ARGES: Radial segregation and helical instabilities in metal halide lamps studied under microgravity conditions in the international space station

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HID lamps (High-Intensity Discharge) are gaining ground in the lighting industry because of their very high energy efficiency (up to 40%). In these lamps, which are operated in the arc regime and which are contained in a ceramic balloon, filled with argon or xenon, mercury, and salts of various rare earth metals and iodine), de-mixing occurs. This de-mixing is driven by differences in diffusion velocities of molecules and atoms. Furthermore, helical instabilities might occur in the lamp. Both phenomena are severely modified under 1 G conditions: convection will bend a horizontally burning arc channel upwards, and a vertically burning arc channel will exhibit convective cells. This makes it impossible to study these phenomena on the ground. If a proper understanding of these phenomena is to be gained, experiments under microgravity are necessary. The main objectives of the experiment are: (1) determination of the critical factors for the onset of helical instabilities in HID lamps and (2) characterisation of the radial de-mixing processes by radially resolved high-resolution emission spectroscopy. To this end, special hardware has been designed and built which houses a very compact high-resolution spectrometer, a video camera and a caroussel with 20 lamps in it. The lamps are measured consecutively. The experiments have been performed successfully by the Dutch astronaut André Kuipers on board the International Space Station during the Dutch Soyuz Mission "DELTA" on 24 and 25 April 2004. Especially the helical instabilities part yielded immediate and surprising results: the arc channel does bend, but does not rotate under microgravity. This fact is very important in improving the performance of the lamps, especially since the instabilities occur mainly in the most efficient lamps.

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INTRODUCTION

The name of the experiment is "ARGES". This is an acronym for: **A**tomic densities measured **R**adially in metal halide lamps under micro-**G**ravity conditions with **E**mission and absorption **S**pectroscopy. The lamp geometry is quite simple: a burner made of quartz or sintered aluminum oxide contains the gas mixture (see figure 1a). The burners are contained in a second envelope made of quartz. Between the electrode in the burners, a discharge is struck in the background gas (argon) by a high voltage pulse. After ignition, the discharge quickly moves from the glow regime to the arc regime, and then the mercury rapidly evaporates. Due to this evaporation, the total gas pressure increases to several tens of Bars. The metal salts start to evaporate also. In the central arc channel the temperature can get as high as 5000 K. At these temperatures, the salt molecules dis-

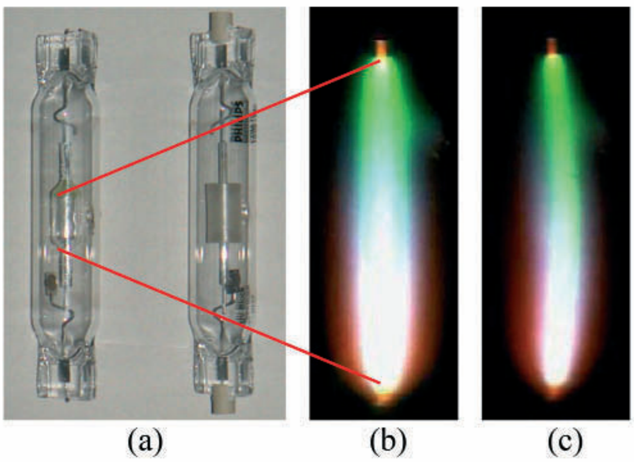

Figure 1: HID lamps. (a): geometry of the burners inside the outer balloon. (b): axial and radial demixing illustrated. (c): frame of a lamp which shows helical instabilities.

sociate into atoms, and the metal atoms even ionize to a substantial degree. Differences in diffusion velocity of atoms and molecules cause radial segregation, which in combination with convection results in axial segregation or axial de-mixing, which is apparent from the colour distribution in the lamp (see figure 1b)[1]. Probably driven by self-generated magnetic fields, the discharge channel starts forming a helix, which rotates around its axis (figure 1c).

