UV-Optical Missions for Space Astrophysics Detector Technology Development

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Abstract

I present science goals and mission concepts that require ultraviolet-optical detector development for space-based applications during the next two decades. A broad range of science objectives in NASA's *Astronomical Search for Origins* and *Structure and Evolution of the Universe* themes can be addressed by imaging and spectroscopic studies at UV-optical wavelengths, from detecting and characterizing extra-solar planets to tracing large-scale structure and the evolution of galaxies via intergalactic absorption lines. I emphasize the need for detector development that yields large formats, high quantum efficiencies, very low intrinsic noise, and broad spectral response. I also strongly encourage the development of photon-counting energy-resolving detectors for UV-optical applications in both 1-d and 2-d array formats.

1. Introduction

Optical observations have been the mainstay of astronomy for centuries, and the spectacular images made by the *Hubble Space Telescope* (*HST*) have continued this tradition of discovery into the modern age. Over the past three decades, ultraviolet astronomy from space has provided access to a rich range of diagnostic atomic and molecular absorption and emission features from species and ionization states not available in other wavebands, as well as the majority of radiated energy from massive stars in the nearby Universe. By combining UV-optical data with observations made at gamma-ray, X-ray, infrared, and radio wavelengths, we bring to bear for the first time in the history of science the capability to study the cosmos across the entire electromagnetic spectrum. It is often said that we are in a "Golden Age" of astronomy. The next several decades promise to deliver exciting discoveries that will engage the scientific community and public alike, arising from over a dozen newly commissioned ground-based optical-IR telescopes of 6 to possibly 30 meters in diameter, large mm-wave and radio interferometric arrays, and a plethora of powerful space telescopes included in the new NASA Long Range Strategic Plan. I believe that UV-optical space missions will play a vital role in increasing our understanding of the Universe during the coming decades. Much of this discovery potential will stem from advances made in UV-optical space detector technologies. In the following sections, I summarize small, moderate, and large UV-optical space telescope initiatives that will provide some of the most useful data for building a coherent model of the origins and evolution of planets, stars, galaxies, and the Universe, mentioning key requirements for detector technology development as I proceed.

2. UV-Optical Space Missions

I begin with an overview in the form of mission roadmaps that address science objectives in the *Origins* and *SEU* themes. Figures 1 and 2 show the nominal mission roadmaps for each of the themes and I have added UV-optical missions that contribute scientifically and technologically to achieving NASA's goals. Missions currently in the *Origins* roadmap are described in the most recent overview called *Origins 2000*. Those in the *SEU* roadmap are described in the *Cosmic Journeys* booklet. The principal science goals, mission concepts, and technology roadmaps for each space observatory are detailed in these documents. I briefly discuss the additional UV-optical missions below.

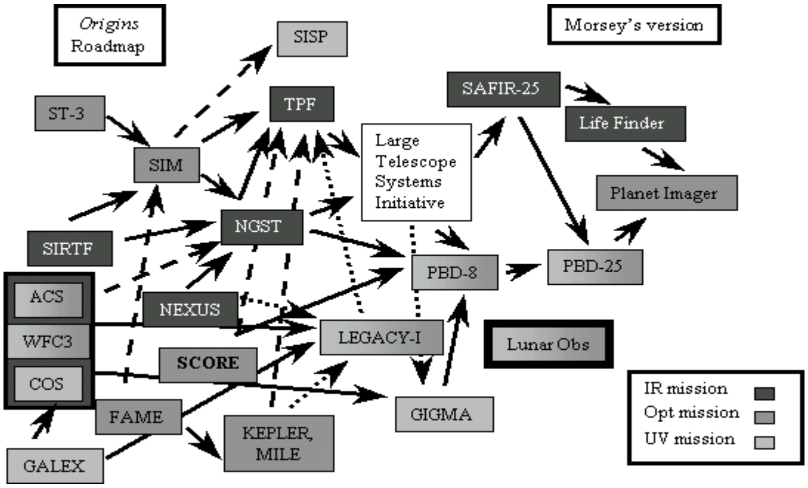


Figure 1

The missions in Figures 1 and 2 are shaded by wavelength region, though these boundaries are becoming increasingly blurred. Scientifically, as we probe to higher and higher redshifts, radiation which was emitted in one wavelength region is received here on Earth in another. For example, the *Next Generation Space Telescope* (*NGST*) will study light in the 1-5 mm region that originated from the first stars at UV-optical wavelengths. In many ways, *NGST* is an ultraviolet-optical science mission using infrared technology. From a technical standpoint, detectors employing superconductors or bolometers, for example, have applications from the X-rays to the far-infrared and radio. Thus, wavelength domains that have traditionally had very little inter-dependence technologically, now share a common need for developing space-based cryogenic systems that obtain sub-1K temperatures on orbit.

