Title: Experimental Measurements of Non-Equilibrium Flow Relaxation for Uranus Entry using Vacuum-Ultraviolet and Visible Spectroscopy

Authors: D. Joslyn, S. G. Lock, Y. Liu, R. G. Morgan and C. M. James

The ice giants, Uranus and Neptune, are the least explored planets in our solar system. Voyager 2 conducted a brief flyby of Uranus in 1986, before reaching Neptune, but the visit provided incomplete data and left many phenomena unexplained. As such, a larger-scale return mission, named the Uranus Orbiter and Probe (UOP), was designed to perform a multi-year orbit and deploy a probe into the planet's atmosphere. The UOP mission was classified as the highest-priority flagship mission in the 2023-2032 Planetary Science and Astrobiology Decadal Survey, ideally launching in the early 2030s, so it is vital to better understand the entry environment. Current models of the flow chemistry demonstrate great uncertainties for a number of reasons, so their development is crucial.

As the Uranian atmosphere is composed mostly of hydrogen, alongside helium and trace species, unreliable hydrogen dissociation rates limit computational models. Additionally, the extreme entry velocity of approximately 22.3 km/s is challenging to reproduce, so there are few facilities capable of experimental simulations. In such simulations, vacuum-ultraviolet (VUV) spectroscopy is required for the analysis of molecular hydrogen behaviour, which is a highly complex system to operate successfully, especially in impulse facilities. These factors have prevented the accurate quantification of the non-equilibrium flow relaxation that would occur in the shock layer during UOP probe entry. The rate of dissociation and potential recombination of hydrogen contributes significantly to the total heat flux impacting the probe's heat shield, so it must be considered for design optimisation [1]. Spectroscopy enables the analysis of this behaviour, particularly in the VUV region, as the presence of molecular hydrogen is measurable through its radiative emissions.

Various studies have reported that hydrogen emits radiation at negligible or very low intensity under Uranus entry conditions. The Electric Arc Shock Tube (EAST) at NASA Ames Research Center was used for Uranus and Saturn entry simulations, but the post-shock relaxation of hydrogen could only be analysed for Saturn entry, given limitations in exposure time for a moving shock [2]. However, giant planet entry experiments in the Oxford T6 Stalker Tunnel demonstrated that hydrogen emissions may be detectable in an expansion tube, in which a model enables the analysis of a stationary shock. Longer exposure times could be used, increasing the signal of less-intense features. As the facility was not equipped with VUV spectroscopy at the time, only H-alpha could be measured, but no molecular bands [3].

The X2 expansion tube at the University of Queensland (UQ) is capable of replicating Uranus entry conditions through the Stalker Substitution method. While current driver conditions limit the freestream velocity to roughly 20 km/s, the target post-shock temperature can be achieved, allowing the replication of flow chemistry. By increasing the composition of helium in the test gas, to act as an inert diluent, the specific heat of the mixture is reduced, producing a higher post-shock temperature with a lower velocity. In recent X2 experiments, three peak-velocity Uranus entry conditions were tested with varying test gas compositions, while spectral measurements were taken in the VUV, ultraviolet (UV) and visible wavelength regions. These conditions were designed to replicate the post-shock properties of the 34.5 s trajectory point proposed by Palmer et al., developed using the TRAJ program [1]. James et al. utilised PITOT3 to determine that the equilibrium post-shock temperature at this trajectory point was achievable in X2 with an approximate 40%He/60%H_2 mixture, while the frozen post-shock temperature requires an approximate 60%He/40%H_2 mixture [4]. As such, the test gas compositions tested in the current study were 45%He/55%H_2, 50%He/50%H_2 and 55%He/45%H_2.

Various instrumentation was used to ascertain the test times of each condition, ensuring accurate spectral measurements of the hydrogen/helium shock layer. This included two high-speed cameras, one with an H-alpha bandpass filter to detect the region of steady hydrogen flow. Additionally, a visible photodiode and three pitot probes beneath the model supported the test time evaluation. Flow contamination was found to increase the intensity of hydrogen spectral emissions and shift the test time, so great effort was made in the pre-shot procedure to minimise it. Methods included several passes of acetone and isopropyl alcohol in the shock tube, acceleration tube and nozzle, the maintenance of a low vacuum in the facility at all times excluding turnarounds, and immediate firing after filling the shock tube. A cleaned fused silica window was used to maximise transmission in the UV and visible regions, and a single-use, alumina-polished magnesium fluoride window was installed before each shot for maximum transmission in the VUV region.

The 50%He/50%H_2 and 55%He/45%H_2 test conditions resulted in similar spectral measurements, and approximate shot repeatability was obtained. The Lyman-band of molecular hydrogen was observed in the VUV region and spanned at least half of the shock layer, indicating a slow dissociation and mostly non-equilibrium flow. Recombination was not clearly detected at the model edge. Negligible contamination was emitted in this region, despite atomic nitrogen lines being previously observed, suggesting that air contamination in the shock tube was successfully minimised. The atomic hydrogen features were generally much weaker, where the Lyman-alpha and H-beta lines were not measurable at all. The H-alpha line was detected in the visible region, but it was low in intensity. As the wavelengths measured with the visible spectrometer ranged from approximately 635nm to 915nm, many contaminants could be observed, emitting at a similar intensity relative to H-alpha.

In contrast, the 45%He/55%H_2 condition resulted in a slightly brighter Lyman band in the VUV region, and it appeared to exhibit recombination at the model edge, as shown in Figure 1. As this condition contained less inert diluent, it reached a lower post-shock temperature and hence a greater post-shock density, likely causing such phenomena. The radiative emissions in the UV and visible regions displayed similar patterns, where the spectra observed were similar to the preceding conditions but with a slightly greater intensity.

The results indicate a clear capability for measuring hydrogen relaxation in Uranus entry simulations using the X2 expansion tube, as the molecular Lyman band is detectable and quantifiable in the VUV region. However, further analysis is required to determine the appropriate test gas substitution that yields the expected post-shock temperature. As the relaxation behaviour was not consistent between all conditions, it cannot be concluded which condition best represented the proposed peak-velocity Uranus entry trajectory point. Spectral fitting will be implemented to derive the post-shock temperatures, furthering the analysis.

[1] Grant Palmer, Dinesh Prabhu, and Brett A. Cruden: Aeroheating Uncertainties in Uranus and Saturn Entries by the Monte Carlo Method. Journal of Spacecraft and Rockets 51.3, 801-814 (2014).

[2] Brett A. Cruden and David W. Bogdanoff: Shock Radiation Tests for Saturn and Uranus Entry Probes. Journal of Spacecraft and Rockets 54.6, 1246-1257 (2017).

[3] Joseph Steer et al.: Commissioning of Upgrades to T6 to Study Giant Planet Entry. Journal of Spacecraft and Rockets 61.6, 1545-1562 (2024).

[4] C. M. James et al.: Simulating Gas Giant Atmospheric Entry Using Helium and Neon Test Gas Substitutions. Journal of Spacecraft and Rockets 56.3, 725-743 (2019).