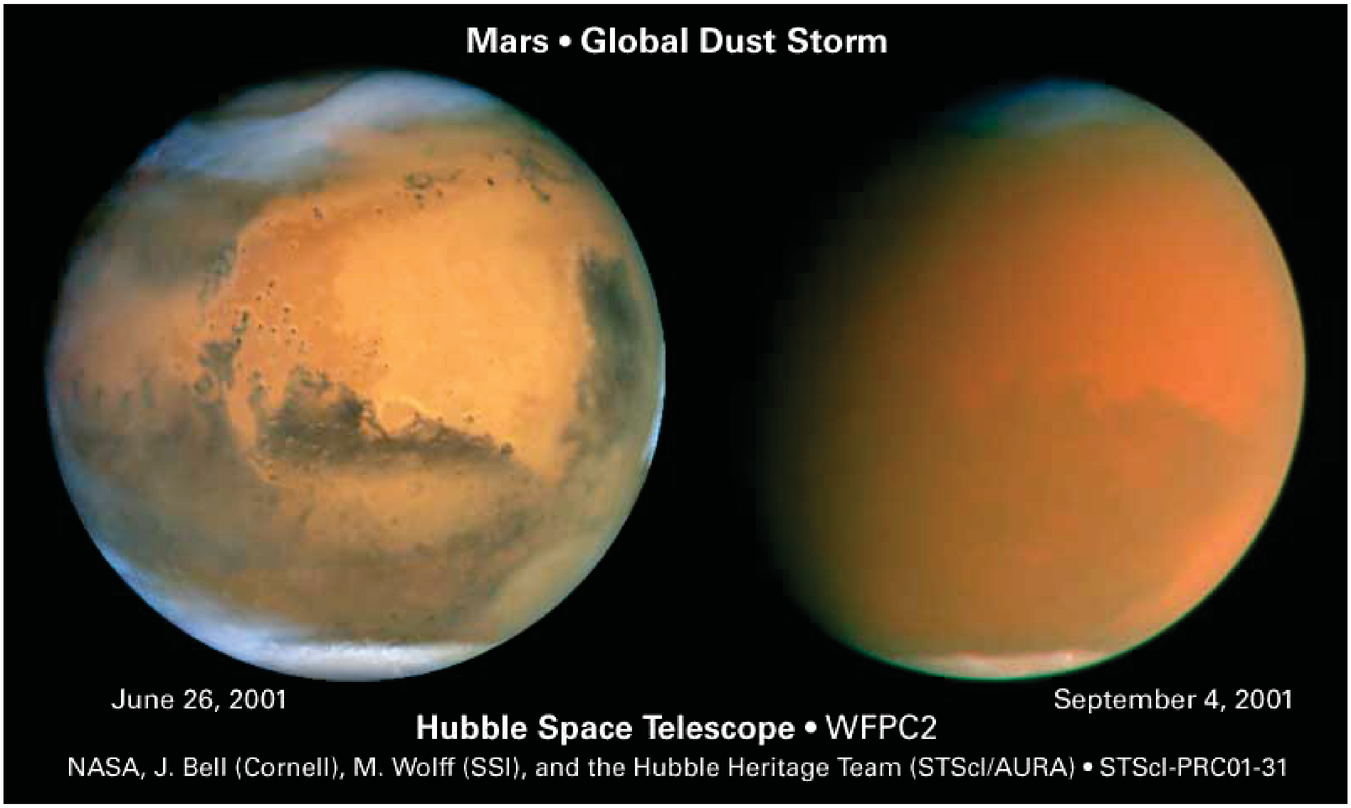

Figure 2. On June 26, 2001, the Hubble Space Telescope spotted a dust storm brewing in the southern crater (Hellas Basin) on Mars. Within days, the storm "exploded" and became a global event. In September, the storm obscured all surface features. (http://www.spacetoday.org/SolSys/Mars/MarsThePlanet/MarsDustStorms.html).

is the image of Mars, after the whole planet was engulfed by dust obscuring all surface features.

Montabone et al. (2015) produced a continuous multiannual climatology of column dust optical depth from March 1999 (Mars Year (MY) 24) to July 2013 (MY 31). During this period, the Thermal Emission Spectrometer onboard MGS, Thermal Emission Imaging system on Mars Odyssey, and the Mars Climate Sounder on Mars Reconnaissance Orbiter provided a global coverage of radiance observations at IR wavelengths from which the column optical depth was estimated. During 2001 (MY 25) and 2007 (MY 28), planet-encircling dust storms were observed. Figure 3 is useful in summarizing the inter-annual similarities and differences in the column dust optical depth for 8 Mars Years. For Ls = 0° - 180° there is little inter-annual variability. Except those years with global dust storms (MY 25 and 28), the opacities show a similar pattern with a peak at Ls = 220° - 260° and a smaller peak around Ls = 320°.

