Survey of vacuum ultraviolet experimental data in relation to radiation characterization for Earth high-speed re-entry

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Abstract. This contribution is a survey of the available experimental radiation data measured in the VUV range related to hypersonic atmospheric entry. The objective is to identify the datasets already gathered during aerothermodynamics studies for preparing Mars, Venus, and sample return missions. The final goal is to identify the most valuable datasets for comparisons with future data measured in the European shock-tube ESTHER. Due to the limited number of studies covering VUV radiation in relation to space exploration missions, the review has been extended to domains such as nuclear fusion, exobiology, chemical and process engineering.

1 Introduction

The European Space Agency (ESA) is actually supporting the development of a high-velocity shock-tube, ESTHER [1, 2] for preparing future exploration missions of the solar system. These missions could potentially be missions to Mars or sample return missions to comets and asteroids involving the superorbital Earth re-entry of a return capsule. Such entries are characterized by high heat fluxes, and the return capsule has to endure severe entry conditions in terms of radiative and convective heating. Such high levels of heat fluxes characterize all sample return missions performed so far, like Stardust [3], Genesis [4] and Hayabusa [5].

The current effort focuses on the support of the European shock-tube ESTHER [6] and its instrumentation. ESTHER is a facility under development by an international consortium led by IST of Lisbon, under funding from the European Space Agency. It is a two-stage combustion-driven shock tube, as shown in Fig. 1, with laser ignition. ESTHER has a 16 m length, a main section of 80 mm diameter and can reach shock velocities from 4 up to 12 km/s for Earth atmospheric entry, with pre-shock pressures in between 0.1 and 100 mbar (10 to 10 000 Pa). ESTHER’s capabilities are going to be extended via the integration of a system measuring vacuum ultraviolet (VUV) radiation. Such instrumentation will be of interest for high-speed Earth, Venus entries and also Mars entry with radiation from CO(4+) system. The goal of the current survey is to support the development of this VUV instrumentation by identifying the most relevant experimental datasets in the perspective of potential cross-checking with other facilities.

Measurements in VUV range cover wavelengths from 62 to 200 nm (6–20 eV). In hypersonic flows, radiative heating can be significant in this range of the spectrum; this particularly applies to sample return mission and to Venus entry. Unfortunately, VUV emission is difficult to investigate due to the instrumentation limitations: Lamps are thermally driven and below wavelengths of 300 nm they do not reach a sufficient temperature to be efficient. Usually, dedicated deuterium lamps [7] are used for such measurements (but other alternative are possible such as Ar, Xe or H₂ lamps). These devices required a specific calibration based on advanced photon metrology [8].

Due to the limited amount of studies performed so far, focusing on VUV radiation in relation with hypersonic entry, the focus has been initially extended to other domains such as tokamaks, chemistry applications and exobiology. This survey [9] has shown that VUV measurements are also taken for nuclear [10, 11], exobiology [12–14], chemistry [15], process engineering [16, 17] and material [18] applications. However, this effort showed that the most relevant data obtained for VUV radiation are those obtained in the frame of studied undertaken to support planetary exploration investigations. As a consequence the present contribution focuses only on experimental data related to space exploration missions.

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Some European research institutes such as IRS or Ecole Centrale have also participated to airborne observation campaigns performed during entries of Stardust and Hayabusa. During these campaigns, radiation measurements [19, 20] were taken for post-flight analysis [21, 22] purposes. However, no measurements were taken in the VUV range; as a consequence, these data have little relevance for future VUV test campaigns in ESTHER.

For the current effort, the emphasis has been put on Earth superorbital re-entry conditions; the data found for CO$_2$ atmospheres like those of Venus and Mars have been also considered. The effort has been focused on VUV data only; as a consequence, other existing datasets for other parts of the spectrum obtained in many facilities have not been considered, since they are outside the scope of this survey.

2 Earth superorbital re-entry

Several test campaigns have been carried out focusing on VUV measurements for Earth re-entry conditions, this, in different facilities: NASA EAST shock tube, X2 expansion tunnel at University of Queensland, plasma wind tunnels at IRS and CNRS Orléans, ICP plasma torch at ECP (“Ecole Centrale de Paris”) and HVST JAXA shock tube, where pure nitrogen tests [23] were performed to support the preparation of the Hayabusa mission. More details on most of these different facilities can be found in [2, 24].