EXPERIMENTAL

The discharge is studied with high-resolution spectroscopy and video imaging (helical instabilities). The optical emission spectrocopy has two goals: analysis of the self-inversion of the spectral lines of mercury for temperature determination and determination of the intensities of various of the very numerous spectral lines of the rare earth metal additives atoms and ions for the study of the radial de-mixing processes[2]. All measurements have to be done as a function of the radius in the lamp. In the flight hardware, 20 lamps are combined in a caroussel. At any one time, only one lamp is in the measurement position, where it can be analysed by the two diagnostics. The spectrometer had to be small, light weighted, and robust. The requirement for compactness is solved by using an Echelle grating with a high blaze angle (74o). Because of the high dispersion, due to the high angle of incidence and the high orders used, the focal length of the main lens can be relatively small, and consequently the spectrometer can be very compact. A disadvantage of Echelle-type spectrometers is however that they have a small free spectral range (FSR), which results in wavelength overlapping of adjacent orders. By installing an interference filter in the optical system for selecting a small wavelength interval, the problem of overlapping orders can be avoided. When several interference filters can be selected, these filters can be used for wavelength selection, and the angle of the grating can remain fixed. In this way the requirement for robustness is also fulfilled, because in this case no critically moving parts exist inside the spectrometer. The assignment of the 5 filters is given in table 1. The light originating from the plasma inside the lamp first reaches lens I (100 mm focal distance) and after that forms a parallel beam. A parallel beam is necessary for the proper functioning of the wavelength selection by the interference filter, which is situated between lens I and lens II (also 100 mm focal distance). Lens I & II combined with the interference filter are called the *entrance optics* and form a 1:1 image of the burner on

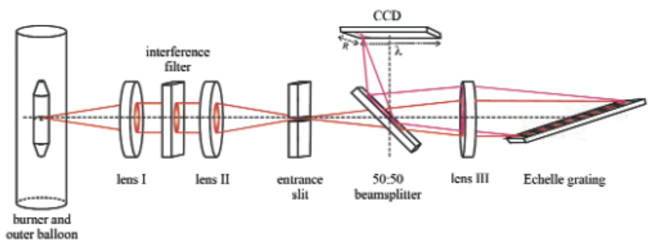

Figure 2: Schematic view of the integrated emission spectrometer. An Echelle type spectrometer is used in the Littrow configuration, meaning that the imaging lens (III) is used for the collimation of both the undispersed beam of light as well as the reflected dispersed beam of light.

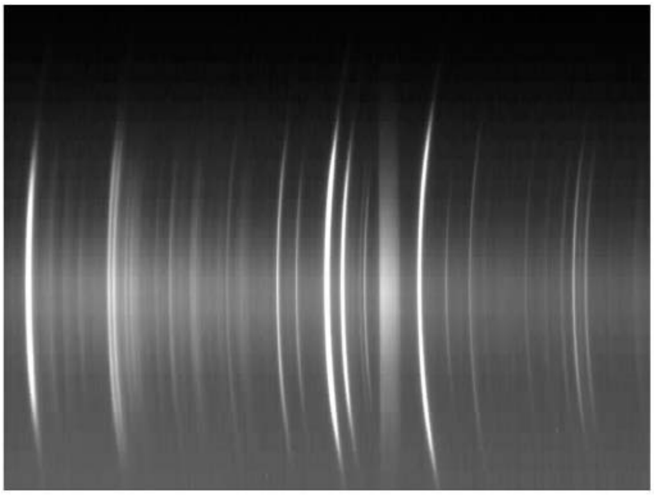

Figure 3: Example of a 2-D image as it is recorded by the integrated CCD camera. The horizontal axis respresents the wavelenght, the vertical axis the lateral position in the burner. The spectral lines appear to be curved. This is, however, an artefact which results from peculiarities in the diffraction at the Echelle grating. Ex posteriori the images are processed to straighten the lines.

filter specifications		Selected lines (nm)		
CWL (nm)	FWHM (nm)	Dy	Ce	Goal
640.0	10.0	642.19, 642.73, 643.67	643.44, 643.64, 644.61	Determine radial salt-densities
400.1	5.0	400.05 (ion-line)	401.24, 399.92 (ion-lines)	Determine radial salt-densities
580.0	10.0	579.06 (optically thin Hg-line)		Determine temperature-profile
404.4	2.0	404.66 (self-reversed Hg-line)		Determine temperature-profile
435.8	5.0	435.83 (self-reversed Hg-line)		Determine temperature-profile

