New Insights from the ST-ECF Lamp Project

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The Space Telescope European Coordinating Facility (ST-ECF) and the National Institute of Standards and Technology (NIST) are collaborating to study Pt/Cr-Ne hollow cathode lamps used onboard the Hubble Space Telescope(HST). The two main components of this study are the production of a comprehensive list of the spectral lines emitted by the lamp and observations of the lamp performance over an extended period to simulate operation in a space mission. Spectra recorded by the NIST 10.7-m grating spectrograph and the vacuum ultraviolet Fourier Transform Spectrometer (FTS) have yielded accurate wavelengths for more than 8000 lines that can be used for calibration purposes in the region 1150 Å to 3200 Å. Typical uncertainty (one standard deviation) is 0.0020 Å for lines measured with the grating spectrograph at wavelengths shorter than 1800 Å and 0.0005 Å for longer wavelength lines measured with the FTS. Observations of the dependence of the lamp spectrum on operating current show that Ne lines dominate the discharge at low current but decline in intensity relative to the metal lines as the current is increased. Accelerated aging tests that mimic the use of the calibration lamps in orbit have been conducted for four lamps. The spectrum emitted was found to be very stable for cumulative operating times as long as 2500 hours. Lamp operating voltage was found to increase as the lamps aged, and it appears that the rate of increase accelerates as the lamp approaches the end of its useful life. Results of this study will be prepared for online dissemination in a form fully compliant with the standards of the Virtual Observatory (VO) initiative of the International Virtual Observatory Alliance (IVOA).

Spectral characterization of calibration lamps as used on STIS

As a primary objective, we have observed the spectra of Pt/Cr-Ne lamps to obtain a comprehensive list of emission lines between 1150 Å and 3200 Å, a spectral region corresponding to the Space Telescope Imaging Spectrograph (STIS) echelle modes. This project was initiated in direct support of the ST-ECF's STIS Calibration Enhancement (STIS-CE) effort. Previously, wavelength calibration of all HST spectrographs has been based on the line list produced by Reader et al. (1990) using a Pt-Ne lamp, despite the fact that STIS and the Faint Object Spectrograph (FOS) use a Pt/Cr-Ne lamp. The addition of Cr is especially significant in the near ultraviolet (UV) where up to 90% of the observed lines are Cr. However, published Cr wavelengths are not sufficiently accurate for the calibration of STIS and FOS. We have determined improved wavelengths for about 5000 Cr lines. The combination of our new line lists with the NIST Pt-Ne list of Reader et al. (1990) provides about 11500 lines for calibration purposes in the region 1115 Å to 4332 Å. This forms the basis for the STIS-CE model-based wavelength calibration (Rosa 2000). Results of STIS-CE and its impact on the wavelength calibration and the scientific quality of STIS echelle data will be reported in a future edition of the Newsletter.

The secondary objective of the project is to better understand the performance of hollow cathode lamps and the physical processes involved in their long-term operation; see Kerber et al. (2004) for an overview. Among the issues we have studied is the dependence of the spectrum on lamp current and cumulative operating time. We have performed accelerated aging tests that simulate operation on STIS using newly made space-qualified lamps.

Here we will describe some of the results of these experiments. Our findings also include important lessons for the design and operation of future UV and optical spectrographs in space.

The spectrum of Pt/Cr-Ne hollow cathode lamps

All observations were made at NIST using the 10.7-m normal-incidence spectrograph and a Fourier transform spectrometer (FTS) optimized for the vacuum ultraviolet. For an overview of the project and the experimental work we refer the reader to Kerber et al. (2003) and Sansonetti et al. (2004). The project has clearly met its primary objective with respect to quality and quantity of data. In the far UV we have published a list of more than 1200 lines observed in the range 1132-1827 Å (Sansonetti et al. 2004). Analysis of near UV spectra from the FTS is nearing completion, and the resulting line list is already being used by the STIS-CE project. The full list and a description of the experimental work with the FTS will be published soon. Our work has established accurate wavelengths for more than 8000 lines. The uncertainty is 0.0020 Å (one standard deviation) for lines in the 1150-1800 Å region measured with the grating spectrograph and 0.0005 Å for the 1800-3200 Å region observed with the FTS. Wavelength accuracy for some Pt lines is limited by

