TECHNICAL REPORT

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Title: JWST Absolute Flux Calibration I. Proposed Primary Calibrators		Doc #: JWST-STScI-001855 Date: August 28, 2009 Rev: -
Authors: Karl Gordon, Ralph Bohlin, Alex Fullerton, Tracy Beck, Massimo Robberto	Phone: 410 – 338 - 5031	Release Date: 5 November 2009

1.0 Abstract

We propose a set of primary flux calibrators for JWST and show how the capabilities of the different JWST instruments map to these calibrators. The expectation is that these calibrators will be used for both photometric and spectrophotometric calibration. The goal of this report is to determine if this set of proposed calibrators is large enough and covers a large enough dynamic range to serve as the primary calibrators for all the JWST instruments. The basic answer is yes, but there is also a need for a larger number of calibrators to ensure that all the instrumental capabilities can be well calibrated.

2.0 Introduction

The goal of absolute photometric calibration is to convert science data from instrumental to physical units. JWST will not have an onboard calibration sources (e.g. a National Institute of Standards and Technology [NIST] blackbody source) and, therefore, will rely on observing sources for which the absolute level and spectral shape are well known. This standard method for space based telescopes has been used to calibration Hubble and Spitzer. In fact, the calibrators for Hubble and Spitzer are prime candidates for Webb calibrators, as together they cover the entire Webb wavelength range. In this report, we present a set of primary calibrators for Webb that have been well observed by Hubble and Spitzer.

2.1 Proposed JWST Primary Standards

There are several classes of astronomical sources that have been used as primary photometric calibrators. We have chosen to concentrate on three classes: white dwarfs, A0V, and G2V stars. The white dwarfs and A0V stars have fairly simple atmospheres that have well determined stellar atmosphere models. G2V stars are analogs to our Sun and, thus, one can rely on high quality solar measurements and stellar atmosphere models. The white dwarfs are the primary standards for Hubble (Bohlin et al. 1995).

The A0V and G2V are the primary standards for Spitzer (Rieke et al. 2008).

Our proposed primary standards for Webb are given in Table 1. All of these stars have been (e.g., Bohlin et al. 2008) or will be (HST program, "JWST Calibration from a Consistent Absolute Calibration of Spitzer & Hubble", cycle 17, PI: Bohlin) observed with the Hubble spectrographs STIS and NICMOS. In addition, there are many observations with Hubble imagers. These stars have also been observed with the Spitzer instruments IRAC, IRS Peakup, and MIPS in many programs, including a Spitzer cycle 5 DDT proposal ("Consistent Absolute Calibration of Spitzer, Hubble, & Webb," PI: Gordon). The predicted fluxes for these stars for the Spitzer bands are given in Table 2 for reference. The predicted spectra for most of these proposed primary calibrators are shown in Figure 1. These SEDs are from the CALSPEC[1] database and are model calculations for the WDs, while the A and G star SEDs are measured fluxes below ~2.5 micron and models at the longer wavelengths.

The combination of the Hubble and Spitzer observations will establish a consistent calibration of these two observatories and this will provide a basis for the calibration of Webb.

2.2 SED Details

The three pure hydrogen WDs, GD153, GD71, and G191B2B, are some of the easiest kind of stellar SEDs to model and have temperatures and gravities derived from fitting the models to the Balmer lines. These three models are normalized to precision Landolt V band photometry and are the primary absolute flux standards for all of the HST flux calibrations (Bohlin et al. 1995). For the cases of the pure helium WD LDS749B, the A, and the G stars, the spectral distributions below 2.5 microns are measured by calibrated STIS and NICMOS spectrophotometry; and then the best fitting model is used to estimate the fluxes longward of 2.5 microns. Because the stellar models have their greatest uncertainties in regions of heavy line blanketing, broadband averages are used to find the best models, which match the observed fluxes to an rms scatter in the broad bands of <1% for all of our WD, A, and G standard stars. Thus, the continuum regions of the model extensions above 2.5 microns should be good to the same 1-2% that is the quoted precision for STIS+NICMOS. The state of the art for computing line profiles approaches perfection for the simple hydrogen atom; however, modeled line profiles for He and heavier atoms are unreliable because of uncertainties in both the abundances and in the atomic physics.

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[1] http://www.stsci.edu/hst/observatory/cdbs/calspec.html

Table 1 The proposed set of JWST primary calibrators

Name	**RA**	**DEC**	**SpType**	**V**	**K**
White Dwarfs					
G191B2B	5 05 30.62	+52 49 54.0	DA0	11.781	12.764
GD71	5 52 27.51	+15 53 16.6	DA1	13.032	14.115
GD153	12 57 02.37	+22 01 56.0	DA1	13.346	14.308
LDS749B	21 32 16.01	+00 15 14.3	DBQ4	14.73	15.217
A Stars					
HD165459	18 02 30.74	+58 37 38.1	A1V	6.864	6.584
1732526	17 32 52.64	+71 04 43.1	A3V	12.530	12.254
1740346	17 40 34.7	+65 27 15.0	A5V	12.478	11.996
1802271	18 02 27.17	+60 43 35.6	A3V	11.985	11.832
1805292	18 05 29.3	+64 27 52.1	A1V	12.278	12.005
1812095	18 12 9.56	+64 29 42.3	A2V	11.736	11.286
G Stars					
HD209458	22 03 10.8	+18 53 04	G0V	7.65	6.3
P041C	14 51 58.19	+71 43 17.3	G0V	12.01	10.479
P177D	15 59 13.59	+47 36 41.8	G0V	13.48	11.857
P330E	16 31 33.85	+30 08 47.1	G0V	13.01	11.379