Table 1: The chosen interference filters and their objectives. CWL stands for Central Wave Length.

the horizontally placed entrance slit (10 mm x 10 μm). The image consists only of light with the desired small wavelength interval. The entrance slit acts as source for the actual spectrometer, by 'selecting' a narrow horizontal slice from the burner of the vertical lamp. The light originating from the entrance slit passes a 50:50 beam splitter and after being collimated by an achromatic doublet (Lens III), the light reaches the Echelle grating having 79.01 lines/mm and a 74° blaze angle. Lens III is positioned at its focal distance (150 mm) from the entrance slit to create a parallel beam of light on the Echelle grating. Then the light is back-reflected and dispersed with conservation of the spatial information. The angle of the reflected light with the optical axis of the system is dependent on the wavelength of the light. The reflected light is collimated by the same doublet (Lens III) and focused via the 50:50 beam splitter on the CCD-surface of the camera (SBIG 2000XM). This optical system creates a 1:1 dispersed image of the burner on the CCD-surface (1600x1200 pixels of 7.4x7.4 μm each), with wavelength information due to dispersion of the grating in one direction, and spatial information in the other direction. The CCD is positioned in such a way that the wavelength information is imaged in the '1600-pixel' direction, and the spatial information in the '1200-pixel' direction. The spectral resolution is proven to be ~0.024 nm around 640 nm, where the Spechelle is optimized for. This is sufficient for the distinction of the spectral additive lines which are situated around 640 nm. The detectable spectral range is approximately 7 nm for order 38, corresponding to wavelengths around 640 nm. However, the detectable spectral range becomes smaller when going to higher orders, i.e. smaller wavelengths. For instance, the detectable spectral range for

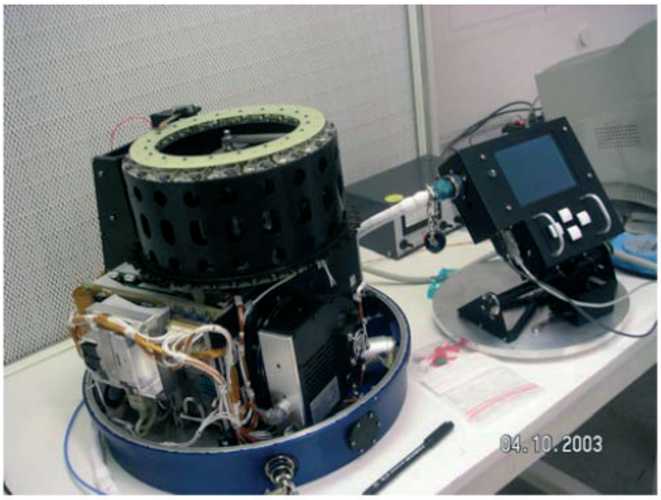

Figure 4: The interior of the Arges container, together with the HMI, prior to closure of the container with the aluminium dome.

Fig. 5: One of the authors (Anré Kuipers) installing the Arges hardware in the MSG aboard ISS. Photo: ESA

Species	λ(nm)	E_{up}(eV)	Pos.
Dy I	642.19	1.93	4
Dy I	642.73	2.44	6
Dy I	643.67	3.94	7-8
Dy II	400.05	3.20	5-6
Ce I	643.44	1.95	7
Ce I	643.64	2.39	7-8
Ce II	401.24	3.65	8
Ce II	399.92	3.39	5-6
Hg	435.83	7.73	5-6
Hg	579.07	8.84	2-3

Table 2: Spectral lines which are detected with the integrated high resolution spectrometer of the Arges hardware. In the last column the position on the wavelength axis on the CCD camera is given, expressed as a number between 1 and 10. In the third column the energy of the upper level of the transition is given.

