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RESEARCH IN EXTREME ULTRAVIOLET AND FAR ULTRAVIOLET ASTRONOMY

NASA Grant NGR-05-003-450

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SEMI-ANNUAL STATUS REPORT

June 1, 1984 - November 30, 1984

INTRODUCTION

Work under this grant has continued on several fronts. The Berkeley portion of the "UVX" program, described in previous reports, has been integrated and awaits a shuttle flight opportunity. The "Far Ultraviolet Imager" (FUVI), which flew on the Aries class sounding rocket 24.015, has produced outstanding results. This experiment is described in the first section of this report. The second section of this report describes the diffuse extreme ultraviolet (EUV) background spectrometer which is under construction. It will be launched on the Black Brant sounding rocket flight number 27.086. The final section of this report discusses our ongoing design studies of a high resolution spectrometer. This instrument incorporates a one meter normal incidence mirror and will be suitable for an advanced Spartan mission.

I. THE FAR ULTRAVIOLET IMAGER

A. The Value of a Far Ultraviolet Measurement of the Power Spectrum of Cosmic Light

Studies of diffuse background in all bandpasses are advanced by measurements of the spectral distribution and spatial isotropy of the emission. Recent moderate spatial resolution ($\sim$ 1/2°) observations of Jakobsen et al. (1984) and Joubert et al. (1983) show a significant correlation of intensity with neutral hydrogen column density: the magnitude of the dependence is consistent with the hypothesis the galactic starlight is scattered by high latitude dust with albedo $\sim$ 0.5 and phase function g $\sim$ 0.5. Their results also show a large isotropic offset with an intensity (1500 Å) of $\sim$ 300 ph $cm^{-2}s^{-1}Å^{-1}sr^{-1}$. The origin of this component is not known, but it is presumably extragalactic. Several processes have been proposed to account for an extragalactic FUV background: (1) integrated light from galaxies, (2) integrated light from QSO's, (3) recombination radiation from a hot intergalactic medium, or (4) exotic processes.

This theoretical ambiguity argues strongly for an observational attack to separate and determine the relative importance of these contributions. Spectral measurement can separate some effects, but QSO's, galaxies, and IGM recombination radiation all produce indistinguishably flat spectra.

Galaxies, the most likely major component, will produce small scale spatial fluctuations in the background intensity. If galaxies were randomly distributed in space, they would produce a white-noise spectrum of fluctuations (i.e., a flat power spectrum). The clustering of galaxies enhances the probability that a galaxy will be located closer to another galaxy. This causes the power spectrum of light from these galaxies to increase towards lower spatial frequencies. This distinction between the galaxy power spectrum and that resulting from white noise from other sources (i.e. poisson, star halos, unresolved stars) permits a relatively clean separation and removal of these potential systematic errors.

The first and only measurement of the power spectrum of extragalactic light was made by Shectman (1974). He used the Palomar Schmidt camera and photographic plates, and performed a careful analysis to check for and remove systematic effects, particularly those of star halos and plate noise. The difficulties involved in that measurement were substantial. The cosmic component of diffuse background is only 2% of the total in the optical (which is dominated by airglow and zodiacal light), making the fluctuations at 3' only 0.4% of the total. In addition, the surface density of stars (even at the galactic poles) is quite high: ~ 650 stars deg^{-2} brighter than 17th magnitude. In spite of these major difficulties, Shectman made a measurement of the cosmic power spectrum that was relatively free of most systematic errors.

The power spectrum can be modelled on the basis of the two-point galaxy correlation function (Peebles, 1980) and shows reasonably good agreement with Shectman's measured spectrum. This confirms the covariance of luminosity density with galaxy number density. The inferred optical luminosity density of galaxies is in excellent agreement with independent determinations of this number (Peebles, 1980).

The purpose of the rocket-borne FUV measurement of the power spectrum is to determine the FUV luminosity density of galaxies and the contribution of galaxies to the extragalactic FUV background. The success of Shectman's determination at optical wavelengths under severely adverse conditions is promising in this regard, considering the favorability of the FUV bandpass (c.f. section C). It may be the *only* method for determining whether the extragalactic FUV background is dominated by integrated light from galaxies or by some more exotic and cosmologically interesting process.