Table 2: Predicted Fluxes in Spitzer Bands (mJy)

name	IRAC1	IRAC2	IRAC3	IRAC4	IRS15	MIPS24
White Dwarfs						
G191B2B	1.96	1.25	0.75	0.39	0.11	0.041
GD71	0.57	0.36	0.22	0.11	0.031	0.012
GD153	0.47	0.30	0.18	0.09	0.026	0.010
LDS749B	0.22	0.14	0.09	0.04	0.013	0.004
A Stars						
HD165459	654	432	265	142	42	15.5
1732526	3.53	2.33	1.43	0.77	0.22	0.083
1740346	4.48	2.96	1.81	0.98	0.29	0.106
1802271	5.21	3.44	2.11	1.13	0.33	0.123
1805292	4.44	2.94	1.80	0.97	0.28	0.105
1812095	8.61	5.69	3.49	1.88	0.55	0.204
G Stars						
HD209458	878	555	350	189	54	22
P041C	18.7	11.8	7.46	4.03	1.16	0.47
P177D	5.25	3.32	2.09	1.13	0.32	0.13
P330E	8.16	5.16	3.25	1.76	0.5	0.21

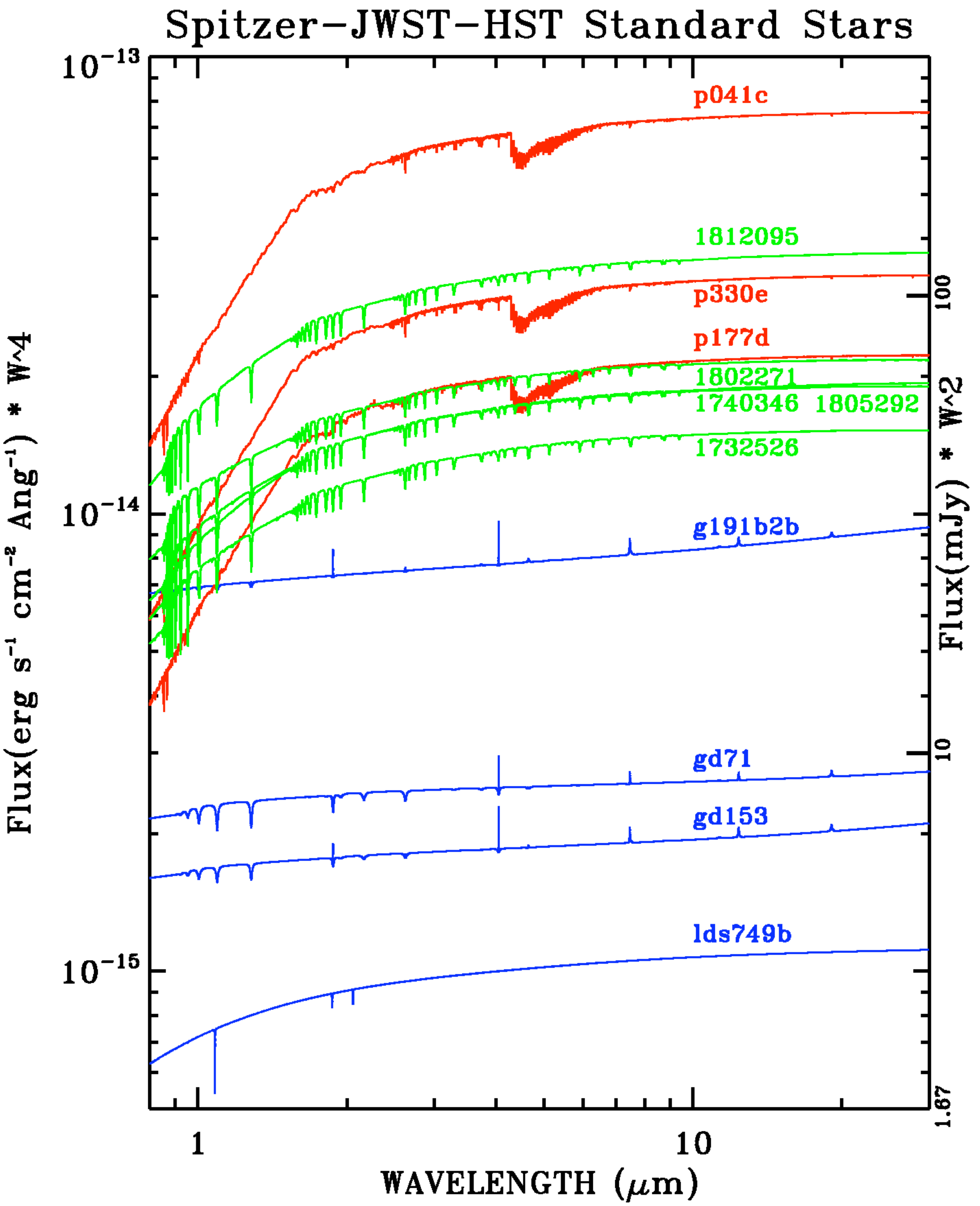

Figure 1: Spectra of a representative sample of the proposed primary calibration sources: white dwarfs (blue), A0V stars (green), and G2V stars (red). The multipliers, W^4 and W^2, on the ordinates are in units of micron.

