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ALICE—AN ULTRAVIOLET IMAGING SPECTROMETER FOR THE ROSETTA ORBITER

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ABSTRACT

We describe the design concept and scientific objectives of *ALICE*: a lightweight (2.2 kg), low-power (2.9 W), and low-cost UV imaging spectrometer for the ESA *Rosetta* Orbiter. Ultraviolet spectroscopy is a powerful tool for studying astrophysical objects, and has been applied with great success to the study of comets. *ALICE* is designed to obtain far-UV (FUV) spectra of the *Rosetta* comet nucleus and coma in the 700-2050 Å bandpass; it will achieve spectral resolutions between 9.8 and 12.5 Å across the bandpass for extended sources that fill its 0.1 x 6.0 deg.^{2} field-of-view. It employs an off-axis telescope feeding a 0.15-m normal incidence Rowland circle spectrograph with a concave holographic reflection grating. The imaging microchannel plate detector utilizes dual solar-blind opaque photocathodes (KBr and CsI) and a 2-D wedge-and-strip readout array. *ALICE* will deepen the *Rosetta* Orbiter remote sensing investigation through its ability to detect and measure (1) noble gases; (2) atomic abundances in the coma; (3) major ion abundances in the tail; and (4) production rates, variability, and structure of H_2O and CO/CO_2 molecules that generate cometary activity. In addition, *ALICE* will allow an investigation of the FUV properties of the nucleus and its solid grains, and can provide unique information during asteroid flybys and at en-route planetary encounters, most notably, Mars.

INTRODUCTION

The *ALICE* UV Spectrometer is a low-cost instrument designed to perform spectroscopic investigations of planetary atmospheres and surfaces at far and mid-ultraviolet wavelengths between 700 and 2050 Å. *ALICE* is a derivative of the existing Pluto mission HIPPS UV spectrometer (HIPPS/UVSC) which scientists at SwRI developed and breadboarded with funds from NASA, JPL, and SwRI (Stern *et al.* 1995). The HIPPS/UVSC instrument has been optimized for *Rosetta* cometary science by increasing its sensitivity, instantaneous field-of-view, and wavelength coverage, and by adding a lightweight microprocessor to meet the interface requirements necessary for the *Rosetta* Orbiter. *ALICE* was recently selected to fly aboard the European Space Agency's (ESA) *Rosetta* Mission, which will rendezvous and orbit the periodic comet P/Wirtanen. During the *Rosetta* mission, *ALICE* will characterize the cometary nucleus, its coma, and the nucleus/coma coupling.

Ultraviolet spectroscopy is a powerful tool for studying astrophysical objects, and has been applied with dramatic success to the study of comets (e.g., Feldman 1991; Festou *et al.* 1993). The *ALICE* UV Spectrometer will provide unprecedented improvements in sensitivity and spatial resolution over previous cometary UV observations. For example, *ALICE* will move the sensitivity threshold from the ~1 Rayleigh level achievable with the *Hubble* Space Telescope to the milli-Rayleigh level in deep integrations. In addition, *ALICE* will (by virtue of its location at the comet) move the spatial exploration of nucleus UV surface properties from the present-day state-of-the art (i.e., no data available on any comet) to complete nuclear maps at Nyquist-sampled resolutions of a few hundred meters.

The *ALICE* imaging spectrometer uses modern technology to achieve its low mass (2.2 kg) and low power targets (2.9 W). *ALICE's* optical design is relatively conventional, but its mechanical and electrical configuration includes several innovations to reduce mass, power consumption, and cost.

