TECHNICAL REPORT

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Title: Title: JWST Absolute Flux Calibration II: Expanded Sample of Primary Calibrators		Doc #: JWST-STScI-002540, SM-12 Date: August 31, 2011 Rev: -
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1 Abstract

We propose to expand the set of JWST primary flux calibrators to provide a minimum of five standard stars per bandpass/grating setting for all four JWST instruments. A set of 5 is the minimum necessary to achieve the required goal of high quality absolute flux calibration. We show how the capabilities of the different JWST instruments response and sensitivities map to these calibrators. These calibrators can be used for both photometric and spectrophotometric calibration. This report expands the sample given in the 1st report in this series (Gordon, Bohlin et al. 2009).

2 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 astrophysical sources whose absolute flux level and spectral shape are well known. This standard calibration method is used to calibrate the Hubble and Spitzer Space Telescopes. Our set of flux calibrators for JWST includes high quality (usually S/N > 100) Hubble and Spitzer observations. For a subset of these calibrators, the existing Hubble and Spitzer calibrations are consistent within 2% (Bohlin, Gordon, et al. 2011). The list of these stars has also been given to Claire Cramer, who is coordinating the NIST absolute stellar flux standard program (eg. Zimmer, et al. 2010).

2.1 Calibration Goal

A goal for JWST is to provide an absolute flux calibration with the highest level of accuracy that can be achieved in a reasonable amount of effort. The formal requirement on the absolute flux calibration accuracy for the NIRCam and MIRI imaging observations is 5% and the error budget allocation for the required predicted fluxes of the calibration stars is 2.83% (Koekemoer et al. 2010). In order to achieve this goal (and potentially push below 1% for the predicted fluxes), multiple calibrator stars of the same spectral class are needed to account of the unavoidable differences between the actual stars and the adopted stellar model atmospheres. Calibrators of different spectral types are required to control for systematic uncertainties in the stellar atmosphere modeling. The spectral types that can be modeled to high accuracy are hot stars (white dwarfs and OB stars), A-stars, and G-stars (solar-like) stars (Gordon et al. 2009). Previous work on Hubble calibrators (Bohlin & Cohen 2008, Bohlin 2010) has shown that there is random modeling noise on the order of 2% for an individual calibration star. Observing 4 stars reduces the random uncertainty to 1% for the average JWST flux calibrations in each spectral bin. Given that 1 star out of 4 turns out to be not suitable as a calibrator at the 2% level, 5 stars minimum are required. Results for the three spectral categories can be compared to rule out any systematic uncertainties in the stellar models; and any outliers can be explored in more detail.

2.2 Expanded Sample of JWST Primary Standards

The expanded sample of JWST primary standards is listed in Table 1. This list includes the majority of the preliminary sample from the 1st report in this series (Gordon et al. 2009). Stars not in the preliminary sample are noted as 'Y' in the 'New' column. The main weakness of this preliminary sample is the concentration on stars that are faint enough for NIRCam and, as a result, are at or below the faint limit for TFI, NIRSpec, and MIRI. In particular, very few stars in this preliminary sample are observable at the long wavelengths of MIRI.

The Gordon et al. (2009) sample has been expanded by including standards that are brighter than the majority of the preliminary sample. In addition, the sample has also been extended by a few stars to provide better coverage at the faint end. See Table 1 for the distribution of spectral types and magnitudes of the expanded sample. The additional stars were selected from the Spitzer/IRAC standards (A-stars), IUE standards (hot stars), and MIRI Instrument Team spectroscopic proposed sample Stars with existing or planned Spitzer and/or Hubble observations were preferred. . The bright stars provide a better set of calibrators for most of the JWST instruments and significantly reduce the amount of observing time required for deriving the base absolute flux calibration. Hubble STIS spectroscopy obtained during 2010-2013 time frame will provide the basis for fitting the model atmospheres that will predict fluxes at JWST wavelengths.

One star in the preliminary list (Gordon et al. 2009), P041C, is a double and has been removed. Gilliland & Rajan (2011) discovered the M companion to P041C that is separated by 0.57 arcsec and is 1000 times fainter in the optical, but only 30 times fainter at 1.6 μm.

The predicted spectra for proposed representative set of the primary calibrators are shown in Figure 1 from 0.8 to 28 μm. The published subset of these SEDs are from the CALSPEC[1] database . The predicted spectra are from model calculations for the WDs, while the A and G star spectra are measured fluxes below ~2.5 μm and models calculations at the longer wavelengths. The new stars that are not yet in CALSPEC are just scaled SEDs of the same spectral type. While complete models of these new stars

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

are planned for addition to the CALSPEC archive, the scaled SEDs are sufficient for the purpose of this report.

2.3 SED Details

Pure hydrogen WDs are straightforward to model. , GD153, GD71, and G191B2B are hydrogen WDs and have temperatures and gravities derived from fitting the models to their observed Balmer lines. Their 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 stars, and the G stars, their spectral distributions below 2.5 μm are measured from calibrated STIS and NICMOS spectrophotometry; and then the best fitting model is used to estimate the fluxes longward of 2.5 μm. Unfortunately, NICMOS is no longer available; and STIS covers only wavelengths below 1 μm. Because the stellar models are most uncertain 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 less than 1% for all of our WD, A, and G standard stars. Thus, the continuum regions of the model extensions above 2.5 μm should be good to the same 1-2% that is the quoted precision for STIS+NICMOS.

