Year: 2017 **Term:** Jul–Dec **Proposal type:** short-term⋆

Identifying Flux Calibrators for JWST - Completion

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Abstract of Scientific Justification

JWST will provide unprecedented infrared images and spectra of the first galaxies, and enable frontier studies of the epoch of re-ionization, star formation, exoplanets and solar system objects. A critical part of the imaging will be the absolute calibration of the infrared imaging instruments: NIRCam, the near-infrared camera led by M. Rieke and MIRI, the mid-infrared instrument led by G. Rieke and G. Wright. It is essential to prepare targets well before the commissioning phase from 2018 to 2019. We will employ the Solar analog method, which uses absolute fluxes from optical and infrared measurements of stars close to G2 V spectral type and then applies a Solar spectral energy distribution to calculate the absolute fluxes in the NIRCam and MIRI filters. Existing well-calibrated stars are too bright for JWST instruments, so a fainter group of stars is necessary. Our program was nearly complete but due the availability of the higher resolution grating on MMT, we could not complete all spectroscopy. We propose to observe the remaining two clusters (NGC 2506 and NGC 6811) with HectoSpec/MMT for a partial night each to identify Solar analogs. The clusters in this survey are the only set of targets that have suitable compactness, distance, metallicity, age, low extinction and JWST visibilities. Previous work shows that this Solar analog method can be used to find absolute fluxes in the wavelength regions covered by the NIRCam and MIRI imagers at the ∼2% flux accuracy. Ancillary with this calibration data will be spectra of ∼100 stars within the clusters to improve stellar evolution models, which require empirical constraints to improve their theoretical isochrones.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	MMT	f/5	Hectospec			0.5	grey	Jul–Aug	Jul–Sep	yes	yes
2	MMT	f/5	Hectospec			0.5	grey	Nov–Jan	Oct–Jan	yes	yes

Scheduling constraints and unusable dates *(up to 4 lines)***:** None

no text past this line

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	NGC 2506 (1 Gyr, 3.5 kpc)	08:00:01	-10:46:12	Open Cluster, R=5′, [Fe/H]=-0.2, E(B-V)=0.08
2	NGC 6811 (0.7 Gyr, 1.2 kpc)	19:37:10	+46:22:30	Open Cluster, R=13′, [Fe/H]=+0.1, E(B-V)=0.16

Approval for Instrument Use from PI: ______________________

(have instrument PI signature appear on, or attach PI e-mail to, ***all*** *copies)*

Graduate students *(provide the following information if student is PI on the cover page or if this is a 2nd-year or Thesis program. Send confirmation email to TAC chair in place of signature.)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

JWST's Broad Science Capabilities: The James Webb Space Telescope (JWST) will explore new frontiers in the re-ionization of the Universe, the assembly of galaxies, the birth of stars and planetary systems and it will determine chemical and physical properties of planetary systems (e.g. Gardner et al., 2006). These broad classes of new science will be achievable with JWST's unprecedented sensitivity to the infrared using its large (6.5m) mirror and cold optics (<50 K). JWST will advance our understanding of these science areas with images (such as of the very first galaxies made up of zero-metallicity stars) and infrared spectra (such as of the atmospheres of extrasolar planets).

Absolute Calibration In order to make progress on these new science fields, *it is necessary to convert the data number (DN) counts of the digital images/spectra into physical flux units.* Accurate flux calibration can have a profound impact on the interpretation of astrophysical observations, such as the well known measurements of distant Type I supernovae for the study of dark energy (e.g Riess et al., 1998). Accurate flux calibration is also essential to estimate metallicity and other intrinsic properties of stellar populations. This conversion of JWST raw counts to physical flux units requires careful flux measurements of standard stars with all instruments and configurations. These flux standards can be measured and extrapolated to accuracies of ∼2% (Rieke et al., 2008). However, *the known sets of standard stars for absolute calibration are too bright for NIRCam on JWST, so a set of faint but well-measured standards must be identified and measured before commissioning in 2018.*

Flux calibration is usually done with A0, G2 V or white dwarf stars. The A0 and white dwarf stars benefit from smoother spectra over many wavelengths, but can have infrared excess due to debris disks. Even Vega, which was once the standard of absolute calibration has infrared emission from debris (Aumann et al., 1984), which must be accounted for when comparing to other A0 V stars and photometric models. Recently, Absil et al. (2013) found that disks of hot dust are common for A0 V stars and contribute significant but unpredictable amounts of flux at 2 μm. White dwarfs may also contain dust and have fewer mid infrared measurements. We therefore adopt the Solar Analog method (Johnson, 1965), by finding a set of nearly Solar-analog stars in a cluster and indirectly calibrating their mid-infrared fluxes using a Solar model (which fits the Sun's spectral energy distribution to within a few percent or better) and measurements at other wavelengths. Rieke et al. (2008) demonstrate that the solar analog method can be used to calibrate 2MASS, IRAC, and MIPS photometry with an uncertainty of 2%. The photometric standard P330E/GSC 02581-02323 will be used for calibrating the JWST spectrographs because it has a near-Solar SED (Bohlin et al., 2014) and multi-wavelength calibration. P300E is too bright at K=11.4, however, to calibrate the NIRCam imager (Rieke et al., 2005)[1] in full frame mode because the saturation limit is $K \approx$15 for the wider filters. It is possible to use a sub-array mode to decrease the readout time and observe P330E, but it is essential to independently check the full-frame mode for systematic offsets and uncertainties in subarray timing.

