Infrared calibration stars as millimeter standards

Martin Cohen, RadioAstronomy Laboratory,UC Berkeley
and
Jeff Mangum, NRAO

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Abstract

Our goal is to establish new mm standards by extrapolating the photospheric radiation of K-M giants that are already established as mid-infrared (MIR) absolute calibration stars. Their mm fluxes cannot be below the Rayleigh-Jeans (RJ) extrapolations. If one of these cool giants is observed to have the expected RJ at 3mm then it becomes a mm standard. If a cool giant's 3mm flux significantly exceeds prediction then it becomes a science target, potentially with a sub-mm or mm chromosphere. Only mm observations can determine the nature of these stars. We wish to begin the process of testing such stars for suitability as mm calibrators by observing 16 stars. Each will be compared with the primary calibrators, Uranus and Neptune. We have an all-sky network of over 615 of these MIR absolute standards. Each is represented by a complete, continuous spectrum between 1 and 35 microns. The procedure for creating these spectra has been absolutely validated by the MSX mission (Midcourse Space eXperiment). MSX made direct, on-orbit comparisons of the fluxes of the bright archetypes of these stars with absolutely characterized "emission reference spheres". MSX validated the brightness of tens of fainter cool giants selected from the 615. Every MIR calibrator also has a known radiometric diameter so that a requirement by ALMA for standards with diameters smaller than some specified size can be applied. The entire network of K-M giants has also recently been observed photometrically by AKARI's Far Infrared Surveyor (FIS) from 60-160 μm. We plan to reject otherwise potential candidates if they exceed the RJ flux within the FIS wavelength range

Scientific Justification

ALMA is in the transition from a construction project to the phase of operations and early science. It is timely to begin the preparations for astronomical calibration sources. ALMA is so powerful a facility that a 1 sec integration with the fifty 12m antennas at 90 GHz will achieve an rms noise of 0.3mJy (ALMA online sensitivity calculator). Achieving good detections of faint continuum flux sources in a few minutes is not an issue but the availability of a consistent set of amplitude calibrators at mm wavelengths has remained problematic. There is an ongoing need (Sandell 2003, ESA, SP.481, 439S) for far-infrared (FIR), submm, and mm flux calibrators for ground-based and space-based use, and an immediate need for more mm wave calibrators with higher accuracy. ALMA requires 1% relative accuracy at mm wavelengths (frequencies below 370 GHz), and 3% at sub-mm wavelengths (frequencies above 370 GHz). The ALMA specification for absolute amplitude calibration, which is the relevant specification for these measurements, is 5% at all frequencies.In addition, ALMA specifies amplitude calibrators with known angular diameters below 3.4 arcsec (90 GHz, compact array) and below 5 milli-arcsec (660 GHz, 16km configuration) (e.g.,Nyman 2009, RMxAC, 35, 265). All these specifications are highly demanding.

This proposal is a proof of concept to explore the extent to which one can build upon cool giants that are already absolutely calibrated in the mid-infrared (MIR) and thereby link MIR and mm calibrations. Our goal is to identify normal stars that can serve as flux calibrators at mm wavelengths by extrapolating the photospheres of K and M giants to submm and mm wavelengths.

For twenty years my colleagues and I have carried out a major effort to rationalize and unify absolute calibration from optical to infrared (IR) by providing absolute spectra, complete from $1-35\,\mu$m, of K and M giants (e.g., Cohen et al. (1999,AJ, 117, 1864). Currently these constitute an all-sky network of 615 stars offering about one star per 70deg^2. These calibrators are widely used and have supported many IR satellites, instruments on large ground-based telescopes, airborne and space-based sensors. Stellar spectra for all the 422 stars of the published network (version 2.1) are available to the community on the Web [1]

Price et al. (2004, AJ, 128, 889), of US Air Force Phillips Laboratory, published their 3-year independent appraisal of our calibrators using the Midcourse Space eXperiment (MSX) precision radiometric measurements. These validated our radiometric basis from $8-21\mu$m at the 1.1% absolute level, within our quoted 1σ errors.