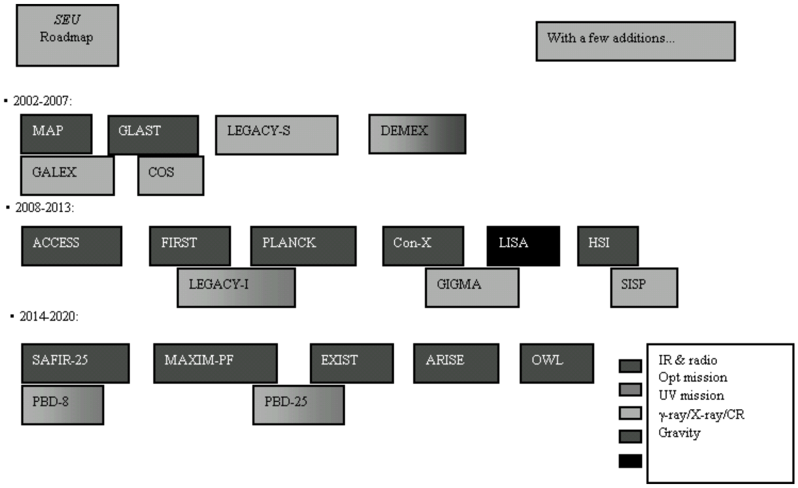


Figure 2

Brief descriptions of the individual UV-optical mission concepts follow. I note those mission concepts that are being developed by other U.S.-based groups, and which I support. I do not mention ESA missions or mission concepts, though the goals of missions like *GAIA* clearly overlap with those I discuss.

2.1 Origins Missions

The *Origins* theme is defined by two fundamental questions: "Where did we come from?" and "Are we alone?" The power and profundity of these questions lies in that any school age kid may understand what it means to ask them, and yet they require our most creative scientific minds and frontier technology to attempt to answer them. They also require patience and dedication to pursue the answers step by step over the decades it will take to develop a mission as powerful as the *Planet Imager* that actually allows us to investigate other Earth-like planets in detail. But without question such a far-view vision, no matter how impractical it may seem today, is necessary to provide direction and impetus to our current efforts.

There are four scientific goals of the *Origins* program: (1) "How did galaxies form in the early Universe?" (2) "How do stars and planets form and evolve?" (3) "Are there habitable planets orbiting other stars?" (4) "How and when does life form and evolve?" Clearly, UV-optical observations have contributed greatly to our pursuit of the first two astrophysically oriented questions, and, in my view, will continue to do so in the future. I also believe that these wavelengths will yield unique spectroscopic signatures of organic molecules in the interstellar medium (ISM) and planetary atmospheres, in the same way that they have provided rich diagnostics for so many other fields of astrophysics, that may shed light on the other astrobiology related questions.

HST-ACS, COS, WFC3 — In this time of planning future missions and charting out roadmaps, it is easy to forget that *HST* will be upgraded with three new science instruments in the next few years, and that each of them will provide significant gains in sensitivity over current cameras and spectrographs. I mention these instruments because the performance they achieve in the UV, optical, and near-IR will set the benchmark against which to compare the performance of future missions and instruments. The *Advanced Camera for Surveys* (*ACS*) will fly the largest CCD detector in space astronomy to date – a 4096× 4096 pixel wide-field camera with high quantum efficiency, large field of view, and an image scale of 50 mas/pixel – paving the way to future large-format mosaic cameras. The *Wide Field Camera 3* (*WFC3*) also will have a 4096× 4096 pixel wide-field UV-optical camera, but with a pixel scale of 40 mas/pixel. The *ACS* wide-field camera is optimized for sensitivity at red wavelengths and contains a versatile set of broad-band filters for mapping galaxies and clusters over a large redshift range. The *WFC3* CCD camera will be optimized for sensitivity at blue and NUV wavelengths for studying starburst regions and stellar populations. It will also contain a large set of narrow-band filters for imaging star forming regions, supernova remnants, planetary nebulae, and other ionized gaseous environments, as well as planets, their satellites, comets and other bodies in the Solar System. *WFC3* will image in the near-IR between ~0.8 – 1.7 mm using a 1024× 1024 pixel array and an assortment of broad-band, medium-band, and narrow-band filters. The *Cosmic Origins Spectrograph* (*COS*) is an ultraviolet spectrograph optimized for point source spectroscopy over the wavelength range 1150 – 3200 Å at medium (R ≈ 20,000) and low (R ~ 2000) resolutions. Once installed, *COS* will deliver the first order of magnitude gain in sensitivity for UV spectroscopy in over a decade for studying interstellar and intergalactic gas, galaxies and starbursts, stars and stellar winds, and Solar System objects. I note that in addition to the frontier discoveries these three instruments will make aboard the flagship *HST* observatory, they will also lay the foundation for *NGST* studies of very high redshift objects by accumulating UV-optical data on nearby targets that will serve as templates for deducing the nature of the most distant objects in the Universe.

