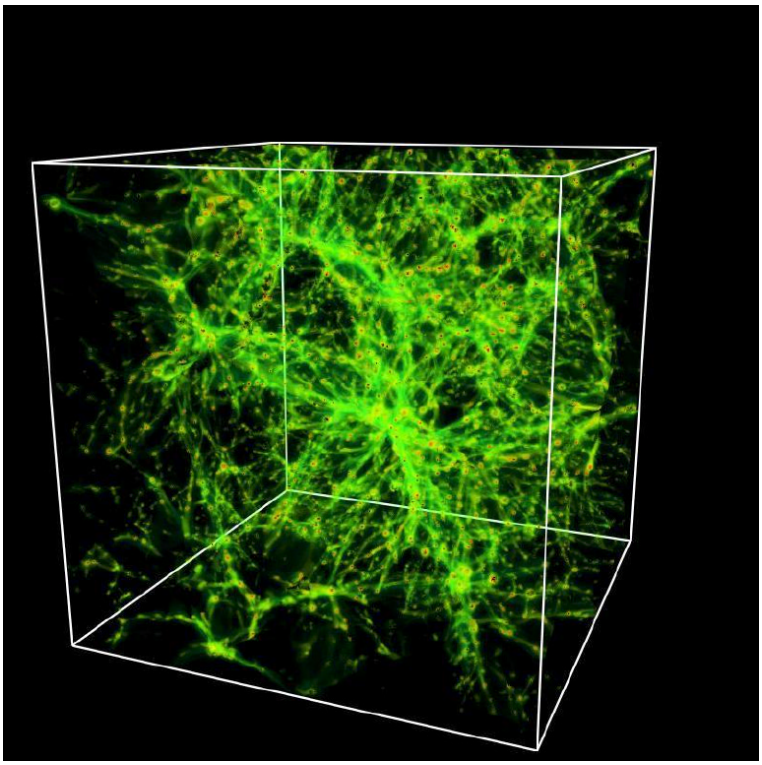
THE EMERGENCE OF THE MODERN UNIVERSE: TRACING THE COSMIC WEB

(November 1999)



White Paper of the UV-Optical Working Group (UVOWG)

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UV-Optical Working Group (UVOWG) White Paper

ABSTRACT

This is the report of Ultraviolet-Optical Working Group (UVOWG) commissioned by NASA to study the scientific rationale for new missions in ultraviolet/optical space astronomy approximately ten years from now, when the *Hubble Space Telescope* (HST) is de-orbited. Building on scientific talks at the August 1998 Boulder meeting, the UVOWG discussed the outstanding unsolved scientific problems that can be answered by high-throughput UV spectroscopy and wide-field UV/O imaging. Following the exciting next decade of studies by HST (STIS, ACS, COS, WFC-3) and new surveys by MAP (microwave background at 1° scale), the Sloan Survey, and GALEX (discovery of over 10^6 new QSOs for background targets), the stage is set for cosmological explorations of galaxy assembly and the evolution of the intergalactic medium (IGM). Realizing that a major new UV/O mission would produce forefront science in all areas of modern astronomy, the UVOWG focused on a scientific theme, *"The Emergence of the Modern Universe"*, that unifies many of the unsolved problems in UV/O astronomy. We define this era as the period from redshifts $z \approx 3 \rightarrow 0$, occupying over 80% of cosmic time and beginning after the first galaxies, quasars, and stars emerged into their present form. The exciting science to be addressed in the post-HST era includes studies of dark matter and baryons, the origin and evolution of the elements, and the major construction phase of galaxies and quasars. Key unanswered questions include: Where is the rest of the unseen universe? What is the interplay of the dark and luminous universe? How did the IGM collapse to form the galaxies and clusters? When were galaxies, clusters, and stellar populations assembled into their current form? What is the history of star formation and chemical evolution? Are massive black holes a natural part of most galaxies?

A large-aperture UV-visible telescope in space will provide a major facility in the $21^{\rm st}$ century for solving these scientific problems. The Space Ultraviolet-Visible Observatory (SUVO) mission will focus on UV spectroscopy and wide-field imaging. An 8m-class aperture with deployable optics similar to NGST should deliver over 100-fold increases in spectroscopic throughput and multiplex efficiency, and similar gains in imaging field of view and sky mapping efficiency. The UVOWG recommends that, like SIRTF and NGST, the SUVO mission requires significant NASA investments in technology, including UV detectors, gratings, mirrors, and large-format imagers.

Preface: Background on the Study and Process

This document represents the "White Paper on UV-Optical Space Astronomy" commissioned by the Office of Space Science at NASA. The scientific ideas and mission concepts grew out of a NASA-sponsored conference held in Boulder, CO between August 5–7, 1998, entitled *Ultraviolet-Optical Space Astronomy beyond HST*. On the final day of that conference, a panel discussion focussed on mission priorities for the period approximately ten years from now, when the *Hubble Space Telescope* (HST) completes its 20-year lifetime and is de-orbited. At this time, the astronomical community will lose capabilities for high-resolution imaging and spectroscopy with a stable point-spread function, high dynamic range, and wide field of view in the UV and optical.

This panel formed a strong consensus for a mission whose main focus was high-throughput UV spectroscopy and wide-field UV-visible imaging. The most credible mission concept was one whose core science included cosmological studies of the major epochs of galaxy assembly, the large-scale structure of the intergalactic medium (IGM), and the origin and chemical evolution of heavy elements. Addressing even the initial (small) portions of these science goals would require an enormous dedication of HST observing time (over 10,000 orbits) to key or legacy projects, as we outline in Appendix 1. Moreover, even the new HST instruments soon to be installed cannot break through the required thresholds of source sensitivity or field of view. The panel concluded that the scientific goals of the next UV-visible mission required at least an order-of-magnitude advance in UV spectroscopic throughput, compared to HST with the Cosmic Origins Spectrograph (COS). In addition, imaging in the optical and UV will be important for studies of galaxy assembly and related areas, if one can achieve wide-field detector formats to facilitate efficient measurements at cluster and supercluster scales. Wide fields are also critical for studies of star-forming and nebular regions in the Milky Way and nearby galaxies.

Subsequent to that meeting, NASA requested a study of these issues, and chartered the UVOWG ("Ultraviolet - Optical Working Group"). The UVOWG will report to NASA and its advisory groups, the subcommittees for *Origins* and *Structure and Evolution of the Universe*. The UVOWG was chaired by Mike Shull (Colorado), and its core membership included Blair Savage (Wisconsin), Susan Neff (NASA-Goddard Space Flight Center), Anne Kinney (Space Telescope Science Institute), John Clarke (Michigan), Ed Jenkins (Princeton), Tim Heckman (Johns Hopkins), Andrea Dupree (Harvard-Smithsonian Center for Astrophysics), and *ex officio* members Hashima Hasan (NASA HQ and STScI), Stefi Baum (STScI), and Jon Morse (Colorado). Additional contributions to our discussions and report were made by Harley Thronson (NASA HQ), Harry Ferguson, Melissa McGrath, Marc Postman, Megan Donahue, Carol Christian, Steve Beckwith (STScI), Ken Sembach, Julian Krolik, Zlatan Tsvetanov (Johns Hopkins), Bruce Balick (Washington), Todd Lauer (NOAO), Scott Trager (Carnegie Observatories), Bruce Woodgate, Randy Kimble, Chuck Bowers, Ritva Keski-Kuha, David Leckrone (NASA-Goddard), James Green, Erik Wilkinson, Jeffrey Linsky, Brad Gibson, Mark Giroux, John Bally (Colorado), Chris Martin, David Schiminovich (Caltech), Ossy Siegmund (Berkeley), Bob Woodruff (Ball Aerospace), and Charles Lillie (TRW). Many others provided comments and reactions to our work, and we thank them for their efforts.

1. INTRODUCTION

The *HST and Beyond* (Dressler) Committee emphasized that HST will be unique for conducting UV studies during the first decade of the 21st century. They recommended that HST be operated past 2005, with an emphasis on ultraviolet spectroscopy and wide-field, high-resolution optical imaging. The second decade of HST has great promise, as powerful new spectrographic (STIS, COS) and imaging instruments (ACS, WFC-3) are installed and commissioned. Our committee considered the primary science that HST may do, through a system of key projects or "legacy" projects (Appendix 1). However, in thinking about the ten-year HST horizon, the UVOWG and others in the UV-visible community have been forced to confront the limitations of HST for solving new scientific issues. To solve the critical science problems posed in this report, it is essential to have a highly capable Space Ultraviolet-Visible Observatory (SUVO) shortly after HST is de-orbited.

Space astronomy has made enormous scientific advances in the 1990s with the imagers and spectrographs aboard the *Hubble Space Telescope*. However, UV spectroscopy has not kept pace with ground-based scientific instruments, which are revolutionizing studies of galaxies, quasars, star-forming regions, and cosmology. Forefront spectroscopic studies of galaxies, stars, quasars, and the universe cannot be done in the 21st century with a 2.4-meter telescope. The proposed mission or missions, referred to under the title SUVO, promise to fulfill the 1946 vision of Lyman Spitzer for a *"large reflecting satellite telescope, possibly 200 to 600 inches in diameter"* whose major scientific missions would be to study the *"extent of the universe, the structure of galaxies, the structure of globular clusters, and the nature of other planets"* (see Spitzer 1990). To this list, we might add, with 50 years of hindsight, the nature of quasars, the formation of galaxies, and the cosmological processes that govern the formation of large-scale structure of the intergalactic gas and dark matter.

The reasons for planning large-aperture (4-8 meter) telescopes in space have not changed since Spitzer's visionary report. Cosmology is inherently a photon-starved endeavor, particularly when one requires significant spectral resolution to detect the key astrophysical diagnostics of structure, velocity, and composition. Emission-line regions that probe the assembly of galaxies and quasars are distant and faint. Viable background targets (hot stars, quasars, clusters) are faint and rare. Consequently, our panel highlighted the need for high performance, to be achieved through a combination of larger aperture, advances in optical and detector efficiency, multiplexing, and orbits that permit high operational efficiency.

A 4–8 meter telescope in space (SUVO) will provide a major facility in the 21st century for solving a wide range of scientific problems in cosmology, galaxy formation, stellar evolution, and the origin and evolution of structure and chemical composition. An aperture this large should be used for forefront science in both spectroscopy and imaging. Diagnostic spectroscopy lies at the heart of astrophysical inference, while imaging offers enormous opportunities for new discovery and inspiration. To be an effective instrument in the world of 21st-century astronomy, the SUVO spectrographs must deliver a sizeable increase in throughput and multiplex efficiency, over that of any of the instruments aboard HST. With detector arrays growing rapidly in size, the SUVO imagers

should achieve similar large gains in size and efficiency.

In the "Mission Concepts" section of this report, we describe both 4m and 8m mission concepts. The 4m concept could be accomplished within a SIRTF-class cost envelope ($\sim$ \$400M) by employing enhancements to today's technology. The 8m-class mission requires a giant leap in technology development of mirrors and detectors. One key recommendation of our report surpasses all others: The UVOWG recognizes that no UV-visible mission of either 4m or 8m class will be possible without these significant gains in technology, including UV detectors, gratings, mirrors, and large-format imagers. As with SIRTF and NGST, we believe that NASA should significantly boost its investment in UV-visible technology over the next five years, to ensure that SUVO can fulfill the ambitious science goals laid out in this report.

SUVO will produce forefront science in nearly all areas of modern astronomy, from extragalactic to Galactic and planetary arenas, as described in later portions of this report. To highlight the most compelling science, we focus on a major scientific theme that unifies many of the unsolved issues – *"The Emergence of the Modern Universe"*. This theme refers to the study of the era from $z \approx 3 \rightarrow 0$, beginning just after the first galaxies and stars took their present form and quasar and starburst activity reached their peak. Included in this theme are such questions as:

- *Where is the rest of the unseen universe?*
- *What is the interplay of the dark and luminous universe?*
- *How did the IGM collapse to form the galaxies and clusters?*
- *What is the role of star-formation "feedback" in radiation and energy on galaxies?*
- *When were galaxies, clusters, and stellar populations assembled into their current form?*
- *Are massive black holes a natural part of most galaxies?*
- *What is the history of star formation and galactic chemical evolution?*
- *How do solar systems form, and what do they look like?*

These questions and projects satisfy the human desire to understand where we came from, and how planets, stars, and galaxies formed and evolved. To provide more specifics on the scientific goals contained within this general theme, we have chosen to highlight three major areas:

- **Dark Matter and Baryons**
- **The Origin and Chemical Evolution of the Elements**
- **The Major Construction Phase of Galaxies and Quasars**

Section 2 of this report discusses these topics in more depth, together with other scientific programs that would be enabled by the missions contemplated.

2. EMERGENCE OF THE MODERN UNIVERSE

The UVOWG was specifically commissioned to perform the following tasks:

- Develop high-priority science goals for UV-visible space astronomy for the period approximately a decade from now.
- Summarize a plausible mission or missions that will be capable of carrying out the high-priority science program.
- Outline a technology roadmap that might plausibly lead to a "New Start" for construction of the recommended missions.

To capture the power of the SUVO mission most dramatically, we highlight the key science in the theme "*The Emergence of the Modern Universe*" – studies of planets, stars, galaxies, and large-scale structure from redshifts $z = 3$ down to the present epoch. This period occupies over 80% of cosmological time, and captures both the origin and evolution of nearly every major astronomical structure, from galaxies and clusters to quasars and the IGM. During this time (8–10 Gyr), large-scale structure developed in both dark matter and baryons. Much of the intergalactic gas collapsed onto galaxies, over 90% of the heavy elements were formed, and the energy sources of radiation, hot gas, and dynamic outflows acted back on the surrounding galaxies and gas clouds. This "feedback" of galaxy formation is the least understood aspect of galaxy formation and assembly. The proposed SUVO mission will provide definitive measurements, with unprecedented accuracy, of the key epochs from $z = 3$ to the present, to fill in the evolutionary gap of galaxies, the IGM, and large-scale structures from infancy to maturity. This mission will also provide accurate low-z templates required to understand the high-z phenomena.

SUVO will connect the high-redshift universe observable by NGST to the low-redshift universe, which will be studied in detail by quantitative spectroscopy and wide-field imaging. If properly designed, SUVO will also relate near-infrared observations of the distant (NGST) to optical and ultraviolet observations of the local universe. The NIR view provided by NGST is related to the visible and ultraviolet view of the "local universe," since the rest-frame ultraviolet light of the first galaxies is redshifted to 1–5 μm by cosmological expansion. For cosmological studies of the distant universe, 21$^{\rm st}$-century space astronomy must take a multi-spectral view, in which NGST and SUVO complement one another, both in wavelength and across cosmological time.

The rest-frame ultraviolet is a particularly crucial wavelength regime, since it contains the dominant emission from massive hot stars and sensitive resonance transitions of nearly all abundant atoms and ions. For the era that SUVO will study ($z = 0 \rightarrow 3$), most of these transitions will be observed in the spectral region between about 1200 and 6000 Å. In absorption, these lines provide a unique, sensitive diagnostic for first detecting and then investigating warm and cool intergalactic gas (which may well comprise the major cosmic repository of baryons). In emission and absorption, these transitions allow one to study the dynamics, chemical composition, and physical conditions in

environments ranging from the atmospheres and winds of stars, to protostellar outflows, to galactic disks, halos, and the IGM.

2.1. Dark Matter and Baryons

The current state of affairs in cosmology is both fluid and exciting. Just around the corner are powerful new techniques (observations of Type Ia supernovae at high redshift) and new missions (the MAP microwave background explorer) that should obtain accurate measurements of fundamental cosmological parameters, such as the Hubble expansion rate (H_0), the age of the universe (t_0), and the contributions of baryons, dark matter, and vacuum energy to spacetime curvature. The cosmological parameter Ω measures the ratio of the density of gravitating matter (or energy) to the critical value needed to halt the Hubble expansion. Various types of matter are labeled by subscripts: Ω_b measures baryonic matter, Ω_0 measures matter of all types, and Ω_Λ measures an exotic new form of "vacuum energy" associated with a repulsive cosmological constant.

Current measurements of mass and space curvature suggest that we live in a universe dominated by dark matter, and possibly permeated by a mysterious vacuum energy. A working hypothesis has recently developed in which the various contributions to the closure density have the approximate values: total matter $\Omega_0 \approx 0.3$ and vacuum energy (cosmological constant) $\Omega_\Lambda \approx 0.7$. Nucleosynthetic modeling of D/H (Burles et al. 1999) suggests that the baryons contribute only $\Omega_b \approx 0.045$ (for $H_0 \approx 65$ km s^{-1} Mpc^{-1}), which requires that a substantial amount of the mass density is dark and probably non-baryonic. In ten years, these parameters may be well determined, and the major challenge will be to identify the exact forms of the various components of mass/energy in the universe. An even more fundamental physical issue is to address the question of how and why these parameters took their current ratios. For example, what sets the ratios $\Omega_0/\Omega_b \approx 6.6$ and $\Omega_\Lambda/\Omega_0 \approx 2.3$? What is the form of the exotic dark matter, and how is it distributed relative to the galaxies and the gaseous IGM?

Ultraviolet spectroscopy (mapping the Lyα forest on sub-degree scales) and wide-field imaging (weak gravitational lensing on cluster and supercluster scales) can address some of these fundamental issues. At moderate redshifts, $z < 1.5$, quasar absorption spectra contain evidence for the epochs of galaxy formation, metal production, reionization, and reheating of the baryons left over from the Big Bang. Theories of primordial nucleosynthesis and cosmological structure formation predict a distributed IGM containing a substantial fraction of the hydrogen and helium synthesized in the Big Bang. According to cosmological N-body hydrodynamic models (Cen et al. 1994; Hernquist et al. 1996; Zhang et al. 1997) gas in the high-redshift IGM begins to collapse into the filamentary web of dark-matter potential wells. The first collapsed objects ("proto-galaxies") may form between redshifts $z = 10 - 20$, and the first galaxies and QSOs are probably present by $z = 5 - 10$. As far as we can tell, the universe at redshift $z > 5$ is nearly opaque at UV and optical wavelengths, owing to the strong absorption from hydrogen Lyα in the IGM (the Gunn-Peterson trough).

The era at $z > 5$ has often been termed the "dark ages". Probing these dark ages forms one of the key goals of NGST. The NGST hopes to detect the first stars, first galaxies, and first supernovae in their redshifted light between 1 and 5 μm. SUVO will observe the fruits of these seeds of galaxy formation, to see "how it all turned out". The type of object that NGST will study at $z > 5$ needs to be characterized in the rest-frame ultraviolet, especially in the low-redshift "modern universe", where we can obtain high-resolution UV/Optical images, UV spectra, and large-scale maps of the distributions of galaxies and intergalactic clouds.

Thus, the premier challenge for UV astronomy in 2010 will be to follow the evolution of the universe from the "dark ages" down to the "renaissance" of star formation, supermassive black holes (quasars), and metal production in the present epoch. Measuring the evolution of the Lyα baryon content is vital if we are to understand the mass evolution of galaxies, the rate at which gas in the IGM is incorporated into galaxies, and the rise of metallicity over cosmic time. At low redshifts ($z < 1$) new astronomical instruments on SUVO will be able to see these objects in remarkable clarity. To elucidate the emergence of the modern universe in the gas, stars, and galaxies, NASA needs to set into motion the technological development that will make SUVO ready for a New Start late next decade.

Mapping the Large-Scale Structure of the IGM

Based on recent galaxy redshift surveys, astronomers have detected the existence of an organized large-scale structure in the galaxy distribution, which takes the form of large filamentary walls and "empty" voids. By 2010, these galaxy surveys will outline the distribution of luminous matter in fine detail, but the dark, gaseous universe (the IGM) will remain largely unexplored at $z < 1.65$. (At $z > 1.65$, the Lyα line is redshifted into the visible band, although several key metal transitions at $\lambda < 1216$ Å remain in the ultraviolet.) Theoretical models suggest that studies of the H I and He II Lyα forest of absorbers in QSO spectra should probe the large reservoir of gas left from the major epoch of structure formation. In fact, the intergalactic Lyα absorbers persist down to very low redshifts, and observations from HST show that many Lyα clouds exist in voids as well as in filamentary walls (see Fig. 1).

Studies of the He II Lyα forest are particularly effective at probing the lowest-density regions of the baryon distribution, while the H I Lyα lines at redshifts $z < 1.65$ (Bahcall et al. 1996; Stocke et al. 1995; Jannuzi et al. 1998; Weymann et al. 1998) may be used to follow the hydrogen structures down to the present epoch. In combination, these two diagnostics allow astronomers to follow the interplay between the formation of galaxy structures and the IGM. They can also be used to study mass exchange: the depletion of the reservoir of intergalactic gas into galaxies, and the flow of mass from galaxies back to the IGM through galactic winds and tidal stripping.

Because of the steepness of the quasar luminosity function, particularly in the UV, a factor 10 better sensitivity will open up 50–100 times more background AGN targets to probe the IGM and

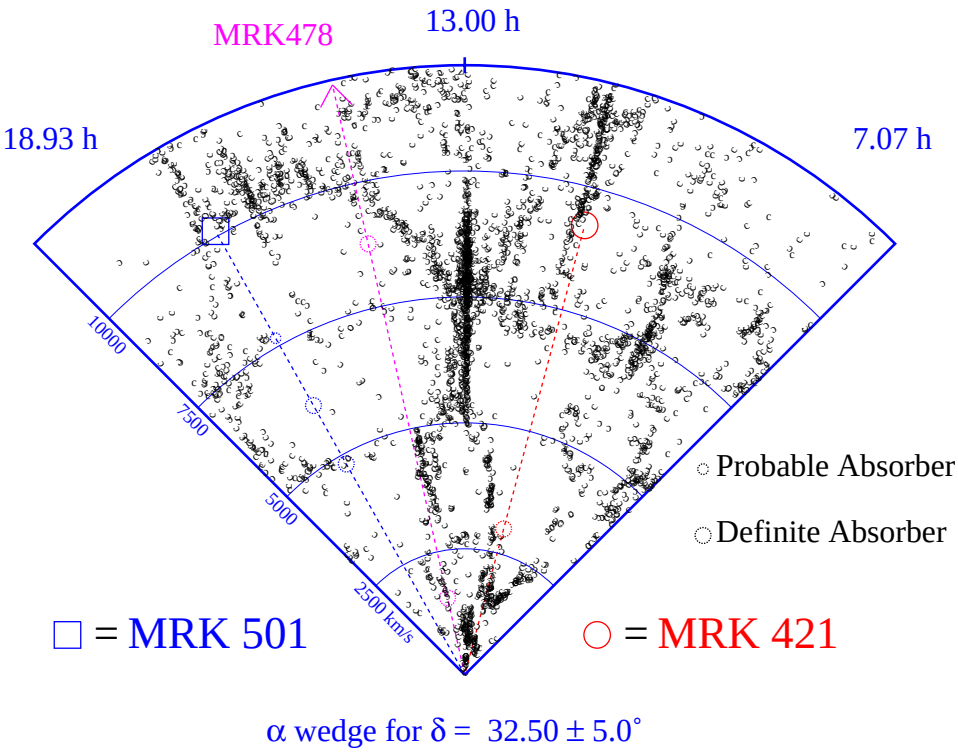

Fig. 1.— Large-scale cosmological structure, consisting of filaments of galaxies surrounding voids, is seen in the CfA2 redshift survey (Huchra 1999). This "pie-diagram" shows the distribution in recession velocity and right ascension of bright galaxies and four Lyα absorbers found by HST/GHRS toward Mrk 501 and Mrk 421 (Penton, Stocke, & Shull 1999). Evidently, the voids are not entirely empty: two Lyα clouds lie in voids, with the nearest bright galaxies more than 4 Mpc away.

galaxy halos at intermediate and low redshift. With these UV background sources, we can make tomographic maps of the full "cosmic web" (Cen & Ostriker 1999) of the filamentary distributions of hot (shocked) and warm (photoionized) baryons left over from the epoch of large-scale structure formation. This theoretical prediction is robust among many models, but the structures have not yet been detected. Mapping the evolution of these gaseous structures down to low redshift will be a prime scientific goal of SUVO.