SCIENTIFIC OBJECTIVES AND CAPABILITIES

Primary Scientific Objectives

The primary scientific objectives of the *ALICE* investigation are described as follows:

(1) *Determining the evolved rare gas content of the nucleus to provide information on the temperature of formation and thermal history of the comet since its formation.* Some of the most fundamental cosmogonic questions about comets concerns their place and mode of origin, and their thermal evolution since their formation. As remnants from the era of outer planet formation, one of the most important things that comets can tell us about planetary formation and the early solar nebula is their thermal history (cf., Bar-Nun *et al.* 1985, Mumma *et al.* 1993). Owing to their low polarizabilities, the frosts of the noble gases are both chemically inert, and extremely volatile. As a result, the trapping of noble gases is temperature dependent, so noble gases serve as sensitive "thermometers" of cometary thermal history. *ALICE* is ideally suited to determine (or set stringent limits) on the abundances of the He, Ne, Ar, Kr sequence via observations of their strongest ground state resonance transitions at 584 Å (He I, to be observed in second order), 736/744 Å (Ne I), 1048/1067 Å (Ar I), and 1236 Å (Kr I). In addition to their importance as thermal history probes, evolved rare gas abundances also provide critical data for models requiring cometary inputs to the noble gas inventories of the planets. *ALICE* will also determine the abundances of another important low-temperature thermometer species, N_2 (electronic transitions in the 850-950 Å c'4 and 1000-1100 Å Birge-Hopfield systems). Neither the *Giotto* flybys nor remote-sensing from UV telescopes in Earth orbit have been able to detect any cometary noble gases, or N_2. In fact, the only truly constraining upper limits available at present are the $He/H<10^{-4}$ obtained by an EUV rocket observation of comet Austin in 1990 (Stern *et al.* 1992) and $N_2/H_2O<10^{-3}$ (obtained indirectly using N_2^+ emission by groundbased techniques; Wyckoff *et al.* 1991). *ALICE* will be able to detect noble gases without the m/e ambiguities of mass spectroscopy, and at levels hundreds-to-thousands of times below their cosmogenic abundance levels.

(2) *Directly determining the production rates of the key parent molecule species, H_2O, CO and CO_2, and their spatial distributions near the nucleus, thereby allowing the nucleus/coma coupling to be directly observed and measured on many timescales.* The hallmark of cometary outgassing activity is the sublimation of three key species: H_2O, CO, and CO_2. *ALICE* has been designed to directly detect each of these key parent molecules. *ALICE*'s optical axis will be boresighted with the main instruments to be looking at or near the nucleus most of the time. Sunlight scattered by the nucleus and background H I Lyman-α (Ly-α) will be absorbed at a detectable level by water, and possibly other molecules such as CO_2. By measuring the H_2O column abundance in absorption in the UV, rather than by fluorescence (as in the IR), *ALICE*'s measurements will provide a more direct, less model dependent, "cleaner" signature for interpretation. As such, *ALICE* will provide an excellent, and most importantly, a direct probe of these key parent molecules. Water molecules reveal themselves in a continuum absorption (backlit by cometary and interplanetary H Ly-α) below 1700 Å. Much weaker CO_2 absorption peaks between 1500 and 1600 Å. CO will be observed via fluorescence in the well-known fourth positive band system from 1400 to 1700 Å which give total CO; the CO Cameron bands between 1900 and 2000 Å will give a direct handle on that CO produced by CO_2 dissociation, and therefore the total CO_2 content. With most *ALICE* observations being directed toward the nucleus,

the H_2O, CO, and CO_2 gas abundances we derive will directly measure the production source(s) on the nucleus. As we noted above, water absorption will be seen against the cometary and interplanetary Ly-α line all around the nucleus. Inside 2 AU, the cometary Ly-α background will produce 100-1000 counts/sec over the slit, and the H_2O optical depth 5 km off the nucleus at Ly-α will be ~0.1 - 1; this compares well to *ALICE*'s capability to measure absorption optical depths of just a few percent at Ly-α with integration times of order 1 minute. By moving the slit to various locations around the coma (either by spacecraft pointing or simple changes in spacecraft location), it will be possible to map out, and even to tomograph, the H_2O distribution around the comet. If the *Rosetta* observing program permits *ALICE* to observe stellar occultations, such observations can provide sensitive probes of gas and particulate abundances. The combination of these various types of observations will allow *ALICE* to completely map the water distribution in the near environment of the nucleus and address the question of the coupling between the gas and the nucleus near the surface, as well as the characterization of the outgassing pattern of the surface. The latter will be particularly important for determining how much H_2O is derived from discrete, active regions, and how much from the "background" subsurface flow on the nucleus as a whole. When *ALICE*'s line-of-sight is directed away from the nucleus, it will be able to observe the extended CO source (resulting either from grains, or from molecular dissociation of species like H_2CO) first detected by *Giotto* to search for extended H_2O and CO_2 sources (cf., Krankowsky 1991), and to routinely map the spatial distribution of all three molecules throughout the regions interior to their dissociation scale lengths. When coupled with dust measurements in the coma, these data will yield information on the temporal and spatial variation of the dust/gas ratio in the cometary coma. When coupled with IR mapper measurements, their data will yield information on the depths of the various icy reservoirs from which H_2O, CO, and CO_2 are derived.