Table 1 JWST primary calibrators: Hot Stars

Name	RA	DEC	SpType	V	K	New
x^2 Cet	02 28 09.54	+08 27 36.2	B9III	4.28	4.39	Y
l Lep	05 19 34.52	-13 10 36.4	B0.5IV	4.28	5.00	Y
10 Lac	22 39 15.68	+39 03 01.0	O9V	4.88	5.50	Y
m Col	05 45 59.89	-32 18 23.2	O9.5V	5.17	5.99	Y
HD 60753	07 33 27.32	-50 35 03.3	B3IV	6.68	6.83	Y
G191B2B	05 05 30.62	+52 49 54.0	DA0	11.781	12.764	N
GD71	05 52 27.51	+15 53 16.6	DA1	13.032	14.115	N
GD153	12 57 02.37	+22 01 56.0	DA1	13.346	14.308	N
LDS749B	21 32 16.01	+00 15 14.3	DBQ4	14.73	15.217	N
WD1057+719	11 00 34.31	+71 38 03.3	DA1.2	14.8		Y
WD1657+343	16 58 51.10	+34 18 54.3	DA1	16.1		Y

Table 2 JWST primary calibrators: A Stars

Name	RA	DEC	SpType	V	K	New
HD 158485	17 26 04.84	+58 39 06.8	A4V	6.50	6.14	Y
HD 14943	02 22 54.67	-51 05 31.7	A5V	5.91	5.44	Y
HD 37725	05 41 54.37	+29 17 50.9	A3V	8.35	7.90	Y
HD 163466	17 52 25.37	+60 23 46.9	A2	6.86	6.34	Y
HD 116405	13 22 45.12	+44 42 53.9	A0V	8.34	8.48	Y
HD 180609	19 12 47.20	+64 10 37.2	A0V	9.41	9.12	Y
BD+60 1753	17 24 52.27	+60 25 50.7	A1V	9.67	9.64	Y
1757132	17 57 13.25	+67 03 40.9	A3V	12.0	11.16	Y
1812095	18 12 9.56	+64 29 42.3	A2V	11.736	11.286	N
1808347	18 08 34.75	+69 27 28.7	A3V	11.9	11.53	Y
1802271	18 02 27.17	+60 43 35.6	A3V	11.985	11.832	N
1805292	18 05 29.3	+64 27 52.1	A1V	12.278	12.005	N
1732526	17 32 52.64	+71 04 43.1	A3V	12.530	12.254	N
1743045	17 43 04.48	+66 55 01.6	A5V	13.5	12.772	Y

Table 3 JWST primary calibrators: G Stars

Name	RA	DEC	SpType	V	K	New
HD 159222	17 32 00.99	+34 16 16.1	G1V	6.56	5.00	Y
HD 205905	21 39 10.15	-27 18 23.7	G2V	6.74	5.32	Y
HD 106252	12 13 29.51	+10 02 29.9	G0	7.36	5.93	Y
HD 27836	04 24 12.46	+04 24 12.4	G1V	7.6	6.01	Y
HD 37962	05 40 51.97	-31 21 04.0	G2V	7.85	6.27	Y
HD 38949	05 48 20.06	-24 27 49.9	G1V	8.0	6.44	Y
P330E	16 31 33.85	+30 08 47.1	G0V	13.01	11.379	N
P177D	15 59 13.59	+47 36 41.8	G0V	13.48	11.857	N

Name	RA	DEC	SpType	V	K	New
C26202	03 32 32.88	-27 51 48.0	G0-5	16.64		Y
SF1615+001A	16 18 14.23	+00 00 08.4	G0-5	16.75		Y
SNAP-2	16 19 46.13	+55 34 17.7	G0-5	16.2		Y

