MODS
A Multi-Object Double Spectrograph for the Large Binocular Telescope

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1 Introduction

This document describes the Multi-Object Double Spectrograph (MODS) that OSU is proposing to build for the Large Binocular Telescope (LBT). MODS will be a high throughput, moderate resolution ($R=10^3$-10^4), visible-wavelength (320-1000 nm) double spectrograph located behind the first of the two 8.4-m LBT primary mirrors.

Optical spectrographs are essential instruments for large telescopes and are central to a wide variety of research programs. Optical spectroscopy is one of the most fundamental tools of astronomy for several reasons:

1. The richness of spectral features at ultraviolet and optical wavelengths provides a wealth of information and diagnostics for the determination of redshifts, physical conditions, and chemical compositions.

2. In combination with observations at other wavelengths or from space observatories, optical spectroscopy leads to the identification and understanding of newly discovered classes of objects (radio sources and quasars are a classic example; more recently Keck observations of high-redshift galaxies in the Hubble Deep Field have opened a new window for research).

3. The near-perfect quantum efficiency of current CCD detectors and the darkness of the sky at optical wavelengths enable observations of the faintest and most distant objects known in the universe.

Spectroscopy of the faintest objects requires the most effective possible use of the full 2-mirror collecting area of the LBT (11.8-m equivalent). The best approach in our opinion is to build two independent double spectrographs, one for each of the two LBT mirrors, and then combine the measurements after observation using standard data-reduction processes. Functionally, this is equivalent to taking two consecutive observations to build up signal-to-noise ratio on a faint object, but with the observations acquired simultaneously. Such digital beam combination is practical since modern CCDs have very low readout noise, permitting co-addition of two data sets with nearly no noise penalty. Furthermore, if the two spectrographs are identical, there are significant cost savings due to non-recurring design and engineering expenses.

We propose to develop and build one of these spectrographs as a first-light instrument for the LBT 1-mirror configuration in 2001. Later, a second spectrograph can be built and deployed at the second mirror of the telescope. This ultimate double-double spectrograph combination will be a very efficient and practical way to use the unique configuration of the LBT at its full 11.8-m aperture at optical wavelengths.

At optical wavelengths, the two-spectrograph approach is superior to a single spectrograph at the combined focus of the two mirrors for several reasons. First, the optics needed to combine the beams would reduce throughput and restrict the effective field-of-view, especially if operated over a wide range of wavelengths. Second, the exit pupil of interferometrically combined, twin 8.4-m beams has the same size as the pupil from a 23-m aperture (the baseline of the LBT), but with ~27% of the pupil filled. Thus, the optics for an instrument using the interferometrically combined beam could be as much as 2.74 (=23.0/8.4) times larger than the optics of an identical instrument for a single 8.4-m telescope. Even the most favorable non-interferometric beam combination scheme would require a camera f-ratio one-half that of the cameras proposed herein. Such a fast camera cannot have the required image quality and throughput for our multi-object application. It will be at infrared wavelengths for interferometry that the combined focus of the LBT will be uniquely powerful.

Below we present examples of the scientific problems of interest to us at OSU for which MODS will be ideally suited, and describe representative observing programs that define the performance requirements of the spectrograph. We then describe the basic properties of the instrument and its operating modes, followed by a discussion of the details of the instrument design and the detector requirements together with possible future upgrade paths. We conclude with the management plan for the project.

2 Research Program

The formation and evolution of galaxies and their nuclei and the growth of large-scale structure are a particularly compelling class of problems on which the OSU Astronomy department plans to focus its observational effort during the first years of operation with MODS on the LBT. Since optical spectroscopy is critical to an enormous variety of research programs, we also expect that MODS on the LBT will make many exciting and unanticipated discoveries in other areas.

In the last three years, redshift surveys from the ground and imaging with Hubble Space Telescope (HST) have greatly advanced our understanding of galaxy evolution from z=1 to z=0, although these studies have raised as many questions as they have resolved (see, e.g., the review by Ellis 1997a). Still more dramatic has been the discovery of a large population of "normal" star-forming galaxies at z>3, through a combination of multi-color candidate selection and spectroscopic confirmation with Keck (Steidel et al. 1996, 1997, Lowenthal et al. 1997). These developments have made possible a first attempt at one of the major objectives of observational cosmology: determining the global history of star formation in the universe from z=4 to the present (e.g., Madau et al. 1996, Madau 1997).

Alongside these observational breakthroughs have come major advances in the theoretical framework for describing galaxy formation and evolution, with increasing sophistication of semi-analytic models (e.g., Kauffmann, White, & Guideroni 1993; Cole et al. 1994; Baugh et al. 1997) and hydrodynamic numerical simulations (e.g., Navarro & Steinmetz 1997; Weinberg, Katz, & Hernquist 1997 and references therein). In contrast to the traditional picture in which galaxies maintain their identity and evolve largely in isolation, theoretical studies of hierarchical galaxy formation suggest that mergers and radical morphological transformations are a common feature of galaxy evolution, and that many of a galaxy's stars form in sub-units that only later assemble into the galaxy itself. Furthermore, many theoretical studies are investigating the connection between quasars and the formation of galactic nuclei.

Our primary research program with MODS and LBT will focus on three broad, related problems: the *global star formation history of the universe*, the *evolution and assembly of galaxies*, and the *growth of large scale structure* in the galaxy distribution and in the underlying dark matter distribution. We will discuss observational strategies below, after briefly summarizing the main scientific.

2.1 Global Star Formation History

While remarkable progress has been made towards understanding the cosmic history of star formation, this understanding still suffers from systematic uncertainties that could change inferred star formation rates by an order of magnitude or more. A major goal of our observational program will be to develop a much firmer and more thoroughly tested picture of this history. Galactic star formation rates in most current studies are estimated from the UV continuum luminosity, and are highly sensitive to uncertainties in our assumptions about the amount of dust extinction and the stellar initial mass function (IMF). We will use high signal-to-noise spectroscopy to investigate the metallicities and the ages of the stellar populations in the star forming galaxies, to gain a better understanding of dust extinction and IMF effects, and to compare alternative measurements of the star formation rates, e.g. from H-alpha and H-beta emission lines. These studies will give more secure numbers for the star formation rates of individual galaxies.