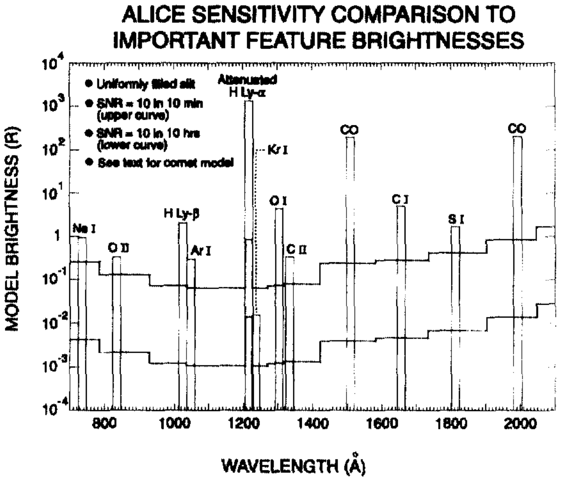

Fig. 1. ALICE *will be able to detect many spectral features at comet Wirtanen. Here we show only the brightest features of the major species of interest, compared to the predicted instrument sensitivity curves for signal-to-noise ratio = 10 detections in 10-min (upper curve) and 10-hour integrations (lower curve). To be conservative, the instrument sensitivity used is 50% of the nominal predicted sensitivity. Note that the sensitivity at H Ly-α is purposely made low to keep the Ly-α count rates low (see discussion below under Detector). To be conservative, the line brightnesses of all the features except the noble gases shown here are a factor of three times lower than that calculated for comet Wirtanen at perihelion; for the noble gases, the reduction factor is 300.*

(3) ***Obtaining unambiguous atomic budget measurements of atomic C, H, O, N, and S in the coma.*** As a UV instrument, *ALICE* will be unique among the remote sensing investigations aboard *Rosetta* in its ability to detect atoms in the cometary atmosphere. Among the most abundant atomic species in comets are C, H, O, and N (Jessberger and Kissel 1991; cf., also Festou and Feldman 1987). *ALICE*'s bandpass captures the strongest resonance fluorescence lines of all of these (C I 1561, 1657, 1931 Å; H I 972, 1025, 1216 Å; O I 989, 1304, 1356 Å; N I 1134, possibly 1200 Å), as well as those of another important, cosmogonically abundant species, S I (1425, 1474, 1813 Å). When *ALICE* is viewing a portion of the coma, we will obtain species abundance ratios, which we will normalize to H_2O. When the FOV encompasses the entire coma (e.g., during approach), the total content of the coma can be measured and its variation with time can be monitored. These quantities can be measured independently of any model. In addition, the most abundant coma ion, O^+, has its strongest resonance line at 834 Å that will allow one to investigate the ionization mechanism at play in the coma and the interaction of the comet ionosphere with the solar wind. Another ion that will be detected, C^+ (1335 Å), will give complementary information on the competing ionization processes (photoionization vs. electron impact) as the two species are created from neutral atoms that are not similarly spatially

distributed and the ions are thus differently affected by solar wind particles. The weak O I 1356 Å emission will be an excellent tracer of electron impact processes in the coma. Together, these various probes will provide what is perhaps the best measurements of the abundances and spatial structures (e.g., distributed sources from CHON particles) in the atomic coma around comet Wirtanen. As a remote sensing instrument, *ALICE* enjoys the advantage that it can obtain such measurements throughout the 3-year comet rendezvous, independently of the orbital location of the spacecraft.

