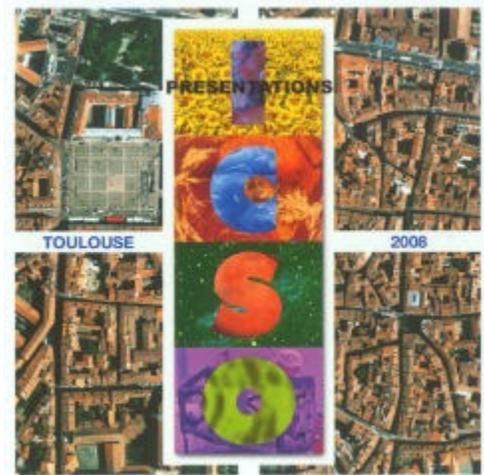


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Nicolas Rouanet

Jean Francois Mariscal

Jean-Luc Maria

Pierre-Olivier Mine

et al.



PROBING OF HERMEAN EXOSPHERE BY ULTRAVIOLET SPECTROSCOPY: PRELIMINARY CALIBRATION RESULTS OF AN ULTRAVIOLET SPECTROMETER

Nicolas ROUANET⁽¹⁾, Jean-François MARISCAL⁽¹⁾, Jean-Luc MARIA⁽¹⁾, Pierre-Olivier MINE⁽¹⁾, Ichiro YOSHIKAWA⁽²⁾, Kazuo YOSHIOKA⁽²⁾, Go MURAKAMI⁽²⁾, Victor GNEDYKH⁽³⁾, Piergiorgio NICOLOSI⁽⁴⁾, Sébastien GALLET⁽¹⁾, Jean-Baptiste RIGAL⁽¹⁾, Eric QUEMERAIS⁽¹⁾, François LEBLANC⁽¹⁾, Eric CHASSEFIÈRE⁽¹⁾, Jean-Pierre GOUTAIL⁽¹⁾

⁽¹⁾ Service d'Aéronomie/IPSL, UPMC Univ. Paris 06, CNRS, UVSQ, Paris, FRANCE. E-mail :
Nicolas.Rouanet@aerov.jussieu.fr, Jean-Luc.Maria@aerov.jussieu.fr

⁽²⁾ University of Tokyo, JAPAN

⁽³⁾ Space Research Institute (IKI), Moscow, RUSSIA

⁽⁴⁾ LUXOR-CNR-INFN DEI University of Padova, ITALY

ABSTRACT

PHEBUS (Probing of Hermean Exosphere by Ultraviolet Spectroscopy) is a double ultraviolet spectrometer for the MPO (Mercury Planetary Orbiter) of the ESA BepiColombo cornerstone mission, which is dedicated to the study of Mercury. The goal of this instrument is to detect emission lines of Mercury exosphere in the bandwidth between 55 to 315 nm by recording full spectra. The instrument is basically composed of two ultraviolet spectrophotometers and one scanning mirror with a single axis of rotation. This movable mirror will collect the light coming from the exosphere above the limb onto the entrance slit of the spectrometers. The mirror is protected from straylight by an entrance baffle characterized by a good rejection capability. Each detector has a specific range of wavelengths: the EUV (Extreme UV) channel spreads from 55 to 155 nm, and the FUV (Far UV) channel from 145 to 315 nm. A couple of photomultipliers receive two additional wavelengths in the Near UV range (NUV) at 404 and 422 nm.

1. PHEBUS INSTRUMENT OVERVIEW

1.1 BepiColombo mission

ESA BepiColombo is a cornerstone mission devoted to the exploration of Mercury and its environment. The mission consists of two spacecrafts: the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO). The PHEBUS instrument will be mounted onboard MPO. PHEBUS is an international cooperation between France (Service d'Aéronomie, CNRS-IPSL), Russia (IKI) and Japan (JAXA).

The launch of the spacecraft is foreseen in 2014. BepiColombo will reach Mercury orbit in 2020 after a 6 years cruise.