Another large uncertainty in estimates of the global star formation rate arises from the contribution of galaxies below the detection limit of existing surveys. Madau (1997) and others compute this contribution by extrapolating the galaxy luminosity function assuming a Schechter (1976) form. This is a sensible approach given the available data, but there are now several observational studies suggesting that a Schechter function does not fit the faint end of the luminosity function even at z=0, and that the shape of the luminosity function is strongly dependent on bandpass, galaxy type, and redshift (e.g. Lin et al. 1997, Bromley et al. 1997). We will therefore design our observational program to probe as far down the luminosity function as possible to minimize the role of extrapolation in estimates of the global star formation rate, and to address questions about evolution of the luminosity function of different galaxy types.

Recent analyses imply that the peak of star formation activity in the universe occurs at z=1-2 (Connolly et al. 1997). Estimates of the star formation rate at these redshifts rely critically on photometric redshifts. Comparison between photometric and spectroscopic redshifts reveals encouraging agreement to I=24. However, as Ellis (1997b) emphasizes, the conclusions about star formation rest mainly on galaxies with I=24-26. In this regime the photometric redshifts are mostly unconfirmed by spectroscopy, and different photometric redshift techniques do not agree well with each other. We will devote special attention to obtaining spectroscopic redshifts in this redshift and magnitude range in order to test and calibrate photometric redshift techniques.

2.2 Evolution and Assembly of Galaxies

The observations needed to address the issues of the global star formation history described above will also answer many questions about the properties of galaxies as function of redshift and luminosity. Perhaps the most fundamental of these questions concerns the nature of galaxies with high rest-frame UV luminosities (which predominate in magnitude-limited samples of high redshift objects): are they massive systems forming stars at a fairly steady rate or small systems whose UV emission has been temporarily boosted by sudden bursts of star formation? Both points of view have been advocated with respect to "Lyman-break" objects (e.g., Steidel et al. 1996 vs. Sawicki et al. 1997), and they have radically different implications for the place of these systems in the overall story of galaxy formation and evolution. We will use widths and strengths of absorption and emission lines, overall spectral-energy distribution shapes, and diagnostic line indices to determine the stellar populations, metallicities, kinematic properties, and dynamical masses of high redshift galaxies. This information is crucial if we are to understand the mechanisms that drive galaxy evolution and the connection between high redshift systems and the galaxies that we observe today.

We will also examine the history of AGN activity and its relation to star formation activity. In a qualitative sense, plots of the global star formation rate against redshift are reminiscent of plots of quasar evolution, although the UV emissivity of the quasar population peaks earlier ($z>2.5$ vs. $z>1$) and declines more rapidly (Osmer 1998). Recent "demographic" studies of the cores of nearby galaxies suggest that most galaxies harbor black holes with mass ~1% of the bulge mass (Magorrian et al. 1997). If this is the case, then the level of AGN activity in a galaxy may be in large part connected to the dynamical disturbances that feed material to the central black hole. Comparing AGN and star formation activity is one way to evaluate the importance of dynamical interactions in triggering star formation. The overall decline of AGN activity may reflect the "settling down" of the core regions as galaxy assembly proceeds. To make progress on this problem, we need to observe both AGNs and galaxies at luminosities below L^* at high redshift, so that we are examining typical objects, not just those at the tip of the luminosity function.

2.3 Growth of Large Scale Structure

The detection of high redshift "superclusters" in the distribution of luminous Lyman-break galaxies suggests that they are strongly biased, i.e. much more clustered than the underlying dark matter (Steidel et al. 1997). Does this strong bias continue to low luminosities? This question is important for understanding the dark matter clustering and, perhaps even more, for understanding the nature of the Lyman break galaxies themselves, since (according to theoretical models) the clustering strength should depend on the masses of the dark halos in which they live. We will study Lyman break galaxies to substantially fainter magnitudes than existing surveys, so we can address the dependence of clustering on luminosity and measure finer details of structure through greater sampling density.

As discussed below, the combination of LBT and MODS will enable unprecedented studies of three-dimensional structure in the space distribution of Lyman-limit systems (from emission measurements) and Lyman-alpha forest systems (from absorption measurements toward close quasar configurations). Lyman-limit systems, which to date have been detected only in absorption, are an order of magnitude more common than the damped Lyman-alpha systems that correspond to the neutral regions of high-redshift galaxies. Emission searches can provide much more densely sampled maps of high-redshift structure than galaxy surveys alone. The best tool for understanding structure in the underlying mass distribution is low column-density, Lyman-alpha forest absorption, which arises in the diffuse, smoothly fluctuating intergalactic medium (IGM). Cosmological simulations show that the physics of this medium is remarkably simple, enabling variations in the Lyman-alpha optical depth to be directly related to fluctuations in the dark matter density (Weinberg, Katz, & Hernquist 1997 and references therein).

Relative to current studies of galaxies and quasars, these observational programs with MODS on LBT will probe high-redshift structure over a wider range of scales using a greater variety of tracers. They will therefore provide firmer clues to the processes of galaxy formation and more stringent tests of theoretical models for the origin of structure.

2.4 Observational Programs

Here we describe four observational programs that address the scientific problems described above and that illustrate the performance requirements of the spectrograph.

