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Candidate Calibrators for the In-Orbit Spectrophotometric Calibration of the MIRI Medium Resolution Spectrograph Onboard the James Webb Space Telescope

E. K. J. Bauwens[1], T. Nakos[2], L. Decin[1,3], J. A. D. L. Blommaert[1], G. Rieke[4], C. Waelkens,[1], P. Degroote[1], C. Engelbracht[4], M. Groenewegen[5]

Instituut voor sterrenkunde, KULeuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

Department of Physics and Astronomy, University of Ghent, Krijgslaan 281 S9, WE05, B-9000 Ghent, Belgium

Sterrenkundig Instituut Anton Pannekoek, University of Amsterdam, Kruislaan 403, NL-1098 Amsterdam, The Netherlands

Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA

Royal Observatory of Belgium, Ringlaan 3, B-1180, Belgium

Abstract. The James Webb Space Telescope (JWST), due to launch in 2014, will provide an unprecedented wealth of information in the near and mid-infrared wavelengths, thanks to its high-sensitivity instruments and its 6.5 m primary mirror, the largest ever launched into space. MIRI, the Mid-InfraRed Instrument, will be the only instrument (onboard JWST) with a spectrograph operating in the $5 - 28\,\mu$m wavelength range. We present a list of 32 stellar sources that have been selected as candidates for the in-orbit calibration of the Medium Resolution Spectrometer (MRS) of MIRI. We describe the selection criteria, the modelling of the stellar atmospheres, and also present some preliminary results.

1. Introduction

We present the current status of an effort to generate a list of stars for the in-orbit calibration of the *Medium Resolution Spectrograph (MRS)* of MIRI, the Mid-IR Instrument onboard the James Webb Space Telescope. By comparing the predicted theoretical spectra (computed using stellar atmosphere models) to the spectra obtained with MIRI observations, it will be possible to compute the Relative Spectral Response Function (RSRF), that characterises the wavelength-dependent response of the spectrometer.

To reach a calibration accuracy of a few percent, a careful selection of calibrators is essential. The final accuracy depends critically on both (a) observational issues (e.g., the non-uniformity of the data used for the selection) and (b) uncertainties in the theoretical spectra fitted to the data. In the following sections, we describe (a) the selection criteria used to select candidate calibration stars; (b) the observational data sets associated with these candidates, and (c) some results about the theoretical spectra.

2. JWST & MIRI

The James Webb Space Telescope is a project led by NASA, with major contributions from the European and Canadian Space Agency (ESA, CSA, respectively). JWST is due to

Table 1: Properties of the MIRI integral field units. The region of the sky corresponding to a spatial sample is set by the slice width in the across slice direction, and by the pixel field of view in the along slice direction.

λ	Slices	Spatial sample dimens.		FoV		R
μm		Across ($''$)	Along ($''$)	Across ($''$)	Along ($''$)	
5.0 − 7.7	21	0.18	0.20	3.7	3.7	2400 − 3700
7.7 − 11.9	17	0.28	0.20	4.5	4.7	2400 − 3600
11.9 − 18.3	16	0.39	0.25	6.1	6.2	2400 − 3600
18.3 − 28.3	12	0.64	0.27	7.9	7.7	2000 − 2400

launch in 2014. The minimum life of the mission is five years, although there is a possibility of extension up to ten years. A detailed description of the space observatory and its science cornerstones can be found in Gardner et al. (2006).

MIRI (Wright et al. 2004) is a European-American collaboration and is unique, in many aspects. First of all, it will be the only instrument operating in the mid-IR wavelength range ($5 - 28\,\mu$m). Second, it is also the only JWST instrument that can perform imaging, spectroscopy and coronagraphy. MIRI consists of three identical 1024×1024 Si:As sensor chip assemblies (SCA), of $25\,\mu$m pixel size, that will operate at 7 K. As the spacecraft will be passively cooled down to ≈ 35 K, the 7 K temperature will be achieved by means of a mechanical cooler. The MIRI SCAs and cryo-cooler are provided by Jet Propulsion Laboratory, while MIRI's optical system is provided by a European Consortium (EC) that consists of 28 institutes from 10 European countries.