3.0 Instrument Sensitivities

Each instrument on JWST has different sensitivities and wavelength ranges. Thus, each instrument has a different set of min/max fluxes that can be observed. The question is: can they observe the proposed list of primary calibrators?

We define the following sensitivity levels:

MAX observable flux = flux that can be observed in the normal observing modes (full frame and subarrays) without reaching saturation

MIN observable flux = flux that can be observed with a S/N of 200/50 in 3600 sec for imaging/spectroscopy.

3.1 NIRCam

For NIRCam, the clock time for MIN flux was set to 3800 seconds as this corresponds to an exposure time of 3609.3 s of integration in Marcia Rieke's spreadsheet model of NIRCam sensitivity. For MAX flux, a single read integration time of 10.6s was used. We also considered subarrays, in particular the Nominal Target Acquisition Subarrays, i.e. SUB128 (128x128 pixels) for SW and SUB64 (64x64 pixels) for LW. These subarrays correspond to 4.10x4.10arcsec and 2.05x2.05arcsec fields, with single frame times of 53.24ms and 183.16ms, respectively. For the MAX flux in subarray mode we used a single read time frame. The resulting NIRCam sensitivities are given in Table 3 and overplotted on the calibrator sample in Figure 2.

Table 3: NIRCam Sensitivities

	Full Frame		**Subarray**
Band	**Min [mJy]**	**Max [mJy]**	**Max [mJy]**
F070W	1.27×10^{-3}	1.63	94.7
F090W	0.77×10^{-3}	0.70	40.2
F115W	0.69×10^{-3}	0.63	36.7
F150W	0.65×10^{-3}	0.72	41.8
F200W	0.54×10^{-3}	1.20	69.2
F277W	0.55×10^{-3}	0.55	110
F356W	0.57×10^{-3}	0.90	180
F444W	0.85×10^{-3}	1.54	307

