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The Lyman Imaging Telescope Experiment (LITE)

Final Report

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Summary
The Lyman Imaging Telescope Experiment (LITE) is a UV Branch funded advanced mission concept proposal funded over a 12-month period. The prime scientific aim of the LITE mission is to carry out the first set of very high spatial resolution (0.2 arc sec), wide field of view (10 arc minute), pointed astronomical observations in several narrow wavelength bands in the far ultraviolet region of the spectrum (900 - 1600Å). The design of LITE has been chosen to possess excellent detection sensitivity, such that limiting magnitudes for typical images are expected to be close to that of the HST WFPCII instrument.

Although we have worked on the design of the LITE instrument for only one year, we believe that work has progressed well in defining the LITE advanced mission concept. We have held two LITE Science Team meetings at Berkeley in December 1995 and May 1996. The members of the team were: Prof. C. McKee [Berkeley], Dr. J. Hutchings [DAO, Canada], Dr. R. Winterbros [New Mexico State], Prof. E. Wright [UCLA], Dr. Carol Christian [STScI] and Dr. R. Polidan [GSFC]). They met with the EAG core team-members (Dr. Pat Jelinsky, Dr. B. Welsh and Dr. O. Siegmund) to discuss some new approaches to the original mission plan and to discuss changes to to the originally proposed instrumental set-up, particularly on the topics of choice of filter pass-bands in the FUV and on-orbit observational strategies.

Two wavelength regions in the far UV were chosen to be of prime scientific importance for the LITE mission: 1030Å and 1240Å. It was therefore decided to design and test novel, narrow band, high reflectance multilayer filters for these observations. We are currently progressing with the initial fabrication of these FUV filters which are a central part of the LITE mission. A paper outlining the salient features of the LITE Mission was presented at the SPIE meeting in Denver, Colorado in August 1996. A copy of this paper is attached.

The Lyman Imaging Telescope Experiment (LITE)

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ABSTRACT

We describe the Lyman Imaging Telescope Experiment (LITE) which is a NASA Ultraviolet Astrophysics Branch supported Advanced Mission Concept mission. The prime scientific aim of the LITE mission will be to carry out the first set of very high spatial resolution (0.2 arc sec), wide field of view (10 arc minute), pointed observations in several narrow wavelength bands in the far ultraviolet region of the spectrum (900 - 1600Å). LITE will possess excellent detection sensitivity, such that limiting magnitudes for typical images are expected to be close that of the HST WFPC II instrument. The proposed far ultraviolet astrophysical studies will encompass the emission of diffuse gas with temperatures in the range 80,000 - 1,000,000 K.

1.0 INTRODUCTION

The appearance of the Universe looks very different at visible wavelengths than it does in the radio, infrared, γ-ray, or X-ray regimes. This is particularly important for astrophysicists since the way in which astronomical objects "appear" to the eye (via the form of images) has had a profound effect on the many theories forwarded to explain the varied astrophysical processes at work within our Universe. Today the importance of imaging in astronomy is still paramount, as demonstrated by the recent beautiful visible images from the Hubble Space Telescope (HST) and the eagerly awaited X-ray images from AXAF. High resolution (< 1 arc second) astronomical images have now been taken across most of the electro-magnetic spectrum, although imaging in the ultraviolet region has been limited to broad-band observations longward of 1250Å by the HST Wide-Field and Faint Object Cameras[1], the Shuttle-borne *UIT* instrument[2], and a few sounding rocket flights[3]. These broad-band ($\Delta\lambda \sim 300$Å) ultraviolet imaging observations have (for the majority of source types) been dominated by the integrated emission from the underlying source continuum. Hence, true spectro-photometric images recorded in a single, narrow UV emission line such as the important species of C IV (1550Å) or Si IV (1390Å) are presently unavailable.

The portion of the FUV region between 912Å - 1250Å contains a great wealth of astrophysical spectral information, with the emission lines of C III (977Å), O VI (1032 & 1038Å), S VI (933 & 945Å), N V (1238 & 1242Å), and the Lyman series of atomic hydrogen lines being of particular astrophysical importance. The strongest of these lines uniquely sample the emission from hot gas in the 80,000K - 1,000,000 K range, which can arise in plasmas in astrophysical environments ranging from supernovae shocks to active galactic nucleii. The study of gas at lower temperatures requires observations in the near ultraviolet, visible and infreared regions, while observations using soft and hard X-rays sample very hot gas with temperatures in excess of 2 million K.