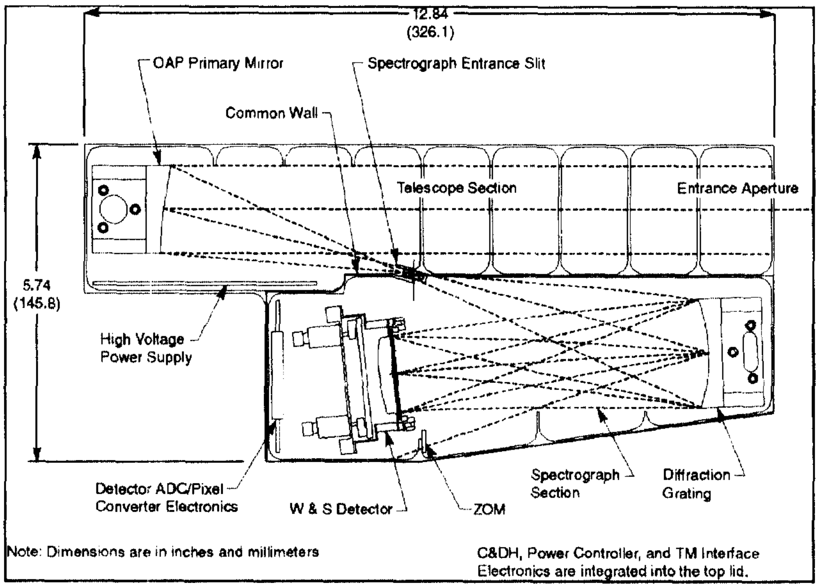

Fig. 2. The opto-mechanical layout of ALICE.

(4) *Studying the onset of nuclear activity in ways* Rosetta *otherwise cannot. ALICE* is particularly well-suited to the exploration of one of the most fascinating cometary phenomena: the onset of nuclear activity. This area of interest has important implications for understanding cometary phenomenology, and for the general study of cometary activity at large distances (e.g., in Halley, Schwassmann-Wachmann 1, Chiron, etc.). *ALICE* will accomplish this by searching for and then monitoring the "turn-ons" of successively "harder volatiles" including N_2, CO_2, and H_2O (in absorption), and the noble gases, CO, and atomic sulfur (all in fluorescence) as a tracer of H_2S and CS_2.

Figure 1 shows a plot of the predicted sensitivity of *ALICE* as a function of wavelength along with the predicted brightnesses of the brightest emission lines of the major species of interest in the coma of comet Wirtanen.

Additional Scientific Objectives

Although we do not have the space to describe *ALICE*'s other scientific objectives in detail, we can briefly summarize the scientific opportunities:

(1) *Spectral mapping of the complete nucleus at far-UV wavelengths to characterize UV absorbers on the surface.* With its imaging capability, *ALICE* can obtain either multispectral or monochromatic images of the comet at a resolution of $500/R_{50}$ meters, where R_{50} is the comet-Orbiter range in units of 50 km. UV images can be used to: (i) search for regions of clean ice, (ii) study the photometric properties of small (10^{-9}-10^{-11} g) surface grains (both at and away from active zones) as a function of solar phase angle, and (iii) search for regions of electrical or photoluminescent glows on the surface. Further, by correlating regions that are dark below the ice absorption edges of H_2O (1600-1700 Å), CO_2 (1500-1600 Å), or NH_3 (1950-2050 Å) with visible albedo measurements made by the *Rosetta* imager, *ALICE* will be able to search for nuclear regions rich in these important volatiles.

(2) *Studying the photometric and spectrophotometric properties of small grains in the coma as an aid to understanding their size distribution and how they vary in time.* UV photometry can be carried out with *ALICE* (a) using the solar continuum near 2000 Å and (b) at H I Ly-α (1216 Å). In both of these bandpasses, the photometric phase function of coma grains can be measured in order to map the distribution of grains with 10-100 times less mass than can be observed with the *Rosetta* imager. We will separate the total optical depth so derived into icy and non-refractory components using the depth of the characteristic H_2O absorption knife-edge near 1650 Å as a compositional constraint.