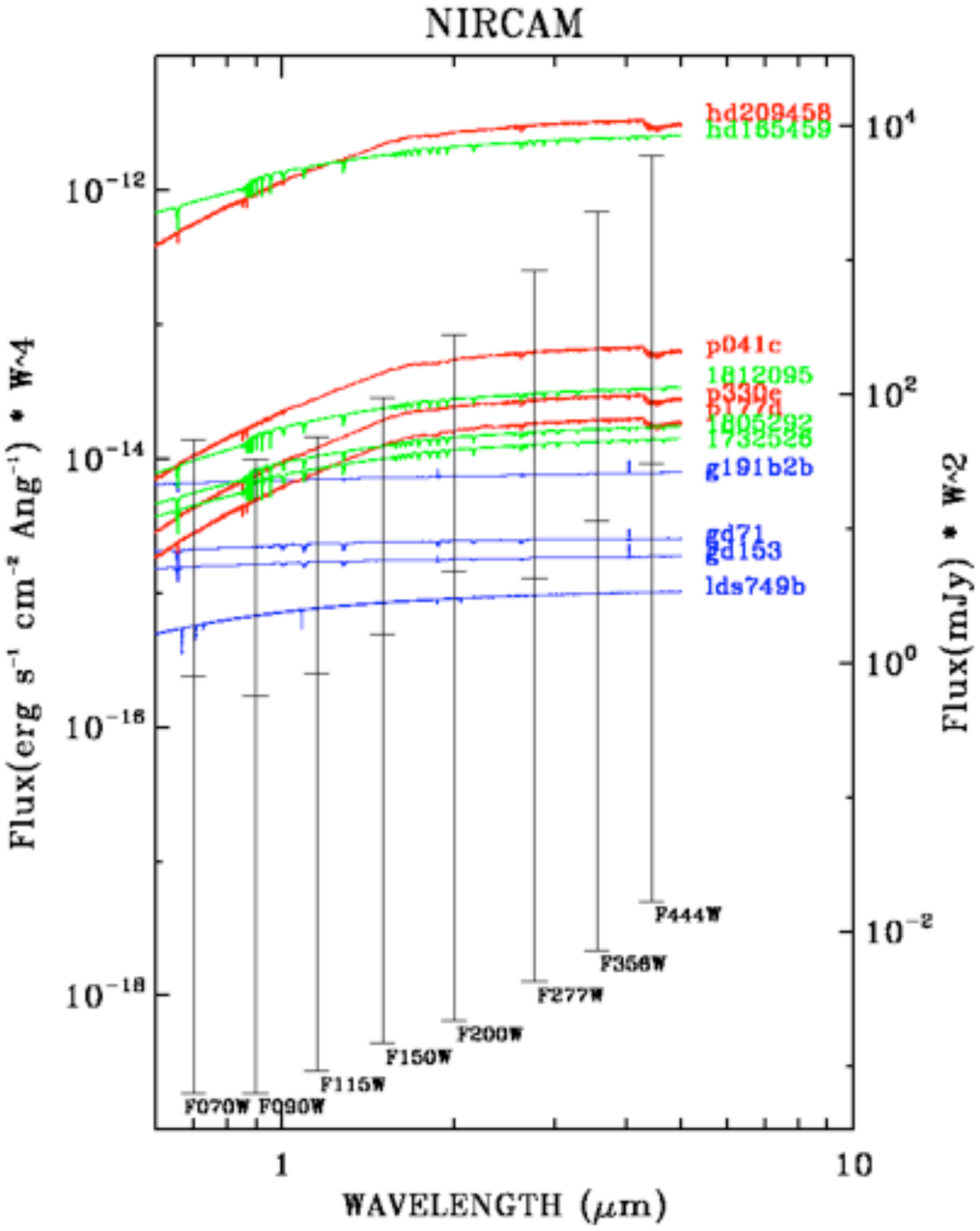

Figure 2; The NIRCam sensitivity limits and the spectra of the proposed primary calibrators are shown with blue for WDs, green for A types, and red for G stars. The sensitivity in each filter is given by the vertical bar where the min, middle, and max marks give the min full frame, max full frame, and max subarray sensitivities, respectively.

3.2 NIRSpec

The NIRSpec sensitivities given are relevant for MOS Spectroscopy and 0.2” wide Fixed Slits. The values in the table are estimated using model calculations of NIRSpec preliminary sensitivities described by Jakobsen (2003; 2007). NIRSpec sensitivity calculations are always presented in units of AB magnitudes by the ESA instrument team. The sensitivities in AB magnitudes are converted to Jy using the standard formula magAB = -2.5 x log(Fν) + 8.926 with Fν measured in Jy.

At the moment we cannot estimate the sensitivity values for the 0.4” slit, the wide aperture, and the IFU mode. In practice, the sensitivity of the 0.4” and wide aperture modes will scale with the greater level of flux through the wider apertures per the NIRSpec PSF shape and size. Additionally, the IFU has a requirement that the throughput shall be no less than 60% of the total throughput for NIRSpec optics, at all wavelengths sampled by NIRSpec. Hence, the sensitivities for the 0.4” slits and wide aperture mode should turn out to fainter than those given in Table 4, while for the IFU mode the values will be about 40% higher.

The NIRSpec sensitivities given in Table 4 are overplotted on the calibrator sample in Figure 3.

Table 4: NIRSpec Sensitivities for 0.2 arescsec Slit

Full Frame (R=1000)			**128x32 Subarray (R=1000)**
Wavelength	**Min [mJy]**	**Max [mJy]**	**Max [mJy]**
1.3 μm	$180x10^{-3}$	112	28200
2.4 μm	$150x10^{-3}$	93	23400
3.7 μm	$150x10^{-3}$	91	21500
Full Frame (R=2700)			**128x32 Subarray (R=2700)**
1.3 μm	$590x10^{-3}$	395	93800
2.4 μm	$490x10^{-3}$	315	70800
3.7 μm	$490x10^{-3}$	317	71300
Full Frame (R=100)			**128x32 Subarray (R=100)**
2.2 μm	$6.6x10^{-3}$	4.3	1100