The Sloan Digital Sky Survey (SDSS) modeled $N_{\rm QSO}$, the expected QSO number counts per square degree, using data from Crampton et al. (1987) and La Franca & Cristiani (1997). If the sources are distributed randomly, with mean value $N_{\rm QSO}$ (QSOs per square degree), then the mean angular distance between sources is $\theta_{\rm QSO} = (1/2)/N_{\rm QSO}^{1/2} = (30')/N_{\rm QSO}^{1/2}$. As shown in Table 2.1, the QSO counts rise rapidly at magnitudes $m_B > 18$. For suitable UV background targets, one should reduce $N_{\rm QSO}$ from these values, to allow for some QSOs being faint in the UV. To attain sufficient spatial coverage of the large-scale structures in galaxies (Fig. 1) and the IGM (Fig. 2), we need to observe QSOs at magnitudes down to $m_B \approx 19 - 20$, where the the mean angular

Table 2.1: Quasar Number Counts and the Mean Angular Distance Between QSOs

m_B (magn)	$N_{\rm QSO}$ (sqdeg^{-1})	$\theta_{\rm QSO}$ (arcmin)
16	0.01	$300'$
17	0.13	$83'$
18	1.1	$29'$
19	5.3	$13'$
20	17	$7.3'$
21	41	$4.7'$

distance between QSOs on the sky is 20-30 arcmin, allowing for the lower UV continuum owing to intergalactic absorption. After accounting for ultraviolet absorption from Lyman-limit systems, Picard & Jakobsen (1993) found a steep rate of increase, $d(\log N)/d(\log F_\lambda) = 2.7 \pm 0.1$ for quasars in the flux range 10^{-14} down to 10^{-16} ergs cm^{-2} s^{-1} Å^{-1} (approximately $m_B = 15$ down to $m_B = 20$). The current limit of HST/STIS for moderate-resolution spectroscopy is $m_B \approx 15$, while HST/COS will take this limit to $m_B \approx 17.5$. Another order-of-magnitude improvement is required to capitalize on the large increase in QSO populations at magnitudes $m_B = 18 - 20$.

In the next several years, the GALEX mission is expected to identify large numbers (10^{5-6}) of QSOs in the magnitude range $18 < m_B < 20$. The Sloan survey will provide redshifts for $\sim 10^5$ of these targets. The task of mapping the IGM structures from $z = 2 \rightarrow 0$ will be a major highlight of SUVO's program. Its spectroscopic throughput is sufficient to undertake a major survey of sightlines at high spatial frequency. The goal is to make an IGM baryonic survey on sub-degree angular scales, comparable to that of the MAP explorer and to the structure seen in galaxy surveys. In doing so, we will connect the high-redshift seeds of galaxies and clusters with the distributions of galaxies and IGM in the modern epoch, at redshifts $z < 1$.

A Baryon Census of the Local Universe

It has been estimated (Fukugita, Hogan, & Peebles 1998) that 50% of all baryons predicted by Big Bang nucleosynthesis may reside in undetected form at low redshift, perhaps in a hot intergalactic medium (Cen & Ostriker 1999), in photoionized H I clouds (Shull 1998), or in small groups of galaxies. Identifying these "missing baryons" and other dark matter can be done by studying the Lyα absorbers, galactic halos, and weak gravitational lensing on cluster and supercluster scales. In fact, the Lyα surveys may be a better tracer of dark matter than galaxies, since they can probe relatively uncollapsed material in the IGM. Measuring the evolution of the Lyα baryon content is vital if we are to understand the mass evolution of galaxies, the rate at which gas in the IGM is

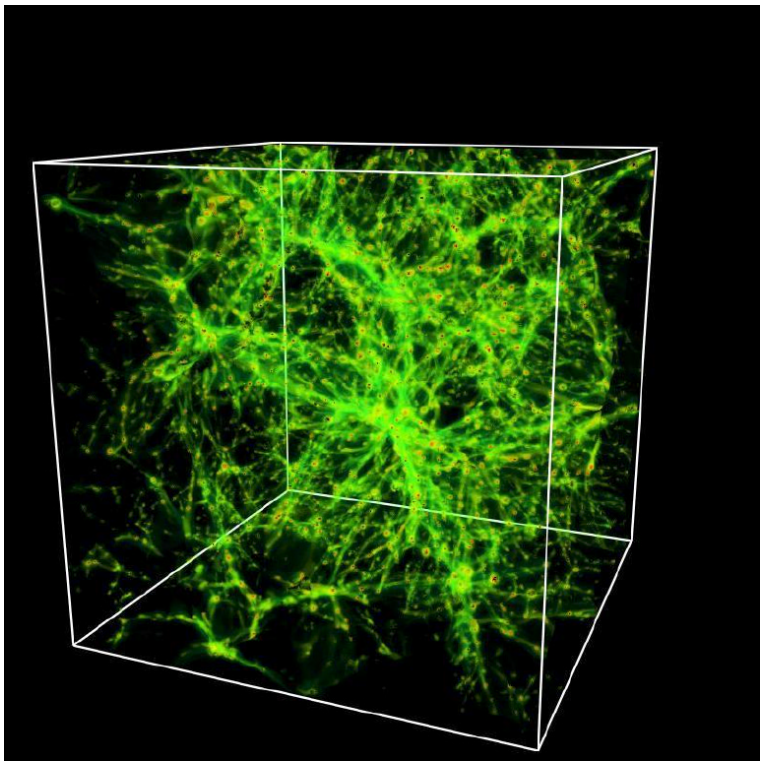

Fig. 2.— Large-scale filamentary structures in both hot and warm baryons are predicted in numerical N-body hydrodynamical models (cf., Cen & Ostriker 1999). Mapping these structures in absorption requires SUVO spectra toward background quasars at $m_B = 19 - 20$.

incorporated into galaxies, and the rise of metallicity over cosmic time.

The low-redshift Lyα clouds provide powerful probes of large-scale structure, since they are easy to detect and far more numerous than bright galaxies. Preliminary studies by HST/GHRS and HST/STIS toward 15 bright QSO targets have shown that the low-redshift Lyα forest remains ubiquitous, even down to $z = 0$ (Fig. 3). Moderate resolution spectroscopic surveys (Penton et al. 1999) identify one low-z Lyα absorber for every 1500 km s^{-1} of redshift down to column density N(H I) $= 10^{12.6}$ cm^{-2}. As with the Lyα absorbers at high redshift, these clouds appear to have large cross sections, of order 100 kpc in size. However, the inferred space density of these Lyα absorbers is still remarkably large, ~ 0.4 Mpc^{-3}, which is comparable to the density of dwarf galaxies and some 20 times larger than that of typical bright (L^*) galaxies. A rough estimate (Shull 1998) of the clouds' contribution to the local mass density of the universe gives $\Omega_{\rm cl} \approx (0.008 \pm 0.004) h_{75}^{-2}$, or some 20% of the baryon density consistent with D/H nucleosynthesis.

Clearly, a significant number of baryons are left in the IGM, even at low redshift, but a more detailed baryon census is needed. The goal of this survey would be to measure the frequency of absorbers, per unit redshift, and the distribution in H I column density for a large ensemble of

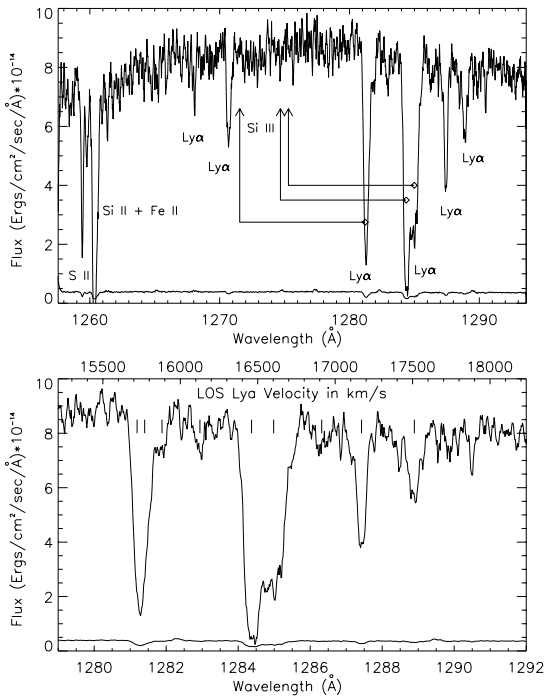

Fig. 3.— Intergalactic Lyα clouds are ubiquitous, even at low redshift. This HST/GHRS spectrum of the background source PKS 2155-304 shows multiple Lyα absorption systems between 1281–1290 Å, or line-of-sight (LOS) recession velocity $cz = 15,700 - 17,500$ km s^{-1}. These absorbers appear to arise from clumps of intergalactic hydrogen gas, spread over a region ~ 1 Mpc around a group of intervening galaxies (Shull et al. 1998). The gas may be pristine in metal abundances, as shown by the absence of Si III or C IV at the velocities of the H I absorption.

sightlines. To convert the distribution, $f(N_{\rm HI}, z)$, into a space mass density requires two additional pieces of information: first, the range of sizes and topology of the clouds (their cross section), and second, a realistic ionization correction for $n({\rm H}^+)/n({\rm H}^o)$. Crude values for these parameters went into the preliminary estimates of $\Omega_b(z = 0)$, but this is no substitute for a large-scale tomographic survey, using neighboring sightlines to constrain the cloud sizes and shapes. To derive the evolution of $\Omega_b(z)$ from $z \approx 2$ down to the present epoch will require major surveys of many QSOs, down to $m_V \approx 20$, a task that exceeds the capability of HST/COS by a factor of 10. In addition, because of the low detector efficiency in the near-UV on STIS and COS, adequate surveys for Lyα absorbers at $z = 1.4 - 1.8$ are difficult. This is precisely the epoch when the evolution in the absorbers appears to change drastically. Finally, a vastly increased sample of Lyα absorbers will produce a statistically significant measure of the evolution of the metagalactic ionizing background radiation, from the diminution of Lyα absorber frequency near quasars – the so-called "proximity effect". This effect is used to measure the metagalactic ionizing background, which is a key ingredient in the ionization

corrections needed, both for hydrogen and for accurate measurements of metallicity.

Reionization of Hydrogen and Helium

One workable definition of the "end of the dark ages" and the emergence of the modern universe is the time when the universe becomes largely transparent to ionizing photons (1 – 10 Rydbergs). The universe and IGM becomes transparent after the epochs when hydrogen and helium are re-ionized by the ionizing radiation from the first stars and first quasars. This occurs at $z > 5$ for H I, but helium is probably not reionized until $z \approx 3$, as inferred from the strong He II Lyα absorption troughs at (304 Å)$(1 + z)$ in the UV spectra of high-z QSOs (see Fig. 4).

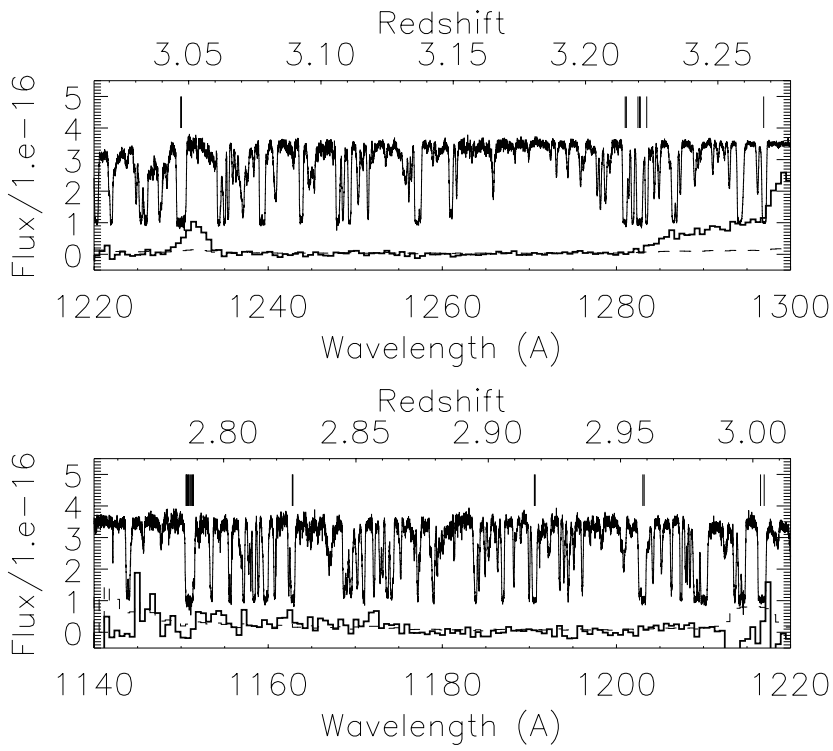

Fig. 4.— Absorption in the high-z He II and H I Lyα forest occurs in a myriad of discrete absorbers, probably arising from density fluctuations in the IGM. The HST/STIS spectrum (solid line at bottom) of the quasar Q0302-003 shows He II absorption shortward of 1300 Å (Heap et al. 1999) with superposed higher resolution spectrum of H I Lyα from Keck/HIRES. The H I Lyα data were normalized and multiplied by 0.25 in wavelength to match the He II wavelength scale.

The $z = 3$ epoch may have other significance for the build-up and transport of heavy elements throughout the IGM. The metallicity of intergalactic space can be measured from the strong UV resonance lines such as C IV λ1549, Si IV λ1400, C III λ977, Si III λ1206, and O VI λ1035. These

UV resonance lines are the most sensitive abundance indicators available in astrophysics, and they are widely used as abundance indicators in stars, in the low-redshift interstellar medium, and in the high-redshift IGM. Current evidence at high redshift suggests that C IV/Si IV abundance ratios shift at $z \approx 3$, possibly due to a spectral renaissance stimulated by the breakthrough and overlap of the cosmological He II ionization fronts from QSOs and starburst sources (Songaila & Cowie 1996; Giroux & Shull 1997). The ionizing UV radiation field from high-redshift QSOs and starburst galaxies is strongly filtered and processed by the IGM (Haardt & Madau 1996; Fardal, Giroux, & Shull 1998). Because helium is more difficult to ionize than hydrogen, singly-ionized helium builds up a significant trace population, He II/H I ≈ 100, which then blocks all radiation at energies above the He II ionization edge at 54.4 eV. The 304 Å (Lyα) lines of He II can be used to probe low-density regions of the IGM, particularly the void-like gaseous structures in the baryon distribution that develop in concert with the large-scale structures in dark matter and the reionization.

A challenging scientific project for SUVO will be to probe several hundred high-z QSOs, most at $m_B = 18 - 20$, that will be found by GALEX, SDSS, and other surveys, so that we can observe the He II reionization epoch in detail. These measurements will also constrain the spectral nature of the ionizing sources (QSO or starbursts) and provide the critical information for the ionization corrections needed to obtain accurate metal abundances and to monitor the chemical evolution rates with redshift. Thus, the reionization project should be done simultaneously with the study of chemical evolution described next.

2.2. Origin and Chemical Evolution of the Elements

To understand the chemical evolution of the universe, we need to determine the elemental composition of the gaseous matter and its relation to cosmic epoch and physical environment. Abundances of various species are expected to vary with gas density, star-formation rate, and proximity to galaxy structures. In the very early evolution, H, He, and trace amounts of other light elements such as D and Li were created in the expanding Big Bang fireball. At later times, stars converted the gaseous products of the Big Bang into heavier elements and returned the processed elements back to the interstellar medium via stellar winds and supernova explosions. Subsequently, the metal-enriched interstellar gas was transported to the IGM by galactic outflows, gravitational interactions, and mergers of galaxies. Numerical models of IGM enrichment (Gnedin & Ostriker 1997) predict a strong dependence of metallicity on density; the highest density regions are expected to reach 0.1 solar metallicity at $z \approx 3$, while the matter in the voids remains nearly pristine. Subsequent stellar processing created new elements and slowly modified the nucleosynthetic imprint of the Big Bang. These processes of stellar element production and destruction have continued to the current epoch. A study of elemental abundances as a function of lookback time and environment provides a detailed, quantitative assessment of the history of element production and destruction.

The Primordial Value of D/H

One of the critical parameters for studies of the early universe is the primordial D/H ratio. By measuring D/H in a variety of environments and following its evolution with metallicity, one can extrapolate back to the primordial D/H, which provides an accurate measurement of the baryonic contribution, Ω_b, to the closure density (Fig. 5). By measuring D/H in a wide variety of environments, one can understand the rate at which deuterium is destroyed as matter is cycled through stars ("astration"). It is now recognized that, beyond the local 100 pc, precise measures of D/H are extremely difficult to obtain for any astrophysical site. Therefore, the ultimate goal of determining the primordial value of D/H may become a long-standing problem in observational astronomy, equivalent to the current quests for obtaining accurate values of the Hubble Constant, H_0, and the closure and deceleration parameters, Ω_0 and q_0, respectively.

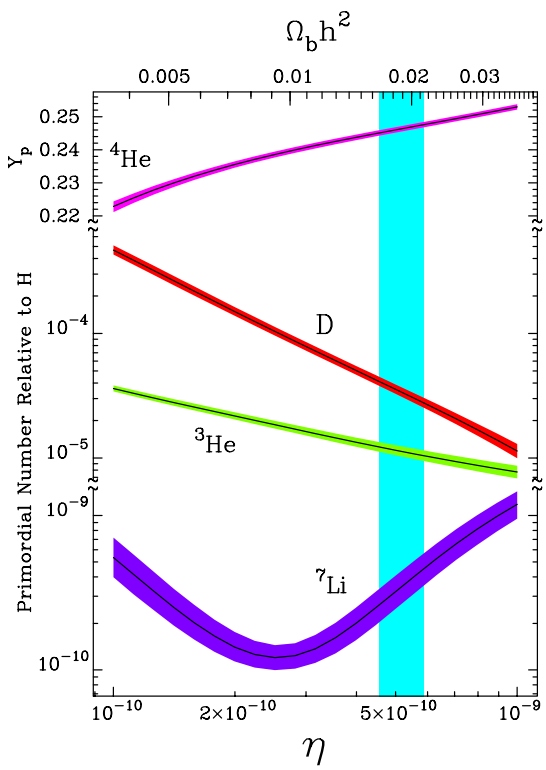

Fig. 5.— Summary of Big Bang Nucleosynthesis predictions for light elements (Burles et al. 1999), compared to observed abundances of D, Li, and He. The vertical band indicates the baryon density, measured in terms of $\Omega_b h^2$, inferred from recent D/H observations (best-fit is $\Omega_b h^2 = 0.019 \pm 0.0024$), where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1} (recent estimates give $h = 0.6 - 0.8$). The parameter η is the baryon-to-photon ratio.

Measuring D/H from the ground in high-redshift QSO absorption line systems has been difficult because of the confusion produced by the Lyα forest of absorbers. Measuring D/H from space

has been equally difficult because of the faintness of the possible background sources and the low sensitivities of current UV spectrographs in space. While continued progress can be expected from STIS, FUSE, COS, and spectrographs on ground-based telescopes, a precise measurement of the primordial value of D/H will require fully understanding the formation and destruction processes affecting D and then following D/H versus X/H as X/H $\rightarrow 0$. Here, X represents a nucleosynthetic product of the stellar evolutionary pollution of the gas. For example, measures of D/H versus C/H, N/H, or O/H would be extremely important.

Galactic studies of D with FUSE should provide new insights about the formation and destruction processes affecting D. Preliminary evidence is now appearing (Jenkins et al. 1999) that the value of D/H may vary by a factor of 2 in a few places in the solar region of the Milky Way. Such variations are difficult to understand, and they suggest that our current knowledge of D production and destruction in galaxies is limited. We know even less about D/H in matter with low metallicity, because QSO absorption-line systems suitable for obtaining precise measures of D/H are rare. Unless astronomers are exceptionally lucky over the next 10 years, it is very likely that an accurate measurement of the primordial value of D/H will require a UV spectroscopic capability, beyond the HST era, that can produce high S/N spectra of faint QSOs with a resolution exceeding 30,000. To have a reasonable chance of finding a suitable QSO absorption system to measure D/H requires observing many QSOs at $m_B = 19$; the success rate is only about 2% at $m_B \approx 16$.

Star Formation History

The deep imaging by the *Hubble Space Telescope* has stimulated interest in a search for the history of massive star formation from redshifts $z = 5$ to the present. The "Hubble Deep Fields" taken by WFPC-2, STIS, and NICMOS have shed new light on the evolution of the stellar birthrate, initially highlighting $1 \leq z \leq 2$ as the interval when most of the optical starlight was produced. Subsequent ground-based studies of "U-band dropout" galaxies by *Keck* and of reprocessed sub-mm emission by the *SCUBA* imager have challenged this interpretation. As shown in Fig. 6, the star formation rate may be rather flat from redshifts $z = 2$ back to $z = 5$.

Although the star-formation history at $z > 5$ will be measured by NGST, most of the stars and metals are formed more recently, at wavelength bands accessible by HST and SUVO. The starlight probed by these deep surveys is generated primarily by massive stars, although dust processing and radiative transfer play an important role in calibrating the total star formation rates. The rapid decrease in star formation and AGN activity at $z < 2$ parallels the development and assembly of modern galaxies and clusters, when over 90% of the heavy elements are produced and distributed. SUVO imaging and spectroscopy can follow this star formation rate and compare it to the rate of chemical evolution and galaxy assembly through accurate abundances and kinematic mass determinations. At low redshift, SUVO can perform detailed studies of the "local counterparts" of the high-z star-forming regions – the massive stars, OB associations, and super star clusters in the

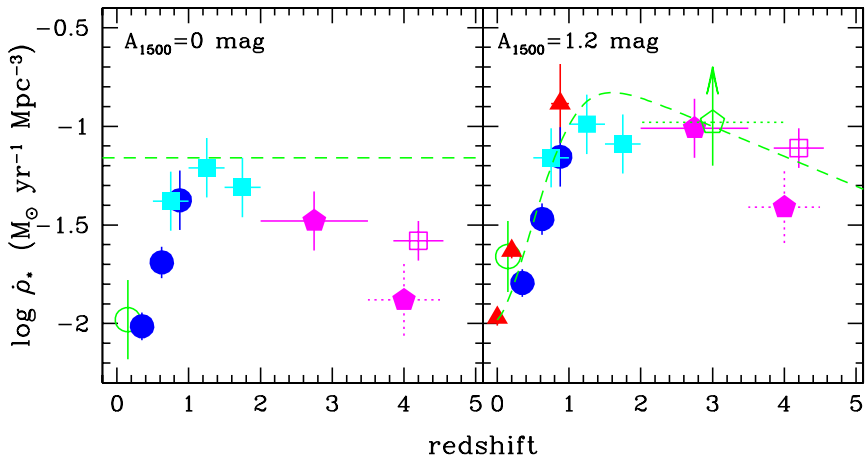

Fig. 6.— Comoving density of star formation versus redshift (Madau 1999). *Left:* Unreddened values, inferred from UV continuum luminosity densities. Dotted line shows the fiducial rate needed to generate the extragalactic background light. *Right:* Dust-corrected values, including measurements from the Hubble Deep Field (filled pentagons) and from the $z = 4$ survey (open squares). The Hα determinations (filled triangles) and *SCUBA* sub-mm lower limit (empty pentagon) are added for comparison.

Milky Way and Local Group.

Chemical Evolution and Metal Production in the Universe

QSO absorption-line surveys have shown that the Lyα systems seen at high redshifts contain the bulk of the gas mass in the universe (Madau & Shull 1996; Weinberg et al. 1997). Moreover, this mass is comparable to the luminous (stellar) mass in the universe at the present epoch. In the earliest interpretation of the damped systems, it was suggested that they represent the progenitors of present-day galaxy disks (Wolfe et al. 1986). While this interpretation might still be approximately (but not universally) true, recent studies of low-redshift examples (Rao & Turnshek 1998) show that the galaxies responsible for the damped systems also include dwarf or low surface brightness galaxies. Spectroscopic studies of the damped Lyα systems should allow astronomers to measure directly element abundances and kinematics in gaseous systems that eventually evolve into galaxies. The combined method of QSO absorption-line studies with follow-up imaging and galaxy identification offers a unique opportunity to study the extended gaseous and stellar components of non-local galaxies at the same time. In principle, studies of a significant number of damped systems could be used to measure accurately the build up of the elements and trace the changing physical and kinematical properties of galaxies or their progenitors over the redshift interval $0 < z < 4.5$.

At present, important abundance studies are being pursued with major time allotments on large ground-based telescopes for a wide range of elements including: O, N, Mg, Al, Si, S, Cr, Mn, Fe, Ni, and Zn. These studies have been undertaken for damped Lyα systems with redshifts $1.65 < z < 4.5$ (Pettini et al. 1994, 1997; Lu et al. 1996; Prochaska & Wolfe 1999). The redshift range $1.65 < z < 4.5$ corresponds to cosmic lookback times from approximately 77% to 90% of the age of the universe (assuming $q_0 = 0.5$). This high-z epoch is certainly an important time period in the history of the universe. However, to truly understand the implications of the ground-based measurements of the higher-redshift systems, it will be necessary to combine them with analogous UV measurements over the redshift interval $0 < z < 1.65$, to follow the Lyα systems over the last 77% of lookback time.

