Icarus 251 (2015) 128–144

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Solar System dynamics and global-scale dust storms on Mars

James H. Shirley

Jet Propulsion Laboratory-California Institute of Technology, Pasadena, CA 91109, USA

ARTICLE INFO

Article history:
Received 31 January 2014
Revised 29 May 2014
Accepted 22 September 2014
Available online 6 October 2014

Keywords:
Mars
Mars, atmosphere
Mars, climate
Planetary dynamics

ABSTRACT

Global-scale dust storms occur during the southern summer season on Mars in some Mars years but not in others. We present an updated catalog of Mars years including such storms ($n = 9$) and Mars years without global-scale storms ($n = 11$) through the year 2013. A remarkable relationship links the occurrence and non-occurrence of global-scale dust storms on Mars with changes in the orbital angular momentum of Mars with respect to the Solar System barycenter ($\boldsymbol{L_{Mars}}$). All of the global-scale dust storms became planet-encircling in both latitude and longitude during periods when $\boldsymbol{L_{Mars}}$ was increasing or near maxima. Statistical significance at the 1% level is obtained for the clustering tendency of $\boldsymbol{L_{Mars}}$ phases for the 5 mid-season storms with L_s ranging from 208° to 262° (1956, 1971, 1982, 1994, and 2007). The 11 Mars years without global-scale dust storms exhibit mainly decreasing and minimum values of $\boldsymbol{L_{Mars}}$ during the first half of the dust storm season; this tendency is statistically significant at the 5% level. A systematic progression is present in the phasing of the solar irradiance and $\boldsymbol{L_{Mars}}$ waveforms for the global-scale storm years. $\boldsymbol{L_{Mars}}$ phases for the early season global-scale storms of 1977 and 2001 are advanced in phase with respect to those of the mid-season storms, while the phase for the late season storm of 1973 is delayed with respect to those of the mid-season storms cluster. Factors internal to the Mars climate system, such as a spatial redistribution of surface dust from year to year, must be invoked to account for the non-occurrence of global-scale dust storms in five years (1986, 2003, 2005, 2009, and 2013) when the $\boldsymbol{L_{Mars}}$ phase was otherwise favorable. Our results suggest that the occurrence of increasing or peak values of $\boldsymbol{L_{Mars}}$ immediately prior to and during the Mars dust storm season may be a necessary-but-not-sufficient condition for the initiation of global-scale dust storms on Mars.

1. Introduction

Dust in the Mars atmosphere scatters, absorbs, and re-radiates solar radiation in the infrared and thereby profoundly affects the atmospheric thermal structure and the large-scale atmospheric circulation of the planet (Gierasch and Goody, 1973; Leovy et al., 1973; Zurek, 1981a, 1981b; Haberle et al., 1982; Haberle, 1986; Kahn et al., 1992; Leovy, 2001; Clancy et al., 1994, 2000; Heavens et al., 2011a, 2011b; Medvedev et al., 2011; Guzewich et al., 2013). Warming of the atmosphere may exceed 40 K in the middle atmosphere during global-scale dust storms, in comparison with conditions for the same season in the absence of significant dust loading (Clancy et al., 1994, 2000). Surface temperatures and pressures are likewise profoundly affected (Barnes, 1980, 1981; Zurek et al., 1992). The inter-annual variability of the Mars climate is largely dominated by the inter-annual variability of global-scale dust storms occurring in the southern summer season. The occurrence of these storms in some years but not in others has been characterized as a major unsolved problem of the physics of planetary atmospheres (Haberle, 1986; Kahn et al., 1992; Zurek et al., 1992; Zurek and Martin, 1993; Pankine and Ingersoll, 2002, 2004; Basu et al., 2006; Cantor, 2007).

Prior investigations have sought causal factors for global-scale dust storms originating entirely within the physical system consisting of the Mars surface and Mars atmosphere as subjected to the seasonally varying external forcing of solar radiation over the period of the Mars year. In the present investigation we consider the possibility that factors external to the above system may play a role. Specifically, we look for a relationship linking the occurrence of these storms with changes in the orbital angular momentum of Mars with respect to the barycenter of the Solar System ($\boldsymbol{L_{Mars}}$). This approach, while new to Mars, has a long history in connection with efforts to understand the origins and periodicity of magnetic activity cycles of the Sun (Jose, 1965; Blizard, 1981; Fairbridge and Shirley, 1987; Shirley et al., 1990; Charvátová, 1991; Juckett, 2003; Javaraiah, 2005; Shirley, 2006; Paluš et al., 2007). Coupling of the orbital and rotational angular momenta of the Sun has been suggested as a possible explanation for the

http://dx.doi.org/10.1016/j.icarus.2014.09.038
0019-1035/

relationships found (Blizard, 1981; Juckett, 2003; Shirley, 2006). Observations support this hypothesis; relationships linking changes in the orbital angular momentum of the Sun with observed changes in the rotation rates of solar features have been reported by Juckett (2003, 2005), Javaraiah (2005), and Wilson et al. (2008).

If the orbital and rotational angular momenta of the Sun are in fact coupled in some way, it then follows that the same physics may be operable elsewhere, including in the cases of planets such as the Earth and Mars. The present investigation represents a first step in the evaluation of this possibility. In companion papers we will approach this question both analytically (through a formal derivation of a coupling term) and through atmospheric modeling studies. Here however we restrict ourselves to an empirical approach, in which we search for relationships linking the observational phenomena (Mars global-scale dust storms) with a suspected driving mechanism (the temporal variability of the orbital angular momentum of Mars with respect to the Solar System center of mass).