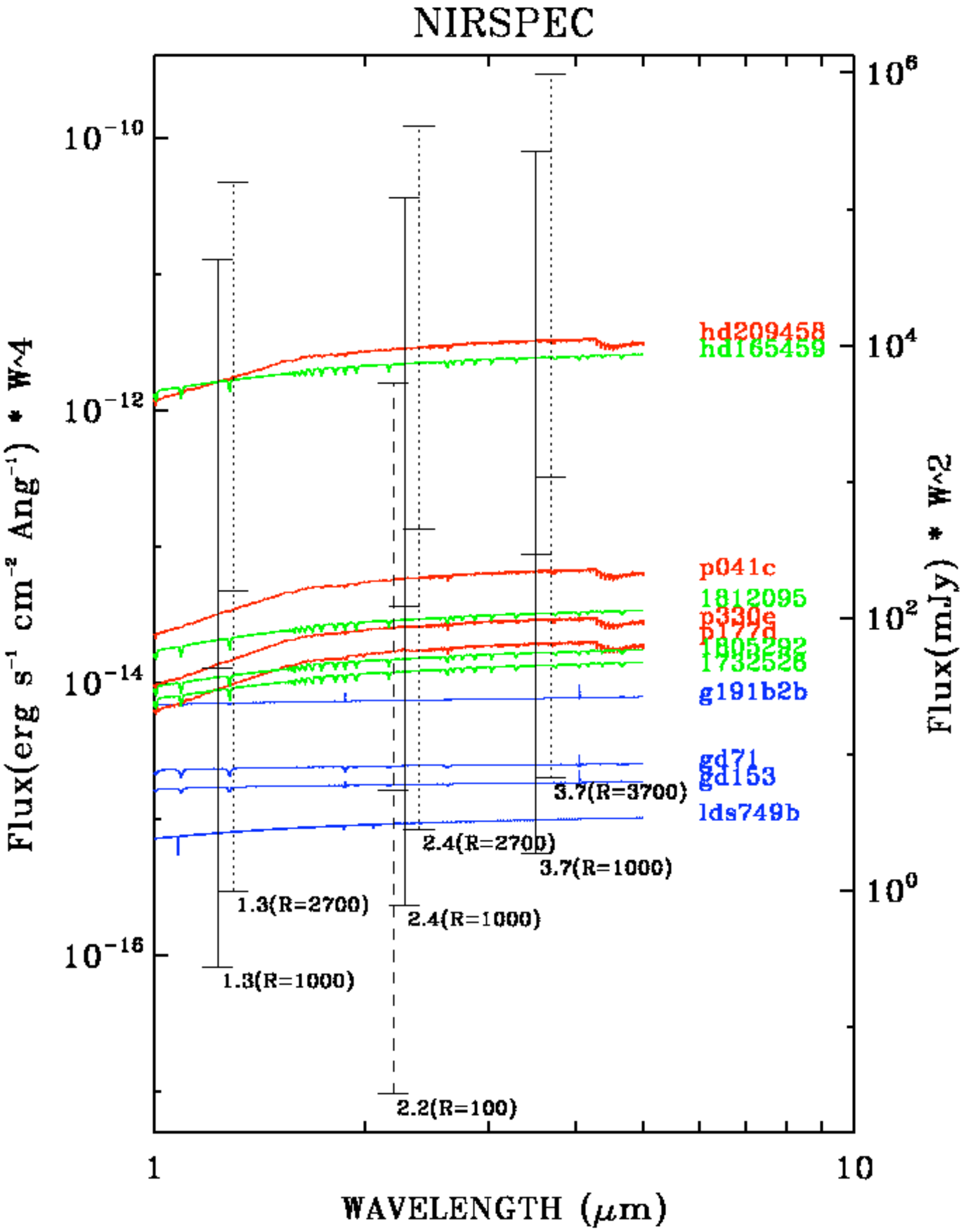

Figure 3: The NIRSpec sensitivity limits and the spectra of the proposed primary calibrators are shown as in Figure 2. The vertical lines are the ranges of the sensitivities and are solid: R=1000 spectroscopy, dashed: R=100 spectroscopy, and dots: R=2700 spectroscopy. The sensitivity in each wavelength range is given by the vertical bar where the min, middle, and max marks give the min full frame, max full frame, and max subarray sensitivities, respectively.

3.3 FGS/TFI

The MIN flux corresponds to a detection with S/N=200 in 3600 s (as opposed to the usual figure of merit for requirement verification of S/N=10 in 10,000 s). These fluxes were calculated with the TFI sensitivity spreadsheet `TF_Sensitivity_Oct08_scatt.xls`, which is derived from the analogous spreadsheet developed for NIRCam by the Riekes. These fluxes correspond to End-of-Life (EOL) estimates, and include noise from various backgrounds (but not, apparently, flat-fielding errors).

The maximum flux corresponds to the flux that will saturate the detector during the shortest full-frame integration at Beginning-of-Life

The TFI is required to be able to observe sources as bright as 7 Jy at 2.2 microns with an absolute photometric accuracy of better than 5% after routine post-processing. This “dynamic range” requirement is specifically included to enable the observation of bright, well-characterized photometric standards. The baseline strategy for meeting this requirement is to use subarrays. In particular, a 16 pixel × 16 pixel subarray permits observations of stars as bright as 12.8 Jy at 2.2 microns. For observations of calibration stars, using a bigger subarray (32x32) is desirable to ensure that the majority of a star's flux is measured, especially at the longer wavelengths.

The TFI also has an Optical Density = 2 neutral density filter (FND) in its Pupil Wheel, which provides the potential for increasing the dynamic range by a factor of 100 at the cost of still more cross-calibration. At present, the FND is not expected to be available for general use in scientific observations: it is not a “supported mode”.

The sensitivities associated with other observational modes depend on the instrumental configuration but scale with the values listed in Table 5.

Coronagraphic observations will generally be made through one of the apodization masks (Lyot stops). The current suite consists of masks that transmit 23%, 53%, and 57% of the light incident on the pick-off mirror of the TFI.

The non-redundant phase mask transmits only ~17% of the light incident on the pick-off mirror.

The TFI sensitivities are given in Table 5 and overplotted on the calibrator sample in Figure 4.

Table 5: TFI Sensitivities

Full Frame			32x32 Subarray
Wavelength	**Min [mJy]**	**Max [mJy]**	**Max [mJy]**
1.5 µm	$15.3\text{x}10^{-3}$	3.1	8000
2.0 µm	$13.1\text{x}10^{-3}$	4.8	12400
2.5 µm	$12.4\text{x}10^{-3}$	5.8	15000
3.2 µm	$13.5\text{x}10^{-3}$	7.3	18800
3.5 µm	$13.6\text{x}10^{-3}$	10.0	25700
4.0 µm	$14.1\text{x}10^{-3}$	12.2	31400
4.5 µm	$14.7\text{x}10^{-3}$	14.4	37100
5.0 µm	$16.0\text{x}10^{-3}$	14.4	37100