2.1 Shock facilities

Most of the experimental data covering the VUV range have been obtained in the EAST shock tube, for supporting the Orion project [25] involving a Lunar return, and sample return missions [26]. In [27], if a test campaign involving VUV measurements in LENS-XX performed for the Orion project is mentioned, no spectrum covering the VUV range is provided. As a consequence, all data found in the literature for NASA projects on

Table 1 VUV data obtained with EAST for Earth superorbital entry conditions

| Pressure (Pa) | Velocity (km/s) | Reference |
|--------------|----------------|-----------|
| 13.3, 26.6   | 9.5 to 15.5    | 26        |
| 13.3, 26.6, 40, 93.1, 133 | 10     | 28        |
| 13.3, 40, 133 | 10           | 27        |

Fig. 1 Sketch of ESTHER shock tube (credit IST)

Fig. 2 VUV spectrum obtained in EAST (10.546 km/s, 266 Pa) (from [28])
this topic have been obtained with EAST. The instrumentation available with EAST is detailed in [27, 28], the calibration in [28]: It has been applied to Mars, Earth and Neptune entry conditions (shock velocity up to 34 km/s for Neptune). VUV, as well as UV, visible and NIR, can be investigated in this facility for a wavelength range from 110 up to 4000 nm. A typical spectrum obtained with the VUV spectrometer is shown in Fig. 2. The tests performed in EAST for investigating Lunar return, and sample return conditions are resumed in Table 1.

Different spectra are available in [28]; the VUV measurements are available for pressures of 26.6 and 93.1 Pa and velocities around 10 km/s. One spectrum with some O, N and C lines obtained at a pressure of 26.6 Pa is shown in Fig. 3. In a recent effort [26] the range of shock velocity from 9.5 up to 15.5 km/s has been extensively explored for 13.3 and 26.6 Pa.

Some results for the Orion project with the spectra obtained in EAST for the VUV range at 26.6, 40 and 93.1 Pa (around 10 km/s) have been published by Bose et al. [29] and numerically reconstructed with NEQAIR [30]. An example of the results available for 93.1 Pa and 10 km/s is shown in Fig. 4. These different test campaigns carried out in EAST have also allowed the estimate [31] of the electron density for Lunar return conditions as highlighted in Fig. 5. The electron density is not directly measured but derived from the radiation intensity using a Lorentzian shape fitting. In [31], the H α, N 410 nm and N 411 nm lines have been selected.

Experimental data for the VUV range have been detailed in [26] with the complete spectra obtained at 15.5 km/s (13.3 Torr) and 13.64 km/s (26.6 Torr). The experimental data have been numerically reconstructed with the NASA radiation codes NEQAIR [30] and HARA [32, 33] as highlighted in Fig. 6, where the computed and measure radiances for each range are plotted.

Some of the tests carried out in EAST have also been analyzed, in the VUV and IR ranges at JAXA by Lemal et al. [34] for shock velocities of 10.54 and 11.17 km/s. The objective was to assess a collisional-radiative model for VUV and IR ranges. Good agreement was obtained for the IR and VUV intensity profiles, for both conditions after a tuning of the model for accounting heavy particle impact.

To support the Hayabusa mission, test campaigns have been performed using the JAXA HVST shock tube and pure nitrogen [23]. Emission intensity from VUV to NIR has been investigated for a pure nitrogen.
Fig. 5 Measurements of electron density for Lunar return conditions in EAST (from [31])

Fig. 6 Computed and measured radiance in EAST at 11 km/s (from [26])

Fig. 7 Spectrum of the VUV region in pure nitrogen at 10.4 km/s and 40 Pa (from [23])

Fig. 8 Experimental VUV radiation in X2 for 12.2 km/s (from [36])

atmosphere and two experimental conditions 120 Pa and 7.8 km/s, and 40 Pa and 10.4 km/s. These two points are located along the Hayabusa re-entry trajectory. Results show that C and N atomic lines are predominant in the VUV region (see Fig. 7) and no molecular band is seen. The UV region is dominated by N$_2$(2+) and N$_2^+$(1-) systems, while atomic lines of N are intense in the visible. The results show that the spectrum of the VUV region becomes more intense that those of UV, NIR and VIS regions, when increasing the shock velocity. The experimental data were numerically reconstructed and radiation analysis performed with SPRADIAN2 [35], and good agreement was obtained when the electronic temperature was higher than the vibrational one.