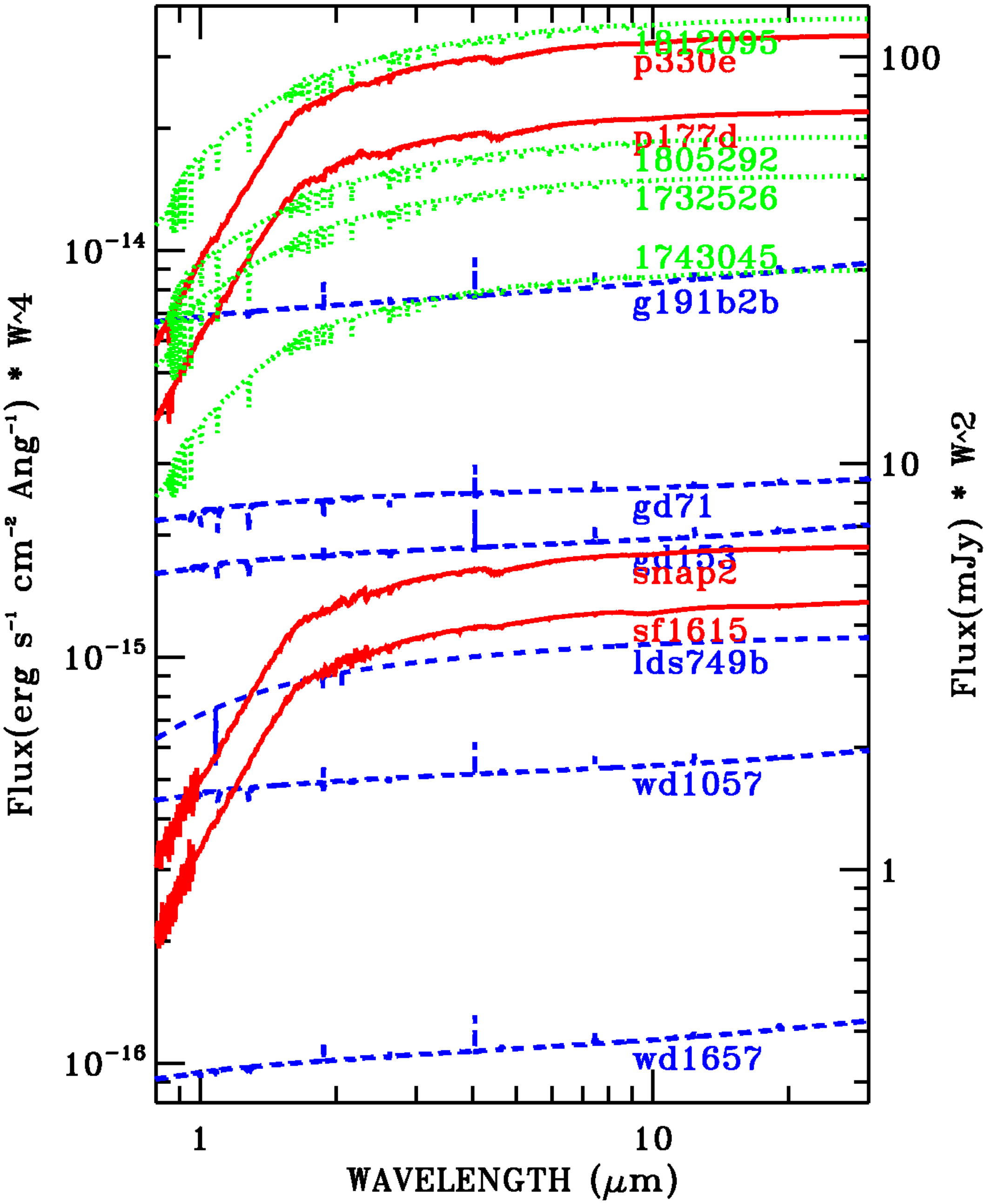

Figure 1: Spectra of a representative sample of the proposed primary calibration sources: white dwarfs (blue, dashed), A-stars (green, dotted), and G-stars (red, solid). The multipliers, W^4 and W^2, on the ordinates are in units of µm.

3 Instrument Sensitivities

Each instrument on JWST has different sensitivities and wavelength ranges ranges and, therefore each has a different range of observable minimum and maximum fluxes. The question is does the proposed list of primary calibrators match the instrument capabilities?

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

The sensitivities for the broad imaging filters are given in Gordon et al. (2009) and overplotted on the expanded calibrator sample in Figure 2. The sensitivities for the medium and narrow band filters were determined using the NIRCam prototype ETC and scaling of the broad imaging saturation limits for the differences in filter widths. They are given in Table 4 and overplotted on the calibrator sample in Figure 3.

Table 4: NIRCam Medium & Narrow Band Sensitivities

Medium Bands				Narrow Bands			
Full Frame			Subarray	Full Frame			Subarray
Band	Min [mJy]	Max [mJy]	Max [mJy]	Band	Min [mJy]	Max [mJy]	Max [mJy]
F140M	$2.0x10^{-3}$	1.8	105	F164N	$2.0x10^{-2}$	18	$1.0x10^{3}$
F162M	$2.25x10^{-3}$	1.8	105	F187N	$2.1x10^{-2}$	18	$1.0x10^{3}$
F182M	$1.75x10^{-3}$	3	173	F212N	$1.8x10^{-2}$	30	$1.7x10^{3}$
F210M	$1.75x10^{-3}$	3	173	F323N	$2.0x10^{-2}$	23	$4.5x10^{3}$
F250M	$2.2x10^{-3}$	1.4	275	F405N	$2.0x10^{-2}$	39	$8.0x10^{3}$
F300M	$1.5x10^{-3}$	1.4	275	F466N	$2.2x10^{-2}$	39	$8.0x10^{3}$
F335M	$1.6x10^{-3}$	2.3	450	F470N	$2.5x10^{-2}$	39	$8.0x10^{3}$
F360M	$1.65x10^{-3}$	2.3	450				
F410M	$1.9x10^{-3}$	3.9	770				
F430M	$4.0x10^{-3}$	3.9	770				
F460M	$2.5x10^{-3}$	3.9	770				
F480M	$3.0x10^{-3}$	3.9	770				

3.2 Number of Calibrators

The number of calibrators in the expanded sample that fall within the sensitivities of each NIRCam band is given in Table 5.

Table 5: NIRCam Number of Calibrators per Band

Band	Hot Stars	A Stars	G Stars	Band	Hot Stars	A Stars	G Stars
	Wide Bands				**Medium Bands**		
F070W	6	6	5	F140M	6	6	5
F090W	6	3	5	F162M	6	6	5
F115W	6	3	5	F182M	6	6	5
F150W	6	6	5	F210M	6	7	5
F200W	6	6	5	F250M	6	8	5
F277W	6	7	5	F300M	6	8	5
F356W	6	8	5	F335M	7	8	5
F444W	8	9	5	F360M	7	8	5
	Narrow Bands			F410M	7	10	8
F164N	5	9	5	F430M	7	11	9
F187N	6	9	5	F460M	8	11	9
F212N	7	10	5	F480M	8	11	9
F323N	11	13	11				
F405N	11	13	11				
F466N	10	13	11				
F470N	10	13	11				

