Mars as a Far-IR to Submm Calibrator

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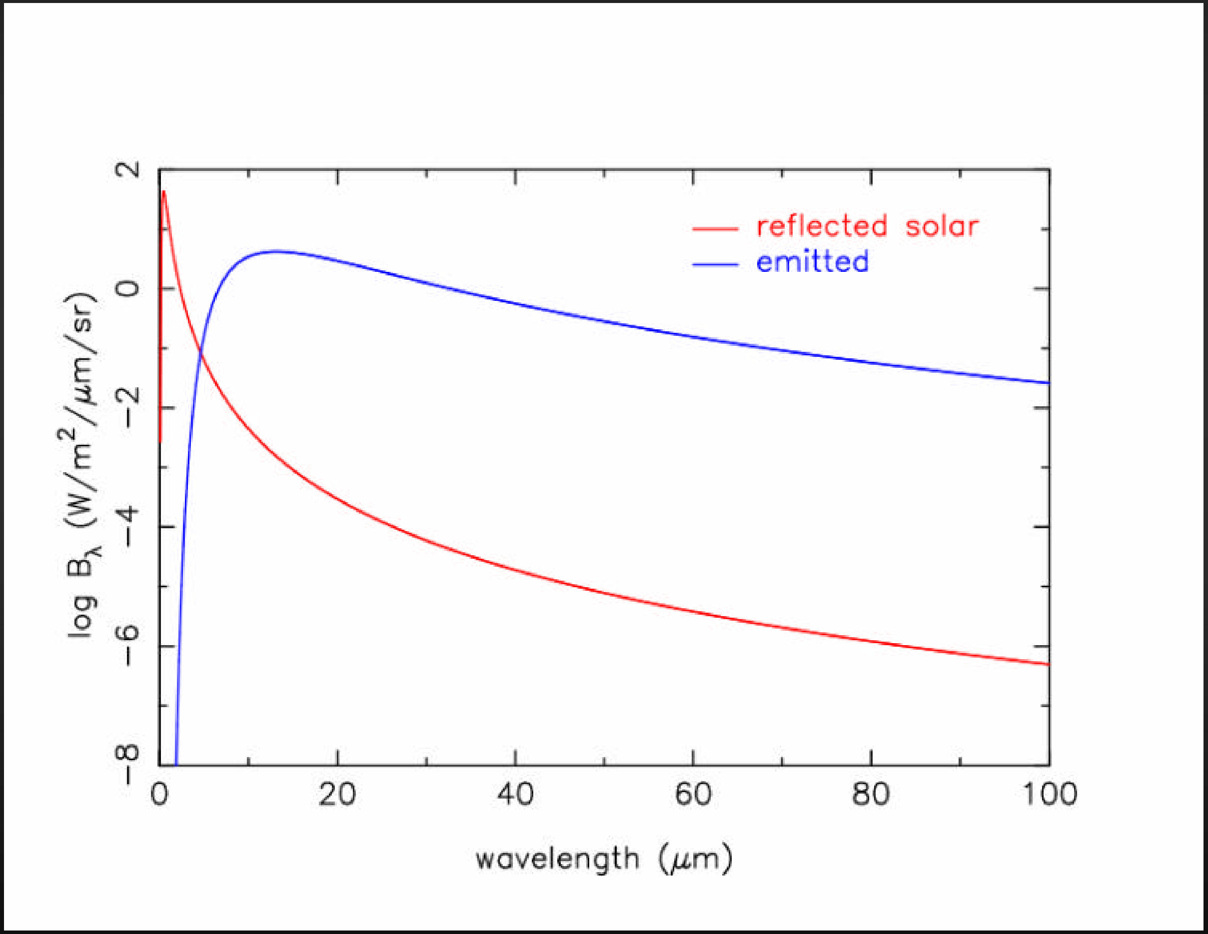
Introduction

In order to use Mars as a primary flux density scale calibrator for Herschel observations, in addition to the instrumental constraints we must either:

- have very well calibrated previous (or concurrent or even future) observations in the wavelengths of interest, or
- have observations which can constrain a thermophysical model for those wavelengths, or
- have some combination of the two.