Unfortunately, damped Lyα systems at low redshift are rare, and the background quasars are often faint. For example, the HST QSO Absorption Line Key Project discovered only one damped Lyα system in 83 sightlines (Jannuzi et al. 1998). However, a special search technique employed by Rao & Turnshek (1998, 1999) has substantially expanded the sample of low-redshift damped systems. There are approximately 20 known low-redshift classical damped Lyα systems (with neutral hydrogen column densities of 2×10^{20} cm^{-2} or larger), including the systems found by Rao & Turnshek (1999). For all these systems, the background QSOs have relatively low-to-moderate far-UV fluxes and represent extremely difficult targets for high-resolution studies with either HST/STIS or COS.

A first major survey of element abundances and kinematics in low-redshift damped Lyα systems would realistically require a spectroscopic resolution of $R = 30,000$ at $S/N > 30$ for approximately 100 such systems, uniformly covering the redshift interval $0 < z < 1.65$. By the time such a program could be undertaken, the amount of ground-based information on higher redshift damped systems will be enormous. Therefore, the data obtained on the lower redshift systems will be even more crucial to developing a self-consistent interpretation of the chemical and kinematic evolution of the bulk of the neutral gas in the universe. To understand fully the implications of the measured abundances and kinematics of the damped systems, it will be necessary to obtain information on the corresponding absorbing galaxies through their luminous emissions. Therefore, high angular resolution UV, optical, and IR imaging studies of the fields of each QSO will be an important element in any such program.

A significant complication in previous studies of element abundances in QSO absorption-line systems is introduced by the possible incorporation of various heavy elements into dust. The most important elements for future studies by SUVO are those elements not usually found in dust, but which have different nucleosynthetic origins. Particularly important undepleted elements include Zn, S, P, N, and Ar. Of these, S, P, N, and Ar have rarely been studied from the ground since their resonance lines usually lie in the Lyα forest and are often confused by intervening absorption due to hydrogen Lyα absorption at other redshifts. However, this spectroscopic confusion is greatly reduced at lower redshifts, because of the rapid decrease in the number of Lyα forest lines.

Nucleosynthesis in Supernovae and Young SNRs

We have discussed the need to invest significant observing time over the next decade in UV studies of QSO absorption-line systems, probing the physical conditions and chemical evolution of the IGM and the halos of galaxies over a large redshift range. This database of absorption-line systems will be used 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 thus measure the production rates and dissemination of heavy elements from massive stars in the early universe via statistical studies of the integrated light from gas and stars in galaxies and the IGM. A complementary, though crucial tactic is to study the nucleosynthesis yields directly in nearby supernovae and young supernova remnants (SNRs). Elemental abundance determinations in supernova ejecta are essential for testing theories of nucleosynthesis occurring in massive stars, and, ultimately for models for the chemical enrichment of the ISM in galaxies. Likewise, Wolf-Rayet stars and asymptotic giant branch stars are important contributors to this enrichment, and their mass-loss rates and wind abundances need to be understood much better.

By studying supernova remnants throughout the Galaxy and the Local Group, we can investigate the role that supernovae play in the structural and chemical evolution of galaxies. Galaxies become chemically enriched when supernovae inject the by-products of nucleosynthesis occuring in the cores of massive stars into the interstellar medium. In addition, shock waves produced by supernovae heat the ISM, determine the velocity dispersion of interstellar clouds, and govern the scale height of the ISM in galaxies (McKee 1990). Core-collapse supernovae play a major role in enriching the ISM in young galaxies and the surrounding IGM with heavy elements. Thus, understanding nearby core-collapse supernovae, their abundance yields, and energy output, leads to a better understanding of these important processes in the early universe. Of particular interest to the issue of chemical enrichment of young galaxies are the young, ejecta-dominated SNRs in the LMC and SMC (see Fig. 7), which reflect nucleosynthesis in a low-metallicity regime of initial abundances, applicable to high-redshift galaxies.

The fundamental processes of nucleosynthesis that take place deep inside the cores of massive stars are hidden from view until the stars explode as supernovae. Young SNRs therefore allow us to investigate material from the cores of massive stars directly, leading to observational tests of theories for stellar evolution and nucleosynthesis. Our glimpse of the uncontaminated supernova debris lasts for at most a few thousand years before this material mixes into the ISM. There are only eight young SNRs known which contain fast-moving (> 1000 km s^{-1}) optical filaments of uncontaminated debris. Cas A in our Galaxy is the prototype of this oxygen-rich class, and is joined by two additional Galactic remnants, two SNRs in the LMC, one in the SMC, and two unresolved objects in the more distant galaxies M83 and NGC 4449. The highly elevated abundances of oxygen, neon, sulfur, and other heavy elements suggest these debris originated within the helium-burnt layers of massive (> 10 $M_\odot$) progenitor stars.

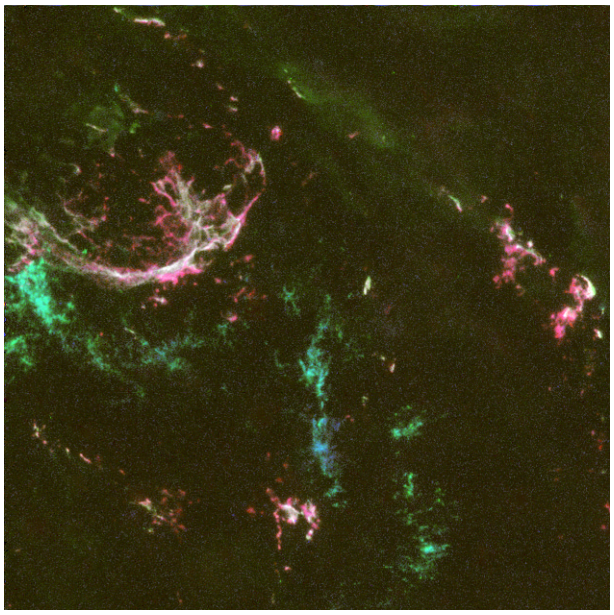

Fig. 7.— Central regions of the oxygen-rich supernova remnant N132D in the LMC. Narrow-band image ($\sim 1'$ FOV) with HST/WFPC2 ([O II] $\lambda\lambda 3727$ in blue, [O III] $\lambda 5007$ in green, and [S II] $\lambda\lambda 6716, 6732$ in red) reveals intricate interactions between supernova ejecta (nearly pure oxygen filaments in blue-green) and circumstellar environment (shocked clouds are pinkish-white strands). Wide-field imaging in diagnostic emission lines combined with UV/O spectroscopy allow us to track the evolution of young SNRs and measure the elemental abundances in core-collapse supernova ejecta.

It is important that the O-rich SNRs be studied as a class. An interesting and important as an object like Cas A is, it needs to be viewed in the context of similar objects. Each object contains distinctive features that allow us to investigate different aspects of SNR dynamics and evolution to attack fundamental questions concerning the origin of the elements: (1) Are these objects the result of Type II, Ib, or Ic supernova explosions? (2) Do the observational data from the various wavelengths lead to a consistent picture of SNR evolution? (3) Do current emission and hydrodynamic models successfully account for the luminosities, morphologies, and kinematics of these objects? (4) Can theories of nucleosynthesis in massive stars and mixing in SN explosions explain the distribution of elemental abundances in the metal-rich ejecta? (5) What are the probable progenitor stars of these SNRs, and are Wolf-Rayet stars viable candidates? (6) Do the O-rich SNRs foreshadow the evolution of SN1987A? (7) What will be the long-term evolution of these objects, and how do they affect the chemical evolution of galaxies?

Important capabilities needed to make major progress in our understanding of young SNRs in the Galaxy and Local Group and the process of chemical enrichment of the ISM are wide-field UV-optical imaging in diagnostic emission lines and spatially resolved UV-optical spectroscopy. Such data can be combined with data obtained at other wavelengths, such as X-ray and IR observations, to characterize the physical state and abundances of the emitting gas. Studies of SNRs and other

nebular objects require a selection of narrow-band filters that cover a variety of ionization stages of several key elemental species. Ideally, we would like to have filters in lines of H, He, C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni. Such a large selection argues for the use of tunable filters that would enable narrow-band imaging in any important emission line over wide fields at arbitrary radial velocity/redshift — an important technology development issue.

We must also study the dynamics and elemental abundance variations within filaments, and from filament to filament, to test models of mixing. Spatial resolutions < 50 mas are needed to isolate specific filaments in Local Group SNRs and to resolve ionization scale lengths in shocks. Fields of view $> 10'$ are desirable to map the Galactic objects, including interesting jet-like protrusions that suggest aymmetrical explosion geometries. It is currently impossible with HST/STIS to obtain spatially resolved UV spectra in the most important UV diagnostic lines (e.g., N V, O IV], C IV, Ne IV], Mg II) with spectral resolution high enough to compare the UV kinematics directly to the motions deduced from optical emission-line profiles. Emission-line fluxes in the ejecta filaments are typically $F \approx 10^{-15} - 10^{-17}$ ergs cm^{-2} s^{-1} and require the next generation large-aperture UV-optical space telescope for further study.

2.3. The Major Construction Phase of Galaxies

How and When were Galaxies Assembled?

In the hierarchical clustering model of cosmological structure formation, the rate of mass consumption from the IGM is tied directly to the history of galaxy assembly and star formation. Both the merging of dark matter halos and the accretion of small satellites determine the triggers to these phenomena. Feedback from massive star formation can also complicate the astrophysical processes that govern radiative cooling and compression of the baryon component within the dark-matter potentials. These micro-physical processes depend sensitively on the type of stars formed and on the initial mass function (IMF).

Over the history of the universe, massive stars dominated the production of radiant energy and heavy elements, and the mechanical heating of the interstellar medium. These O- and B-type stars radiate the bulk of their luminosity in the rest-frame ultraviolet. The Galaxy Evolution Explorer (GALEX) will provide broad-band spectral energy distributions of star-forming galaxies over the range $0 < z < 2$, but will not obtain high-resolution spectra. The GALEX ultraviolet survey will provide the raw material for documenting the history of star formation and metal production during the crucial epoch from $z = 2 \rightarrow 0$, during which time the cosmic star-formation rate declined by more than an order of magnitude. To understand the physical processes that drove the strong evolution during this era requires capabilities for ultraviolet spectroscopy and high-resolution, wide-field optical imaging that greatly exceed those of HST.

First, UV spectroscopy with SUVO of galaxies in this redshift range will measure both the IMF

and the evolution in the chemical composition of the massive stars. The same data will also probe the gas-dynamical and chemical effects of the feedback provided by the massive stars. These data will measure the rate at which star-forming galaxies injected metals and kinetic energy into the ISM and galactic halos in the form of galactic winds and fountains. An order-of-magnitude increase in UV throughput compared to HST/COS is required to reach the flux levels ($F_\lambda = 10^{-17}$ ergs cm^{-2} s^{-1} Å^{-1}) and dispersions ($R = \lambda/\Delta\lambda \approx 10^4$) needed to measure the stellar composition. In a 1 hr exposure of galaxies at $z = 1.7$, a 4m SUVO would be able to obtain a spectrum with S/N = 10 and resolution $R = 3000$ at the knee in the rest-frame, near-UV luminosity function (approximately 2.6 microjansky at 2900 Å). SUVO could also perform spatially-resolved spectroscopy at 0.1 arcsec and beat out ground-based telescopes in the visible. The typical half-light radius of the "Lyman-dropout" galaxies is about 0.2 arcsec, so SUVO spectra of a few hours duration could measure rotation curves, map regions of galactic outflows, and measure spatial gradients of metallicity and age.

Second, high-resolution, wide-field imaging in the 2000 – 6000 Å range will document the cosmic evolution in the structure and morphology of the young and intermediate stellar population in galaxies during this epoch. With V-band imaging at high spatial resolution, it will be possible to use population studies of nearby galaxies to constrain the age of the populations, the timescales for assembly, and the fraction of accreted material. Among the specific topics to be addressed are: the separate histories of bulge and disk formation; the roles of bars and galaxy interactions/mergers in driving the star-formation rate and in establishing the origins of the Hubble sequence and the density-morphology relationship for galaxies. Detailed observations of the stellar content and dynamics of local galaxies are just as crucial to understanding galaxy evolution. Constructing color-magnitude diagrams that reach the main-sequence turn-off in the nearest Local Group galaxies requires observations down to $m_B \approx 23 - 24$ (see Fig. 8). Making such measurements of galaxies out to 3 Mpc is a major task, which is currently impossible for HST, even with ACS and WFC-3. The SUVO imagers would provide the best way of solving this problem.

While the HST has made fundamental contributions in these areas, a complete understanding of how the modern universe of galaxies has emerged will require an increase of at least an order of magnitude in the field of view and a factor of three in imaging sensitivity, compared to HST. A large-aperture telescope with imaging and spectroscopy is required to perform the stellar population synthesis and spectral-line imaging to study the stars and gas at moderate redshifts.

Wide-Field Imaging of Clusters and Superclusters

The advantages of wide-field, optical imaging capability from a space-based platform are substantial. While extensive studies of large-scale structure at $z > 0.5$ will be common by 2010, the ability to combine ground-based spectroscopic data with precision space-based photometric and morphological information on galaxies within clusters, filaments, and superclusters will still be limited by the relatively small fields of view ($< 5'$) available in future HST and NGST instruments. The existence of superclusters at $z = 1$ is now confirmed. These systems span scales of $5 - 20h^{-1}$

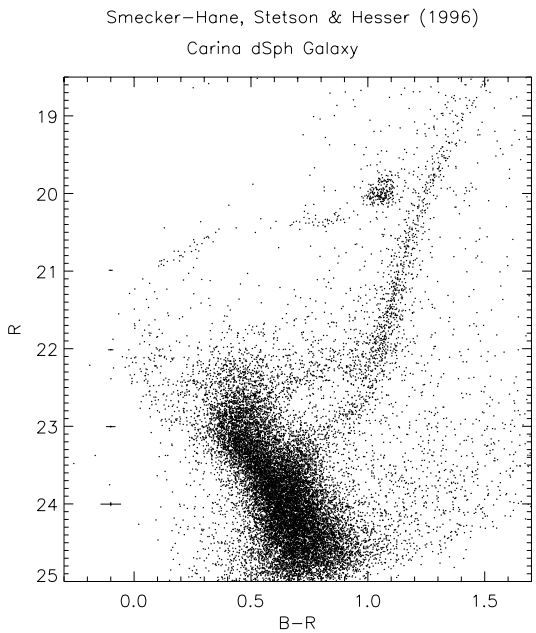

Fig. 8.— The color-magnitude diagram for the Local Group dwarf Carina at $D = 91$ kpc (Smecker-Hane et al. 1999). The main sequence turnoff of one population occurs at $m_V \approx 23$, but evidence for an older population occurs at $m_V \approx 24$. Similar studies of more distant Local Group galaxies will require imagers with wide field of view (FOV) and ten times more sensitivity than HST/ACS.

Mpc. Here, h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1} (current estimates suggest that $0.6 < h < 0.8$). A $10 - 15'$ field of view (FOV) also provides a good match to the the correlation lengths of cosmological structures in galaxies and the IGM, to sizes of low-z galaxy halos, and to quasar spacing on the sky at magnitudes $m_B = 19 - 20$.

A thorough and efficient study of photometric redshifts in QSO fields, as well of gradients in galaxy properties across clusters and superclusters, could be done with an imager that provides a $10' - 15'$ field of view. At $z = 1$, a $10'$ FOV subtends $3h^{-1}$ Mpc, an order-of-magnitude gain over the discovery capability of ACS. Even clusters of galaxies, with sizes typically $1 - 3h^{-1}$ Mpc require at least 4 ACS fields for proper study of the full dynamic range of the intracluster environment. A $10'$ camera would allow such studies to be done in a single pointing.

Multi-channel, multi-object spectrographs (MC/MOS), soon to be commissioned on 10m class ground-based telescopes, will have FOV that extend to $15'$ (e.g., the UCSC DEIMOS system for Keck). As noted above, this is a good match to the QSO spacing at $m_V = 20$, allowing a photometric survey of galaxies in nearly every QSO field. Consequently, it is likely that many deep survey fields will be studied spectroscopically by 2010. Ground-based photometry cannot provide accurate color measurements or precise morphological parameters of galaxies lying much beyond $z = 0.2$, because of atmospheric seeing. The ability to obtain efficient internal broad-band color and morphological data for an entire MC/MOS field in a single spacecraft pointing enables studies that would be

extremely time-consuming with HST or NGST. One can use large-scale weak gravitational lensing (see Fig. 9) to probe the underlying matter in galaxy clusters or galactic sheets. The search for very rare objects, like supernovae at $z > 1$, also requires wide-field, high resolution imaging.

By 2010, large, ground-based CCD mosaic imagers will be mapping out several thousand square degrees of sky to faint limiting magnitudes ($I > 23$). Large-scale weak-lensing surveys based on such data will always be inherently limited by seeing effects; one needs to measure ellipticities of faint ($I > 24$) galaxies with high ($< 10\%$) precision. In general, the detection of very faint sources is much easier from space, where one avoids complexities of sky brightness and time-dependent point-spread function gradients due to telescope flexure and atmospheric variations. Given the present rate at which the area of CCD mosaic imagers have been increasing in size (a factor of 25 over the past decade), it is reasonable to expect that by 2010 a 16k $\times$ 16k system could be flown with few technological challenges Even a 24k $\times$ 24k system might be possible. Such CCD mosaics would provide angular resolutions of 25 to 40 mas, if a $10'$ field of view were achieved. This would enable diffraction-limited imaging at 4000 and 8000 Å, respectively, for a space-based 4m and 8m telescope. SUVO will probably out-perform NGST at blue wavelengths, which provides the best match to the lensed galaxies.

If a slitless spectroscopic mode is available with this imager (e.g., grism or prism), it might be possible to obtain redshifts for a large number of distant galaxies in a single pointing. Photometric redshifts should be possible to $\Delta z \approx 0.02$ precision. The Lyman break, which lies in the UV for $z < 2.6$, provides a robust feature for estimating photometric redshifts, but it is currently limited by the FOV and sensititivies on HST. With medium-band filters and a large-field near-UV imager, one could obtain photometric redshifts for galaxies at $1 < z < 3$. A 4m class SUVO will enable more precise quantification of the intrinsic properties of $z < 1.5$ galaxies than HST and will complement the work presumably to be done with NGST on $z > 3$ galaxies. The advantages of an 8m class facility are that slitless spectroscopy at low-z will rival and possibly exceed what can ever be achieved from ground-based high-redshift surveys, even from 10m class telescopes. One would focus the slitless spectroscopy on the range 2000 – 4000 Å, to study Lyα emitters in the range $0.6 < z < 2.3$. At $z = 1$, when the observed wavelength is 2432 Å, the sky background is so low that detection is extremely easy. With a $12'$ FOV, one can cover $3.6h^{-1}$ Mpc in a single exposure, sufficient to map an entire cluster in a single exposure or reach $20h^{-1}$ Mpc scales with a handful of adjacent exposures. The flux of the Lyα line recently detected in the $z = 5.6$ galaxy was $F \approx 10^{-17}$ ergs cm^{-2} s^{-1}. Whereas it took 14,000 s on Keck/LRIS to obtain S/N = 10, SUVO could obtain S/N = 10 (4m aperture) or S/N = 20 (8m aperture) in only 2000 s. Surveys at $z < 2$ would nicely complement the work of NGST, which will focus on much higher redshift.

Stellar Populations in Nearby Galaxies

The stellar populations of nearby galaxies carry the fossil record of galaxy formation. The ages and abundances of the stars in these galaxies constrain the timescales of their formation and

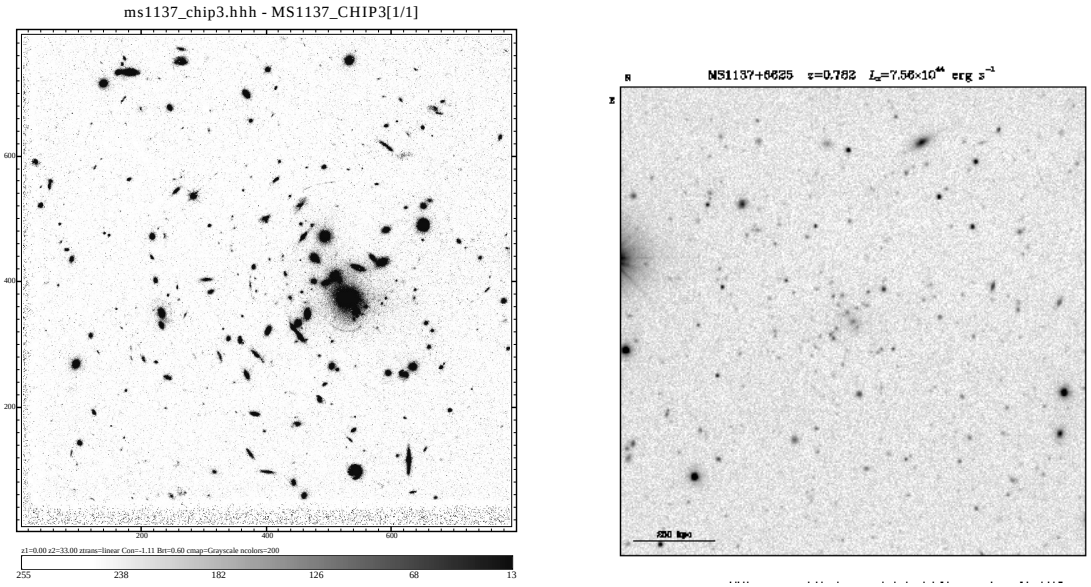

Fig. 9.— The distribution of dark matter in a galaxy cluster such as MS1137+6625 can be mapped using wide-field images of weak gravitational lensing. The dark matter distribution can be derived from strong lensing in the cluster core evident in the HST/WFPC2 image. But to map the dark matter over much larger scales via weak lensing requires a larger field of view, like that obtained from ground-based telescopes, and very high spatial resolution. HST/WFPC2 image [left] courtesy of M. Donahue; R-band ground-based image [right] from Luppino & Gioia (1995).

assembly. The rate of material accreted by these galaxies, as evidenced from the distribution of stellar ages, also constrains cosmological models, which predict definite and different accretion rates. This fossil record is difficult to decode from the integrated spectra and colors of galaxies, particularly if NGST lacks the important V-band to probe the flux peak of stars with the highest age sensitivity. The decoding becomes progressively more accurate as individual stars are resolved. Historically, color-luminosity relations of resolved stellar populations have been central to the development of our astrophysical understanding of stellar and Galactic evolution. This can be expected to remain true even in the era of NGST and SUVO.

Important features in the HR-diagram of old stellar populations include the Main Sequence Turnoff (MSTO), the Horizontal Branch (HB), and the Tip of the Red Giant Branch (TRGB). The key to determining the age of a stellar population is to measure the effective temperature of the MSTO. That requires photometry accurate to $\pm 10\%$ about 1 magnitude below the turnoff. Indirect constraints are possible via surface brightness fluctuations in the near-UV (Worthey 1993). At higher luminosities, the distribution of core-helium burning stars on the HB and in the "red clump," and the identification of RR-Lyrae variables in particular, provides an indication of the existence of an old population as well as an estimate of the chemical composition. The ratio of the number of HB stars to the number of RGB stars provides a measure of the helium abundance (Iben 1968).

At still higher luminosities, the colors and luminosities of stars at the tip of the RGB constrain the possibilities for the age and metallicity distribution of the underlying stellar population.

Information about the MSTO for Local Group galaxies is exceedingly difficult to obtain (see Fig. 8). HST studies of the MSTO are now possible only for the Milky Way and its immediate companions. After the installation of ACS it will be possible with great effort to measure the MSTO in the halo of M31 and M32. The Horizontal Branch is accessible now with HST out to the distance of M31. The RGB tip is accessible with HST now out to the distance of the Virgo Cluster. A 4m class UV-optical telescope with better detectors would make it possible to study the MSTO out to distances of 3 Mpc, bringing into view galaxies such as Centaurus A, M81, M101, and their complement of dwarf companions. The HB could be characterized out to the distance of the Virgo Cluster, and the TRGB could be detected at the distance of the Coma Cluster. With an 8-m class telescope the MSTO of some of the nearest normal giant elliptical galaxies (NGC 3379 for example) becomes accessible with great effort. SB fluctuation studies in the NUV at the distance of Virgo would be possible and would provide an estimate of the MSTO luminosity.

The temperature of the MSTO in even the oldest galaxies is $\sim$ 5500 K. In the absence of contamination from other types of stars, the V band is the most efficient place to study the MSTO. In the inner regions of galaxies, the light from the individual MSTO stars is overwhelmed by that of neighboring RGB stars. Observations shortward of 3000 Å with strong red-leak suppression offer the only prospect for isolating the MSTO near the centers of nearby galaxies such as M31. A valuable output of the SUVO imagers would be a UV Spectral atlas of hot massive stars, a crucial ingredient in the templates used to interpret the UV spectra of distant star-forming galaxies.

