DARK DUNES ON MARS

Analyses on Origin, Morphology, and Mineralogical Composition of the Dark Material in Martian Craters

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Eidesstattliche Erklärung

Hiermit versichere ich, die vorliegende Dissertation selbständig angefertigt und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet zu haben.

Daniela Tirsch Berlin, 29.10.2008

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ABSTRACT

The research presented in this thesis focuses on the morphological, mineralogical, and thermal characteristics of dark material deposits in Martian craters. The information gained will be used to deduce the history and development of the material and to shed light on evolution processes and scenarios of its origin. Special aspects of this topic include revealing the sources of the material, identifying possible mineralogical correspondences between deposits, and examining dune surfaces for mobility or induration. A comparative analysis on a global scale will serve to investigate whether all deposits examined are of common origin, and whether any correlations exist between the characteristics analyzed. Thus, this work is intended to bridge the gap between detailed local analyses and global studies. Carried out on the basis of 70 selected localities comprising individual dark dunes, dune fields and sand sheets, analyzed based on imaging, spectral, and thermal orbiter data, this work aims to derive and compare morphological, compositional and physical properties.

Morphological analyses reveal dark layers exposed in a number of crater walls, showing indications of material transport from the layers down-wall to the intra-crater deposits. Further sites show dark material emerging from the floors of several craters, suggesting a dark material source beneath. Spectral analyses showed for the first time that a direct mineralogical analogy exists between the dark layers in the crater walls and the intra-crater dune and sand sheet material. Based on these findings, it could be shown that these layers are the local sources for the dark material inside the craters. Spectral analyses further indicate that all deposits are nearly of the same mafic mineralogical composition, hinting at a similar origin. It is shown that the thermal properties of the dunes point to consolidation on several dune surfaces, whereas the bulk of the dunes seem to consist of unconsolidated sands with coarse grain-size particles. A global consideration reveals no correlation between the geographical location of the deposits and their mineralogical composition in terms of mafic minerals. However, the cluster of hydrated minerals detected in Arabia Terra is supposed to be associated with former water-related processes in this region. Correlation between thermal properties and geographical localities may be assumed for the alignment of immovable deposits along the lowland-highland boundary. To explain their immobility, water-related processes as well as mechanical cementation might be considered. However, a convincing correlation between hydrated minerals and immovable deposits cannot be established. This indicates that mineral hydration does not consequently result in the immobilization of dunes in every case. Two different hypotheses and time ranges of origin will be considered, one suggesting a volcanic origin of the material and the other one claims for impact related processes such as impact glasses and melts. This work provides new insights into the development of deposited layers of dark material, their modification, and their exposition, which led to the distribution of dark materials on Mars.

KURZFASSUNG

Diese Arbeit beschäftigt sich mit der Untersuchung morphologischer, mineralogischer und thermaler Eigenschaften von dunklem Material in Kratern auf dem Mars. Die gesammelten Informationen werden dazu genutzt, die Geschichte und Entwicklung des Materials sowie mögliche Zeiträume seiner Bildung abzuleiten und denkbare Entstehungsszenarien zu durchleuchten. Insbesondere sollen die Fragen nach Sedimentquellen des Materials, nach Gemeinsamkeiten in der mineralogischen Zusammensetzung der Materialvorkommen und nach dem Zustand der Dünenoberflächen hinsichtlich einer Verfestigung oder Mobilität der Dünen beantwortet werden. Eine vergleichende Analyse der Materialeigenschaften im globalen Maßstab soll die Fragen beantworten, ob von einem gemeinsamen Ursprung des Materials ausgegangen werden kann, und ob es Korrelationen zwischen dem Materialeigenschaften untereinander sowie der geografischen Lage der Materialvorkommen gibt. Somit soll diese Arbeit einen Bogen zwischen Detailstudien und global angelegten Analysen spannen. Als Datenbasis dienen 70 global ausgewählte Lokalitäten, in denen dunkles Material in Form von Dünen, Dünenfeldern oder auch dünnen Sandlagen vorkommt. Die Materialeigenschaften werden mit Hilfe von Bild-, Spektral- und Thermaldatenauswertung verschiedener Satellitenmissionen ermittelt und verglichen.