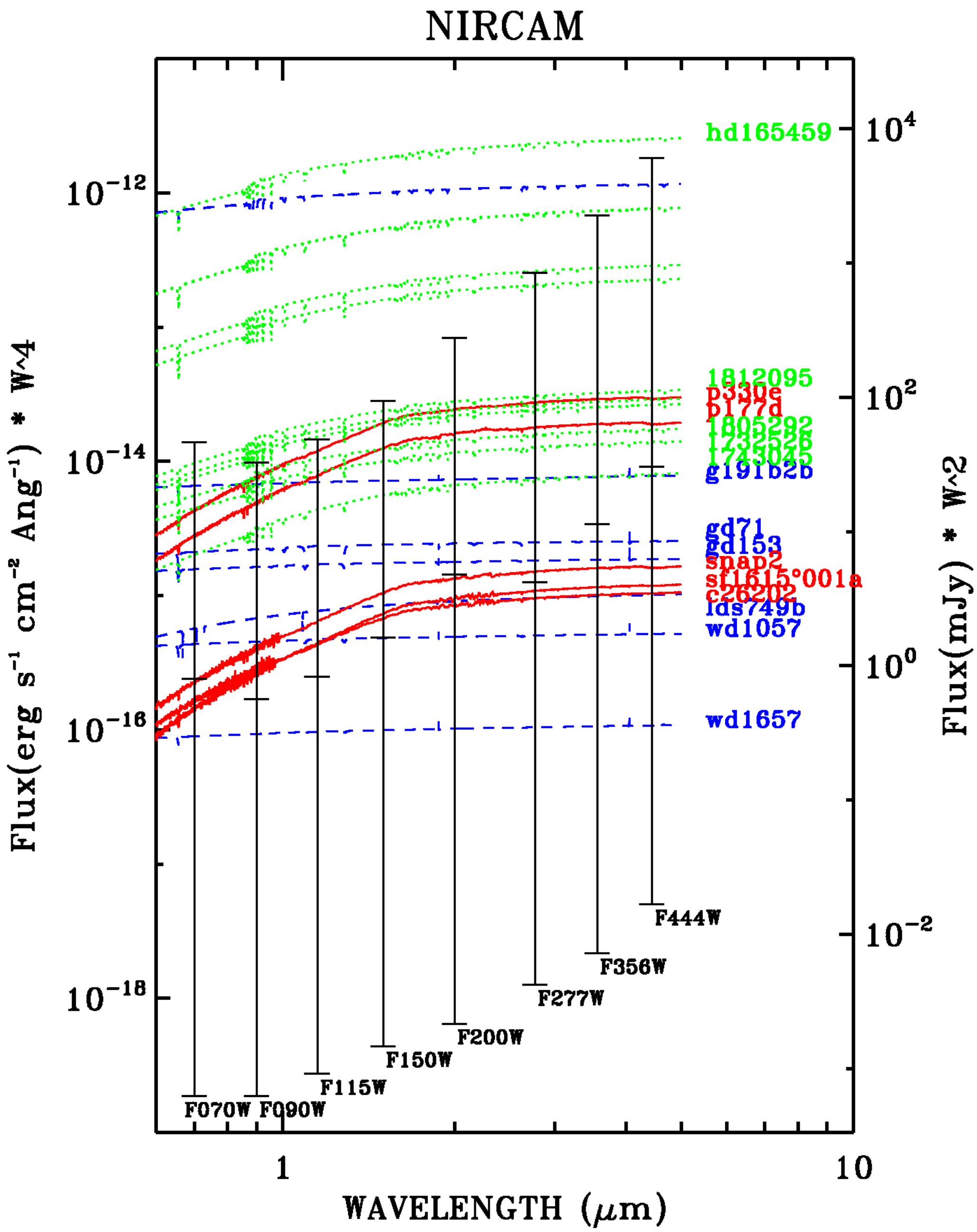

Figure 2; The NIRCam sensitivity limits for the wide bands and the spectra of the proposed primary calibrators are shown with blue for WDs, green for A types, and red for G stars. The sensitivity in each filter is given by the vertical ba where the min, middle, and max marks give the min full frame,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