Two of the MIRI SCAs will be used for integral field spectroscopy, via four image slicers. The two integral field units (IFUs) will provide spectral and spatial information of the targeted objects with a resolution of R $\approx 2000 - 3700$ over the $5\,\mu\mathrm{m} < \lambda < 27\,\mu$m wavelength range. The IFUs provide four simultaneous and concentric fields of view, that increase in size with wavelength. One of the two IFUs will cover the short-wavelength range ($5 - 11.9\,\mu$m) while the second one will cover the long-wavelength range ($11.9 - 28.3\,\mu$m). The main properties of the MIRI medium resolution spectrometer (MRS) are presented in Table 1.

3. Selection criteria

Quantitative use of the MRS ultimately depends on observations of well-understood calibration stars. The selection of the candidates has been based on a combination of (a) requirements (imposed by the instrument specifications), (b) strict criteria that have to be respected by all stars and, (c) a "wish-list", i.e. conditions that we would like at least some of the calibrators to fulfill. In the following sections we give a detailed description of the steps followed for the selection of the calibration candidates.

3.1. Spectral Type

To avoid systematic errors introduced by features associated to a specific spectral type of stellar sources, the calibrator list should include sources spanning a large spectral type range. According to Decin et al. (2007), a combination of A dwarfs, cool giants (G9III to K5III) and solar analogs provides an ideal data set, as the modelling of the stellar atmospheres of stars of the above spectral types is well understood. For an elaborate discussion on this topic we refer to Decin & Eriksson (2007), and we may summarise as follows:

- For the A dwarfs, the possible presence of a debris disk will result in a flux excess in the MIRI wavelength range. Spitzer MIPS 24 μm (Rieke et al. 2004) photometric data should allow checking for IR excess and rejecting objects where one is present. Concerning the modelling of the stellar spectra, the main uncertainties for the A dwarfs arise from the hydrogen line predictions. However, as ISO spectra have demonstrated, there are no hydrogen lines present in the MIRI wavelength range.
- The late type giants have strong molecular absorption bands in the MIRI wavelength range. These features can be modelled with sufficient accuracy, provided that stellar parameters like effective temperature, gravity and chemical abundances, are accurately known. A mid-IR flux excess might also be introduced due to a circumstellar shell, which can also be identified thanks to MIPS 24 μm photometric data.
- For the solar analogs, both atomic and molecular lines are present. However, high resolution solar spectra places constraints that can lead to accurate models of their atmospheres.

3.2. Other criteria

Some additional requirements for considering a stellar source as a good spectrophotometric calibrator are:

- the star is photometrically stable in time
- its 10 μm flux density is in the range $4 - 500$ mJy (this is a MIRI MRS requirement).

Additional factors that were taken under consideration for the selection, are

- the Right Ascension and Declination of the sources, as it is essential to be able to observe at least a few calibrators at any time, during the mission,
- the flux density of some sources to be close to the faint limit of the requirement range ($\approx$ 4 mJy), so that a cross-check calibration with the MIRI imager can be performed for some of the calibrators in our list[1], and
- MIPS 24 μm data should either exist at the Spitzer archive, or should have been possible to obtain, to check for a possible IR excess.

4. The list of candidate calibrators

A preliminary list of 79 MIRI-MRS candidate calibrators was presented in Decin et al. (2007), containing

- calibration sources from Spitzer's IRAC (Reach et al. 2005), MIPS 24 μm (Engelbracht et al. 2007) and IRS (Houck et al. 2004) instruments
- ISO's ISOCAM (Blommaert 1998)
- an object list presented in Cohen et al. (2003), originating from the Landolt standard stars (Landolt 1992) and the Carter-Meadows catalog of faint IR stars (Carter & Meadows 1995), and
- solar analogs, suggested by G. Rieke (priv. comm.).

[1] According to the latest specifications, it will be possible to observe with the MIRI imager even the brightest of the sources in the list, in sub-array mode.