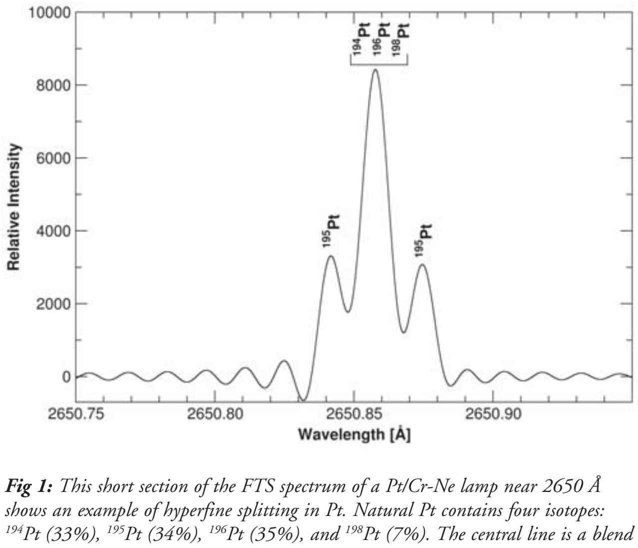

Fig 1: *This short section of the FTS spectrum of a Pt/Cr-Ne lamp near 2650 Å shows an example of hyperfine splitting in Pt. Natural Pt contains four isotopes: ^{194}Pt (33%), ^{195}Pt (34%), ^{196}Pt (35%), and ^{198}Pt (7%). The central line is a blend of the even isotopes while the two satellite lines result from the hyperfine splitting of ^{195}Pt. At the limiting resolving power of the STIS echelle modes (R ~ 100 000), hyperfine structure may be resolved for some lines.*

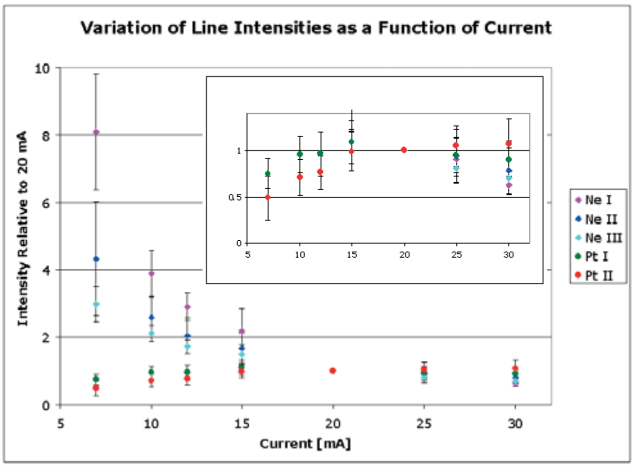

Fig 2: Variation of the line intensities as a function of the operating current of the lamp. The error bars represent uncertainty at the one standard deviation level. Spectra were taken at 7, 10, 12, 15, 20, 25 and 30 mA. Note the pronounced difference in the behaviour of the gas and metal (inset) lines.

asymmetric line shapes due to unresolved hyperfine and isotope structure, see Figure 1.

Dependence of spectral output upon current

In our photographic spectra of the far UV region we recognized that the relative intensity of the Ne lines with respect to the metal lines was significantly enhanced at lower lamp currents (Sansonetti et al. 2004). In the near UV region the linear intensity response of the FTS enabled a more quantitative investigation of the change in the spectrum as a function of operating current. We took spectra at 3.9 mA (low power mode on STIS), 7, 10 (standard current on STIS), 12, 15, 20, 25 and 30 mA. While this is still work in progress, it is safe to say that the operating current does indeed have a profound influence on the ratio of the lines from different elements and ionisation stages.