In addition to dust, aerosols in the form of condensate clouds made up of water-ice and CO_2-ice have been observed on Mars. Water ice aerosols nucleating on the dust particles appear to remove dust particles from the atmosphere. Water ice clouds take many forms including a low-latitude belt of clouds generated during the aphelion season between Ls = 40°-140°. The cloud belt begins to form around Ls = 0° and reaches maximum density and spatial coverage by about Ls = 80° with a significant optical depth between 10°S and 30°N latitude. The cloud belt starts to disappear when the atmospheric temperature rises (Ls = 140°). In general, the optical depth of water ice clouds is anti-correlated with that of dust, which means that large dust storms form usually during the perihelion season (Ls=180°-360°), and that water ice clouds are mainly observed during the cooler aphelion season (Ls=0°-180°). The CO_2 ice clouds have been observed at places where atmospheric temperatures are cold enough for CO_2 to condense. These are commonly observed in the region of polar winter total darkness. Various spacecraft observations also confirmed the presence of CO_2 ice clouds at altitudes 60 - 80 km above the surface. (More details about Martian clouds

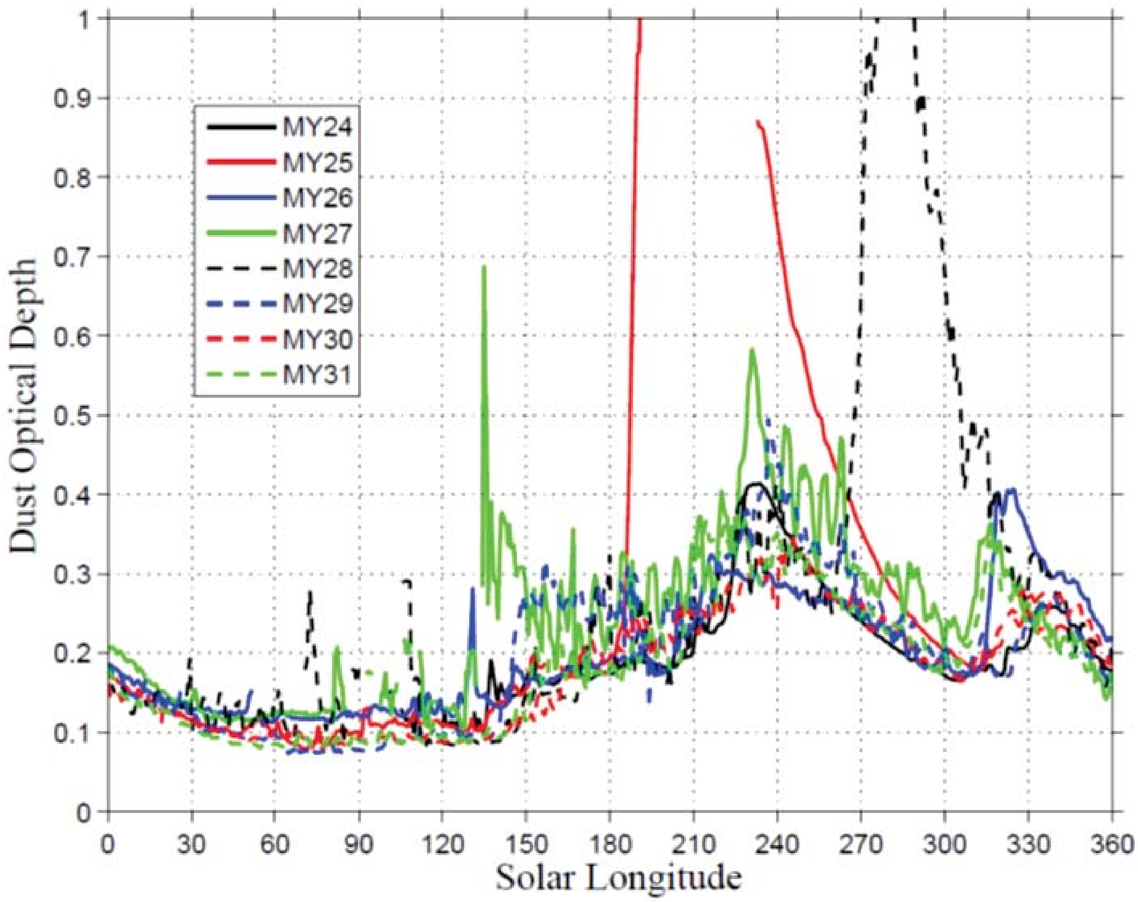

Figure 3. Plot of equatorial (5°S - 5°N) 9.3μm absorption column dust optical depth as a function of solar longitude for eight Martian years (MY 24 - MY 31) (Montabone et al., 2015).

can be obtained from Whiteway et al., 2009; Smith, 2008)

