Performance overview and science goals of the Cosmic Origins Spectrograph 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* during the fourth (and final) *HST* servicing mission scheduled for 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-Ultraviolet channel that is sensitive in the 1150 – 1775 Å wavelength range and a Near-Ultraviolet channel that operates between 1750 – 3200 Å. The COS Science Team 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.

Keywords: Ultraviolet spectroscopy, Hubble Space Telescope, QSO absorption line systems, interstellar medium, planetary atmospheres

1. INTRODUCTION

NASA recently selected the Cosmic Origins Spectrograph (COS) as a replacement instrument for the fourth *Hubble Space Telescope* (*HST*) servicing mission scheduled for late 2002. COS will go into the bay currently occupied by COSTAR, which, after the 1999 servicing mission, will no longer be in use. COS will complement and extend the suite of scientific instruments aboard *HST*, joining ACS, STIS, NICMOS, and WFPC2 (or WF3) at the focal plane for the period 2002 until 2010 (the projected end of the *HST* mission).

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.

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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. 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, such as optics, detectors, and electronics.

In designing COS, we have assumed that STIS will continue to work well. COS is not intended to duplicate the powerful capabilities of STIS for observing bright or extended sources. COS does not have many "bells and whistles," but the capabilities of COS are unique. The order-of-magnitude gains in UV sensitivity over STIS and previous UV spectrographs will open a huge volume of discovery space. Researchers will be able to obtain moderate resolution spectra of objects down to unprecedented flux levels, drawing on the new target lists compiled by UV imaging telescopes, such as *UIT* and *GALEX*.

2.1. Science Operations Summary

COS has two channels: a primary Far-Ultraviolet (FUV) channel that covers the 1150 – 1775 Å wavelength region, and a secondary Near-Ultraviolet (NUV) channel that covers the 1750 – 3200 Å wavelength region (with a reduced capability back-up of the FUV wavelength domain). Each channel has its own detector and selection of gratings. The two channels cannot make parallel observations, as the primary FUV optics select mechanism either rotates a grating into position for FUV spectroscopy or else an optic that feeds the secondary NUV channel. An observer will specify a target, its coordinates, an exposure time, and then select which channel (COS/FUV or COS/NUV), which aperture, and which grating to use. Finally, the observer will specify the central wavelength of the exposure. The central wavelength will be chosen from a table of "legal" pre-set values designated for each grating. These values will allow any region of interest in the entire 1150 - 3200 Å wavelength region to be covered. The NUV gratings, in particular, are flat gratings mounted in a collimated beam that are meant to be scanned in order to achieve wide wavelength coverage (due to the relatively small format of the NUV detector). The FUV gratings, on the other hand, each cover approximately 300 Å per exposure. They will normally operate at a "standard" central wavelength setting. However, some wavelengths that fall within the FUV "detector gap" are lost with these standard settings, so the FUV gratings will also have a limited set of alternate central wavelength positions that make it possible to shift the spectrum on the detector in order to recover the needed wavelengths.

2.2. COS FUV Channel

The primary (FUV) COS channel covers the wavelength range 1150 - 1775 Å. The FUV channel employs concave diffraction gratings and a curved detector. It is fundamentally a Rowland spectrograph, modified to meet the specific needs of *HST*. There is *one* reflection between the aperture and the detector (see 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 grating efficiency over a narrow range of wavelengths. Two gratings, G130M and G160M, are used to cover the range 1150 – 1775 Å wavelength range 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 short wavelength cut-off of the low-dispersion grating is designed to avoid bright geocoronal Lyman α emission at 1216 Å.) 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. A fourth optic mounted on the primary optics select mechanism feeds light to the NUV channel. Table 1 summarizes the COS FUV spectroscopic modes.

2.3. COS NUV Channel

The secondary (NUV) COS channel employs a Czerny-Turner design (see Fig. 2). This channel provides excellent sensitivity for moderate resolution spectroscopy of faint UV targets in the 1750 – 3200 Å region. It serves partially to back up the STIS NUV spectroscopic modes and also will restore capability to observe faint targets that has been mitigated by the high background of the STIS NUV MAMA detector. The COS NUV channel is fed by a mirror on the primary optics select mechanism. The beam is collimated by a second optic and sent to the secondary optics select mechanism which contains several flat, first-order gratings and a mirror used for imaging during instrument

Table 1. COS FUV spectroscopic modes.