Moreover, a determination of the FUV luminosity density due to galaxies is quite important in its own right. The FUV flux from spiral galaxies is dominated by early type, short-lived Population I stars, and is therefore a direct indicator of the current star formation rate in galaxies. As was mentioned above, the FUV luminosity density depends critically upon the history of star formation over the last 10^{10} years. This evolutionary history is totally unknown, which reflects our ignorance about the processes governing the global structure and evolution of galaxies. Observa-

tional evidence is indirect and limited, but tantalizing. Faint galaxy counts generally show little evolution for $z < 0.3$, but hint at significant evolution for $z > 0.3$ (Gunn, 1981; Kron, 1980). Redshift distributions show puzzling evidence of an excess of bright, distant galaxies which may be undergoing vigorous star formation (Butcher and Oemler, 1984), but which would not fit neatly into a simple evolutionary scenario. Tinsley and Danly (1980) discuss evidence that the gas content of spiral galaxies was two times higher as redshifts $z \sim 0.3$ and three times at $z \sim 1.0$.

Evolutionary effects must be understood in order to correct for their effects on cosmological tests. Faint galaxy counts may provide the deepest, most sensitive measure of cosmological parameters--the technique is free of most systematic errors, but *is* affected by evolution in the stellar population and flux distribution. Determination of the level of these effects is therefore crucial for the correct interpretation of these cosmological tests.

B. The Experiment

The experiment consisted of an imaging microchannel plate detector in the focal plane of the 1-meter Aries mirror. The detector has a 75-mm active area, and has a circular field of view 1.6 ° in diameter.

The 1-meter mirror size and the high speed of the mirror (f/2.8) made it ideal for this measurement. A barium fluoride window was used to provide a short wavelength cutoff at ~ 1350 Å to exclude the three major airglow emissions: Lyman alpha (1216 Å), OI 1304 and 1356 Å. The detector was coated with 6000 Å of CsI, which provided a high quantum efficiency in the vicinity of 1500 Å, and a convenient cutoff longward of 1900 Å, eliminating NO emission at ~ 2000 Å, zodiacal light, F stars and long wavelength contaminates.

