Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 55 (2015) 2217–2238

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Atmospheric movies acquired at the Mars Science Laboratory landing site: Cloud morphology, frequency and significance to the Gale Crater water cycle and Phoenix mission results

John E. Moores [a,*], Mark T. Lemmon [b], Scot C.R. Rafkin [c], Raymond Francis [d], Jorge Pla-Garcia [e], Manuel de la Torre Juárez [f], Keri Bean [b,1], David Kass [f], Robert Haberle [g], Claire Newman [h], Michael Mischna [f], Ashwin Vasavada [f], Nilton Rennó [i], Jim Bell [j], Fred Calef [f], Bruce Cantor [k], Timothy H. Mcconnochie [l], Ari-Matti Harri [m], Maria Genzer [m], Michael Wong [i], Michael D. Smith [n], F. Javier Martín-Torres [o,p], María-Paz Zorzano [e], Osku Kemppinen [m], Emily McCullough [d]

[a] *York University, Centre for Research in the Earth and Space Sciences (CRESS), Canada*
[b] *Texas A&M University, United States*
[c] *Southwest Research Institute, United States*
[d] *University of Western Ontario, Canada*
[e] *Centro de Astrobiología, Spain*
[f] *Jet Propulsion Laboratory/Caltech, United States*
[g] *Ames Research Centre, United States*
[h] *Ashima Research Corporation, United States*
[i] *University of Michigan, United States*
[j] *Arizona State University, United States*
[k] *Malin Space Science Systems, United States*
[l] *GSFC/U Maryland, United States*
[m] *Finnish Meteorological Institute, Finland*
[n] *NASA-Goddard Space Flight Center, United States*
[o] *Instituto Andaluz de Ciencias de la Tierra (CSIC-UGR), Spain*
[p] *Division of Space Technology, Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Kiruna, Sweden*

Received 15 July 2014; received in revised form 20 January 2015; accepted 4 February 2015
Available online 20 February 2015

Abstract

We report on the first 360 sols (L_S 150° to 5°), representing just over half a Martian year, of atmospheric monitoring movies acquired using the NavCam imager from the Mars Science Laboratory (MSL) Rover Curiosity. Such movies reveal faint clouds that are difficult to discern in single images. The data set acquired was divided into two different classifications depending upon the orientation and intent of

* Corresponding author. Tel.: +1 416 736 5731.
E-mail addresses: jmoores@yorku.ca (J.E. Moores), lemmon@tamu.edu (M.T. Lemmon), rafkin@boulder.swri.edu (S.C.R. Rafkin), Raymond.francis@cpsx.uwo.ca (R. Francis), jpla@cab.inta-csic.es (J. Pla-Garcia), mtj@jpl.nasa.gov (M. de la Torre Juárez), Keri.Bean@jpl.nasa.gov (K. Bean), David.Kass@jpl.nasa.gov (D. Kass), Robert.M.Haberle@nasa.gov (R. Haberle), Claire@ashimaresearch.com (C. Newman), Michael.A.Mischna@jpl.nasa.gov (M. Mischna), Ashwin.R.Vasavada@jpl.nasa.gov (A. Vasavada), nrenno@umich.edu (N. Rennó), Jim.Bell@asu.edu (J. Bell), Fred.Calef@jpl.nasa.gov (F. Calef), cantor@msss.com (B. Cantor), timothy.h.mcconnochie@nasa.gov (T.H. Mcconnochie), Ari-Matti.Harri@fmi.fi (A.-M. Harri), Maria.Genzer@fmi.fi (M. Genzer), mike.wong@umich.edu (M. Wong), michael.d.smith@nasa.gov (M.D. Smith), javiermt@iact.ugr-csic.es (F. Javier Martín-Torres), zorzanomm@cab.inta-csic.es (M.-P. Zorzano), osku.kemppinen@fmi.fi (O. Kemppinen), emccull2@uwo.ca (E. McCullough).
[1] Now at JPL/Caltech.