For Mars, we have some of all of these, but the previous observations are probably not accurate enough for our purposes - I will describe some of them later though…

Mars IR Spectrum



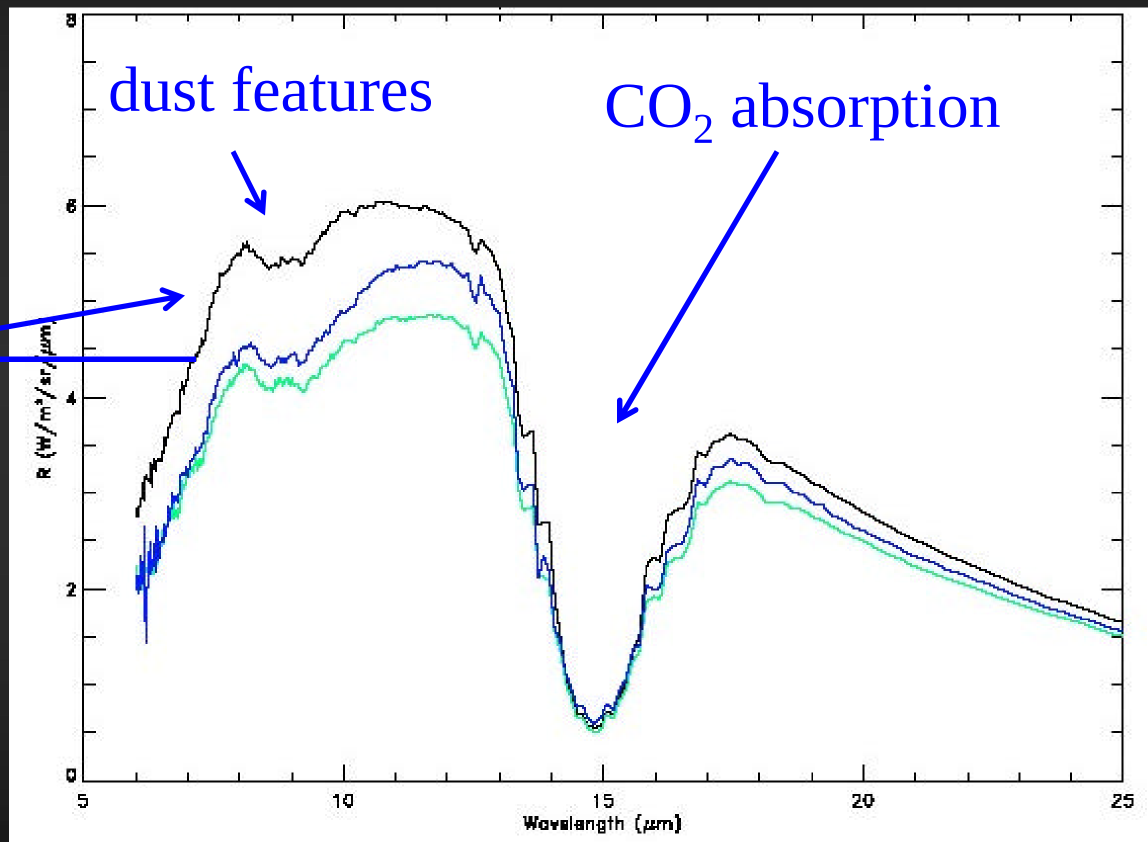
Mars IR Spectrum

A true emission spectrum shows the effects of five main mechanisms:

- emission from the surface + subsurface, including mineralogical spectral features, and from both the seasonal and residual ice caps;
- absorption/scattering of solar insolation, cooling the surface;
- absorption of surface + subsurface emission by the atmospheric dust (lowers the entire spectrum);
- absorption from atmospheric dust - spectral features;
- absorption from atmospheric molecules - notably CO_2 and H_2O, but also CO and potentially others.

Mars IR Spectrum

dust opacity raises or lowers entire spectrum



as observed by TES - Christensen et al.