Super-orbital re-entry flow conditions [36] were investigated in the X2 expansion tunnel at the University of Queensland, corresponding to 12.2 km/s and a static pressure of 870 Pa. VUV measurements were taken
Table 2 Experimental conditions for plasma torch tests (from [39])

| Condition                  | Value  |
|----------------------------|--------|
| Gas                        | Air    |
| Freestream pressure        | 1 atm  |
| Plate power                | 62 kW  |
| Maximum temperature        | 6708 K |
| Specific enthalpy          | 21.8 MJ/kg |
| Specific mole fractions    |        |
| O                          | 0.23   |
| N                          | 0.28   |
| O₂                         | 1.1 × 10⁻⁴ |
| N₂                         | 0.47   |
| CN                         | 5.9 × 10⁻⁶ |
| CO                         | 2.3 × 10⁻⁴ |

for a wavelength range of 116–185 nm using a deuterium lamp. The corresponding spectrum is shown in Fig. 8. Population densities were estimated by analyzing the radiative transport in the flow, temperature from the measured spectra. The experiment was numerically reconstructed using CFD URANUS code [37] and PARADE line-by-line code [38]. The numerical results obtained are in a good agreement with the electron density and temperature derived from the measurements.

2.2 Tests with air in plasma facilities

Several test campaigns have been carried out at Ecole Centrale de Paris [39, 40], CNRS Orléans [41] and IRS [42, 43] for performing VUV measurements in air. This development of the VUV measurement technique, in some European plasma facilities, is due to the lack of a high-velocity shock facility in Europe with the capability of reproducing superorbital re-entry conditions.

Jacobs et al. [39, 40] have performed spectroscopy measurements in the VUV region for air plasma in an ICP plasma torch. Measurements were taken in the range of 170–200 nm for equilibrium emission conditions at 6708 K and a specific enthalpy of 21.8 MJ/kg. The test conditions are summarized in Table 2. The measured calibrated spectrum is displayed in Fig. 9. The measurements have been numerically reconstructed using the line-by-line radiation code SPECAIR [44] and little differences found between the experimental data and the numerical predictions as shown in Fig. 10.

Air (80% N₂ and 20 O₂) plasma flows have been investigated at CNRS Orléans in the PHEDRA low-density plasma wind tunnel at ICARE (former SR5 facility at CNRS Orléans) by Lago [41]. The recent test campaign performed by Lago [41] focused on VUV radiation for both Earth and Mars entry conditions. Spectral emission was measured from 110 to 900 nm in low-pressure flows: Pressure chamber was in between 2 and 3.9 Pa for air. VUV spectrum is shown in Fig. 11, but the exact flow conditions for which it has been obtained are not clearly defined in [41]. For air, VUV radiation presents only atomic lines for N and O since no molecular system was identified, as highlighted in Fig. 11. VUV contribution to the total radiation was evaluated for the different flow conditions. Results are summarized in Fig. 12, on the left for air and on the right for a Mars atmosphere. Low enthalpies (2–4.5 MJ/kg), the VUV contribution ranges from 8 to 14%, for medium enthalpies (8.5–11 MJ/kg) a contribution in between 2 and 10% is observed, while at high enthalpy (15–16 MJ/kg) VUV radiation reaches 25% of the total radiation which is close to the level observed in some shock tube experiments for super-orbital re-entry conditions [46].

