PLANETARY SPECTRAL MODELS AS REFERENCES FOR CALIBRATION

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ABSTRACT

The spectra of solar-system objects have been viewed as a means to establish a calibration system for the far infrared that bridges the gap between bright infrared stars and strong radio sources. One of the earliest objects used for this purpose is the planet Mars. Although there are several problems with Mars models, most can, in fact, be overcome by devising models with an appropriate level of detail, as well as the increasing characterisation of larger and larger areas of Mars' surface by spacecraft missions over a variety of seasons. Griffin & Orton (1993) suggested Uranus, which served as a calibration source for the ISO Long Wavelength Spectrometer team. Other sources, such as minor planets and Jupiter's satellite Callisto, can be subsumed into a calibration system. For instruments with large fields of view and capable of good observations of bright objects, Jupiter itself can serve as a standard. Venus' deep atmosphere has few thermal variations in time and position that have not been well characterised by a host of interplanetary probes, and the bulk of its far-infrared through submillimetre spectrum is governed by a predictable carbon dioxide collision-induced opacity that has been characterised by *ab initio* quantum mechanical models. Unfortunately, Venus is both extremely bright and found inside a region that is forbidden observationally for solar avoidance. The ultimate goal of the calibration system is, in fact, to be capable of deriving spectral flux values that are trustworthy to within 1% on an absolute scale, commensurate with, or better than, the current level of confidence in the stellar standard system.

Key words: planets, Mars, Neptune, Venus, Uranus

1. INTRODUCTION

Planetary astronomers generally wonder why anyone would consider using planetary spectra at all in a calibration scheme. They are expecting variations of properties over the planet and with time. They are hoping, of course, that the spectra of a sufficient number of stars are invariant and that stellar sources are placed conveniently everywhere in the sky. Furthermore, they would hope to find such sources at all wavelengths of interest. Calibrate planets with stars, not stars with planets! Alas, we planetary astronomers must consider that stellar sources are no match for the strength of planetary fluxes at wavelengths beyond about 20–30 μm (*cf.* the standard star catalogue developed by Cohen et al. (1995) and references therein). There are also standard radio sources, but they are not useful until nearly centimetre-scale wavelengths.

2. THE IDEAL INFRARED CALIBRATOR

We'd like to see an object with a time-invariant infrared spectrum that is both bright and consists only of a slowly varying continuum in wavelength. We could launch a network of large, perfectly black and spectrally neutral geosynchronous satellites, but somehow it's hard to see this plan achieving the status of the next cornerstone project!

Is there anything close? Yes, although there are several strings attached. The spectrum of Venus beyond 30 μm is a virtual continuum that is dominated by collision-induced CO_2-CO_2 absorption (Aumann et al. 1982) that can be modelled by the *ab initio* quantum models of Gruszka & Borysow (1997) (Fig. 1). Venus' atmosphere has only small temperature variations with longitude, all of which are extremely well documented by a host of *in situ* and remote sensing spacecraft starting with Pioneer Venus results (*e.g.* Kliore & Patel 1980, Taylor et al. 1980). Its spectral continuum is likely to be interrupted by a regularly spaced series of rotational lines of SO_2, HCl and CO, whose vertical abundance as a function of planetary latitude is also well documented from radio and ultraviolet studies.

So, what's wrong with Venus? For starters, Venus is probably inside the angular solar avoidance limit of most earth-orbiting spacecraft. Venus is also quite large, with a diameter that is something like 30$''$ when it is sufficiently far from the sun to be observable. This may cause some problems with instruments with fields of view that are not substantially larger. Finally, Venus is very, very bright: the large size, combined with brightness temperatures in excess of 230 Kelvin, exceeds the linear response limit (and probably also the warranty!) of sensitive spacecraft instruments.

