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Aerobraking at Venus: A science and technology enabler ☆

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ABSTRACT

Venus remains one of the great unexplored planets in our solar system, with key questions remaining on the evolution of its atmosphere and climate, its volatile cycles, and the thermal and magmatic evolution of its surface. One potential approach toward answering these questions is to fly a reconnaissance mission that uses a multi-mode radar in a near-circular, low-altitude orbit of ~400 km and 60–70° inclination. This type of mission profile results in a total mission delta-V of ~4.4 km/s. Aerobraking could provide a significant portion, potentially up to half, of this energy transfer, thereby permitting more mass to be allocated to the spacecraft and science payload or facilitating the use of smaller, cheaper launch vehicles.

Aerobraking at Venus also provides additional science benefits through the measurement of upper atmospheric density (recovered from accelerometer data) and temperature values, especially near the terminator where temperature changes are abrupt and constant pressure levels drop dramatically in altitude from day to night.

Scientifically rich, Venus is also an ideal location for implementing aerobraking techniques. Its thick lower atmosphere and slow planet rotation result in relatively more predictable atmospheric densities than Mars. The upper atmosphere (aerobraking altitudes) of Venus has a density variation of 8% compared to Mars' 30% variability. In general, most aerobraking missions try to minimize the duration of the aerobraking phase to keep costs down. These short phases have limited margin to account for contingencies. It is the stable and predictive nature of Venus' atmosphere that provides safer aerobraking opportunities.

The nature of aerobraking at Venus provides ideal opportunities to demonstrate aerobraking enhancements and techniques yet to be used at Mars, such as flying a temperature corridor (versus a heat-rate corridor) and using a thermal-response surface algorithm and autonomous aerobraking, shifting many daily ground activities to onboard the spacecraft. A defined aerobraking temperature corridor, based on spacecraft component maximum temperatures, can be employed on a spacecraft specifically designed for aerobraking, and will predict subsequent aerobraking orbits and prescribe apoapsis propulsive maneuvers to maintain the spacecraft within its specified temperature limits. A spacecraft specifically designed for aerobraking in the Venus

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Abbreviations: ACE, Advanced Composition Explorer; Cg, center of gravity; Cp, center of pressure; DRM, Design Reference Mission; DSN, Deep Space Network; GSFC, NASA Goddard Space Flight Center; HGA, high-gain antenna; IR, Infrared; JAXA, Japan Aerospace Exploration Agency; JEO, Jupiter Europa Orbiter; JHU/APL, The Johns Hopkins University Applied Physics Laboratory; JPL, Jet Propulsion Laboratory; LOLA, Lunar Orbiter Laser Altimeter; LRO, Lunar Reconnaissance Orbiter; MESSENGER, MErcury Surface, Space ENvironment, GEochemistry, and Ranging; MGS, Mars Global Surveyor; MOLA, Mars Orbiter Laser Altimeter; MRO, Mars Reconnaissance Orbiter; NASA, National Aeronautics and Space Administration; OSR, optical solar reflector; POST2, Program to Optimize Simulated Trajectories II; RF, radio frequency; SAR, synthetic aperture radar; SOHO, SOlar and Heliospheric Observatory; VEx, Venus Express; VEXAG, Venus Exploration Analysis Group

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environment can provide a cost-effective platform for achieving these expanded science and technology goals.

This paper discusses the scientific merits of a low-altitude, near-circular orbit at Venus, highlights the differences in aerobraking at Venus versus Mars, and presents design data using a flight system specifically designed for an aerobraking mission at Venus. Using aerobraking to achieve a low altitude orbit at Venus may pave the way for various technology demonstrations, such as autonomous aerobraking techniques and/or new science measurements like a multi-mode, synthetic aperture radar capable of altimetry and radiometry with performance that is significantly more capable than Magellan.