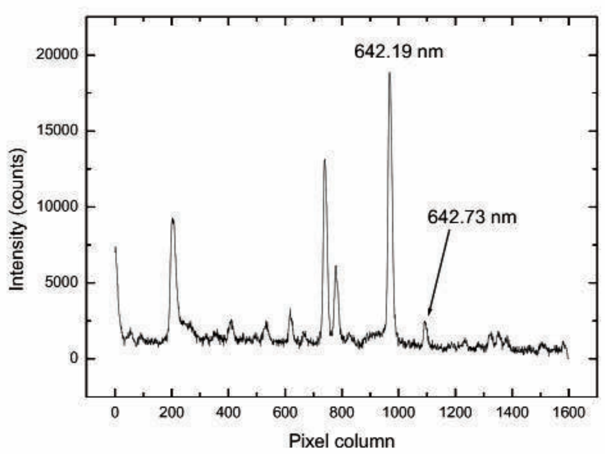

Figure 6: Measured spectrum of a Dy lamp at a certain lateral position during microgravity phase.

order 60 (around 406 nm) is ~4.4 nm. The spectral lines which have been chosen as subjects for analysis are given in table 2. Lines from neutral (I) and singly ionised (II) Dysprosium and Cerium as well as lines from neutral Mercury are used. When the CCD-surface is imaginary divided into ten equal areas, we can calculate what the position of a certain emission line on the detector will be with a certain angle of the grating. In order to avoid the risk that small misalignements could cause certain spectral lines to disappear from the CCD surface, we have avoided choosing measurement lines positioned very close to the edge of the detector. An example of an image as it is recorded by the CCD camera is given in figure 3. The spectral lines appear to be curved. This is, however, an artefact which results

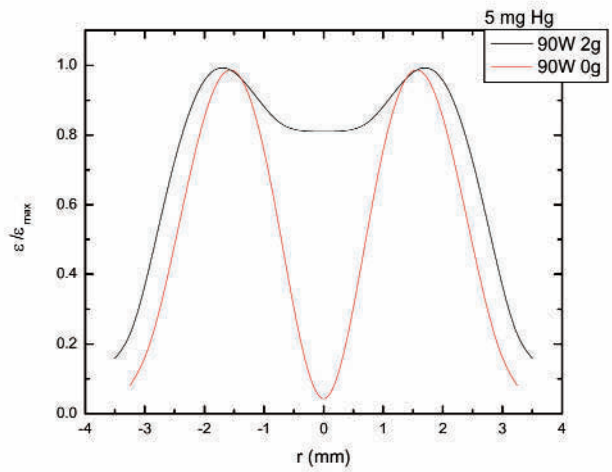

Figure 7:Radial profile of the dysprosium line emission for microgravity and hypergravity conditions.

from peculiarities in the diffraction at the Echelle grating, which are primarily caused by the extremely high diffraction order we are using. Ex posteriori, the images are processed to straighten the lines. All hardware is integrated on one frame, which is enclosed by an aluminum dome structure. The frame holds the spectrometer, the video camera which is used to observe the Helical Instabilities (a stripped Philips Toucam webcam), and it also supports the lamp caroussel in which 20 lamps can be mounted. Figure 4 shows the flight hardware, just before the aluminium dome is mounted on the bottom plate which holds the frame.

The astronaut operates the experiment using a Human Machine Interface (HMI). The experiments have operated in the ESA Microgravity Science Glovebox (MSG), in the US Destiny lab. Figure 5 shows a picture of one of the authors (A. Kuipers) installing the Arges hardware into the MSG on board of the ISS during the Delta Soyuz Mission.