3. MARS AS A CALIBRATOR

So, if Venus is close to ideal, what is second best? The most <u>popular</u> planetary substitute for a time-invariant, spectrally continuous infrared source is Mars. Yes, this is the same Mars that has both a solid surface with major topographic variations and that rotates irritatingly with nearly the same rate as ground-based observatories. The same Mars whose atmosphere contains CO_2 and H_2O, <u>both</u> of which are condensible and cre-

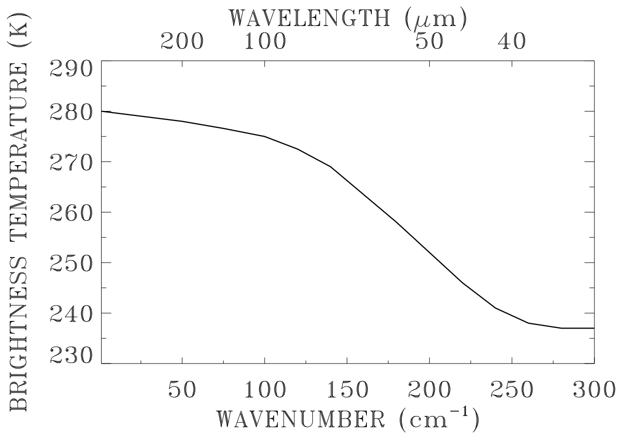

Figure 1. Schematic continuum model of Venus' brightness temperature spectrum, dominated at wavelengths greater than 100 μm by the collision-induced opacity of CO_2-CO_2. Potential discrete spectral features are not included in the model. Brightness temperature spectra are shown for illustration in this paper, as they can be extrapolated to any distance from the earth for the purpose of flux calculations.

ate seasonal polar caps. The very same Mars that hosts unpredictable local and global dust storms that both obscure and cool the surface.

On the other hand, Mars is convenient, not too big, and not quite so bright. Mars was used to calibrate many earth-based observations between 20 μm and the submillimetre up to the start of ISO operations. The first comprehensive attempt at a model for Mars was offered by Wright (1976) and extended by Wright & Odenwald (1980). It was based on the absolute radiometry measurements provided by Mariners 6 and 7 (Neugebauer et al. 1971), and extended by model to variations of wavelength, phase and distance from the sun. Although these models ignored polar caps, they served as a much more reasonable approximation of Mars' disk-integrated radiance than single brightness temperature "models" used before them. However, the simple approximation that the model brightness temperature at 350 μm could be extrapolated uniformly to longer wavelengths was not a good one. It failed to simulate the emergence of radiation from effectively deeper, cooler layers of Mars' subsurface at longer wavelengths. The systematically high temperatures of the resulting model led Hildebrand et al. (1985), for example, to derive systematically high brightness temperatures for Uranus in the far infrared. In turn, this became one of the factors that contributed to the conclusion of Orton (1986) that Uranus' spectrum was most consistent with an unexpectedly high mixing ratio of helium relative to molecular hydrogen. A combined experiment involving the Voyager-2 infrared Fourier-transform spectrometer (IRIS) and the radio occultation experiment (Conrath et al. 1987) that determined the atmospheric mean molecular weight showed that such a result was extremely unlikely.

These Mars models were modified in the far infrared by Griffin & Orton (1993) who used an interpolation between the 350 μm brightness temperatures of the Wright (1976) model and the absolutely calibrated 3.3 mm observation of Ulich (1981) to calibrate far-infrared and submillimetre narrow-band photometry of Uranus and Neptune. These models were compared favourably with the more physical results of a spatially-resolved radiative model of Mars by Rudy et al. (1987) that had been used to interpret spatially resolved VLA radio observations of Mars. In fact, this model had been used already in a review of Uranus' spectrum by Cohen et al. (1995) to provide a consistent calibration of the observations of Uranus. A model that assumed a dielectric constant of $\epsilon = 2.8$ for the Martian soil predicts brightness temperatures that differed from the Griffin and Orton interpolation by less than 1.2%. The Rudy et al. (1987) models, in addition to being based on VLA mapping results at 2 and 6 cm wavelength, were also consistent at shorter wavelengths with the Viking thermal mapping data (Kieffer et al. 1977). Sidher et al. (2000) provide a more detailed review of these sophisticated thermophysical models of Mars, but it is worth mentioning that they include accounting for the details of surface property and altitude variations across the globe (except near polar regions which were more poorly sampled). Lellouch et al. (2000) and Burgdorf et al. (2000) also fitted ISO observations of Mars' water vapour spectrum and determined the emissivity in the 17–45 μm and the 50–180 μm spectral ranges, respectively. Improvements to these models will arise from both (1) mapping the planet in more detail and extending the results to the poles, and (2) improving the surface emissivity spectrum. The latter continues to be examined by the LWS team, using comparisons with Uranus' spectrum.