The above list was finally reduced to 32 sources with MIPS 24 μm photometry, which is essential to reject sources with a circumstellar dust shell or a disk. The current list of *candidate* calibrators, containing seven solar analogs, seven late-type giants and 18 A dwarfs, is presented in Table 2. The term "candidate" has the meaning that the present list can still be reduced. In the subsequent sections we shall explain how the refinement of the list will be achieved.

Table 2: Candidate calibrators for the MIRI MRS, with spectral type, position and flux at 10 μm, in mJy. These fluxes are estimates made by extrapolating observations at different wavelengths, using an appropriate Kurucz model (Vega, Arcturus and the Sun for the A, K and G-type stars, respectively).

nr	Identifier	Sp. Type	RA (J2000)	Dec (J2000)	F_{10} (mJy)
1	HD 001644	K0	00 20 43.6	+03 26 58.0	376.0
2	HD 002811	A3V	00 31 18.5	−43 36 23.0	57.0
3	HD 014943	A5V	02 22 54.7	−51 05 31.7	175.9
4	HD 015646	A0V	02 28 04.4	−64 17 59.0	113.8
5	HD 017254	A2V	02 44 10.6	−52 34 14.0	172.4
6	HD 021981	A1V	03 30 37.0	−47 22 30.5	204.0
7	HD 037962	G4V	05 40 52.0	−31 21 40.0	120.0
8	HD 038949	G1V	05 48 20.1	−24 27 50.0	72.3
9	HD 040335	A0	05 58 13.5	+01 51 23.0	57.0
10	HD 042525	A0V	06 06 09.4	−66 02 23.0	169.4
11	HD 046819	K0III	06 30 22.7	−66 01 23.0	316.8
12	HD 057336	A0IV	07 09 30.5	−79 25 55.0	53.9
13	HD 073666	A1V	08 40 11.5	+19 58 16.0	102.3
14	HD 073819	A6Vn	08 40 56.3	+19 34 49.0	121.0
15	HD 101452	A2	11 40 13.6	−39 08 48.0	73.5
16	HD 106252	G0	12 13 29.5	+10 02 29.9	257.0
17	HD 108799	G1/G2V	12 30 04.8	−13 23 35.5	475.5
18	HD 113314	A0V	13 03 33.3	−49 31 38.1	488.0
19	HD 128998	A1V	14 38 15.2	+54 01 24.0	226.6
20	HD 159048	K0	17 23 34.5	+76 03 18.2	353.6
21	HD 158485	A4V	17 26 04.9	+58 39 06.8	113.3
22	HD 159222	G5V	17 32 01.0	+34 16 16.1	535.0
23	HD 163466	A2	17 52 25.4	+60 23 46.9	128.1
24	HD 172728	A0V	18 37 33.5	+62.31 35.7	191.2
25	HD 175510	A0V	18 58 27.8	−52 56 19.1	417.0
26	HD 196724	A0V	20 38 31.3	+21 12 04.2	450.3
27	HD 197806	K0III	20 47 30.8	−43 10 33.6	95.5
28	HD 205905	G2V	21 39 10.2	−27 18 24.0	301.3
29	SA 103-526	G8III	11 56 54.2	−00 30 13.8	23.5
30	SA 112-275	K2	20 42 35.4	+00 07 20.2	74.2
31	SA 112-595	K2III	20 41 18.5	+00 16 28.3	64.0
32	[RMC2005]KF09T1	K0III	17 59 23.0	+66 02 56.0	26.3

5. Available spectroscopic and photometric data

For the candidate MRS calibrators, ground-based observations are essential to (a) test the reliability of the candidates and (b) constrain the stellar parameters, needed for computing the theoretical spectra of the calibrators. More specifically, the optical and infrared observations can be used in the following way:

- $UBVRI$ photometric data, to constrain the effective temperature, $T_{\rm eff}$.
- NIR photometric data, in particular K-band, to constrain the effective temperature in the case of late type giants.
- Optical and/or NIR spectroscopy, to set constraints on the effective temperature, $T_{\rm eff}$, the surface gravity, $\log g$, and the abundances.
- Parallaxes (if possible), to derive the distance and hence to estimate the dust reddening $E(B-V)$ and the surface gravity.