Mars IR Spectrum

But for the wavelengths of Herschel (> 60 μm), the effect of the atmospheric dust on the emission is very small in most circumstances (typical dust size is 2 μm and even in global storms only gets as large as 10 μm which would only really be a problem for PACS), as is the effect of the atmospheric CO_2. However, the effect of the atmospheric water vapor is still quite strong; this was seen clearly in ISO LWS observations in the range 50-200 μm, as well as SWAS and ODIN observations of the 557 GHz H_2O transition. CO is also a potential problem. There are probably others. In addition, the absorption of the solar insolation which cools the surface must be modelled properly.

I assume that Paul Hartogh will cover this much more completely in his talk (and note also Glenn Orton's and Ted Bergin's presentations), so will note it as a potential problem, but leave the conclusion for discussion, and assume that the emission is all surface + subsurface from this point on.

Past Far-IR/Submm Observations and Early Models

- Neugebauer et al. 1971 - presented Mariner 6 & 7 data (8-25 μm), along with a model (or at least some conclusions about the thermophysical parameters of interest);
- ground-based work was being done at the same time (McCord & Westphal 1971), but not absolutely calibrated - merely as a means to essentially do martian geology;
- Armstrong, Harper, & Low (1972) observed Mars in 6 broad-band filters from 30-300 μm, but Mars was assumed as the standard (assuming 235 K blackbody) to calibrate the others - only result is a "consistency check" on blackbody spectrum - note that this is a common theme in Far-IR/submm observations including Mars - it is often taken as the calibrator. See, e.g., Hudson et al. 1974; Loewenstein et al. 1977; Stier et al. 1978; Cunningham et al. 1981; etc…
- Wright (1976) takes the Neugebauer results and refines the model, accounting explicitly for geometry. This is the first reasonable thermophysical model for these wavelengths (but, interestingly, does not include the polar caps at all).
- Ward, Gull, & Harwit (1977) observe Mars from 45-115 μm from the LJO, giving a good spectrum which matches a 235 K blackbody, but the absolute calibration is questionable;

Past Far-IR/Submm Observations and Early Models, part 2

- Simpson et al. (1981) observe Mars from 30-100 μm from the KAO, and construct what I would call the first *real* thermophysical model for this wavelength range - including effects of the atmospheric dust and CO_2 and the polar ice caps. For some reason this model does not seem to be as well accepted as the Wright model, despite clearly being superior in the physical representation;
- Rudy et al. (1987) (see also Muhleman & Berge 1991) observe Mars at 2 and 6 cm with the VLA and construct a complete thermophysical model including all relevant effects except subsurface scattering and surface roughness (and ignoring atmosphere, given the wavelengths);
- Goldin et al. (1997) observe Mars from 500 μm to 2 mm from a balloon-borne platform, and compare ratios obtained with the other planets and also compare the Wright and Rudy et al. models (getting good agreement, perhaps surprisingly!);
- Sidher et al. (2000) use ISO to observe Mars from 50-200 μm. They use the Rudy et al. model to describe the data and detect longitudinal variations (tied to surface features). See also Burgdorf et al. (2000) and Lellouch et al. (2000).

Thermophysical Models

The models are based on observations both by spacecraft and earth-based (sometimes earth-orbiting spacecraft or balloons) telescopes, and have been driven from two directions:

- the model of Wright, driven by near-IR observations;
- the model of Rudy et al., driven by cm-wave observations.

The model of Simpson et al. is between, but wasn't intended to represent observations at wavelengths longer than 100 μm anyway.

So these models have been pushed to where they meet in the submm, far beyond what they were originally intended to represent.

Let's see if this is even remotely reasonable by examining the theory.

