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Final Technical Report

Grant Title: Global Mapping of the Interstellar Medium in the Far Ultraviolet

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Principal Investigator: Christopher Martin

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Grantee Institution: The Trustees of Columbia University In the City of New York.

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A Program Status

In early 1993, funding for the NUVIEWS experiment was initiated. The experiment was completed and delivered to Wallops Flight Facility in March 1996, where it has completed flight integration and testing successfully. We feel that the three year development time was too long by a year, and that the history deserves some explanation. The construction of four complete four-mirror telescope systems with unique multilayer coatings, superpolished aspheres, and four large-format, high-resolution microchannel-plate detectors required a substantial effort. Our original design included only three telescopes, but we added a fourth 18 months ago to ensure rejection of all potential contaminating line features. A six-month SMEX Definition study in 1994 required substantial efforts by key personnel. There was great synergy here: the four NUVIEWS detectors are prototypes for the SMEX UV-survey mission (JUNO). In 1993, the Principal Investigator C. Martin took a position at Caltech. The transition of the laboratory from Columbia to Caltech was unfortunately timed and led to more delays, including an additional laboratory move and calibration tank/clean room reconstruction. Following the May NUVIEWS launch, the laboratory move to Caltech will be complete.

The following summarizes the accomplishments over the grant period:

- The NUVIEWS instrument was constructed and delivered to Wallops Flight Facility in Spring 1996. Activities included:
  - Completion of all optics (16 optical elements)
  - Completion of multilayer coatings (12 coatings) and testing
  - Completion of detector construction (4 detectors) and testing
  - Photocathode coating of 4 detectors
  - Detector quantum efficiency testing
  - Completion of baffling/contamination-purge boxes (4)
  - Assembly, alignment, and focussing of 4 complete telescopes.
  - Completion of digital electronics and testing
  - Adjustment and tuning of analog electronics
  - Assembly of a make-shift clean tent in our temporary laboratory
  - Assembly of a field-testing UV calibration system
  - Complete integration of the 4 telescopes and electronics.
  - Completion of scan-path design
- Integration proceeded successfully without incident.
- First launch attempt May 17, 1996 was scrubbed at t-5 minutes due to a combination of instrument CPU software error and noise on tie lines between the launch pad and control center. The problem was corrected.
- NUVIEWS was successfully launched on July 14, 1996 from White Sands Missile Range. At the time of the launch, the data looked completely nominal. This has been confirmed in the subsequent analysis.
- The first analysis is nearing completion. Preliminary sky-maps (shown below) have an enormous amount of information.
- The Columbia laboratory was decommisioned and moved to Caltech.

- David Schiminovich will receive a Ph.D in July 1997.
- Flight test of SMEX/JUNO UV-survey detectors- development of a fully flight-qualified Serpentine Delay-Line Microchannel Plate detector design and associated flight electronics. Four detectors and electronics systems are now awaiting flight.
- Design and construction of the first wide-field, multi-mirror telescope that uses high- efficiency, reflective multilayer dielectric coatings. Tests of flight substrates indicated excellent performance.
- Fabrication of a Fabry-Perot etalon and development of a coating design suitable for high-resolution Far UV spectroscopy of the cosmic background.
- Initiation of a collaborative program for Superconducting Tunnel Junction detectors, the first truly 3-D UV/optical detector.
- Design and oversight of a new 4000SF experimental astrophysics laboratory.
- Schiminovich, Friedman, Martin, Kaye, Fleischman, Rochwager 1996, "The Narrow Band Ultraviolet Imaging Experiment for Wide-field Surveys (NUVIEWS)", in preparation for submission to The Astrophysical Journal.
- Friedman *et al.* 1996, Rev. Sci. Instrum, "Multilayer anode with crossed serpentine delay lines for high spatial resolution readout of microchannel plate detectors", **67**, 596.
- J. Fleischman, P. Friedman, C. Martin, D. Schiminovich, "NUVIEWS", SPIE **2006**, 149 (1993)