With a photon-counting detector and 100 seconds observing time, poisson noise limits sensitivity of the measurement to fluctuations, at a scale of ~ 2 arcmin. Fig. 1 shows the predicted power spectrum in the FUV due to galaxies that make up 10%, 30% and 100% of the extragalactic background, along with the white noise contribution from count statistics. Note that even the 10% contribution produces a spectrum somewhat less than white noise at $f \sim 1000$ rad^{-1}, and six
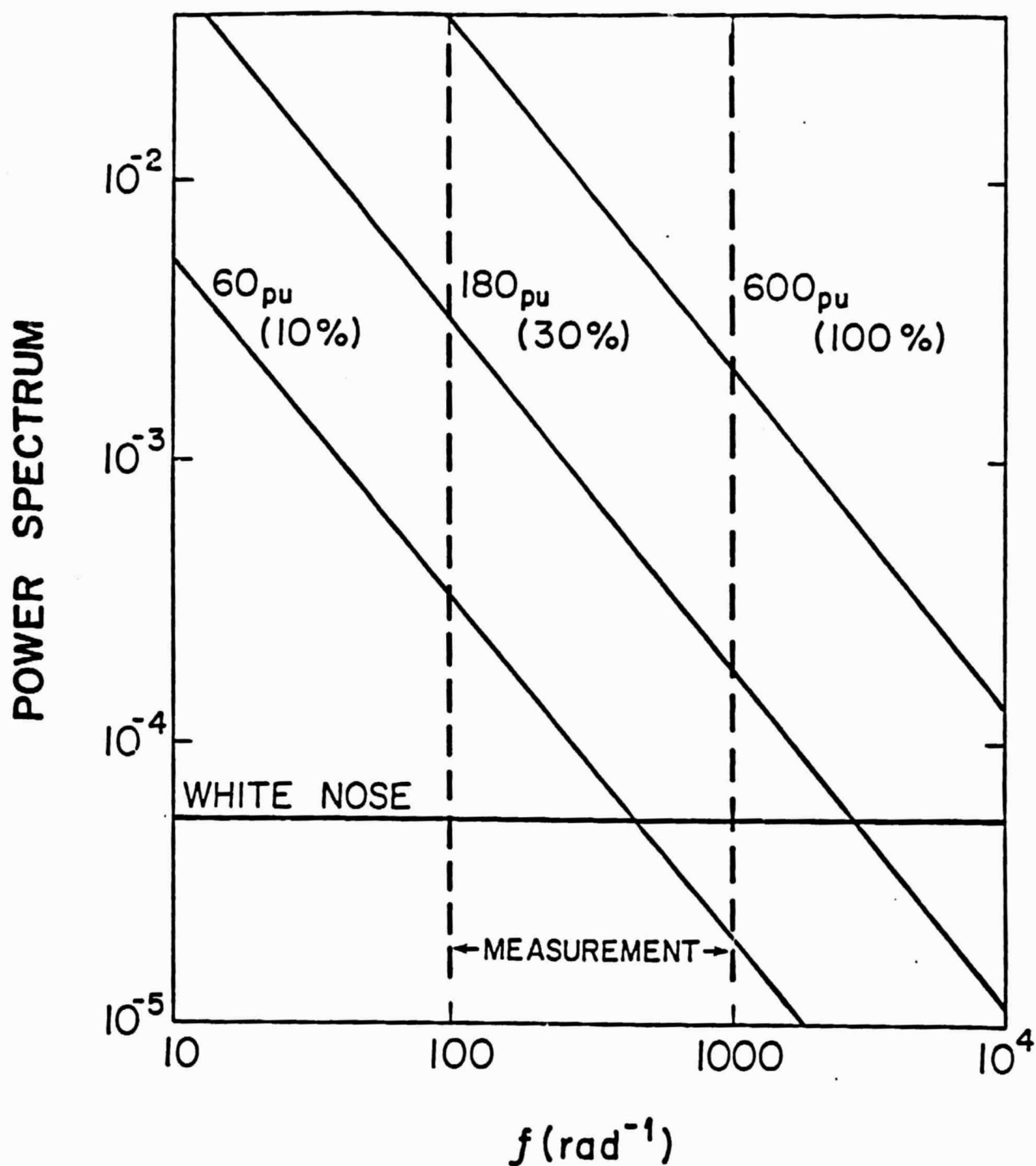
Figure 1: Predicted power spectrum in the FUV due to galaxies that make up 10%, 30% and 100% of the extragalactic background, along with the white noise contribution from count statistics.

times higher at $f \sim 100$ rad^{-1}. The 100% level produces a PS 40 times above the noise at 1000 rad^{-1}, and 600 times at 100 rad^{-1}.

Figure 2 illustrates predictions of the integrated light from galaxies for unevolved, partially and fully evolved combinations, assuming evolutionary models of Tinsley (1972) and Bruzual and Kron (1980). A null result would rule out models in which any spiral galaxies undergo evolution. In addition, it would imply that at least 250 ph cm^{-2}s^{-1}Å^{-1}sr^{-1} of the extragalactic background is due to the other components discussed above, such as recombining intergalactic medium at 10^{5-6} K.

C. The Analysis

The FUVI instrument was launched on November 28, 1983 from White Sands Missile Range, and performed successfully. The task ahead is the reconstruction from the raw data of a map of the sky background, free of systematic errors and spurious fluctuations.

Detector quantum efficiency variations would of course introduce spurious fluctuations if uncorrected. A relative calibration was performed and the considerable calibration data must be reduced and incorporated in the background map reconstruction. An additional source of fluctuation is differential nonlinearity in the detector image digitization electronics, which introduces a high frequency, pixel-to-pixel variation of $\sim 2\%$ in the relative bin width. To substantially reduce the effects of errors in this calibration, a short, slow scan was performed during the observation. This averaged each sky bin over many electronics pixels and over the quantum efficiency variations, and thus made every sky bin subject to similar detection conditions. The resulting detector images must therefore be corrected for the continuously changing aspect.