We note that all calibrations based on Mars will always be subject to systematic errors that arise from unpredictable events, such as regional and global dust storms that both obscure and cool the surface, often for many weeks. While these storms have a seasonal component, their actual occurrence is as unpredictable as any weather phenomenon. What saves Mars as a useful calibration object is the infrequency of these storms.

4. THE CASE FOR URANUS

Griffin & Orton (1993) suggested that Uranus be used as a calibrator. It is less variable than Mars, and its dimmer thermal spectrum is less likely to challenge the linear range of infrared detectors. The LWS team, in particular, has adopted a standard model spectrum of Uranus for its primary calibration. The spectrum of Uranus in the far infrared is overwhelmingly dominated by the quasi-continuous collision-induced opacity of H_2-H_2, H_2-He and H_2-CH_4 pairs, for which H_2-H_2 is the dominant component. A recent summary of the results of extremely accurate *ab initio* models for H_2-H_2 and H_2-He absorption was given by Birnbaum et al. (1996); a similar treatment of H_2-CH_4 pairs was given by Borysow & Frommhold (1986). Note that the morphology of this absorption spectrum also depends on the ratio of *para*-H_2 to *ortho*-H_2 (*i. e.* molecules where the two protons have parallel or anti-parallel spins, respectively.)

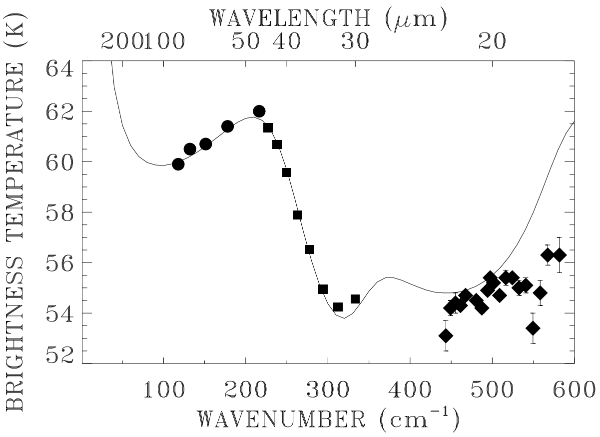

Figure 2. Brightness temperature spectrum of Uranus, dominated by the collision-induced opacity of H_2. Filled circles represent LWS photometric results calibrated against a standard Mars model. Squares represent SWS spectral averages calibrated for consistency with the Voyager IRIS whole-disk spectrum (Pearl et al. 1990), shown by the curved line. Diamonds illustrate the spectrum of Orton et al. (1990) whose radiances are uncertain by as much as $\pm$60%.

A portion of Uranus' spectrum that is considered most accurate was given from whole-disk-equivalent observations produced by the Voyager IRIS experiment. These observations were used to estimate Uranus' radiative energy balance by Pearl et al. (1990). Their determination of the spectrum between 200 and 300 cm^{-1} (33 and 50 μm) provided a description of the mean temperature structure in the upper troposphere, a region of the atmosphere from which most of the rest of the infrared spectrum emerges. The He/H_2 ratio was determined by Conrath *et al.* (1987), and the CH_4/H_2 ratio was determined as about 2% from evidence in the visible and near-infrared (Baines & Bergstralh 1986) and the submillimetre (Orton et al. 1986). The *para- vs ortho*-H_2 ratio was assumed to be at equilibrium with the local temperature.