NEXUS — *NEXUS* is a technology pathfinder mission for *NGST*. Its effective aperture is ~3m and it will be placed in an L2 orbit similar to *NGST*. I mention this mission here for two reasons. First, besides testing *NGST*-like optics and detector technologies, *NEXUS* will blaze a path for enabling 3-4 meter class Explorer/Discovery missions by late in the decade. Second, currently *NEXUS* has no science program. Given the tight fiscal constraints on NASA’s Office of Space Science, I find it remarkable that a ~$300M mission should have effectively no science return. I believe that a science program could be crafted which would not conflict with the basic engineering requirements of the mission. The incremental cost of a limited MO&DA phase is small compared to the overall mission costs. By implementing a focussed science program, we not only demonstrate the technological potential of *NGST*, but also its scientific potential.

SCORE — The *Space Coronagraphic Explorer* (*SCORE*) is my designation for a 2-3 meter Explorer/Discovery class coronagraphic imaging mission. Other groups (e.g., the group led by John Trauger at JPL) are developing similar mission concepts under other names. *SCORE* has three primary science goals: (1) Detect and characterize extra-solar planets in the 1-80 M_{Jup} range around nearby stars; (2) Search for evidence of planet formation in the inner regions of debris disks around young stars; and (3) Map the structure and evolution of proto-planetary disks around newly formed stars. Ideally, we would like to study these objects from the V-band to the H-band. For the giant exo-planets, the 2MASS and Sloan Digital Sky Survey results have shown that these so-called L-dwarfs and T-dwarfs can be distinguished using R, I, Z, J, and H colors. In this context, there will also be a substantial contribution by reflected light from the solar-type star, which is dominant in the V-band. In the circumstellar disks, we would like to investigate line emission properties over a range of species and ionization states, such as [O III] 5007Å, Ha, and [Fe II] 1.6mm, as well as broad-band colors for determining grain properties (e.g., sizes). Hence, an optimized detector would cover the range from ~0.5 – 1.7 mm. Perhaps a variant of the detectors being developed for *NGST* could be used. I view *SCORE* (or someone else’s version of it) as the most important new mission for *Origins*, and perhaps all of space astronomy, during this decade. So far, *all* of the several dozen planet candidates have been deduced via indirect detection methods. The direct imaging in visible light of a Jupiter-class planet orbiting a nearby star, especially one orbiting in the habitable zone (even if we do not suspect life to be there), will have a profound scientific and sociological impact, opening the floodgates to the more ambitious extra-solar planet searches of later missions and simultaneously energizing support for space astronomy in general.

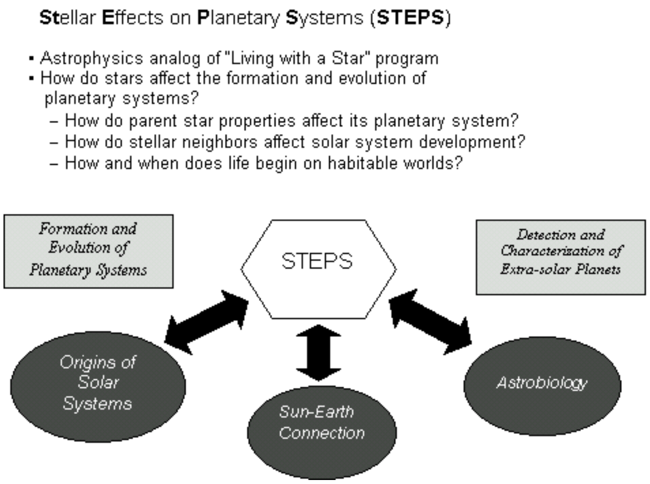
GALEX — Dr. Chris Martin (Caltech) is the Principal Investigator (PI) of the *Galaxy Evolution Explorer* (*GALEX*), a space ultraviolet imaging and spectroscopic Small Explorer (SMEX) mission scheduled for launch in late 2001 (according to the Explorer Program manifest). *GALEX* will study the star formation history of galaxies over the redshift range $0 < z < 2$ using FUV and NUV imaging and low-resolution spectroscopic data obtained on large-format micro-channel plate (MCP) based detectors. In addition, *GALEX* may identify up to 10^6 QSOs in its UV all-sky survey, forming a rich target list for follow-up investigations, e.g., with *HST-COS*.