(3) *Mapping the spatial and temporal variability of* O^+, N^+, S^+ *and* C^+ *emissions in the coma and ion tail in order to connect nuclear activity to changes in tail morphology and structure near perihelion.* Using their well-known emissions at 904 Å and 1335 Å (C^+), 1085 Å (N^+), 910 Å and 1256 Å (S^+), and 834 Å (O^+), *ALICE* will be able to probe the ion formation and tail region behavior of the comet at any time when the comet is active.

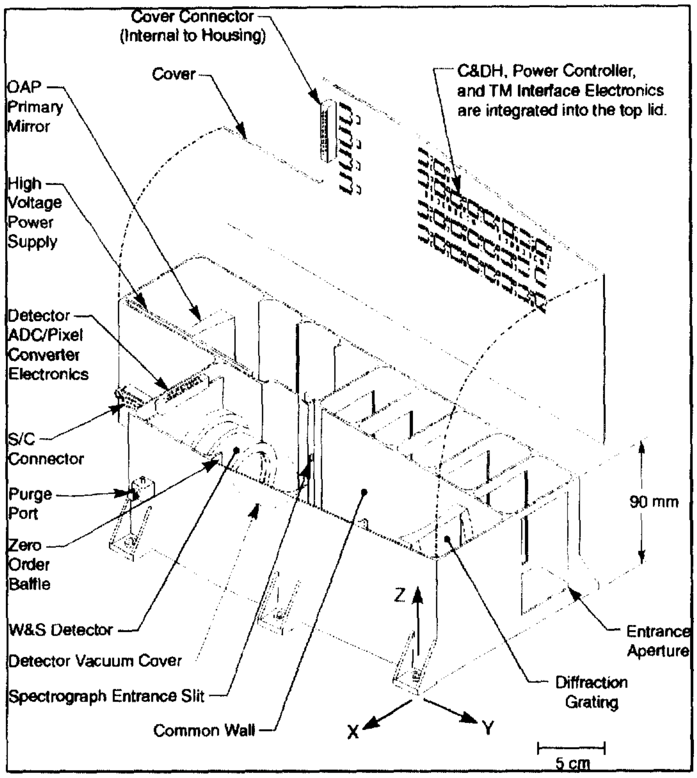

Fig. 3. 3D view of ALICE with the top cover raised.

TECHNICAL DESCRIPTION

Instrument Overview

The *ALICE* UV spectrometer is a very simple instrument. An opto-mechanical layout of the instrument is shown in Figure 2. Light entering the telescope is collected and focused by an f/3 off-axis paraboloid primary mirror onto the 0.1 x 6 deg.^{2} spectrograph entrance slit. After passing through this aperture, the light falls onto an ellipsoidal holographic grating, where it is dispersed onto a microchannel plate (MCP) detector using a wedge-and-strip readout scheme common to many flight instruments, including our working Pluto HIPPS UVS breadboard. Both the telescope primary mirror and the spectrograph reflection grating use SiC coatings for high reflective efficiency. The 2-D (512x32)-pixel format, MCP detector uses dual, side-by-side, solar-blind photocathodes: potassium bromide (KBr) and cesium iodide (CsI). The predicted spectral resolving power ($\lambda/\Delta\lambda$) of *ALICE* is in the range of 55-200 for an extended source that fills the instantaneous field-of-view (IFOV) defined by the size of the entrance slit. *ALICE* is controlled by a microprocessor, and utilizes very lightweight, compact, surface mount electronics to support the science detector, as well as the instrument support and interface electronics. Figure 3 shows a 3D view of *ALICE* with the top cover raised. The resulting design is highly systems-engineered to minimize mass and complexity, and enjoys strong parts-level heritage from previous UV spectrometers.