The Voyager IRIS spectrometer that measured Uranus was thermally controlled to within $\pm$0.1 Kelvin and measured by two platinum resistance thermometers that were calibrated at the U. S. National Bureau of Standards (now the National Institute for Standards and Technology) prior to launch. Thus, the fundamental radiance calibration uncertainties are no greater than 1.5% in the 33–50 μm spectral range. Uranus' effective global thermal spectrum was then constructed from 610 individual spectra of various points on the disk that were gathered from a broad range of latitudes and weighted by the cosine of the emission angle. The resulting spectrum is in full agreement with a noisier version that was taken from a series of measurements of Uranus' whole disk during the distant inbound leg of the encounter. The temperature profile above the tropopause level (pressures less than 100 mbar) is not well constrained by this spectral region; it is assumed to be the same form as the one derived from the radio occultation profile (Conrath et al. 1987). The model derived from this temperature profile fits the 30–50 μm region very well, of course; it is further extrapolated to shorter wavelengths, where it fits a series of ground-based observations of Uranus that were obtained at the NASA Infrared Telescope Facility by Orton et al. (1987) and even more carefully by Orton et al. (1990). Toward longer wavelengths, the Voyager IRIS model was extrapolated to 100 μm where the Griffin & Orton (1993) model was then used for all longer wavelengths; their model was modified by adding 0.5 Kelvin in brightness temperature in order to make it completely compatible with the Voyager extrapolation in the region of overlap. Recent work by the LWS team that analyses lines in Mars' spectrum derives an effective emissivity of 0.93. This value would be completely consistent with the Uranus calibration model if its model spectrum were increased by 2%. Such a small value is probably indicative of the current fundamental uncertainty of the models for both planets.

There are, in fact, several aspects of Uranus that make it appealing as a calibration source. It is not very big and not very bright. It has a very deep atmosphere with no longitudinal variability that has yet been detected. Does this model have problems? Maybe. One is the fact that, after several years, Uranus' pole will have moved so that we are looking at a different hemisphere than we did when these observations were made (see Figs. 3 and 4), and there is likely to be a systematic difference between polar and equatorial temperatures. Of a more subtle nature is the fact that the model extrapolation has assumed some parameters, such as the *para- vs ortho*-H_2 ratio. The model assumed this was at local equilibrium, but recent intensive analyses of the IRIS spectra of the outer planets (Conrath et al. 1998) shows that there are departures from equilibrium locally that could well imply a net departure to the globally averaged value. It remains to be shown whether the effects of assuming an inappropriate value for the average *para- vs ortho*-H_2 ratio in Uranus predisposes a Uranus-calibrated data set for, say, Neptune to systematically incorrect values for the *para- vs ortho*-H_2 ratio. It is also possible that there are absorption lines in Uranus' spectrum from as yet unknown constituents. We <u>do</u> know that at some level there should be weakly forbidden rotational CH_4 lines in absorption, as well as possible lines from even more minor constituents.

5. WHY NOT NEPTUNE?

Neptune (Fig. 5) could serve almost equally well as an independent calibrator, although at this point the LWS spectrum of Neptune is dependent on the calibration of Uranus. Just as for Uranus, one must also assume that there is no important longitudinal thermal variability. While there are no indications of thermal features in the relatively noisy individual Voyager IRIS spectra, there are many large features in the visible. If these features have corresponding thermal signatures (as is the case for Jupiter), then it would be harder to assume the absence of systematic variability with rotational phase. If this assumption is valid, at least below one's target uncertainty tolerance,