Cepheid Variables in the Coma Cluster

Cepheid variable stars provide one of the primary distance indicators used to establish the cosmic distance scale and Hubble expansion rate (H_0) of the universe. Although the MAP explorer hopes to determine H_0 to 10% accuracy, this is comparable to the goals of the HST Cepheid Key Project. Even though some cosmologists believe that H_0 and Ω_0 will be measured conclusively during the next decade, past history cautions us to be prudent and seek confirmation of these critical cosmological parameters. Both Cepheids and Type Ia supernovae distance scales need to be reconciled with values of H_0 determined from the microwave background fluctuations and water-maser disk kinematics.

Despite heroic efforts to reach the Centaurus Cluster, at distance modulus $\mu_0 = (m - M) = 33.0$, corresponding to distance $D = 40$ Mpc, by Zepf et al. (HST Program IDs #6439 and #7507), the practical limitation encountered by both the HST Key Project (Gibson et al. 1999) and the Type Ia SNe Calibration Project (Saha et al. 1997) has been $\mu_0 < 32.0$ (or $D < 25$ Mpc). For the WFC, photon-starvation and crowding set a limit of $\sim$ 12 pc pixel^{-1}. With SUVO, one could uncover Cepheid variables directly at the distance of the Coma Cluster ($D = 85 \pm 10$ Mpc or $\mu_0 = 34.65$).

Cepheids at Virgo have been discovered and monitored by HST/WFPC at phase-weighted mean magnitudes $\langle m_V \rangle$ ranging from 24.5 to 26.5. At Coma, which is 5 times more distant than Virgo, Cepheids would range from $\langle m_V \rangle = 28 - 30$. A high-resolution imager on a 4m SUVO would have three times the field of view of WFPC2, and would draw upon the 3-fold increase in collecting area over HST. It would also possess a resolution at Coma of 6 pc pixel^{-1}.

The discovery of Cepheids in the Coma Cluster would allow a direct determination of the Hubble Constant, via Cepheids, well out in the Hubble Flow where peculiar velocities are <5% of the recessional velocity. Other H_0 determinations, to date, generally require calibrating other secondary indicators locally (out to Fornax) before pushing out into the Hubble Flow. SUVO will provide a unique opportunity to bypass this intermediate step, yielding H_0 directly. NGST will be non-optimal for discovering Cepheids, because the light-curve amplitude is a factor of two greater at V than it is at I. Thus, Cepheid searches are almost exclusively attempted shortward of R. Therefore, SUVO is the only facility on the horizon that will allow this direct probe of the cosmological scale size, free from the effects of peculiar velocities that are important for nearby galaxies.

Interactions of Galaxies with their Environment

Perhaps the most important missing ingredient in our current understanding of the formation and evolution of galaxies is the role played by the back reaction of the energy produced by young stars on the interstellar gas out of which the stars form and from which the galaxy is built. This "feedback" takes the form of radiation and mechanical energy from massive stars and their evolutionary by-products. The tight correlations between such disparate galaxy properties as mass, size, surface brightness, velocity dispersion, and metallicity strongly suggest that galaxy-building is determined or regulated in some way by this feedback. The simple cooling and dissipation of baryons in dark matter potential wells does not by itself explain the properties of present-day galaxies. In an even broader sense, the role played by the radiation and kinetic/thermal energy supplied by massive stars may have been central to determining the location, physical state, and chemical composition of the baryons not presently incorporated into stars (which probably comprise the majority of baryons in the universe today).

Spectroscopy in the ultraviolet provides a unique suite of diagnostic tools for investigating the physics of feedback and its astrophysical consequences. The rich array of resonance absorption lines lying in the rest-frame spectral region between the Lyman edge and roughly 2000 Å makes it possible to study the dynamics, chemical abundances, and physical state of gas ranging from cold molecular hydrogen to coronal-phase gas at $T > 10^5$ K. By studying the gas seen in absorption against the UV continuum in the star-forming regions themselves, we can directly study the process of the feedback in action at its point of origin. These regions have typical flux densities at 1400 Å of 10^{-16} ergs cm^{-2} s^{-1} Å^{-1} and need to be studied at resolution $R \approx 30,000$. Whereas HST/COS will only study typical starbursts at low resolution, $R \approx 3000$, a 4m SUVO mission could obtain S/N = 10 spectra in several hours.

Existing HST spectra show that under the most extreme conditions (strong starburst nuclei), cool and warm gas is being expelled at velocities of 10^2 to 10^3 km s^{-1}, close to galaxy escape velocities, and at a rate comparable to the star-formation rate. These data do not have high enough spectral resolution or signal-to-noise to make more than a qualitative characterization of the outflow, and then only for a handful of the brightest starbursts. An increase in spectral sensitivity by a factor of 10 would allow us to undertake the necessarily detailed investigations of selected starburst regions. Just as importantly, we could expand such investigations beyond the extreme conditions in starbursts to more normal star-forming regions in the disks of normal late-type galaxies. It would finally be possible to investigate whether there is a threshold in the rate of star-formation per unit area or volume above which a galactic fountain or wind is established.

The cumulative effect of feedback and outflows can be traced by using background quasars to probe the gas in galactic halos. Ironically, this technique has taught us a lot about the properties of the gaseous halos of galaxies at high redshift, while we are quite ignorant about their counterparts in the local universe. This could change dramatically in the next decade, if SUVO were available.

Intervening Galaxy Halos

As just noted, galaxy halos provide a transition or interface between the high-density, star-forming environment in galactic disks and the IGM. For galaxies at moderate redshift, their halos often extend beyond 100 kpc, and can be studied in absorption against background QSOs. Ultraviolet spectra are important in detecting and measuring physical parameters of these halos, through resonance lines of ions such as C IV, N V, O VI, Si III, Si IV, and Mg II. As was done for the stellar winds of hot, massive stars, UV spectra of galactic halos could detect galactic winds and outflows and quantify the chemical composition of the flows injected into the IGM. A spectral resolution $R \approx 10^4$ (30 km s^{-1}) is needed to perform these abundance studies.

Table 2.1 showed the anticipated gain in the number of quasars and AGN if SUVO can reach at least $m_B = 19 - 20$. These counts translate into an effective average separation between objects, which will allow SUVO to study sightlines toward various types of intervening galaxy halos from a "structure of the universe" vantage point. At present, astronomers can only make spectroscopic observations of a few halos. At $m_V = 19$, SUVO will probably find one UV-bright QSO every $20' - 30'$, which can be used for absorption studies of many intervening galaxy disks and halos of different morphological types.

The Sloan Digital Sky Survey (SDSS) and the GALEX UV survey together will measure redshifts, colors, and star-formation rates for $\sim 10^6$ galaxies in the "local" universe ($z < 0.2$) by 2005. These surveys will also find several $\times 10^4$ UV-selected quasars brighter than $m_B = 18$. This implies that there will be roughly 500 quasar-galaxy pairs with impact parameters (at the galaxy) less than about 100 kpc. With a high-efficiency UV spectrograph, it will be possible to survey this sample and determine the baryonic content, chemical abundances, dynamics, and physical conditions

in the halos of a sample of galaxies spanning the complete manifold of galactic properties (mass, metallicity, Hubble type, star-formation rate, starburst vs. normal galaxy, AGN host galaxy vs. normal galaxy, cluster vs. group vs. field).

In addition, UV absorption lines seen in the lines of sight to luminous sources in nearby or distant galaxies permit the study of gas in a number of important environments including the Milky Way halo and its system of high velocity clouds (HVCs), the halo gas and HVCs of the target galaxy, and the environment associated with the luminous source in the target galaxy. The Milky Way is surrounded by a system of HVCs that likely have a number of origins. Some of the possibilities include gas pulled out of the Magellanic Clouds by tidal stripping, gas ejected into the halo by vigorous galactic fountain activity in the disk, remnant gas from the formation of the Milky Way, and Local Group intergalactic gas. Recent UV spectroscopic observations with the HST are now beginning to provide important insights about the nature of the HVCs. Lu et al. (1998) have shown that the HVC in the direction of the AGN NGC 3783 has a metallicity that is most consistent with the HVC being tidally stripped gas in the leading arm of the Magellanic stream. Wakker et al. (1999) have studied UV and optical absorption toward Markarian 290, which lies in the direction of Cloud Complex C, and find that this huge gas complex has a metallicity of approximately 0.09 times solar and is situated more than 3.5 kpc from the Galactic plane. They conclude that Complex C provides the first observational evidence for the accretion of low metallicity gas onto the Milky Way as required in current models of Galactic chemical evolution. Sembach et al. (1999) have identified a new type of high velocity cloud (the highly ionized HVCs) which they believe may be associated with very low density and low pressure Local Group intergalactic gas.

These interesting new results suggest that a full attack on the Milky Way HVC phenomena will provide a wealth of information about gas left over from the galaxy formation process, gas ejected into the halo by energetic phenomena occurring in the disk, and gas circulating around galaxies because of tidal interactions. To pursue a comprehensive study of the elemental abundances and physical conditions in the HVCs, it will be necessary to obtain high-resolution UV spectra of faint Galactic and extragalactic sources situated beyond the HVCs. While a few of the brighter suitably positioned extragalactic sources will be observed with STIS and COS on HST, a vigorous study of the HVC phenomena will require a spectroscopic facility more capable by at least a factor of ten. Spectral resolution of at least $R = 20,000$ is required to obtain accurate abundances.

The observations required to study the HVC system of the Milky Way could also be used to study the analogous phenomena associated with the target galaxies. The absorption at extragalactic velocities could be used to answer such questions as: How common are systems of HVCs in other galaxies? Is there evidence for gas left over from the era of Galaxy formation in other systems of galaxies? Do groups of galaxies have associated clouds of intergalactic gas similar to the highly ionized HVCs seen in the local group? How do the abundances and physical conditions in gas clouds observed at relatively low redshift, which are associated with current epoch galaxies, compare to those in clouds found in the high redshift universe observed through QSO absorption-line measurements?

The strongest UV emitting regions in external galaxies that could be used as sources of continuua for the absorption line studies discussed above are either associated with the luminous nuclear regions of the galaxies or with regions of enhanced star formation activity situated elsewhere in the disk of the external galaxy. In such cases, the UV spectra will also yield direct information about the processes whereby the starburst phenomena releases vast amounts of mass, energy, momentum, and chemically-enriched gas into the surrounding halos or intergalactic medium through supernova-driven galactic fountains or, in the extreme cases, galactic winds. Measures of the physical conditions and metal enrichment of this gas would provide information about the chemical enrichment and star-formation history of the galaxy and the extent to which starburst galaxies modify the chemical and physical environment of the surrounding halo gas or the surrounding IGM.

The Demographics of Massive Black Holes

Massive black holes have long been suspected to be the central engines of active galactic nuclei. During the 1980s, this hypothesis moved closer to proof with the finding that the central dynamics of a handful of nearby galaxies could be explained by invoking a massive compact object at their center. Given the exotic nature of black holes, however, most of the initial work was heavily slanted towards finding more mundane explanations for unusual central stellar dynamics. The general acceptance of massive black holes in galaxies was thus hard fought, and really only fully conceded for one or two systems. Moving into the 1990s, however, work with high-resolution spectrographs both on the ground and on HST, slowly fleshed out the picture that black holes indeed might be common to galaxy centers.

At the close of the century, the question has thus moved from the simple question, "Do black holes exist in galaxies?" to richer issues of "Are they a natural part of galaxies, and if so what role do they play in their formation and evolution?" Simple arguments imply that black holes are ubiquitous. The integrated energy flux of QSOs over the age of the universe, for example, suggests that fully 0.2% of the mass of galaxy spheroids may be in the form of black holes; today most of this mass would be in the form of quiescent "extinct," or more accurately, "dormant" black holes at the centers of garden-variety normal galaxies. Further, because most galaxies observed with sufficient central resolution do indeed appear to harbor central black holes, the best hypothesis is that nearly all galaxies have a central black hole. In other words, the collection of fossil black holes was not parceled out to just a few rare systems. Indeed, the work to date suggests that central black mass correlates with spheroid mass with a coefficient very close to that suggested by QSO energetics.

Massive black holes thus may be the anchors around which galaxies form. They may exert profound effects on the forms of central structure that we see today, and their historical activity has perhaps moderated even the global properties of forming galaxies. Imaging work with HST, for example, suggests that the central structure of the most massive galaxies (characterized by low-density cores with shallow cusps) can only be understood in terms of being built from the mergers of less luminous galaxies (which have high-density steep central cusps) with already extant

black holes. The latter systems themselves would have been assembled around seed black holes formed in the early universe.

The critical path to understanding the role of central black holes in galaxies has thus evolved into an investigation of black hole "demographics." At what stage in galaxy formation did a central black hole form? Do most galaxies indeed harbor central black holes? Are they a critical part of all normal systems? How are they parceled out? Is there a simple linear relationship between galaxy mass and central black holes mass? Is the functional relationship more complex? Are other parameters involved in the relationship such as galaxy type or environment? Given the answers to these questions, what has been the back-effect of the central black hole on the structure and dynamics of the rest of the galaxy? In the end, the goal is to unify the history of energetic activity in the universe to formation of galaxies, with the link between them being the massive black holes at the hearts of galaxies.

Work on black hole demographics has been started with HST, but progress has been slow. By increasing the telescope aperture and detector sensitivity above that of HST, one expects to find many more black holess in more distant galaxies. Fixing the band luminosity, νL_ν, for both quasar and host, the maximum redshift that can be studied increases as aperture to the 3/4 power. Thus, doubling the mirror size allows one to move from the HST limit of $z \approx 0.3$ out to $z \approx 1.3$. If the greater redshift increases the luminosity in the observed band (likely to occur for both quasar and host), one does even better. Therefore, a 4m mirror will take us from marginal studies of only the remnants of the quasar phenomenon, near the present epoch, to decent signal/noise at times close to the peak epoch of quasar activity.

The classic approach to studying central black holes requires obtaining high spatial resolution spectra at multiple points within a galaxy at sufficient signal level to measure accurate line-of-sight velocity distributions. Unfortunately, slicing the central light into small pixels, all fed with a small mirror, biases the observations to galaxies with the highest central surface brightnesses, which leads in turn to strong biases in the global properties of the systems. Imaging the centers of high-luminosity elliptical galaxies with low central surface brightness currently requires prohibitively long exposures. Observations of gas dynamics in galaxies helps reduce exposure time, when bright emission lines are found. This introduces other biases in system selection. With the coming decade of HST observations, it may be possible to obtain a rough sketch of the relationship between galaxy luminosity and black hole mass over a significant luminosity range. However, it probably beyond the capability of HST to perform an analysis of the width of the relationship and its general variability, much less an investigation of additional parameters. With SUVO, it is critical to invest sufficient time to probe systems in which the black hole may be non-existent or weak. Basing a relationship on the galaxies that may be observed versus a systematic sample risks introducing profound biases in any picture of black hole demographics.

Quasar Hosts

The epoch $z \approx 2$ appears to corresponds both to the greatest quasar activity and to the peak in cosmological star formation. Because the bulk of the starlight emerges in the mid-ultraviolet (unless there is very strong dust extinction), this light appears in our frame in the visible band. The likely cutoff of NGST at 6000 Å, or even 1 μm, places even more importance on SUVO for studies of the rest-frame UV of the galaxies.

Perhaps the most fundamental unanswered question about active galactic nuclei is why they exist at all. Only the most speculative ideas exist to explain why some galaxies create supermassive black holes in their centers, and then feed them at a rate anywhere from 0.01 to 10 solar masses per year. Similarly, while it has been known for decades that the epoch around redshift 2–3 was particularly conducive to the ignition of luminous AGN, explanations of this fact are primitive at best. Perhaps it has something to do with the much greater rate of galaxy encounters at that time; or perhaps it was the result of the relatively large ratio of gas mass to stars that existed in galaxies then. Detailed explanations are far beyond us.

SUVO could contribute to answering these questions in a number of ways. First, there are indications that nearby AGN are associated with nuclear starbursts – primarily an ultraviolet phenomenon. Unfortunately, HST is too small to permit spectroscopy of any but the brightest of these. Installation of COS will not greatly change this situation, for it will improve throughput by only a factor of a few in the mid-UV region that is important for such studies, and it has no capacity for spatially-resolved spectroscopy. A larger throughput UV spectrograph with either long slits or an integral-field system would permit detailed studies of the stellar populations near the centers of local galaxies hosting AGN. This might provide the conditions favorable to the creation of AGN, and possibly the time-relationships between AGN and starbursts.

Second, the studies that found starbursts in nearby AGN hosts used very optically thick dust obscuration located only ~ 1 pc to ~ 100 pc from the galactic nucleus as a "coronagraph" (i.e., only type 2 Seyfert galaxies were observed). Without that screening of the central nucleus, it would have been much harder to observe the starlight in the inner several hundred to 1 kpc of the host. Unfortunately, very few obscured AGN are known beyond redshifts ~ 0.1. Consequently, the successful study of quasar host galaxies depends critically on the ability to subtract (or artificially block) the light of the central nucleus. This ability is promoted by having a telescope with a larger aperture both because of the gain in resolution (if it is diffraction-limited) and because of the gain in signal/noise for observations having a fixed integration time. Rather than a conventional filled-aperture scheme, it might be better to use some sort of coronagraph in order to block out the quasar light. Choosing the best size for the spot requires carefully thinking through a trade-off: Larger spots give better central source elimination, but also cover more of the inner low surface brightness structure that is the object of study.

Third, studies of quasar host galaxies during the epoch of greatest quasar activity ($z \approx 2$) should

shed important light on triggers of AGN activity. Through such studies, in concert with NGST data at longer wavelengths, one can contrast galaxies *then* with galaxies *today*. One can thus compare the mix of stellar ages and masses, the chemical composition and physical conditions in the interstellar medium, the presence of features like bars that might drive non-radial motions, and the frequency of encounters. To be able to make these comparisons requires imaging with physical resolution scale smaller than 1 kpc, i.e. $\sim 0.1''$ or less for objects at cosmological distances. Observations from space are clearly required to meet this criterion alone. The dark sky of space is also important because of the $(1+z)^4$ dimming in bolometric surface brightness.

Although HST has begun the study of quasar hosts, its results have been more tantalizing than instructive (e.g., Bahcall et al. 1997; McLure et al. 1999). For the reasons explained above, only a larger mirror will improve this situation. In fact, the effective signal/noise of these observations is so sensitive to telescope aperture that doubling the size of the HST mirror should move us from marginal results to data that can support quantitative analysis. SUVO imaging will allow us to study the relationships between the luminosity and other properties of the quasar and the luminosity and morphology of its host. SUVO integral-field spectroscopy will extend those investigations to quantitative determination of the host's stellar population. Astronomers have long speculated whether quasars are born after their host galaxies are assembled, or ignition of a quasar initiates formation of a galaxy around it. With SUVO, we can hope to answer questions such as this, and investigate more generally how the two processes influence each other.

Gravitationally-Lensed Quasars

After twenty years of study, there are still only a few dozen confirmed examples of gravitationally-lensed quasars. Of these elements, a handful have been particularly scientifically fruitful due to special circumstances. For example, the very first lensed quasar to be discovered, 0957+561, has proven to be a good test-bed for detecting the inter-image time-lag; the time-lag combined with measurement of the lensing galaxy's potential has permitted an inference of the angular diameter distance from us to the quasar. Similarly, the Einstein Cross quasar (2237+0305) is especially well-suited to observations of microlensing because the lensing galaxy is so close to us. As a result, the smooth lens inter-image lag is very short, and the characteristic microlensing timescale is compressed from decades to a few weeks.

In the next few years, very large sky surveys like the Sloan Digital Sky Survey should increase the number of known lensed quasars tremendously. Because the typical image separation is $\sim 1''$, imaging from space will be essential for obtaining a clear picture of their configurations, and instruments such as ACS should do a very good job with their initial description.

It is a reasonable expectation to suppose that some of the lensed quasars to be discovered will have lensing properties even more favorable than the examples already known. From studies of these new quasars, we can hope to obtain additional absolute distance measurements. We can

also hope that there will be quasars in which monitoring of how the ultraviolet flux varies during a microlensing event allows construction of an "image" of the actual central engine. However, we can also expect, due to the sharp increase in the number of quasars with decreasing flux, that many of these will be relatively faint. Consequently, detailed study and monitoring will require a telescope with better throughput, especially in the ultraviolet, than HST.

2.4. Other Scientific Programs

There are numerous additional scientific programs that would be impacted significantly by one or more future large-aperture UV-optical space missions. Below we highlight the science goals of several representative projects that would rely on the high-throughput spectroscopic or wide-field imaging capabilities needed to complete the core science mentioned above. The investigations described do not comprise an exhaustive list of such projects but provide a flavor of the scientific diversity enabled by a powerful facility for UV-optical astronomy from space.

Origin of Stellar and Planetary Systems

Protoplanetary disks. Stars form from dense molecular cloud cores which are often so deeply embedded in their host clouds that they cannot be directly investigated at visual wavelengths. However, in many cases, such as when a nearby massive star ionizes the surrounding medium, cloud cores and the young stars that form in them can be exposed and rendered visible at UV and optical wavelengths. Indeed, two of the most stunning results from HST are the discovery of *proplyds* (proto-planetary disks) in the Orion Nebula, which are young stars surrounded by circumstellar disks embedded within the Orion Nebula that are ionized from the outside by the hot Trapezium stars (e.g., Bally et al. 1998; O'Dell & Wong 1996), and the stunning *"Pillars of Creation"*, which consist of isolated 'elephant trunks' of dense molecular gas that have been overrun by the expanding H II region powered by a cluster of hot stars in M16 (cf. Hester et al. 1996). In both cases, the superior resolving power of HST has provided new insights into star formation and the structure of interstellar gas. However, it is only through the laborious mosaicking of the Orion Nebula that a sufficient field of view has been covered to study the entire star forming region. The next frontier of star formation studies is to achieve wide fields of view ($> 10'$) with high spatial resolution. The HST/WFPC2 images show that it is necessary to obtain at least 50 mas resolution in order to trace the disk structure and the disk-jet connection in proplyds in Orion, and a factor of 2 or better is desirable to extend these studies to the many star-forming regions within 1–2.5 kpc of the Sun (Fig. 10).

The vast majority ($> 90\%$) of stars currently forming within ~ 2.5 kpc of the Sun form in Orion-type environments. If planetary systems are common in the Galaxy, they must be able to form and survive within these surroundings. Studies must therefore show that (a) proto-planetary

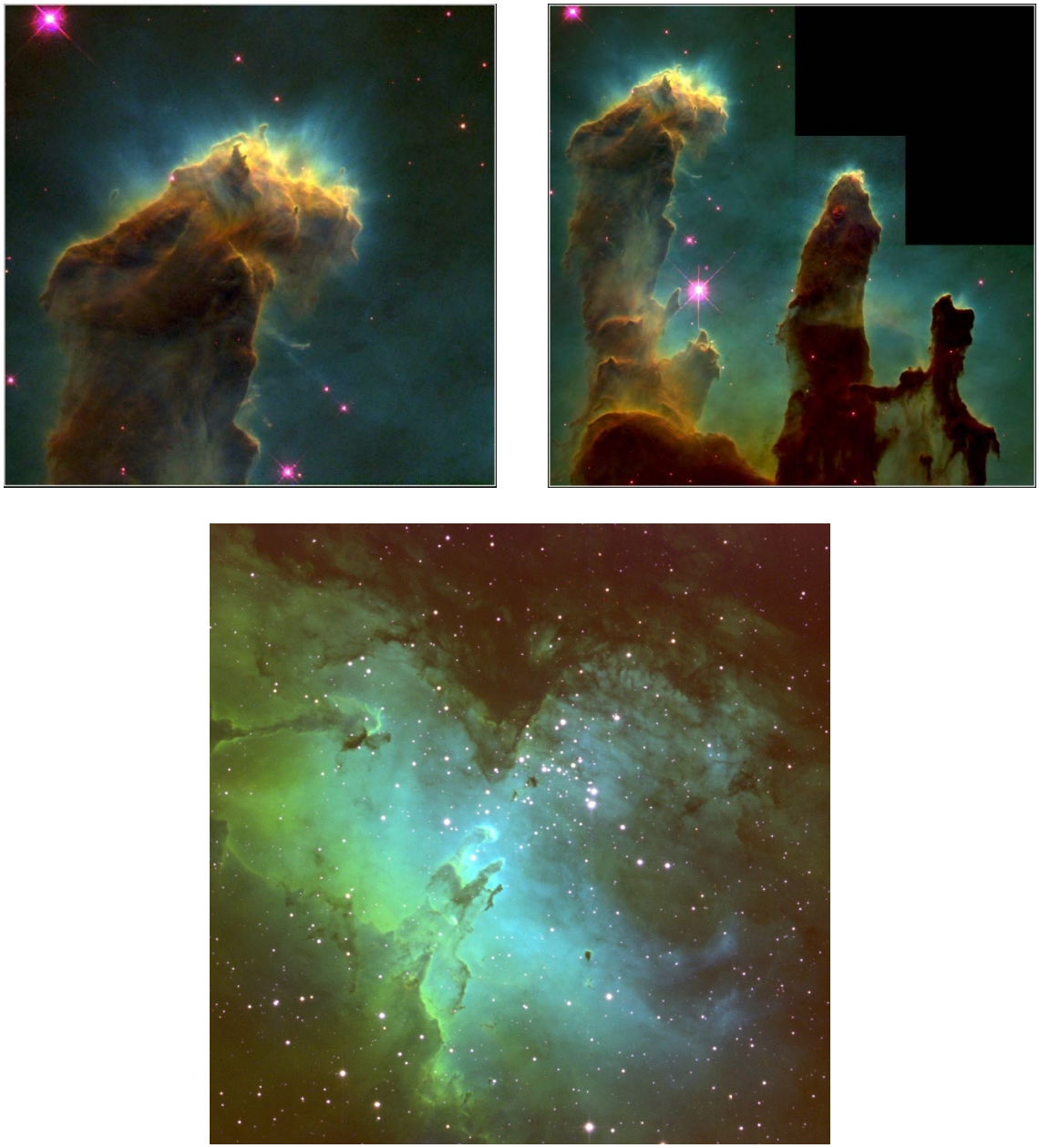

Fig. 10.— Evaporating gaseous globules (EGGs) that harbor nascent stars are revealed in the HST images of the Eagle Nebula in M16 (top panels). Studying the "Big Picture" of star formation and its feedback on molecular clouds and the interstellar medium requires high-resolution imaging over a much wider field, as shown in the ground-based image (bottom panel). HST/WFPC2 images from J. Hester, the WFPC2 IDT, and NASA; ground-based image obtained at KPNO courtesy of J. Bally.

disks are common in OB associations, and (b) planet formation can occur in the face of energetic processes (e.g., photoevaporation, stellar winds, supernovae) that destroy disks. Questions we might address include, How does planet formation depend on the IMF and massive stellar content? How does disk survival depend on distance from the massive stars? What are the disk properties as a function of position within the star-forming regions? Clearly, IR and sub-mm observations will contribute significantly to answering such questions; however, considerable important and unique information about proto-planetary disks can be gathered from optical observations as well.