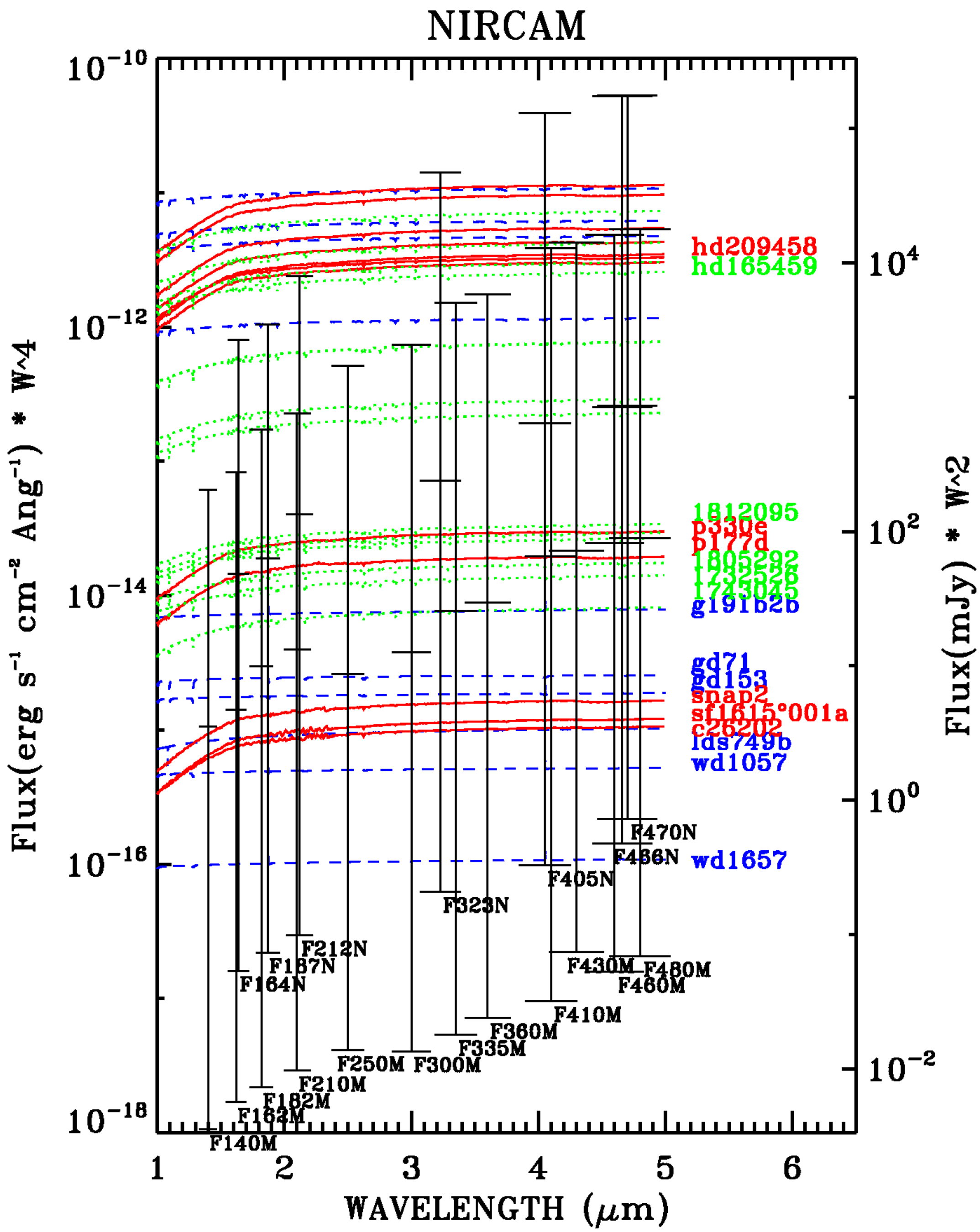

Figure 3; The NIRCam sensitivity limits for the medium and narrow bands and the spectra of the proposed primary calibrators are shown with blue for WDs, green for A types, and red for G stars. The sensitivity in each filter is given by the vertical bar where the min, middle, and max marks give the min full frame, max full frame, and max subarray sensitivities, respectively.

3.3 NIRSpec

The sensitivities are given in Gordon et al. (2009) and overplotted on the expanded calibrator sample in Figure 4.

The number of calibrators in the expanded sample that fall within the sensitivities of each NIRSpec central wavelengths is given in Table 6.

Table 6: NIRSpec Number of Calibrators at Selected Wavelengths

Wavelength	Hot Stars	A Stars	G Stars	Wavelength	Hot Stars	A Stars	G Stars
	R=2700				**R=1000**		
1.3 μm	10	13	11	1.3 μm	11	13	11
2.4 μm	9	13	11	2.4 μm	10	13	11
3.7 μm	7	13	8	3.7 μm	9	13	11
	R=100						
2.2 μm	8	9	5				

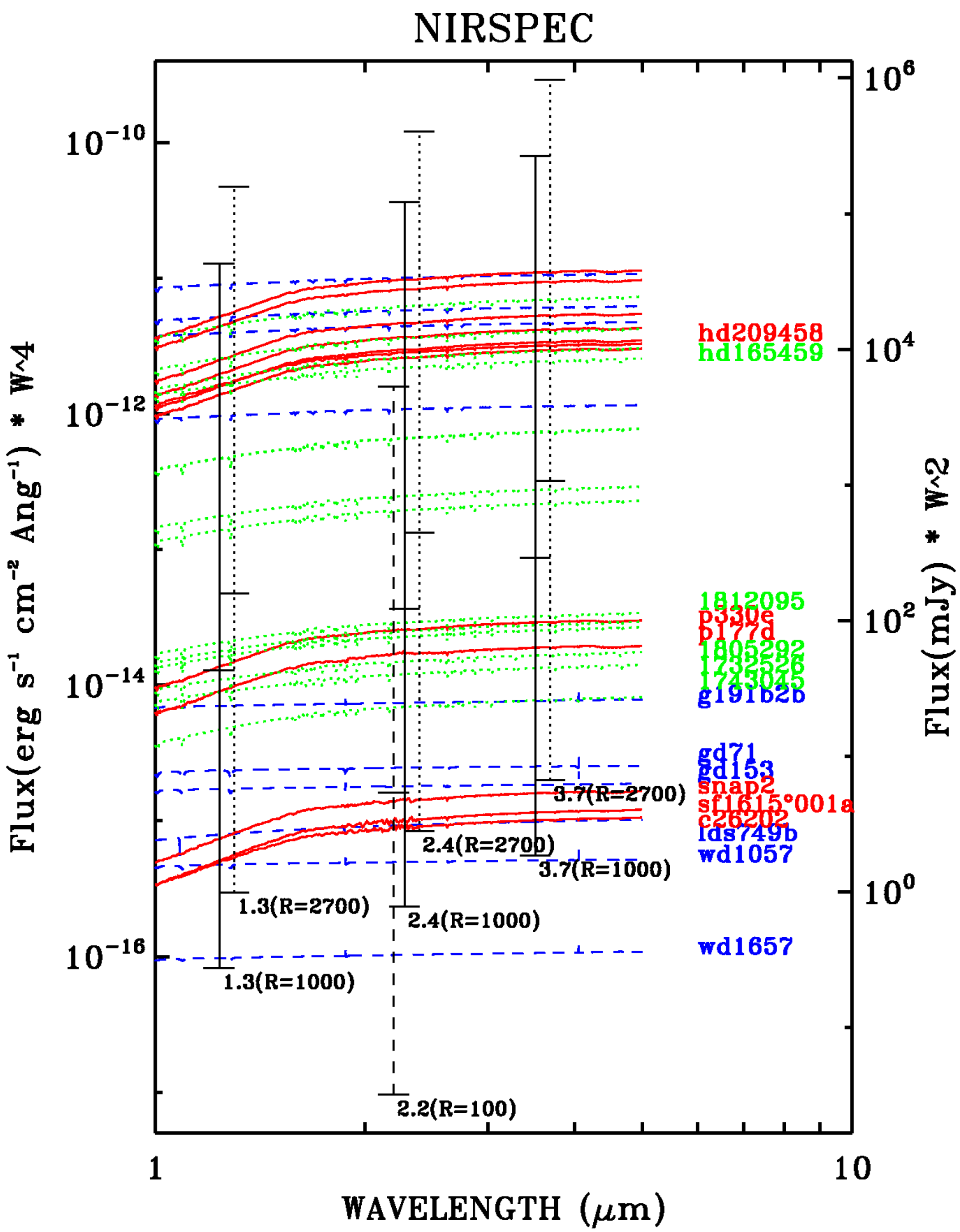

Figure 4: The NIRSpec sensitivity limits and the spectra of the proposed primary calibrators are shown as in Figure 2. The vertical lines are the ranges of the sensitivities and are solid: R=1000 spectroscopy, dashed: R=100 spectroscopy, and dots: R=2700 spectroscopy. The sensitivity in each wavelength 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.