Off-axis geometric aberrations caused by the imperfect focusing of the mirror will introduce attenuation at high frequencies, as was discussed above. But the effect of this can be calculated and will introduce negligible effects at the relevant frequencies. A correction must be made for off-axis vignetting, which must be calculated for each position in the field of view.

Stars have always been the main diet of astronomers--but they are a constant annoyance to
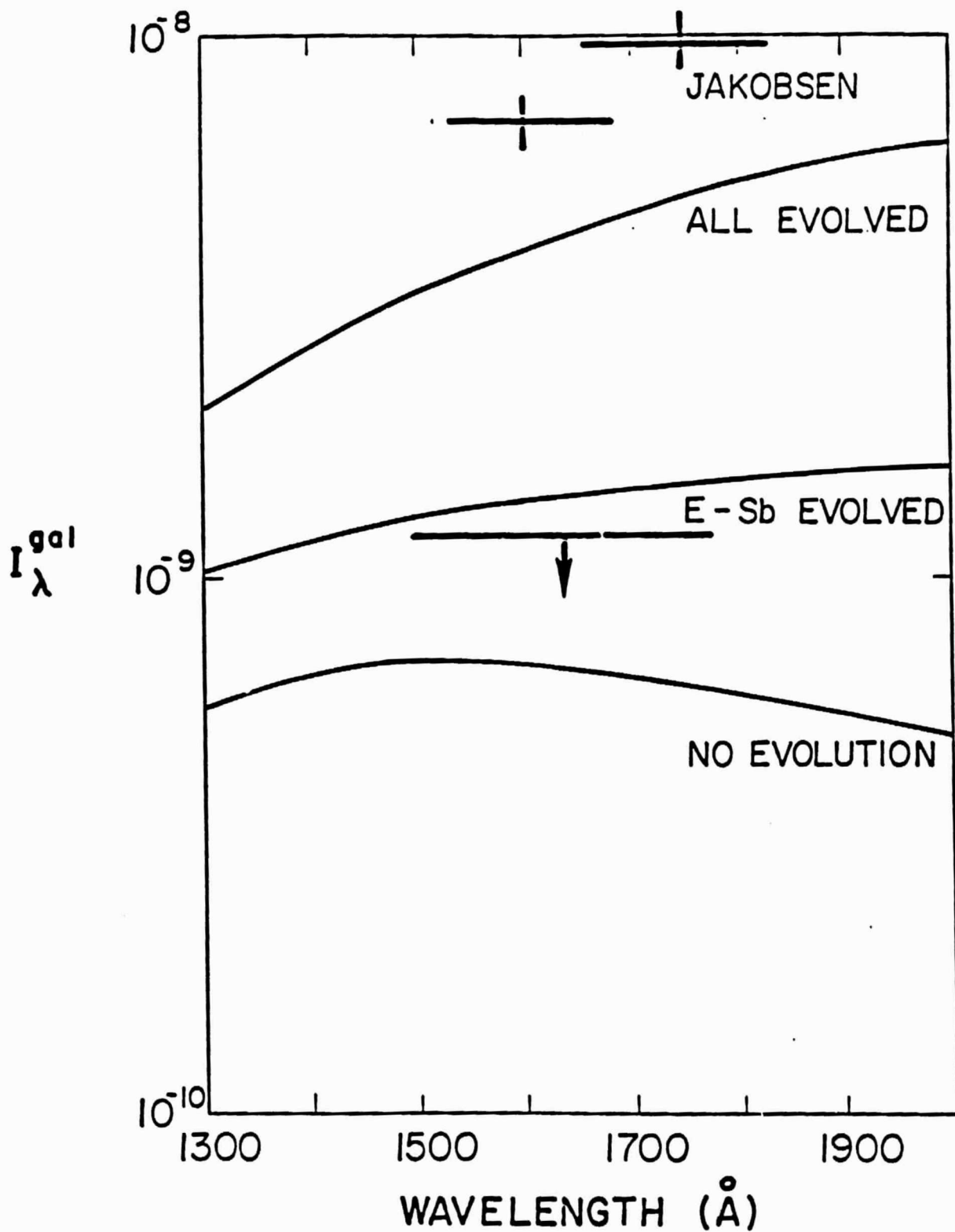
Figure 2: Predictions of the integrated light from galaxies
for unevolved, partially and fully evolved
combinations, assuming evolutionary models of
Tinsley (1972) and Bruzual and Kron (1980).