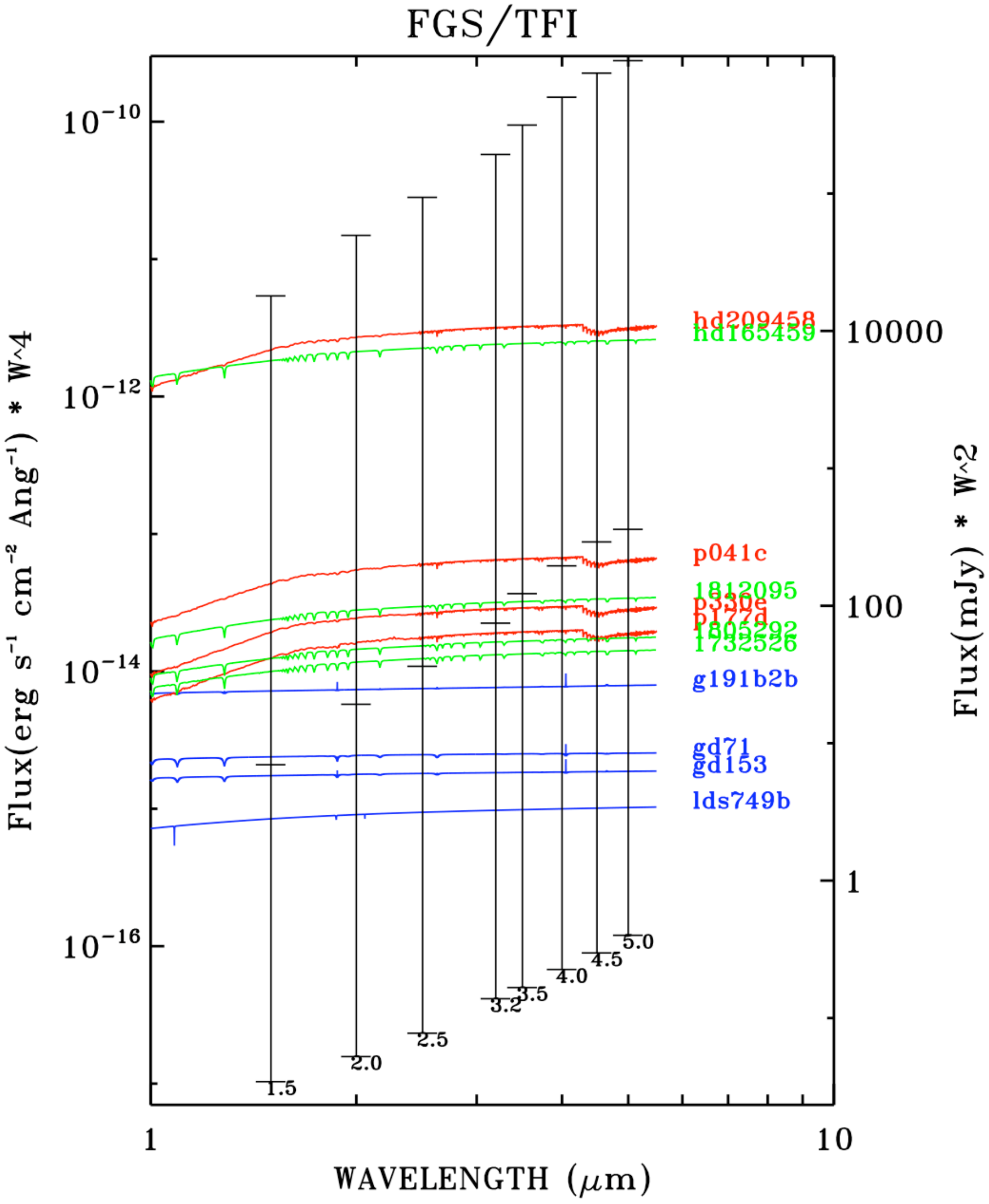

Figure 4: The FGS/TFI sensitivity limits and the spectra of the proposed primary calibrators are shown as in Figure 2. The sensitivity in each filter is given by the vertical bar where the min, middle, and max marks give the min full frame, max full frame, and max subarray sensitivities, respectively.

3.4 MIRI

The limits for the MIRI observing modes were determined using George Rieke's spreadsheet model of MIRI (MIRIradmodeldb.xls). The accuracy of these sensitivities depends on a number of factors and should be accurate to around a factor of 2. The minimum and maximum sensitivities are in Table 6. For the spectrographs, only sensitivities for selected wavelengths are given. The limits are plotted along with the proposed primary calibrator spectra in Figure 5(for direct imaging) and Figure 6 (for the coronagraphy, LRS-SLIT and MRS-IFU).

Table 6: MIRI Sensitivities

Imager				**Coronagraph**		
Full Frame			**64x64 Subarray**			
Band	**Min [mJy]**	**Max [mJy]**	**Max [mJy]**	**Band**	**Min [mJy]**	**Max [mJy]**
F560W	8x10^{-3}	11	770	F1065C	112x10^{-3}	500
F770W	12x10^{-3}	10	700	F1140C	160x10^{-3}	475
F1000W	30x10^{-3}	25	1750	F1550C	268x10^{-3}	750
F1130W	74x10^{-3}	100	7000	F2300C	610x10^{-3}	110
F1280W	57x10^{-3}	50	3500	**LRS-Slit/MRS-IFU**		
F1500W	85x10^{-3}	65	4550	LRS-7.5	57x10^{-3}	450
F1800W	154x10^{-3}	110	7700	MRS-6.4	230x10^{-3}	14000
F2100W	302x10^{-3}	115	8050	MRS-9.2	610x10^{-3}	30000
F2550W	910x10^{-3}	225	16000	MRS-14.5	765x10^{-3}	35000
				MRS-22.5	4625x10^{-3}	110000