Although several missions[4,5] are carrying out very successful Shuttle-borne programs of far ultraviolet (FUV) spectroscopy in the 900 -1600Å regime, the region below the HST cut-off ($\lambda < 1180$Å) still remains one of the few spectral regimes where photometric imaging has been largely inaccessible to astronomers. To date, the best attempts at performing such imaging have been the spectro-photometric mappings in OVI of the Cygnus Loop supernova remnant by Blair *et al* [6] and Ramussen and Martin[7], with both observations being taken at rather coarse angular resolutions of ~ 0.2 degrees. Hence, at present, astrophysicists have very little empirical knowledge of the spatial characteristics (i.e. images) of

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low red-shift emission from gas in the 80,000K - 1 million K regime. This is doubly important since UV-bright objects are responsible for most of the ionization in the Universe, and are thus critical for understanding the total energy budgets for most astrophysical systems.

Clearly, the FUV region has great potential for astronomers, but it still remains largely unexplored. Progress in the far ultraviolet regime has been severely hampered by the unique instrumental challenges encountered in performing observations at these short wavelengths, especially in the development of large format FUV detectors and narrow-band (tunable) filters for precision FUV photometry. In this paper we describe an instrument concept for LITE, the Lyman Imaging Telescope Experiment, whose prime scientific aim will be to carry out the first very high spatial resolution (~ 0.2 arc second), wide field of view (10 arc min) pointed astronomical observations. Data will be gained in several narrow wavelength bands in the FUV region (912 - 1600Å) sampling emission from both galactic and extragalactic plasmas arising in a wide variety of astrophysical sources with temperatures in the 10^5 K - 10^6 K regime. The high angular resolution imaging capability of the proposed LITE observations will mean that gaseous structures only 10 pc in extent will be resolved within galaxies of distances as great as 10 Mpc, and the sub-parsec thick shock-front filaments in nearby supernova remnants such as the Crab Nebula will be resolvable.

2.0 TECHNOLOGICAL CHALLENGES

Scientific progress in this wavelength regime has been severely hampered by the unique technical challenges encountered in fabricating instrumentation that will perform FUV astronomical observations, especially in the development of large format FUV detectors and narrow-band (tunable) filters for precision FUV photometry. Furthermore, all such measurements have to overcome the severe problem of minimizing scattered light from the intense geocoronal emission at Lyman α (1216Å), and to a lesser degree contamination from geocoronal Ly β at 1025Å. Although progress is currently being made by the NASA FUSE program in the field of high resolution spectroscopy, further major instrumental developments are required, particularly in the fields of narrow band FUV filter design and large format-high count rate FUV photon counting detectors. The Experimental Astrophysics Group at UC Berkeley is currently playing a major role in leading the research and development in these fields in the FUV regime, through space projects such as FUSE[8], SOHO[9], ORFEUS[10], and through several NASA funded R & D programs.

In order to achieve the scientific goals outlined in Section 1.0, the LITE science team are developing a straw-man instrument concept that meets both the the required detection sensitivity, field of view, and spatial resolving power in the 900 - 1600Å wavelength range. The choice of 0.2" spatial resolution is based on the desire to resolve individual OB stellar associations in several nearby spiral galaxies. A field of view of 10' will allow entire galaxies and clusters with distances > 10 Mpc to be imaged. The current baseline LITE instrument complement consists of a 1 meter aperture Ritchey-Chretien telescope that feeds a large format, 3500 x 3500 resolution element (oversampled by a factor of ~ 2.5) cross delay-line photon counting detector. Five narrow bandpass multilayer reflection filters, each inserted into the light path by means of a filter wheel, will enable FUV photometric observations to be carried out over the entire 900 - 1600Å wavelength range. The utilization of such a high resolution, large format detector exploits the widefield / high resolution capability of the optical system to a level unmatched by any current instrument at these wavelengths. In addition, we have incorporated novel, new multilayer FUV filter designs that have the potential of giving high throughput (R > 0.5) over narrow bands (Δλ ~ 50Å) with good out-of-band rejection. The present baseline LITE mission has a preliminary cost of less than \$100 million, and the predicted payload mass, size and power all lie within the present guidelines of the NASA Mid-Explorer program.