To calibrate the NIRCam and MIRI[2] imagers, it is necessary to find a cluster that maximizes the number of observable Sun-like stars within NIRCam's $2.2' \times 4.4'$ field of view and MIRI's $74'' \times 113''$ FOV. For these reasons, a distant ($\gtrsim$ 1 kpc) star cluster is required. The metallicity of the cluster should be close to solar for direct use of a Solar SED and finally it needs to be the right age (0.3 Gyr $\lesssim$ Age $\lesssim$ 8 Gyr) so that Solar-type stars are on the main sequence. A final constraint is that the extinction towards the cluster should be minimal to ensure that the extinction correction uncertainties do not contribute significantly to the flux calibration. The measured extinction for NGC 2420, NGC 2506 and NGC 6811 is modest at E(B-V) = 0.04, 0.06 and 0.05 respectively despite the distances of 1.2 kpc to 3.5 kpc.

While photometric colors (such as B-V) can identify Sun-like stars within the cluster, spectral classification will dramatically improve the identification of stars with a near-Solar spectral energy distribution. The spectral classification of O through K-type stars requires "essential" spectral lines over the 3918 - 4500 Å bandpass (Gray & Corbally, 2014). Resolutions of around 2 Å are generally used for spectral typing. This leads us to choose Hectospec's 600 gpm grating at a central wavelength of 4800 Å covering ∼3540 Å to ∼ 6040 Å with a FWHM of 1.9 to 2.2Å. Furthermore, we need photometric data in the J, H and K infrared

[1] http://www.stsci.edu/jwst/instruments/nircam

[2] http://www.stsci.edu/jwst/instruments/miri, http://ircamera.as.arizona.edu/MIRI/index.htm

bands because the G2V stars in these clusters are too faint have accurate 2MASS photometry.

The NIRCam team has investigated a variety of clusters to use for JWST's absolute calibration and identified NGC 2420 as the best balance of brightness, compactness, age and metallicity. We successfully observed NGC 2420 in semester 2016B in the high resolution grating and were able to classify all the stars observed with `mkclass` (Gray & Corbally, 2014), as seen in Figure 1. One pointing with NIRCam will contain 4 suitable G2 V stars with many other sources for cross-calibration.

However, due to uncertainties in the launch date, a suitable calibration cluster must be available at other times of the year. The clusters NGC 2506 and NGC 6811 will complement NGC 2420 to ensure calibration is possible if there are schedule changes (see Figure 3) and provide independent checks at other metallicities, extinctions and ages. These three clusters have 2MASS (for giant stars), WISE and IRAC photometry to anchor the G2V spectral model and interpolate that model to the NIRCam and MIRI (shorter wavelength) photometric filters.

Ancillary Science Although the goal of this program is to support the absolute calibration of JWST, the data we propose to obtain has independent scientific value. Stellar open clusters provide the perfect astrophysical laboratory to test models of stellar evolution. The members of such systems share many important properties, namely: age, metallicity, physical distance, and the levels of interstellar extinction. Therefore, their observable astrophysical properties depend solely on their initial masses, which can be traced to their measured spectral types.

While young ($\lesssim$ 200 Myr) open clusters are relatively abundant, older ones are more difficult to identify, mainly due to the fact that the members disperse given enough time. Only initially dense open clusters remain at ages of a few Gyr. Furthermore, older clusters tend to be located further away, obscured by interstellar extinction. However, these are the most interesting ones for testing stellar evolution models, as solar-type stars start evolving off the main sequence (MS) at later times, while early-types have long evolved to their final white dwarf states. The lowest mass stars, on the other hand, are now on the MS.

The clusters in our survey will provide a great testing ground for stellar evolution models. The clusters are old ($\sim$ 2 Gyr) and yet allow for good identification of member sources. Although they are located relatively far away, their interstellar extinction is significantly lower (E(B-V) $<$ 0.06) than expected for sources located at few kpc. The spectral classifications and parameters (e.q. radius, luminosity, metallicity) will allow us to refine memberships and further aid the tests of models.