Grating	Wavelength Range	Coverage per Exposure	Resolving Power ($\lambda/\Delta\lambda$)
G130M	1150 – 1449 Å	300 Å	20,000 – 24,000
G160M	1406 – 1775 Å	375 Å	20,000 – 24,000
G140L	1230 – 2050 Å	820 Å	2500 – 3500

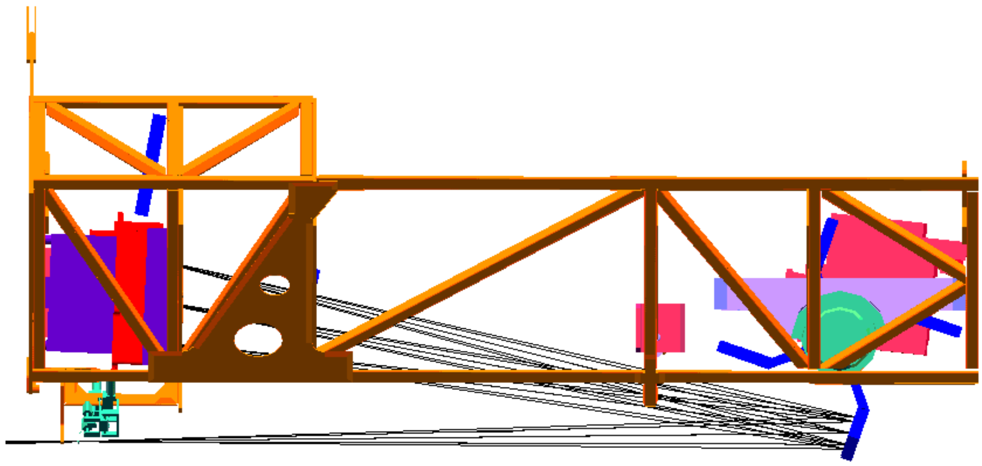

Figure 1. *Schematic of the COS primary FUV channel. Light is received from the HST OTA through an aperture (lower left), is dispersed by a concave diffraction grating, and finally is recorded on a curved double delay-line MCP detector adapted from the FUSE mission. The secondary NUV channel is fed by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

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. Because the CsTe NUV MAMA is also sensitive to FUV wavelengths, we include a reserve grating, G130MB, that 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 COS NUV spectroscopic modes are summarized in Table 2.

Table 2. COS NUV spectroscopic modes.

Grating	Wavelength Range	Coverage per Exposure	Resolving Power ($\lambda/\Delta\lambda$)
G190M	1750 – 2400 Å	3 $\times$ 45 Å	20,000 – 27,000
G260M	2400 – 3200 Å	3 $\times$ 55 Å	20,000 – 27,000
G230L	1700 – 3200 Å	1000 Å	850 – 1600
G130MB	1150 – 1800 Å	3 $\times$ 30 Å	20,000 – 30,000

The predicted effective areas for the high-dispersion FUV and NUV spectroscopic modes are shown in Fig. 3.

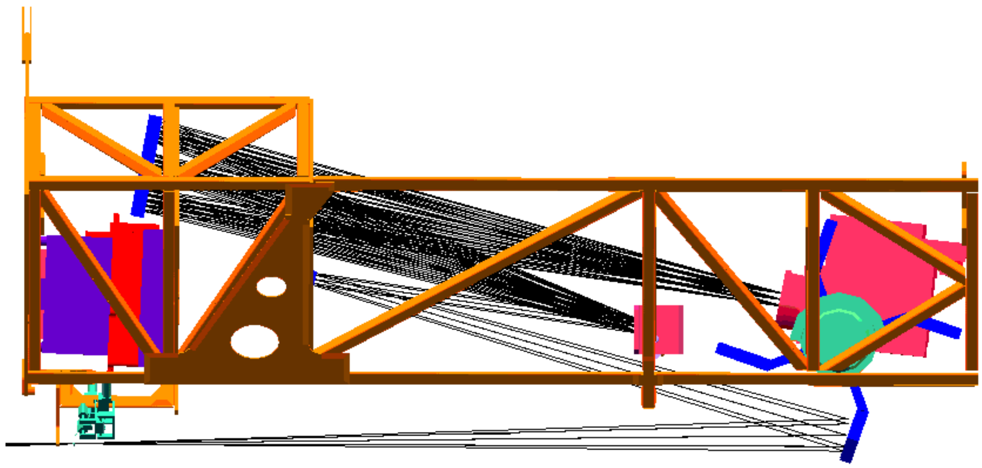

Figure 2. *Schematic of the COS secondary NUV channel. The optical beam is received from the HST OTA through the aperture (lower left), and is magnified by a mirror on the primary optics select mechanism. The light is directed to a second optic which collimates the beam and sends it to the secondary optics select mechanism (small box near center) containing several flat gratings and a mirror. The dispersed spectrum is imaged by three camera optics onto a CsTe MAMA detector adapted from STIS.*

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 sec per exposure 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.