Observational programs to be carried out with the next generation UVO space telescope may include: (1) A census of circumstellar disks in major star-forming regions within 2.5 kpc of the Sun. Optical imaging from space of dark disks surrounding nascent stars against the bright background emission of ionized gas is very efficient for finding and studying proto-planetary disk systems at sub-Solar System scales (e.g., Bally et al. 1998; Fig. 11). Extending these studies to distant H II regions requires high spatial resolution and wide-field imaging. Such a census could be combined with IR studies of embedded sources in nearby clouds that have not yet been exposed by the presence of massive stars in the vicinity. (2) Study of the physics of disk/planet formation and survival in star-forming environments. The high angular resolution of space imaging allows us to probe important physical scales in diagnostic UVO tracers of gaseous flows and mass loss. In particular, is the timescale to form ~ 1 cm size bodies in circumstellar disks that are resistant to photoevaporation shorter than the disk destruction timescale? (3) Resolve the relationship between massive stellar content and the IMF/star formation efficiency. For example, do massive stars trigger or hinder solar-type star formation in surrounding clouds?

Protostellar outflows. Our current picture of star formation is that during gravitational collapse, angular momentum inherited from the parent cloud core results in the formation of a disk through which much of the mass is accreted onto the young stellar object (YSO). It is believed that magnetic fields regulate the accretion rate, the dissipation of angular momentum, and the ejection of powerful outflows along the rotation axis of the system. The earliest phases (≤ 2 Myr) in the evolution of proto-planetary/accretion disks are best probed by indirect observations of the jets and outflows that YSOs produce. The spatial distribution, morphology, and velocity field of shock excited gas in such outflows preserve a fossil record of the sequence of mass ejection events that are driven by stellar accretion, over a time-scale comparable to the formation time of a young star. The outflows from young stars manifest themselves as (1) loosely collimated bipolar molecular flows which carry large amounts of energy and mass, or (2) highly collimated stellar jets that move at speeds of several hundred km s^{-1} away from the star and become visible as material cools behind shock waves in the flow. The optically emitting radiative shock waves are called Herbig-Haro (HH) objects, and evidence is mounting that the high-velocity outflows drive the molecular outflows through 'prompt entrainment' processes at the jet/ISM interface (e.g., Heathcote et al. 1996; Reipurth et al. 1997).

The past several years have seen significant advances in our understanding of protostellar outflows: (1) Ground-based wide-field, narrow-band CCD imaging of several well-known star forming regions in Taurus, Perseus, and Orion has revealed hundreds of new Herbig-Haro outflows,

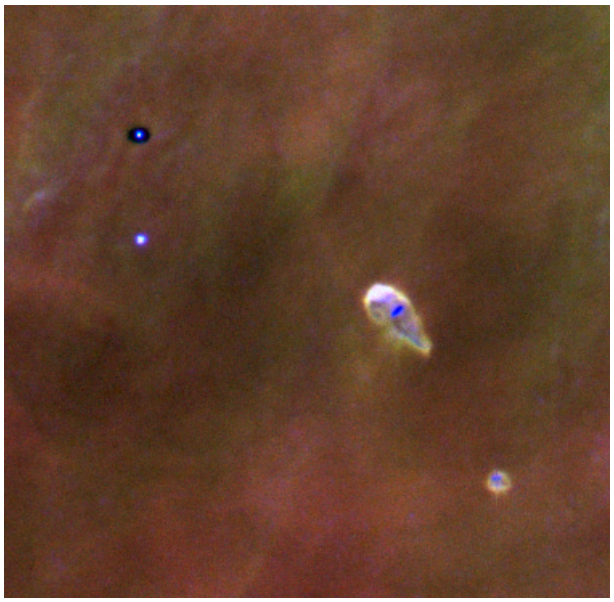

Fig. 11.— Protoplanetary disks in Orion are seen against the background emission in this optical HST-WFPC2 image provided by J. Bally. The object near the center is clearly being disrupted by the energetic winds and photon field of nearby massive stars. Such processes are predicted to destroy the disks on relatively short timescales. The object in the upper-left, on the other hand, appears to be a foreground star/disk system which is evidently outside the influence of the destructive forces of the massive stars. High-resolution imaging of such disks against the bright background emission could reveal the presence of gaps in the disks that may indicate planet formation has occurred.

supporting the notion that all stars undergo a phase of energetic mass loss during formation. These (optical) flows typically span parsec scales and may range up to 10 pc in total length. It is now clear that protostellar outflows impact their local molecular clouds over much larger spatial scales and longer time scales than previously believed. (2) Stellar jets are highly variable, both in mass flux, which generates a series of bow shocks, and in ejection direction, so that even very highly collimated outflows are able to excavate large cavities in the surrounding cloud. (3) The high spatial resolution of HST has finally resolved individual shocks in protostellar jets. For the first time, we can see how shocks propagate from the jet to the surrounding medium, a process that transfers energy and momentum to molecular outflows. The structure and kinematics of protostellar jets provide clues to the conditions very close to the YSO which are inaccessible by direct observation. The challenge is to decipher the information encoded in the jet structure and to draw conclusions about the accretion process.

Future research will address the physics of the shock waves in protostellar flows, the extent (and nature) of the entrainment of surrounding material, and the cumulative impact the outflows have on star forming regions and the interstellar medium (ISM). In particular, we need to resolve the shock structures in jets and monitor their propagation, cooling timescales, and directional variability.

These goals require narrow-band imaging of Galactic star-forming regions in diagnostic emission lines over $> 10'$ fields with better than 50 mas (few AU) spatial resolution at multiple epochs. We also need to extend our studies to major star-forming regions in the Local group, such as the dynamic 30 Dor region in the LMC (cf. Scowen et al. 1998). Studying such local 'mini-starbursts' bears directly on our understanding of massive star formation in young galaxies at high redshift.

UV Absorption Lines in our Galaxy: Stars with Heavy Extinction

At ultraviolet wavelengths, stars dim very rapidly when extra interstellar material is added in front. For the usual gas-to-dust ratio and extinction law for dense clouds in our Galaxy, the logarithm of the flux at 1150 Å decreases at a rate $-6.4 \times 10^{-22}\mathrm{cm}^2 N(\mathrm{H}_{\mathrm{total}})$, relative to its value without the obscuration. This rapid attenuation for stars inside or behind dense clouds makes them very hard to observe in the UV, but at the same time it makes them more interesting to study. As a result of the shielding of dissociating UV radiation by dust grains and molecular hydrogen absorption features, molecules can survive for long times in the cloud interiors and, as a consequence, lead to profound changes in the chemical makeup. This simple conclusion is confirmed by detailed theoretical models and observations at infrared and sub-mm wavelengths that show that molecules are indeed plentiful at the higher extinctions. For instance, observations of the 3.05 μm ice-band absorption feature indicate that ice-coated grains have appreciable concentrations only within the densest portions of compact clouds. For such clouds, the approximate linear trends in $\tau(3.05\ \mu\mathrm{m})$ vs. A_{V} extrapolate to zero ice absorption for A_{V} that ranges from 2.6 to 5.0 in different surveys.

While radio and IR techniques can probe many kinds of molecules in the gas phase, their sensitivities are significantly worse than those achievable from UV absorption studies. It follows that research on most molecular constituents can, as a rule, only be conducted for very dense regions. In instances where the optical depths become large, studies of emission features in the radio region are confounded by radiation transfer effects. Completely out of reach of the IR and sub-mm observations are the single atoms and ions – these constituents can only be studied at UV wavelengths (and to a very limited extent, in the visible). Unfortunately, limitations in present-day telescope and spectrograph sensitivities have prevented us from doing research on stars with visual extinctions in excess of $A_{\mathrm{V}} \approx 1$. In short, the important regime where the interstellar medium undergoes a transition from pure atomic to pure molecular states has been an elusive one.

It should be possible to observe clouds with A_{V} up to 10 or so with a 4–5m class UV telescope. This limit may even be exceeded, but this depends critically on how the UV extinction varies with wavelength. If dust grains continue a trend seen in some clouds and stick together to make a significant number of larger grain clusters, the extinction law could become favorable enough to permit us to probe the centers of clouds that are about to form new stars. To study such clouds in the UV would give important insights on the depletions of atomic constituents and the concentrations of various molecules in the gas phase at different depths within the clouds. Comparisons with observations of IR solid-state features along the same sight lines should yield important clues on the

affinity for certain molecules to the surfaces of dust grains.

UV Absorption Lines in our Galaxy: Halo Stars of Moderate Luminosity

With HST, we can probe the gaseous matter in the halo of the Galaxy by observing extragalactic objects that are bright in the UV (quasars and Seyfert nuclei) or rare, main-sequence, early-type stars that are at large distances from the Galactic plane. The problem with both kinds of objects is that there are not very many of them that are bright enough to study with much precision in the UV. The brightest stars in the Magellanic Clouds are of some use in principle, but the picture they present may be misleading due to interference from tidally stripped gas along the line of sight. Extragalactic sources have the shortcoming that they are of no use in determining distances of the intervening material, as one might hope to learn from stars within the Galactic halo. Thus, the best that we can do at present is to conduct a very sparse study of the halo, and we could reach misleading conclusions because we are studying material that is very patchy.

With a more powerful telescope, we can overcome the problem of sparse sampling. Stars on the blue end of the horizontal branch that have effective temperatures in excess of 20,000 K are plentiful, and apart from their faintness they are excellent light sources in the UV. Such stars at distances ranging from 5 to 40 kpc from the plane have visual magnitudes between 13.5 and 19.5, and they can offer sweeping insights on the nature of the High Velocity Clouds, the distribution of coronal-type gas ($10^5\ K < T < 10^6$ K), the driving forces of a "Galactic Fountain" (if one exists), how well the gas follows galactic rotation as a function of distance from the plane. This information, in turn, will tell us how to interpret the absorption lines in quasar spectra that are produced by gases in the halos of other galaxies.

Planetary Science: Origin and Nature of Solar Systems

The discovery of extra-solar planets is historic, opening new areas of research that overlap with classical astronomy, offering new targets for study, and changing the way planetary scientists think. At the same time, we need to first characterize the planets in our solar system to be able to understand extra-solar planets. At the August 1998 workshop, two main questions emerged from the solar system panel discussion, which are entirely consistent with the scientific goals of the NASA Strategic Plan:

- How and why do planetary systems form, and what do they look like when they do?
- What makes planets evolve into habitable worlds?

Today an increasing fraction of planetary science is being done by remote observations, and given the high cost and difficulty in sending missions to the more distant planets, we expect

that the planets and satellites far from the Sun will continue to be studied mainly by remote observations. By virtue of their distance from the Sun, these objects are also the ones most likely to be detected around other nearby stars. The advent of a new mission, SUVO, with a discovery efficiency approxmately 50 times that expected for HST/COS, will make available important new measurements of distant planets and satellites in our solar system.

The Nature of Distant Planetary Surfaces and Atmospheres

Solar reflectivity spectra of planets and satellites give critical compositional information about their atmospheres and surfaces, and UV spectra at wavelengths below 2000 Å sample the most important and sensitive transitions of simple atoms and molecules. The present HST sensitivity limits spectra of distant and/or small objects (e.g., Galilean and more distant satellites, Neptune, Pluto) to near-UV wavelengths above roughly 2000 Å. The SUVO increase in effective area will extend UV spectra to more distant and fainter objects, including asteroids and possibly Kuiper belt objects, and extend wavelengths down to the critical UV range where simple atoms and molecules have the strongest absorptions. Another promising technique for studying planetary and satellite atmospheres is to make long-aperture spatially resolved emission scale height measurements, from a variety of atmospheres and for different emission lines.

High-Resolution Studies of Planetary Atmospheres by Stellar Occultations

Visible and UV stellar occultations provide altitude profiles of the atmospheric composition of planetary and satellite atmospheres, with altitude resolution proportional to the time resolution and thereby signal to noise. UV occultations furthermore provide the highest sensitivity to small columns of planetary upper atmospheres and satellite atmospheres (e.g., Io, Ganymede, Triton, Pluto etc.). However, the present rate of suitable candidate events is 1 per several years with HST. SUVO will increase the effective area for spectroscopy by a factor of 10 over HST/COS. This will greatly increase the number of occultations available and the signal to noise of each event. UV observations are critical, especially when taken in conjunction with groundbased visible or IR occultation observations. Some expected benefits of UV occultations include the detection of haze or clouds, estimates of optical depth due to haze or clouds, and the determination of atmospheric constituents (e.g., CH_4, from its ionization cutoff). One example of a situation where UV observations would have been useful is the 1988 stellar occultation by Pluto. A kink in the occultation lightcurve at a Pluto radius of 1215 km may be due to (a) a haze layer, (b) a thermal inversion, or (c) some combination thereof. UV observations of this occultation by a spectrograph with the capability of SUVO would have resolved this basic question.

Direct Detection and Characterization of Extra-Solar Planets

The present detections of extra-solar planets proceed from stellar radial velocity measurements. Direct imaging in the thermal IR is planned for NGST, where the contrast of planetary to stellar emission is expected to be highest. At the same time, there are several candidate observations in the UV which may prove to be sensitive indicators of the composition of both mature and forming planetary systems. One is the direct detection and characterization of the known extra-solar planets, many of which are Jupiter-sized and located near the star. During an occultation of a star by the planet, the planet's extended atmosphere can be studied by observing the time-variable absorption with wavelength within the broad stellar emission line profiles. High sensitivity UV spectra of known disks and planets would be obtained spatially resolved from the parent star to characterize the composition and/or disk temporal absorptions from infalling material (as in β Pic). Direct imaging would reveal far-UV emissions from planet-forming material near young, nearby stars. Finally, high-sensitivity UV spectra of known brown dwarfs, either isolated or spatially resolved from companion star, would characterize their composition and excitation properties. It may be some years before the true potential of these observations is known, but these examples illustrate some of the most exciting science that might be accomplished by a future NASA UV mission.

Stellar Outflows across the H-R Diagram

For stellar ejecta, the primary science goal is to probe the structure of outflows down to a few thousand stellar radii or smaller in order to understand how the winds and outflows are formed, accelerated, and, apparently, collimated into highly structured patterns. Even though many types of stellar outflows are nonisotropic, they do have a high degree of point or reflection symmetry. This says that the process that governs the outflow is anchored to the star one way or another. The most common classes of physical models with this attribute are magnetic fields, rotationally-driven processes of one sort or another, or complex combinations of the two as in T-Tauris, for example.

Models that might explain the nonisotropic outflows are at a very early stage of their evolution. They desperately need more geometric and kinematic data for constraints. The classes of models divide into two main groups: processes that work within a few stellar radii (e.g., wind-compressed flows and disks), and those that rely on the ambient molecular medium (such as a torus) for a structured pressure environment. The size scales are thus about 10^{12} cm (10^{-4} arcsec at 1 kpc) or about 10^{16} cm (1 arcsec at 1 kpc). Observations seem to take little heed of these models, however. WFPC2 observations of several types of collimated outflows (e.g., bipolar PNe and H-H objects) show structure on every visible scale (10^{15} cm or larger). It seems plausible that the models have adopted the wrong paradigms.

Progress will require both the best possible spatial resolution and dynamic range so that the near-stellar flow region can be probed. This translates into the need for filled, large, obstruction-free

apertures, perhaps with an off-axis secondary. Of high (but secondary) importance is the need for excellent spectral coverage (from Paschen α at 1.87 microns) to N V] in the mid-UV. A tunable filter is ideal; however it must be able to reject nearby bright lines separated by 15 Å (e.g., [N II] 6548 and Hα; Hγ and [O III] 4363; [S II] 6717/6731) with a relative transmission of 10^{-4}. It might be useful to aim for resolving the [O II] 3736/3729 and C III] 1907/1909 lines for diagnostic purposes.

3. UV-OPTICAL MISSION CONCEPTS FOR THE POST-HST ERA

There is consensus on the UVOWG that any substantial hiatus between the de-orbit of HST and launch of the next generation UV-visible space astronomy mission(s) would severely compromise crucial aspects of our ability to study astrophysical phenomena. The exquisite imaging and versatile spectroscopic capabilities of HST have provided a myriad of important discoveries during the 1990s that have sparked a fervor among researchers as well as the general public. With the addition of new high-throughput imaging and spectroscopic instruments (ACS, WFC3, COS), HST will continue to produce forefront scientific results that arise from its uniqueness, even with the advent of numerous 8-meter class ground-based telescopes during the next decade. In its recommendation of the next generation space telescope concepts for the post-HST era, the UVOWG refers to "SUVO" missions to emphasize the need to sustain forefront UV-optical capabilities from space, along with the need to press forward on technology development programs that would enable significant new scientific studies not possible with current missions.

We identify mission options to undertake the science described in the previous sections. Depending on the pace of technology development and its impact on mission costs, one may regard these options as a roadmap. We present performance requirements for mission concepts with 4-meter (Class I) and 8-meter (Class II) apertures. The Class I missions are designed to accomplish directed science goals, to obtain "discovery factors" roughly an order of magnitude larger than current capabilities, and to be cost-constrained to SIRTF-class experiments. The Class II mission will achieve tremendous gains in sensitivity, though depend on significant technological developments during the next decade. The Class II mission will draw on heritage from other space missions by leveraging technology investments, such as in the area of large deployable mirrors, but also relies on the development of new detector technologies that will enhance mission performance. Ultimately, each mission concept should be capable of pursuing a broad range of science objectives by achieving UV-visible sensitivity limits comparable to or exceeding the largest ground-based telescopes and providing key complementary capabilities to NGST.

When contemplating the viability and impact of various mission concepts, we must consider the following areas for trades and technology assessment/development.

1. **System throughput:** Geometric aperture size, number of optics, spectral efficiency/coatings, grating efficiency, detector quantum efficiency.
2. **Wavelength coverage:** Coatings, detectors, number of observing modes.
3. **Telescope configuration:** Field of view, resolution, wavefront error, tolerancing, facility size.
4. **Large primary mirror configuration:** Substrate material; Monolith vs. segmented; Launched in-place vs. on-orbit deployment; Segment shape, size, figure, polish, coating; Testing.

5. **Telescope alignment and testing:** Wavefront sensing/correction, active correction on primary mirror vs. on secondary or internal to instruments.

6. **Spectrometer configurations:** Number of optics/modes, resolution, wavelength coverage, detector format and type.

7. **Imaging camera configurations:** Field of view, resolution, wavelength coverage/filter selection, detector format and type.

8. **Orbit:** LEO, HEO (elliptical orbit), geosynchronous, or L2.

Figures of merit can be derived that relate the performance of a mission to current capabilities, especially those aboard HST. In order to accomplish the science goals described in Sec. 2, we must achieve substantial improvements in OTA+instrument performance, which we term the "discovery factor" (similar to its use to compare the performance of ACS to WFPC2). For spectroscopy, the discovery factor F_S is a combination of throughput (or effective area, A_{eff}) and simultaneous wavelength coverage ($F_S = A_{eff} \times \lambda_{range}$) for a given spectral resolution needed to complete the science goals. In the case of a multi-object or integral field spectrograph, we also account for the spatial multiplexing capability. For imaging, the discovery factor F_I combines throughput and field of view ($F_I = A_{eff} \times FOV$) for a given spatial resolution needed to complete the imaging science goals, assumed to be superior to that afforded over wide fields by ground-based telescopes or Explorer-class missions at the wavelengths observed. We also can increase the observing efficiency, O_{eff}, compared to HST by choosing an orbit that allows long continuous target visibility periods and that lowers or eliminates bright-Earth and geocoronal emissions that contribute to background count rates. Combining the discovery factors with observing efficiency, we can create metrics called discovery efficiencies: $D_S = F_S \times O_{eff}$ for spectroscopy, and $D_I = F_I \times O_{eff}$ for imaging.

Table 3.1 summarizes some of the performance characteristics of the Class I and II missions that are described in more detail below.

3.1. Class I Mission Concepts

The Class I mission concepts are of $\sim$ 4-meter aperture. There are three principal drivers behind pursuing this size aperture:

1. *Scientific return* — Factors of 10 to several hundred gain in discovery efficiencies are possible over current capabilities, enabling frontier scientific studies not currently possible.

2. *Technological feasibility* — There is a clear technological path to implementing missions of this class, both in terms of mirror development and advancements in instrumentation. A 4.2-meter monolithic mirror can just fit inside a Delta-class launch vehicle (i.e., segmented mirror technology is not needed). Assuming NGST weight constraints on the total mass, we

Table 3.1: Class I and II Mission Performance Compared to HST

Mission	Aperture	Mode	λ Coverage	Resolution	Field of View	Discovery Factor	Discovery Efficiency
SUVO Class Ia	4.2-m	Point-source Spectroscopy	1150 – 3200 Å	R $\geq$ 30,000	$\sim 2''$	$F_S \approx 50$	$D_S \approx 100$
SUVO Class Ib	4.2-m	High-Res 16k×16k Imager	0.2 – 1 μm	30 mas @5000 Å (15 mas pixel^{-1})	$4\farcm1 \times 4\farcm1$	$F_I \approx 5$	$D_I \approx 10$
		Wide-Field 16k×16k Imager	0.2 – 1 μm	30 mas @5000 Å (50 mas pixel^{-1})	$13\farcm6 \times 13\farcm6$	$F_I \approx 50$	$D_I \approx 100$
		Integral Field Spect.	0.35 – 1 μm	30 mas μ-lens^{-1} R $\approx$ 5000 – 10,000	$8'' \times 8''$	$F_S \approx 240$	$D_S \approx 480$
SUVO Class II	8-m	Point-source Spectroscopy	1150 – 3200 Å	R $\geq$ 30,000 (1-D STJ array)	$\sim 2''$	$F_S \approx 250$	$D_S \approx 500$
		High-Res 24k×24k Imager	0.2 – 1 μm	15 mas @5000 Å (8 mas pixel^{-1})	$3\farcm3 \times 3\farcm3$	$F_I \approx 10$	$D_I \approx 20$
		Wide-Field 24k×24k Imager	0.2 – 1 μm	15 mas @5000 Å (30 mas pixel^{-1})	$12\farcm3 \times 12\farcm3$	$F_I \approx 150$	$D_I \approx 300$
		Integral Field Spect.	0.35 – 1 μm	15 mas μ-lens^{-1} R $\approx$ 5000 – 10,000	$8'' \times 8''$	$F_S \approx 880$	$D_S \approx 1760$

can scale the 12 kg/m^2 restriction for an 8-meter NGST primary mirror to ~44 kg/m^2 for the SUVO Class I primary mirror. This latter performance has already been met by the secondary mirrors manufactured for the VLT telescopes.