3.0 INSTRUMENTATION

3.1 The LITE Telescope System

We have chosen a Ritchey-Chretien telescope configuration to achieve the desired high spatial resolution of 0.2" over a field of view of 10'. This design consists of a 1.0 meter diameter f/2.4 hyperboloid primary mirror, and a 17.4 cm aperture f/2.7 hyperboloid secondary mirror. This optical design of the mirror system has been chosen to achieve optimization of the many trade-offs between field-of-view, limiting magnitude, spatial resolution, and minimization of overall size and weight. With such a design both coma and spherical aberration are corrected to produce an aplanatic optical system.

Our present design is an f/15.5 system, with a focal length of 1550 cm. The overall length of the system is 2.5m, which is sufficiently small to fit easily into the shroud of the new NASA Med-Lite series of launch vehicles such as the OSC Taurus launcher. A schematic of the telescope layout is shown in Figure 1. Spot diagrams produced by ray tracing through the telescope and filter system predict an on-axis image size of only 0.3 μm which blurs to only 1μm at the edges of the 10' field of view for an optically perfect system. The ultimate (practical) resolution of the entire LITE system will be dominated by the FUV detector resolution (i.e. 15μm). Positioning of the detector at the optical focus is not critical, since a detector mis-alignment of at least 200μm is needed to cause only a 0.2" blur of the final image.