To minimize the impact of the observational uncertainties to the total calibration error budget, the data should be obtained (and reduced) in a consistent and homogeneous way. As a consequence, the number of instruments involved in the data acquisition should be reduced as much as possible. For the purposes of the MIRI MRS calibration, data have either been collected thanks to telescope time allocated to our project, or have been retrieved from astronomical databases:

- The U, B and V band photometry where obtained using the Swiss Euler telescope, at La Silla, Chile and the Flemish Mercator telescope, at La Palma, Spain (which is identical to the Euler telescope). Three instruments were involved in the data acquisition. The first one is the P7 photometer. As it was installed in the past on both telescopes, it has been used to observe targets covering a wide declination range. Unfortunately P7 was decommissioned before all stars in our list were observed. Data for the remaining stars were obtained either with the MEROPE CCD camera on the Mercator telescope, or the C2 CCD camera on the Euler telescope.
- R and I band observations were obtained using the MEROPE and C2 cameras. However, due to technical issues, very limited information can be extracted from the data. For most objects these data will therefore not be used in the modelling.
- The 2MASS catalogue provides J, H and K-band photometry for all but one star (SA 112-595). The quality flags for the results were checked to make sure only high quality data was used. This resulted in excluding the J, H and K-band photometry for HD 159048, the J and H-band photometry for HD 113314 and HD 175510, and the H-band photometry for HD 196724.
- Recently, Ishihara et al. (2010) published the AKARI results for the IRC point-source catalogue, which includes photometry at 9 and 18 μm. These data are particularly useful to verify if stars in our list show any flux excess, in the MIRI wavelength range, with respect to the models. For 27 of the candidate calibrators there is 9 μm photometry available (there is no information for HD 040335, SA 103-526, SA 112-595, SA 112-275 and [RMC2005]KF09T1). 18 μm photometry is available for just four sources, namely HD 046819, HD 113314, HD 159048 and HD 196724.
- In addition to the AKARI data, IRAC photometry (covering the wavelength range $3.6-8.0\,\mu$m) is also available for 17 of our targets, but the data still have to be reduced. Finally, MIPS data at 24 μm are being used for all stars to check whether the calibrator candidates show an IR excess. These data were either retrieved from the Spitzer archive, or were obtained based on observing proposals submitted by us.

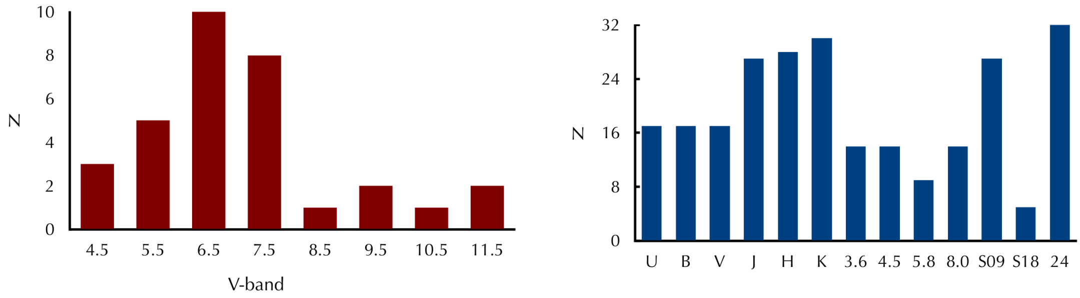

Figure 1: *Left panel:* V-band magnitude distribution of the calibration sources. *Right panel:* Distribution of the calibration sources as a function of photometric bands. The UBV photometry comes from the P7 Geneva catalogue, the J, H and K-band from the 2MASS archive, the $3.6 - 8.0\,\mu$m measurements from the IRAC Spitzer Heritage Archive, the S09 and S18 from the AKARI IRC point-source catalog and the $24\,\mu$m measurements from the MIPS 24 Spitzer observations.