1.2 PHEBUS scientific measurement objectives

The atmosphere of Mercury is very tenuous, with a pressure of a fraction of picobar. It results from a complex interplay of the solar wind, its planetary magnetic field and its rocky surface. It is nearly noncollisional, and is highly variable with time and space, characterized by a global asymmetry between dayside and nightside and rapid temporal variations, possibly related to varying magnetospheric activity.

The core scientific objectives of PHEBUS are oriented toward a better understanding of the coupled surface-exosphere-magnetosphere system. The main measurement objectives are the following:

- To detect new species, including metallic species (Si, Mg, Fe, ...), atoms (C, N, S, ...), molecules and radicals (H₂O, H₂, OH, CO), noble gases (Ar, Ne), ions (He⁺, Na⁺, Mg⁺, ...), in addition to already detected species (Na, K, Ca, O, H, He).

- To measure an average exosphere (densities of constituents, vertical structure), with as much as possible species monitored together, at different positions of Mercury around the Sun.

- To measure sharp local and temporal variations of the exosphere content, at specific times and places of interest.

- To search for albedo variations of Mercury's nightside surface, lighted by the interplanetary H Ly- α glow, at 121.6 nm, in order to exhibit possible signatures of surface ice layers (H₂O, SO₂, N₂, CO₂) in high latitude polar craters.

1.3 Instrument configuration

PHEBUS (Fig. 1) is a double spectrometer for the Extreme UltraViolet (EUV) range (55-155 nm) and the Far UltraViolet (FUV) range (145-315 nm) with an extension for some extra visible emission lines (Potassium and Calcium at 404.7 nm and 422.8 nm respectively).

The instrument is composed of several subsystems, all mounted to the main structure. The front end consists of a stray-light rejection baffle and an off axis parabolic mirror allowing to scan the Mercury exosphere thanks to a rotating mechanism. This movable mirror collects the light from the exosphere above the limb and focuses it to the entrance slit. The parameters of the mirror were calculated so as to have a 170 mm effective focal length and a folding angle of 100°. The beam is then spectrally spread by two holographic gratings and reaches the detectors.

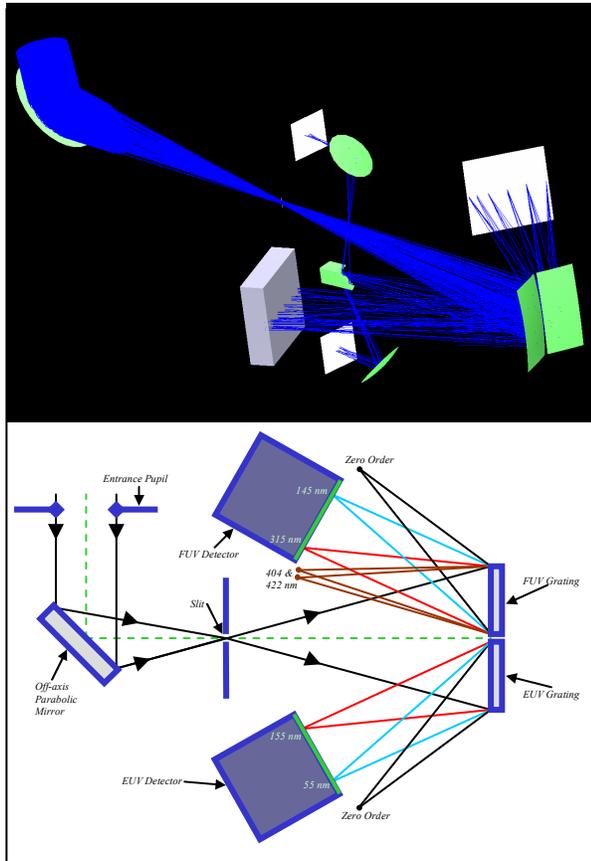


Fig. 1. PHEBUS optical configuration

The spectrum detection is based on the photon counting method and is done using Micro-Channel Plate (MCP) detectors with Resistive Anode Encoder (RAE). Photocathodes are CsI for the EUV range, and CsTe for the FUV range. The size of the detectors active area is 40x20 mm² equivalent to a matrix of 512x256 virtual pixels (spectral x spatial).

