THE COSMIC ORIGINS SPECTROGRAPH: A 2002 REPLACEMENT INSTRUMENT FOR THE HUBBLE SPACE TELESCOPE*

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ABSTRACT

We present an overview of the expected performance and science goals of the Cosmic Origins Spectrograph (COS), a fourth generation instrument to be installed aboard the *Hubble Space Telescope* in late 2002. COS is an ultraviolet spectrograph optimized for observing faint point sources with moderate spectral resolution (R $\geq 20,000$). The instrument has two channels: a far-UV channel that is sensitive in the 1150 – 1775 Å wavelength range and a near-UV channel that operates between 1750 – 3200 Å. The COS science program concentrates on QSO absorption line systems and the IGM, dynamics of the ISM in galaxies and galaxy halos, UV extinction in the Milky Way, horizontal-branch stars in globular clusters, and volatile gases in the atmospheres of Solar System bodies.

Key words: spectroscopy; intergalactic and interstellar media; UV extinction; planetary atmospheres.

1. INTRODUCTION

NASA recently selected the Cosmic Origins Spectrograph (COS) as a replacement instrument for the fourth *HST* servicing mission in 2002. COS will go into the bay currently occupied by COSTAR, which, after the 1999 servicing mission, will no longer be in use.

COS is a high-throughput ultraviolet (UV) spectrograph that is optimized to observe faint point sources. COS will be, by a large factor, the most sensitive UV spectrograph ever flown aboard *HST*. It will bring the diagnostic power of UV spectroscopy to bear on such fundamental issues as the ionization and baryon content of the intergalactic medium and the origin of large-scale structure in the Universe; the ages, dynamics, and chemical enrichment of galaxies; and stellar and planetary origins. These science programs require having the capability to obtain moderate resolution (R > 20,000) spectroscopic observations of faint UV sources, such as distant quasars.

2. COS SCIENCE MODES

COS offers dramatic improvement in sensitivity to faint objects over previous UV spectroscopic instruments flown aboard *HST*. COS achieves high sensitivity, particularly in the far-UV (FUV), by minimizing the number of reflections, which leads to an inherently simple spectrograph design (see Fig. 1). Because the unique capabilities of COS derive from a fundamentally different design approach, and not from new technology, we are able to provide an instrument with flight heritage in all of its critical areas: optics, detectors, electronics, etc. The primary FUV channel of COS covers the wavelength range 1150 – 1775 Å, and the secondary near-UV (NUV) channel covers the wavelength range 1750 – 3200 Å.

2.1. COS FUV Channel

The primary (FUV) COS channel employs concave diffraction gratings and a curved detector. There is ONE reflection between the aperture and the detector (Fig. 1). The gratings have aspheric concave surface figures specified to compensate for spherical aberration. Holographically generated grooves provide dispersion and correct the astigmatism. Ion-etching creates a blaze that optimizes the efficiency over a narrow range of wavelengths. Two gratings, G130M and G160M, are used to cover the 1150 – 1775 Å region at high resolution (R = 20,000 – 24,000). Each high-dispersion grating covers roughly 300 Å in one exposure. A third grating, G140L, covers the entire 1230 – 2050 Å region at lower resolution (R = 2500 – 3500). The three gratings are mounted on a rotating mechanism, similar in concept and function to the GHRS carrousel. The detector is a windowless microchannel-plate (MCP) array, with an opaque CsI photocathode, and a double delay-line readout that has been adapted from the *FUSE* mission.