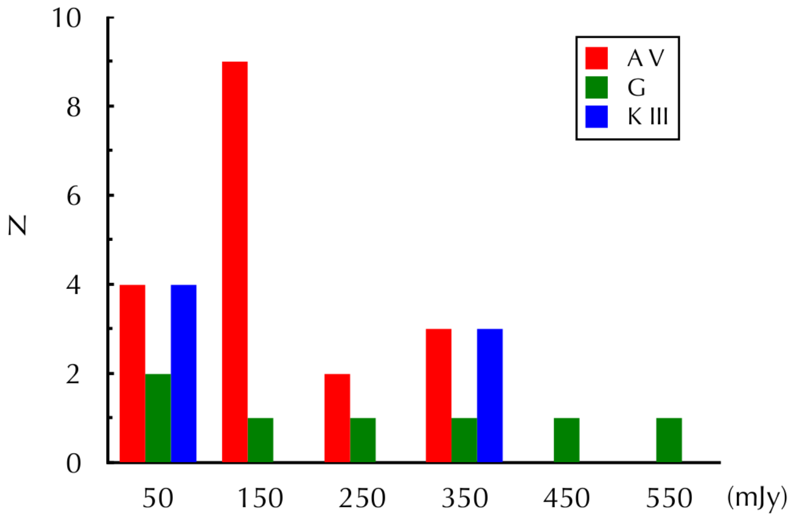

Figure 2: 10-μm, colour-coded, flux distribution of the calibrators.

6. Models, SED fitting and preliminary results

The data mentioned above were used as input for a χ^2 minimisation procedure, that selects the best-fit Spectral Energy Distributions (SED) among 1615 models, to fit the observed data points. These SEDs, taken from the literature, originate from eight different codes used to model stellar atmospheres. The 1615-SED grid spans an effective temperature range from $2400 - 55\,000$ K and a surface gravity from -1 up to 9 (in $\log g$ units).

As the MRS candidate calibrators are A dwarfs, solar analogs and late type giants, the best-fit model is chosen from a subset of 556 SEDs, which originate from three different stellar atmosphere codes. More specifically,

- 409 SEDs come from the Kurucz (1993) models, that span the effective temperature range $3500 - 50\,000$ and $0 \leq \log g \leq 5.0$. The $T_{\rm eff}$ step size is 250 K between 3000 K$-$10 000 K and 500 K between 10 000 K and 13 000 K (we do not expect higher temperatures for the candidate calibrators, given their spectral type).