Morphologische Analysen weisen anstehende dunklen Lagen an mehreren Kraterwänden auf, an denen ein Materialtransport beginnend an den Lagen, bergab der Kraterwand, bis hin zu den Ablagerungen im Kraterinneren zu beobachten ist. An anderen Stellen kann ein „Entspringen“ des Materials im Bereich der Kraterböden beobachtet werden, was auf eine Sedimentquelle unterhalb der Kraterböden hinweist. Mit Hilfe spektraler Analysen ist es gelungen, eine direkte Übereinstimmung zwischen der Mineralogie des Materials der anstehenden Lagen und des Dünenmaterials innerhalb der Krater nachzuweisen. Dadurch kann bewiesen werden, dass diese dunklen Lagen als lokale Quellen für das Dünenmaterial in den Kratern dienen. Ebenso kann durch Spektralanalysen festgestellt werden, dass sich die einzelnen Materialvorkommen hinsichtlich ihrer Mineralogie kaum unterscheiden, was auf einen gemeinsamen Ursprung der Ablagerungen hindeutet. Es wird weiterhin dargelegt, dass die thermalen Eigenschaften einiger Dünenoberflächen auf eine Verfestigung hinweisen, während der Großteil der Dünen aus unverfestigten Grobsanden zu bestehen scheint. Die globale Betrachtung deckt keine eindeutige Korrelation zwischen der geographischen Lage der Materialvorkommen und deren Mineralogie auf. Einzig die Detektion von hydratisierten Mineralen weist eine Korrelation mit der Region Arabia Terra auf. Frühere Wasseraktivitäten in diesem Gebiet werden für die Erklärung dieses Zusammenhanges herangezogen. Die Anordnung immobiler und somit wahrscheinlich verfestigter Dünen entlang der Hochland-/Tieflandgrenze wird ebenfalls vergangenen aquatischen Prozessen zugeschrieben, wobei jedoch auch eine mechanische Verfestigung der Dünenoberflächen

nicht ausgeschlossen werden kann. Eine Übereinstimmung zwischen unbeweglichen Dünen und einer veränderten Mineralogie im Vergleich zu beweglichen Dünen kann nicht festgestellt werden. Dies weist darauf hin, dass der Verfestigungsprozess nicht in jedem Falle zur Bildung neuartiger Minerale führte. Zwei verschiedene Hypothesen über Ursprungsszenarien und Bildungszeiträume werden in der Arbeit vorgestellt. Diese gehen einerseits auf einen möglichen vulkanischen Ursprung des Materials ein und schlagen andererseits vor, dass das dunkle Material impakt-genetische Schmelzen und Gläser darstellen könnte. Abschließend bietet diese Arbeit einen Einblick in die Entwicklungsgeschichte der abgelagerten Lagen aus dunklem Material, deren Modifikation, bis hin zu ihrer Freilegung, die damit eine globale Verteilung dieses Materials auf dem Mars zur Folge hatte.

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LIST OF ABBREVIATIONS

ASCII	American Standard Code for Information Interchange
ASU	Arizona State University
BTR	Brightness Temperature Record
CCD	Charged Coupled Device
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
DLR	Deutsches Zentrum für Luft-und Raumfahrt (German Aerospace Center)
DTM	Digital Terrain Model
ESRI	Environmental Systems Research Institute
GCM	Global Circulation Model
GIS	Geographic Information System
GML	Geography Markup Language
HCP	High Calcium Pyroxene
HiRISE	High Resolution Imaging Science Experiment
HRSC	High Resolution Stereo Camera
IAU	International Astronomical Union
IDL	Interactive Data Language
ILD	Interior Layered Deposits
ISIS	Integrated Software for Imagers and Spectrometers
LCP	Low Calcium Pyroxene
MarsGRAM	Mars Global Reference Atmospheric Model
MAWD	Mars Atmospheric Water Detector
MCD	Mars Climate Database
MER	Mars Exploration Rover
MGD³	Mars Global Digital Dune Database
MIMOS 2	Miniaturized Mössbauer Spectrometer
MOC	Mars Orbiter Camera
MOLA	Mars Orbiter Laser Altimeter
NA	near angle
NIR	near infrared
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
SI	Système International d'unités
SRC	Super Resolution Channel
TAR	Transverse Aeolian Ridges
TES	Thermal Emission Spectrometer
THEMIS	Thermal Emission Imaging System
TI	Thermal Inertia
VICAR	Video Image Communication And Retrieval
VIS	visual
WA	wide angle