http://dx.doi.org/10.1016/j.asr.2015.02.007

the observation. Up to sol 360, 73 Zenith movies and 79 Supra-Horizon movies have been acquired and time-variable features could be discerned in 25 of each. The data set from MSL is compared to similar observations made by the Surface Stereo Imager (SSI) onboard the Phoenix Lander and suggests a much drier environment at Gale Crater (4.6°S) during this season than was observed in Green Valley (68.2°N) as would be expected based on latitude and the global water cycle. The optical depth of the variable component of clouds seen in images with features are up to 0.047 ± 0.009 with a granularity to the features observed which averages 3.8°. MCS also observes clouds during the same period of comparable optical depth at 30 and 50 km that would suggest a cloud spacing of 2.0 to 3.3 km. Multiple motions visible in atmospheric movies support the presence of two distinct layers of clouds. At Gale Crater, these clouds are likely caused by atmospheric waves given the regular spacing of features observed in many Zenith movies and decreased spacing towards the horizon in sunset movies consistent with clouds forming at a constant elevation. Reanalysis of Phoenix data in the light of the NavCam equatorial dataset suggests that clouds may have been more frequent in the earlier portion of the Phoenix mission than was previously thought.

Keywords: Mars; Clouds; Atmospheric dynamics; Water cycle

1. Introduction

The atmosphere of Mars undergoes changes on short timescales. Meteorological conditions observed at a surface station, such as the Mars Science Laboratory Rover (MSL) landing site, are affected by both local and regional forcing. The MSL Rover is equipped with an instrument suite, the Rover Environmental Monitoring Station (REMS) that observes the local pressure, temperature of the air at the height of the remote sensing mast (1.5 m), relative humidity, wind speed and direction, ultraviolet radiation and ground surface temperature (Gómez-Elvira et al., 2012, 2014). When combined with numerical modeling of the atmosphere that attempts to simulate the local and large-scale processes (e.g. Haberle, submitted for publication; Vasavada et al., 2012; Tyler and Barnes, 2013), REMS measurements can help to answer many questions, including validating models of thermal inertia (e.g. Hamilton et al., 2014) and elucidating the role played by thermal tides and the crater circulation in creating the observed pressure variations and whether the atmospheric reservoir of carbon dioxide may be changing over long time scales (e.g. Haberle et al., 2014)

To complement these measurements and to better understand conditions away from the rover, imaging may augment measurements made by REMS. Observations can be made of the optical depth within the crater by directly observing the solar disk at 880 nm and the scattering profile of the dust within the crater may be examined using sky surveys and line-of-sight extinction observations (Moores et al., 2015). It is also possible to directly observe expressions of super-saturation, e.g. water–ice clouds, and density variations in the dust. These may be brought about by inhomogeneities in the circulation and the redistribution of surface dust by vortices (Kahanpää et al., 2013, 2014; Moores et al., 2015). Acquiring a series of images instead of a single static frame permits the assessment of short time scale variability. Assuming a static background over the relatively short imaging period, the mean image may be subtracted from individual frames to yield perturbation images. With this data reduction technique, it becomes possible to focus on the time-varying component only.

Similar searches for clouds and dust variations had previously been conducted at Green Valley, the Phoenix Landing Site using the Surface Stereo Imager (Moores et al., 2010). This high latitude (68.22°N) data set may be compared with the images acquired at Gale Crater, an equatorial (4.6°S) landing site (Vasavada et al., 2014). In the Phoenix data set, temporally varying features were seen to move across the frame in nearly all image sequences acquired and the sensitivity of the instrument allowed variations in density of as little as 0.01 optical depths to be detected. Determinations of condensate clouds were made using morphological arguments and comparing a blue-to-red ratio of images, taken in two filters simultaneously with good spectral separation, to a numerical scattering model (Moores et al., 2010).

The equipment carried by MSL differs from that carried by Phoenix. Some of these differences as well as a description of the data sets acquired from sol 0 (L_S 150°) up to sol 360 (L_S 4.8°) are described in Section 2. Section 3 presents the observations and the corresponding results. These results are discussed in Section 4 where they are compared to other data sets acquired by other MSL instruments, results obtained from models, and data sets acquired by orbital instruments and at other landed sites.

2. Acquisition strategy, dataset and analysis methods

2.1. The MSL NavCam imager compared to the Phoenix Surface Stereo Imager (SSI)

The Navigation Cameras or NavCams consist of two pairs of cameras, four cameras in total, designed to acquire stereo imagery of the MSL rover and its surroundings for traverse planning. Their radiometric calibration (Maki et al., 2012) also makes these instruments able tools for science observations. Furthermore, their ease of use in the context of MSL operations when combined with their large field of view (FOV) of 45° makes them attractive for observing processes, such as atmospheric clouds, that change with time or subtend a large solid angle.