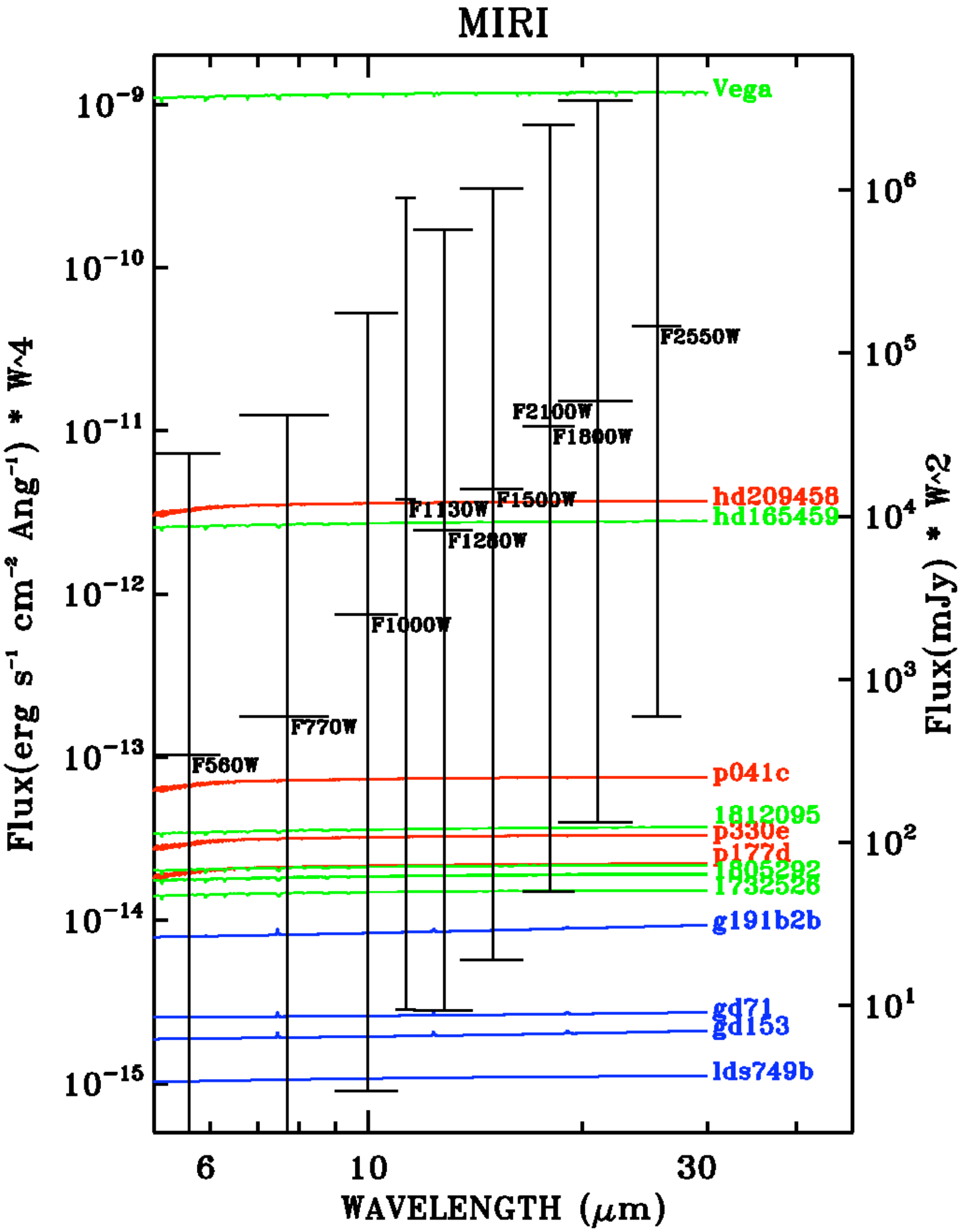

Figure 5: The MIRI sensitivity limits for direct imaging and the spectra of the proposed primary calibrators are shown as in Figure 2. The stars are labeled. The sensitivity in each filter is given by the vertical bar where the min, middle, and max marks give the min full frame, max full frame, and max subarray sensitivities, respectively. The width of the marks gives the filter FWHM. Vega has been included to illustrate that MIRI can observe very bright targets at the longest wavelengths.