Theory

the measured flux density in the beam is:

$$S_n = \frac{2k}{l^2}\frac{1}{D^2}\int_{beam} A(x,y)\, T_B^{pol}(x,y)\, dx\, dy$$

and the brightness temperature is:

$$T_B^{pol} = \left(1 - R^{pol}\right)\int_0^{\infty} k(z)\sec q_i\, T(z)\, e^{-\int_0^{z} k(z)\sec q_i\, dz}\, dz$$

Surface Reflectivity

The reflectivity is related to the surface bulk dielectric:

$$R^{pol} = | r_{pol} |^2$$

$$r_s = \frac{\cos q_i - \sqrt{e - \sin^2 q_i}}{\cos q_i + \sqrt{e - \sin^2 q_i}} \qquad r_p = \frac{-e \cos q_i + \sqrt{e - \sin^2 q_i}}{e \cos q_i + \sqrt{e - \sin^2 q_i}}$$

surface roughness complicates this.

Absorption Coefficient

the absorption coefficient can be written:

$$k = \frac{2pn}{c}\sqrt{e}\ \tan\Delta$$

note that this ignores scattering, and that the dielectric is a function of density:

$$e = e_0\left(1 - \frac{3P\left(e_0 - 1\right)}{P\left(e_0 - 1\right) + 2e_0 + 1}\right)$$

for porosity $P = 1 - r / r_0$

Theory

The subsurface temperatures as a function of depth are found by solving the 1-D thermal diffusion equation:

$$\frac{\partial}{\partial z}\left(K(z,T)\frac{\partial T}{\partial z} \right) = r(z)\, c_p(z,T)\frac{\partial T}{\partial t}$$

where *K(z,T)* is the thermal conductivity as a function of depth and temperature, and *r(z)* and $c_p(z,T)$ are the density and heat capacity of the material in the subsurface.

Theory

In order to solve the diffusion equation, two boundary conditions are needed:

$$\left.\frac{\partial T}{\partial z}\right|_d = -\frac{J_0}{K_d}$$

$$\left(\frac{L_0}{4p\, D^2}\right)(1-A_b)\sin^+ q_i - J_0 = e_{IR}\, s_B\, T_s^4 - K_s \left.\frac{\partial T}{\partial z}\right|_s$$

Theory

the thermal conductivity can be written:

$$K(z,T) = A + BT^3(z)$$

and the heat capacity is relatively well described by:

$$c_p(z,T) = T(z) / 2000$$

Theory

the thermal quantities are often combined into a single “thermal inertia”:

$$I = \sqrt{K\,r\;c_p}$$

which is a measure of how well the subsurface conducts and stores heat energy away from the surface during the day and returns that heat energy to the surface through the night. Rocks have high thermal inertia, dust and sand have low.

Two Important Length Scales

two important length scales result from the solution of simplified versions of this:

- the “thermal absorption length”:

$$\ell_T = \sqrt{\frac{w\, r\, c_p}{2k}}$$

- the “radio absorption length”:

$$\ell_R = \frac{l}{2p\sqrt{e}\tan\Delta}$$

Two Important Length Scales

the thermal skin depth is of order 1-3 cm for Mars.

the radio absorption length is of order 10-20 λ

this means that at all Herschel wavelengths, we are very sensitive to the diurnal thermal wave, and in fact do not probe beneath the thermal skin layer at all.