3. *Cost constraints* — Extrapolation of several proposed Discovery missions of 2.4-m aperture up to a 4-m class aperture suggests that a 4-m mission is feasible within a SIRTF-class cost envelope ($\sim$ \$220M for the telescope, $\sim$ \$50M for an efficient spectrometer, $\sim$ \$100M for a very wide-field imager, and \$60-80M for launch).

3.1.1. SUVO Class Ia Mission (4-m)

The Ia mission is a 4-m class observatory optimized for UV point-source spectroscopy. This concept may be viewed as the most affordable option, as the main science goals do not require diffraction-limited imaging nor wide field of view. However, as a UV optimized mission, the requirements on mirror surface roughness and scattered light are still likely to be stringent. The UV

point-source spectroscopy science goals drive the following mission characteristics.

1. Orbit: geosynchronous or L2 orbit
   - Achieve high observing efficiency
   - Operate simply and efficiently
   - Achieve low sky backgrounds for long-duration exposures
     - Minimize or eliminate geocoronal emission
     - Shield or discriminate against cosmic rays
2. Spectral Resolution:
   - Optimized for (slitless) point-source spectroscopy
   - Spectral resolution R = 30,000 – 50,000 for primary science
   - Faint-object "survey mode" (R = 1000)
3. Effective Area: At least 10× HST/COS
   - Achieve $A_{\rm eff} > 2 \times 10^4$ cm^2 (target AB = 17-20 mag QSOs)
   - 4.2-meter primary aperture
   - Next generation (low-background, high-QE) detectors
   - High-efficiency UV coatings; holographic gratings; minimal reflections
4. Spectral Multiplexing:
   - No more than 2 integrations to cover 1150-3200 Å at R = 30,000
5. Spatial Resolution:
   - 0.3 arcsec or better (Rayleigh criterion)
6. Wavelength Coverage:
   - Current HST UV band: 1150-3200 Å
7. Minimal Imaging:
   - Off-the-shelf CCD imager for tracking/target acquisition
8. Launch Date: 2010
   - Ready when HST is de-orbited
9. Mission Lifetime:

- Design lifetime 5 yrs; mission goal 10 yrs

A large increase in the discovery efficiency of the Ia mission compared to HST will depend on several technological developments (see Sec. 4 for more details):

- Flight qualification of lightweight 4.2-m monolith mirror
- 2- or 3-bounce optical design of slitless UV spectrograph that compensates for figure control and aberrations
- Next generation of large-format MCP-based detectors with low dark count (< 0.1 cts s^{-1} cm^{-2}) and high-QE performance ($> 60\%$) over a broad wavelength range
- High-reflectivity, broad-band UV coatings
- High-efficiency ($> 60\%$) holographic gratings

The effective area of the HST/COS R=20,000 spectral modes is predicted to be $A_{\rm eff} \approx 1500 - 2000$ cm^2 in the FUV and half that in the NUV. A factor of 10 gain in effective area over HST/COS must arise from a combination of larger aperture, higher OTA UV reflectivities, more efficient gratings, and higher QE detectors. We achieve a factor of ~3 gain in collecting area with a 4.2-meter telescope compared to HST. It is estimated that the HST OTA delivers roughly 50% of incident Lyα photons to the focal plane, implying reflectivities of the primary and secondary mirrors of ~70%. OTA reflectivities of ~85% have been achieved with the COSTAR and STIS optics, and so could supply a gain of a factor of nearly 1.5 over HST. The COS (1st-order) gratings have groove efficiencies of about 60%, and the next generation holographic gratings may deliver as high as 75% (see Sec. 4), providing a factor of 1.25 gain. These three improvements combine to give a factor of ~5.6 gain in effective area over HST/COS. Hence, to achieve a factor of 10 gain requires that the detector QE improve by almost a factor of two, in the FUV from ~30% to ~60%. Clearly, the largest burden is on achieving higher QE detectors.

The next component of the discovery factor is wavelength coverage. The COS R = 20,000 FUV modes deliver ~300 Å coverage and the NUV modes ~150 Å using 1st-order gratings. Covering the entire 1150 – 3200 Å range in two integrations requires either much larger detector formats and/or much better detector resolution. Alternatively, we could use echelle gratings, as is done on STIS. This approach may compromise our groove efficiencies and add an additional optic, hence not aid our net gain in discovery factor. Assuming, however, that we can solve the problem of providing broad wavelength coverage with efficient gratings and large detectors gains us a factor of ~5 advantage over HST/COS, so that the total discovery factor could be as high as $F_S \approx 50$.

It will take a concerted technology development effort to achieve a ten-fold increase in effective area over HST/COS, although the issues appear tractable. When we multiply by the factor of ~ 2 greater observing efficiency by operating in a geosynchronous or L2 orbit, we attain a gain in

discovery efficiency of $D_S \approx 100$ over HST/COS. Such gains provide the capability to attack the point-source spectroscopy science goals detailed in Sec. 2.

3.1.2. SUVO Class Ib Mission (4-m)

Every image of the sky that HST takes tells us something new about the Universe in which we live. This continues to be true even for bright objects such as the Orion nebula that have been studied for literally hundreds of years. The new discoveries generally derive from the improved spatial resolution and sensitivity that HST delivers versus ground-based imaging, which enables us to investigate important scale lengths in faint structures from the planetary arena to cosmological scales. HST's advantage in spatial resolution has declined to only about a factor of 2-3 in recent years with the advent of adaptive optics (AO) systems on ground-based telescopes (cf. the AO bonnette system at CFHT). With progress on ground-based and space-based optical interferometers over the next decade, we can expect many experiments to supersede HST's spatial resolution, in some cases by orders of magnitude. However, neither AO-assisted imaging nor optical interferometry will achieve these high resolutions over wide fields of view with high dynamic range, and, of course, imaging in the UV is completely unique to space-based astronomy.

When considering the next frontier of UV-optical imaging from space, there are several avenues to explore, such as spatial resolution, field of view, limiting sensitivity, and dynamic range. The science goals of, e.g., mapping the distribution of dark matter in superclusters, conducting UV imaging surveys of nearby galaxies, and studying the origin of stellar and planetary systems in Galactic and Local Group star-forming regions all require the ability to detect faint targets distributed essentially randomly over large areas on the sky with spatial resolution high enough to discern important physical scales.

The SUVO Mission Ib 4-m class concept is designed to accomplish these performance goals, occupying an extremely important and unique region of parameter space that is rich in discovery potential. The essential characteristics of the Ib mission follow. These are in addition to many of the mission properties identified in the Ia mission, such as orbit, launch date, mission lifetime, lightweight mirrors, and high-reflectivity coatings, that are shared by the Ib mission.

Wide-field NUV-Optical Imaging:

- 0.2-1 μm wavelength coverage (overlapping with NGST in at least one band in the red)
- Broad-band and narrow-band imaging
- Sky coverage greater than 10× HST/ACS Wide Field Channel
- Full point spread function (PSF) correction for diffraction-limited performance at 5000 Å (= 30 mas), matching the resolution of an 8-m NGST diffraction-limited at 1 micron

Critically sampling with 15 mas pixels a field of view (FOV) that covers 10 times more sky than the Wide Field Channel of ACS would require a CCD detector array roughly 44k $\times$ 44k in size, perhaps unrealistically large. However, it may not be unrealistic to pursue arrays 16k $\times$ 16k, or perhaps even 24k $\times$ 24k in size, as large-format mosaics of this scope are currently being constructed for ground-based cameras. If we baseline a 16k $\times$ 16k CCD, critically sampling the FOV with 15 mas pixels yields a $\sim 4' \times 4'$ field, congruent with the baseline FOV performance of NGST. Using a pixel size of 50 mas yields a field over $13' \times 13'$, 16 times larger than the FOV of the ACS WFC and commensurate with the imaging science requirements detailed in Sec. 2. This pixel scale would undersample the PSF, however, the Hubble Deep Field images made with 100 mas pixels clearly show that dithering techniques recover information and yield sufficient resolution to produce frontier science. Implementing both pixel scales to provide a high-resolution, critically sampled mode as well as a wide-field survey mode could be accomplished either by sharing the focal plane of the telescope and feeding two separate CCD mosaics, or by means of a focal reducer that alters the plate scale delivered to a single detector mosaic.

The SUVO survey imaging mode with 50 mas pixels has the same pixel scale as the ACS WFC. With a 4.2-m aperture, the SUVO Class Ib collecting area provides a factor of $\sim$3 greater sensitivity over HST/ACS. Then even with very modest improvements in detector QE and surface reflectivities, the discovery factor is 50 times higher than HST/ACS. Operating in high-Earth orbit — provided a proper solution to cosmic ray shielding can be implemented — may increase the observing efficiency by as much as two times, leading to a discovery efficiency enhancement for the SUVO wide field imaging mission Ib of $D_I \sim 100$. Larger enhancements may be obtained in the NUV (0.2 – 0.3 microns) because current CCD QE performance at these wavelengths is substantially lower than in the visible bandpass.

Science goals such as exploring the kinematics and physical conditions in galaxy cores and supermassive black holes require spatially resolved spectroscopy, and we can take advantage of the excellent image quality of the Ib mission to provide this capability. The simplest application may be a long-slit mode, though achieving complete spatial sampling with an integral field spectrograph would be more desirable for such investigations. Spectral resolutions of R $\sim$ 5000 – 10,000 are adequate for most kinematic studies and resolve important diagnostic absorption and emission lines. It would be desirable to use the existing large-format detector to capture the spectra from a micro-lens array at least a couple hundred elements on a side, in order to provide fine spatial sampling (30 mas) over a field $\sim 8'' \times 8''$ in size. The relevant discovery efficiency comparison is with HST/STIS, which would require stepping a long-slit across the FOV in order to obtain complete spatial sampling. Comparing to the available $0\farcs1$-wide STIS slit, a huge gain in discovery factor ($F_S \approx 240$) results from the complete spatial sampling of the integral field unit and the increased collecting area of the telescope. Including the gain in observing efficiency of operating in high-Earth orbit yields a discovery efficiency of $D_S \approx 480$.

Achieving the performance of the Class Ib mission requires the development of several technological capabilities.

1. Develop lightweight 4-m class monolithic primary mirror with excellent figure and/or (active) figure control.
2. Optical design that achieves wide FOV and high spatial resolution.
3. Requires excellent tracking and pointing stability.
4. Develop large CCD mosaics for space.
5. Improve detector QE performance, especially in the near-UV.
6. Lower read noise and dark currents.
7. Improve charge transfer efficiency performance.
8. Implement shielding against harmful cosmic rays.
9. Develop UV-optical tunable filters for broad-band and narrow-band imaging, that provide access to numerous diagnostic lines at arbitrary redshift.

3.1.3. Stretch Goals

The following stretch goals would enhance the performance of the Class I missions and increase the scientific return if such capabilities can be made both feasible and affordable.

1. Achieve spectral resolution of R = 50,000 – 200,000.
2. Extend UV imaging down to 1150 Å to include access to rest Lyα, C IV, and other diagnostic lines.
3. Extend spectroscopy to the FUSE band (912 – 1180 Å).
4. Achieve diffraction-limited imaging in the UV ($<$ 10 mas resolution).
5. Include UV-optical coronagraphic mode for high contrast imaging studies.

3.1.4. Combining the Class Ia and Ib Missions

Integrating the Ia and Ib missions together into a single mission could be accomplished by sharing the focal plane between the imaging and point-source spectroscopy channels (similar to the way HST shares its focal plane among multiple instruments). The point-source spectroscopy channel does not require a field of view more than a few arcseconds, which could be accommodated at the periphery of the imaging field. Technological advances that constrain mission costs are very important in this concept in order to fit this more capable, higher science return concept within the

SIRTF-class cost envelope. Figure 12 shows an optical design concept, based on a scalable NGST design. In this example, the imaging and spatially resolved spectroscopy channel with full PSF correction is fed by an off-axis tertiary, while the on-axis beam feeds directly into a point-source UV spectrograph. Many other design concepts are possible.

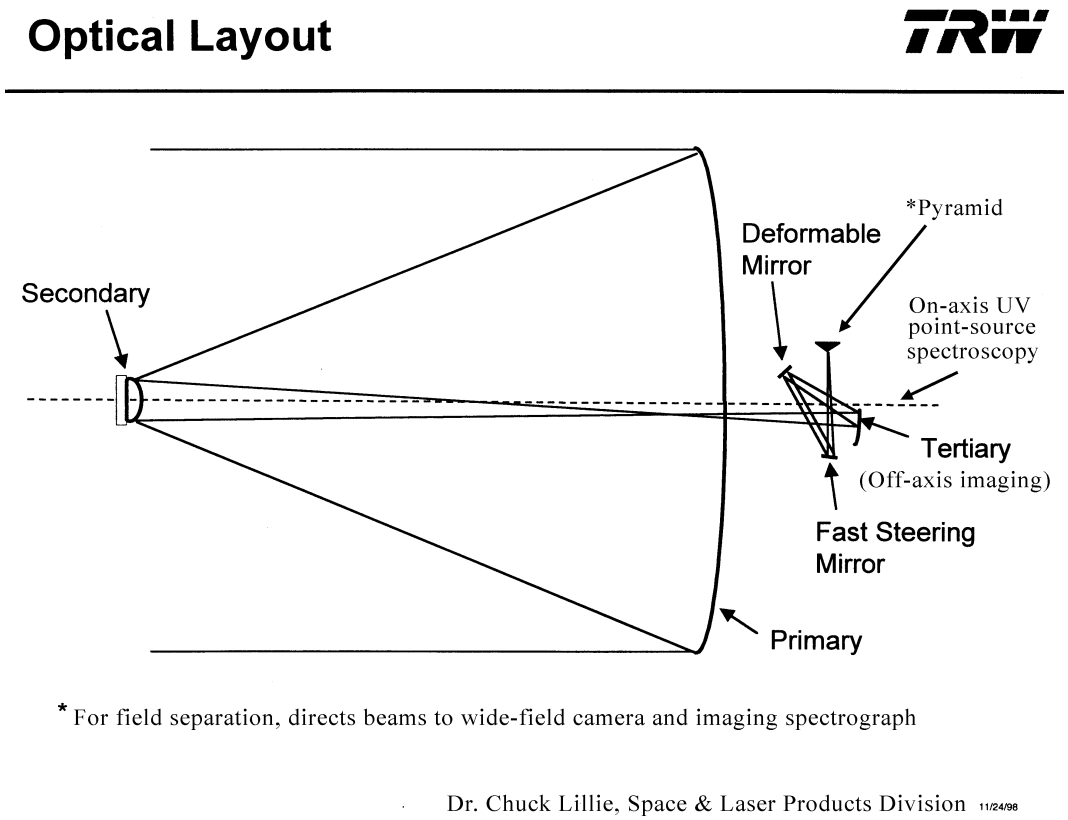

Fig. 12.— Optical design concept for a large-aperture UV-optical space telescope that shares the focal plane between wide-field imaging and spectroscopy instruments. This optical layout, with the fast steering and PSF correction mechanisms housed in the instrument module, borrows heavily from the yardstick NGST design concept. Many other design concepts are possible. (Contributed by Dr. Charles Lillie, TRW.)

3.2. SUVO Class II Mission (8-m)

The SUVO Class II 8-m mission offers tremendous gains in discovery efficiency over current capabilities. This option would provide enormous scientific return, and would maximize the return on NGST technology investments. While the scope of this mission may delay its readiness beyond the HST de-orbit, there is a logical path towards its implementation. Significant funds are being invested in developing technologies to build a passively cooled 8-meter telescope for NGST. For

those requirements in common, it may be less expensive to utilize NGST developments and designs directly for a UV-optical mission, rather than develop independent technology. Depending on the technology selections made for NGST, common requirements could include optical surface supports, structures, deployment mechanisms, spacecraft elements, actuators, control systems, and power systems. Better surface accuracy is required for the UV-optical than for the IR, but the optical surfaces would not be cooled, so the temperature gradients and accompanying structural distortions would be lower. Adaptive optics controls would require less range, and so could be more accurate.

If an 8-m UV-visible mission were envisioned by NASA, we must take full advantage of the large aperture by employing efficient instrumentation with the very latest detector technologies. For example, an efficient spectrograph would follow the same strategies as for the Class Ia telescope option, a minimum of surfaces and high-efficiency, low-scatter gratings. A resolving power of 20,000 – 30,000 can be obtained with a single curved echelle grating, with one exposure over the 912 – 3000 Å range. An energy resolving detector, such as a superconducting tunnel junction (STJ) device, with 50 – 100 resolving power could sort the orders and separate them by more than 3 FWHM over that range. Alternatively, a prism could order-sort for a non-energy resolving two-dimensional detector.

Some of the essential characteristics of the SUVO Class II mission follow.

- 8-m class telescope in L2 orbit that leverages NGST segmented mirror technology investment and on-orbit deployment and operations experience
- Utilize NGST-type packaging into launch vehicle
- Some performance goals are more difficult than for NGST: e.g, diffraction-limited performance in optical or UV; co-phasing of mirror segments
- Some performance goals are easier: e.g., cold telescope not necessary; relaxed thermal requirements and fewer pointing restrictions
- Employ energy-resolving, high-QE (STJ-type) detectors to maximize performance and efficiency

The large 8-m aperture represents a significant increase in collecting area over HST. When combined with an efficient spectrograph that employs high-QE ($\sim 80\%$) detectors, it is possible to obtain an effective area of $A_{\rm eff} \sim 1 \times 10^5$ cm^2. Obtaining the complete UV spectrum in one exposure using a curved echelle grating and operating in high-Earth orbit may yield a gain in discovery efficiency of $D_{\rm I} \approx 500$ compared to HST/COS!

Ostensibly, a large-format optical camera could be included for very deep, wide-field imaging. However, the prospects for achieving diffraction-limited imaging ($\sim$15 mas at 5000 Å for an 8-m telescope) in the optical with the segmented mirror technology are more dubious at this time compared to the Class I monolithic missions. A 24k $\times$ 24k CCD detector array with 30 mas pixels

could reach faint limiting magnitudes eleven times faster than HST/ACS and with 13 times greater sky coverage.

Some basic development issues for the Class II mission (in addition to those mentioned for the Class I missions) are:

1. Achieve diffraction-limited imaging at optical wavelengths with segmented 8-m mirror design, leveraging NGST mirror technology development and on-orbit experience.
2. Develop innovative optical design to accommodate both high-resolution spectroscopy and wide-field imaging (probably not an NGST "clone").
3. Development of concave echelle gratings that can be employed in a Rowland circle-type, high-throughput spectrograph.
4. Develop large (1-d or 2-d array) energy-resolving detectors. Only small arrays ($\sim 6 \times 6$) currently exist; arrays of at least 1×2048 (1-d, spectroscopy only) or 2k $\times$ 2k (imaging and spectroscopy) are needed. Point-source echelle spectroscopy: 1-d detector array with sufficient energy resolution (R = 50 – 100) to sort orders. Imaging and long-slit spectroscopy: 2-d detector array large enough for significant FOV and with sufficient energy resolution (R $\approx$ 200 – 500) to obtain crude redshifts and for simultaneous narrow-band imaging in numerous UV-optical diagnostic lines.
5. STJs operate at milli-K (!) temperatures, requiring space qualification of next generation cryogenic technology.
6. Pointing stability may be difficult, and a fast tip-tilt seconday may be necessary. But for a point-source spectroscopy mission, good stability is only necessary in the dispersion direction.

Finally, we briefly mention an intriguing possibility of flying a descoped implementation of the "chord-fold" NGST design without the chords — i.e., a 4m $\times$ 8m elliptical telescope that would fit into a Delta-class launch vehicle. The PSF may not be suitable for detailed imaging studies, but would serve as a "light bucket" for point-source spectroscopy.

3.3. Pathfinder Mission: Gossamer

We briefly mention the possibility of devising a pathfinder mission for high-throughput UV spectroscopy. The roadmap to very large (> 20m) aperture space telescopes of the future will require the development of ultra-light optics, such as thin film deployable mirrors. A 10-m class pathfinder mission using the new thin film ("gossamer") technology would yield ground-breaking sensitivity limits for UV spectroscopy, while providing a platform for testing the deployment, image quality control, and operations of a large aperture telescope.

3.4. Additional Missions

The UVOWG was charged with considering the next frontier of UV-optical space astronomy in the post-HST era. We did not spend a large amount of time considering small, Explorer-class mission concepts, for which NASA already has an implementation process. However, there were new Explorer and Discovery class UV-optical mission concepts presented at the Boulder conference with science goals that the UVOWG endorse. An underlying theme of several of these mission concepts is to provide dedicated facilities to study time-variable phenomena, following the important science executed by IUE during the latter years of its mission life. We also provide a brief description of a UV interferometer concept that would provide ultra-high spatial resolution.

1. Explorer class UV spectroscopic mission dedicated to long-term monitoring of time variable sources, such as cataclysmic variables, young stellar objects, and active galactic nuclei. Time-resolved spectroscopic data will be used to diagnose the physical conditions in accreting systems and to study the disk/jet connections so ubiquitous in astrophysics.

2. Explorer/Discovery class optical photometry mission dedicated to detecting extra-solar planets via occultations of the central stars by planetary bodies (especially those in 51 Peg-type orbits), or via microlensing events as distant stars are lensed by planetary systems orbiting foreground stars.

3. Discovery class UV-optical telescope dedicated to remote sensing (imaging and spectroscopy) of time-variable phenomena occuring in planets in the Solar System, as well as characterization of extra-solar planets (e.g., 51 Peg-type systems) via changes in the central star spectrum due to occultations by the extended atmospheres of giant planets as a function of orbital phase.

4. Explorer class mission dedicated to imaging and spectropolarimetry. Polarimetric observations provide a unique and powerful technique for determining the three-dimensional structure and geometry of many astrophysical objects. Polarization is also useful for mapping magnetic fields at scales ranging from the stellar to planetary and as a means of determining the characteristics or thermodynamic properties of interstellar, proto-planetary, or cometary gas and dust. Observations of polarization are particularly useful in the UV, with access to strong resonance lines for determining scattering geometries, physical conditions, and composition in numerous astrophysical objects. The primary caveat is that polarimetric measurements require high S/N to achieve meaningful results, and the instrumentation requires elaborate and precise calibration. The current suite of sub-orbital experiments (with 5-10 minute missions) have been limited to a small list of bright targets. Building from the existing instrumentation, which have honed the techniques, the next logical step is the development of an Explorer-class polarimetric observatory. Even a modest ($\sim$0.3m) aperture instrument would dramatically increase the number of accessible objects and provide an unequivocal demonstration of the power of the technique.

5. Ultra-high resolution imaging with a space UV interferometer. Science goals include (1) resolving surface features on nearby stars; (2) obtaining ≥ 10 resolution elements across the inner 0.1 AU region of the nearest protostars to image hot gas in accretion flux tubes to address how stars are made; (3) resolving 1 AU (or better) scales in the Magellanic Clouds for studying stellar systems and interstellar processes along a sight-line with low reddening; (4) obtaining ≥ 10 resolution elements over 0.1 pc scales in the nearest AGN to study galaxy cores and black holes; (5) resolving 1-10 pc scales at 1 Gpc distance to study individual star-forming groups in high-redshift galaxies.

4. TECHNOLOGY ROADMAP

4.1. Overview

Throughput is the single most important technology driver for the future of UV-optical space astronomy, especially for spectroscopy. Significant astrophysical problems as discussed above — the formation and early evolution of galaxies, the nature of dark matter, the formation and (re)cycling of elements, the nature of the dynamic interstellar/intergalactic medium, the formation and early evolution of galaxies — cannot be properly addressed now because of the lack of sensitivity to low-surface-brightness or intrinsically faint objects. Throughput can be improved significantly by (1) using more sensitive detectors, (2) using significantly larger aperture telescopes, and (3) by improving the efficiency of the instruments, especially through clever designs and improved optical surfaces. Throughput can also be improved greatly by achieving high levels of multiplexing, particularly in spectroscopic applications.

UV-optical studies of faint or low-surface-brightness objects also require low backgrounds (natural or instrumental), good signal-to-noise over a wide range of signal strengths, and linear responses. These goals can be addressed by using (1) low-noise detectors with (2) high dynamic range.

Technology needed to advance UV-Optical astronomy can and will benefit greatly from advances being made in other wavelength regimes. In particular, detector developments in the X-ray, ground-based visible, and infrared wavelength bands are invaluable and can often serve as good starting points for UV detector development. Large, lightweight optics are of interest to the infrared/visible community (e.g., NGST), where investments in optical materials and deployment mechanisms are already showing positive results.

