WFIRST Science with a Probe Class Mission

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ABSTRACT

WFIRST is the highest priority space mission of the Decadal review, however, it is unlikely to begin in this decade primarily due to a anticipated NASA budget that is unlikely to have sufficient resources in this decade. For this reason we present a lower cost mission that accomplishes all of the WFIRST science as described in the Design Reference Mission 1 with a probe class design. This is effort is motivated by a desire to begin WFIRST in a timely manner and within a budget that can fit within the assets available to NASA on a realistic basis. The design utilizes dichroics to form four focal planes all having the same field of view to use the majority of available photons from a 1.2 meter telescope.

Key words: Instrumentation, WFIRST

1 INTRODUCTION

The Wide Field Infrared Survey Telescope (WFIRST) is ranked as the highest priority space mission by the Astro 2010 Decadal Survey, New Worlds, New Horizons. It is envisioned as a multi-purpose observatory combining wide field near infrared imaging and spectroscopy with a microlensing survey for exoplanet detection. In follow up studies conducted after the publishing of the Decadal Survey telescope diameters ranging from 1.1 to 1.5 meters were considered with the smallest diameter version performing only a subset of the Decadal Review recommended science. More recently the acquisition of two 2.4 meter telescope structures referred to as the Astrophysics Focused Telescope Assets (AFTA) has motivated the study of an expanded capability 2.4 meter version of WFIRST. The science capabilities of this Hubble class mission are undeniable, however, it has moved the expected mission cost into the $2B range and imposed significant restrictions on the temperature of the telescope that compromises the performance at wavelengths longer than 2.0 microns. An additional concern is the time scale for implementing WFIRST. The NASA Astrophysics Implementation Plan for 2013 (NASA 2012) shows the planning for a WFIRST like mission beginning in approximately 2023, as compared to the 2013 start anticipated by the Decadal Survey. Even if the late start date is taken as conservatively pessimistic it is appropriate to consider whether a smaller and less expensive approach can achieve all of the expected WFIRST science.

For this reason we investigate a WFIRST probe class mission where probe class in this context is a mission cost of $1B. We find that a mission with a telescope diameter of 1.2 meters and multiple focal planes fed by a dichroic tree can accomplish all of the data requirements of Design Reference Mission 1 (DRM1) as described in the WFIRST Final Report of the Science Definition Team Green et al. (2012). We present this concept under the name WPROBE as a demonstration that the WFIRST science goals do not need to be compromised to produce an affordable mission that can move forward significantly sooner than the currently expected date for WFIRST. We encourage the Science Mission Directorate at NASA headquarters to consider a call for proposals for additional concepts that can also carry out the WFIRST science at significantly reduced cost and accelerated schedule relative to the use of the AFTA telescope assets.

2 DRM1 DATA REQUIREMENTS

DRM1 is comprised of 4 major surveys; a High Latitude Survey (HLS) with both imaging and low resolution spectroscopy, a supernova detection and spectroscopic survey, a galactic plane imaging survey and a microlensing survey for exo-planet detection. The data requirements for these surveys are summarized in Table 1. This information is taken from Table 1 of
3 INSTRUMENT CONCEPT

Traditional imagers and imaging spectrometers utilize individual filters in sequence to provide multicolor photometry and spectroscopy. In this mode most of the photons in the spectral range of the instrument are not used. More modern space instruments such as NIRCam, being installed in JWST, utilize a dichroic to observe at two wavelengths simultaneously. WPROBE takes this practice to its logical next step by utilizing a dichroic tree to observe the same field of view in 4 wavelengths simultaneously.

Modern dichroic manufacturing techniques insure very sharp transitions from transmission to reflection to make this practice very efficient. WPROBE has 4 focal planes to utilize the majority of photons incident on the telescope. Fig. 1 gives a schematic of the dichroic tree and focal planes.

WFIRST DRM1 observations utilize the Y, J, H and K bands with a Z band also specified but with no DRM1 observational program associated with it. WPROBE utilizes dichroics to define the bands with bandwidths slightly smaller than the traditional filters. The first dichroic splits the Y and J bands from the H and K bands while the second dichroic in each arm splits the light between the two bands. In this concept there are four focal planes that view the four bands simultaneously in the same field of view. The bandwidths are slightly smaller than the traditional Y,J,H and K bands but the small loss in bandwidth is more than made up for in the total speed of the system. Note that the dichroics play the role of the filters so no additional filters are required except for the short wavelength cutoff of the Y filter. The wavelength response of the detectors acts as the long wavelength cutoff in the K band.