those interested in the truly diffuse emission. To limit the number of stars in the field, the obser-vation was made at high galactic latitudes. Even so, F-stars are sufficiently numerous and have enough residual flux to be detectable. At a galactic latitude of 70°, there will be $\sim$ 30 F-stars total in the FOV, most in the range $m_v \sim$ 10-14. These stars would add fluctuations of $\sim$ 100 ph $cm^{-2}s^{-1}Å^{-1}sr^{-1}$ (@ f $\sim$ 1000 rad^{-1}) if left uncorrected for in the data. To find the stars in field of view, we will perform optical survey work with the Lick 20" Astrograph. We will take B and V plates of a 3° x 4° area including the scan area, and search for stars bluer than B-V = +0.5. In order to do this, we will PDS the plates using the Berkeley Astronomy microdensitometer. To perform the necessary star finding and photometric reduction of the PDS data, which will contain many thousands of stars (to V = 19^m), we will use the Kitt Peak FOCAS package.

Finally, we must demonstrate that fluctuation in a residual galactic diffuse background is not significant. To do this, we plan to examine IRAS maps of diffuse infrared radiation. IRAS has discovered IR "cirus" in many directions, which could indicate a fluctuating dust component that can back-scatter galactic starlight and cause variation in the diffuse UV background. We will search for correlations between any FUV and IR fluctuations.

II. THE EXTREME ULTRAVIOLET BACKGROUND SPECTROMETER

A. Scientific Objective

Diffuse radiation in the extreme ultraviolet (EUV) was first detected with a wide field broadband photometer on a sounding rocket (Cash, Malina and Stern 1976). Since then additional broadband observations have confirmed this detection and have set upper limits for the radiation in longer wavelength bands (Stern and Bowyer, 1979; Paresce and Stern, 1981; Paresce and Bowyer, 1976; Sandel et al., 1979; Kimble, 1983). However, no spectral measurements have been made in the 80 to 600 Å range.

Through the discovery of the soft x-ray background radiation (Bowyer, Field and Mack, 1968) we have learned that much of the local interstellar medium is filled with hot tenuous gas. The soft x-ray flux indicates a gas temperature of 10^6K, while the EUV background originates from gas almost an order of magnitude cooler. Furthermore, OVI absorption lines detected by the Copernicus satellite indicate 10^6K gas (Jenkins, 1978). Most workers in this field agree that the 10^6K gas is produced by supernova explosions. The origin of the 10^6K gas is much more controversial. In the McKee and Ostriker (1977) model of the interstellar medium, the gas originates at the interface between the hot 10^6K gas and the cooler 10^4K clouds. In the "displacement" model of the local interstellar medium (McCammon et al., 1983) such interfaces would only exist on the outer edges of the "bubble" of 10^6K gas. A better knowledge of this 10^6K gas is crucial to advancing our understanding of the interstellar medium. In particular, spectral measurements of emission lines from the diffuse EUV radiation would confirm the thermal nature of this gas and indicate its temperature or distribution of temperature much more accurately than can be done with the existing photometric measurements.

B. The Optical Design

Observing diffuse EUV emission requires a specialized instrument. Sensitivity to diffuse radiation depends on solid angle and area, and therefore requires a fast optical system. To obtain

high throughput at wavelengths below 350 Å it is necessary to use grazing incidence optics. We have invented a novel spectrometer design incorporating grazing optics and a large solid angle to produce spectra of moderate resolution.