Every star in the network has a computed angular diameter. The radiometric diameters of 374 of the first network of 422 published stars have been adopted for use as long-baseline stellar interferometric calibrators (Bordé et al. 2002, A&A 393, 183). Consequently, the network of cool giants has been peer-reviewed, carries an independent absolute validation from the USAF, and has been accepted by a community quite different from that for which it was originally intended. What are its credentials to furnish longer wavelength calibrators? Several bright cool giants were used in the absolute calibration of the European Space Agency's Infrared Space Observatory (ISO) for its long wavelength photometer. These stars were extrapolated to 300μm on the basis of purely radiative photospheres and merged well with planet and asteroid flux calibrators (Schulz et al. et al. 2002, A&A, 381, 1110). The same role was recently fulfilled by the same giants for the calibration of Japan's FIR all-sky surveyor (FIS: 65-160μm) (Shirahata et al. 2009, PASJ, 61, 737).

Cohen et al. (2005, AJ, 129, 2836) imaged two normal, non-coronal, MIR-bright, K-giant, standards: α Tau and α Boo, in the 1.4 and 2.8 mm continuum using BIMA. If a star radiates as predicted for a photosphere then its flux can be used as a fiducial at that wavelength. If the flux rises above the expected photospheric level, regardless of the physics, this renders it invalid for amplitude calibration. Fig.1 illustrates the situation for α Tau whose flux rises above the RJ extrapolation beyond 200 μm. The combination of observations from FIR and mm regimes, together with theoretical modeling of both radiative equilibrium model atmospheres (Carbon et al.1982, ApJS, 49,207) and a NLTE chromospheric model (McMurry 1999, MNRAS, 302, 37), indicates that the RJ approximation fails in this star due to chromospheric emission. α Boo is likewise not useful as a sub/mm flux calibrator.

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[1] http://iopscience.iop.org/1538-3881/117/4/1864/fulltext;via the HTML Table 4. Spectra of the brightest stars can be found through §8 in this same paper by links to the first 14 papers in the series entitled "Spectral Irradiance Calibration in the Infrared". Ver. 4.0 of the network appeared as Walker, R. G.,& Cohen, M. (2002)," Walker-Cohen Atlas of Calibrated Spectra: Explanatory Supplement to Release 4.0"; (Contractor Report to Air Force Res. Lab., contract F19628-98-C-0047). There are roughly 200 stars in ver. 4.0 that were not published in ver. 2.1 and these are currently distributed by M. Cohen on request.

Despite the mm results for α Tau and α Boo, not every cool giant has a mm-chromosphere. In May 2010 we undertook an initial test of our concept by observing the MIR southern standard, γ Cru, with the ATCA equipped with the Compact Array Broadband BackEnd. FIR data show this star to be a RJ emitter from 65 to 160μm. Its predicted RJ flux at 94 GHz is 8.6mJy and it was strongly detected at 8.0$\pm$0.6mJy.

One can eliminate some stars from consideration if their FIR fluxes already exceed the RJ level. Lacking such data of good quality there is no *a priori* way to determine whether a cool giant has only a radiative equilibrium photosphere in the mm regime without observing it. Modeling shows that, when mm wave chromospheric emission is present in cool giants, this rapidly overwhelms the photospheric radiation with increasing wavelength. If a 3-mm measurement indicates photospheric levels in a star then it is highly unlikely that the flux would not also be predictable at 1mm and in the sub-mm, where stellar photospheres are much brighter. A 3mm standard becomes a gratuitous 1mm and sub-mm candidate standard even without observing at those high frequencies.

Sub-mm measurements from the ground are still difficult. Millimeter observations are more readily made and we plan to begin by observing 16 cool giants at 3mm. Their anticipated 90-GHz RJ flux densities probe flux levels an order of magnitude below that of α Tau. This sample takes the mm calibration effort to a new level.

Technical Justification

The discovery of the bright RJ radiator, γ Cru, is highly encouraging and it is now appropriate to turn to ALMA itself. At 3mm, ALMA's 8 or 10-antenna configurations offer many more baselines than are available to the ATCA, and ALMA's site has vastly better transmission than any other mm observing site. Therefore, we have predicted the RJ flux densities for ALMA at 90 GHz (the most favorable wavelength in terms of receiver performance and terrestrial transmission) and have selected the first 16 cool giants, observable with the current (October, 2010) ALMA configuration, from our flux-sorted list. These stars span the range of 3mm photospheric flux levels from 8.0 to 0.72mJy. Our targets are intended as candidate standards so ideally we must achieve a S/N of at least 10 in this first examination, and preferably well above 20 for any eventual standards. We also need to gain experience from faint stars because LogN-LogS dictates that our network contains many faint giants. The stellar fluxes at any wavelength cannot be fainter than RJ predictions so we can reliably assess the required observing time. Consequently we have included γ Cru with a target S/N of 40, which the ALMA Sensitivity Calculator indicates requires a total integration time of only 68 sec (with 8 or 10 antennas; at 90GHz; 16 GHz bandwidth; ETC chooses the water vapor). We seek 20 σ measurements of the next two fainter stars closest to the flux density of γ Cru, and 10 σ measurements for the 13 remaining target stars. We offer two tables - Table 1, for the October 2010 configuration with 8 antennas and a second, Table 2, based on the anticipation of 10 antennas during Winter 2010. Each table presents the names, ICRS coordinates, desired S/N, corresponding flux sensitivity, and the on-source integration time to yield the each desired S/N. Total integration time for all 16 stars is 6964sec (116 min) for 8 antennas and 4400sec (73 min) for 10 antennas. The interleaved observations of Uranus and Neptune are in addition to the stellar observations in each table and add 40sec of integration per stellar target. Slews between target stars and planetary calibrators are additional overheads.