Furthermore Calcium and Potassium lines are selected by the FUV grating. These extra visible lines are monitored using photomultipliers (PM) with bi-alkali photocathode also used in photon counting mode.

The main advantages of the MCP+RAE detectors are their very high sensitivity mainly due to a very low dark current. Thus photon counting is easily achievable on typical experiment temperature range (from -20°C to

+40°C), avoiding mass and power expensive devices to cool the detectors. Seven orders of magnitude for the detection are then a typical value and offer the monitoring of a wide range of emission.

Moreover PHEBUS is a very flexible instrument due to the rotating scan mirror at the entrance. The instrument is then quite independent from the spacecraft on an observation point of view, avoiding spacecraft slew for specific pointing request. This scanning mirror is also very helpful to maintain the line-of-sight close to the limb during long integrations, to make the search and monitoring geometry less dependant on orbit and to extend the vertical range of scanning.

1.4 Optical specifications

The wavelength ranges are 55-155 nm for the EUV, and 145-315 nm for the FUV. The spectral resolution is defined in terms of FWHM and Full Width at 1% of maximum (FW1%). The required spectral resolution is 1 nm for EUV and 1.5 nm for FUV. These values are to be compared with the result of the optical design optimization: the FWHM is about 0.5 nm on EUV, and 0.8 nm on FUV. Furthermore, the FW1% is about 0.9 nm on EUV, and 1.5 nm on FUV. These calculated values do not include any spreading effects due to scattering by gratings.

The paraxial Field of View of the instrument is about 2° by 0.1°, and the stray light attenuation baffle is designed to protect from bright sources outside a guard angle of 8.3°. High level of attenuation is obtained by combining a very dark black treatment inside the entrance baffle and a superpolished entrance mirror (0.5 nm RMS) compatible with EUV range.

The two gratings of the PHEBUS instrument are aberration corrected holographic gratings. The mean groove density is ~1600 grooves/mm for the FUV, and ~2700 grooves/mm for the EUV. Groove profile is laminar ion-etched optimized for the respective spectral range. AFM measurements on real prototypes show a micro-roughness of about 1nm RMS. The absolute efficiency can be deduced from AFM measurement of the groove profile via electromagnetic theory software codes: about 6% for EUV and 13% for FUV. The gratings are made of aluminium with a reflective platinum coating. Their active area size is 42 mm by 15 mm.

A radiometric model of the PHEBUS instrument has been implemented in order to simulate recorded spectrum. The mean sensitivity of PHEBUS is in the order of 0.1 count per second per Rayleigh of emission, and the mean detection limit can be estimated to about 0.1 Rayleigh for EUV, and about 0.2 Rayleigh for FUV.

2. OPTICAL CALIBRATION OVERVIEW

2.1 Optical calibration purpose

An optical ground calibration plan has been established to summarize all the foreseen optical calibration activities.

First the detectors will be characterized separately. The spatial resolution of the resistive anode electronics must be verified to be at least 9-bit (512 pixels). Dark count rate measurement will be performed for EUV, FUV, and NUV detectors at ambient temperature, and at different temperatures between -20°C and $+40^{\circ}\text{C}$. Dark count rate dependency to the high voltage will be checked. Solar blindness of EUV detector will also be verified, by using a visible calibrated source of variable intensity. The spatial uniformity of the detector response will be tested with flat field illumination. Spectral responsivity will be measured at low signal level for photocathode characterisation, by using a few UV lamps covering the spectral range of the two UV detectors. Non-linearity due to limited electron delivery capability of micro-channels (for EUV and FUV detector only) will be estimated. Non-linearity due to limited electronic sampling frequency will also be observed. Finally, along the whole life of the detectors, all the illuminations undergone by the detectors will be reported into a single document, in order to determine the ageing of the response.