2.4.1 Spectroscopic survey of galaxies with z<1

We will undertake an extensive study of the redshifts, luminosities, and dynamical states of ordinary galaxies from the present back through more than half the age of the universe. There are many ongoing ground- and space-based imaging surveys which are generating large samples of photometric redshifts and morphological information which can form the basis of our survey. Crucial diagnostics of average stellar ages, metallicities, dust extinction, and star formation rates include the [O II], H-alpha and H-beta emission strengths, the strengths of the 4000Å break and of numerous stellar absorption features, the intensity and slope of the (redshifted) UV continuum, and the overall spectral energy distribution. We will explore the behavior of these diagnostics with galactic luminosity and dynamics (both internal and in the local environment). The largest possible wavelength coverage is essential for sampling wide range of redshifts and achieving overlap between the z=0 and z=1 populations. Resolutions up to 8000 will enable us to study the kinematics of these objects.

2.4.2 Spectroscopic survey of galaxies and quasars with 1<z<6.

While we cannot study faint, z>1 galaxies in as much detail as z<1 systems, we can measure the luminosity function and estimate star formation rates and dynamical masses of the luminous components. Cosmological simulations suggest current observations are only detecting a tiny fraction of the galaxies at z>3 (Weinberg, Katz, & Hernquist 1997). There should be a large population of less luminous galaxies at z=3 and a significant population to z=6 and beyond. The quasar population declines at z>3 but much better statistics are needed to compare the "turn on" history of quasars to the star formation and assembly history of galaxies.

Spectroscopic confirmation at these faint levels requires suitable imaging surveys and dedicated large telescope time. Surveys for faint quasars such as the BTC50 and BFQS (Falco et al., Hall et al., see description in Osmer 1998) will provide the galaxy samples needed for such a program. The BTC50 survey is covering 50 deg^2 in BVI to limiting magnitudes of 25 to 26 in B and V and 24 in I, while BFQS will reach as faint at B=26.7 over 8 deg^2. As shown in Table 1, the surface density of galaxies down to these magnitudes is more than high enough to provide a wide selection of candidates within the 4' field of MODS. Follow-up spectroscopy with the LBT is crucial for confirming the identifications and establishing redshifts for all selected candidates, both quasars and galaxies. These samples will provide ideal quasar targets for absorption-line studies and for studying the relation between galaxy and quasar formation. To carry out these observations, we need to have low spectral resolution (R~2000), excellent sensitivity from 320 to 900nm, and multi-slit capability.

Table 1: Surface density of ordinary galaxies in the MODS field

	Number of galaxies in 4´ MODS field					Time to S/N=20	
R	Total	0<z<1	1<z<2	2<z<3	z>3	High-res	survey
21	11	7	0	4	0	.3 hr	---
22	18	11	4	4	0	1	0.3 hr
23	22	15	4	4	0	2	0.8
24	55	47	4	4	0	8	3
25	171	138	15	18	4	28	12
26	458	291	55	95	14	---	70

Cols 2-6 show number of galaxies brighter than the given R as a function sorted by photometric redshift (HDF analysis by Conti & Osmer, priv. comm.; cf. Steidel et al (1996) value of 6.4±1.1 galaxies for z>3 at R=25 from spectroscopic redshifts). Cols 7-8 show time (hr) to achieve S/N=20 per resolution element in the red high-res mode (R=8000) and a lo-res survey mode (R=1500 binning the CCD), respectively, for the two-mirror LBT.

We also note that programs (1) and (2) can be multiplexed where advantageous by judicious use of the multi-slit capabilities of the spectrograph. For example, objects of high surface density, such as faint galaxies of low to intermediate redshifts, can be observed in the vicinity of lower surface density candidates (e.g. brighter galaxies at z=0.5 or candidates for z>5 quasars and galaxies).

2.4.3 Search for fluorescent emission from Lyman limit systems.

To date, high-z Lyman limit systems have been detected only in absorption against background quasars, so the maps of structure that they provide are 1-dimensional and sparse. However, these systems must also produce fluorescent Lyman-alpha emission because they are photoionized by the UV background, and emission searches can yield 3-dimensional maps of their space distribution (Gould & Weinberg 1996). The observations require a large aperture telescope, a high-efficiency spectrograph, and spectral resolution of ~8,000. Because the difficulty of detection increases rapidly with redshift, MODS will be ideally suited to this work, especially because of its blue sensitivity. Gould & Weinberg (1996) estimate that long slit exposures of ~20-40 hours would be required to detect fluorescent emission, but one such observation would be expected to find ~100 Lyman limit systems. A dedicated program of ~200 hours over several years has the potential to produce a 3-dimensional map of high-redshift structure with unprecedented detail.

2.4.4 The Lyman-alpha forest.

While high-resolution spectra of the Lyman-alpha forest give information on small-scale structure, larger scale structures are more efficiently probed with large numbers of lower resolution spectra (Croft et al. 1998). The spectra can be analyzed by methods that treat each spectrum as a continuous, 1-dimensional field instead of a collection of discrete lines. MODS will be ideally suited to such an approach because of its wide spectral coverage (allowing a wide range of redshifts) and the LBT's large aperture (allowing fainter objects). MODS will be especially valuable for studies of close quasar configurations, because in these cases the quasars are normally faint. Absorption along parallel lines of sight to close quasar configurations provides a unique way to study 3-dimensional structure in the low density IGM. By comparing structure along the line of sight to structure transverse to the line of sight, it will be possible to set strong constraints on the value of cosmological constant (Croft et al., in prep).

3 General Description of the Instrument

Our scientific interests dictate that the instrument have moderate spectral resolutions (10^3-10^4), wide wavelength coverage (320-1000nm), and the ability to observe extremely faint objects (~25 mag). These objectives require that the instrument have excellent throughput from the atmospheric cut-off in the ultraviolet to the practical sensitivity limit of CCDs in the far red. No single reflective or antireflective coating will work optimally over this wide a wavelength range without sacrificing one extreme or the other. This has led us to adopt a double spectrograph design (like the Palomar DBSP; Oke & Gunn 1982) with separate blue- and red-optimized channels to maximize the throughput. To further improve the effective throughput, a multi-object capability over a field large enough to include many typical objects is also required. As demonstrated in Table 1 above, there is a sufficient density of objects within the 4' field of view to give considerable multiplex advantage with a multislit system. As argued above, the most effective use of the full LBT collecting area is to employ two independent spectrographs, so costs must be kept reasonable and the CCDs capable of very low readout noise. The typical seeing expected at the LBT is ~0.6" (similar to that currently obtained at the MMT, WIYN, and KPNO). Slit widths should also allow for the best anticipated conditions (i.e. ~0.3"; active/adaptive optics are planned, and the LBT image error budget is 0.34") and for worse-than-average conditions (i.e. ~1.2"). Table 2 summarizes the baseline operating modes of MODS with 0.6" slits.