Analysis of the spectra taken at different currents revealed a very well defined behaviour of the line intensities as a function of current (Figure 2). The intensities of all lines in all spectra were normalized with respect to the intensity of the same line in the 20 mA spectrum. Then, this ratio was averaged for all the lines of a given species observed at a given current. Figure 2 shows the average behaviour of the line intensities as a function of current. 27 lines were used to form this average for Ne I, 202 for Ne II, 55 for Ne III, 378 for Pt I and 552 for Pt II. There is a pronounced distinction between the behaviour of the metal and the gas lines. The gas lines show much higher relative intensities at lower currents, whereas the metal lines (inset) show only a limited variation with current.

A qualitative explanation of this behaviour is that there is less sputtering of metal atoms from the cathode at lower lamp currents. The sputtering of atoms from the cathode is caused by the impact of positive ions accelerated across the cathode fall. The electron density (and corresponding ion density) in the discharge is approximately proportional to lamp current. At higher lamp currents more ions are available in the plasma and there is a corresponding increase in sputtering. Since the density of Ne atoms is independent of current while the density of metal atoms increases with increasing current, the relative intensity of the metal spectrum is enhanced at higher currents. The increasing ionization of the plasma at higher currents also explains the relative enhancement of the spectra of Ne II, Ne III, and Pt II at 20 mA with respect to the corresponding neutral atom spectra. For Cr lines this effect cannot be verified yet since the classification of the Cr lines is still in progress.

To our knowledge, this is the first time the change of the spectrum of a Pt/Cr-Ne lamp has been studied at different currents. These data sets and the well established behaviour of the line intensities could serve as the basis for a more quantitative understanding of the operation of the lamp. In space applications, ozone mapping instruments like the Global Ozone Measuring Experiment (GOME) use similar lamps for wavelength calibration over a wide wavelength range. In order to optimize the lifetime of these lamps they are usually operated at 10 mA, but the strong Ne lines in the visible region make it difficult to observe a rich spectrum with a single exposure. Our findings suggest that operating the lamp at a current of 20 mA would reduce the relative intensity of these lines by a factor of 4, likely alleviating this particular problem.

The aging and failure of Pt/Cr-Ne hollow cathode lamps

An important secondary objective of this project was to investigate the aging of Pt/Cr-Ne hollow cathode lamps and any changes in spectral output or operational characteristics associated with it. To this end we recorded spectra of lamps used to calibrate the Goddard High Resolution Spectrograph (GHRS) and Faint Object Spectrograph (FOS) on the HST. These are the only lamps that have been returned to earth after years of operation in space (Kerber & Wood 2004). Additionally, we conducted dedicated accelerated aging tests in the laboratory at NIST using new lamps. The lamps were operated in a way designed to mimic as closely as possible the use of the lamps onboard HST. An analysis of the HST/STIS archive (Valenti 2002, private communication) shows

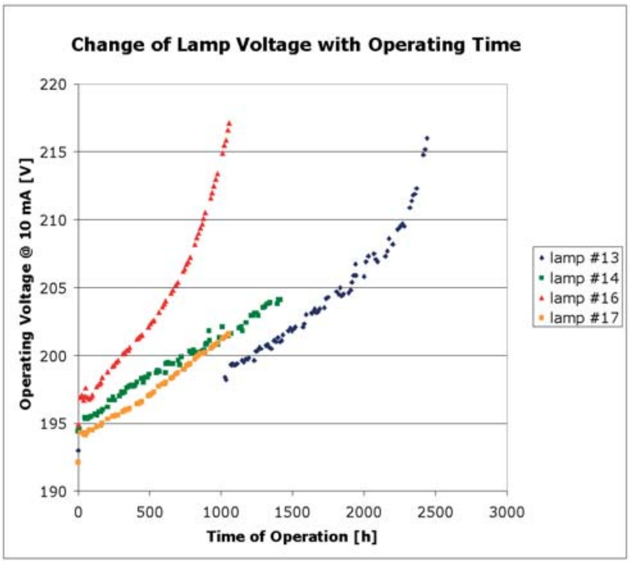

Fig 3: Change of the operating voltage required for a current of 10 mA as a function of accumulated operating time. The lamps were operated in a cycle of 30s on / 30s off in order to simulate operation onboard STIS. The operating voltage increased with usage and, at least in the case of lamp #13, the rate of change also increased. Spectra were taken of lamps #13 and 14 to document any change in the spectral output. Both lamps failed in a similar manner shortly after a set of spectra had been taken. Lamps #16 and 17 are still undergoing aging.