The test conditions reported in Table 3 have been investigated in the plasma wind-tunnel PWK1 at IRS [42, 43]. They correspond to the point at 78.8 km of altitude and 11.7 km/s of the Hayabusa re-entry trajectory. Radiation measurements were taken from 120 nm up to 960 nm using a cooled copper probe in [42] and a carbon phenolic sample in [43]. Calibration results with raw data, calibrated data and smooth data, are shown...
Fig. 10 Experimental data and SPECAIR calculations (from [39]), where SPECAIR 4 mm corresponds to the addition of a 4-mm oxygen air path.
Fig. 11 VUV measurements for air plasmas (from [41])

Fig. 12 Contribution of VUV range to the total radiation as function of specific enthalpy (left air, right Mars atmosphere) (from [41])

Table 3 PWK1 test conditions 20 mm in front of the probe [42, 43]

| Static pressure (Pa) | 1660 |
|----------------------|------|
| Heat flux (MW/m²)    | 4.4  |
| Specific enthalpy (MJ/kg) | 68.4 |
| Temperature (K)      | 11,780 |
| Velocity (m/s)       | 3350 |

in Fig. 13. The contribution of the VUV range to the radiative heating measured at the stagnation point for the conditions reported in Table 3 was 235 kW/m². VUV radiation is dominated by nitrogen and oxygen atomic lines. This is highlighted in Figs. 21 and 22, displaying the measured VUV radiation as function of the wavelength, for a copper and a carbon phenolic probe, respectively. It has to be noted that the presence of the ablative sample has a strong influence on the VUV radiation that is reduced. This is due to the reduction of atomic nitrogen through the decomposition of the carbon phenolic and the blocking effect [45] generated by the pyrolysis gases.

3 Entries into CO₂ atmospheres

Several experimental studies, carried out in EAST, have been focused on VUV measurements for Mars aerocapture and Venus entry conditions (Figs. 14 and 15).

3.1 Venus

Several experimental campaigns for Venus entry were carried out in EAST shock tube by Martinez [7] and Cruden et al. [46]. The calibration of the deuterium lamp selected for the VUV measurements is detailed in [7]. In both studies, a 96.5 CO₂ and 3.5 N₂ (by volume) atmosphere was considered for Venus. The different test conditions investigated for a Venus entry are resumed in Table 4. A comparison between the conditions tested in [46] and some entry probe trajectories is...
displayed in Fig. 16. Measurements were taken from the VUV to IR range, from 120 up to 1700 nm in [7] and up to 5000 nm (for low velocities) in [46]. The spectra obtained in [7] for both Mars and Venus conditions are shown in Fig. 17. The VUV range is dominated by the CO(4+) system, and two carbon atomic lines are also present at 193 and 248 nm. The contributions of the different spectral regions from VUV to IR, to the total radiance for Venus entry conditions (66 Pa, 11.5 km/s) are shown in Fig. 18. The VUV contribution to the total radiance is in between 22 and 36%, which is significant.

Rotational temperature was extracted from radiation measurement of CN violet and C₂ band systems. Tests

**Table 4** VUV data available for Venus entry

| Pressure (Pa) | Velocity (km/s) | Reference |
|---------------|-----------------|-----------|
| 66            | 11.4            | [7, 46]   |
| 66            | 10.6            | [7, 46]   |
| 133           | 9.5             | [7, 46]   |
| 266           | 7               | [46]      |

**Fig. 13** Calibration results for the VUV range using a deuterium lamp (from [42])

**Fig. 14** Measured VUV radiation at stagnation point for a copper sample (from [43])

**Fig. 15** Measured VUV radiation for a carbon phenolic (ASTERM) probe (from [43])
**Fig. 16** EAST test matrix (1 Torr = 133 Pa) for Mars and Venus (from [46])

**Fig. 19** EAST data and NEQAIR results for Venus conditions of 9.5 km/s and 1 Torr (from [46])

**Fig. 17** Mars and Venus spectra obtained in EAST (from [7])

**Fig. 18** Contributions to the different spectral regions to the total radiance for different Mars and Venus entry conditions (0.1 Torr = 13.3 Pa) (from [46])
Table 5 VUV data available for Mars entry and aerocapture

| Pressure (Pa) | Velocity (km/s) | Reference            |
|--------------|-----------------|----------------------|
| 13.3         | 8.5             | [7, 16, 21, 46, 47, 49] |
| 34           | 6.5             | [7, 46]              |
| 34           | 7               | [46]                 |
| 34           | 8               | [7]                  |
| 133          | 7               | [7, 46, 49]          |

were numerically reconstructed using NEQAIR [30] as shown in Fig. 19 where the dotted lines represent the integral of the volumetric radiance. If the main features of the experimental data are reproduced by the calculations, the radiation is largely underpredicted.