Table 2: MODS Baseline Operating Modes

Mode	FWHM (2 pixel)	Resolving Power (R)	Total Range (nm)	Coverage per setting	Grating Order
Blue LoRes	0.15 nm	3000 (450nm)	300-600	300 nm	1
Blue HiRes	0.075 nm	6000 (450nm)	300-600	150 nm	2
Blue Imaging	Filter		300-600	Filter	n/a
Red HiRes	0.1 nm	8000 (800nm)	500-1000	200 nm	1
Red LoRes	0.27 nm	3000 (800nm)	500-1000	400 nm	1
Red XD	0.1 nm	8000 (800nm)	500-1000	500 nm	4-7
Red Imaging	Filter		500 - 1000	Filter	n/a

MODS will have three baseline observing modes: *long-slit*, *multi-slit*, and *imaging*:

Long-slit mode, in which a single 4' slit mask provides continuous spatial coverage across one axis of the MODS field-of-view. Long slits are useful for point sources, especially faint objects where sky subtraction is critical, and for spatially extended objects with a definite axis of symmetry. A 0.6" slit is matched to two pixels of the detector, but a wider slit can be used with no noise penalty by binning the detector.

Multi-slit mode, in which an aperture mask is used to define a series of precisely-located "slitlets" centered on objects falling within the MODS field of view. At a penalty of slightly reduced spectral coverage near the ends of the field along the dispersion axis of the system, spectra can be obtained of objects distributed in 2 dimensions, effectively multiplying the throughput of the spectrograph by the number of slitlets used. For example, we could easily accommodate 48 slitlets 5" long across the 4' field. Consideration of adequate sky subtraction suggests that for the faintest objects, 10"-long slits (for ~24 slitlets) would be optimal. Multislit modes are features of all major spectrographs being designed for use by the current and coming generation of large telescopes (e.g., GMOS, DEIMOS, and FORS). For flexibility and simplicity of operation, the best option appears to be custom aperture plates machined on-site.

Direct-Imaging mode, in which the spectrograph is used without a slit mask and the grating is replaced by a flat mirror. In addition to applications requiring direct imaging *per se*, MODS ability to quickly switch between direct imaging and slit spectroscopic modes provides a foolproof method of precise target acquisition and placement on the slits or multislits. The faintest objects observed with the LBT will be much fainter than the night sky brightness, and direct imaging will be essential for target acquisition.

4 Details of the Instrument Design

In this section we describe some of the details of the MODS design. These are primarily based on a preliminary optical design analysis and our experience with other instruments. Much of the first part of the project will be devoted to thorough investigations of all aspects of the spectrograph design and the comments in this section represent only our current conceptual view of the instrument. Note, however, that this design does follow our general philosophy of simplicity, modularity, and low cost. The optical layout of MODS is shown in Figure 1.