FAME, Point-and-Stare Explorers — Before attempting a mission as ambitious and expensive as the *Terrestrial Planet Finder* (*TPF*), we must obtain sufficient statistics on the prevalence of planetary systems. If *TPF*'s target list is limited to only a few hundred objects, we cannot risk a null result; we essentially need to "stack the deck" toward (if not guarantee) positive detections for *most* of its targets. The ground-based high-precision radial-velocity measurements have led the way to the detection of several dozen (giant) planet candidates, and over the course of this decade, we can expect the number of planets discovered to rise dramatically. Other indirect methods of planet detection require precise astrometric and photometric measurements. The *Full-sky Astrometric Mapping Explorer* (*FAME*), scheduled for launch in 2004, is a Medium Explorer (MIDEX) mission PI'ed by Dr. Kenneth Johnston (USNO). *FAME* astrometric measurements of ~40 million stars will impact a wide variety of astronomical disciplines, including the search for extra-solar planets. It will be capable of detecting giant planets and planetary systems around stars out to ~1 kpc, providing a complementary set of plane-of-the-sky measurements to the line-of-sight measurements of the radial-velocity surveys. Planet candidates, down to terrestrial class objects, can also be detected via micro-lensing events and transits. Recent ground-based detections of giant planet candidates have been made using both methods. The advantages of space-based observations are a stable point spread function (PSF) for high-precision photometry and round-the-clock coverage of large numbers of stars. For example, *KEPLER* is a Discovery mission concept developed by Dr. W. Borucki (NASA Ames) and collaborators for monitoring thousands of solar-like stars for the signatures of transits by Earth-sized or larger planets. The *Micro-Lensing Explorer* (*MILE*) is my designation for a wide-field imager that monitors the Galactic bulge for micro-lensing events, looking for small, short-term amplifications in the primary light curve caused by planets orbiting the lensing star. Again, other groups are developing both transit and micro-lensing mission concepts under other names. (Another investigation that would benefit from a similar type of wide-field space imaging mission would be to monitor distant galaxies for Type 1a supernovae to gauge the accelerating Universe, as at least one group is proposing.) The primary requirement for precise, efficient photometric monitoring over large fields of view is a large CCD detector mosaic, probably at least 8k× 8k in size. Issues regarding data volume management and on-board data processing need to be resolved as well.

LEGACY-I — Multi-epoch *HST* imaging of star forming regions, such as Orion or Taurus, have shown us that stellar nurseries are highly dynamic regions. Gaseous motions in stellar winds and outflows can be detected over intervals of just 1-2 years. Such measurements allow us to estimate the amount of energy injected into the ISM by nascent stars and the self-regulation of the star formation process. Motions in planetary nebulae, mass ejections surrounding luminous blue variables, supernova remnants, nova shells, and other nebular objects have also been mapped with *HST* to help us understand the final stages of stellar evolution and the micro-physics of nucleosynthesis, stellar explosions, and the chemical enrichment of the ISM. One of the most effective ways we can contribute to our understanding of the detailed physics of these processes is to simply *watch what happens*, in the same way that we run hydrodynamic simulations through a long series of time-steps to see how structure forms and evolves given a set of initial conditions. One may consider that the true value of *HST* imaging will be realized when we can answer, "How do protoplanetary disks in the Orion Nebula evolve?" or "How has Cas A expanded and mixed its stellar ejecta into the ISM?" by comparing images taken now to those taken 10, 20, or even 100 years from now. It's the realization that the Universe around us changes measurably over short timescales that has motivated the Large-aperture Synoptic Survey Telescope (LSST) endorsed in the NRC Decadal Survey. The *Legacy-Imaging* (*LEGACY-I*) mission is a concept for a ~3-4 meter class wide-field UV-optical imaging telescope whose primary objective is to obtain multi-epoch images in diagnostic emission lines of all star forming regions within 2.5 kpc of the Sun. Other evolving nebulae would also be included in the target list. These programs can be accomplished efficiently using a field of view at least 10 times larger than *ACS* with diffraction-limited imaging in the optical, requiring a 16k× 16k or larger format CCD mosaic. Executing such a mission would build on the technological developments of *NEXUS* and Point-and-Stare Explorer missions, and would require NASA to implement an astrophysics mission opportunity in the Explorer line with a Discovery-class budget, as encouraged by the NRC Decadal Survey report. I note that in the documented mission concept description of *TPF* that such a 3-4 meter space telescope would form one component of the *TPF* interferometer. From a technical standpoint, clearly we should gain experience with one such 3-4 meter *monolithic* telescope in orbit prior to trying to formation-fly several, in the same way that *NEXUS* is an *NGST* pathfinder for demonstrating deployable segmented optics.