However, the UV/space visible regime is unique in several respects. In the UV (10 – 300 nm), the potential for contamination and subsequent drastic loss of throughput must be considered in every part of an instrument and spacecraft. The short wavelengths of UV light make it intrinsically more difficult (than at visible or near-IR wavelengths) to produce precision optics, to align those optics, and to maintain the optical alignment and wavefront in large optics. In some cases, the diagnostically crucial UV emissions are weak relative to many other regions of the electromagnetic spectrum — thus detectors that are sensitive to UV light may be much *more* sensitive to (and perhaps overwhelmed by) the much brighter red/infrared emission from astrophysical objects.

Because of these unique constraints, there are several areas where UV technology development cannot rely on advancements made in other wavelength regimes, but will progress only through dedicated specific efforts. These areas include:

- Detectors
- Large lightweight precision mirrors

- Optical materials and coatings
- Precision optical elements — gratings, micro-mirrors

A chart illustrating the flow down of the science requirements to the SUVO telescope/instrument performance and technology development is shown in Fig. 13.

We wish to emphasize that major breakthroughs in technology development for UV-optical space astronomy, especially in the area of detectors, almost certainly require a more robust technology development initiative from NASA than is currently in place. For example, the recently closed NRA 98-OSS-10 on "Technology Development For NASA Explorer Missions and SOFIA" was heavily over-subscribed, extremely broad-based in its technology response, and funded at a level that is generally insufficient to provide sustained development of major new hardware over years of effort. Many programs find it necessary to bootstrap multiple sources of funding in order to sustain instrument development. We encourage NASA to supplement current technology and instrumentation programs to take full advantage of community efforts to develop new concepts or improve existing technologies that, in the long run, result in large mission cost savings.

4.2. Detectors

4.2.1. Overarching Requirements

The primary science drivers for the future of UV-optical astrophysics require medium- to high-resolution UV spectroscopy and wide-field UV-optical imaging of faint extragalactic targets. These science goals place demanding requirements on the sensitivity of the detector systems. High quantum efficiency (QE) and low background levels are the critical parameters for the detector(s), both for spectroscopic and imaging applications, and they warrant the greatest investments in detector technology. Highly efficient multiplexing systems should be developed for use at UV-optical wavelengths, with particular attention paid to 3-D (energy-resolving) detectors. Work should also be done to obtain larger formats, to improve dynamic range (critical for precise calibration), and to increase stability (for high S/N operation).

High quantum efficiency — All promising lines of significant QE improvement should be explored. Without major gains in instrument sensitivity, many of the observations required to advance the field of UV-optical astronomy cannot be done. UV astronomy has the dubious distinction that there is a great deal of room for improvement. The most commonly used UV detectors, MCP-based photon counters, provide QEs that are far from unity (typically 10-40%, depending on wavelength). Detector QE offers a great deal of potential leverage on instrumental performance. *A given factor of improvement in QE provides as much return in sensitivity as a corresponding increase in telescope aperture, at potentially much lower cost.*

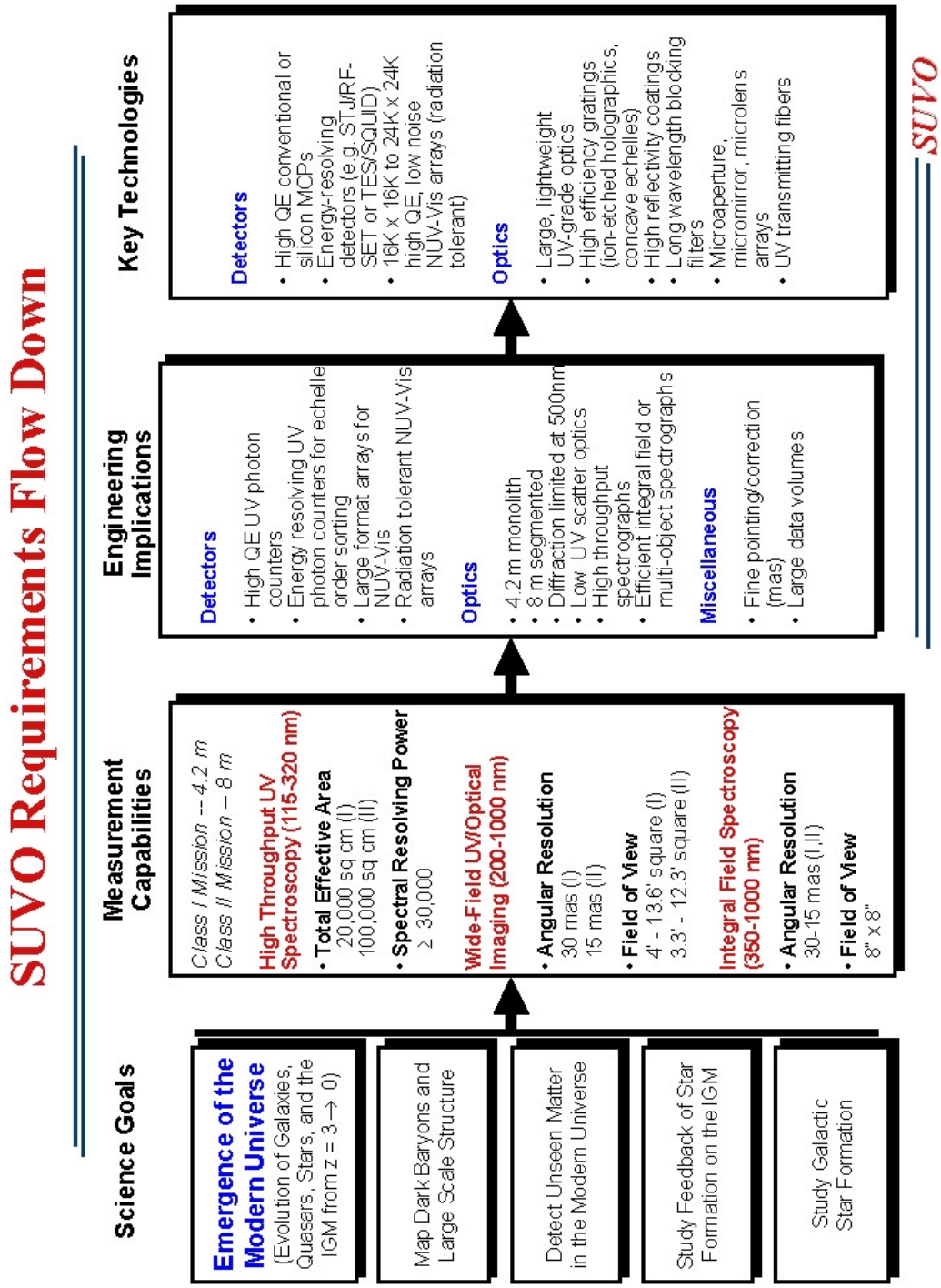

Fig. 13.— Flow down of SUVO science requirements to telescope/instrument performance and technology development. "ST2010" refers to the requirements of a space telescope mission in 2010 and the decade beyond. (Prepared by Randy Kimble.)

Low backgrounds — It is essential to reduce substantially the background rates of all types of detectors. UV-optical studies of faint, diffuse objects require low backgrounds to detect the signal from astrophysical objects. In long observations of the faintest targets, detector background noise becomes the limiting factor and determines the sensitivity of the measurement. Accumulated background counts from the detector ("dark count") may overwhelm the signal from the target object, and the purely statistical fluctuations in the background counts produce a fundamental noise floor on top of which target counts must be measured. For CCD-like detectors, electrical fluctuations in the readout of each exposure ("read noise") add an even larger component of detector background noise.

Dynamic range and linearity — Technology investments should be made to ensure that potential flight detectors have large dynamic ranges, and are stable and linear. It is essential to be able to observe fields containing bright sources without saturating or damaging the detector. It is also important when exploring scientific problems that involve small perturbations in the signals from very bright sources, that detectors provide a linear response to the signals. Finally, it is crucial, in making such measurements, that detector signal-to-noise (S/N) ratios are not compromised by unpredictable position-dependent (and thus uncalibratable) irregularities in detector response.

Multiplexing — Accomplishing the science goals outlined in the previous sections depends on achieving large, simultaneous spectral wavelength coverage. Large (2-D) detector formats are needed to meet this requirement. We may also look to developing "3-D" detectors to improve efficiency and reduce the number of optics. We suggest that a major program of development for energy-resolving UV-optical detectors should be undertaken. Sensitive, multidimensional detectors with both good spatial and moderate-to-good spectral resolution are particularly important. This technology requires an extensive and sustained development program. Overall efficiency of an instrument can also be improved by increasing the number of objects observed simultaneously. This can be accomplished by using larger fields (in imaging applications), or by obtaining multiple spectra simultaneously, or ideally by doing both. Promising avenues for improving UV-optical multiplexing beyond the 3-D detectors include development of micromirror arrays or of UV-transmitting optical fibers.

In the following sections, we comment on the state of the art and developments required in several specific detector types.

4.2.2. Multidimensional Detectors

The so-called 3-D detectors, such as superconducting tunnel junction (STJ) devices and transition edge sensors (TES), have the potential to revolutionize UV-optical astrophysics. With significant and sustained development work, these detectors could be ready to fly in the timeframe of the missions described above. Substantial, long-term, stable funding should be invested to bring these or related 3-D detectors to the astronomy community.

3-D detectors provide photon-counting with intrinsic energy resolution of each detected event. While the energy resolutions currently envisioned are coarse, compared with the spectral resolution requirements presented above, it should be possible to use a linear array of such energy-resolving pixels to provide order-sorting in a high-resolution echelle spectrograph, thereby eliminating the need for a cross-disperser grating and providing a high QE over a wide simultaneous wavelength coverage. A large 2-dimensional array of these devices would provide extraordinarily efficient multi-object spectroscopy.

Serious engineering issues remain to be addressed before these detectors become practical. STJ/TES detectors require cryogenic operations, with UV-optical applications expected to require sub-Kelvin temperatures and the requisite coolers, dewars, and windows. It is likely that the requisite coolers will be developed to support other wavebands (e.g., the sub-mm). However, many of the other cryogenic requirements must be explored and integrated into standard thinking about UV-optical instrumentation. Current prototype arrays are only $\sim 6 \times 6$ pixels (e.g., see Jakobsen 1999; Perryman et al. 1999). Techniques must be developed to create and read out large arrays; then the fabrication of such arrays must be developed. Current versions of these detectors are also quite sensitive to red and near-IR light; future development should stress utilizing this broad-band capability or implementing blocking-filter concepts to reduce red sensitivity while maintaining the excellent UV response, depending on specific application.

4.2.3. Semiconductive Arrays

CCDs have brought about revolutionary increases in capability to record information at visible wavelengths, because of their high QE and their linear responses over a large dynamic range. In the ultraviolet, CCDs are less attractive, because of their much lower QEs as well as their excellent response to unwanted visible/red light. New developments are making these devices more attractive for UV work, particularly for near-UV applications where the "red leak" is not as important (e.g., spectroscopy of intrinsically blue QSOs. Future work should concentrate on reducing read noise, utilizing alternate materials, developing photon-counting versions of these detectors, and implementing very large format detector arrays for space-based applications.

Silicon-based CCDs — CCD detectors have recently made substantial gains in UV response, currently offering QEs significantly higher than those of photo-emissive detectors at NUV wavelengths above 200 nm (e.g., see Clampin 1999). However, for long, background-limited observations of faint sources, even a substantial QE advantage for a CCD detector will be overwhelmed by the read-noise penalty of repeated reads (required for cosmic ray rejection). Until CCD read-noise can be brought well under 1 e^- pixel^{-1} rms, CCDs will not compete successfully with MCP-based detectors for very faint spectroscopic applications in the NUV. At visible wavelengths, current CCDs can achieve QEs exceeding 90%, though improving the detector noise characteristics will further increase the sensitivity to the very faintest targets. The technological emphasis for the next frontier of space-based imaging is the development of very large format CCD mosaics to obtain wide fields

of view with high spatial resolution. In the previous section on mission concepts, we have baselined 16k × 16k arrays as a necessary size to open huge volumes of discovery space. However, even larger mosaics allow us to achieve wide fields with finer pixel sampling. Tied into the development of such large arrays is the need to attain high charge-transfer efficiencies and implement shielding against cosmic rays, especially if the orbit is outside the Earth's magnetosphere.

Alternate material photoconductive devices — Newer devices that employ materials with a larger band-gap energy, such as GaN or diamond, show promise for improved mid- and far-UV QE, for lower dark noise, and for better red rejection. However, the read-noise considerations for CCDs apply equally to these alternative materials. If implemented in a manner with significant read noise, they will not supplant photon-counters for sensitive astronomical applications.

Intensified semiconductive devices — An alternative path is to use semiconductive arrays for photon counting, so that read noise is not an issue. Coupling the photoelectron from an opaque photocathode (deposited on a smooth metal substrate) to an electron-bombarded CCD can yield substantially higher QE than MCP-based photon counters. These or other intensified semiconductive arrays, used for photon counting, promise to be extremely powerful and should receive attention for further development.

4.2.4. Microchannel Plate Detectors

Microchannel plate (MCP) devices are currently the detector of choice for most UV applications. This is primarily because these low-background photon counters can detect fainter sources than a CCD in any application with limited sensitivity, especially for observations in which the scientific goals permit multi-pixel binning. However, current QEs for MCP-based devices are typically ∼10-40%, depending on wavelength. These devices still have considerable potential for improvement, particularly in QE (new photocathode materials and new substrates) and in format size. UV astrophysics will benefit greatly from investments in these areas (see Siegmund 1999).

Photocathode materials — New opaque photocathodes deposited directly onto MCPs are currently being tested and may lead to substantial (factor of 2-3) QE increases in the near-UV. Long-term stability is an issue and remains to be demonstrated.

MCP substrate materials — Another potentially exciting technology, currently in a very early stage, is the so-called "advanced technology" MCP, based on silicon substrates rather than leaded-glass, and fabricated with techniques developed in the semiconductor industry. In addition to other potential advantages, these devices may offer more hospitable substrates for high-efficiency photocathodes, which can be extremely contamination-sensitive.

Larger formats — The number of effective resolution elements in MCP-based detectors is limited by the maximum available size of the MCPs and by the MCP pore spacing (currently 100 mm and ∼5 microns, respectively, though not simultaneously available). Mosaicking MCPs is also somewhat

tricky, with substantial gaps. Improvement in any or all of these areas will be highly beneficial.

4.3. Large Lightweight Precision Mirrors

4.3.1. Overarching Requirements

The science goals discussed here require large apertures, in addition to very efficient detectors, to achieve the requisite throughput. The science goals also benefit greatly from a low sky background, which can best be obtained in a high orbit. Mirrors and their supporting structures are generally the single largest mass contribution to astrophysics missions, thus limiting both aperture and orbit. Lightweight mirrors will allow large apertures to be placed into high orbit at modest cost.

Lightweight glass mirrors currently have areal densities of 30-40 kg m^{-2}, and beryllium mirrors are $\sim$20 kg m^{-2}. NGST has already begun investing in large lightweight optics, and is moving towards much lighter mirrors, with a goal of $\sim$10 kg m^{-2}. NGST and several other groups are already also making progress with deployable segmented mirrors, to accommodate current and expected future launch capabilities. This work will benefit the entire astronomical community.

However, the relatively short wavelengths of UV-visible light will place much more stringent constraints on large lightweight mirrors. Current efforts for NGST are not attempting to achieve performance better than diffraction-limited imaging at $\sim$1000 nm. For UV-visible use, the mirrors will need to be more accurately figured, to have smoother surfaces and to be non-contaminating. If deployable mirrors are used, the alignment requirements will be much more stringent, and if active surfaces are required they will need to be controlled much more accurately.

Large aperture — Throughput is the primary driver for large aperture sizes, with the moderate mission requiring an effective area of $A_{eff} > 2 \times 10^4$ cm^2 and the more ambitious missions requiring apertures to achieve $A_{eff} > 1 \times 10^5$ cm^2 — $\sim$100 times the UV throughput of HST, assuming major gains in detector QE (see above). Even with significant gains in detector efficiencies, these still imply apertures equivalent to diameters $\geq$4 m. The most advanced concept suggested here (Class II mission) also has angular-resolution requirements implying an aperture of $\sim$8 m for the primary mirror. When launch capabilities and costs are considered, the large aperture required for the Class II mission almost certainly requires a system that can be deployed from a more compact state. This effective aperture and resolution must be considered in addition to the other mirror requirements.

Very good figure and alignment — Likely mirror materials should be assessed for stiffness and figure accuracy. Actuation, deployment, and alignment systems should be developed to control large optical surfaces to requisite accuracies for UV-optical uses.

The Class Ib and II missions require diffraction-limited performance at 500 nm or overall wavefront error of about 1/14 waves (500 nm) rms. A two-optic telescope with some allowance for alignment error implies a primary figure error of about 1/25 waves (500 nm) rms. Figure error for

the Class II mission primary will be divided among several segments, which must also be co-phased to achieve this final figure tolerance. Mission Ia has a much less stringent requirement to produce resolution of only about 300 mas (80% encircled energy in a 300 mas diameter), thus permitting a looser figure specification (by a factor of a few) as well as more toleration of scatter.

It must be possible either (1) to manufacture the mirrors to this figure quality with sufficient stiffness to maintain the figure, or (2) to correct the mirror(s) to this figure quality in flight. Alignment techniques developed for large deployable systems (NGST) will almost certainly be inadequate for UV/visible applications and will require considerable refinement or development of alternative methods. Thermal effects on the mirror figure must also be understood and of acceptable magnitude. PSF correction could be accomplished actively using tertiary optics (see below), however, multiple reflections are not desirable in the UV and would require development of deformable gratings for a 1-bounce spectrograph.

Low scattering — Microroughness should be determined for likely lightweight materials. If relevant, attempts should be made to improve surface smoothness. For both spectroscopic and imaging applications, scattering from the mirror surfaces should be minimized, both for throughput and for control of unwanted light in the optical path. The current HST mirror has a microroughness of $\sim$25 Å (rms); the current state of the art for small ($<$ 50 cm) glass mirrors is more like $\sim$3 Å (rms). Whatever technology is used to manufacture the mirrors for the missions discussed above should be able to achieve a microroughness better than $\sim$ 10 Å (rms).

UV-friendly materials — Research into the outgassing properties and contamination potential of likely lightweight optic materials is essential. Contaminants, particularly molecular but also particulate, are deleterious to UV throughput: they decrease reflectance and increase scatter. Vigilant attention is required to assure that no part of the system, in particular the primary mirror / assembly, will introduce contamination onto the optical surfaces. Mirror substrates must also be manufactured of materials that will accept the requisite coatings needed for UV-visible observations. This is particularly true if the detectors to be used require cold windows or other contaminant attractors.

In the following sub-sections, we mention ongoing work in this field and comment on what additional steps will be needed for UV-optical applications.

4.3.2. Monoliths

Missions Ia and Ib can probably each be achieved with a single mirror. Mission II may be built of multiple monoliths or may have a core, high-performance monolith with smaller "outrigger" mirrors.

Lightweight glass or metal mirrors — Glass has a long track record for precision optical surfaces and for accepting a wide variety of coatings. Since solid glass mirrors of any significant aperture

are much too massive for spaceflight use, many creative approaches have been developed to create lightweight glass mirrors. Lightweighting is achieved by carving out a significant fraction of the mirror back or by casting mirrors with honeycomb back structures and curved fronts. An exciting recent development involves attaching a very thin ($\sim$ 1 mm thick) curved glass face-sheet to a honeycomb composite backing structure. A 2-m prototype is being fabricated under the NGST program, with apertures up to $\sim$ 4 m being considered (Burge & Angel 1999). Several other types of thin mirrors are being explored by NGST and other projects. These are flexible, highly actuated, and are made of materials such as Beryllium, Nickel, or glass.

Many of the open development issues for these large thin-face mirrors will be addressed by the already-productive NGST and related technology studies, including wavefront correction, actuator development, and connection of the glass to the composite backing. Wavefront correction will be much more challenging for UV wavelengths than for the currently targeted 1000 nm. However, this appears to be a very promising approach for precision UV monoliths.

Composite mirrors — The possibility of manufacturing large mirrors or mirror segments from very lightweight composites is very exciting, as it could reach areal densities of a few kg m^{-2} (depending on mirror size), with corresponding reductions in mass for supporting structures. Fabricating the mirror(s) and support structure of the same materials would eliminate themal stresses in telescopes. Several composite mirror technologies feature replication instead of grinding and polishing; these techniques could be great cost savers as well as time savers. Double replication techniques are being explored that would allow replication of existing (already fabricated) telescope mirrors.

Some of the major concerns about composite mirrors are being addressed in other development programs. These include material behavior in a high-radiation environment, print-through in manufacture, size of piece that can be made, figure accuracy, mounting, thermal stability, and wavefront control. Other major concerns are unique to the UV and require some investment before these mirrors are validated as useful for spaceflight use. These include the potential for outgassing and potential self-contamination, adhesion of coatings, considerably better wavefront control (than currently targeted), and surface microroughness.

High-density cast silicon carbide — Although several different types of SiC are useful for fabrication of visible wavelength mirrors, none of them have demonstrated suitability for UV applications, having low reflectivity and/or poor surface qualities. However, high-density cast SiC has recently been produced that shows promise for UV mirror fabrication. The high reflectivity, excellent figuring and polishing capabilities, and low-cost manufacturing process combine to make this SiC a promising UV mirror material, deserving of further exploration and possible development.

4.3.3. Deployable Systems

The more moderate science goals described above can probably be achieved with a monolithic ~4m passive mirror (perhaps with dimensions as large as 4m × 8m). However, the more ambitious science goals of the Class II mission will require deployment of multiple segments. Numerous concepts exist (table folds, fixed center with petals, arrays of hexagonal mirrors, etc.) and several prototypes are under development and testing for NGST or other programs. We anticipate that robust, dependable, lightweight deployment systems will be developed in these other programs and will be adaptable to use for a large UV-optical telescope. If these deployment schemes are to be used for UV-visible observations, they must address usual issues of optical figure and contamination control.

4.3.4. Actuators and Active Surfaces

Actuators and active surfaces are required by future large space missions (e.g., NGST) if they are to achieve their challenging performance goals. Active optics are required for wavefront correction of large, lightweight mirrors. Actuators are also required for alignment and co-phasing between sections of segmented mirrors.

Wavefront control — NGST will probably incorporate a flat deformable mirror (DM) system to produce substantial figure correction of the telescope, thereby permitting the use of a lower tolerance (and lower cost) telescope. However, UV designs are driven to use the fewest optics possible (to avoid throughput losses at each reflection). The extra reflections required to produce a pupil image on the DM, and thus to provide correction over a substantial field, lead to unacceptable throughput losses for UV applications. UV-optical telescope designs likely will not include an extra fold flat for this purpose.

If the monolithic ~4m primary mirrors required by Missions Ia or Ib are lightweighted (e.g., thin face-sheets or composite shells), they almost certainly will require active control. These systems will probably achieve the required high accuracy figure by using actuators attached directly to the primary facesheet, or possibly to a thin backing structure. Actuators may also be required to maintain a highly corrected figure throughout changing thermal conditions. Large UV-optical telescopes require development of an actuation system for monitoring and controlling the wavefront, using the primary mirror assembly.

Cophasing — The segmented mirror approach required for the Class II 8 m aperture must have mechanisms to allow on-orbit co-phasing of the segments. This co-phasing aspect is similar to several of the NGST telescope proposals and will be able to build on NGST experience. However, although the Class II telescope is comparable in size to NGST, the goal of diffraction-limited operation near 500 nm is more stringent than the NGST near-IR goal, and the figure correction must be correspondingly better. Metrology and control systems required for large UV-optical telescopes are

considerably more challenging than what is being studied for NGST.

4.4. UV-Optical Components and Coatings

It is important to use every aspect of the optical system to maximize throughput when observing faint astronomical targets. Efficient UV optical systems are therefore reflective (no transmissive materials are efficient at UV wavelengths below ∼200 nm) and contain as few reflections as possible (to avoid significant throughput losses at each bounce). Throughput can be maximized with clever optical system designs and by judicious use of optical materials and coatings. New scientific capabilities may be realized with the development of new materials or optical components. Because of the extreme sensitivity of UV reflectance to contamination, careful attention must be paid to possible contamination sources (and perhaps to new cleaning techniques) with the introduction of these new materials.

4.4.1. Gratings

The scientific problems discussed above all require high throughput. If gratings are to be used in spectroscopic applications, it is essential that they have high efficiency and produce low scatter. Traditional mechanically ruled gratings may achieve groove efficiencies $> 70\%$ but suffer from considerable scattered light, especially at the shortest wavelengths. The most promising future grating technology involves chemically etching diffractive structures directly onto optical substrates (rather than mechanical fabrication). Large formats can be manufactured now, with no physical reasons why format size cannot be substantially further increased. New technologies spawned from the semiconductor and micro-optics industry have a bright future for creating UV diffraction gratings (see Wilkinson 1999). Future development work is likely to be most promising in the area of aberration control, larger formats, improved efficiency, and higher groove density.