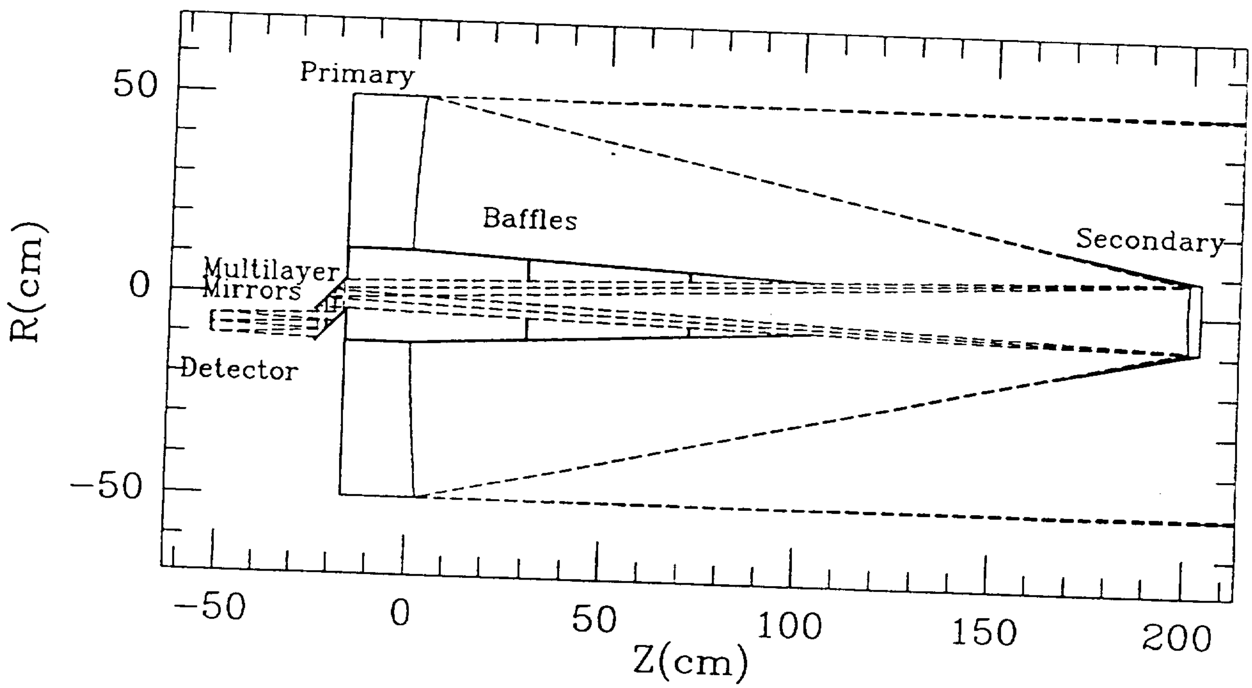

FIGURE 1: LITE Telescope/Detector Layout

We propose using weight-relieved Cer-Vit primary and secondary mirrors which have been figured to sub arcsecond accuracy. To enhance reflectivity of the optics in this wavelength region we propose use of SiC coatings, although the coating of mirror sizes in excess of 80cm aperture has yet to be achieved (Keski-Kuha, private communication). Our baseline telescope metering structure will be constructed from carbon fiber tubing to ensure both rigidity and low thermal expansion. Since the quality of imaging is a sensitive function of the secondary-primary distance separation, we are presently investigating the use of an on-orbit focusing mechanism similar to that used on the HST mission. For example, a shift of only 8μm in the mirror separation distance degrades the image quality by a further 0.2". In Table 1 we list the technical figures of merit for the presently proposed LITE instrument.

TABLE 1: LITE Mission Parameters

Telescope	1m diameter SiC coated Ritchey-Chretien f/2.4 Hyperboloid Primary Mirror 17.4 cm diameter, f/2.7 Secondary Mirror
Detector System	50 mm x 50mm open circular MCP intensifier cross-delay line anode readout (8192 x 8192 pix) CaF2 transmission & multilayer reflection filters
Instrument Bandpass	900 - 1600 Å in 5 filter bands Filter 1: 977Å Filter 2: 1036Å Filter 3: 1240Å Filter 4: 1395Å Filter 5: 1550Å
Limiting Magnitude	V = 19.5
Positional Resolution	~ 15μm FWHM in x and y
Spatial Resolution	< 0.2 arc sec
Field-of-View	10 arc min

3.2 The FUV Filters

Our baseline instrument configuration will consist of five narrow band (< 50Å FWHM), multilayer reflection filters centered at wavelengths between 900 and 1600Å as listed in Table 1. Narrow-band interference filters for use in the ultraviolet region longward of 1250Å have only recently become commercially available. Replacment of the metallic layers of a conventional metal-dielectric-metal "sandwich" filter with high efficiency dielectric coatings (such as LaF_2, MgF_2 or BaF_2) has been shown to drastically reduce absorption. Such filter coatings consist of quarter wave (QW) stacks of high and low index of refraction materials, often with > 20 layers. This technique has recently been used to produce high quality reflection filters with reflectivities of ~ 80% over a narrow bandwidth of only 30Å[11]. However, becuase such filters need to effectively block leaks from longer wavelengths, we shall use 45 degrees reflections from two identical multilayer filters to achieve good out-of-band rejection < 10^{-6} %, while still maintaining high levels of in-band reflectance.

The use of bandwidth limiting filters in the spectral band 912-1250Å is more problemattic than at other wavelengths, since no known solids are transparent below 1050Å. Typical FUV transmissions of thin-film metallic filters such as In, In/Sn and Sn/C are very low in this wavelength regime , < 5%, they also have inherently large bandwidths ($\Delta\lambda$ ~ 300Å), and exhibit signs of degredation over relatively short periods of time due to the processes of oxidation, carbon contamination and hygroscopic absorption [12]. Therefore, we have recently undertaken a program of research into the development of new techniques in multilayer filter development for use at wavelengths < 1250Å. Although this research program is still in its infancy, we have recently designed a novel, narrow band filter combination for observations centered around the astrophysically important emission line-doublet of NV at 1240Å. In order to supress potential short wavelength contamination by scattering from the extremely strong closeby geocoronal line of Ly α (1216Å), our filter design takes advantage of the dramatic transmission turn-on characteristics of the halide crystal material, CaF_2. In Figure 2 we show the transmission properties of a 0.5mm thick crystal, which clearly shows the remarkably sharp transmission turn-on around 1225Å. When used in transmission together with a commercially available reflection multi-layer filter (Zukic Inc., private communication) it is possible to achieve the desired goal of both good in-band performance, and highly effective out-of-band rejection. In Fig 3 (marked as N V) we show the expected theoretical reflection properties of this CaF_2-multilayer filter combination. This unique filter combination gives good in-band reflectivity (R peak ~ 0.55) over a narrow band-width of FWHM 50Å, and has an out-of-band rejection of < 10^{-15} at 1216Å.