GIGMA — The *Large Telescope Systems Initiative* (*LTSI* or "Gossamer Initiative") is a program to develop very lightweight mirrors needed for the 25-40 meter space telescopes in the *Life Finder* and *Planet Imager* interferometers. The *Gossamer Inter-Galactic Mapper* (*GIGMA*) is a non-imaging ~4 meter pathfinder mission using thin membrane mirror technology for doing UV point source spectroscopy of quasars down to $m_B \approx 20$ to study the Lyman a forest. Such a mission, perhaps late in this decade, could be very important if a large-aperture space telescope capable of performing UV spectroscopy is delayed much beyond 2013. The spectrograph design must be efficient, employing the next generation of optical coatings, holographic gratings, and (probably) large-format MCP based detectors.

Pale Blue Dot missions — The path to the *Planet Imager*, which is an *optical* imaging interferometer mission capable of spatially resolving mountain ranges and cloud formations on Earth-like planets orbiting nearby stars, clearly must include a single-aperture imaging mission in the 25-40 meter class range that demonstrates optical quality wavefront control. I believe there needs to be at least two optical pathfinder missions prior to attempting such a bold interferometer as the *Planet Imager*. I have termed these pathfinder missions that create the technology for the *Planet Imager* as "*Pale Blue Dot*" (*PBD*) missions in Figures 1 and 2, where I have included 8 meter (*NGST* class) and 25 meter versions. Initial pathfinder imaging missions using thin membrane optics are easier to demonstrate in the IR. But for each leap in aperture size first demonstrated in the IR, we must develop the equivalent aperture telescope with optical quality wavefront control necessary for the *Planet Imager*. (This is the reason I have listed *SAFIR* as a 25 meter class telescope; an 8 meter far-IR telescope, notwithstanding the limited spatial resolution at wavelengths >100 mm, does not improve our wavefront control technology over *NGST*.) Simulations by Dr. John Trauger (JPL) and collaborators (private communication) indicate that an 8 meter class (*PBD-8*) space telescope with excellent (l/5000) wavefront control and a coronagraph could easily image Jupiters and barely detect Earth-sized planets orbiting stars within a few pc of the Sun. It is an exciting prospect to consider that an optical image, made in the light that our eyes can see, of another Earth-like planet may be possible in ~15 years. In addition to the scientific content of such an image, I believe that its historical impact on society would rival that of the Apollo 8 image of "Spaceship Earth" rising over the lunar surface. With extra-solar planet detection as the centerpiece of the *PBD-8* mission, two additional scientific pillars will make up its research program: very deep imaging of distant galaxies and galaxy fields, and mapping the distribution and properties of the intergalactic medium out of which the galaxies formed. With a large-format CCD mosaic camera, *PBD-8* could obtain in one day 15 images with the equivalent depth of the Hubble Deep Field (which took two 2 weeks to obtain) with 3 times better spatial resolution. It would be possible to detect Cepheids in galaxies out to 100 Mpc, directly accessing the Hubble flow. Color-magnitude diagrams, including near-UV, optical, and near-IR passbands, could be constructed down to the main sequence turn-off in Local Group galaxies and beyond. UV spectra could be obtained of quasars down to 22nd magnitude for tracing the distribution, physical properties, and fate of baryonic matter in the intergalactic medium over angular scales of just a few arcminutes, testing hydrodynamic simulations of the formation and evolution of large-scale structure and the "Cosmic Web." *PBD-8* provides a strong impetus for developing Superconducting Tunnel Junction (STJ) type high-QE, photon-counting, energy-resolving UV-optical detectors. For the extra-solar planet imaging application, we need 2-d arrays of at least 256 × 256 pixel format (preferably larger) to cover effectively a few-arcsecond field surrounding the star at a scale of <10 mas/pixel. With modest energy resolution (R~80-100), we would obtain spatial information and a spectral energy distribution of every object in the field simultaneously. In the point source UV spectroscopy application, Drs. Bruce Woodgate, Randy Kimble (GSFC) and colleagues envision an efficient echelle spectrograph design to obtain high spectral resolution (R ~ 50,000) that feeds a 1-d STJ type array of at least 2048 pixels (preferably 4096 pixels or longer). Energy resolution of R ~ 200 would be needed to sort the echelle orders instead of using a cross-disperser.