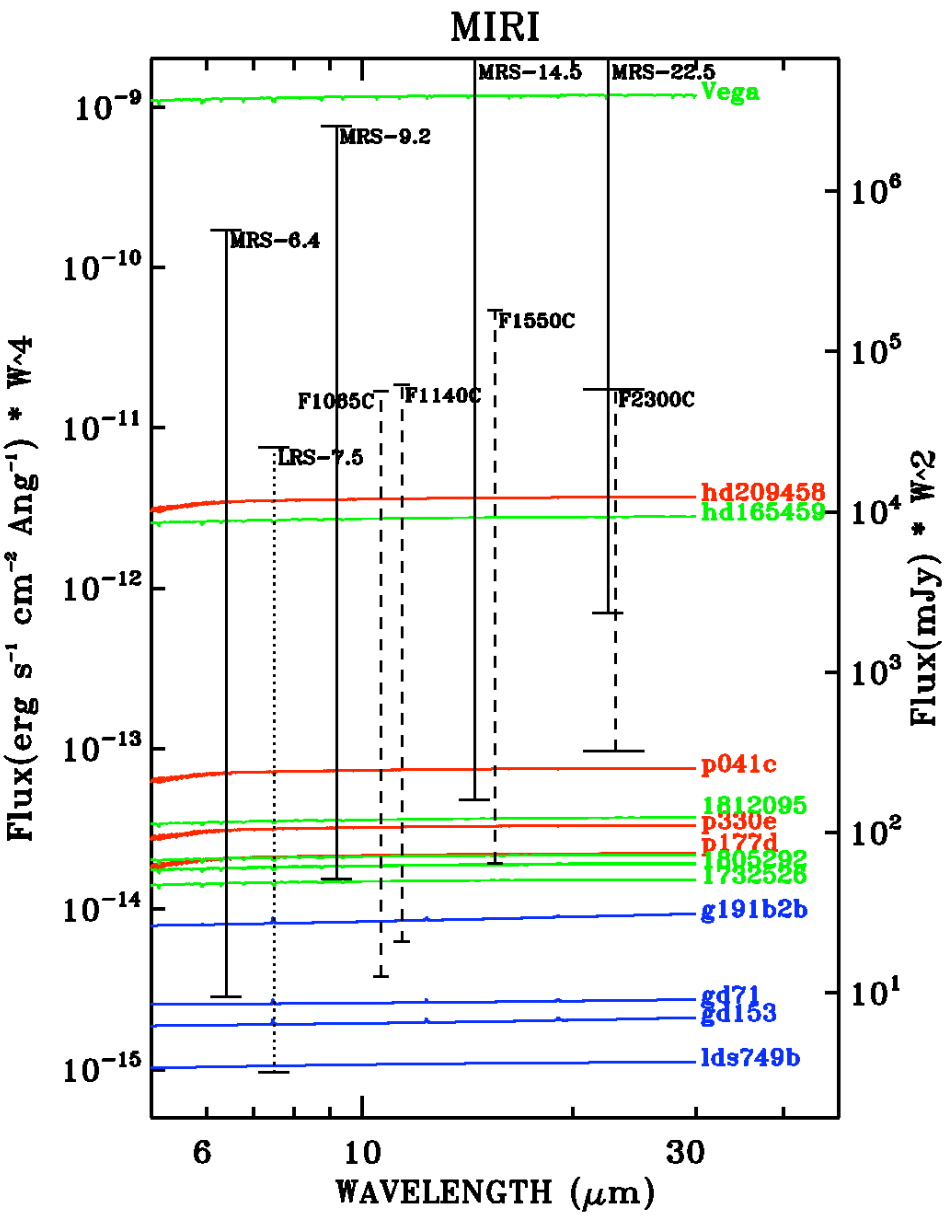

Figure 6: The MIRI sensitivity limits for coronagraphy, medium resolution spectroscopy, and low resolution spectroscopy and the spectra of the proposed primary calibrators are shown as in Figure 2 The stars are labeled and the line types are dashed: coronagraphy, solid: medium resolution spectroscopy, and dots: low resolution spectroscopy. The sensitivity in each filter/wavelength range is given by the vertical bar where the min, middle, and max marks give the min full frame, max full frame, and max subarray sensitivities, respectively. The width of the marks gives the filter FWHM. Vega has been included to illustrate that MIRI can observe very bright targets at the longest wavelengths.

4.0 Conclusions

All JWST instruments can observe at least a subset of the proposed calibration stars. However, some of the more sensitive modes of NIRCam and TFI can observe only a few stars, or even none in full frame mode. Other problems are that significant portions of the dynamic range of some instrument modes are not covered by the proposed set of stars and that subarray observations are required, which creates an additional step in calibrating the full frame observations.

The next steps to defining the full list of JWST primary calibrators will be:

1. Define the criteria that will indicate whether a specific filter/wavelength range can be calibrated to the desired level. A minimum number of calibrators of different spectral types should be observable to ensure that a high quality calibration is obtained in each specific filter/wavelength range.
2. Using the above criteria, determine where we need more calibration stars. The Figures in this report already point out where we will likely want to expand the sample (e.g. long wavelengths for MIRI and short wavelengths for NIRCam).
3. Expand the dynamic range of the calibrators. The faint end for NIRCam and TFI could benefit from additional faint calibrators, in order to verify that the derived calibrations apply equally well to bright and faint sources.
4. Perform a detailed study to ensure that the spectrophotometric calibration derived from the combination of the 3 different types of calibrators will provide good calibration at all wavelengths. For example, the A-star calibrators will have strong HI absorptions that will pose challenges to the spectrophotometric calibration. Fortunately, the combination of G-stars (which do not have strong HI absorptions), white dwarfs, and A-stars should allow for the full wavelength range to be well calibrated.

The next report will concentrate on expanding the sample to answer the above issues and on starting the process of fully vetting the sample (e.g. using archival and new Hubble and Spitzer observations).

5.0 References

Bohlin, R. C. et al. 1995, AJ, 110, 1316

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