The whole PHEBUS instrument alignment shall be verified (under vacuum for the EUV) by using sources with numerous fine lines in the considered spectral ranges. The spectral image produced by a few monochromatic sources (punctual and/or extended) covering the spectral range of the detectors will be compared with the results of the radiometric model in order to measure directly the Instrument Spectral Response Function at different wavelengths, and to compare it to the results of the radiometric model. Scientific objectives require an absolute responsivity calibration of the instrument of about 30%. The signal will be measured for the 3 detectors when using well calibrated sources (punctual and/or extended) at different wavelengths in order to measure the absolute responsivity in terms of counts / s / nm of the complete detection chain to a known signal. At last, the instrument straylight and noise will be characterized, as well as the observation dynamic range.

2.2 Optical calibration facilities and sources

Some calibration facilities are already available at Service d'Aéronomie (Fig. 2). We dispose of a vacuum chamber of diameter 700 mm, with an operational vacuum pumping device capable to reach down to 10^{-6} millibars. This chamber volume is just sufficient to accommodate the complete PHEBUS instrument, and it

is large enough to easily accommodate a single detector. Sources at 121.6 nm (Ly- α lamp) and above, monochromator and spectrometer (Jobin-Yvon) are available to determine the illumination of the detector. Thus, instrument alignments and preliminary calibrations down to Ly- α will be done at Service d'Aéronomie. A thermal chamber working down to 10 millibars is also available.



Fig. 2. Vacuum facilities at Service d'Aéronomie

Official calibrations activities will be performed through a scientific cooperation with Padova University (LUXOR Laboratory). A bigger vacuum chamber ($\sim 2\text{m} \times 80\text{cm}$) is available (Fig. 3) and well adapted to the complete PHEBUS instrument. Illumination characteristics will be determined using a large variety of EUV and FUV sources, such as deuterium lamps and

hollow cathodes lamps, and monochromator and collimating tools (McPherson collimator).

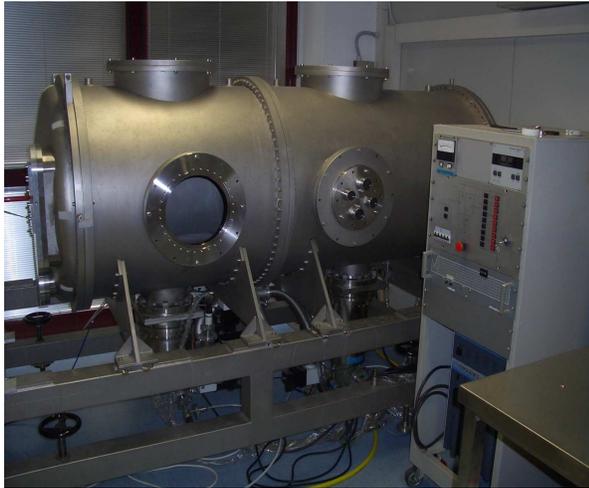


Fig. 3. Vacuum facilities at Padova University

2.3 Optical calibration schedule

The Qualification Model (QM) will be delivered in 2010. A full range of calibration at subsystems and instrument levels will have to be performed. The calibration plan written with the breadboard model will be revised and validated according to the results. Environment tests impact (before / after) will be also be verified.

The Flight Model (FM) will be delivered in 2011, with a complete set of calibrations.

The Flight Spare (FS) will be delivered in 2011 after the Flight Model. It will be based on a refurbished QM, with a new set of calibrations in order to update QM calibrations.

3. OPTICAL CALIBRATION PRELIMINARY RESULTS

3.1 Entrance baffle geometrical and attenuation validation

PHEBUS entrance baffle (Fig. 4) was designed to satisfy several optical constraints concerning its guard angle, its field of view, and its attenuation. Thus, like all others subsystems of the instrument, it is necessary to conduct an experimental phase of validation to observe the behaviour of the entrance baffle and validate these specifications. The first step described here is to qualify the combination {baffle + scanner + entrance mirror + entrance slit}. In a second step the specifications of the entrance baffle can be deduced knowing the specifications of all others elements.