4.1 Optical Design

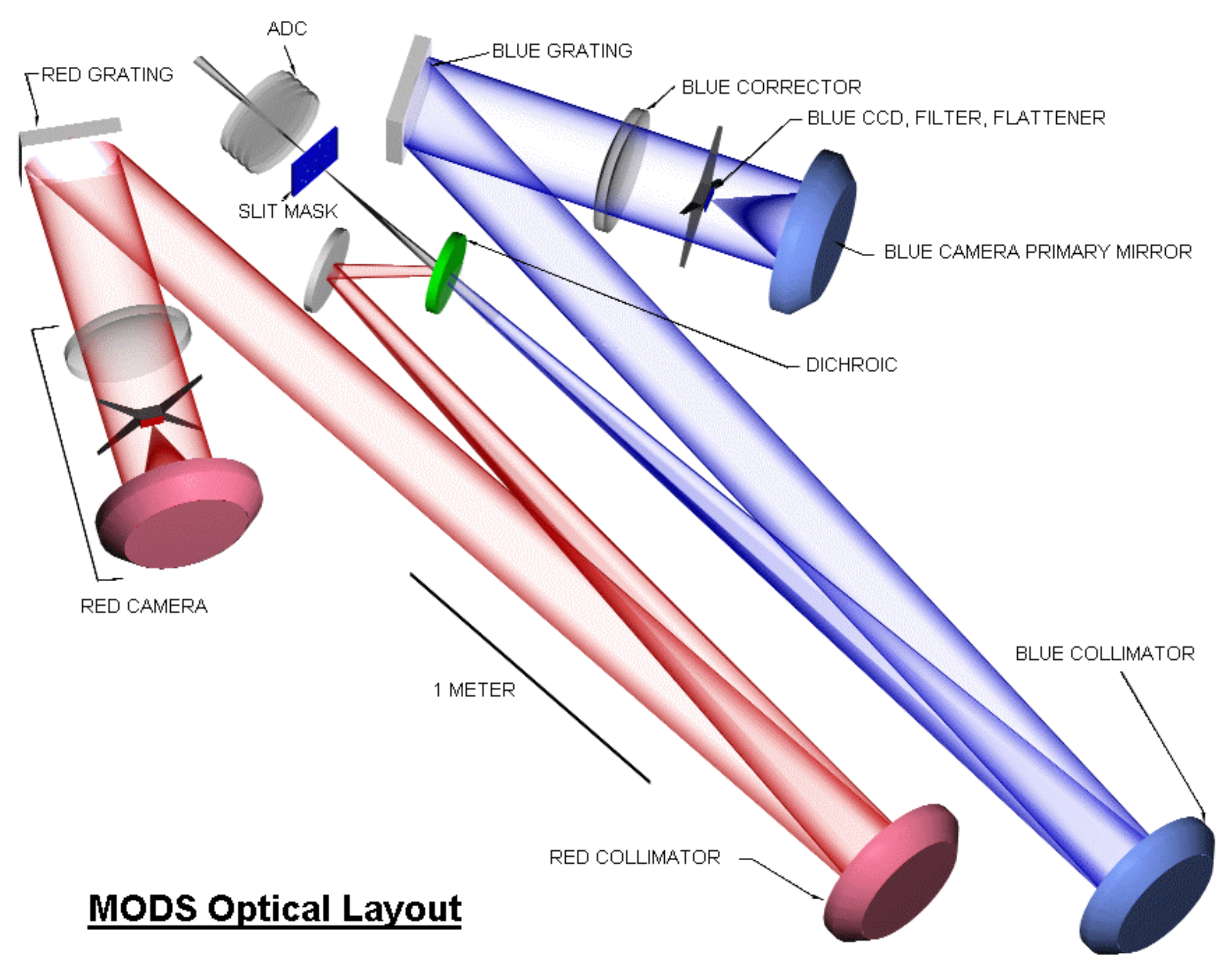

Figure 1: MODS Optical Layout

4.1.1 Design Goals

The optical design of the MODS spectrographs must have high throughput from 320 nm to ~1000 nm, good images over a 4' field, and resolutions of up to ~10^4 to meet the science goals for the instrument. These requirements introduce important design constraints. For example, optical designs with many transmissive elements are likely to have marginal ultraviolet (or red) throughput due to the limitations of both the broad band coatings and the materials that have good transmission in the near UV.

We have adopted a design using a reflective collimator and a single-mirror camera with a correcting optic and a field flattener as the best way to meet our requirements. Figure 1 shows a design which has been fully analyzed, meets the science requirements, but has not been fully optimized. The individual components of the design are discussed in more detail in the next section. Note that Figure 1 shows *all* of the optical surfaces in the spectrograph design. The large instrument volume available at the LBT allows for an instrument of this size (3.5x1.5-m) with only one reflection added for packaging.

4.1.2 Optical Layout

ADC: An atmospheric dispersion compensation (ADC) assembly will be required when observing away from the zenith. One surface of the ADC will have weak positive power to move the pupil to the desired location in the instrument.

Focal Plane: The focal plane location is occupied either by a long slit or an array of slitlets aligned with a selection of objects over approximately a 4' field.

Dichroic: A dichroic beamsplitter reflects light of wavelength greater than 600nm to the red channel of the spectrograph and transmits light shortward of this wavelength to the blue channel. The dichroic can be removed under remote control to pass all of the light to the blue channel or replaced with a red-optimized mirror to pass all the light to the red channel. Light loss due to the dichroic will be less than 15%. The dichroic will have a transition from reflecting to transmitting over a wavelength of approximately 50nm allowing for enough overlap between red and blue spectra to simultaneously calibrate both channels. A flat dichroic would introduce some astigmatism in the blue channel. This astigmatism will be avoided with a weak cylindrical figure on the rear surface of the dichroic substrate.

Collimators: Each channel will have an aspheric collimator mirror ~3.5-m from the f/15 Gregorian focal plane to produce 230-mm diameter collimated beams. The 230-mm beam size, while large, has distinct advantages and comes at a relatively modest cost. The angular magnification at the camera aperture is the ratio of the telescope diameter to the point-source collimated beam diameter. A larger beam therefore reduces the camera field angle for a given field of view, thus reducing important camera aberrations that increase very rapidly with the field angle. For the detector location we have chosen, the large beam also reduces the fraction of the beam obscured by the detector. Since the optical power in our collimator and camera comes from reflective elements of relatively modest size, there is little cost difference between the required elements and ones half the size. An all-refractive collimator or camera with such a large beam, by contrast, would be prohibitively expensive.

Gratings: The angle between the camera and the collimator has been chosen to allow MODS to operate at all required wavelengths and resolutions without using the grating at an angle where light reflected from the detector back toward the grating is re-imaged on the detector, and to simultaneously avoid major blaze function anomalies in both polarizations. The grating size is consistent with existing "Large Astronomical Gratings" and therefore permits the use of existing rulings and new rulings with existing equipment and technology.

Cross Disperser Grism (not shown): Cross dispersion in the red channel will be with a removable grism. The grating portion of the grism will be ruled on a fused silica prism with 80mm base and will be of approximately 170 lines/mm to disperse the 600nm to 1000nm band perpendicular to the primary dispersion.

Camera: Nearly identical f/1.4 cameras will be used in both channels giving 0.26" per 15-micron pixel in imaging mode, and mapping a 0.6" slit onto two pixels when accounting for anamorphic magnification. The Maksutov-Schmidt design give good imaging performance over entire field, and, since there are only two refractive elements and one reflection, throughput can be high over the entire wavelength range. The detectors are located at a trapped focal position between the corrector and camera mirror. Obviously, in this position the detector (and associated field flattener and filter; see below) will obstruct some of the beam. However, assuming a detector with 2048x4096, 15-micron pixels, we estimate the vignetting of <8% for the CCD and support structure. A similar camera, the "Air Schmidt", designed by one of the Co-Is, has been in use on the Cerro Tololo Inter-American Observatory RC and Echelle spectrographs for many years. The dimensions of the camera elements have been chosen to accept all the light from the grating over the width of the detector.

4.1.3 Expected Performance

Image Quality: The analysis (Code-V) of the collimator and camera combination shows that in direct imaging mode MODS will produce image sizes of <0.3" (80% encircled energy diameter) over the full 4' field.