Stellar Effects on Planetary Systems (STEPS)

- Astrophysics analog of "Living with a Star" program
- How do stars affect the formation and evolution of planetary systems?
  - How do parent star properties affect its planetary system?
  - How do stellar neighbors affect solar system development?
  - How and when does life begin on habitable worlds?

Figure 3

SISP and STEPS — At the Boulder conference on "UV-Optical Space Astronomy Beyond HST" in August 1998, Dr. Heidi Hammel (MIT) described the seeds of a program of investigation called "Stellar Effects on Planetary Systems" (STEPS). The premise of STEPS is that the properties of any planets orbiting a given star likely correlate with the properties of the star (spectral type, age, metallicity, magnetic activity, etc.) and its interaction with the planetary system. Hence, it isn't sufficient to simply detect and characterize the planets; we must also carefully study the central stars in order to understand why the planets have the properties they do and whether life can form and evolve in that environment. I include a rough overview of the STEPS program in Figure 3, showing the interdisciplinary nature of the research that culls aspects of the science goals from the *Origins of Solar Systems*, *Astrobiology*, and *Sun-Earth Connection* programs. STEPS is in some ways the astrophysical analog of the new "Living with a Star" program at NASA. One mission that certainly would fall within the STEPS program is the *Stellar Imager and Seismic Probe* (*SISP*), which is a UV interferometer concept being developed by Drs. C. Schrijver (LMMS/ATC) and K. Carpenter (GSFC). *SISP* may contain about nine 1 meter class telescopes forming an interferometer to detect UV diagnostic radiation from stars. It will spatially resolve stellar surfaces of nearby stars, charting magnetic activity and photometric variations for understanding stellar dynamos and interiors that may ultimately lead to better predictions of our Sun's activity. Such a mission may also obtain images of magnetized accretion columns in T Tauri stars, to glimpse directly how stars are built. The *SISP* planning team points out the excellent opportunity for using a 2-d energy-resolving detector array on this mission.

2.2 SEU Missions

The science quests of the *Structure and Evolution of the Universe* (*SEU*) theme are to: (1) Explain the structure in the Universe and forecast our cosmic destiny; (2) Explore the life cycles of matter and energy in the evolving Universe; and (3) Examine the limits of gravity and energy in the Universe. The pursuit of these science goals involves half a dozen research campaigns that include identifying dark matter and its effects, determining where and when the chemical elements were created, tracing the exchange of matter, energy, and magnetic fields between stars and the ISM, understanding accretion disks and the jet/outflow phenomenon that is ubiquitous in astrophysics, identifying the sources of gamma-ray bursts and high-energy cosmic rays, and measuring how strong gravity operates in black holes and the early Universe.

As with the astrophysical science goals of the *Origins* program, UV-optical observations from the ground and space have impacted our pursuit of each of the *SEU* science goals. It is therefore astonishing to me that there are *no UV-optical missions* in the *SEU* long range strategic plan! (See p. 25 in the *Cosmic Journeys* booklet.) Astonishing because, given the research campaigns outlined in the previous paragraph, UV-optical data will form the foundation for our understanding of so many varied astrophysical systems, from stars to galaxies to interstellar and intergalactic gas to accretion disks and shock waves, etc., etc. In Figure 2, I have added UV-optical mission concepts to the *SEU* roadmap that will contribute to the *SEU* science quests. Many of these (*GALEX*, *COS*, *LEGACY-I*, *GIGMA*, *SISP*, *PBD-8*, and *PBD-25*), with science goals pertinent to both themes, also appeared in my version of the *Origins* roadmap and were described above. Below I briefly describe two remaining mission concepts which are geared primarily towards *SEU* research.