Although the dichroics define the bands for the Y-K bands there is the ability to define additional filters and spectroscopy. The dichroics are mounted on dichroic wheels that also contain a mirror aperture and a clear aperture. The clear apertures provide the wide filter option for total band imaging for microlensing studies. The combination of clear and mirror apertures allows complete flexibility to send light to any combination of focal planes. The addition of filter wheels allows more general filters for general observer programs and provides the mechanism for introducing the grisms required for the spectroscopic requirements of WFIRST. Table 2 gives a summary of the basic WPROBE characteristics.

| Component                        | Characteristics          |
|----------------------------------|--------------------------|
| Telescope Diameter               | 1.2m                     |
| Detectors                        | Teledyne H4RG            |
| Pixel Size                       | 0.18 arc sec.            |
| Focal Planes                     | 4                        |
| Dichroics                        | 3                        |
| Detectors per Focal Plane        | 3x3                      |
| Science Field of View            | 0.25 sq. deg.            |
| Total Field of View              | 0.37 sq. deg.            |
| Orbit                            | L2                       |
| Filters                          | Z, Y, J, H, K, Wide      |
| Grisms                           | 2                        |
| Grism Resolutions                | 75, 600                  |

Table 2. WPROBE Characteristics preliminary estimates
3.1 Focal Planes

The WFIRST concept used for the DRM1 analysis has a pixel size of 0.18 arc seconds which we will adopt for WPROBE as well. Each of the four focal planes contains a 3 by 3 mosaic of Teledyne H4RG 4096 by 4096 pixel detector arrays with a 2.5 micron long wavelength cutoff. The area covered by a focal plane is 0.378 square degrees. A requirement is to have diffraction limited image quality over the entire focal plane, however, we will use 0.25 sq. deg. in this document since the design is preliminary. The one exception is for microlensing where the resolution requirement of 0.4 arc seconds is easily met for the entire 0.378 sq. deg. of the focal planes.

At this point the 18 micron pixel H4RG arrays are our base line as some problems with crosstalk have been reported for the 10 micron pixel arrays. If these problems are eliminated by the time of the mission we would switch to the smaller arrays. The larger arrays do, however, have an advantage in reducing the amount of focal plane area lost to gaps. Since the size of the small gap between arrays in a mosaic of detector arrays is independent of the size of the pixels the percentage of gap size to array size is smaller with the larger arrays. The success of the Kepler mission is a significant demonstration that mosaics much larger than the 3x3 mosaic considered here is quite achievable.

3.2 Spectroscopy

The required $\lambda/\Delta \lambda$ 75 and 600 resolution spectroscopy is accomplished with grisms situated in the filter wheels between the last dichroic reflection or transmission and ahead of the focal planes. Grisms have the advantage of centering the spectrum at the location of the image of the object in the focal plane. This concept has been used very successfully on both the NICMOS and WF3-IR instruments on HST. The disadvantage of all slitless spectrometers is that the full background flux is present on each pixel rather than just the background in the spectral resolution element of the pixel as with dispersing spectrometers with a slit. The primary background is the zodiacal light. In all spectroscopic sensitivity calculations we use the same zodiacal light model as is used in the NICMOS instrument team exposure time calculator that successfully modeled the zodiacal flux observed by NICMOS. The flux has been spatially averaged since the locations of the observed fields has not been set. All spectral sensitivity calculations have been done assuming all of the zodiacal light in the observed bands set by the dichroics falls on each pixel.

3.3 Z filter

The shortest wavelength band determined by the dichroics contains both the Y and Z bands. These bands must be isolated via filters that reside in filter wheels as shown in Figure 1. The Z filter is specified in Table 1 of Green et al. (2012), however, none of the science programs described in DRM1 use the Z filter. Double filter wheels are shown in front of all four focal planes in Figure 1 to provide spaces for the grisms and blanks for darks. They are also there to provide useful filters for a GO program and can be specified by input from the community. Some cost saving can be accomplished if the filter wheels are reduced to one per focal plane and the number of filters is set to a minimal set.

3.4 Orbit

The current AFTA restrictions require operation of the telescope at a warm temperature that adversely affects K band observations. WPROBE, on the other hand, can exploit the advantages of an L2 orbit where the telescope can be cooled passively to a temperature that does not compromise sensitivity in any of the bands and also provides cooling for the detector focal planes. The passive cooling negates the need for cryogens or mechanical coolers resulting in significant cost savings over concepts that require active cooling for the detectors or other optical components.