Throughput: The total throughput of the spectrograph is determined by the combination of the transmission and reflectance of the optical surfaces, the efficiency of the grating in use, the vignetting of the beam by the detector and its support structure and the CCD quantum efficiency. Figure 2 (below) presents the calculated throughput for the spectrograph and ADC based on published reflectivities for the mirrors, actual traces of anti-reflection coatings we have used on similar transmissive optics, measured detector quantum efficiency and granting blaze curves calculated with the GSOLVE package. We have not included slit losses or the efficiency of the primary and secondary in this calculation. Note that the throughput redward of 800nm would be as much as 2-3 times greater with a detector having a quantum efficiency similar to the thick fully-depleted demonstration devices made by LBNL/Lick.

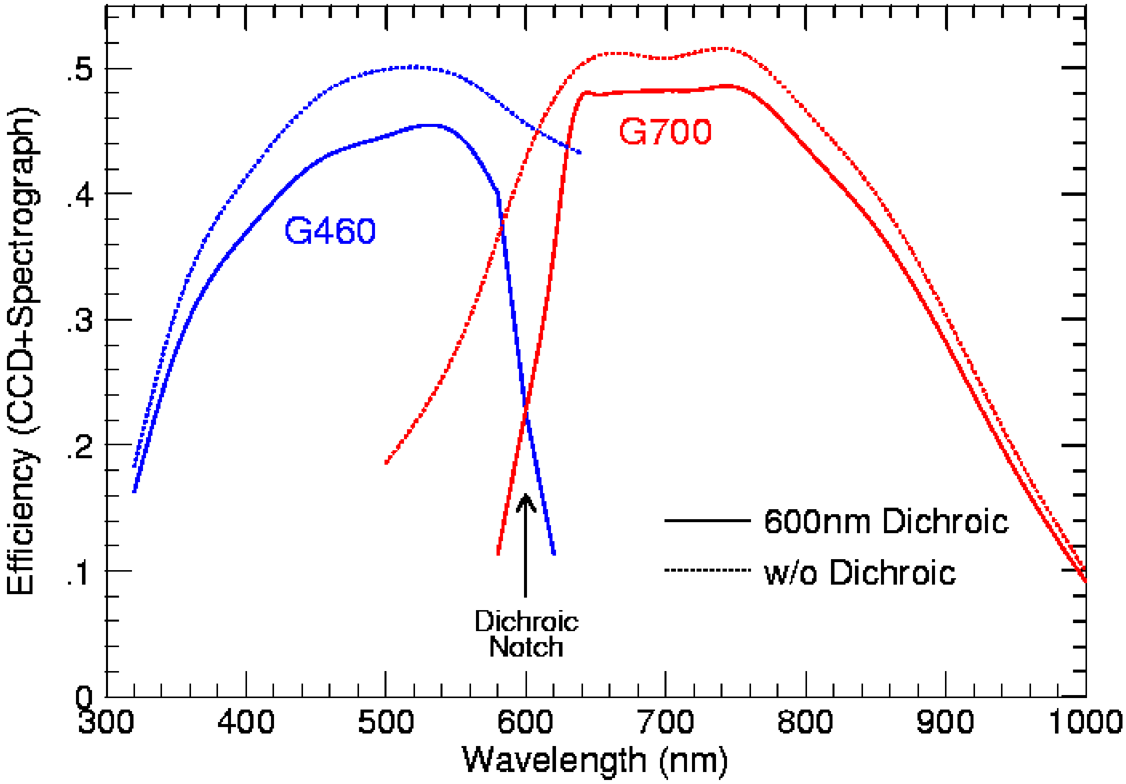

Figure 2: MODS System Throughput (exclusive of telescope & atmosphere).

4.1.4 Detectors

The design of MODS is predicated on the availability of very low readout noise CCDs. For example, if the readout noise is <3e$^-$, then the signal-to-noise ratio of digitally combined MODS observations are ~10% less than single 11.8-m telescope measurements (assuming resolution ~10^4,~0.6" wide slit, and dark sky conditions). Detector size, read-noise, cosmetics, and red quantum efficiency are all improving so rapidly that it would be unwise to commit to a given detector three years before an instrument is to be used. Nevertheless there are at least three sources of detectors that meet our basic requirements for format, low noise and high quantum efficiency. The SITe ST-002a, while not having the best noise or quantum efficiency, is commercially available. The MIT/Lincoln Labs CCID20 has excellent read noise, reasonable cosmetics, but has not demonstrated good blue quantum efficiency nor is its availability guaranteed. Devices with 4Kx2K format made from the "Orbit Mask Set #1" have operated successfully and although they are not plentiful, it would be straightforward to make more devices with the same design, perhaps with a mask set having two or more copies of the device per wafer. We anticipate that devices from any of these sources would be thinned, packaged and coated by the Steward Observatory CCD Laboratory.

4.2 Mechanical Design

The MODS spectrograph is a large structure to which modular components are attached. The structure supports the optical elements and mechanical modules against gravity loads. The configuration of the modules determines the instrumental mode. We have extensive experience in the design of precision automatic mechanisms for astronomical instruments. We have specified, designed, fabricated, and operated in the field devices such as filter wheels, slit wheels, camera interchange turrets, camera focus stages, pupil masks, and image rotators, all with excellent performance and reliability. Furthermore, we regularly use finite-element analysis techniques to design instruments that meet tight flexure and thermal stability requirements. The design of MODS will draw heavily from these previous efforts.

4.2.1 Structure Design

The flexure design goal is to maintain image position on the detector to within 0.05 pixels (~0.75-micron) for a 1-hour exposure in both the dispersion and slit directions. This insures that science programs requiring excellent sky subtraction can be successful and that imaging performance and fringe pattern removal in the red will not be degraded by flexure.

A welded steel frame will be designed to minimize translations and tilts of the optical elements, particularly the collimators. Welded steel construction is desirable because of its low hysteresis, high stability, moderately low coefficient of thermal expansion, low cost, and ease of fabrication. Careful interaction between the optical design (using Code V) and the structural design (using ALGOR finite element analysis software) will insure that the structure is optimized for its optical support functions.