Summary of Parameters

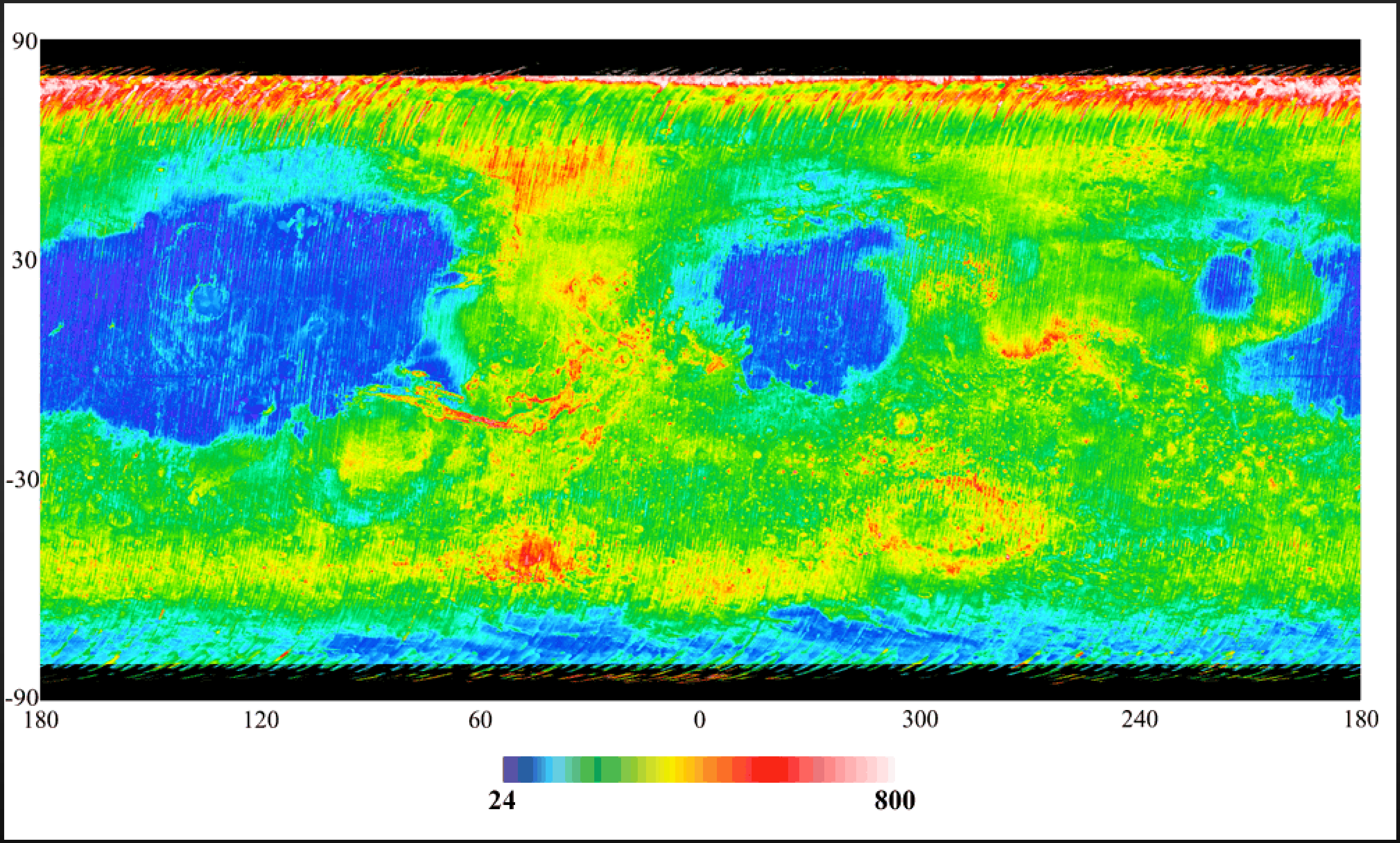
So, the list of necessary parameters for the model are:

- R^{pol} - the surface Fresnel reflectivity (and hence ε)
- $k(z)$ - the subsurface absorption coefficient
- $K(x,T)$ - the subsurface thermal conductivity
- $r(z)$ - the subsurface density
- $c_p(z,T)$ - the subsurface specific heat
- J_0 - the heat flow at depth
- L_o - the solar luminosity
- A_B - the surface Bond albedo (visible)
- e_{IR} - the surface IR emissivity
- rms surface roughness
- scattering properties (if included - complicates model significantly)

Variable Parameters - Albedo

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Variable Parameters - Thermal Inertia



Mellon et al. 2002

Rudy et al. Model

The model takes into account the viewing geometry and martian season. Here are the models over one martian day and one martian year.

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

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Rudy et al. Model

Although it is a good model, there are some problems:

- based fundamentally on cm scale (Baars et al.), since measurements were done at 2 & 6 cm at VLA (though some of it is independent of this);
- no roughness;
- no subsurface scattering;
- no lateral heat transport;
- uncertainties with surface CO_2 ice, extent & properties;
- somewhat outdated surface albedo and emissivity information (based on old Viking information);
- no atmosphere.