Titan

Titan possesses an atmosphere that is often compared to that of the Earth as it is composed mainly of N_2. It also possesses CH_4 and a wealth of organic materials. A well-defined haze structure has been observed on the Titan since the Voyager era. Until recently, the haze obscured the surface of the Titan from direct visible observations. The ongoing Cassini/Huygens mission has provided valuable data which has helped the researchers to understand the haze structure and the surface of the satellite. The origin of the haze is linked to the photochemistry taking place in the atmosphere. Nitrogen and methane are photo dissociated by solar ultraviolet radiation, energetic particles from Saturn's magnetosphere, and galactic cosmic rays, leading to the initiation of a complex organic photochemistry, which finally produces the haze.

Cassini-Huygens observations have shown that there is a thick layer of haze close to the surface of the satellite, and then a detached layer of haze particles in the altitude range of 500 - 800 km. Cassini instruments have also observed heavy charged particles in the ionosphere of the Titan (950 - 1200 km). Several modelers have studied such a structure of haze in the atmosphere. (Liang et al., 2007; Lavvas et al., 2008). A representative diagram is provided in Figure 4. Galactic cosmic rays are energetic enough to penetrate deep into the atmosphere and reach the lower atmosphere of the Titan, interact with nitrogen containing species or nitriles, and produce haze particles at altitudes less than 300 km. Solar radiation in the extreme ultraviolet and energetic electrons from Saturn's magnetosphere ionize and dissociate nitrogen molecules above 1000 km, produce nitrile species and eventually produce haze particles of tens of nanometer size in

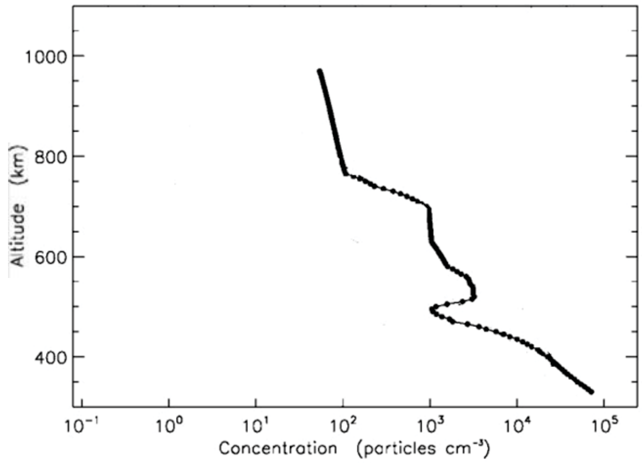

Figure 4. Aerosol density in the atmosphere of Titan (Liang et al. Photolytically generated aerosols in the mesosphere and thermosphere of Titan, Astrophysical journal, 661, L199-L202, 2007).

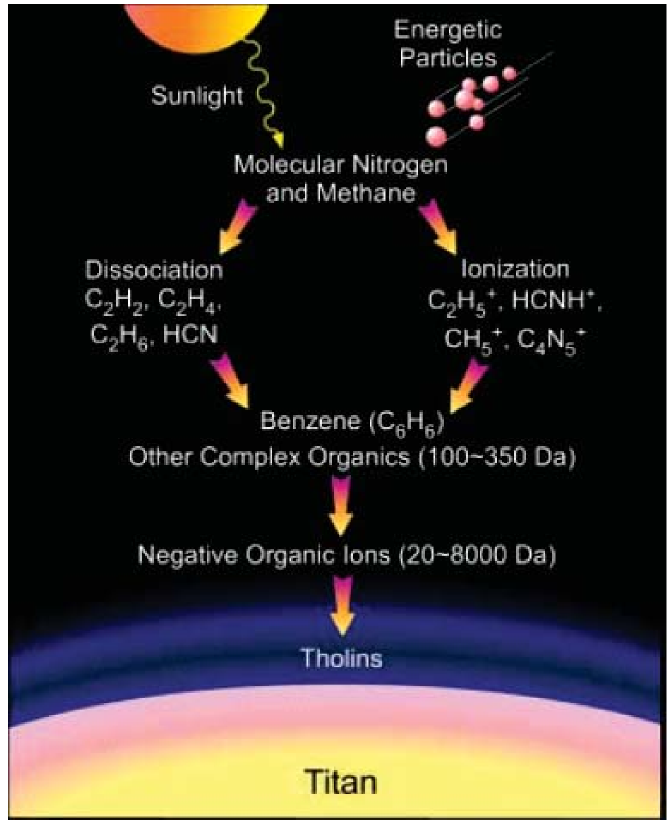

Figure 5. A diagrammatic representation showing the chemical process leading up to the formation of tholins in the Titan's upper atmosphere. The process begins with free energy from solar UV radiation and energetic particles impinging on the Titan's atmosphere. N_2 and CH_4 undergo a lot of chemical reactions to form larger organic and nitrile compounds that eventually leads to the formation of tholin aerosols (Waite et al., The process of Tholin formation in the Titan's upper atmosphere, Science, 316, 870-875, 2007).