1. Aerobraking: importance for Venus science

One of the key science objectives for Venus, as identified by the Venus Exploration Analysis Group (VEXAG), is to improve understanding of the structure and dynamics of the interior of Venus [1]. In contrast to Earth, Venus does not exhibit evidence of plate tectonics at the surface, indicating that the crust must act as a “stagnant lid,” allowing internal heat to be lost primarily through conduction through the crust. Because Venus is similar to Earth in both size and distance from the Sun, it is probable that the interior must still dissipate heat in some way. The lack of impact craters visible at the surface of Venus has led to a hypothesis that the crust of Venus periodically (every ~750 million years or so) completely overturns and founders into the mantle beneath [2–6]. The key measurement required to characterize the interior structure is detailed topography, tied to the center of mass for the planet [7].

Such center-of-mass referenced, or geodetic, topography has been fundamental to understanding Mars. Geodetic topography data from the Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) have changed the way we think about Mars [8], and the Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) is in the process of providing the data necessary for a similar paradigm shift at the Moon. The key to achieving the geodetic precision required for such a topographic dataset is detailed knowledge of the spacecraft orbit; i.e., the vertical accuracy of the surface elevation estimates is only as good as the accuracy to which the orbiter location is known. Such high-precision orbiter tracking can only be achieved from a near-circular orbit, similar to that achieved by MGS, which also utilized aerobraking [9].

Other high-priority science investigations that greatly benefit from a circular orbit include characterization of the surface composition and possible volcanic activity. Recent spectroscopic observations by the European Space Agency’s orbiter, Venus Express (VEx), have indicated that infrared (IR) measurements at ~1 μm can penetrate the dense CO_2 atmosphere of Venus and “see” the surface. These observations have led to inferences regarding continental crust on Venus [10,11] and possible recent volcanism [12]. Although these observations are of great interest, the highly elliptical orbit of the VEx spacecraft limits observation to the South Pole during apoapsis passes. These observations have very low spatial resolution and do not allow for global coverage. A near-circular orbit would facilitate observation in regions of Venus where possible recent or current volcanism has been postulated as well as in other highland regions that may have continental origins distinct from the volcanic plains.

Attempting to achieve a circular orbit at Venus using only propulsion requires on the order of 2 km/s delta-V. This is a tremendous challenge for most spacecraft. No Venus mission to date has attempted a circular or near-circular orbit. Despite the Magellan end-of-life aerobraking experiment, even Magellan never achieved a circular orbit. Aerobraking to a circular orbit at Venus enhances science and technology capabilities while minimizing mission costs due to otherwise required propellant (or alternatives like a solid rocket motor) and the subsequent higher mass, although these savings are traded against the aerobraking costs themselves [13].

2. Aerobraking execution at Venus

There have been four successful aerobraking missions to date: Magellan at Venus in 1989 [14], MGS in 1997, Mars Odyssey in 2001 [15], and Mars Reconnaissance Orbiter (MRO) in 2005 [16]. Future Venus missions that require low altitude circular orbits for instrument precision, will require an aerobraking mission different from any previously flown aerobraking mission.

First, a mission-enabling aerobraking orbiter at Venus cannot easily be compared to Magellan. Magellan was an aerobraking demonstration; aerobraking was performed to prove that the concept was feasible. Aerobraking was conducted at the end of the primary science mission, starting from an already reduced orbit; there were no prime science criteria to meet for aerobraking termination. It was by design not an aggressive aerobraking phase, and the heat rates and dynamic pressures induced on the spacecraft were intentionally low to help ensure the success of this National Aeronautics and Space Administration (NASA) first. Although some characteristics of the aerobraking phase (e.g., heat rate and aerobraking duration) were comparable to Mars Odyssey, the most aggressive aerobraking mission to date, the orbital-period reduction of Magellan was only from 3.2 h to 1.6 h. By contrast, Odyssey, MRO, and MGS began from 18, 34, and 45 h, respectively, and aerobraked to <2 h [17]. Any spacecraft employing aerobraking to significantly reduce its orbital period must be more aggressive than Magellan