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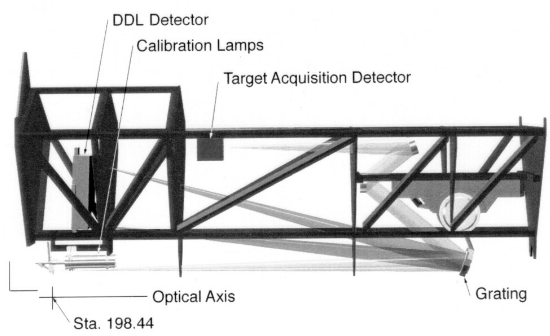

Figure 1. Schematic of the COS primary FUV channel (as proposed). Light is received from the HST OTA through an aperture (lower left), is dispersed by a concave diffraction grating, and finally is recorded on a curved double delay-line MCP detector adapted from the FUSE mission. The target acquisition detector has been replaced in current designs. The secondary NUV channel is fed by a fourth optic on the grating select mechanism.

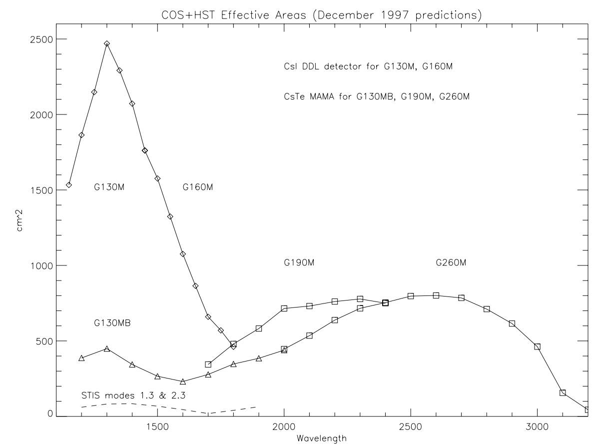

Figure 2. Effective area predictions for the COS FUV and NUV high-dispersion grating modes. The effective areas shown include a 'slit' transmission of ~ 87% through the standard 2″ aperture. Effective areas for the STIS echelle modes in the FUV are shown for comparison.

2.2. COS NUV Channel

The secondary (NUV) COS channel employs a Czerny-Turner design. This channel serves partially to back up the STIS NUV spectroscopic modes and also to restore the capability to observe faint targets that has been mitigated by the high background of the STIS NUV MAMA. The COS NUV channel is fed by a mirror on the main grating select mechanism. The beam is (nearly) collimated by a second optic and sent to the secondary grating select mechanism which contains several flat, first-order gratings and a mirror used for imaging during instrument testing and alignment. Two high-dispersion gratings, G190M and G260M, deliver resolutions R $\geq$ 20,000 over the wavelength range 1750 – 3200 Å. The dispersed light from the gratings is imaged onto a CsTe MAMA detector by three camera optics. The spectra appear as three non-contiguous $\sim$ 50Å strips on the MAMA detector, allowing $\sim$ 150Å wavelength coverage per exposure. The gratings can be scanned to cover the entire NUV wavelength band. A low-dispersion grating, G230L, delivers 1000Å coverage per exposure with a resolution of $\sim$ 2Å. A reserve grating, G130MB, covers the FUV wavelength region with resolution R $\geq$ 20,000. This grating serves as a reduced-capability back-up to the FUV channel in case of a failure in the primary FUV channel.

The predicted effective areas for the high-dispersion FUV and NUV gratings are shown in Fig. 2. As a figure of merit, we expect to obtain S/N $\approx$ 10 per resolution element in the R $\geq$ 20,000 channels for sources with fluxes of $1 - 2 \times 10^{-15}$ ergs cm^{-2} s^{-1} Å^{-1} in 10,000 seconds across most of the 1150 – 3200 Å wavelength range covered by COS. More details about the COS instrument can be found at the COS Web site at http://cos.colorado.edu. This Web page will be updated periodically as the COS instrument capabilities and performance are developed.

2.3. COS Apertures

As previously mentioned, COS is optimized for observing faint UV point sources. The 'standard' aperture is a two-arcsecond diameter circular field stop located on the *HST* focal surface near the point of maximum encircled energy. This aperture transmits close to 90% of the light from an aberrated stellar image delivered by the *HST* OTA. The standard aperture is expected to be used for most COS observations. We also provide an attenuating 'bright-object aperture' with diameter $\sim 0\farcs1$ that permits COS to observe targets several magnitudes brighter than the Bright Object Protection limits allow through the standard aperture. Finally, COS will have a $\sim 4''$ diameter aperture that can be used to observe faint, diffuse sources and to aid in target acquisition.