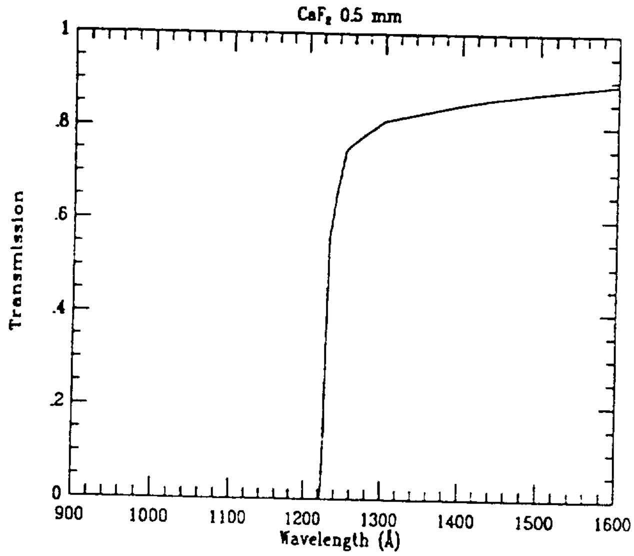

Figure 2: transmission of 0.5mm CaF_2

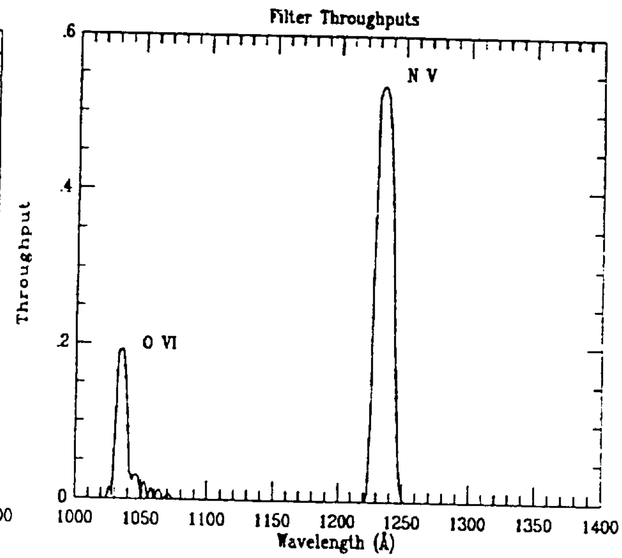

Figure 3: reflection throughputs for NV and OVI filters

We are also actively investigating choices of various multilayer filter materials for possible use at wavelengths < 1150Å, in particular at 1035Å which would be suitable for observations of emission from the astrophysically important line of OVI. Our program of research involves measurement of both the bulk and thin-film refractive indices of LiF and In in this short wavelength regime, together with their dependence on temperature. Cooling a LiF crystal by only 30 degrees moves the cut-on wavelength longward by 5Å. This is an attribute that could be used in schemes for varying the central operating wavelength of FUV filters such that astronomical objects with red-shifts in the range z = 0 - 0.05 could be successfully observed. In Figure 3 we show the theoretical reflection properties of such a multi-layer filter combination (marked OVI in Figure) which achieves an in-band reflectivity of ~ 0.2 with a FWHM of 30Å. Further laboratory work is required to refine the exact properties of this FUV filter.

3.3 The FUV Detector System

The LITE detector is one of the key areas where recent advances in technology are providing the significant improvements in instrument performance that allow new scientific areas to be explored. The proposed detector system is a novel, but rational, extension of the detector systems built by the EAG at Berkeley for the SOHO[9] and FUSE[8] missions, and builds on our previous experiences with the EUVE and ORFEUS projects. The LITE detector is a two dimensional photon counting, centroiding device. The format is ~ 50mm x 50mm electronically digitized to > 8192 x 8192 pixels. A KBr and/or CsI coated low resistance Z stack of curved microchannel plates (MCP's) provides detection and amplification, and a multilayer cross delay line anode (XDL) accomplishes the position readout. The basic design uses an open face detector for which we would use our prior detector construction techniques employing brazed metal/ceramic detector bodies. This and the asscociated mounting schemes have been proven reliable in vibration, thermal vacuum, shock, and cleanliness tests for numerous successful prior missions.