Optical Design

The optical design of the *ALICE* foreoptics consists of a 40 x 40 mm^2 clear aperture off-axis paraboloidal (OAP) mirror, housed in the telescope section of the instrument (see Figure 2). The OAP collects the incoming light from the target and directs it towards the entrance slit of a 0.15-m normal incidence Rowland Circle style imaging spectrograph with a reflective holographic diffraction grating. The imaging spectrograph, housed in the spectrograph section of the instrument, contains both the diffraction grating and a UV sensitive, solar-blind, 2-D open-structure microchannel plate (MCP) detector located on the Rowland circle. The design also incorporates a Zero-Order Monitor (ZOM), located at the grating's zero-order focus next to the detector. The ZOM is used as a tool to simplify ground and in-flight alignment determination.

The spectrograph utilizes the first diffraction order throughout the 700-2050 Å spectral passband. We also note that the lower half of the first order wavelength coverage (700-1025 Å) will show up in second order between the first order wavelengths of 1400 and 2050 Å. However, very few spectral features show up between 700 and 1025 Å, so there should be little order-sorting confusion.

Both optical elements (OAP and grating) and their mounting fixtures are constructed from monolithic pieces of diamond-turned Al, coated with electroless Ni and polished using low-scatter polishing techniques. The optical surfaces are overcoated with sputtered SiC for optimum reflectivity within the EUV/FUV spectral passband of *ALICE* (Osantowski *et al.* 1991). Besides using low scatter optics, additional control of internal stray light is achieved by the use of telescope baffles, and a holographic diffraction grating that has low scatter and near-zero line ghost problems. The telescope baffles also act to shield the OAP primary mirror from bombardment of small particles that can enter the telescope entrance aperture over a large range of incoming angles.

For contamination control of the optics and detector, heaters are mounted to the back surfaces of the OAP mirror, the grating, and the detector to prevent cold trapping of contaminants during flight. In addition, a detector vacuum cover will keep the interior of the detector tube body and its photocathodes protected during ground operations (see below) and during the initial phases of flight. A possible front aperture door designed to protect the interior of the instrument housing during the flight when the dust and gas levels are too high for safe operation and exposure (i.e., when the *Rosetta* Orbiter is close to the comet nucleus) is also under study for inclusion to the *ALICE* design.

Detector

The detector of choice for *ALICE* is a 2-D imaging photon-counting detector that utilizes an MCP Z-stack, a 3-channel wedge-and-strip (W&S) readout array (Martin *et al.* 1981; Siegmund *et al.* 1986), and a dual, solar-blind, photocathode coating of KBr (700-1500 Å) and CsI (1500-2050 Å) (Siegmund *et al.* 1987). The input MCP surface is cylindrically curved to match the Rowland circle (150-mm dia.) for optimum focus. The detector tube body is a custom design made of lightweight ceramic and kovar. To capture the entire 700-2050 Å bandpass and 6 degree spatial FOV, the size of the detector's active area is 35 mm (in the dispersion direction) x 20 mm (in the spatial dimension), with a pixel format of (512 x 32)-pixels. The 6 degree slit-height will be imaged onto the central 20 of the detector's 32 spatial channels; the remaining spectral channels are used for dark count monitoring. Our pixel format allows Nyquist sampling with a spectral resolution of ~5.6 Å, and a spatial resolution of 0.6 degrees (2 pixels per resolution element for each of the 10 resolution elements across 6 degrees). The estimated size of the tube body necessary to support an active area of this size is ~70 mm in diameter x 50 mm in length. The estimated mass of the tube body assembly is 210 g. The detector electronics includes the preamplifier circuitry, the analog-to-digital converters (ADCs), and pixel converter circuitry, which converts the amplified output pulses from the MCP to pixel addresses that are then passed on to *ALICE's* command-and-data handling (C&DH) electronics. These electronics require ~1 W of power, and are estimated to weigh ~200 g.

The predicted H I Lyman-α emission brightness from comet Wirtanen is ~4 kR at a heliocentric distance of 1 AU (based on IUE observations of periodic comets and appropriate scaling for activity levels). To prevent saturation of the detector electronics, it is necessary to attenuate the Lyman-α emission brightness to an acceptable count rate level well below the maximum count rate capability of the electronics (i.e., below 10^4 c s^{-1}). An attenuation factor of at least an order of magnitude is required to achieve this lower count rate. This is easily achieved by physically masking the area of the MCP active area where the H I Lyman-α emission comes to a focus during the photocathode deposition process. The bare MCP glass has a quantum efficiency about 10 times less than that of KBr at 1216 Å. This masking technique has been successfully demonstrated in the past with the detectors for the SUMER instrument on SOHO, and with the HIPPS/UVSC breadboard detector (e.g., Stern *et al.* 1995).