COS has a limited multiplexing capability, and can spatially resolve two point sources separated by $> 0\farcs7$ in the cross-dispersion direction. However, we note that COS re-images the *sky* onto the detectors and not the aperture; COS is essentially a slitless spectrograph. Because COS is a slitless spectrograph, the spectral resolution depends on the nature of the target. The high-dispersion gratings deliver resolutions R $\geq$ 20,000 for unresolved sources (intrinsic diameter $\leq 0\farcs1$). However, for an extended source, for example, $\sim 0\farcs5$ in diameter, the spectral resolution is degraded to R $\sim$ 5000. Though not optimized for extended objects, COS can be used to detect faint, diffuse sources with degraded spectral resolution.

3. COS SCIENCE GOALS

Spectroscopy lies at the heart of astrophysical inference. Our understanding of the origin and evolution of the cosmos critically depends on our ability to make quantitative measurements of physical parameters such as the total mass, distribution, motions, temperatures, and composition of matter in the Universe. Detailed information on all of these properties can be gleaned from high-quality spectroscopic data. For distant objects, some of these properties (e.g., motions and composition) can only be measured through spectroscopy. UV spectroscopy, in particular, provides some of the most fundamental diagnostic data necessary for discerning the physical characteristics of planets, stars, galaxies, and interstellar and intergalactic matter. The UV offers access to Lyman α at low to moderate redshift, high ionization stages of key diagnostic elements, and unique abundance information for both atomic and molecular species that cannot be obtained at other wavelengths. Such data are essential to draw a complete picture of the Universe.

COS will build on the scientific legacies of *Copernicus*, *IUE*, GHRS, FOS, STIS, and, in the future, *FUSE*, giving *HST* the greatest possible grasp of faint UV targets, a capability perhaps not available from future space-based observatories for decades. COS will complement and extend the suite of *HST* instruments, ensuring that Hubble maintains a powerful UV spectroscopic capability from 2002 until the end of its mission.

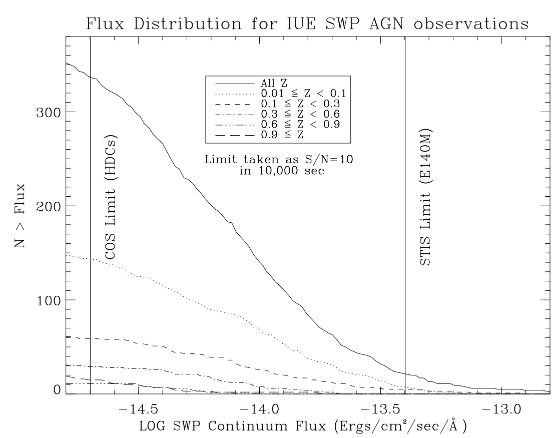

Figure 3. Number distributions of AGN observed by IUE brighter than a given flux limit (Penton & Shull 1997). Top curve shows all IUE observations of AGN; lower curves show various redshift intervals. Using the high dispersion channels (HDCs) G130M, G160M, G190M and G260M, COS can observe over ten times more targets with moderate spectral resolution than STIS.

The science goals of the COS GTO team address problems of fundamental importance in astrophysics and cosmology which require the moderate resolution and high throughput of COS, and four unique capabilities of *HST*: access to ultraviolet wavelengths, large collecting area, precise pointing stability, and excellent image quality. Our study is organized into three broad categories, united by the theme of cosmic origins: (1) the origin of large-scale structure and the intergalactic medium (IGM); (2) the formation, evolution, and ages of galaxies; and (3) the origins of stellar and planetary systems.