An opaque photocathode material is deposited on the MCP Z-stack and incoming photons interact with the photocathode, resulting in photoelectron emission and a subsequent charge avalanche in the MCP's, giving an overall charge multiplication of ~ 2 x 10^7. This charge cloud is drifted from the MCP output to the delay line anode. The XDL image readout has been selected on the basis that it can achieve the required resolution and high counting rate performance. Delay lines of this type are produced by a multi-step process to cut the anode pattern into conductor and insultor layers deposited on a low loss microwave substrate. The MCP charge pulse (~ 3 to 5 ns width) is detected on, and divided between, two sets of conductive fingers. The charge is divided ~ 50% / 50% between the XDL charge collection fingers in the X and Y axes which are connected to external serpentine delay lines[8]. X and Y photon event centroid positions are deduced from the signal arrival time differences at the two ends of each delay line. The photocathode materials for this wavelength region of interest have been extensively studied[13] and are currently available. Local event counting rates in excess of 200 events/resel/sec (resel = 15 x 15 μm) have been achieved[9] for low resistance MCP's with no degredation of the gain. We are continuing to devlop new ways in which the 2000 events/resel/sec level of performance that is required for LITE is to be achieved.

The baseline optical system produces a slightly curved focal plane with radius of curvature of 41cm. We plan to match this focal surface using curved microchannel plates, as demonstarted by EAG on the ALEXIS and ORFEUS missions in which focal plane curvatures of 7cm (over a 40mm area) and 50cm (over 90mm) were used. Detector flat field images are usually dominated by MCP fixed pattern noise and are stable. However, we propose to achieve MCP multifiber modulation of an uncharacteristically low level (a few %) as was attained for the MCP's used on the SOHO mission[8]. Small pore MCP's with fibers of 8μm or smaller will also be required to meet the resolution and sampling criteria, a value not yet common for large MCP's. All these prior factors are components of our ongoing studies currently being funded under the NASA SUVDDP program.