2.4. COS Science Apertures

COS is optimized for observing faint UV point sources. The "standard" aperture is a two-arcsecond 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 a well-centered 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 $\sim$ $0''\!.1$ that permits COS to observe targets several magnitudes brighter than the Bright Object Protection limits allow through the larger 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.

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 $\leq 0''\!.1$). However, for an extended source, for example, $\sim 0''\!.5$ in diameter, the spectral resolution is degraded to R $\approx$ 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. Ultraviolet 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

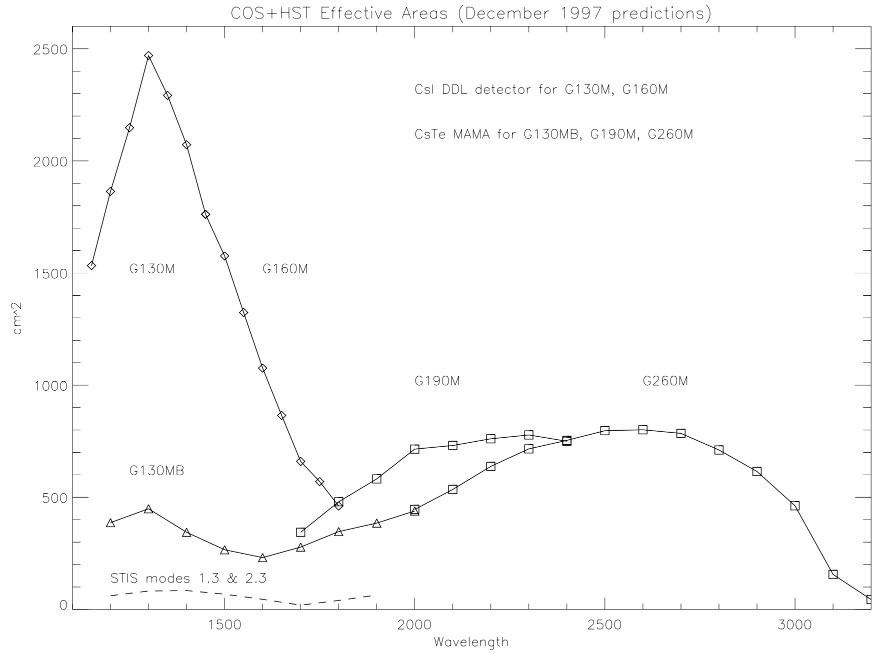

Figure 3. *Effective area predictions for the COS FUV and NUV high-dispersion grating modes. The effective areas shown include a 'slit' transmission of* $\sim 87\%$ *through the standard* $2''$ *aperture. Effective areas for the STIS echelle modes in the FUV are shown for comparison.*

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.

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. 4). 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.

We will use COS 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. The large redshift coverage and high sensitivity provide access to numerous diagnostic features, such as C IV $\lambda\lambda$1550, O VI $\lambda\lambda$1035, and He II λ304 in a variety of high-redshift environments. 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

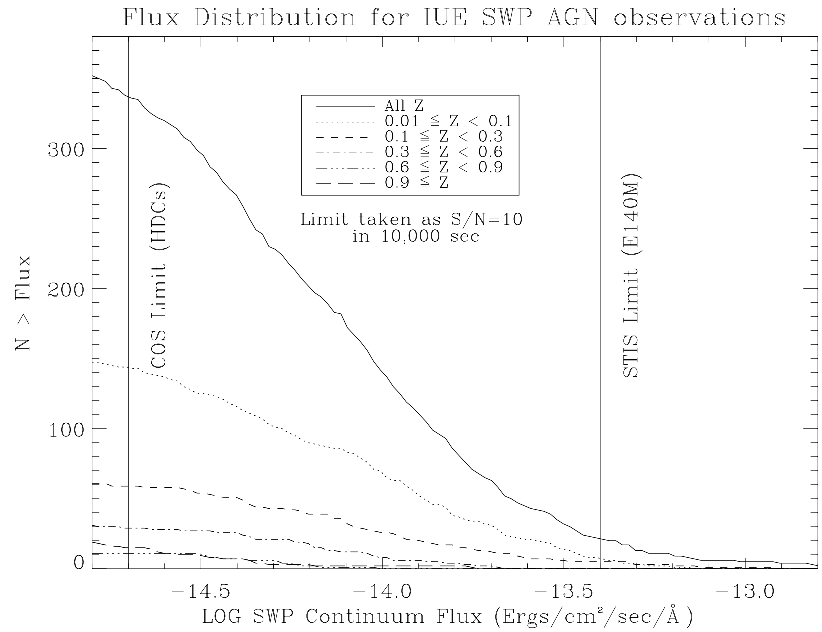

Figure 4. *Number distributions of AGN observed by IUE brighter than a given flux limit. Top curve shows all IUE observations of AGN; lower curves show various redshift intervals. Using the high dispersion channels (HDCs) G130M, G160M, G190M and G260M, COS can observe over ten times more targets with moderate spectral resolution than STIS. From http://casa.colorado.edu/~spenton/IUEAGN/FUSE.html.*