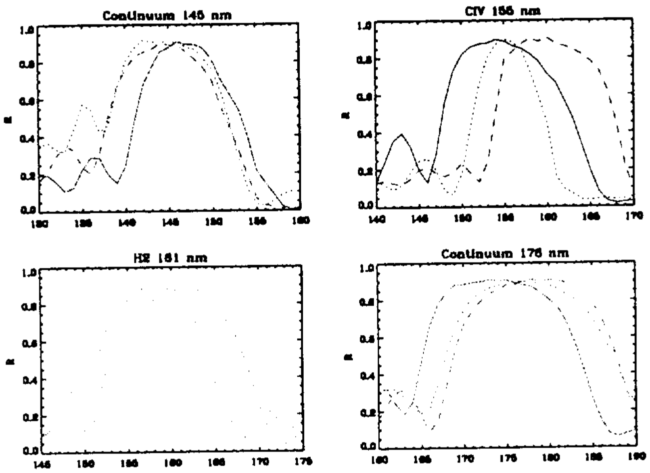


Figure 1: Individual RDM reflectivities on flight mirrors. Primary solid, secondary dotted, tertiary dashed.

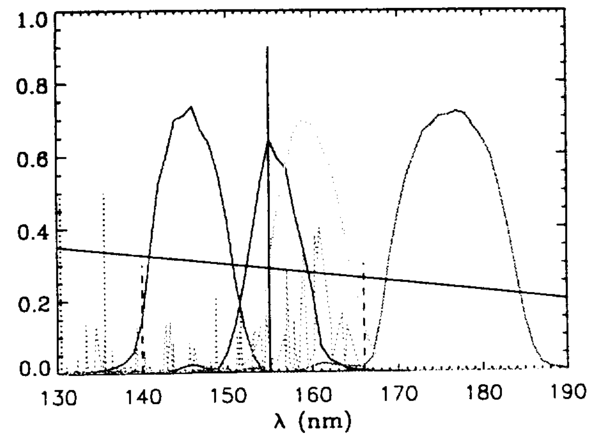


Figure 2: NUVIEWS bands compared to UV background emission features. CIV, dust continuum solid lines, OIII, SiIV/OVI dashed line, H_2 dotted, airglow (OI1304,1356; NO 1909) dashed.

B Technical Approach

The NUVIEWS instrument has been designed and fabricated to make possible a measurement of the global distribution of CIV 1550 emission that provides the maximum possible sensitivity and freedom from systematic errors. Principal design features include:

- Four wide-field, narrow-band telescopes: two 10 nm wide bands (145 nm & 176 nm) to map the continuum level and slope. Two 7 nm wide bands to measure CIV 155 nm and H_2 (161 nm).
- Telescopes have three mirrors to provide good imaging (3′) over a very wide field (>600 square degrees).
- Each mirror is overcoated with a reflective dielectric multilayer coating to provide narrow band response. Three mirrors together provide excellent peak throughput ($\sim$ 70%), bandwidth (7-10 nm), and out-of-band rejection.
- Band profiles designed to block weak, potentially contaminating airglow and ISM lines.
- Carefully designed instrument baffling to eliminate out-of-field scattering.
- Large-format photon-counting microchannel plate detectors with serpentine delay-line anodes for high spatial resolution and high countrate capability.
- Flight program will provide long continuous scans for throughput averaging and calibration. A large number of stars previously observed by IUE will pass through the field for accurate absolute and extremely accurate relative band calibration.