The spectrometer uses a wire grid collimator to restrict the field of view in one dimension to 40 arc minutes, while allowing 15 degrees of sky to enter the instrument in the orthogonal direction. This wedge of light is than diffracted by an array of flat, blazed reflection gratings at grazing incidence. Once diffracted, the light is focused in the spectral direction by an array of mirrors, and passes through a thin filter to reduce scattering. The filter also seals the detector below from particles or high pressure. The detector is a microchannel plate system with a wedge and strip type anode (Martin et al., 1981) and a high yield photocathode deposited on the front surface.

The gratings are conventionally ruled and can be replicated at minimal cost. The mirrors are off-axis sections of parabolas of translation which would be difficult to construct by conventional means. Therefore, we have developed a procedure to fabricate these mirrors without expensive diamond tooled machines or complicated polishing. We avoid polishing by using float glass which is naturally quite flat with low micro roughness. To form the curve in the glass we place it over a steel block with the desired form cut into the block's surface. The glass and block are then heated until the glass softens and sags onto the surface. With proper control, the glass will maintain the correct shape as the materials are cooled. A standard milling machine cannot cut an off axis section of a parabola into the block, but it can cut a section of an ellipse. By numerically matching sections of ellipses to the desired section of parabola we find that the optimum match focuses quite well. Computer ray traces of the entire optical system show that these elliptical mirrors, with their expected errors in manufacturing, do not degrade the resolution of the spectrometer.

The general system described has many possible permutations and configurations. A large number of specific designs have been evaluated to find the optimum parameters for this novel spectrometer. The final design uses three separate systems to cover wavelengths from 80 Å to 650

Å. The instrument is packed into the 17 inch diameter of a Black Brant sounding rocket and is short enough to fit in a GAS type container for extended missions. The resolution of the spectrometer was chosen to allow interesting sets of potentially strong lines to be separated from each other and from the much stronger airglow, geo-coronal and interplanetary lines that crowd the spectrum. Near 150 Å the resolution (λ / $\Delta\lambda$) is 15, and it rises to 50 at 584 Å keeping the bright HeI line from spreading over many interesting interstellar lines. The minimum detectable flux ranges from 50 to several hundred ph cm^{-2} sec^{-1} str^{-1} providing more sensitivity to a single line than previous photometric instruments.

C. Mechanical Design

The instrument has 67 optical elements that must be positioned within a few thousandths of an inch of their proper place. The design must allow for additional positioning flexibility to compensate for the errors inherent in the mirror fabrication process, and it must withstand the vibration of a sounding rocket launch. Furthermore, baffles must be carefully placed to avoid "ghost" lines while blocking as little of the aperture as possible. We have developed an optical bench system that fulfills all of these criteria and has withstood vibration testing with glass elements in place. The design simplifies the alignment process by dividing the instrument into eight modules. Each module holds the glass parts with a small piece of soft material that is captive in the larger module structure. Shims between this soft material and the module allow each grating or mirror element to be positioned independently. Once a module's elements have been aligned with respect to each other, the modules are mounted to a larger support structure. The modules can then be aligned as eight simple units to provide the proper diffraction and focusing of light onto the detectors.

III. OPTIMIZATION OF A HIGH RESOLUTION FAR ULTRAVIOLET SPECTROMETER

The spectral region from 900 to 1200 Å is a particularly rich one. In it are found lines of elements in many ionization states and density-sensitive lines of many species. Of particular interest are the resonance lines of hydrogen and deuterium converging to the Lyman limit at 912 Å, lines of O VI, N I, N II, and N III, S III, S IV, and S VI, and lines of the molecular species H_2 and HD. Observations in this spectral region are particularly well-suited to the study of plasmas at $\sim 3 \times 10^5$ K and, if performed at sufficiently high spectral resolution, can be used to measure the abundance of deuterium relative to hydrogen, a parameter of great cosmological significance. A high resolution spectrometer operative at 900 - 1200 Å would return tremendous amounts of information about cosmology, the dynamics of the interstellar medium, the galactic corona, extragalactic objects such as quasars and Seyfert galaxies, and cataclysmic variable stars. Most of this spectral region will be inaccessible to the Hubble Space Telescope, and the last instrument operative at these wavelengths — *Copernicus* -- became inoperative nearly a decade ago and was capable of observing only bright stars. We plan to develop a high resolution spectrometer using detector and grating technology unavailable to the makers of *Copernicus*. The spectrometer will be fed by a 1-meter normal incidence mirror provided by our collaborators at the Astronomisches Institut at Tübingen, West Germany. Our collaborators are also working with Dornier Systems to provide a a Spartan carrier derived from the ROSAT satellite. With this system, the telescope/spectrometer could enjoy relatively long observing times.