To protect the KBr and CsI photocathodes against damage from exposure to moisture and other contaminants, the detector tube body employs a built-in vacuum cover at the detector input which allows the detector to remain under vacuum (< 10^{-5} Torr) during ground operations, testing and handling, and transportation. The cover has a built-in LiF window port that transmits light at wavelengths >1150 Å which allows testing of the detector with the cover closed, and provides redundancy during flight if the cover mechanism fails to deploy.

Electrical Design

The instrument support electronics on *ALICE* include the power controller electronics (PCE), the command-and-data handling electronics (C&DH), and the telemetry (TM) interface electronics. All of these systems are controlled by a

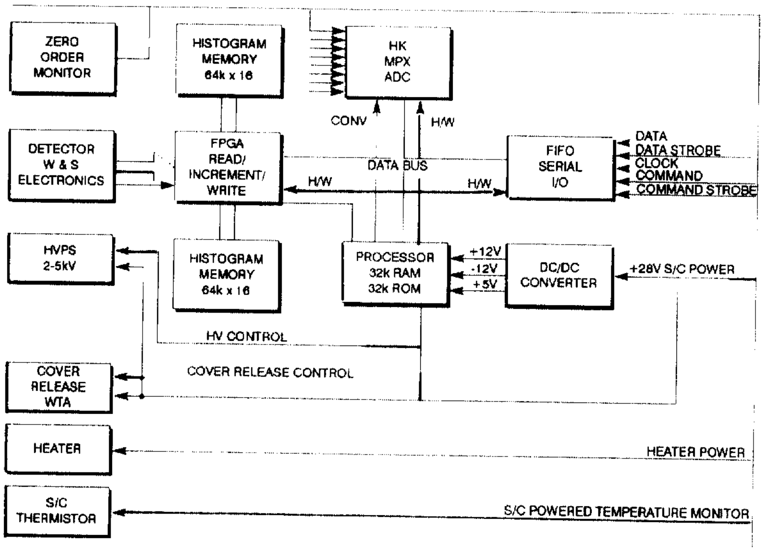

Fig. 4. ALICE's electronic block diagram.

microprocessor, and are contained on a single multilayer circuit board that also serves as the top cover of the instrument. Figure 4 shows a schematic block diagram of *ALICE's* electronics.

The PCE is composed of DC/DC converters designed to convert the spacecraft power to +5 and ±12 VDC required by the detector electronics, the C&DH and the TM interface electronics, and the detector high-voltage power supply (HVPS). The PCE also includes solid-state relays for turning on the detector HVPS, and to release the detector vacuum cover. The DC/DC converters provide the required DC-isolation between spacecraft ground and instrument signal ground.

The *ALICE* C&DH electronics, which is controlled by a rad-hardened microprocessor, handles the following instrument functions: (i) the interpretation and execution of commands to the instrument, (ii) the histogramming of the raw event data from the detector, (iii) telemetry formatting of both science and housekeeping data, (iv) the detector HVPS, (v) the vacuum cover release mechanism, (vi) the control of the housekeeping ADC's which are used to convert analog housekeeping data to digital data for inclusion into the TM data stream, and (vii) on-board data compression. The candidate microprocessor is the Rad-hard RAD 6000SC Single Chip Processor, supplied by Loral Federal Systems.

Predicted Performance Summary

An overview of the instrument characteristics, spacecraft resource requirements, and predicted performance of *ALICE* is summarized in Table 1. Figure 5 shows the predicted point and extended source spectral resolving power for *ALICE* as a function of wavelength. Figure 6 shows a plot of the expected signal-to-noise ratio (SNR) as a function of integration time at 700 and 1150 Å for an extended source that fills the slit, and across 10 Å of spectral bandwidth.