diameter. A schematic diagram showing this process is provided in Figure 5. Solar radiation of higher wavelength interact with hydrocarbons at altitudes less than 1000 km, and produce haze particles in the altitude region of 500 - 1000 km. (More details can be found in the book: Titan from Cassini Huygens, 2009; Waite et al. , Science, 2007)

Methane clouds on the Titan were observed in the troposphere and over the North Pole during the Voyager flybys. Cassini images showed frequent clouds in the southern hemisphere that were elongated in the east-west direction (Rannou et al., 2006). Recently, methane clouds were observed in the stratosphere, which were expected to be produced due to the temperature difference between the equatorial region and the north pole. The warm air in the summer hemisphere enters the stratosphere and flows towards the winter pole. There the air mass sinks down, cooling as it descends, forming the stratospheric clouds (Anderson et al. , 2014).

Summary

The generation of dust in the atmosphere of Mars and some of the interesting characteristics about the dust activities on Mars have been discussed here. The presence of CO_2 and water ice clouds on Mars has also been mentioned. Despite being different in a number of ways, the atmosphere of Titan is very similar to that of the Earth mainly due to the presence of N_2. The haze formation in the atmosphere of Titan at various altitudes have also been described here. Recent spacecraft observations were able to point out the presence of methane clouds in the atmosphere of Titan.

Reference

[1] Anderson, C.M., et al. Subsidence-induced methane clouds in Titan's winter polar straosphere and upper troposphere, Icarus, 243, 129-138, 2014.

[2] Cantor, B.A., MOC observations of the 2001 Mars planet encircling dust storm, Icarus, 186, 60-96, 2007.

[3] Fernandez, W., Martian dust storms: A review, Earth, Moon and Planets 77 19-46, 1998.

[4] Kok J. F., et al., The physics of wind-blown sand and dust Rep. Prog. Phys. 75 106901, 2012.

[5] Lavvas, P.P., et al., Coupling photochemistry with haze formation in Titan's atmosphere, Part II: Results and validation with Cassini/Huygens data, Planetary and Space Science, 56, 67-99, 2008.

[6] Liang, M.C. et al., Photolytically generated aerosols in the mesosphere and thermosphere of Titan, Astrophysical journal, 661, L199-L202, 2007.

[7] Montabone, L. et al., Eight year climatology of dust optical depth on Mars, 251, pp.65-95, Icarus 2015.

[8] Rannou, P. et al. The latitudinal distribution of clouds on Titan, Science, 311, 201-205, 2006.

[9] Smith, M.D., Spacecraft observations of the Martian atmosphere, Annu. Rev. Earth Planet. Sci. 36:191-219, 2008.

[10] Waite, J.H., et al. The process of Tholin formation in Titan's upper atmosphere, Science, 316, 870-875, 2007.

[11] Whiteway, J.A., et al., Mars water-ice clouds and precipitation, Science, 325, 5936, 68-70, 2009.

Professor Sachchida Nand Tripathi had his Ph. D. from Reading University and post-docs at Bhabha Atomic Research Center and Oxford University. He currently holds professor position in Civil Engineering Department and is an adjunct professor in Earth Sciences at Indian Institute of Technology, Kanpur. He has been a Senior Fellow at NASA Goddard Space Flight Center. He obtained his B. Tech. in Civil Engineering from IIT-BHU (Formerly IT-BHU). Sachchida Nand Tripathi has been awarded NASI-SCOPUS young scientist award-2009 in Earth Sciences and Shanti Swarup Bhatnagar Award 2014 in Earth, Atmosphere, Ocean and Planetary Sciences. His research interests are aerosol optics and cloud forming properties, aerosol-rainfall interactions and climate mitigation.

Dr. Marykutty Michael completed her doctoral research in Space Physics Laboratoty, Vikram Sarabhai Space Centre, ISRO, Thiruvananthapuram and obtained the degree in 2001. She worked as a Post-doctoral Research Associate in the University of Virginia, USA during the period 2001-2004 and then in Centre-d-Etude-des-Environnements-Terrestre-et- Planetaires (CETP), CNRS, Paris, France. In 2005 she moved to Indian Institute of Technology Kanpur to work as a Research Scientist and from 2010 to 2013 she was a DST fast track Scientist. She has worked mostly on the interaction of ions, electrons and charged aerosols with the neutrals in the atmospheres of various heavenly bodies (Io, Titan, Mars, Venus) and also in the terrestrial atmosphere. She has published about 30 papers in international journals, and 3 book chapters. There are about 600 citations for her articles.