4 MEETING THE WFIRST SCIENCE REQUIREMENTS

Given the increased efficiency of WPROBE over traditional one filter instruments a decreased aperture telescope is able to meet the stated WFIRST science goals as expressed in the DRM1. It is very important to note that the decrease in aperture is solely to increase the probability that WFIRST will actually happen. Of course a larger aperture telescope will be able to do enhanced science. We put forward the reduced aperture WPROBE concept only to address the concern that the 2.4 m AFTA aperture requires an expenditure that puts the mission at risk. As described in the following sections a 1.2 m telescope is sufficient to carry out all of the DRM1 science in a 2.6 year mission and provide another 0.4 years of General Observer science for a total 3 year mission. The only expendable is propellant for station keeping at L2. Enough propellant can easily be carried for at least a 5 year mission if desired.

4.1 High Latitude Survey Imaging Program

The imaging component of the High Latitude Survey (HLS) covers 3400 square degrees to a 5$\sigma$ H band point source AB magnitude of 26 which is equivalent to $1.46 \times 10^{-7}$ janskys. The survey covers the Y, J, H, and K band filters as described in Table 1. Figure 4 shows the limiting magnitude versus time for the H band filter. The figure shows that it takes 708 seconds to reach a SNR of 5 for an AB magnitude of 26. With an overhead of 10% it takes 123 days to complete the survey which shows the power of the multi-focal plane concept. The SNR of 5 limiting magnitudes in the other bands are Y(26.8), J(26.4) and K(25.84). To reach an AB magnitude of 26 in all filters takes 173 days with enhanced depth in the other bands since in the dichroic concept all bands have the same observation time.

The sensitivity calculations assume that the H4RG detectors have the same quantum efficiency, read noise and dark current as the NIRCam H2RG detectors for JWST. The physical pixel size is 18 microns rather than the smaller 10 micron pixel version. At present time it appears that the smaller pixels may have cross talk issues that are avoided in the larger pixels. The telescope and optics are radiatively
cooled to 100 K and the detectors radiatively cooled to 70 K, numbers which are easily achieved in the L2 orbit. Even though the total field of view is large enough to cover one square degree with only three images we have done the calculations with 4 images per sq. deg. Preliminary optical calculations indicate that there is acceptable image quality over the total area but we have conservatively assumed that we use only the central 0.25 sq. deg. for science where the image quality is the best. These same characteristics are assumed in the other following WFIRST science programs.

4.2 High Latitude Survey Spectroscopic Program

The spectroscopic component of the HLS, also known as the Galaxy Redshift Survey (GRS) requires a 7σ minimum detectable line flux of $10^{-16}$ ergs cm$^{-2}$ sec$^{-1}$ over the entire 3400 sq. deg. The survey is carried out with the R = 600 grisms in the wavelength range of 1.5 to 2.4 microns. This corresponds to the H and K bands defined by the dichroics. The short wavelength cutoff is provided by the first dichroic that transmits all wavelengths longer than 1.5 microns. The second dichroic wheel is set to the clear aperture so that the 2.5 micron cutoff of the detector provides the long wavelength cutoff with no filters required.

The right hand graph in Figure 4 indicates that it takes 526 seconds to reach that signal to noise where we have multiplied the time to achieve 5σ by the square of 7/5. With this individual integration time and a 10% overhead the total time needed to accomplish the HLS spectroscopic survey is 91.1 days.

4.3 Galactic Plane Survey

The Galactic Plane Survey (GPS) covers 1240 sq. deg. to a 5σ H band point source AB magnitude of 25.1 in the Y, J, H, and K bands. Using the same calculations as for the HLS we find that the survey takes only 40 days to complete, again assuming a 10% overhead.

4.4 Microlensing Exoplanet Survey

The Microlensing Exoplanet Survey (MES) requires a signal to noise of 100 for a J band AB magnitude of 20.5 which is $2.31 \times 10^{-5}$ janskys. The required cadence is 15 minutes to cover a field of view greater than 2 sq. deg. The wide filter described in DRM1 spans 0.92 to 2.5 microns. We achieve this by rotating the first and following dichroic wheels to the open aperture position. This puts all of the light onto one focal plane. Although comments from the exoplanet community indicate that this is the desired option we have assumed that the wide filter described in the DRM1 is in place to be consistent with the DRM1 program. Under these conditions a SNR of 100 at $J_{AB}$ of 20.5 is achieved in 3 minutes. Since the imaging requirements are quite loose, imaging resolution of 0.4 arc seconds or less, we can use the entire focal plane covering 0.377 sq. deg. rather than just the 0.25 sq. deg. science area. Five exposures covers almost 2 sq. deg. satisfying the 15 minute cadence. This can be expanded to 6 exposures to cover more than 2 sq. deg. with an 18 minute cadence or the filter can be eliminated to let all of the light fall on the detector array to shorten the integration time. There is also a requirement to monitor the area every 12 hours with the Y filter to determine color but there is no stated depth requirement. If we assume that a 10σ measurement in the Y band is sufficient to establish color then only 3 seconds are needed to measure a 20.5 AB magnitude star at that signal to noise level. The measurement time is then set by the slew and settle time of the probe which is set at < 30 seconds in the DRM1 program.