A previous study at our lab identified and analyzed several options for the design of the spectrometer. It is now clear that only two designs can provide the high resolution required over the entire bandpass: an echelle or Rowland circle design. The only element common to both spectrometer types is the presence of a secondary mirror to slow the beam. If a spectrometer were fed directly by the f/2.7 beam from the primary mirror, the grating aberrations would be too large to provide the high spectral resolution required. The two options are discussed in some detail below.

If the echelle is chosen, the design will resemble that in Figure 3A. The collimator in the entrance aperture of the telescope blocks rays further than 3/4 degree from the optical axis, and the pinhole aperture stop at the focus of the primary mirror blocks rays between 5' and 3/4 degree of the axis. The ellipsoid folds the beam back around the pinhole and feeds the two gratings of the echelle spectrometer. An analysis by Hettrick (1985) has identified the best choice of gratings for such a system: a varied-angle fan or radial groove grating as the echelle preceded by a concentric groove grating as a cross-disperser. Although the manufacture of these gratings is beyond the limits of present grating technology, simpler variable line spaced gratings can be used to achieve high resolution. In either case the spectrum is dispersed in an "echellogram" format well suited to the two-dimensional microchannel plate detectors now available.

If the Rowland circle is chosen, the design will resemble that in Figure 3B. An off-axis hyperboloid slows the beam and brings the light to a real focus at the entrance to the Rowland circle. A pinhole aperture stop blocks rays farther than 5' from the optical axis; to prevent vignetting of the beam by the outer edge of the aperture stop, it may be necessary to place a 3/4 collimator across the entire 1-meter entrance to the telescope. In the Rowland circle design, the entire spectrum is dispersed along a single direction, requiring an array of detectors to obtain the necessary number of pixels in the dispersion direction.

It is our task to analyze the designs cited here, and to optimize the best design given the constraints imposed by the availability of gratings and detectors, the physical size of the instrument, the pointing and stability of the Spartan platform, and imperfections in mirror figure. The performance of the design can be tested by two independent numerical raytrace codes available at our lab. Once the design is finalized, we will begin construction of the spectrometer, contingent upon continued development of the Aries-class Spartan platform by the Germans.