medium, and as templates for deriving the properties of high-z galaxies. COS UV spectra of horizontal-branch stars in globular clusters (Fig. 5) 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 (Fig. 6). Resolution R = 20,000 UV spectroscopy with the COS high-dispersion modes will provide detailed information on gas-phase atomic and molecular abundances in the regime where the gas has become largely molecular and grain mantles begin to grow by direct deposition from the gas phase. These processes signify the earliest phases of collapse and accretion of stellar and planetary systems. Low-dispersion spectroscopy can be used to probe the UV extinction properties of the dust at high A_V. We will also be able to search for structure in the UV extinction curve with unprecedented sensitivity, enabling us to determine whether the optical diffuse bands extend into the UV, and allowing us to search for specific features predicted to be formed by interstellar PAH molecules.

The strengths of COS for faint object UV spectroscopy of point sources are by their nature more applicable to cosmology and certain Galactic observations than planetary science. However, the high sensitivity of COS does open up new spectroscopic investigations by *HST* within the Solar System. COS data will 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 scientific program attacks fundamental topics in astronomy and astrophysics. However, our GTO program represents just a small fraction of the total observing time with COS that is available to the world-wide astronomical

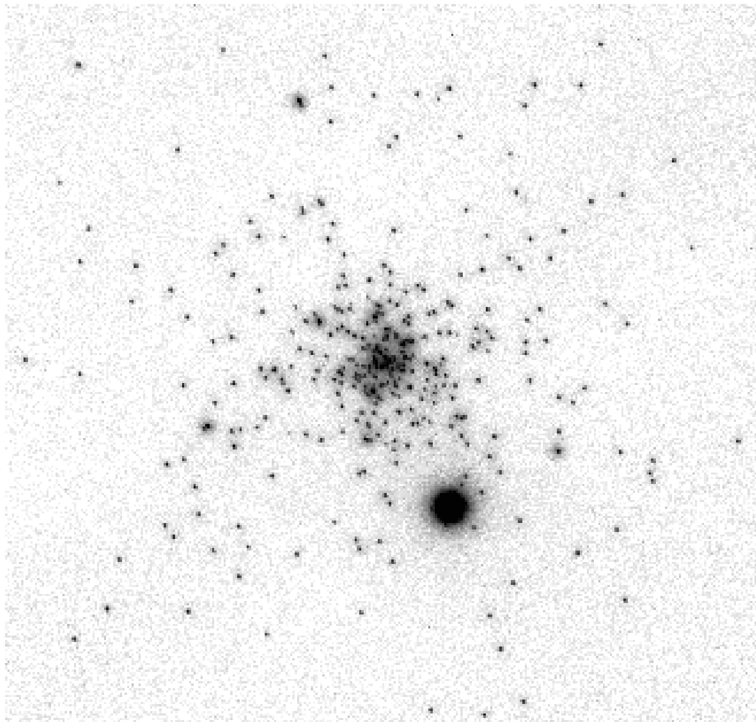

Figure 5. *Far-UV image of NGC 6752 (λ_c=1620 Å) obtained by the Ultraviolet Imaging Telescope (UIT). The 20-arcmin field of view shown encompasses nearly the entire cluster. Although NGC 6752 contains more than 10^5 stars, nearly all of these stars are too cool to emit any UV light. The 330 stars seen in this UIT image are all HB stars, except for the over-exposed bright star $4'$ southwest of the cluster center, which is a foreground star. COS will provide follow-up spectroscopy of targets identified by UV imaging telescopes. From http://fondue.gsfc.nasa.gov/UIT/Astro2/.*

community. COS is an extremely potent instrument for a broad range of science problems. Most of the science to be pursued with COS will actually be accomplished by the Guest Observer (GO) community, tackling a very wide range of projects that address many astrophysical problems. Such problems may include: AGN monitoring campaigns; UV upturn in elliptical galaxies; UV monitoring of distant supernovae; monitoring of SN1987A as it impacts its circumstellar material; stellar winds and UV properties of massive stars in the LMC and SMC; cataclysmic variables and other high-energy systems with accretion disks; line emission from heated plasma in accretion columns in young stellar objects; UV continuum measurements to determine SEDs and bolometric corrections in YSOs with accretion disks; chromospheric emission from cool stars and the evolution of magnetospheric activity in young stars; planetary aurorae; emission characteristics of cometary comae; studies of diffuse objects where the goal is to reach the deepest possible UV flux levels, for example, detecting high-ionization (e.g., C IV) emission from the Milky Way halo, the outer blast wave of the Crab nebula, or shock waves in supernova remnants and Herbig-Haro jets.