LEGACY-S — *Legacy-Spectroscopy* (*LEGACY-S*) is a Explorer mission concept to do EUV/FUV/NUV (preferably 30 – 300 nm) time-resolved spectroscopy of variable sources, and is the complementary mission to *LEGACY-I*. Spatially unresolved objects such as accretion disk and flaring systems (e.g., T Tauri stars, cataclysmic variables, active galactic nuclei, black holes), close binaries with interacting stellar winds, young stars with infalling cometary debris, or even transiting 51 Peg-type giant planets can be monitored spectroscopically to determine kinematics, column densities, temperatures, composition, and, through Doppler tomography, sometimes detailed morphology. Many such investigations with *HST* spectrogaphs, in the later stages of the *IUE* mission, or in the X-rays with *RXTE*, have shown that the essential physics is revealed in the time-varying behavior of the luminosity or spectral characteristics of these dynamic sources. A new mission devoted to such phenomena would benefit from simultaneously covering the *EUVE*, *FUSE*, and *HST* UV bandpasses, from He II Lya to the atmospheric cutoff.

DEMEX — The *Diffuse Emission Explorer* (*DEMEX*) will conduct a deep all-sky survey of diffuse emission in the Galaxy in the O VI ll1032Å, Lyman a, and Paschen a lines. The data could be combined with the Wisconsin H-alpha Mapping survey (WHAM) results to map the structure, ionization, extinction, and kinematics of the warm and hot ionized media (WIM/HIM) in the Milky Way.

2.3 Space Astronomy and the Manned Space Program

Eventually, mankind will venture to Mars – NASA Administrator Dan Goldin has said (e.g., in a CNN interview) not before 2010 but (hopefully) by 2020. A manned mission to Mars will last at least ~1-2 years. In my opinion, the road to Mars starts with the International Space Station (ISS) and passes by the Moon and L2. Preparation must include years of experience with weightless living, extensive spacecraft testing, practice landings, and intermediate duration journeys. I believe that the space science community should be poised to add scientific value to these developmental stages by devising scientific payloads (e.g., space observatories) that can be deployed and made operational by astronauts. Such "Missions of Opportunity" have already been solicited for the ISS. Orbital maneuvers, landing, and surface operations at Mars will be primarily in the hands of the crew since near real-time communication with Mission Control on Earth is not possible. In many ways, the astronauts will need to serve both as pilots and flight controllers during critical mission phases when split-second decisions must be made. Once landing has occurred, Mars rotates every 24 hours and the crew will be out of direct sightline with the Earth for substantial periods each day. Hence, one or more communications relay satellites will be necessary to maintain a round-the-clock link. In case of a satellite failure, the crew must be able to function with infrequent interaction with Earth. Achieving this level of crew autonomy will require training missions of equal or greater duration and isolation. I believe that at least four long-duration lunar landings will be needed, two at the poles and two on the far side, in order to develop the necessary techniques for a safe and successful manned Mars mission. Not only are these locations of geological interest, given Apollo observations and the recent *Clementine* results, but they may offer unique opportunities for erecting moderate aperture space observatories.

Prior to making the journey to Mars, I believe crews must make at least one intermediate range flight beyond the Earth-Moon system that tests the direct abort capabilities of the spacecraft and the functionality of the crew when the Earth is reduced to a small "pale blue dot" in the window. An excellent destination for such a mission would be the Earth-Sun L2 point, the proposed parking orbit for *NGST*. I propose that the *NGST* flight detectors and electronics (i.e., those systems that are susceptible to radiation damage over time) be designed as modular components that can be replaced on orbit. Such modularity expedites integration on the ground and allows the best possible detectors to be swapped in for flight late in the I&T process. I do not propose that on-orbit servicing be vital to the success of the *NGST* mission, but believe this design approach to be prudent in case an opportunity to upgrade and extend the life of *NGST* presents itself. At ~1.1 AU, this location would be ~25% of the way to Mars (when Mars is at opposition). *NGST* would represent "a little piece of home" to the crew and its upgrade would provide clear mission objectives while advancing our Mars readiness.