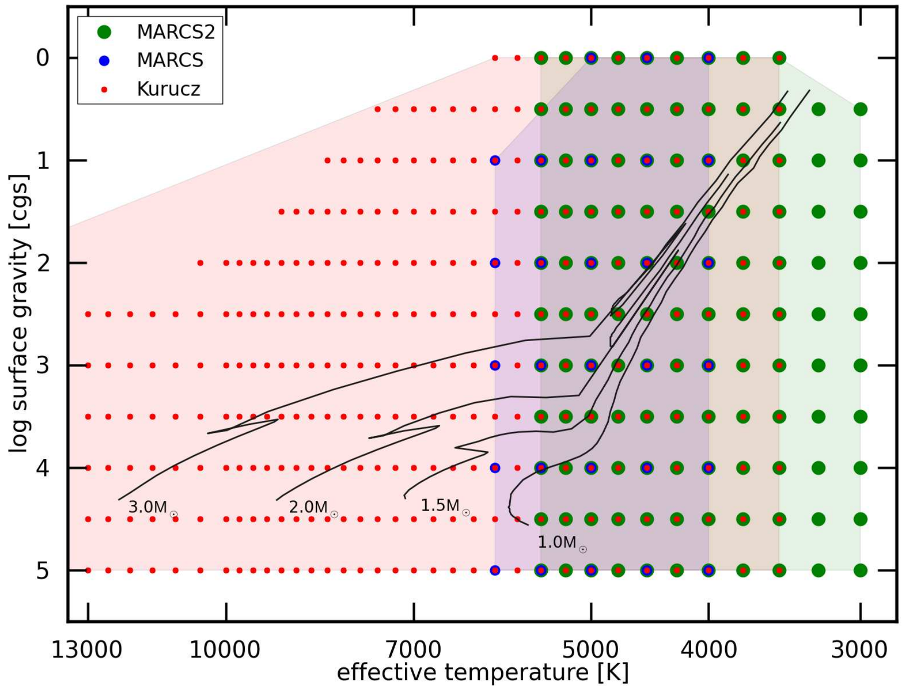

Figure 3: Grid of SEDs used to compute the stellar properties of the calibrators (see Section 6. for more details). The Kurucz SEDs are from the Kurucz (1993) library, the MARCS models from Gustafsson et al. (2008) and the MARCS2 from Decin (priv. com.). The evolutionary tracks are from Schaller et al. (1992).

- 28 SEDs come from the Gustafsson (2008) models, with $4000\,\mathrm{K} \leq T_{\mathrm{eff}} \leq 6000\,\mathrm{K}$ and $0 \leq \log g \leq 5.0$. The step size is 100 K between $2500 - 4000\,\mathrm{K}$ and 250 K for temperatures higher than 4000 K.

- 119 SEDs are an improved version of the Gustafsson (2008) models, developed by members from our team (namely L. Decin, which we shall call MARCS2), with 3000 K $\leq T_{\mathrm{eff}} \leq 5500\,\mathrm{K}$ and $0 \leq \log g \leq 5.0$.

The $\log g$ step-size is 0.5 for all models, and we assume solar abundances for all cases. Although the available models have been computed at a resolution of $\Delta T_{\mathrm{eff}} = 250\,\mathrm{K}$ and $\Delta \log g = 0.5$, it is possible to interpolate between the models, to reach a more precise effective temperature and surface gravity estimation. Our goal is to derive the best fitting values for T_{eff} and $\log g$ at a resolution of 100 K and 0.25 respectively. The grid of models used for the SED fitting is presented in Fig. 3.

Additional information derived from the χ^2 minimization is the $E(B-V)$ reddening factor and the calibrator's angular diameter. It should also be noted that in order to check whether the star shows a possible flux excess in the MIRI wavelength range, the photometric points above $5\,\mu m$ are not included in the fitting procedure. An example of the resulting best fitting model for HD 037962 is shown in Fig. 4, where the photometric points longer than $5\,\mu m$ are simply over-plotted.

For a subset of 17 MRS candidate calibrators, for which we required the objects to have available P7 photometry, we derived the stellar parameters T_{eff}, $\log g$, reddening, $E(B-V)$ and angular diameter, θ, using the SED fitting procedure described above. The results are presented in Table 3.

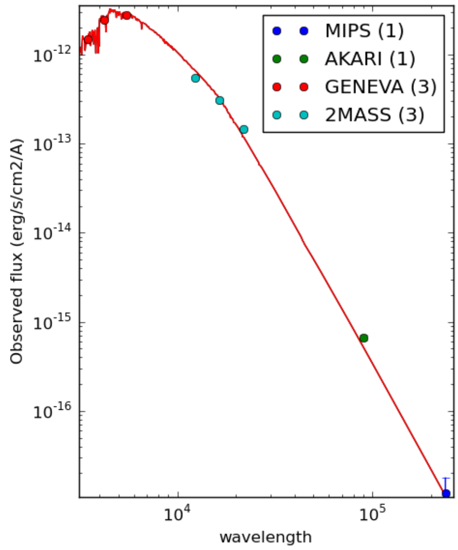

Figure 4: Example of SED fitting results for HD 037962, based on six photometric points (three coming from the Geneva catalog (UBV) and three from the 2MASS archive (JHK)). Longer wavelengths do not participate in the fit, to check whether the calibrator experiences an infrared excess. The photometric errors are also plotted but they are smaller than the symbols, except for the 24 μm measurements.