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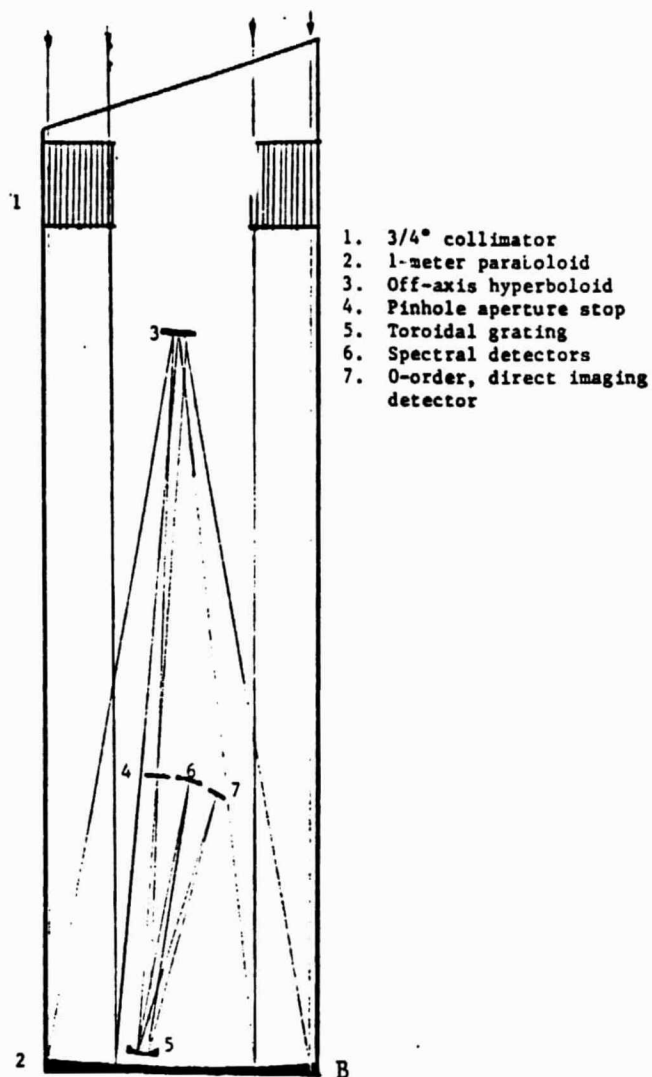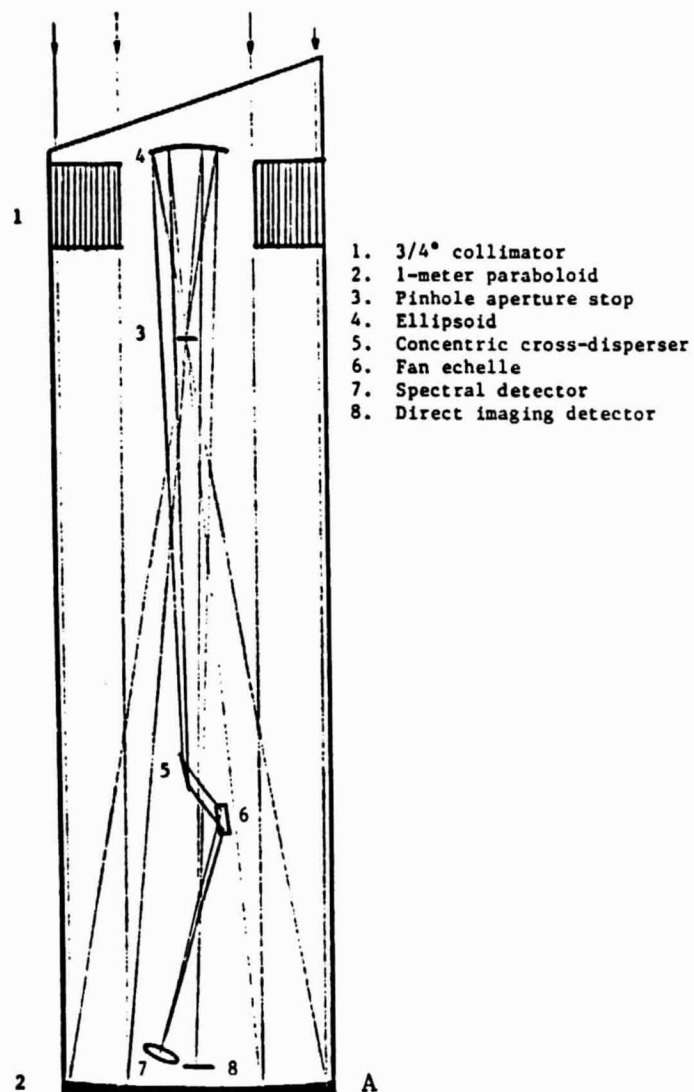Tinsley, B. M., and Danly, L 1980, *Ap.J.*, **242**, 435.

1. 3/4° collimator
2. 1-meter paraboloid
3. Pinhole aperture stop
4. Ellipsoid
5. Concentric cross-disperser
6. Fan echelle
7. Spectral detector
8. Direct imaging detector

1. 3/4° collimator
2. 1-meter paraboloid
3. Off-axis hyperboloid
4. Pinhole aperture stop
5. Toroidal grating
6. Spectral detectors
7. 0-order, direct imaging detector

Figure 3: Preliminary designs for the high resolution far ultra-
violet spectrometer. 3A shows an exhelle design; 3B
shows a Rowland circle mount.