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. 7) 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.

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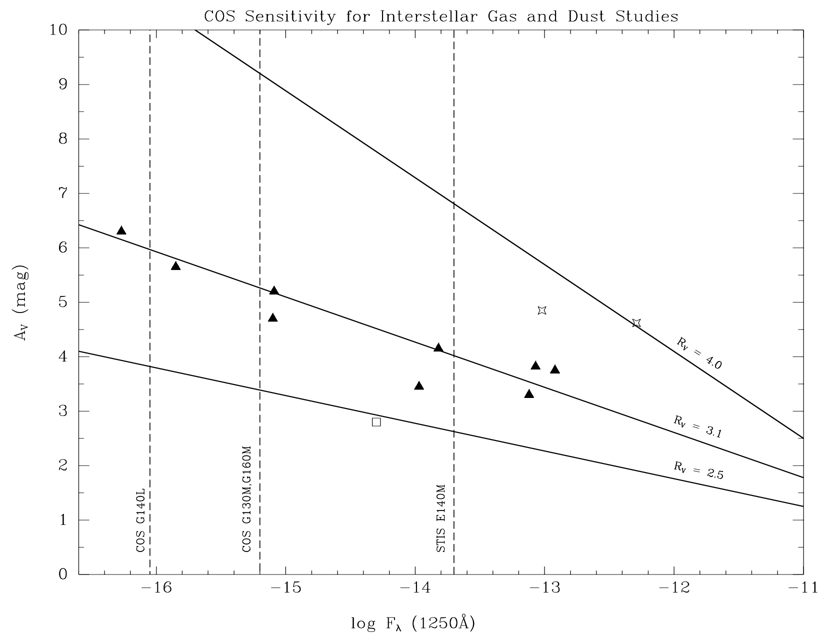

Figure 6. *COS extends UV extinction studies by several magnitudes. Dashed lines represent limiting fluxes for* $t_{exp} = 20,000$ *sec and S/N = 10 per resolution element for the indicated spectroscopic modes. The points denote low-resolution flux measurements of stars, and the symbol types indicate their association with different extinction curves.*

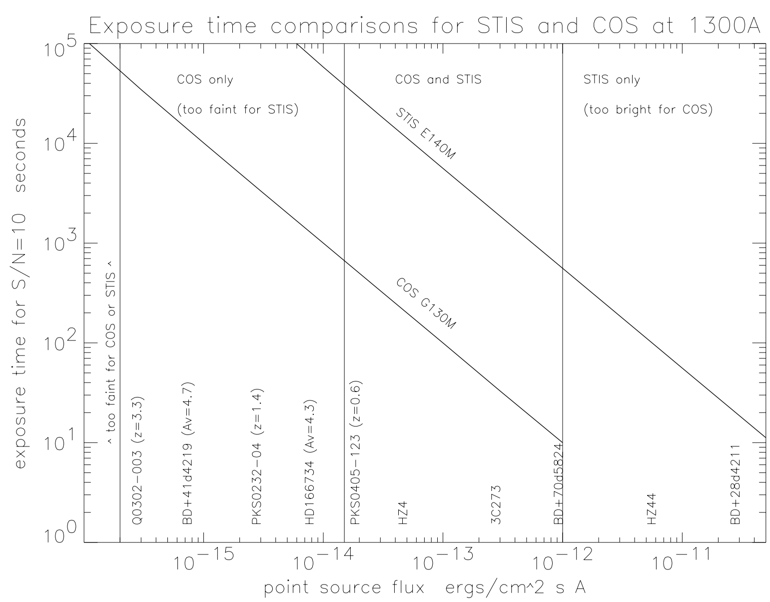

Figure 7. *Summary of predicted exposure times to achieve S/N=10 per resolution element as a function of flux for the* $R \geq 20,000$ *resolution COS G130M FUV grating, assuming the standard 2″ COS aperture is used. Example targets are noted along the horizontal axis above their corresponding UV fluxes. Exposure times for the STIS E140M echelle mode are shown for comparison. The region of bright fluxes to the right* can *be accessed by COS using the small, bright-object aperture.*