If other target stars than γ Cru are found to be RJ photospheric radiators the next phase would require observations of each candidate calibrator (including γ Cru) over a period of time long enough to check for variability, and the same repeated observations would greatly enhance the S/N of these potential standards, in the absence of mm flux variations. In this context, only ALMA itself could be capable of making the decision to elevate a candidate stellar calibrator to a fiducial source.

Special Requirements

We wish to establish new mm amplitude calibrators. We plan to compare these potential standards with the primary mm planetary calibrators, Uranus and Neptune. We would like to observe these two planets both before and after each target star, and three times, evenly spaced, within each designated stellar integration period. The pattern would be as follows, if one began the observing with γ Cru using 8 antennas:

...previous STAR+planets sequence of observations
– Uranus 10sec - Neptune 10sec
- STAR - 37sec
Uranus 10sec - Neptune 10sec
- STAR 37sec
Uranus 10sec - Neptune 10sec
- STAR 37sec
Uranus 10sec - Neptune 10sec – NEXT STAR+planets sequence of observations.

Similarly for the faintest star, HD12929 using 8 antennas:
...previous STAR+planets sequence of observations
– Uranus 10sec - Neptune 10sec
- STAR - 286sec
Uranus 10sec - Neptune 10sec
- STAR 286sec
Uranus 10sec - Neptune 10sec
- STAR 286sec
Uranus 10sec - Neptune 10sec – NEXT STAR+planets sequence of observations

In this scheme, once the observations have begun, the closing calibration observations of one star are also used for the opening calibration observations of the succeeding star.

References

Bordé et al. 2002, A&A 393, 183
Carbon, D. F., et al., 1982, ApJS, 49, 207
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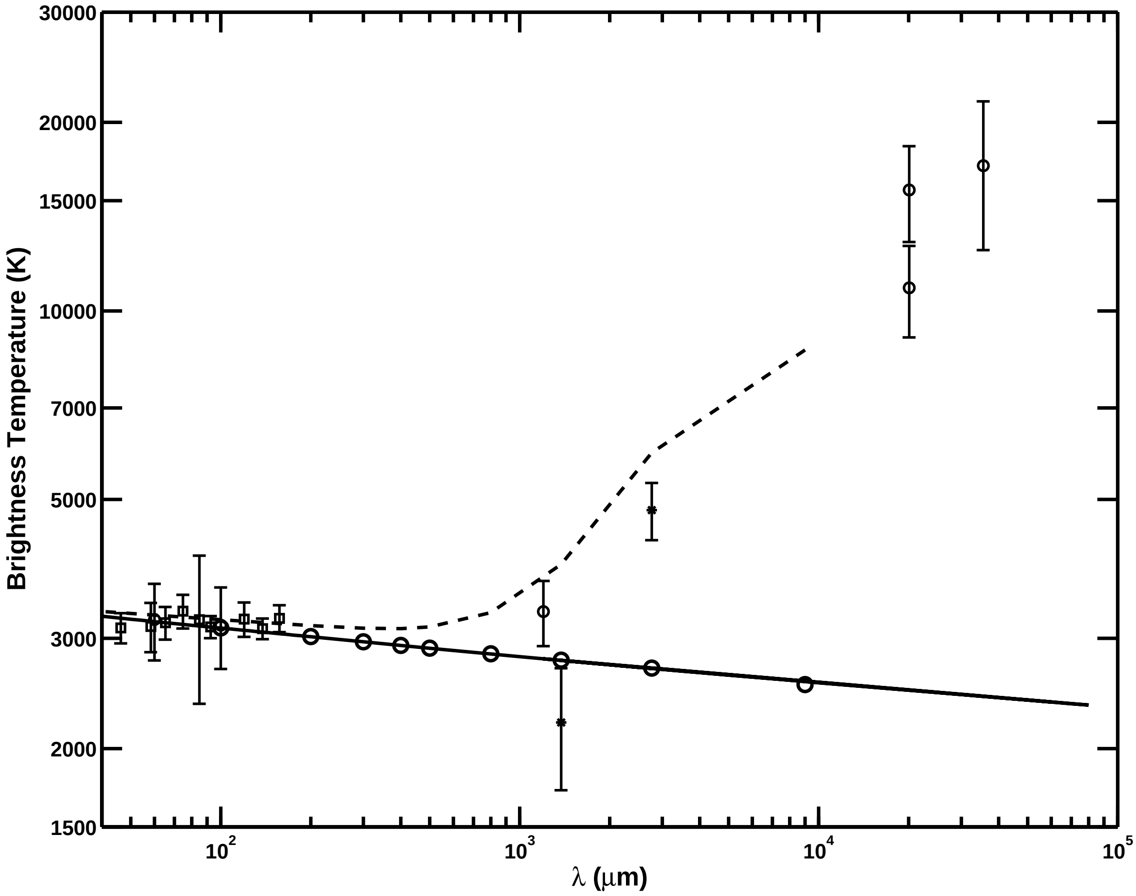