We begin by assembling a catalog of Mars years with global-scale dust storms. For comparison purposes we also identify years in which such storms definitely or almost certainly did not occur. We next review elementary aspects of the cyclic changes of the planetary orbital angular momentum ($\boldsymbol{L_{Mars}}$) with respect to the Solar System barycenter. The phasing of the $\boldsymbol{L_{Mars}}$ cycle in relation to the periodic changes in solar insolation of the Mars surface over the Mars year is next examined. We find systematic and statistically significant relationships linking the variability of $\boldsymbol{L_{Mars}}$ with the occurrence and non-occurrence of global-scale dust storms.

2. The historic record of global-scale dust storms on Mars

Dust storms are observed during all seasons on Mars. In some years, multiple regional storms explosively grow and coalesce into global-scale storms (Zurek and Martin, 1993; Martin and Zurek, 1993; Wang and Richardson, 2013). These storms generally originate in southern middle latitudes during southern spring and summer. The dust clouds typically first encircle the planet in southern latitudes before extending across the equator. The expansion phase lasts only for a few weeks, while the decay and return to normal conditions may require several months. The onset and development of the global-scale storm of 2001 (Fig. 1) was captured by remote sensing instruments on board the Mars Global Surveyor (MGS) spacecraft. Diverse aspects of this storm are described in Smith et al. (2002), Strausberg et al. (2005), Cantor (2007), Clancy et al. (2010), Martinez-Alvarado et al. (2009), Wang and Richardson (2013), and Guzewich et al. (in press).

Some ambiguity is found in the terminology historically applied to these events. Earlier work has referred to these events as "great" dust storms (Gierasch and Goody, 1973), "planet encircling" dust storms (Martin and Zurek, 1993; Zurek and Martin, 1993), or "global dust storms." The latter may suggest that the phenomenon is a single-source event, when in fact these events typically involve multiple dust lifting centers whose combined activity leads to an expansion to global scale. The term "planet-encircling" is likewise ambiguous, as this may also be employed to describe storms that encircle the planet in certain latitudes, but fail to become global in extent. We prefer to characterize these extraordinary events as "global-scale dust storms," or GSDS events.

2.1. Mars years with global-scale dust storms

When the Mariner 9 spacecraft arrived at Mars in 1971 the planet's surface was found to be almost entirely obscured by a huge dust storm which persisted for several months before disappearing (Martin, 1974). GSDS events also occurred one Mars year later in 1973, and then again in 1977 during the Viking Orbiter and Lander Missions (Zurek et al., 1992). Direct observation of these storms by robotic spacecraft stimulated scientific interest in these events and led to an extensive search of historical records. Martin and Zurek (1993) and Zurek and Martin (1993) present detailed descriptions and an analysis of dust storm activity observed on Mars in the years 1873–1990. These authors advanced the concept of a dust storm season on Mars, consisting of the period from $L_s = 160°$ to 330° (where L_s is the areocentric longitude of the Sun). This interval is roughly centered on the time of perihelion ($L_s \sim 250°$), when the solar irradiance is greatest.

The list of global-scale dust storms of Table 1 for the years prior to 1990 is drawn directly from Table 2 of Zurek and Martin (1993). The 1924 and 1956 storms were observed telescopically during favorable observing opportunities (when the Mars perihelion occurs close to the time of closest approach of Earth to Mars). The 1971, 1973, and 1977 storms were observed directly by robotic spacecraft (Martin, 1974; Zurek, 1981a, 1981b; Zurek et al., 1992). The storm in 1982 was not observed from Earth or by orbiting

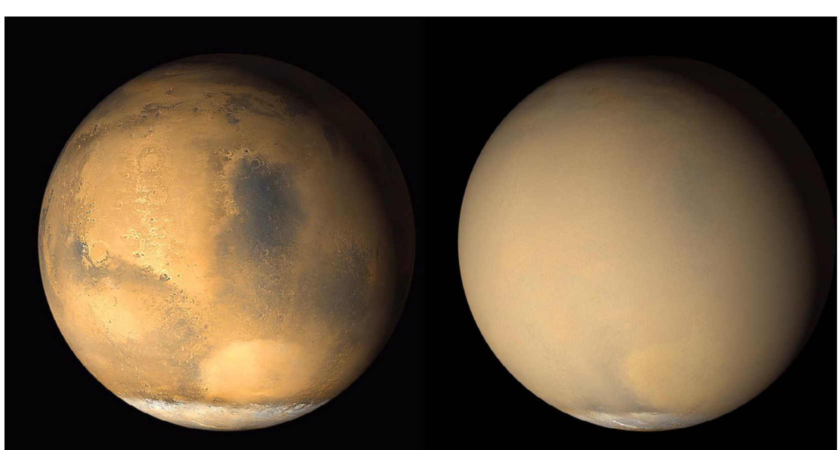

Fig. 1. The martian global-scale dust storm of 2001. At left: An image of Mars from late June 2001 shows clear conditions over much of the planet, with regional dust storm activity occurring in the Hellas basin (bright oval feature) near the edge of the south polar cap. At right: An image from one month later (July 2001) from the same perspective shows the planet almost completely enveloped in dust. Dust extends to altitudes of more than 60 km during global-scale storms; the decay phase can last several months. *Source*: Modified from NASA PIA03170