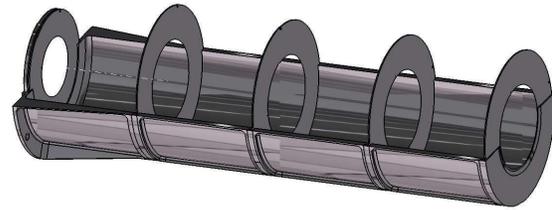


Fig. 4. PHEBUS entrance baffle with its internal diaphragms

To achieve the first stage, the baffle is fixed to the scanner in a way that the assembly can turn around the vertical axis going through the entrance pupil of the baffle. The set is placed in a dark box to protect it from any straylight (Fig. 5). The light source is placed outside the dark box in front of the entrance pupil of the baffle, so a hole is drilled on the wall of the chamber between the source and the baffle. Then the light intensity can be measured according to the angle of incidence of light rays at the level of entrance pupil of the baffle. In this case we can deduce the attenuation of the set composed by the baffle, the mirror and the slit, compared to the nominal direct illumination (point source in the middle of the field of view).

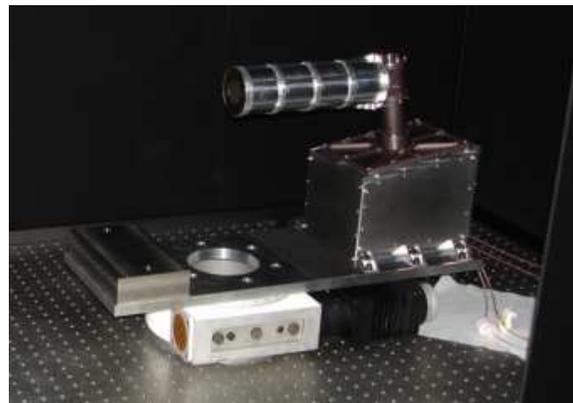


Fig. 5. Baffle optical test bench

Measurements were made with two different light sources. At first we used a Xenon lamp whose advantage is a high level of illumination ($P = 75 \text{ W}$) and a large spectral range ($200 \text{ nm} < \lambda < \text{NIR}$) adjustable with optical filters, however the beam uniformity is very poor. To solve this problem of homogeneity a laser can be used (Helium-Neon laser, $P = 2 \text{ mW}$, $\lambda = 632.8 \text{ nm}$) with a spatial filtering device. It is important to note that the attenuation induced by the baffle is expected to be almost independent of the wavelength. Nevertheless, this point will be checked later.

The optical detector placed under the slit is a Hamamatsu silicone photodiode linked to a logarithmic amplifier with a dynamic range of almost 8 decades.

All these measurements have been made with an Aluminium mirror and not with the SiC mirror of the Flight Model. The roughness of this Aluminium mirror is about ten times higher than the SiC mirror; therefore it leads to a level of straylight one hundred times higher.

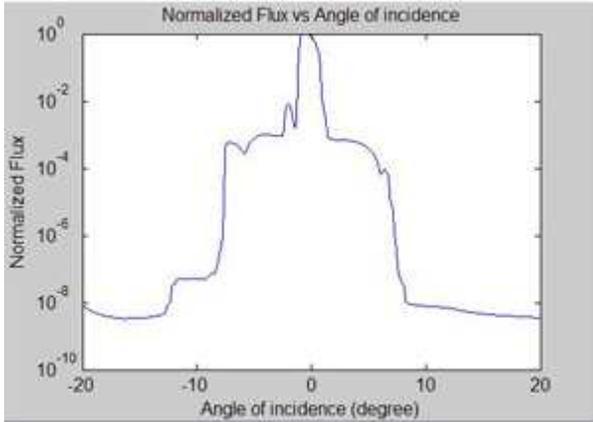


Fig. 6. One of the first measurements of the baffle attenuation as a function of the incidence angle

One of the first measurements is presented in Fig. 6. This graph represents the normalized incident flux passing through the entrance slit, according to the incidence angle. Two significant transitions are obvious on this curve, the first one around -1 and 1 degree, and the second one around -8 and 8 degrees. These transitions correspond respectively to the field of view and to the guard angle. The next manipulations will aim to improve the optical bench (better alignment of some optical components, installation of light traps...) to reduce the artefacts that can be seen on the curve.

3.2 NUV detectors calibration

The photomultiplier used in the NUV detector is a head-on ruggedized PM with a low noise bialkali photocathode usable up to 70°C (Fig. 7). A complete characterization of this photomultiplier has been established. Its dark current has been verified (16 ± 5 c/s). The pulse height distribution (PHD) and the gain have been studied as functions of high voltage supply.