3.4 FGS/TFI

The sensitivities are given in Gordon et al. (2009) and overplotted on the expanded calibrator sample in Figure 5. The design of the TFI instrument is currently undergoing significant revisions (new instrument to be called NIRISS) and we will update this report when the necessary sensitivities are available.

The number of calibrators in the expanded sample that fall within the sensitivities of selected TFI central wavelengths is given in Table 7.

Table 7: TFI Number of Calibrators at Selected Wavelengths

Wavelength	Hot Stars	A Stars	G Stars
1.5 μm	9	13	10
2.0 μm	11	13	11
2.5 μm	11	13	11
3.2 μm	11	13	11
3.5 μm	11	13	11
4.0 μm	11	13	11
4.5 μm	11	13	11
5.0 μm	10	13	11

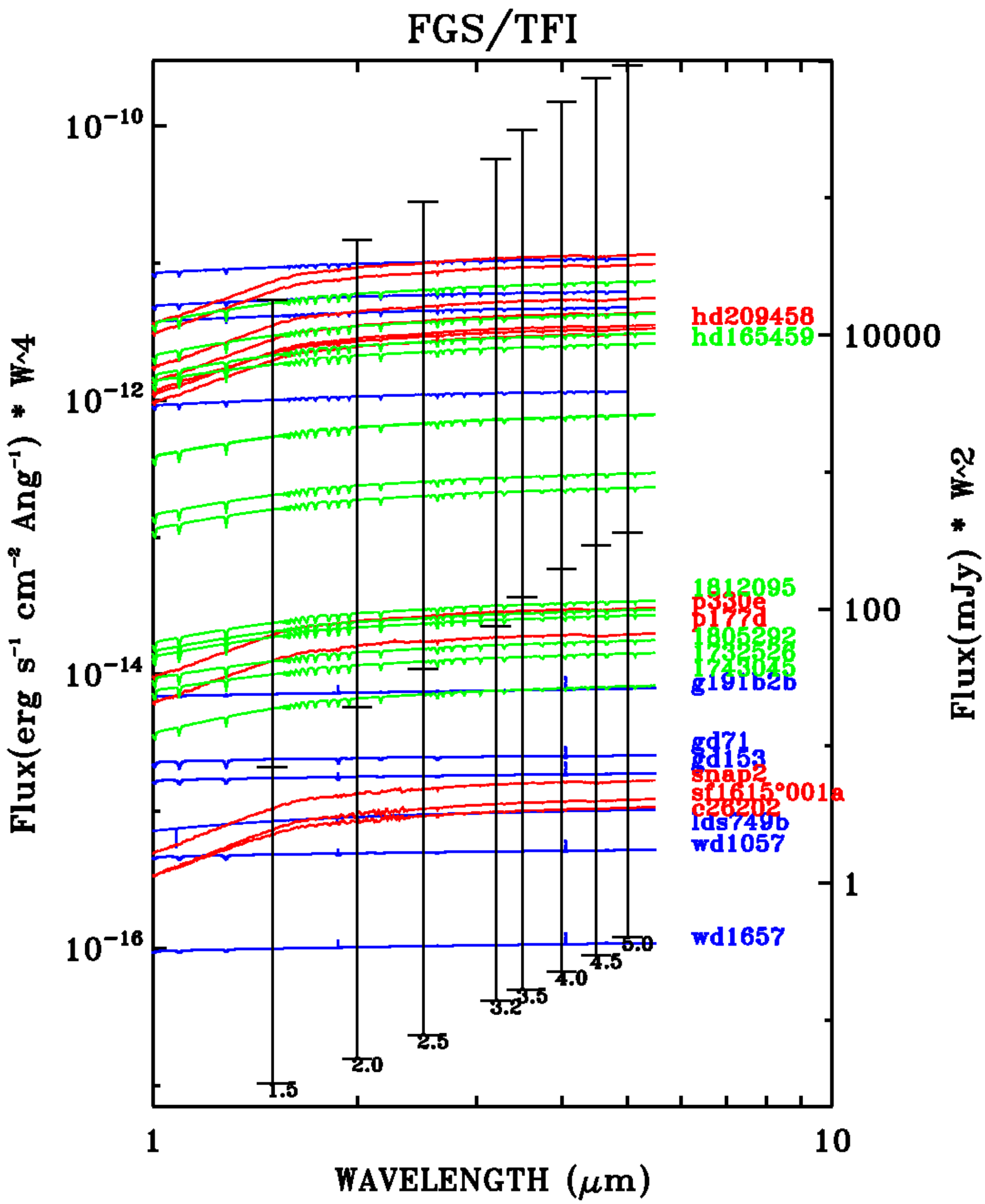

Figure 5: The FGS/TFI sensitivity limits and the spectra of the proposed primary calibrators are shown as in Figure 2. The sensitivity in each filter is given by the vertical bar where the min, middle, and max marks give the min full frame, max full frame, and max subarray sensitivities, respectively.

3.5 MIRI

The sensitivities are given in Gordon et al. (2009) and overplotted on the expanded calibrator sample in Figure 6 (for direct imaging) and Figure 7 (for the coronagraphy, LRS-SLIT and MRS-IFU).

