

**Bow shock instability at hypersonic speed**Adrián Antón-Álvarez <sup>1,\*</sup> and Adrián Lozano-Durán <sup>1,2</sup><sup>1</sup>*Graduate Aerospace Laboratories, [California Institute of Technology](#), Pasadena, California 91125, USA*<sup>2</sup>*Department of Aeronautics and Astronautics, [Massachusetts Institute of Technology](#), Cambridge, Massachusetts 02139, USA*

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Hypersonic entry vehicles are a critical component of space exploration missions, enabling reliable atmospheric reentry and planetary access. One example is the Mars Science Laboratory (MSL) mission, responsible for the Curiosity rover, which is a cornerstone of a multigenerational effort to explore Mars. The MSL was conceived with a primary scientific goal: to determine whether Mars ever possessed environmental conditions favorable for microbial life. This involves assessing not just the presence of water, but also the availability of chemical energy sources and the fundamental chemical building blocks of life [1]. Since its landing in August 2012, the MSL mission has continued to deliver invaluable data, fundamentally transforming our understanding of Mars as a planet that may have once supported, and may still support, the conditions necessary for life.

A key phase for any Mars mission involves the entry, descent, and landing (EDL) of the vehicle. The descent of the MSL through the Martian atmosphere encompassed a wide range of flow regimes [2], with Mach ( $M_\infty$ ) numbers varying from 8 to 30, and Reynolds numbers ( $Re_D$ ) spanning  $1 \times 10^5$ – $3.11 \times 10^6$ . These severe conditions led to heat flux at the surface of the vehicle above  $200 \text{ W/cm}^2$  [3]. During mission design, experiments were conducted to better understand the complex aerodynamics of the entry [3–7]. Three types of gases were used in those experiments: air, nitrogen, and carbon dioxide. The chosen gas considerably affects the density ratio across the shock wave. For example, gases like carbon dioxide achieve much higher density ratios than air, because they activate more vibrational degrees of freedom and achieve a lower effective specific heat ratio  $\gamma_{\text{eff}} = 1 + \frac{P}{\rho e}$ , where  $P$  is the pressure,  $\rho$  the density, and  $e$  the specific internal energy. Therefore, gas composition significantly alters the density ratios across the shock, which plays an important role in the stability of the bow shock [8]. A relevant implication from this analysis is that shock instabilities are much more likely to appear in the Martian atmosphere (lower  $\gamma_{\text{eff}}$ ) than on Earth. Moreover, experiments that use nitrogen or air instead of carbon dioxide, are not replicating Mars conditions (95%  $\text{CO}_2$ ) and consequently, might be missing relevant physical phenomena.

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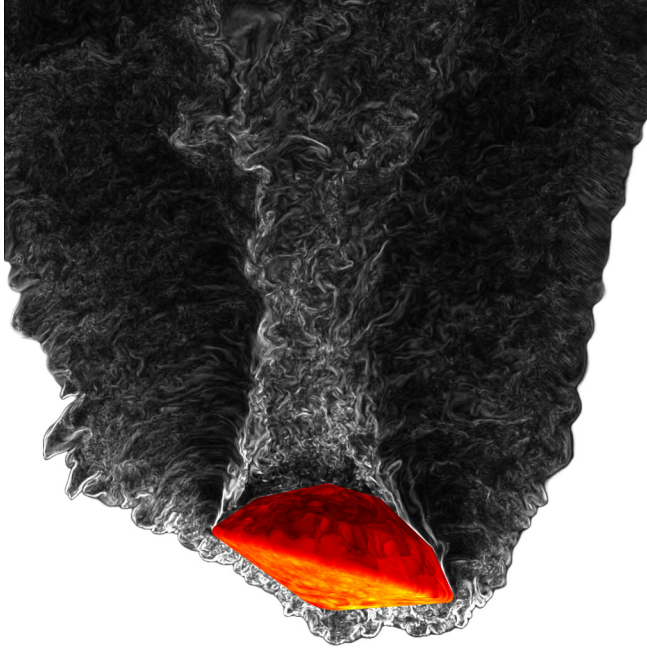


FIG. 1. WMLES of the MSL entry. The flow field is colored by vorticity magnitude, and the capsule surface is colored by wall temperature. The flight conditions are  $M_\infty = 28$  and  $Re_D = 2.74 \times 10^6$  at an angle of attack of  $16^\circ$ . A density ratio across the shock of  $\rho_2/\rho_1 \approx 14$  is achieved for  $\gamma_{\text{eff}} = 1.16$ .

Another important feature that affects the density ratios across the shock wave is the Mach number. This is a limiting factor in current experimental facilities. The maximum achievable Mach number typically ranges between 6 and 10 [3–7], whereas actual Mach numbers during planetary entry can reach up to 30. Due to these lower Mach numbers in experiments, key physical mechanisms may be overlooked. One such example is the stability of the shock wave in front of the capsule at hypersonic speeds.