The issues with current evolution models is emphasized with Figure 14 from Gáspár et al. (2009) (here Figure 2), where theoretical Padova isochrones do not fit to the lower-mass sources in Praesepe. In this cluster, membership is determined to great accuracy with proper motion measurements since the cluster is only at 180 pc.

References

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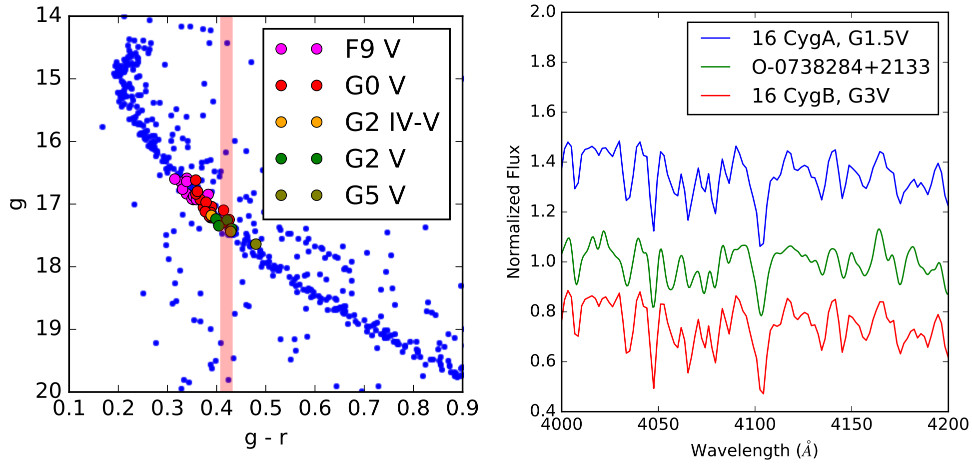

Figure 1: *Left* NGC 2420's color-magnitude diagram (with data from Pan-STARRS) showing the targets observed by Hectospec. We will obtain similar levels of classification and for the additional clusters in our program - NGC 2506 and NGC 6811. Solar g-r is marked as a vertical red band. *Right*. Hectospec data of a solar-like star from the 2016 data shown between two template spectra of spectral type G1.5 V and G3.5V, near the temperature diagnostic 4046 $\mathring{A}$ Fe I and Hδ (4102 $\mathring{A}$) lines.

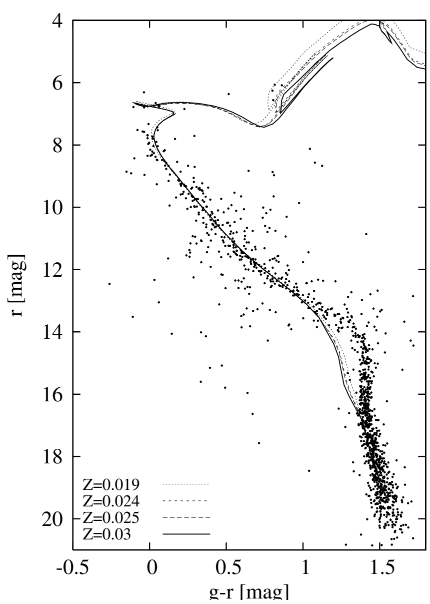

Figure 2: The Color Magnitude diagram for the Praesepe cluster (Gáspár et al., 2009) shows that for cooler stars, the theoretical Padova isochrones deviate from the measured magnitudes. Additional clusters at ($\sim$Gyr ages) will help improve the stellar evolution models.

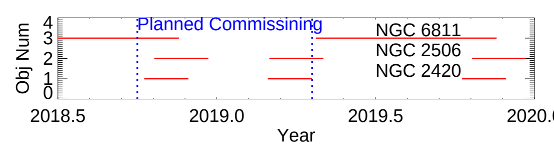

Figure 3: Visibilities of the 3 calibration clusters as compared to the expected commissioning period of JWST. We will need additional sources in NGC 6811 to expand the number of target's within JWST's field of regard at any given time.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (**up to one page**)*

Goals The main goal of our observations is to find spectral types of the Sun-like stars within NGC 2506 and NGC 6811 to find the subset of stars to use as absolute calibrators of the NIRCam and MIRI instruments. These calibrators are essential because the standard stars used by Hubble Space Telescope and other observatories will saturate the very sensitive JWST imagers. We will use the Solar Analog method (Johnson, 1965; Rieke et al., 2008), which takes a Solar model and observations from the optical to infrared to calibrate the JWST filters. In order to successfully identify Solar-type stars within these clusters, we will use moderate resolution spectra (near $2\AA$). Spectra of stars within the cluster can provide superior measurements of effective temperature over photometric colors (such as B-V) due to their sensitivity to subtle spectral features and the reduced dependence on extinction. These clusters, which need to be distant in order to not saturate NIRCam and provide a high enough density of solar analogs with the JWST Field of View, tend to have non-negligible extinction in the optical so the spectral method is preferable to photometric colors.