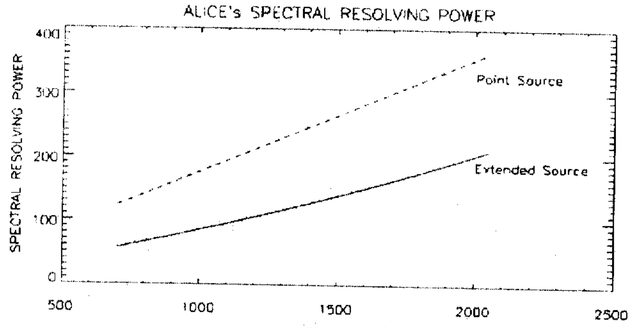

Fig. 5. The predicted point source and extended source (one that fills the entrance slit) spectral resolving power as a function of wavelength.

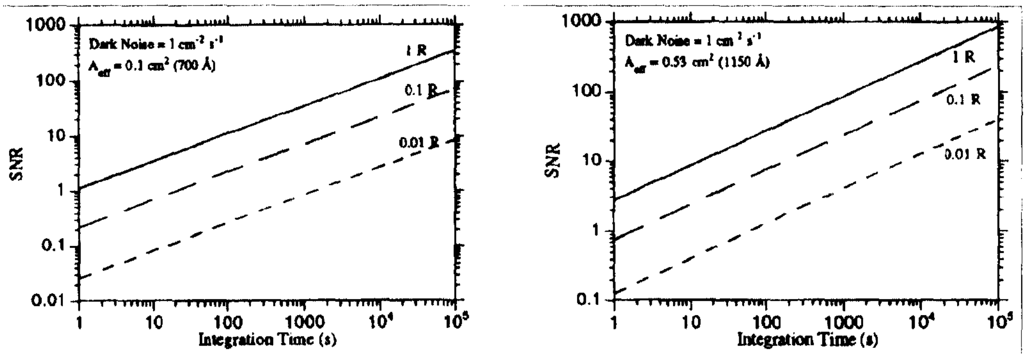

Fig. 6. The predicted SNR versus integration time at 700 Å (left), and at 1150 Å (right) for an extended source that fills the slit, across 10 Å of spectral bandwidth, and at three brightnesses: 0.01, 0.1, and 1.0 R.

Table 1. *ALICE's* Characteristics, Spacecraft Resource Requirements, & Performance Summary

Bandpass:	700 – 2050 Å
Spectral Resolution:	5.6 Å (point source)
	12.5 Å (extended source) at 700 Å
	9.8 Å (extended source) at 2050 Å
Spatial Resolution:	0.1 x 0.6 degrees^2 (70 x 420 m^2 at 40 km)
Active FOV	0.1 x 6.0 degrees^2
Pointing	Boresight with Imager, IR Spectrometer
Nominal Effective Area:	0.03 (1900 Å)-0.53 cm^2 (1150 Å)
Nominal Sensitivity:	0.5 (1900 Å)-7.8 (1150 Å) counts s^{-1} R^{-1}
Telescope/Spectrometer	Off-axis telescope, Rowland circle spectrograph
Detector Type	2-D Microchannel Plate w/ wedge-and-strip readout
External Dimensions	146 x 326 x 90 mm^3
Mass/Power	2.2 kg/2.9 W
Observation Types	Nucleus imaging and spectroscopy; coma spectroscopy; jet and grain spectrophotometry; stellar occultations (optional observations)
Typical Data Volume	0.3 - 1.5 Mbyte/day, uncompressed 0.1 - 0.5 Mbyte/day, compressed

CONCLUSION

ALICE is a highly-capable low-cost UV spectrometer that will significantly enhance *Rosetta's* scientific characterization of the cometary nucleus, its coma, and nucleus/coma coupling. *ALICE* will do this by its access to noble gases, atomic abundances in the coma, major ion abundances in the tail, and powerful, unambiguous probes of the production rates, variability, and structure of H_2O and CO/CO_2 molecules that generate cometary activity, and the far-UV properties of the nucleus and solid grains. *ALICE* will also deepen the Orbiter's in situ observations by giving them the global view that only a remote-sensing adjunct can provide.

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