Despite this, it is in my opinion still the state of the art for Mars thermophysical models - but is it good enough for Herschel?

Calibrator Requirements

As Glenn presented, a good primary calibrator should satisfy:

- flux density known to the desired accuracy;
- not time-variable, or if it is, it varies in a known and predictable way;
- much smaller than the FWHM of the primary beam;
- must not be *too* bright.

(I am less convinced that it needs to be spectrally continuous).

Known Flux Density and Variability

Based on the quality of the information going into the models, I believe that they are good to the required 10%, but probably not as good as the goal of 3%. Note that Muhleman & Berge estimate the uncertainty at 2 mm to be 3%. Even if it is not good enough right now, data can be “back-calibrated” if a new, better, model comes along.

Model Improvements - Now

The model could be improved right now, by incorporating new (in the past 15 years!) spacecraft data. Note that Steve Wood and Ashwin Vasavada are in the process of doing this (Raphael Moreno & Emmanuel Lellouch may be as well, also Paul Hartogh). In addition, other observations at longer wavelengths which are "in the pipe" will improve the situation:

- WMAP observations of the absolute brightness temperature from 20-100 GHz;
- Welch & Gibson (see their Jupiter paper in Icarus);
- CBI (calibrated against Jupiter, but very accurate, from 28-36 GHz);
- VLA observations of bulk dielectric from 5-44 GHz.

Model Improvements - Future

Future improvements will continue to incorporate spacecraft observations, and in addition will benefit from observations with:

- Spitzer;
- SOFIA;
- Planck;
- ALMA;
- Cornell/CIT 25-m Atacama Telescope;
- ASTRO-F;
- SAFIR.

Beam Corrections

If the source is too big, then the primary beam must be known very well - in 2-D, in addition to the source structure being well characterized.

Herpin, Gerin, & Cramer have calculated that Mars gets as big as 15” when observable. How does this compare to the FWHM?

PACS	-	5-15”
SPIRE	-	17-35”
HIFI	-	12-45”

Beam Corrections

Assuming a Gaussian beam, the power pattern at 7.5” from the center (for as big as Mars gets), for various beam FWHM’s is:

FWHM	beam
5	.2
15	.5
25	.78
35	.88
45	.93

So, the primary beam will have to be very well known out to at least the half-power point, and this is a problem for all 3 instruments.

Beam Corrections

A final issue here is the pointing accuracy. This is spec'ed as 3.7" rms. This is generally not a problem when you are near the center of the beam, but when an appreciable amount of the emission is coming from near the half-power point, pointing errors become quite problematic.

Too Bright?

Mars brightness, in Janskys:

λ (μm)	60	100	200	300	400	500
D=0.5 AU	680000	300000	91000	42000	25000	16000
1.0	170000	75000	22000	10000	6100	3800
1.5	75000	34000	10000	4700	2700	1700
2.0	42000	19000	5600	2600	1500	960

Too Bright?

From SPIRE documentation:

"At higher flux levels, the response of the detectors will depart from linearity in a graceful manner, which can be calibrated out with a small associated error. However, there will come a point at which we will have to change the offsets, which we want to avoid unless really necessary. As a guide, the in-band (200-700μm) flux from Uranus is expected to be at the upper end of our dynamic range, beyond which we would need to change the offsets."

Mars is certainly much brighter than Uranus, so this is a big problem.

I believe this is also true for PACS, based on discussion this morning. I'm not sure about HIFI.

Calibrator Requirements

instrument	accuracy?	variability?	small enough?	too bright?
PACS	✓	✓	–	✗
SPIRE	✓	✓	–	✗
HIFI	✓	✓	–	?

Conclusion

Mars is a reasonably good calibrator, with fairly accurately known, predictably variable, flux density in the Far-IR/submm. However, the problems of atmospheric H_2O and CO absorption (and others?), large size, and brightness may prevent it from being the best choice in this respect for Herschel. This is certainly true for SPIRE and PACS - it may still be useful as a primary calibrator for HIFI.