3.2 Mars

Concerning Mars entry, several datasets with VUV radiation measurements, obtained in the NASA EAST shock tube, have been published in the literature [7, 28, 46]. The different test conditions retained for these experimental campaigns are resumed in Table 5. An example of spectrum, covering a large wavelength range, shown in Fig. 20, highlights that the VUV-UV portion of the spectrum represents a large part of the shock-layer radiation. The VUV is dominated by the CO(4+) system that is the most intense across the spectrum. According to Fig. 18, VUV contribution to the total radiation is around 36% for Mars aerocapture conditions. Among the tests performed by Cruden et al. [46], the condition at 13.3 Pa and 8.5 km/s was a repetition of the test performed in the same facility by Bose et al. [47, 48]. Unfortunately, no quantitative

![Fig. 20 Mars composite spectrum at 33 Pa and 8 km/s (from [7])](image)

![Fig. 21 EAST emission spectrum for Mars atmosphere at 8.5 km/s and 13.3 Pa (from [48])](image)
Fig. 22 EAST spectrum of the VUV region for a Mars atmosphere (13.3 Pa, 8.4 km/s) (from [28]).

Fig. 23 Radiation from the CO(4+) system (133 Pa, 7 km/s) in the VUV region measured at JAXA (from [49]).

Fig. 24 Emission spectrum in VUV for the different runs at 7.1 and 7.3 km/s and 200 Pa measure in HVST (from [52]).

Assessment between the results is provided within these papers. The only possible approach is to compare the experimental spectra shown in Figs. 17 and 21. Additional details on the measurements performed in EAST at 8.5 km/s and 13.3 Pa for a Mars atmosphere are also available in [28]. A zoom of the VUV region of the spectrum obtained for 8.5 km/s and 13.3 Pa, highlighting the contribution of the CO(4+) system, with also the atomic lines for carbon and nitrogen (and possibly some contribution from OH) is shown in Fig. 22.

Other datasets covering the VUV region have been obtained in the HVST the shock tube available at the JAXA Chofu Space Centre [49]. Emission intensity from VUV to NIR was investigated for a Mars atmosphere composed of 96% of CO₂ and 4% of N₂. Results were obtained for 133 Pa and 7 km/s, and 13.3 Pa and 8.5 km/s; a deuterium lamp was used for the calibration. These two test conditions reproduce the first and the last conditions of Table 5. VUV measurements for Mars entry have also been taken in VUT-1 shock tube at MIPT in Moscow [50] as reported in [51].

This shall allow some comparisons between the datasets obtained in both facilities and make them very attractive for future ESTHER campaigns with a Mars atmosphere. Radiation from the CO(4+) system was also investigated, and its contribution is shown...
in Fig. 23. Here, the results have not been compared to EAST data but against numerical simulations. The experimental data were numerically reconstructed using CFD and radiation analysis performed using SPRADIAN2 [35], and good agreement was obtained. Other results [52] were obtained for pure CO$_2$ at velocities of 7.1 and 7.3 km/s and a pressure of 200 Pa. Radiation measurements were taken from VUV to NIR region; the VUV measurements are plotted in Fig. 24.

Several test campaigns for measuring VUV radiation in CO$_2$, or Mars-like atmosphere, have been conducted in plasma torch facilities. At least two test campaigns with pure CO$_2$ have been performed in CORIA ICP torch, at CNRS Rouen (France) for two supersonic flow conditions [53, 54]. Pressure and specific test enthalpy were, respectively, of 38 mbar and 25 MJ/kg in [53], and 90 mbar and 8.5 MJ/kg in [54]; more details are available on this last study. Observed spectrum from [53] is reported in Fig. 25. The spectrum can be divided into 4 parts. In the VUV range (part I), the contribution of CO(4+) is well identified, while in part II, the CO(4+) and CO(3+) system is present. C$_2$ Deslandres-d’Azambuja system is shown in part III and C$_2$ Swann in part IV. Some atomic lines for carbon can be also identified, as well as some radiation from CN. This last is present due to the introduction of air during the test for pressure control purpose.