Preliminary analysis of a steel frame with the basic dimensions of the spectrograph indicates that collimator lateral translations of order 25-micron and collimator tilts of order 5-microradian can be expected from gravity induced flexure. The translation and tilt combine to produce image motion at the detector of approximately 5-micron. These results indicate that a simple uncompensated passive structure is unlikely to meet the image motion design requirement of 0.75-micron.

Our analysis indicates that corrections based on a look-up table will provide a technically feasible, cost-effective solution for meeting the flexure requirements. The spectrograph will include 3 active linear actuators on the collimator support cells that will provide tip/tilt and focus movement of the collimator mirror. These actuators will be capable of tilting the collimator with the required precision to null flexure induced image motion to less than 0.05 pixels. The flexure induced image motion will be completely mapped on a telescope simulator in our high-bay laboratory, generating a look-up table that will provide the information necessary to drive the tip/tilt collimator. The success of a look-up table approach depends on a structural design with very low hysteresis, which is best provided by a welded steel frame. This flexure compensation approach is very similar to the pointing maps generated for large telescopes that routinely reduce their pointing errors by more than an order of magnitude.

Temperature gradients across the structure of 1ºC can cause displacements in the structure of tens of microns. To limit thermally induced image motion to <0.75-micron, changes in temperature distribution across the structure must be <0.1C during an exposure. The entire instrument will be enclosed in an insulated cover that provides a homogeneous thermal environment and isolation from ambient temperature gradients in the dome and changing thermal radiation conditions. The hollow tubes of the structure will be actively ventilated by drawing air in through numerous small holes in the tube walls, minimizing temperature gradients in the structure. This ventilation will also keep the structure very near ambient temperature, eliminating any instrument-induced seeing.

4.2.2 Module Design

The spectrograph has six modules:

ADC:

> The atmospheric dispersion corrector mechanism will comprise two identical worm gears driven rotary motions with direct encoder feedback that will allow differential and common mode rotation of the ADC prisms.

Slit-Mask Cassette:

> Automatically selectable focal plane masks will be used for direct imaging single slit spectroscopy, and multi-slit spectroscopy. The masks must be fabricated and positioned in the instrument with high precision to insure registration between the focal plane mask and science field. Both GMOS (under construction for GEMINI) and DEIMOS (under construction for Keck) face similar challenges regarding focal plane masks. The GMOS design team has selected laser machining for fabrication of masks and a cassette mechanism for mask handling. The physical size of the GMOS masks and the slit widths are almost identical to MODS requirements because both instruments are used at f/15 on 8-m telescopes. We plan to follow their progress carefully and to use the technologies and design approaches that best meet the needs of this instrument. This will substantially reduce costs and facilitate completion of this project.
>
> The typical multi-slit observing session will obtain a direct image of the field of interest with the spectrograph direct imaging mode, either that night or using a queue scheduled service image obtained prior to the run. Targets are identified in this finder image, and the coordinates fed to a computer-controlled machine to generate the mask. Existing on-site mask generation systems can go from image to a ready-to-use mask in 30 minutes.
>
> Design challenges for the multislit mode include developing an accurate mask delivery system that can be accessed easily by observing technicians, investigation of machining technologies that will deliver the necessary slit machining precision, structural requirements of the large aperture masks (including thermal expansion characteristics, stiffness against sag, distortions, etc.), and software for mask generation.

Dichroic Changer:

A simple three position linear stage will allow selection of either red/blue dichroic when the spectrograph is used in a dual beam mode, a silver mirror to direct the beam into the red beam for red-only mode, or nothing when the operating in the straight-through blue-only mode.

Collimator:

Each collimator cell will incorporate 3 linear actuators to allow remote tip/tilt and focus adjustments of the collimator. Stepper motor driven fine pitch screw actuators will provide the required resolution, accuracy, and stiffness for this application at moderate cost.

Gratings:

Three gratings and one flat mirror will be mounted on a rotary indexer to permit quick reconfiguration of the instrument on the telescope. There will be a separate grating indexer for each beam accommodating a total of up to six gratings for the instrument. The gratings and flats will be mounted in kinematically docked cells and will be removable on the telescope. The grating indexer must be very accurate to insure that wavelength re-calibration will not be required after changing operating mode from imaging to spectroscopy. A grating tilt mechanism will be provided for each of the 3 grating positions to allow precise wavelength selection. The accuracy requirements for grating tilt are very demanding and the tilt mechanism will need to be very carefully developed.

Cross-dispersing Grism:

The cross-dispersing grism will be kinematically mounted in a cell and removable from the grism select stage. A linear stage (perpendicular to the optical axis) will provide for up to 2 different grisms and one open position in the beam.

Camera/Filter/Detector:

The Maksutov camera requires a simple plano-convex spherical field flattener immediately in front of the detector. This location is also very desirable for filter placement, permitting the use of small and inexpensive filters. The MODS instrument will use field flatteners that carry a cemented rectangular filter on the flat side of the field flattener, providing the additional advantage of higher throughput by eliminating two air-to-glass surfaces and allowing optimized coatings on the convex surface of each flattener. The filter/flattener interchange mechanism will be realized with a rotating arm that swings in and out of the camera beam to swap filters. The filters will kinematically dock in front of the detector insuring good optical alignment of the field flattener. The camera will be focused by moving the primary mirror of the camera. The mirror will be supported on 3 motorized linear actuators, identical to the collimator mirror support actuators. The synchronized motion of the three actuators will provide focus travel while the tip/tilt motions will be used to collimate the camera primary mirror. The detector module will be supported on four tensioned support vanes 4mm thick by 40mm deep. This support arrangement will reduce gravity induced lateral flexure of the detector to less than 1-micron, and also control rotations and piston of the detector to acceptable levels. The techniques required to mount a CCD in a Schmidt camera have been developed and used successfully in the "Air Schmidt" camera used on the CTIO 4-m telescope. Electrical leads will be brought to the detector via conductors inside the support vanes. Cooling for the detector will be provided by the thermal conductivity of the support vanes that will be connected to a cold sink outside the optical beam. The entire camera will be evacuated to insulate the detector and cold spiders.