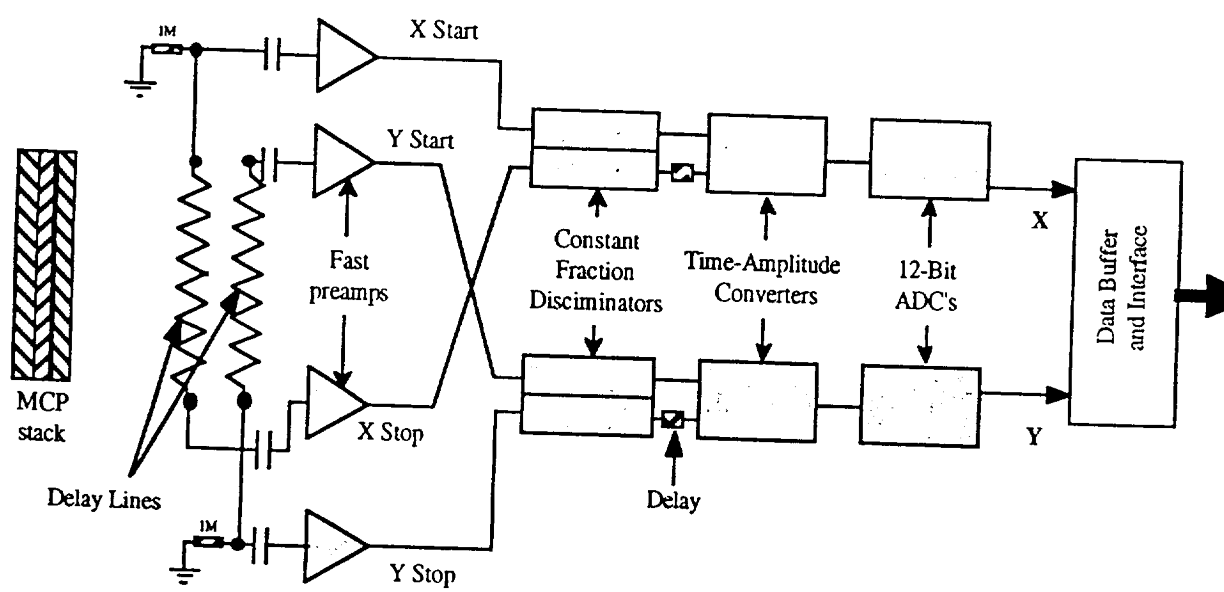

Figure 4: Schematic diagram of the LITE detector electronics system

3.4 LITE Electronics System

In Figure 4 we show a schematic of the LITE detector electronics system. Charge signals from the detector XDL anode are relayed to the front-end amplifier which contains high speed amplifiers. The Time-to-Digital Converter (TDC) module will be an implementation of the Arctangent TDC, a device that has recently been developed at UCB/EAG with ~ 10ps resolution, and up to 320ns anode delays at 5 MHz event rates[14]. Detector science data is then sent directly from the TDC electronics assembly to the LITE spacecraft bus data interface over high speed parallel or serial data paths. In addition, two serial channels are used to transfer command and telemetry information to operate the detector sub-system. Both serial channels will be controlled by a common clock and sample signals originating in the instrument, and both are based on a 16-bit serial word transfer. A monitor box electronics module will provide command and housekeeping activities to operate and monitor the XDL detector. Custom built high voltage supplies will be provided by Battel Engineering Inc., with -6kV output and ~ 100μA maximum current. The high voltage supplies are programmable and will be ramped down to ~2kV whenever the detector is required to be "turned-off" due to rate limit, stand-by mode, or other selection criteria.

Science data will be presented as a 12-bit X-axis address, and 12-bit Y-axis address, and a strobe. The command status words contain information on command registers, high voltage on and off commands etc. Telemetry from analog signals provide monitors for voltages, currents, and temperatures. X and Y pulse height analysis data is provided in the telemetry stream as a diagnostic of the detector health and performance. An on-board electronics pulser will provide end-to-end electronics functionality verification.

4.0 LITE PERFORMANCE PARAMETERS

The total performance efficiency of LITE is the product of the efficiency of the telescope mirrors, the average exposure time for a given area of the sky, the charged particle repulsive grid transmission, the Indium filter transmission, the detector quantum efficiency, and the background count rate. Using a