Fig. 1.— Departure of the brightness temperature of α Tau from RJ. Predictions of the McMurry NLTE chromospheric model (dashed); of two independent LTE computations; (circles & solid line); mm observations (dot or small circle near center with errors); cm literature (circles to the top-right with errors); (some are only upper limits.

Table 1: Attributes of the 16 stars selected for 90-GHz observations using 8 antennas, the current October 2010 configuration.

Name	ICRS RA	ICRS DEC	S/N	Flux(mJy)	time(sec)
γ Cru	12:31:09.959	-57:06:47.562	40	0.201	110
HD44478	06:22:57.627	+22:30:48.909	20	0.125	288
HD71129	08:22:30.836	-59:30:34.139	20	0.100	445
HD167618	18:17:37.635	-36:45:42.070	10	0.178	139
HD106849	12:17:34.277	-67:57:38.649	10	0.168	159
HD133216	15:04:04.216	-25:16:55.073	10	0.163	165
HD25025	03:58:01.766	-13:30:30.655	10	0.104	406
HD24512	03:47:14.341	-74:14:20.264	10	0.101	445
HD187076	19:47:23.262	+18:32:03.500	10	0.098	466
HD213080	22:29:45.433	-43:44:57.205	10	0.097	468
HD145366	16:20:20.806	-78:41:44.682	10	0.089	579
HD189763	20:02:39.481	-27:42:35.441	10	0.088	566
HD11695	01:53:38.742	-46:18:09.607	10	0.081	672
HD216386	22:52:36.876	-07:34:46.557	10	0.077	741
HD89484	10:19:58.427	+19:50:28.530	10	0.075	796
HD12929	02:07:10.407	+23:27:44.723	10	0.072	859

Table 2: Attributes of the 16 stars selected for 90-GHz observations using 10 antennas, anticipated for winter 2010.

Name	ICRS RA	ICRS DEC	S/N	Flux(mJy)	time(sec)
γ Cru	12:31:09.959	-57:06:47.562	40	0.201	68
HD44478	06:22:57.627	+22:30:48.909	20	0.125	179
HD71129	08:22:30.836	-59:30:34.139	20	0.100	277
HD167618	18:17:37.635	-36:45:42.070	10	0.178	86
HD106849	12:17:34.277	-67:57:38.649	10	0.168	99
HD133216	15:04:04.216	-25:16:55.073	10	0.163	103
HD25025	03:58:01.766	-13:30:30.655	10	0.104	252
HD24512	03:47:14.341	-74:14:20.264	10	0.101	277
HD187076	19:47:23.262	+18:32:03.500	10	0.098	290
HD213080	22:29:45.433	-43:44:57.205	10	0.097	291
HD145366	16:20:20.806	-78:41:44.682	10	0.089	360
HD189763	20:02:39.481	-27:42:35.441	10	0.088	352
HD11695	01:53:38.742	-46:18:09.607	10	0.081	418
HD216386	22:52:36.876	-07:34:46.557	10	0.077	461
HD89484	10:19:58.427	+19:50:28.530	10	0.075	495
HD12929	02:07:10.407	+23:27:44.723	10	0.072	540