5 Future Upgrade Paths

The MODS open architecture includes provisions for a number of future upgrades that would enhance the capabilities of the instrument and respond to the evolving scientific needs of its user community. A simple upgrade is to add more gratings to provide other resolution and wavelength coverage modes. Costs depend on the availability of replica gratings meeting the specifications.

An especially powerful upgrade for MODS is to implement an integral-field mode. Not all astronomical objects have axes of symmetry that are convenient for deployment of a slit to measure their spectra. This is especially true of complex extended objects like active galactic nuclei, actively star-forming galaxies at high redshift, or individual HII regions in relatively nearby galaxies. An effective technique is to remap the spatial field with arrays of fibers or microlenses and feed it to a long-slit spectrograph. Called "integral field spectroscopy" (IFS), this technique has been increasingly applied at a number of observatories for the study of angularly small extended objects (e.g., TIGER and MOS/ARGUS at CFHT [Bacon 1995; Vanderreist 1995]; HEXAFLEX and 2D-FIS at La Palma [Garcia et al. 1994]). There are several implementations of integral field that exist: packed fiber bundles, microlens arrays (Bacon 1995), and hybrids joining the two (the "FUEGOS" design proposed by Felenbok et al. 1994 for the VLT and Allington-Smith et al. 1996 for GMOS). The GMOS design is especially pertinent because of the similarities with the MODS optical requirements. We plan to study the alternatives and ensure that MODS will be able to include this capability in the future.

6 Project & Management Plans

6.1 Project Personnel and Approach

The primary participants in the development of the MODS will be B. Atwood, P. Osmer, and R. Pogge.

P. Osmer is the principal investigator for the grant and the Department Chair. He will have overall responsibility for the project as it will be a major initiative for the entire department. Osmer has extensive experience with optical instrumentation for large telescopes, large telescope projects, and the management of observatories and academic programs.

B. Atwood is the Director of the Department's Imaging Sciences Laboratory (ISL) and will be the Project Manager for MODS. He has 29 years of experience in the detector, electronic, and instrument systems that will be needed for the project. As Director of the ISL, he will supervise the design, fabrication, and assembly of the instrument.

R. Pogge will be the Instrument Scientist for the project. He will be chiefly responsible for the commissioning of the instrument and developing observing and calibration procedures, and he will lead the effort to develop the data-reduction pipeline for the user community. He will also be responsible for supervising the graduate students working with the project.

T.P. O'Brien will be the lead mechanical engineer on the project. He has 10 years of experience designing and building dewars and mechanisms for astronomical instrumentation.

P.L. Byard will design the optics using Code-V (for which we have a permanent license). Byard has designed optics for all of our optical and infrared instruments.

The MODS project will be executed by the Department's ISL. This group, including two instrumentation scientists, electronic and mechanical engineers, a mechanical designer, a programmer, two electronic technicians and two machinists, designs and fabricates instrumentation to support the scientific needs of the department, and, through contracts, other observatories. In addition, we work with a number of qualified vendors for optics, printed circuits, and mechanical fabrication. The ISL is one of a handful of university-based astronomical instrumentation efforts with a permanent professional staff. This, combined with a variety of previous projects, has allowed us to develop a stable approach to instrument design and construction. Important elements include reuse of previously successful systems, a highly modular design philosophy, dedication to analysis before construction, close interaction with the observers to insure a sensible melding of instrument specifications and ISL capabilities, and strict control of software costs.

6.2 Project Management

Major phases of the project will include specification review, design studies, detailed design, fabrication, systems integration, laboratory tests and commissioning. Because we are a relatively small group performing only two projects at any one time, we overlap the detailed design, fabrication, systems integration and testing phases of all but the most simple projects. This means that the overall project supervision and project reviews are more important than is the case where each phase can be completed before the next begins. The added level of project supervision is accomplished by frequent (several times/week) informal meetings of the individuals responsible for each subsystem, combined with regular formal evaluations of the project timeline. In addition, we plan to convene an external review panel of two scientists and two engineers for a combined conceptual and design review when the detailed design is about 25% complete and fabrication is just beginning.

6.3 Implementation

MODS will be a first-light facility instrument at the LBT, available for use by the entire LBT community. We expect heavy user demand and that the instrument will be regularly scheduled, especially during dark time. Maintenance, operational and technical support, and time allocation mechanisms will all be part of the LBT organizational structure.

6.4 Risk Management

In a project of this scale, the leading source of potential cost overruns is increased labor costs due to delays in fabrication, testing, or software development. All of the ISL staff (machinists, draftsmen, programmers, electronics fabrication, engineers, and scientists) are permanent salaried employees of the Ohio State University. In the event of unforeseen delays, the Department and ISL will agree to cover any additional labor costs.

Detectors are another common risk factor in instrument development. MODS has been designed for a 2Kx4K 15-micron pixel CCD format that has emerged as the workhorse CCD format in ground-based astronomy. Nearly all large-instrument projects are using some variant upon this detector. In addition, we have no extraordinary detector requirements, and detector procurement will not be a risk factor in this instrument. The aspheric surfaces required on the collimators, rear surface of the corrector plates and camera mirrors are all relativly mild by today's standards. The sizes and materials required for the optics are commonly supplied by several different manufacturers.

Table 3: Project Timeline

Activity	Date
Definition of science requirements & instrument concept	1/99 – 3/99
Preliminary design & review	3/99 – 1/00
Detailed design & preparation for fabrication	6/99 – 6/00
Fabrication	1/00 – 9/01
Integration & Testing	6/01 – 1/02
Shipment to the telescope, initial testing & commissioning	10/01
Release for scheduled observations	6/02

Project phases will naturally overlap to make efficient use of ISL resources. We plan on one external review to take place in the fourth quarter of 1999.

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