The basic NUVIEWS design is shown in Figure ??. The NUVIEWS instrument incorporates four co-aligned identical telescopes, each with a wide field of view (20° x 30°) and an imaging detector. Each telescope is a three-reflection f/3 system consisting of an off-centered convex spherical primary, a concave hyperboloidal secondary and a concave spherical tertiary. A folding quartenary delivers the focused beam to the detector. The 3-mirror design corrects aberrations over the wide field of view, yielding spot sizes

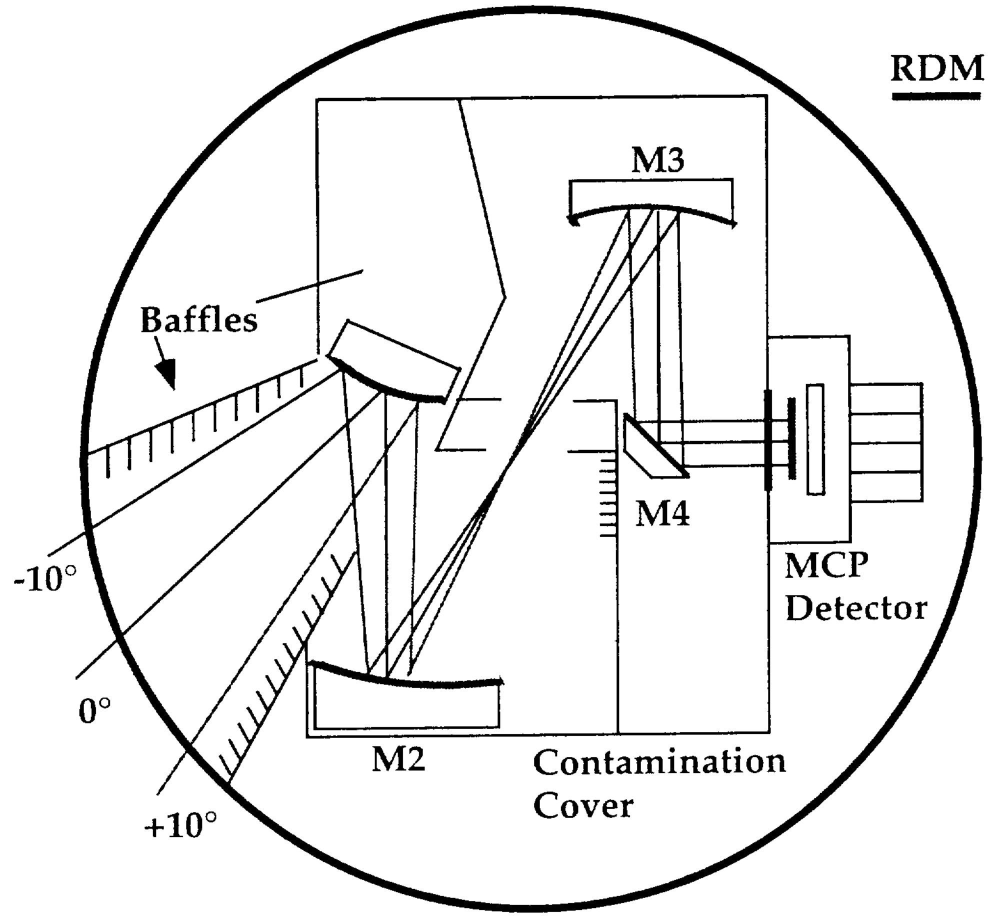


Figure 3: NUVIEWS Instrument schematic.

$\sim$3'over a flat focal plane, while permitting loose mechanical tolerances and accommodating the reflective multilayer filters. The telescopes are well-baffled against direct and scattered out-of-field rays.

Definition of telescope narrow bandpasses is accomplished using recently-developed thin-film far UV interference filters with tuned multilayers to achieve high reflectivity with minimal absorption in the selected bandpass. Each of the three curved mirrors in each telescope is coated with a reflective, dielectric multilayer (RDM). Each RDM is designed to produce in a given telescope, for the full field of view and aperture, a narrow-band response (7 or 10 nm) with excellent peak reflectivity ($R \simeq 60\%$ for all three mirrors in a telescope) and uniform central wavelength. The measured end-to-end response of the bandpasses in the flight telescopes are illustrated in Figure 2. In addition, the detectors are fitted with entrance window filters that provide additional out-of-band rejection: BaF_2 (145 nm), and cultured Quartz (155, 161), and fused SiO_2 (176 nm).