Holographic gratings — Holographic gratings are today's standard gratings for most UV spectroscopic instruments. This is largely due to their scattering (typically around 10^{-5} Å^{-1}), and to their large sizes. Two coherent lasers are used to expose an interference pattern on a substrate coated with photoresist. Rulings are then formed through a chemical etching process, creating smooth sinusoidal facets with a (first-order) groove efficiency of ∼30%. A blaze function is then introduced, using ion etching to ablate material and create triangular grooves. Resulting efficiencies are currently ∼65%, but are expected to exceed 70% as the ion-etching technology is refined, with a coincident increase in the ruling densities. The holographic fabrication process allows non-parallel rulings, useful for controlling aberrations in the instrument light path. In the next five years, we can expect the aberration control afforded by holographic recording techniques to expand significantly with new techniques for introducing aberrated wavefronts into the interference patterns.

Direct writing — Although direct-writing technologies are still in an early stage of development, they are able to produce gratings with very low scatter, efficient groove shapes, and excellent aberration correction. The three direct-write technologies currently in development (laser writing, e^- beam writing, and excimer laser beam ablation) all use a laser or electron beam to expose photoresist in a controlled fashion and to create arbitrary groove shapes. Diffraction gratings using these techniques have been created with 85% groove efficiencies in the visible and with scatter kept to around 10^{-5} Å^{-1}.

Direct writing can also create specific groove patterns for aberration control by controlling the laser's path over the optical substrate. This is likely to become the preferred method to introduce aberration control, because any computer-generated interference pattern can be drawn onto the substrate. Current direct laser writing technologies have been used to create format sizes in excess of 300 mm-square, but much larger sizes should be feasible.

Today, direct-write technologies are too immature for use in high-resolution, UV spectrometers due to low ruling densities, 100-200 g mm^{-1}. However, the industry is moving quickly and much higher groove densities are likely to be achievable in about five years. UV-optical astronomy stands to benefit greatly from efficient, large, corrective gratings.

4.4.2. Optical Coatings

Efficient coatings are needed to maximize throughput. High reflectivities at visible wavelengths are achieved regularly, but the situation is not as positive at UV wavelengths, particularly below 200 nm (see Keski-Kuha et al. 1999). Aluminum has the highest intrinsic reflectance of any known material in the UV above 100 nm, but surface oxidation can severely degrade reflectance below 200 nm. Protective optical overcoatings can help to protect the aluminum and optimize component reflectivity. Coatings, particularly multilayer coatings, can be used to maximize throughput of desired wavelengths and to minimize the transmission of unwanted wavelengths. Surface contamination can severely degrade performance of UV optical components, so strict cleanliness control is required for optimum performance. Modest gains could be achieved in reflective efficiency and scattering properties in the mid-UV region. Large gains may be made in the FUV and EUV regions and in obtaining broad spectral response. Significant efficiency gains may be realizable by using multilayer coatings to "tune" the wavelength response, to suppress the red leak, or to form UV beamsplitters by combining coatings.

Protected aluminum — Protective overcoatings of magnesium fluoride or lithium fluoride can extend the useful range of aluminum mirrors to wavelengths as short as 115 nm and 102.5 nm, respectively. Al+MgF2 is a highly reliable coating, and in the absence of degradation caused by the deposition of contaminants, the reflectance is stable in space. The UV reflectance between 115 nm and 200 nm can exceed 80% (achieved on the STIS and COSTAR optics). LiF overcoating is hygroscopic and exhibits reflectance deterioration and increased scatter with age. Therefore, the

exposure of Al+LiF mirrors to humidity must be controlled carefully. Applying this coating yields UV reflectances of 50 – 75% between 102.5 nm and 200 nm.

Chemically Vapor Deposited SiC — Polished CVD SiC is the current coating material of choice for wavelengths below 100 nm. It exhibits a high normal incidence reflectance of over 40% in the spectral region above 60 nm, has good thermal and mechanical properties, and provides low scatter surfaces. The reflectance degrades slightly with time, but can be returned to its original value by cleaning. CVD SiC optical surfaces must be protected from atomic oxygen exposure in low Earth orbits. CVD SiC deposition is a high-temperature process and not suitable for coating conventional mirror components or diffraction gratings.

SiC and boron carbide films — The reflectance for both SiC and boron carbide thin film coatings (ion beam deposition) is lower than that of CVD SiC but higher than any conventional coating. The reflectance of both materials degrades slightly with time due to oxidation of the surface, but stabilizes with reflectance of over 35% above 90 nm and 70 nm, respectively. Acceptable performance can be maintained by protecting SiC coated optical surfaces from ram direction effects. Ion beam deposited boron carbide thin-film coating appears to be a more robust coating than SiC, able to withstand short-term exposure to atomic oxygen in low Earth orbit.

Broad-band multilayer coatings — Multilayer coatings involve various combinations of undercoating, overcoating, and doped materials. They can be used as filters (e.g., for red leak rejection) or for enhanced reflectivity in specific spectral ranges. This field is just beginning to be explored, with significant work in materials, manufacturing, performance, and long-term stability still to be done. One particularly appealing use of multilayer coatings is as beam splitters, which could be used to increase observing efficiency of instruments by afactor of two or better. Other applications for beam splitters are for tracking using red light during UV observations without requiring a separate startracker telescope.

Diamond films — Diamond reflectivities in the 60 nm to 100 nm range could be higher than for CVD SiC but have not yet been realized. Small prototypes have been produced with acceptable smoothness for UV-visible applications, and progress is being made in polishing diamond. Extensive development work is needed to produce figured diamond mirrors with sizes and surface smoothness useful for EUV/FUV astronomical applications.

Contamination and cleaning — UV coatings are notoriously sensitive to highly absorbing molecular contaminants, which cause reflectance degradation and increased scatter. Exposure to UV light causes the contaminant to photopolymerize. The most commonly used technique for cleaning UV optics is a solvent flush, with the solvent depending on the coating and the contamination (if known). Techniques for removing photopolymerized contamination include mild abrasive cleaning with calcium carbonate and ion beam cleaning. Cleaning to remove particulates is only attempted in an emergency, as many of the coatings are soft and scratch easily; good success has resulted from the use of CO_2 snowflake spray. New cleaning techniques will almost certainly need to be developed as new mirror materials, coating materials, and contamination sources are incorporated

into UV-optical instrumentation.

4.4.3. Other Optical Components

Multi-object Spectroscopy

In spectroscopic applications, where light from stars and galaxies is dispersed for analysis, considerable gains in efficiency can be obtained by observing multiple objects or positions in the focal plane simultaneously. Multiplexing gains of over 1000 are routinely obtained in ground-based optical/NIR multi-object-spectroscopic (MOS) instruments.

Micromirror arrays — Two concepts currently under development use micromirror arrays as programmable masks. In the "straight-through" arrangement, micromirrors function as an array of trapdoors, reflecting/blocking unwanted light but opening a "trapdoor" for the desired rays. Although this concept is still in early development, it shows great promise for UV applications because of the clear path for the desired photons. In the "selective bounce" concept, light is reflected either into a spectrograph (from desired objects) or into a light baffle (unwanted). In principle, such arrays should be coatable for use in the FUV and even EUV, although methods need to be verified for applying UV coatings and for manufacturing mirrors with the requisite surface quality. One advantage over application of these techniques for NGST (at IR wavelengths) is that UV-optical observations do not require operation at cryogenic temperatures.

UV-transmitting fibers — Many ground-based MOS instruments utilize visible-light-transmitting fibers to feed light from selected targets into a spectrograph. Although most optical fibers are opaque in the UV, one type of fused silica fiber will transmit light to wavelengths as short as 180 nm. It would be of great value to develop transmissive fibers for use at shorter wavelengths, to reach many of the most important diagnostic spectral lines. Considerable development work also needs to be done to couple these fibers into a powered optical system (current lenslet arrays also do not transmit shortward of 180 nm), to bundle them, and to understand their flexibility properties and their behavior under extreme thermal conditions.

Filters

Much of the discussion on coatings above is directly relevant to filters. Two types of filters may be required for the missions described: red-blocking filters and wavelength-isolating filters.

Red-blocking filters are required with many current UV-visible detectors, particularly with CCDs. Most red-blocking filters in use today are Woods filters — very thin layers of alkali metal coatings sandwiched between layers of glass. These generally have very low transmission in the UV (as well as blocking the red light), and they are prone to develop pinholes or other instabilities. New versions of Woods filters appear to have considerably better stability, but the lack of UV transmission remains a problem.

A new type of red-blocking filter in early development, the "nanohole filter", consists of a thin gold film with a closely-packed array of holes whose diameters are approximately the longest wavelength of light to be transmitted. Although there is still considerable work to be done in fabricating these filters, they are expected to have good transmittance and excellent long-wavelength rejection. Multiple potential avenues for development of red-blocking filters should be explored.

Tunable filters for broad-band and narrow-band imaging could provide access to numerous diagnostic lines at arbitrary redshift. At visible wavelengths, Fabry-Perot etalons with coated glass surfaces are often employed in ground-based instruments, though application to UV wavelengths is dubious with this technology. Acousto-optical-tuneable-filters (AOTFs) have the potential of providing a bandwidth selectable across $\sim$1 octave. A tunable RF signal is applied across a birefringent crystal, resulting in a selectable output wavelength. AOTFs have been built and are in use at IR wavelengths on ground-based instruments. Transmission efficiencies are not known. For these filters to become a viable option at UV-visible wavelengths, considerable work must be done to characterize birefringent UV-transmitting crystals, followed by extensive prototype development.

4.5. Summary

The science goals set forth in the beginning of this document all require significant gains over current or anticipated UV-visible instrumentation. These goals cannot be achieved without several major technology developments that will not happen elsewhere:

- A sustained and healthy investment in the development of high-QE, low-noise detectors, such as the 3-D STJ/TES devices, for use at UV-visible wavelengths.
- Continued improvements to semiconductive arrays (e.g., CCDs) and microchannel-plate detectors, to achieve simultaneously high QE, large format, and low noise performance.
- Development of large, precision, lightweight mirror surfaces with good microroughness properties.
- Design and prototype development of actuation, metrology, and control for thin primary mirrors.
- Continued investment in UV-visible optical components and coatings.

A number of more modest technology developments are also required or desired and are discussed more fully in the preceding text.

5. APPENDIX 1 – Report to HST Second-Decade Committee

At the UVOWG meeting at GSFC in October, Bob Brown presented an overview of the activities and issues being considered by the HST 2nd Decade Committee. He invited input from the UVOWG, and also from each of us as individual astronomers. This appendix summarizes the thoughts and suggested projects given by the UVOWG to the *HST Second Decade Committee*, regarding the importance of HST UV/O science and HST Key/Legacy Projects. In fashioning the science drivers for SUVO missions, it is important to think about what HST might accomplish in its next 11 years, both in terms of new UV/O science and in support of an SUVO mission (along the lines of HST's support of NGST).

Start of letter to Bob Brown:

At our recent UVOWG meeting (October 21-22, 1998) we discussed with you the potential benefits of providing the HST Second Decade Committee with suggestions for "Key Projects" or "Legacy Projects". Our input would be in the context of connections between HST and a future UV-Optical space mission (SUVO) under consideration by our working group.

See http://casa.colorado.edu/∼uvconf/ for material on the activities of the UVOWG and a preliminary description of the SUVO mission. Based on discussions with members of the UVOWG, we list below some of our thoughts.

First, we all agree that the second decade of HST should be an extraordinary era in UVO space astronomy, with powerful instruments for doing UVO imaging (WFC-3, ACS, STIS) and spectroscopy (STIS, COS). Your committee is in the enviable position of choosing how to optimize the HST science with such instruments. We observe that your Committee is considering recommending implementation of large-scale "Key Projects" (100-1000 orbits), to take advantage of the powerful capabilities of HST and to simplify operations. We also recognize the vast potential of using HST to prepare for the significant gains in throughput available with NGST (0.6 to ~ 20 μm) and SUVO (0.1 to 1 μm). The "Legacy Projects" described below would be of significant size (500-1000 orbits or more, spread over several years, and would utilize the large databases of UV/O targets provided by the GALEX mission and the Sloan Digital Sky Survey.

The UVOWG suggestions for these large projects are:

1. **SPECTROSCOPIC SURVEY OF QSOs (Legacy Project, 750 orbits)**

   One-orbit spectroscopic "snapshots" of 500 QSOs discovered by GALEX and SDSS, using COS low-resolution (0.5 Å) gratings, to attain S/N = 7-10 spectra. All 500 QSOs would be observed with the far-UV grating (G140L). Half of the brighter targets would be observed in the near-UV (G230L) from 1700 – 3200 Å. The key science would be to measure QSO

rest-frame UV and EUV fluxes for qualification of the best targets for IGM and galactic halo science. Of great importance is to discover which targets have damped Lyα and Ly-limit systems. Some targets could be followed up with long duration HST+COS/STIS exposures at higher resolution; however, this survey would define a valuable sample of targets to be pursued by SUVO.

2. **QSO ABSORPTION-LINE SURVEY (Key Project, 1700 orbits minimum)**

   With COS, it should be possible to perform a modest (100-target) QSO absorption-line survey similar to the HST/FOS Key Project, but at 15 times better resolution ($R = 20,000$ with S/N = 20) for the far-UV wavelength range 1150 – 1700 Å. Selected bright targets would also be observed at mid- and near-UV wavelengths with STIS or COS. This survey would provide a significant study of QSO absorption lines (H I and metal-line systems). The COS GTO program will devote about 300 orbits to begin such a study, but much more will be needed. The key science would include an IGM baryon census, study of IGM large-scale structure and its relation to galaxy distributions, the abundance history of the IGM, and galaxy halos. For 100 QSOs with fluxes between $F_\lambda = (1-5) \times 10^{-15}$ ergs cm^{-2} s^{-1} Å^{-1}, COS could do the two far-UV settings in about 1700 orbits. Observing the mid-UV settings and attaining $S/N = 30$ would require a far greater number of orbits, and would probably require waiting for SUVO.

3. **UVO IMAGING SURVEY OF NEARBY GALAXIES (Legacy: 1000 orbits)**

   The two unique scientific capabilities of HST - high angular resolution and access to the vacuum-UV - should be exploited to construct a new "Hubble Atlas" of galaxies. This would be of immense value in its own right, serving to document the UVO morphology and structure of the local galactic population. It would be of even greater value when used as a basis for differential comparison to images of high-redshift galaxies taken at similar rest-frame wavelengths by NGST. Finally, it would serve as an essential pathfinder for detailed UV spectroscopic investigations of the stellar and interstellar components of these galaxies by SUVO. Moderately deep images with ACS or WFC-3 at roughly 2000, 4000, and 8000 Å would be acquired of a sample large enough to populate the multi-dimensional manifold of Hubble type, absolute magnitude, metallicity, and effective surface brightness (several hundred galaxies). In order to optimize the linear resolution of the images, the nearest galaxies of the appropriate types should be selected, and this would necessitate constructing mosaics in most cases. This sample selection would make it possible to resolve the brightest portion of the stellar population in many cases. The UV images would be especially valuable. In star-forming galaxies, this light traces the youngest stellar population, while in galaxies with only an old stellar population, the UV light comes from post-main-sequence stars whose relative numbers and properties provide strong tests of current models of stellar evolution. To date, only a rather small and heterogenous sample of local galaxies has been imaged in this wavelength domain.

4. **UVO IMAGING SURVEY OF GAS-DYNAMICAL SYSTEMS (>500 orbits)**

The recent scientific literature is replete with hydrodynamic simulations of shock interactions with interstellar clouds and the formation and propagation of astrophysical jets. Shock waves produced by supernovae can heat the ISM, determine the velocity dispersion of interstellar clouds, and govern the scale height of the ISM in galaxies. Jets are ubiquitous in astrophysics and the disk/jet connection is an important component of numerous objects, such as young stellar objects, CVs, symbiotic stars, and active galactic nuclei. The radiative shocks in the nearest star forming regions and supernova remnants are the best laboratories for studying high mach number flows and their effects on the ISM and star formation in galaxies. Physical conditions such as densities and temperatures can be deduced by mapping the relative flux distributions of diagnostic emission lines in the UV and optical in radiating filaments using the narrow-band imaging capabilities of WFC-3, STIS, and, to some extent, ACS. Perhaps most importantly, the high spatial resolution and wide field of view afforded by HST allows us to track the motions of these gasdynamical flows on timescales shorter than the typical radiative cooling times. There are hundreds of radiative shocks and filaments in the nearest star forming regions (e.g., Taurus-Auriga, Perseus, Orion) and supernova remnants for testing hydrodynamical models of jets and blast waves. To obtain multi-epoch observations of a sample of 20 representative radiative flows in several of the brightest emission lines (e.g., Hα, [S II], [O III], [O II], Mg II) requires ~ 200 orbits per epoch. Programs with WFPC2 have already begun to track several flows (which hopefully can be continued through the life of HST), however, these programs are generally restricted to the brightest sources and limited fields of view. This Key Project would seek sources with favorable geometries and viewing angles for revealing the physics of supersonic interactions of the stellar ejecta with the ISM.

Other studies might include but not be limited to:

5. **STIS SPECTROSCOPIC SURVEY OF GALAXY CORES AND BLACK HOLES**

6. **UVO MONITORING OF PLANETARY ATMOSPHERES AND AURORAE IN THE GAS GIANTS**

7. **CHEMISTRY OF THE COLD INTERSTELLAR MEDIUM**

8. **UVO SPECTROSCOPIC SURVEY OF T TAURI STARS**

More detailed discussions of some of the Projects follow below:

1. SPECTROSCOPIC SURVEY OF QSOs (Legacy Project, 500 orbits)

The Cosmic Origins Spectrograph (COS) will provide a significant increase in UV spectroscopic throughput on HST. The magnitude limit for moderate resolution, faint-object spectroscopy will increase from about V = 15 mag (GHRS, STIS) to $V = 17.5$ mag (COS). Because the QSO luminosity function rises steeply at $V > 17$, GALEX will find thousands of potential targets for spectroscopic studies in the fields of interstellar medium (ISM), intergalactic medium (IGM), galactic halos, quasar absorption lines (QALs), and cosmology. Studies of the UV continua and emission lines in the quasars themselves will be of significant value. For a few important scientific programs (D/H, baryon census of the IGM, large-scale structure in Lyα clouds, He II Gunn-Peterson effect, and metal evolution), the GALEX targets will be a treasure trove.

The GALEX website suggests that they will find 10^6 new quasars in the All-Sky imaging mode. Of these, they will obtain 10^4 spectra; approximately 1000 targets will be appropriate for He II studies at redshifts $2 < z < 4$. Many targets will be in the northern continuous viewing zone (CVZ). Sorting through these targets to find the best sources for longer-duration spectra with COS and SUVO would best be done through 1-orbit "UV spectroscopic snapshots" with the low-resolution gratings (G140L, G230L). In addition to "UV-qualifying" these targets for moderate-resolution spectroscopy, there will be significant scientific gains from this large survey:

- Measure low-z QSO UV/EUV continua and emission-line fluxes
- Measure the QSO contributions to metagalactic ionizing background
- Search the QSO sightlines for rare damped and Lyman-limit absorbers
- Study numerous sightlines through galaxy halos
- Search for "clear sightlines" for He II studies
- Find partial Lyman-limit systems for D/H and metal studies

To do the really interesting science for studies of IGM and galactic halos, one needs to reach QSOs at $B = 18 - 19$ magnitude. At $B = 18$, quasars are sufficiently abundant (about 1 per square degree) to provide many targets associated with galaxy halos and to map the topology of Lyα clouds. The QSO luminosity function rises rapidly between $B = 18 - 19$. The current flux limit for moderate resolution UV spectroscopy with GHRS, STIS, and FUSE is $F_\lambda = 10^{-14}$ ergs cm^{-2} s^{-1} Å^{-1} ($V \approx 15$). From COS sensitivity curves, we estimate that 19$^{\rm th}$ magnitude QSOs (10^{-16} flux) could be adequately observed with COS/G140L (0.5 Å resolution) in 1 orbit, to obtain 0.015 cts/s/resolution element or S/N = 7 (higher in CVZ). Half of the brighter targets could then be observed in the longer

wavelength band (G230L, from 1700-3200 Å) in 250 orbits. A dedicated survey of 750 orbits spread over 5 years would provide a major legacy of HST/COS that would continue into the SUVO era.

2. QSO ABSORPTION-LINE SURVEY (Key Project, 1700 orbits minimum)

One of the original HST Key Projects involved a spectroscopic survey of QSO absorption lines with HST/FOS (Bahcall et al. 1993). That survey observed 83 QSOs with FOS ($R = 1300$) and revealed 1129 Ly-alpha lines, 107 C IV systems, 41 O VI systems, 16 Lyman-limit systems, and 1 damped Lyα absorber. The resolution of these measurements is too low to derive useful abundances, kinematics, or physical condition information about the absorbers. Using a subset of these targets (Jannuzi et al. 1998) the Key Project team derived scientific results (Weymann et al. 1998) based on 987 Lyα absorption lines toward 63 QSOs, for lines complete to about 0.24 Å rest equivalent width. With COS, it would be desirable to perform a similar survey, at 15 times better resolution ($R = 20,000$ with S/N = 20-30) for the full wavelength range 1150-3200 Å. Even doing just the two far-UV settings (1150-1700 Å) for lines at $z < 0.2$ would be significant improvement over FOS.

This survey would provide a significant study of QSO absorption lines of H I absorbers and related metal-line systems. Towards QSOs located in well-studied galaxy fields at $z < 0.2$, it would be possible to study the baryonic large-scale structure in the IGM, and its relation to galaxy distributions. The key metal absorption lines (C IV 1548,1551 and O VI 1032,1038) can also be measured, to study the abundance history of the IGM and galaxy halos, and to search for metallicity gradients connected with the galactic winds and tidal stripping from early star formnation.

A "modest" survey would require observing 100 QSOs with a wide range of redshifts. The project would require observing QSOs with typical far-UV fluxes $F_\lambda = (1-5) \times 10^{-15}$ — see Table 2.3 in the COS proposal. The number of QSOs as large as 100 is required to build up statistical information about the rare Lyman-limit and damped absorption systems and the Lya forest systems that contain trace metals. As with galaxy surveys, we need many sightlines to probe the intricate large-scale structure predicted by IGM simulations. The Lyα clouds are much more numerous than L^* galaxies, and should thus provide excellent probes of these filaments and voids.

Such a survey, in the COS far-UV band only (1150–1700 Å), requires two settings per target. In the photon-counting limit, the signal-to-noise ratio after N orbits (3000 sec each) would be:

$$(S/N) = (12.2) \left[\frac{N}{10}\right]^{1/2} \left[\frac{F_\lambda}{10^{-15}}\right]^{1/2} \tag{1}$$

Attaining S/N = 20–30 will require a sizeable amount of integration. Instead of picking a single representative number for the QSO fluxes, it is probably best to consider a "logarithmic distribution" of 10 faint QSOs ($F_\lambda = 1 \times 10^{-15}$), 30 with 3×10^{-15}, and 60 with 5×10^{-15}, chosen from the GALEX and Sloan targets. Many would be chosen in selected fields, including those studied in depth by the Sloan survey of galaxy distributions, those in the CVZ, and QSOs in one of the Hubble Deep Fields. To obtain S/N = 20 at R = 20,000 for each far-UV setting with COS requires about

27, 9, and 5 orbits, respectively, for fluxes of $(1, 3, 5) \times 10^{-15}$. The ensemble of 100 targets would thus require around 1700 orbits for two FUV settings. Getting the longer wavelengths would add observing time, and attaining S/N = 30 would double the exposures.

Thus, the "modest" project for S/N = 20-30 would require 1700-3400 orbits, which is about far more time than has gone to previous individual HST Key projects. Although this would be an extremely valuable IGM survey, it would still not address many important science questions that require working on fainter QSOs or require spectra at significantly higher S/N. Observations of fainter QSOs would be needed to go after He II absorption, to study "double sightlines as probes of cloud size, and to find damped Lya systems and Lyman-limit systems, which are quite rare at low redshift. Spectra with S/N = 30 are about the minimum one would want to use for high-quality studies of abundances and physical conditions. For many of the objects, it is likely that S/N = 50 spectra would be required to pull out abundances of particularly important elements.

This exercise illustrates well the photon-starved aspect of extragalactic UV spectroscopy with HST, even with a high-throughput spectrograph such as COS. Some of the project could be done with HST, but it would require a huge allocation of observing time. We conclude that we will not be very far along in this subject area by the time HST ends its life in 2010.

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