Mars (97% CO$_2$ and 3% N$_2$) plasma flows have also been investigated, at CNRS Orléans, in the PHEDRA low-density facility by Lino Da Silva [55], and Lago [41]. If the work of Lino Da Silva [55] focused on the UV radiation for Mars entry conditions, the recent test
campaign performed by Lago [41] focused on VUV radiation for both Earth and Mars entry conditions. Spectral emission was measured from 110 to 900 nm in low-pressure flows: Pressure chamber was in between 2.9 and 5.3 Pa, and enthalpies in between 4.16 and 35 MJ/kg, for the Mars-like mixture. Test results are shown in Figs. 26 and 27. CO(4+) system, C2 Swann and CN violet systems can be identified, as well as molecular lines for CO\(^+\) and CO, and atomic lines for O and C. For the CO\(_2\)-N\(_2\) mixture, O and C atomic lines are visible, but the CO(4+) system is clearly dominating the VUV radiation. VUV contribution to the total radiation was evaluated for the different flow conditions. Results are plotted in the right part of Fig. 12 for a Mars atmosphere. For CO\(_2\)-N\(_2\), the VUV contribution decreases with the specific enthalpy, from 30 to 12%. These values are similar to those obtained with the EAST shock tube [46] for Mars entry conditions. At high enthalpies, there is sufficient energy available for the dissociation of the CO in the shock layer; since the CO mass fraction decreases, the contribution of the CO(4+) system follows the same trend.

4 Discussion

An extensive survey of the available experimental datasets for VUV radiation has been carried out. The objective of this survey is to have an experimental database for preparing the future test campaigns to be performed in ESTHER. The purpose is to use them for cross-checking, and they could be also potentially used for reducing uncertainties, but this is a long-term application that would also require more effort in the data analysis. Moreover, this potential application would request a lot of details on the instrumentation and the related data calibration that is not often available in the literature.

The most relevant data obtained for VUV radiation are those obtained in the frame of studied undertaken to support planetary exploration investigations. Several datasets covering the VUV range for Earth superorbital entry, Mars and Venus entries have been identified. Some of the corresponding test campaigns were performed in shock tubes, the other using plasma torches; they are synthetized in Table 6 for shock facilities and in Table 7 for plasma torches. However, in the frame of ESTHER development, the tests performed in shock facilities will be the easier to duplicate. This will allow future comparisons with ESTHER results as soon as they are available.

In the USA, EAST and LENS-XX have already provided valuable data for Earth high-speed re-entry. For EAST, a large number of shots have been performed for Lunar return conditions [56] and data were collected from UV to near infrared. Similar shock velocities (around 9–10 km/s) have been simulated with LENS-XX [57], at very low pressure (26.6 Pa), and shock emission was investigated for a wavelength range in between 200 and 1000 nm, from UV to infrared bands, but VUV measurements are missing from the collected data. EAST has also been used to simulate Mars entry; data for high entry velocities of 8–9 km/s have been obtained as resumed in Table 5, focusing on atomic
of such smaller facilities is very relevant for developing new measurement techniques, to be used or adapted, later on, in ESTHER. Concerning the comparisons between the future data obtained with ESTHER and the existing ones, so far, similar exercise has already been performed with some shock velocity facilities. X2 experimental data have already been compared against those obtained in EAST and HVST for Mars entry conditions [58] and against EAST results for Earth high-speed entries [59]. However, if these former comparisons did not account for VUV radiation, this makes these two last facilities among the most attractive for a similar exercise with ESTHER.
5 Conclusions

An extensive screening of VUV measurements has been carried out for identifying experimental datasets valuable for future cross-checks with ESTHER measurements. The review has been extended to other domains than atmospheric entry in order to enlarge the number of datasets and also to identifying other fields of interest for the shock-tube activity. However, the most attractive data remain those obtained for supporting space exploration missions.

This has allowed the identification of the datasets for future comparisons with ESTHER. Among the similar facilities, VUV data obtained with EAST and HVST are very interesting since VUV data obtained with these two shock tubes have already been compared. In addition, potential comparisons could be also performed with the datasets obtained using X2, but for wavelength range outside the VUV range.

All these elements present certain usefulness for the future ESTHER calibration. The data presenting the major interest for potential cross-checking are those obtained with HVST, EAST and to a lesser extend X2.

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