Spectroscopic SNR Gray & Corbally (2009) suggest that spectral resolving powers of 1-4Å and signal to noise ratios in excess of 100 are required for effective stellar classification. The solar-like NGC 2420 stars vary from V=15.6 to V=17.2. We confirmed the estimates from the HectoSpec ETC from our 2016A proposal that a SNR of over 100 can be obtained for all G2V stars ($g_{\rm AB}$=17.5) with 2 hours of integration of NGC 2420. NGC 2506 is 12% farther, so requires an additional 25% of integration ($\sim$30 minutes) to achieve the same signal to noise for the comparatively small background and read noise. We include 0.5 hours for overheads for a total of 3 hours. NGC 6811, at 1.2 kpc, will only require 0.5 hours to achieve the same signal to noise, but we allow for 0.5 hr for overheads to give a total of 1 hour.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

(1a) Previous UAO nights already used for this project: ~7 hours of queue observation on MMT with Hectospec on NGC 2420 (2 partial nights) and NGC 2506 (1 partial night). The 600 gpm grating broke in the observing run so we were only able to observe with the 270 gpm grating (4.5 - 5.2 Å) resolution element. We will be re-observing with a fixed 600 gpm grating on NGC 2506 and obtain two fiber configuration for NGC 6811. We successfully acquired WFCAM data with UKIRT in semester 2016 B.

(1b) Nights required for 2017B semester: 0.5 nights on the MMT with Hectospec

Summary of Observations

Object	MMT Time Needed (hr)
NGC 2506	3.0
NGC 6811	1.0

Table 1: Time required to obtain spectroscopy using Hectospec on the MMT with a signal to noise greater than 100.

(1c) Nights required to complete project: For spectroscopy, we may need up to 1 additional night of data if follow-up of G2V stars is needed.

(2) Non-UAO Telescopes: This project has no coordinated observations with other facilities, other than using archival 2MASS, Spitzer, HST and WISE data for the absolute calibrations.

(3) Collaborations with Other Telescopes: These pre-cursor spectra are tied directly to the calibration of the James Webb Space Telescope, which has team leads M. Rieke and G. Rieke for the NIRCam and MIRI instruments. All of the interesting new frontier science with JWST from studying the very first galaxies to star and planet formation to Solar System science will make use of accurate flux calibration. JWST will not include any flux calibration lamps, so it will rely entirely on astrophysical calibrators, which will be chosen based on the requested observations and other information.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

⋆ 2016B: "Identifying Flux Calibrators for JWST". 98% of WFCAM UKIRT data successfully observed and photometry completed. Hectospec/MMT data was completed for NGC 2420 but NGC 6811 was not observed and NGC 2506 was observed at lower resolution due to breakage of the 600 gpm grating. All NGC 2420 data are processed. See Figure 1 *(Left)* for preliminary classification of NGC 2420 on the color-magnitude diagram.

⋆ 2016A: MMT 2 hr of Hectospec observations. The spectra are of high quality and verify the assumptions made in planning the observations for semester 2016A.

2016A: "The Fate of the Disintegrating Planet KIC 12557548b": Successful observations for 5 nights on the 61-inch with the Mont4K (June and July 2016) measuring disintegration activity. The light curves have been preliminarily extracted and show that the transit depths are consistent with the Kepler observatory measurements and do not fade over time. Paper preparation is ongoing.

Other Information *Provide any additional program-related information including, for example, relation of current program to externally funded research, to the development of expanded capabilities for UA telescopes, or to individual timescales (e.g. PI is finishing postdoc appointment and this request would complete program). (**up to one page**)*

There are several TBS nights available in the Summer of 2017. We will apply for these TBS nights in addition to this proposal to observe NGC 6811 (RA=8hr). Should the TBS time be awarded and successful in semester 2017A, we will reduce the total time needed in this proposal by 1 hour.

This is a calibration proposal to support JWST. M. Rieke and G. Rieke are PIs of the NIRCam and MIRI instruments and the rest of the authors are instrument team members in charge of calibrating the instruments during JWST's commissioning phase. The calibration plan put forth by the Space Telescope Science Institute has good calibrators for the spectroscopic modes of instruments but notes that new targets are needed for the full frame NIRCam and MIRI data to avoid saturation. The "Next Steps" include obtaining spectra of calibrator stars and expanding the current sample of calibrators for full frame NIRCam and MIRI data in the broad wavelength filters. Our observations of NGC 2420, NGC 2506 and NGC 6811 will fill this gap in the calibration plan. The requested observations, if successful, should complete this program.