that most of the exposures taken with STIS are short; 91% lasted less than 60 s, with an average exposure time of about 31 s. Therefore we operated our lamps at 10 mA for alternating periods of 30 s on and 30 s off over a span of several months.

Several times during the aging test we photographed the spectrum of the test lamps on the normal-incidence spectrograph and compared them to spectra recorded at the beginning of the test. So far we have completed the aging test for two Pt/Cr-Ne lamps (#13 and #14). One of these (#14) lasted for about 1450 hours and the other (#13) for more than 2500 hours, see Figure 4. Both failed shortly after a set of spectra had been recorded. A preliminary analysis of these spectra shows that the spectral output changed very little over the life of the lamps. Even the absolute intensity of the lines was comparable to that observed initially. As the lamps aged there was a progressive deposition of sputtered cathode material on the inner wall of the lamp envelope. A heavier coating of metal was deposited on the first mica spacer located just behind the front surface of the cathode. After many hours of operation we observed the presence of small metal flakes inside the lamp, indicating that the sputtered metal is not firmly bonded to the mica spacer. Both lamps eventually failed in a similar manner: the discharge no longer concentrated inside the cathode. Instead an anomalous discharge covering the surface of the first mica spacer formed when the lamp was ignited. It is possible that the metal deposited on the spacer forms a conducting layer that leads to failure of the lamp.

The only obvious change observed before failure is an increase in the lamp operating voltage, as shown in Figure 3. This could indicate a change in the Ne gas pressure or in the diameter of the cathode hole. Since the operating voltage seems to be the best diagnostic of lamp aging, and since it can easily be monitored, we suggest that this voltage be part of the housekeeping telemetry of future instruments and that it be used for analysis of the lamp's performance. Currently two lamps (#16 and #17) are still undergoing accelerated aging. Lamp #16 is displaying a strikingly more rapid increase in operating voltage than the other lamps studied. This may be a consequence of the fact that the getter (a barium coating inside the lamp that keeps the fill gas clean by reacting chemically with contaminant gases) in lamp #16 was almost totally depleted when the lamp was received from the manufacturer. After our aging tests are complete, a more detailed account of the results will be given in a separate publication.

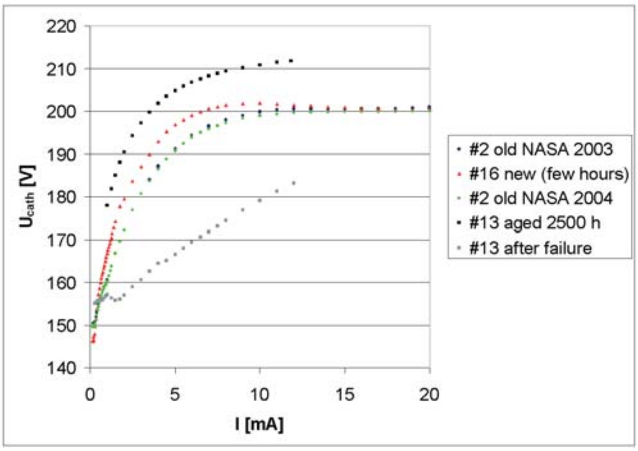

Fig 4: *Voltage-current characteristic of three Pt/Cr-Ne hollow cathode lamps. The three central curves show the general behaviour. Lamp #16 was newly acquired for the experiment and had been used for a few hours when the data were taken. Lamp #2 is a former STIS backup manufactured about 15 years ago. It was provided on loan by the STIS IDT. We measured it twice, once in 2003 and then again in 2004. The curves are virtually identical, illustrating that the passing of time does not lead to change in the electrical characteristics, whereas operating time does. The upper curve represents a lamp (#13), bought in 2002 for aging purposes, after 2500 hours of operation, and the lower curve represents the same lamp after failure.*