Models for the formation of large-scale structure and the reionization of the IGM will be constrained by observing distant quasars to measure the He II Gunn-Peterson effect, the structure of the Lyman α forest, and the D/H ratio in primordial clouds. COS will be capable of obtaining moderate-resolution UV spectra of hundreds more quasars and AGN than existing UV instruments (Fig. 3). The COS database of absorption-line systems will have high enough spectral resolution and adequate S/N to determine accurate column densities, abundances, and kinematics of intergalactic matter at epochs when the first galaxies were formed and the first heavy elements were synthesized.

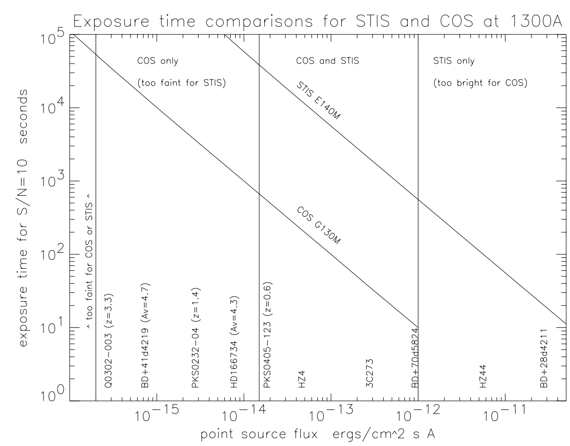

Figure 4. Summary of predicted exposure times to achieve S/N=10 per resolution element as a function of flux for the $R \geq 20{,}000$ resolution COS G130M FUV grating. The calculation assumes the standard $2''$ COS aperture is used. Example targets are noted along the horizontal axis above their corresponding UV fluxes. Exposure times for the STIS E140M echelle mode are shown for comparison. The region of bright fluxes on the right part of the plot can *be accessed by COS using the small, bright-object aperture.*

COS will be used to determine abundances and kinematics of hot gas in galaxy halos, the impact of violent starbursts and supernovae on interstellar and intergalactic environments, and the ages of globular clusters. The numerous quasar sight-lines accessible to COS will intersect hot galaxy halos over a large redshift range. COS spectra will constrain galaxy evolution models by mapping the production of metal-enriched gas through time. COS will also observe nearby starbursting systems over a range of metallicity. These spectra will be used to model the chemical enrichment of the interstellar medium, and as templates for deriving the properties of high-z galaxies. COS UV spectra of horizontal-branch stars in globular clusters will allow significant refinement of globular cluster age estimates, which may be used to reconcile the ages of the oldest stars in galaxies with the age of the Universe derived from recent measurements of the Hubble constant and closure parameter.

The origins of stellar and planetary systems will be investigated by studying the physical processes and chemical abundances in the cold ISM. For the first time in the UV, COS will observe sight-lines toward hot, embedded stars that will probe dense, molecular regions where the star formation process begins.

COS data will also provide clues to the conditions and composition of the outer solar nebula. The high sensitivity of COS will allow an order of magnitude more background stars to be observed in stellar occultation studies of planetary and cometary atmospheres. COS will break new ground with direct moderate-resolution UV observations of Pluto and Triton that will be used to detect fluorescence emission from volatile gases as these bodies both undergo rare seasonal changes during the first decade of the next century.

Our investigation requires observations of very faint targets, taking full advantage of *HST* capabilities (large aperture, UV coatings, excellent pointing and image quality). COS is optimized to observe faint UV sources (Fig. 4) with spectral resolution high enough to determine the physical conditions in a broad range of astrophysical environments. Its design meets programmatic requirements for reliability and redundancy, and its simplicity and efficient operation ensure a high science return. With these capabilities, we anticipate a high degree of interest in using COS throughout the world-wide astronomical community.

REFERENCES

Penton, S., & Shull, J.M. 1997, IUEAGN database of UV spectra of QSOs and AGN, listed in http://casa.colorado.edu/~spenton/IUEAGN/FUSE.html.