CHAPTER I: INTRODUCTION AND MOTIVATION

Mars, the 'Red Planet', is not as red as its name implies. Numerous huge dark patches that consist of a fine-grained dark material dissect the reddish-brown colour of its surface. It is a big motivation to analyze this material and to know why it is so different from the other surface materials on Mars.

The dark features on Mars were first discovered from data provided by Mariner 6 and 7 [*Christensen*, 1983]. Very soon, Mariner 9 and the Viking orbiters revealed that these dark features are frequently associated with impact craters at all latitudes and in a great variety of regions [*McCauley et al.*, 1972; *Sagan et al.*, 1972; *Arvidson*, 1974]. Before it was ascertained that the intra-crater features are aeolian sand dunes coupled with wind streaks in most cases, dark 'splotches' was the term most commonly used to designate these deposits [e.g. *Christensen*, 1983; *Thomas*, 1984].

Dark aeolian material is not only concentrated in impact craters, it can cover extensive regions on Mars. However, dark regions on Mars are not necessarily associated with dark saltating sands. Many authors thought the dark areas were exclusively due to the absence of bright dust and covered by saltating sand, which keeps the surface clean of bright dust [e.g. *Sagan et al.*, 1972; *Christensen*, 1983; *Thomas*, 1984; *Edgett and Christensen*, 1994]. Today it is well known that this interpretation is too simple, and that the albedo alone cannot be used as an indicator in generic surface interpretation. According to *Edgett and Malin* (2000b), next to bright dust and dark sand, bright saltating sands and dark fines are to be found as well. Transported by suspension, dark fines are unable to build any bed forms but cover extensive regions on Mars. However, the object of investigation in this study is the dark saltating sand because of its dune-forming function.

Early investigations described the distribution, colour, and morphology as well as the physical properties of dark material, arriving at a particle size range for which the suggestion of aeolian transport might be proven [e.g. *Breed*, 1977; *Breed et al.*, 1979; *Christensen*, 1983; *Thomas*, 1984; *Edgett and Blumberg*, 1994]. Further investigations determined the effective particle size of the dark Martian dunes to be in the medium to coarse-grained range, discovering that Martian dunes seem to be coarser-grained than typical terrestrial dunes [*Edgett and Christensen*, 1991; 1994]. Early spectral analyses of the dark material were performed by *Singer and McCord* (1979) and *Singer* (1980a; b), for example, revealing a basaltic composition of pyroxenes and olivines disclosing the unweathered nature of the material. These spectroscopic analyses have been continued and refined by a number of authors [e.g. *Christensen et al.*, 2000; *Bibring and Erard*, 2001; *Christensen et al.*, 2001; *Bandfield*, 2002; *Christensen et al.*, 2003; *Bonello et al.*, 2004; *Bibring et al.*, 2005; *Mangold et al.*, 2007; *Mustard et al.*, 2007; *Poulet et al.*, 2007; *Poulet et al.*, 2008; *Christensen et al.*, 2004b], who similarly concluded that composition is mafic.