In this work, we investigate the stability of the bow shock wave at hypersonic speeds in the Martian atmosphere. Freestream conditions were set to match entry conditions of the MSL according to the NASA mission environment definition [9]. In particular, different points of the flight path were simulated, and they are characterized in terms of the Mach and Reynolds number. Additionally, some cases were run following experimental conditions achieved on Earth, to compare with the actual mission results [3–7]. The capsule geometry was obtained from Ref. [9]. An effective specific heat ratio is used to account for chemical-rotational-vibrational equilibrium effects [8]. For reference,  $\gamma_{\text{eff}}$  was varied between 1.4 (low Mach nitrogen used in experiments [3–7]) and 1.15 (fully dissociated carbon dioxide gas found in the actual MSL entry). Several cases were simulated, two of which are shown in Figs. 1 and 2. The results were obtained using wall-modeled large-eddy simulations (WMLES) with the code charLES [10]. Three mesh refinement levels (21 M, 56 M, and 120 M volume cells) were used to verify grid convergence.

It was observed that when the density ratio across the shock,  $\rho_2/\rho_1$ , exceeds 13, the postshock flow becomes chaotic. Higher density ratios occur in points of the flight path where the Mach number is higher, or more chemical dissociation and vibrational effects are present. This leads to transition and therefore large spikes in heat transfer on the heat shield. For the reconstructed

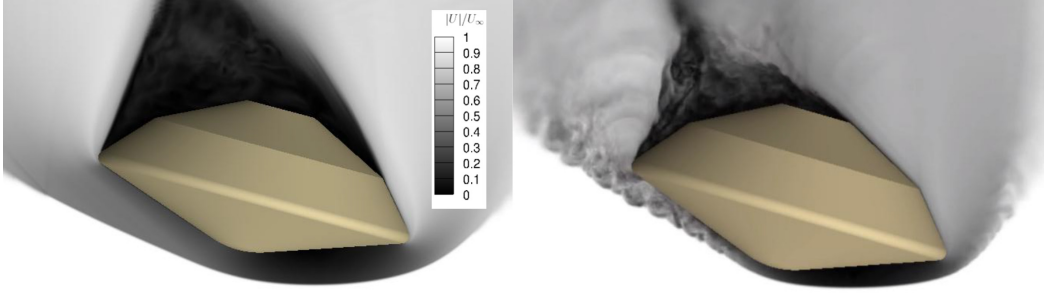


FIG. 2. WMLES of MSL entry. The flow field is colored by velocity magnitude. The left panel shows results under experimental conditions in nitrogen [5]:  $M_\infty = 6$ ,  $Re_D = 2.74 \times 10^6$ ,  $\gamma_{\text{eff}} = 1.4$ , and  $\rho_2/\rho_1 \approx 6$ . The right panel corresponds to actual mission conditions (high temperature dissociated  $\text{CO}_2$ ):  $M_\infty = 28$ ,  $Re_D = 2.74 \times 10^6$ ,  $\gamma_{\text{eff}} = 1.2$ , and  $\rho_2/\rho_1 \approx 11$ .

conditions of the MSL mission (Fig. 2, right), only the leeside of the capsule exhibits this chaotic behavior, consistent with probe measurements obtained during the actual MSL entry [11]. This is in stark contrast to the behavior observed under experimental conditions (Fig. 2, left), where the bow shock remains steady in agreement with experimental studies at similar conditions [3–7].

Similar bow shock instabilities have been documented in earlier research by Hornung *et al.* [8] and Ohnishi *et al.* [12]. Previous investigations hypothesized that these instabilities are initiated by vorticity introduced into the streamlines downstream of an oblique, curved shock. The understanding of the instability presented here is part of ongoing research [13], with preliminary results highlighting the critical role of shear layer vorticity, particularly in three-dimensional configurations where vortex stretching becomes significant. Moreover, boundary layer transition may be strongly influenced by these shear-driven modes near the shock, as they are subsequently advected along the entropy layer and impinge on the wall [14]. This mechanism could promote turbulent transition, leading to a substantial increase in heat flux on the heat shield.

The enhanced heat flux measured on the leeside during the MSL mission may be attributed to multiple factors, such as surface roughness resulting from heat shield ablation, imperfections, and misalignments between thermal protection tiles, laminar-to-turbulent transition due to high Reynolds numbers, or a combination of these effects. In this work, we have demonstrated that bow shock instability presents an additional possible explanation for the observed heat flux. A more in-depth investigation is needed to establish whether this instability was indeed present during the mission. An unexpected amount of heat flux could cause the heat shield to fail, inadequately protect the capsule, and ultimately destroy the payload resulting in mission failure. Consequently, gaining a deeper understanding of these mechanisms is essential to improve the design and reliability of future missions to Mars.

#### DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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