7. Future steps

Future steps for the further characterisation of the calibrators candidates include (a) the reduction of the IRAC photometric data, (b) the SED fitting for the remainder of the sources, and (c) the analysis of the spectroscopic data. From the obtained high resolution optical spectra, the $T_{\rm eff}$, $\log g$ and microturbulent velocity ξ_t will be derived, by measuring the equivalent width of the Fe lines. Through detailed modelling of the spectral lines of other elements it will be possible to refine the chemical abundances of the calibrators. From the above process it will be possible to generate spectra that better represent their stellar parameters.

We currently posses near-IR spectra for seven targets, obtained with the SOFI spectrograph on the ESO NTT telescope at La Silla observatory, Chile. These spectra cover the $0.9 - 2.5\,\mu m$ wavelength range, at a resolution between 600 and 2200. There are also Spitzer IRS spectra available for 17 of the objects in our list. These infrared spectra will be used to compare to the theoretical spectra we will derive for the candidate calibrators, to check whether there are any discrepancies. After rejecting cases with disagreements between models and observations, a final set of 15 to 20 calibrators will be retained from the list of candidate calibrators.

8. Summary

The list of 32 candidate calibration stars presented in this work, contains well known sources of three spectral classes (A dwarfs, solar analogs and late type giants). An extended set of data, photometric as well as spectroscopic and both in the optical and IR wavelength ranges has been obtained for these sources.

For a subset of the sources the first estimates for the stellar parameters based on the photometric data are presented here. In the coming months this analysis will be done for the remaining sources, as well as the analysis of available spectroscopic data. Based on

Table 3: List of the sources for which preliminary stellar parameters have been determined. This subset originates from Table 2 and includes sources with P7 photometry. The accuracy for the $T_{\rm eff}$ and the $\log g$ is 100 K and 0.25 respectively, unless indicated otherwise.

nr	Identifier	Sp. Type	$T_{\rm eff}$ [K]	$\log g$	E(B-V)	θ [mas]
1	HD 002811	A3V	8800	4.00	0.087	0.130 ± 0.009
2	HD 014943	A5V	8950	4.50	0.107	0.276 ± 0.024
3	HD 015646	A0V	10050	4.00	0.000	0.168 ± 0.009
4	HD 017254	A2V	8700	4.00	0.000	0.222 ± 0.012
5	HD 021981	A1V	7950[a]	3.75	0.000	0.279 ± 0.014
6	HD 037962	G4V	5850	4.75	0.000	0.227 ± 0.013
7	HD 042525	A0V	10250[b]	4.25	0.000	0.222 ± 0.015
8	HD 101452	A2	9250[c]	5.00	0.210	0.145 ± 0.008
9	HD 106252	G0	5950	4.25	0.000	0.264 ± 0.014
10	HD 108799	G1/G2V	6100	4.50	0.033	0.426 ± 0.031
11	HD 113314	A0V	9400	4.00	0.000	0.366 ± 0.032
12	HD 128998	A1V	9550	4.00	0.000	0.228 ± 0.010
13	HD 159222	G5V	5850	3.75	0.000	0.413 ± 0.020
14	HD 175510	A0V	10200[d]	3.50	0.013	0.341 ± 0.061
15	HD 196724	A0V	10350[e]	4.00	0.018	0.341 ± 0.072
16	HD 205905	G2V	6050	3.50	0.000	0.341 ± 0.024
17	SA 103-526	G8III	4700	2.00	0.000	0.098 ± 0.005

[a]Not in agreement with the $T_{\rm eff} = 9230$ K found by Wright et al. (2003).
[b]Not in agreement with the $T_{\rm eff} = 9520$ K found by Wright et al. (2003).
[c]The accuracy is 250 K.
[d]Not in agreement with the $T_{\rm eff} = 11\,000$ K found by Wright et al. (2003).
[e]Not in agreement with the $T_{\rm eff} = 9520$ K found by Wright et al. (2003).

the agreement or discrepancies between the models and the observations for the candidate calibrators, 15 to 20 calibrators will be selected from this list to be used as the fiducial calibrators for the MIRI MRS. These stars will be used to calibrate the MRS based on both continuum and spectral line measurements, at a level of $\approx 2\%$.

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