The number of calibrators in the expanded sample that fall within the sensitivities of each MIRI band (imaging & coronagraphy) and selected central wavelengths (spectroscopy) is given in Table 8.

Table 8: MIRI Number of Calibrators per Band (imaging) and Selected Wavelengths (spectroscopy)

Band	Hot Stars	A Stars	G Stars	Band	Hot Stars	A Stars	G Stars
	Imager				Coronagraphs		
F560W	9	12	10	F1065C	6	13	8
F770W	10	13	11	F1140C	6	13	8
F1000W	9	13	11	F1550C	5	10	8
F1130W	6	13	8	F2300C	5	7	6
F1280W	6	13	8		LRS-Slit/MRS-IFU		
F1500W	6	13	8	LRS-7.5	7	12	10
F1800W	5	11	8	MRS-6.4	6	13	8
F2100W	5	7	6	MRS-9.2	5	11	8
F2550W	5	7	6	MRS-14.5	5	7	6
				MRS-22.5	5	5	6

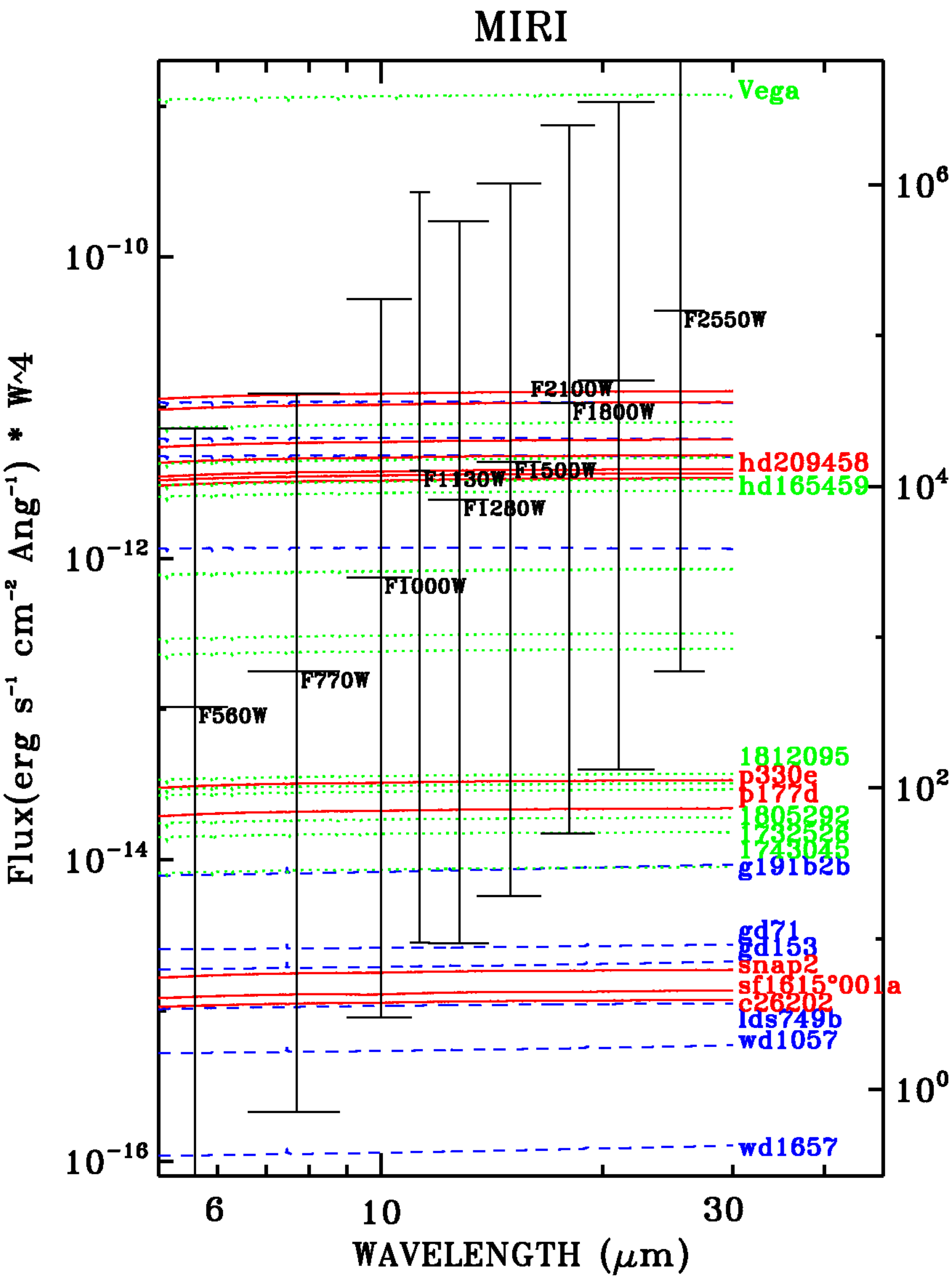

Figure 6: The MIRI sensitivity limits for direct imaging and the spectra of the proposed primary calibrators are shown as in Figure 2. The stars are labeled. The sensitivity in each filter is given by the vertical bar where the min, middle, and max marks give the min full frame, max full frame, and max 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.