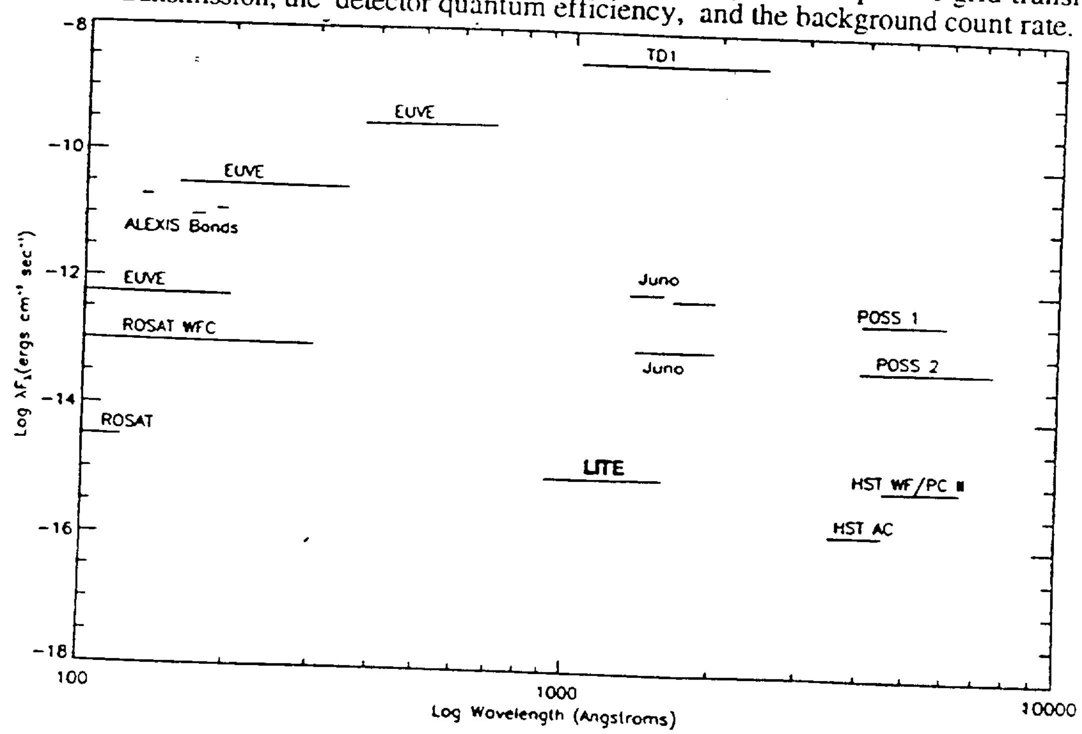

Figure 5: Comparison of the LITE sensitivity with other survey missions

geometric area of the telescope of 1119.2 cm^2, a field of view of 2.39 x 10^{-4} steradians, an observation
time of 300sec, and a fraction of 0.68 source counts in one pixel with a blur radius of 0.035 arc min, and
an internal detector background rate of 10 counts/sec due to the Lyman α and Lyman β geocoronal lines,
we derive a minimum detectable source count rate of 0.0059 counts/sec, which corresponds to a
minimum detectable flux of 0.873 x 10^{-4} photons cm^2 sec^{-1} $Å^{-1}$. This is more easily viewed in Figure 5
in which the predicted LITE sensitivity is compared with that of previous NASA/ESA survey missions in
the ultraviolet regime.

5.0 ORBIT AND SPACECRAFT CONSIDERATIONS

In considering the possible mission concepts for LITE we have concluded that the maximum science
return would be realized from a high Earth orbiting mission. This avenue also produces the lowest cost
mission from both spacecraft considerations and flight operations. The advantages of high Earth orbit
(HEO) for this mission are numerous. Sub-arcsecond attitude control is substantially easier to achieve;
the thermal environment is much more stable yielding a more stable optical system, and the overall cost
for the support of the science payload (spacecraft and operations concept) is significantly lower than an
equivalent low Earth orbit mission (LEO). The two disadvantages of a HEO mission with respect to a
LEO mission are weight and communications issues. The weight penalty for a HEO mission is rapidly
becoming a minor problem due to the availability of lightweight mirrors and light spacecraft structures.

The final choice of the specific orbit for LITE will depend on the mass of the spacecraft and the type of
launcher. The lunar assisted-low eccentricity orbit is one of the lowest energy HEO's because it draws
orbital energy from the Moon. The drawback to this orbit is that it produces a potential communications
problem because of the large apogee distance (60 Earth radii). A geosynchronous orbit would remove
this communication problem, but requires much more energy to insert a spececraft into this orbit than
does the lunar assisted orbit. As the LITE mission definition matures, specific orbit trades will be made
and the most appropriate orbit will be selected.

Superb attitude control is critical to the science return of this mission. Fortunately, the required level of
attitude control in this HEO environment is relatively easily to achieve because of the lack of external
distaurbances (e.g. gravity gradient or aerodynamic drag). It has been demonstrated (analytically) that for
such a mission a spacecraft body stability of 0.2" (1 sigma) is possible with current technology in a
gyro-less mode. With currently expected improvements in star sensor systems and the additon of high
performance gyros, spacecraft stability for LITE should be better than 0.1" (3 sigma) within 5 years.

6.0 LITE MISSION PARAMETERS

A definitive determination of the size, weight and cost for the LITE mission is part of the continuing
study phase. However, based on previous experience and informed estimates we can predict the
following parameters:
Size and weight : Using the FUV f/15.5 LITE telescope design, the science payload could be
mounted within a structure of size 2.5m x 1.2m x 1.2m . Assuming the primary mirror is weight relieved
by a minimum of 25%, and the telescope structure is constructed from carbon fiber rods, we estimate
that the weight of the science instruments plus associated electronics would be ~ 360 kg. Thus, our
present LITE design would be well suited to a Med-Lite type launch vehicle, comparable to the
capabilities of the OSC Taurus launcher.

Power: The thermal control power for the FUV telescope and the instrument electronics is based on
numbers for both the simarly sized HUT telescope currently being flown on the Shuttle, and the SOHO
detector systems. We have estimated a 50-50 share between spacecraft and instrument resources, such
that the total mission power requirement would be ~ 200 watts.

Telemetry: In HEO the communication startegy is quite different from that of LEO. It is possible to have an orbit where, for example, ground passes are typically of order 8 hours. Using standard transponders (5W, S band), and a high gain antennna transmitting to the Wallops 18m dish, it should be possible to achieve data rates of up to 1M bit/sec. By using data compression techniques in combination with a 100 MByte on-board memory and memory management stategies to select between images mode and photon list mode data storage, this should suffice for most LITE observational programs.

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