Most of the analyses of dark dunes concentrated on distinct dune fields or regions on Mars, analyzing local morphology, physical properties, and aeolian processes and revealing a variety of dune shapes, the existence of possibly active and non-active dunes, and the complexity of dune-forming winds [e.g. *Greeley et al.*, 1992; *Greeley et al.*, 1993; *Greeley et al.*, 1999; *Fenton and Bandfield*, 2003; *Bourke*, 2005; *Fenton*, 2005b; a; 2006; *Fenton and Mellon*, 2006]. As far as the source of the dark material is concerned, many questions are still open. *Edgett* (2002) observed correlations between dark dunes associated with exposures of eroded layered material in several craters at Arabia Terra. He speculated that these layers might contribute a portion of the dark sediments. However, he realised that the light-toned colour of the layers contrasted with the dark tone of the dune and wind streak sediments. Although some darker layers are also present at some sites, he found that this difference in colour from the deep dark material rules out the suggestion that a generic connection might exist between the eroded layers and the dark sediment. *Fenton* (2005b) found tentative indications of potential dark sand sources in dark layers exposed in the pit walls of a big crater at Noachis Terra. Although a number of previous studies were concerned with dark dunes and dark material as such, the scenario of the origin and evolution of these dark sediments is not resolved yet.

The aim of this study is to refine the body of knowledge about dark material, especially in terms of its local sources, and to shed light on its origin and evolution by focusing on a widespread selection of dark material deposits in Martian craters. The difference to former studies lies in the global view adopted as well as in the analysis of possible regional or global correlations between specific parameters and features (e.g. dune type, composition, dune surface condition, i.e. indurated or unconsolidated) of the dark material deposits. Therefore, as many characteristics of the dark dunes as possible, including their morphology, mineralogy, and thermal properties, will be analyzed and compared with each other. Although these parameters have been analyzed before in specific dune fields, it is not clear whether differences between the dunes and sand sheets exist on a global scale. Combined, this information will be used to propose possible scenarios of origin and a possible time range of genesis and deposition.

Therefore, various high-resolution image data sets, terrain elevation information, spectral data sets, and thermal data were considered in this investigation. The close view afforded by high-resolution image and elevation data might permit tracing the pathway of the material to its arrival at the crater, to learn more about its relative position inside the crater, and to disclose evidence on the mechanism of material mobilization. The question whether all dunes and sand sheets are made of the same material or not, pointing to a consistent or different genesis, will be answered by a mineralogical analysis. A physical property analysis based on thermal data will provide information about the dune surface condition, i.e. about grain size and induration, which indicates both dune immovability and the relative dune age. A combined consideration of mineralogy and dune surface condition might reveal clues about the formation of specific minerals by induration.

This work is structured so that the reader is first introduced to the fundamentals of Martian geology and its climatic conditions (Chapter II) that are of relevance to the topic of this study, including references to more detailed examinations. The fundamental knowledge about the physics of particle motion and the current status of aeolian processes and bed forms on Mars presented in Chapter III is necessary to understand the problems discussed in this study. An introduction to the datasets and processing methods employed is given in Chapter IV. Given these fundamentals, detailed analyses of the dark intra-crater deposits for the parameters and properties mentioned above will be presented in Chapter V. At this juncture, the methods applied to derive information and the results obtained will be discussed together with the uncertainties and problems involved. Chapter VI provides the result of this work, combining, interpreting, and discussing the information presented in the analysis chapter and deducing from it a final picture of the possible origin and evolution of the dark material. The last chapter presents a comprehensive review of this work, listing its results and summarizing the main conclusions. Furthermore, some important notes on open questions and future investigation proposals will be made.

This work is not intended to analyze the dark material on Mars in its entirety. Several deposits having been omitted, especially in the polar regions. It is probably advisable to analyze these polar dunes separately because of their enigmatically different physical and thermal properties [*Putzig et al.*, 2008] and their different mineralogy [*Langevin et al.*, 2005; *Fishbaugh et al.*, 2007], which might lead to misinterpretations in a global context. The results of such a separate analysis can be compared later with the results of the present analysis so as to arrive at conclusions applying to the whole set of material. Dark material deposits in Valles Marineris have been analyzed by *Lucchitta* (1990; 2001), for example. The results from other sites presented in the current literature have been regarded in this study. Thanks to the huge amount of samples, it should now be more feasible to apply conclusions from the samples discussed to the collectivity of intra-crater deposits, and to make proposals for interpreting further studies at other localities. Due to the comprehensive amount of data and localities analyzed here, it cannot be the intention of this work to go into the details of every single locality, but merely to bridge the gap between detailed local and generalised global analyses, with the aim of being as exact as possible.