RESULTS

A modified version of the Arges hardware has participated in the 34th and 35th ESA parabolic Flight Campaigns. During parabolic flights, only 20 seconds of microgravity is available. This is largely insufficient in view of the long stabilisation times of the plasma in the lamps, which is of the order of 10 minutes, but still one can get a good impression of the proper operation of the hardware and of the phenomena to be expected during the experiments in the ISS. A demonstration of the performance of the high-resolution spectrometer is give in figure 6, where a part of the emission spectrum of dysprosium is given. Two lines, which are seperated by only 0.5 nm, can clearly be distin-

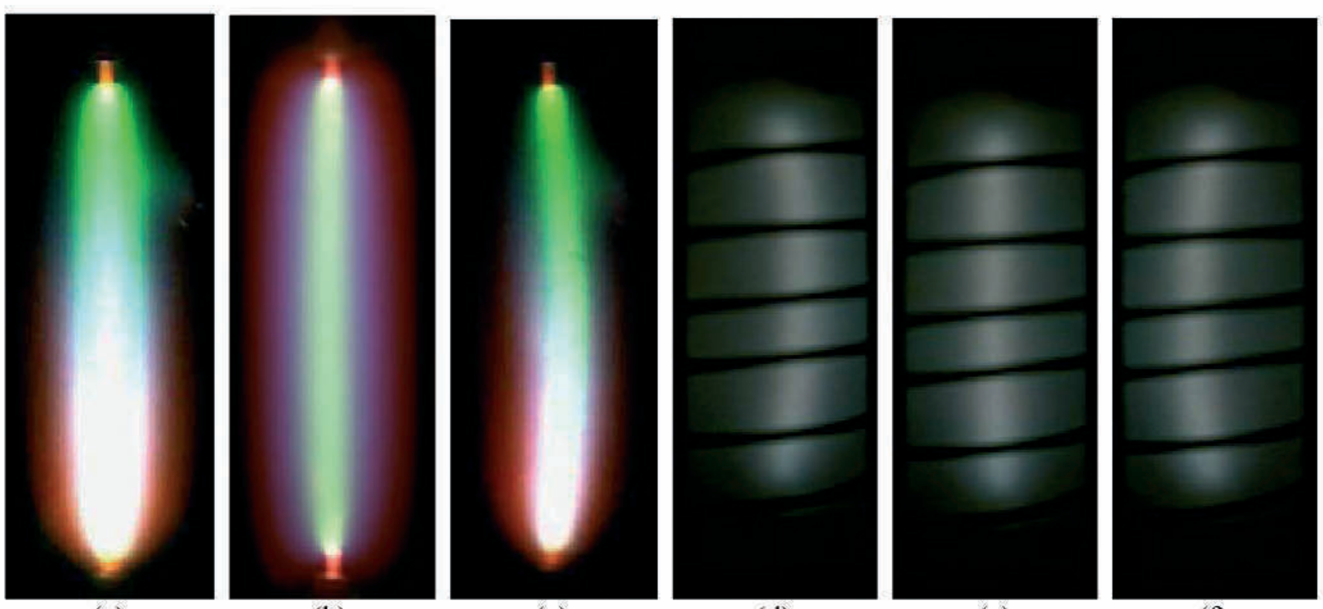

Figure 8: pictures of the plasma in the lamp. (a): on the ground, axial demixing is vlearly visible; (b): same lamp in space: only radial demixing is observed, no axial demixing; (c): helical instability on the ground; (d), (e) and (f): helical instability in space, with suppressed axial demixing and with very slow rotation due to residual gravity of 0.001 g.

guished. The line integrated measurements of the spectrometer represent lateral profiles. They have to be converted to radial profiles by Abel inversion. This has been done for a number of experiment conditions. An extreme example of the differences to be observed for 0g and 2g can be found in figure 7. Under 2 g conditions, it is obvious that the radial de-mixing, which is strongly occuring (see the 0g measurement), is almost totally suppressed by convective mixing or “stirring”.

The experiments in the ISS were a 100 % success. All foreseen measurements have been taken and all data was transported back to the experimenters. Already during the experiment operations, the results proved to be very surprising. Whereas the instabilities in the lamp were expected to be shaped as a rotating helix, they appeared to be a singly bent curve which is not rotating. Analysis afterwards has indicated that the rotation is caused by convection solely and that the curving is caused by self-generated magnetic fields. For one condition, residual gravity caused a very slow rotation. As expected, the axial de-mixing did not occur during the Delta mission experiments, so the radial demixing can indeed be studied udisturbed. The analysis of the spectra is well underway.

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