Fig. 7. PHEBUS NUV photomultiplier

An absolute calibration of the NUV photomultiplier detection chain has been performed. First, a laser diode at 404 nm is calibrated with a commercial calibrated photodiode at high flux level. Then a set of neutral optical density filters (OD1 to OD4) are characterized at the laser wavelength. Finally, the NUV photomultiplier is calibrated at low flux level (photon counting) by attenuating the laser beam with the optical densities. Cumulated optical densities are equivalent to about OD8 to OD10. The result of this absolute calibration is the calculus of the PM efficiency $Q = 0.177 \pm 0.05$.



Fig. 8. Photomultiplier calibration bench

A great effort was made to correctly estimate the error margins, the confidence level, and the reproducibility of the absolute calibration, by taking into account all possible sources of uncertainties. The other main difficulty for this absolute calibration is the very high sensitivity of the photomultiplier to stray light, which requires the use of dark baffles and a black box around the optical bench.

3.3 Instrument complete optical breadboard

In order to calibrate the detectors, and to learn how to adjust optical components (gratings, slit, entrance mirror...), an optical bench of PHEBUS is currently being designed. The objective of the PHEBUS optical breadboard is to be representative from an optical point of view. As a result, the main optical components will be accommodated in the optical bench (Fig. 9).

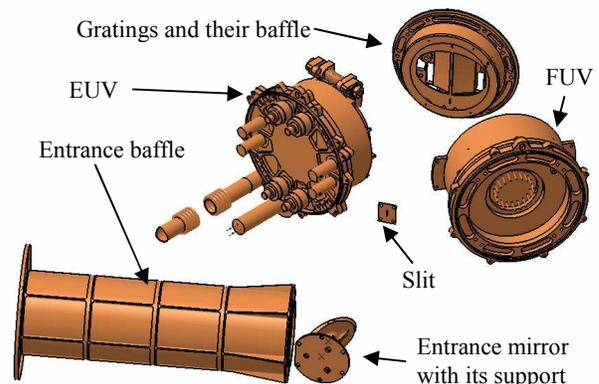


Fig. 9. PHEBUS optical breadboard components

The optical bench will have to hold all these optical components, and will be able to work under vacuum. Indeed, the studied wavelengths, as well as EUV detector power on, require operating under vacuum. Moreover, a black box will be set around detectors and the gratings in order to avoid stray light.

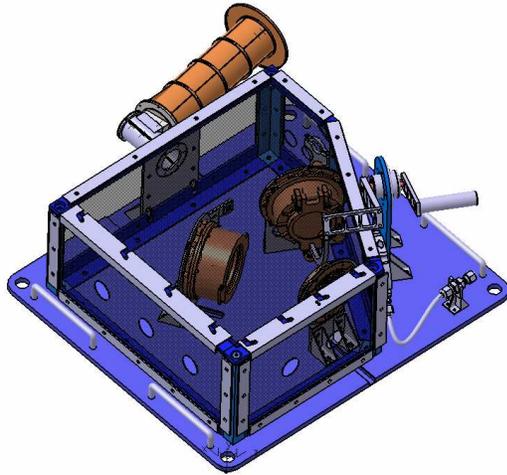


Fig. 10. PHEBUS optical breadboard overview

This optical bench (Fig. 10) should be able to calibrate detectors down to the extreme UV, and also to enable the adjustment of the gratings and the slit. The optical breadboard will be operated with a fixed baffle orientation (the scanner mechanism will not be implemented).

4. CONCLUSION

The PHEBUS instrument will allow measuring precisely the hermean exosphere composition, by the use of a double spectrophotometer in the Extreme UV and Far UV.

Specific optical test benches have been set up in order to qualify some very special sub-systems such as the entrance baffle or the NUV photomultipliers.

After designing each sub-system, an optical breadboard is being manufactured in order to calibrate the entire instrument in an optical point of view. This calibration will then be refined with the next models of PHEBUS.