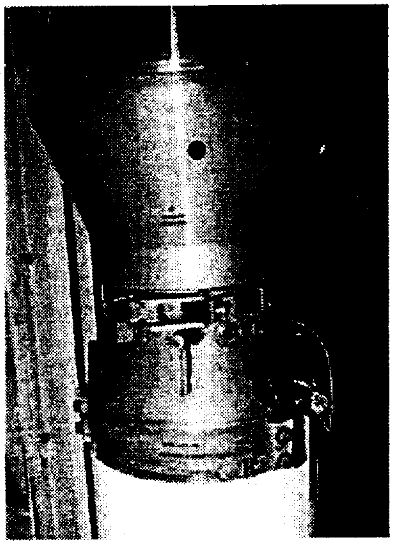
The imaging detector incorporates 65 mm microchannel plate (MCP) device coated with cesium iodide (CsI) to provide QE=5-15% in the 130-190 nm band, with a two-dimensional serpentine delay line readout system. The delay line anode combines a large format and high spatial resolution. We require a large format to accommodate the wide field of view of the instrument. Good spatial resolution (30 μm) is important because it makes it possible to identify point sources, subtract them from the diffuse maps, and utilize them for telescope cross-calibration and overall absolute calibration. The delay-line detector is intrinsically fast ($>10^6$ ct/s) although not optimized in this application, for which the readout/electronics countrate limits are 5×10^4 ct/ s with 10% coincidence loss–local saturation in the MCP limits very bright stars to $< 10^3 - 10^4$ ct/s. The detector resides in an evacuated chamber to maintain the stability of the photocathode and the cleanliness of the detector. The entire payload is mounted in a Black Brant rocket shell, with an sideopening door for each telescope

Our narrow-band filters are state-of-the-art. During the past three years, we have worked closely with M. Zukic, who has pioneered the development of tuned, reflective dielectric multilayer coatings to produce efficient, narrow-band response in the vacuum ultraviolet . We have extended this technique to the fast, wide-field telescope system summarized above. Three technical challenges stand out as most important: (1) Production of fast, curved, and aspherical optics (convex and concave) with surfaces of sufficiently low roughness (< 15Å rms) so that scattering losses to the coating reflectivity were not significant; (2) Design of coating structures that maintained a constant central wavelength over the range of ray angles and positions in the telescope beam; (3) Fabrication of uniform coatings, and verification of the designed response vs. angle and position. At each stage extensive modeling and testing was performed. For example, test tiles were used to verify the flight substrate coating geometry and measured for complete far UV spectral response vs. incident angle, with the coating parameters subsequently adjusted to optimize the results. The coated flight substrates were characterized in the same way. Figure 1 and 2 shows selected individual coating response functions and the resulting three-mirror end-to-end response.

The narrow-band response of the four telescopes was designed to eliminate any ambiguity in the interpretation of the line and continuum data. All possible airglow and ISM lines, with conservative fluxes, were included in a model of the 4-telescope system and in-house RDM code to assess their impact on the measurement of CIV 1550, H_2, and the dust-scattered continuum. The lines that were included and their maximum percentage of the measured continuum are Ly α 1216 (< 0.02%), OI 1304, 1356 (<0.3%), and the NO δ-bands (< 0.2%) for airglow, and OIII] 1663, HeII 1640 (<0.2%), SiIV/OiV 1390-1400 (<0.7%), and CIII] 1909 (<0.1%) from the ISM. The worst case fluxes with the flight complement of filters yields at most a 0.5% systematic error in the average continuum subtraction. UVX CIV levels were 5000 LU, corresponding to 25% of continuum. The one sigma statistical error in our maps will be 500 LU, or 2.5% of the continuum, and 5 times the systematic error. Moreover, the flight scan pattern will provide more information about any residual airglow and even lower errors.