The lamp project as a data provider for the Virtual Observatory

The Virtual Observatory (VO) initiative is an effort by the international astronomical community to allow global electronic access to the available astronomical data archives of space and ground-based observatories and sky survey databases. It also aims to enable data analysis techniques through a coordinating entity. In 2002 the existing VO projects formed this coordinating entity, namely the International Virtual Observatory Alliance (IVOA) (www.ivoa.net). After discussions in expert working groups, the IVOA sets standards for data exchange and procedures that will be presented to the International Astronomical Union (IAU) for endorsement. To date there are 15 funded national and international VO projects and each is represented in the IVOA Executive Committee.

Although the VO is still a research and development project, it has already produced the first scientific result that was made possible by combining in a new manner X-ray data, optical data, and catalogues publicly available from data archives (Padovani et al. 2004). See the European Astrophysical Virtual Observatory (AVO) webpage (http://www.euro-vo.org/) to learn how the VO approach and infrastructure enabled this particular scientific study.

The VO is currently working toward better usability of the huge existing archives of astronomical observational data. In order to realize the full potential of the VO, it is vital to support the scientific process in an integrated manner. Both products of theoretical work (eg, stellar model atmospheres) and laboratory measurements must be included in VO data repositories. It is important to note that for VO use presentation of the data itself in the form of an ASCII table is not sufficient. It is essential to also provide ancillary information describing how the data were obtained, reduced, and analyzed. The goal is to characterise data in such a way that an astronomer can assess whether a given data set is suitable for a particular purpose. Such supporting metadata are readily available at the source, and only a limited amount of effort on the part of the data provider is required to make it accessible as part of the data product. However, this kind of information is sorely lacking in many of the current astronomical data archives.

In order to do full justice to the results of this project, the ST-ECF and NIST have decided to become data providers to the VO (Figure 5) and take a pioneering rôle in this field. We plan to provide the relevant data of the Pt/Cr-Ne lamp project in a fully VO compliant manner. In particular, we will make the complete Pt/Cr-Ne line list available as a VOTable including the pertinent metadata in a form ready for use by VO tools. This effort will be fully supported through our websites, making the results and data products available to the global community.

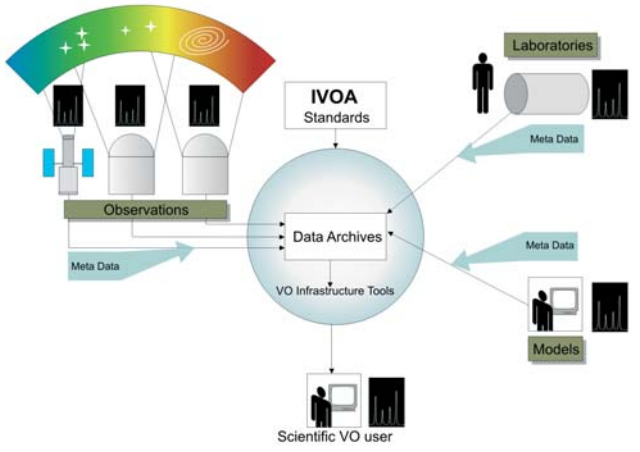

Fig 5: Illustration of the structure of the VO and the relationship of data providers, such as the ST-ECF and NIST, to archives and scientific users.

We are confident that many other data sets exist that are the result of laboratory, theoretical, or modelling work that are highly relevant for astrophysical research (eg, atomic data or stellar model atmospheres). We encourage other scientists to also become data providers to the VO. In this way they can assure that the product of their work can be employed by the astronomical community at large.

Acknowledgments

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