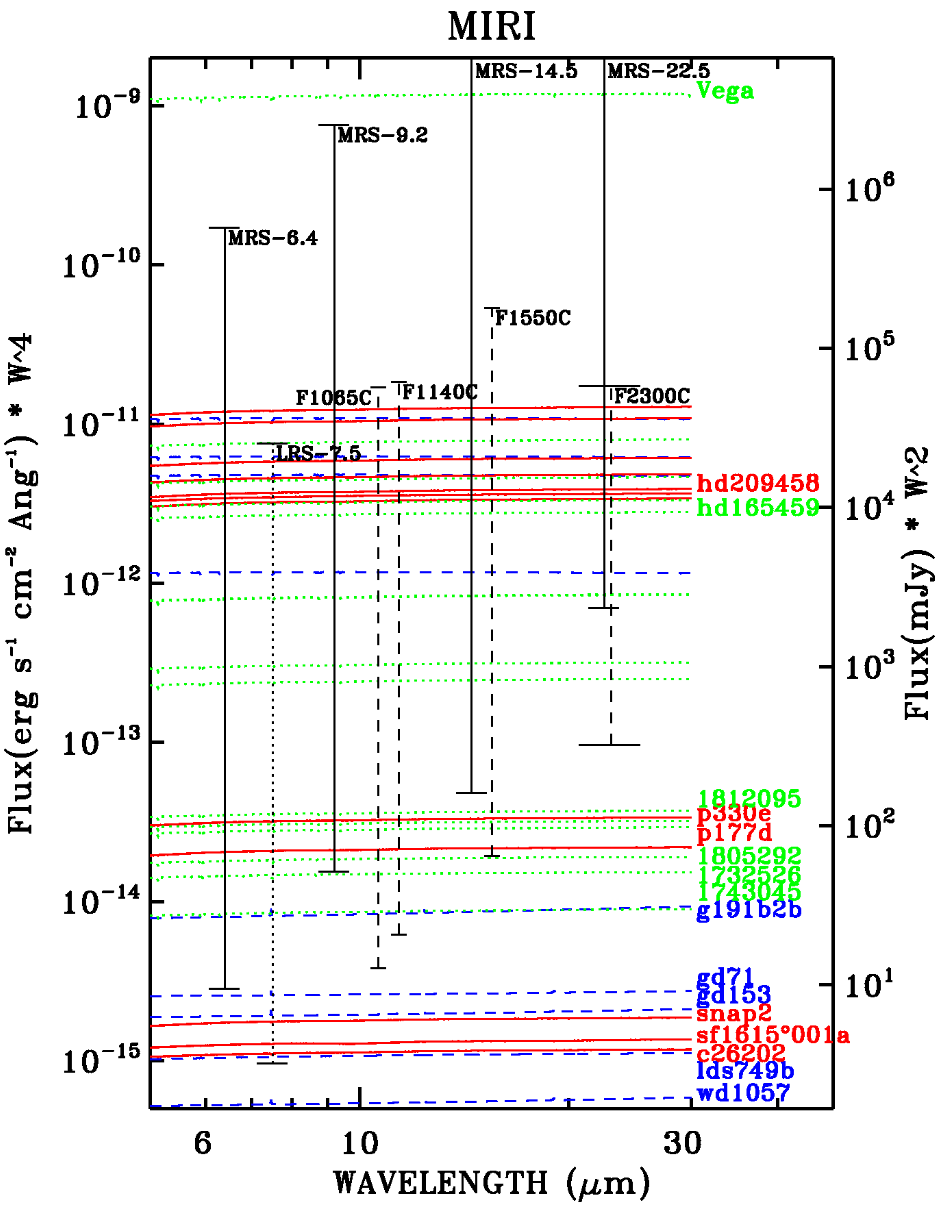

Figure 7: The MIRI sensitivity limits for coronagraphy, medium resolution spectroscopy, and low resolution spectroscopy and the spectra of the proposed primary calibrators are shown as in Figure 2 The stars are labeled and the line types are dashed: coronagraphy, solid: medium resolution spectroscopy, 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 Results

The main goal of the expanded sample is provide enough stars to give 5 per band/grating per star type, which has been achieved for all the instruments, except for two of the NIRCam wide bands for the A-type stars.

For the two NIRCam bands that only have 3 A-type stars available (F090W & F115W), there are 2 more stars more right above the nominal saturation limit of these bands. Given the uncertainties in the sensitivities used and the need to refine the model predictions for the stars, 5 stars may well be observable in both these bands. We will revisit this issue when updated model predictions for these stars and updated sensitivities for NIRCam are available.

5 Conclusions

All JWST instruments can observe a subset of the sample of calibration stars given in this report. All of the instruments have at least 5 stars per band/grating with the possible exception of two NIRCam bands. The sample of calibration stars given in this report should provide sufficient high quality calibration stars to meet the required 2.83% portion of the absolute flux calibration JWST error budget for the imagers (NIRCam & MIRI). In addition, these calibration stars provide the potential to achieving an even better photometric calibration precision, which is estimated to be ~1%.

5.1 Next Steps

The next steps in providing a high quality absolute flux calibration for JWST are:

1. Update the current model predictions that are mainly based on the detailed spectrophotometric SED of each calibration star to include new data (particularly from Spitzer & Hubble) and updated stellar atmosphere models.
2. Acquire ground-based observations of each calibration star in the optical and near-infrared to provide an independent prediction of the stellar atmosphere parameters (e.g., T(eff) & log(g)).
3. Revise the TFI section of this effort when the sensitivities for the new version of this instrument (called NIRISS) are available.
4. Enhance the current sample to provide for the characterization of the calibration, not just the base flux calibration. The most important characterization task it to ensure that the flux calibration transfers to sources of all fluxes (e.g., exploring flux-dependent non-linearities). Linearity measurements require sources with fluxes that span the full sensitivity range of each instrument. A quick perusal of the figures in this report shows that our current sample lacks sources for a large portion of the faint end of the NIRCam wide band sensitivities and, to a lessor extent, the NIRCam medium bands. In addition, more sources at the bright end of the MIRI wide bands and MRS sensitivities would also be useful.
5. 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), hot stars, and A-stars should allow for the full wavelength range to be well calibrated.

6 References

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