Based on our measured efficiencies, band profiles (Figure 1,2), scan pattern and mission timeline, we estimate that we will be able to construct a CIV map with a S/N=10 [I(CIV)=5000 LU, I(continuum)=500 CU] in $\sim 10^\circ \times 10^\circ$ pixels, or roughly 400 pixels over the whole sky. The 5σ minimum detectable flux in a 400 deg^2 area is 1250 LU. A key ingredient is the precise cross calibration of the CIV line and long- and short-wavelength continuum telescopes. The survey is self-calibrating: more than 75 stars will be obtained with S/N>100, and >300 stars with S/N>30, with a variety of spectral types, all with previously calibrated spectra (TD-1 and/or IUE). The summed interstellar radiation field, which is responsible for the dust-scattered continuum that is the dominant background source, is made up of the bright stars that we will measure. Also, potentially biasing airglow features will be calibrated by continuous alternating scans in zenith angle throughout the flight. We estimate that the final systematic error in the continuum subtraction will be <<1%, leading to a subtraction error of <<700 LU for a (high) continuum level of 1000 CU, or <<12% of the UVX CIV flux level.

NUVIEWS data analysis will use software tools already in place for analyzing scanned wide-field imaging data as part of our SMEX UV Sky Survey model. Analysis will begin by reconstructing the sky map in the four bands using the coaligned star camera data, and bright UV stars in the primary data. The flight countrate profile will be examined for evidence of airglow, using regions that are scanned more than once at different flight altitudes (most are). Once the full image is created, stars will be extracted and compared to TD-1 and IUE spectra. The calibrated stars will be followed through their scans to perform an instrument calibration. An effective exposure map will then be generated for each band. The calibrated continuum bands and band-ratios will be correlated with HI surveys, IRAS plates and digitized POSSII scans (which exhibit extensive cirrus) and a model developed to connect these data. Next, the H_2 fluorescence band will be correlated with HI, IRAS, and CO surveys. Finally, the full data set will be modeled *ensemble* with airglow, dust, H_2, and 10^5K gas (dominated by CIV). The 4-maps will be combined and "inverted" (basically a subtraction) to form the CIV and other maps.



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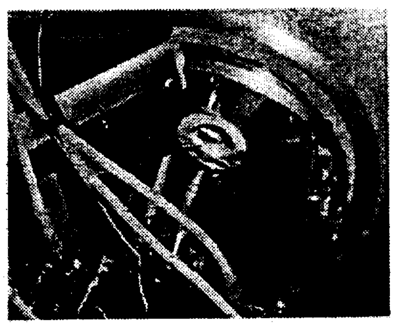

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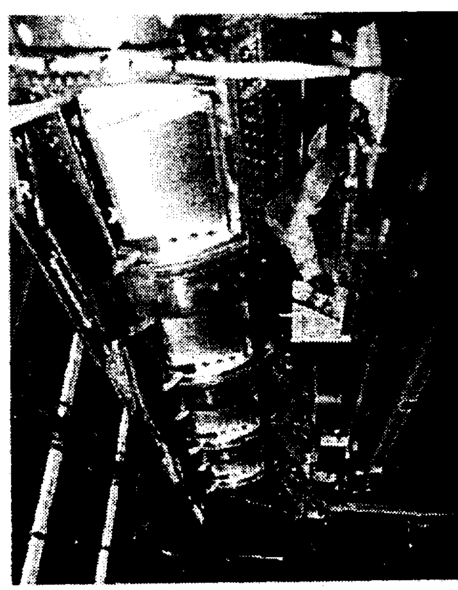

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Figure 3: The NUVIEWS Instrument. MIDDLE: Assembled Payload; LEFT: single telescope; RIGHT: telescope schematic

Sky Maps in 4 Narrow Ultraviolet Bands