4.5 Supernova Survey Imaging Program

The imaging component of the Supernova Survey (SS) has a wide and a deep survey. The wide survey covers 6.5 sq. deg. to an AB magnitude of 28.1 and the deep survey covers 1.8 sq. deg. to an AB magnitude of 29.6 in the J, H, and K bands. The dichroic concept automatically includes the Y band as well for free. The deep band 5σ magnitude limit of 29.6 is achieved in $2.0 \times 10^4$ seconds and wide band limit is achieved in $1.6 \times 10^4$ seconds. Here we assume an overhead of 100 seconds per integration rather than 10% due to the longer integration times. We also presume that the long integration times will be broken into several exposures with integration times sufficient to reach the square root, background limited, signal to noise regime. This occurs after about 3000 seconds. Experience with the infrared Hubble Deep Fields has shown that this is an effective strategy. Calculations similar to the previous programs show that the wide survey is completed in 4.75 days and the deep survey in 16.7 days. These integration times are the total times, not the duration of the survey. The temporal spacing of the observations will be optimized for SN detection.

As an example the total integration times for both the deep and wide fields is slightly less than 21.5 days. The DRM1 suggested cadence is 5 days for 0.45 years which gives about 33 visits on a 5 day cadence. WPROBE therefore completes the imaging survey with less than a day of observation every 5 days for a little less than half a year. As described in Section 4.5 spectroscopic observations also occur at each imaging pointing to minimize slew times.

4.6 Supernova Survey Spectroscopic Program

The SS spectroscopic program is carried out with R=75 grism in the 0.6 to 2.0 micron spectral region. The resolution refers to a 2 pixel resolution element so the resolution is 150 per pixel. The requirement is for a signal to noise of 1 per pixel for a continuum signal of ABmag = 27.6 for the wide (6.5 sq. deg.) and ABmag= 28.5 for the deep (1.8 sq. deg.) field. This translates to $1.04 \times 10^{-9}$ janskys for the wide field and $4.5 \times 10^{-10}$ janskys for the deep field. Using the H band as an example this requires $2.5 \times 10^5$ seconds for the wide field and $1.3 \times 10^6$ seconds for the deep field. These are cumulative times not individual exposure times. The total time required is 75.5 days for the wide field and 110 days for the deep field using only the 0.25 sq. deg. science area of the focal plane. Individual exposure times will be on the order of an hour so the overhead times in this program are minimal. The DRM1 reserves 1.8 years for this program but does not state a cadence. We assume that on each visit for the imaging program two days are spent on the spectroscopic program. At each pointing for the imaging program spectroscopic observations are also taken for a
Program Time in Days

| Program                          | Time in Days |
|---------------------------------|--------------|
| HLS Imaging                     | 173          |
| HLS Spectroscopic (GRS)         | 91.1         |
| Galactic Plane Imaging          | 40           |
| Microlensing Survey             | 438\(^a\)    |
| Supernova Imaging Wide          | 4.75         |
| Supernova Imaging Deep          | 16.7         |
| Supernova Spectroscopy Wide     | 75.5         |
| Supernova Spectroscopy Deep     | 110          |
| Total Program                   | 949 (2.6 years) |

Table 3. WPROBE Program Times

\(^a\)Set by requested duration

A longer period of time. After the imaging program has been completed the spectroscopic program will continue in the remaining 1.4 years allotted to it.

5 TOTAL PROGRAM TIME FOR THE WFIRST DRM1 SCIENCE

The times expressed in Table 3 are the total integration times needed to reach the sensitivity limits expressed in DRM1. The individual integrations are arranged to optimize efficiency and to best sample temporal events.

6 WPROBE RELATIVE TO WNEW

Although the WPROBE dichroic concept presented here is oriented toward a low cost probe mission that can carry out all of the WFIRST DRM1 science it can also be used to greatly enhance the efficacy of an AFTA mission. WPROBE is similar in concept to the WNEW mission presented at the SALSO conference in Huntsville Alabama in February of 2013 on the use of AFTA for other purposes. It is clear that a 2.4m version of WPROBE or WNEW will accomplish more science but at a significantly larger cost.

REFERENCES

Green, J. et al. 2012, Wide-Field InfraRed Survey Telescope WFIRST Final Report
NASA 2012, Astrophysics Division Science Mission Directorate NASA Headquarters, "Astrophysics Implementation Plan", Fig.1, p14.
Figure 3. The H band filter performance for signal to noise ratios of 1 (lower), 3 and 5 (upper) for a single pixel. The dash dot line is for a 5 pixel coadded PSF at a SNR of 5.