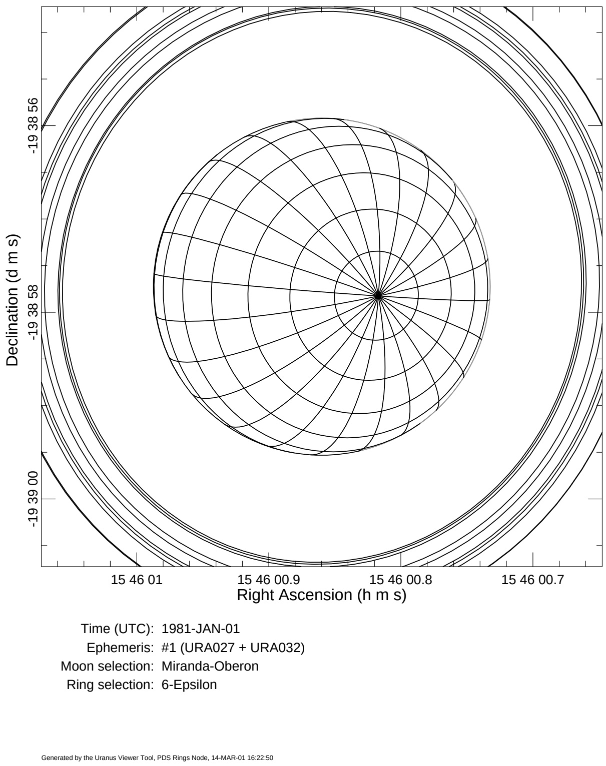

Figure 3. Rotational aspect of Uranus on 1980 Jan 1. (Courtesy of the Planetary Data System Rings node web site.)

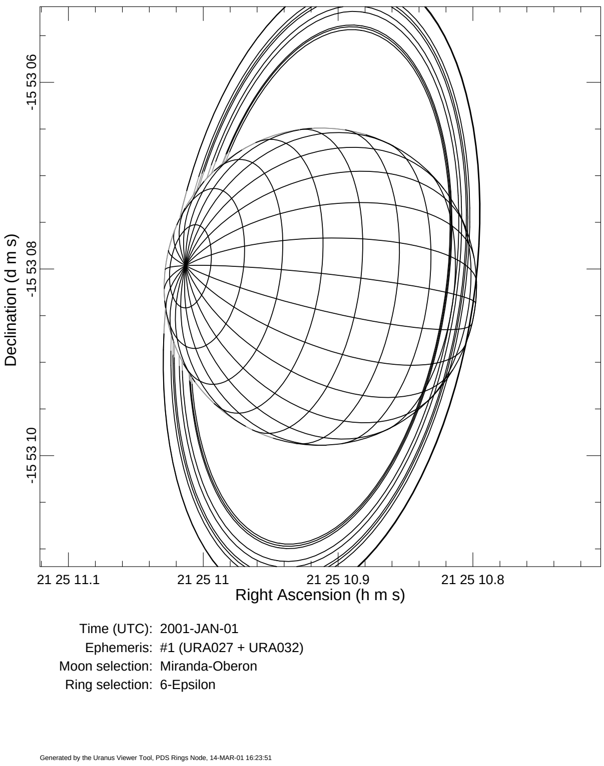

Figure 4. Rotational aspect of Uranus on 2001 Jan 1. (Courtesy of the Planetary Data System Rings node web site.)

then Neptune should be more impervious to long-term variations than Uranus.

6. WHAT ABOUT ALTERNATIVES?

Even if one accepts them as "ideal" calibrators, Uranus and Neptune are both in the same part of the sky, and one may wish to find ancillary calibration objects elsewhere. Jupiter has the disadvantage of being large and relatively bright, with a complicated set of NH_3 and PH_3 lines, along with the further spectral confusion of additional trace constituents in the far infrared (Fig. 6). It also has the Great Red Spot which is a substantial temperature perturbation of the average diurnal spectrum. Saturn is smaller and has very small longitudinal variability, but one must create a detailed model for not only the atmosphere but the thermophysics of the ring system and its obscuration of the planet. The optical thickness of the ring systems of Uranus and Neptune, on the other hand, is small enough in the infrared as to be a negligible influence on the thermal output of their respective primary bodies.

Mueller spoke at this meeting about asteroids as calibrator objects. One could add to this Jupiter's outermost Galilean satellite, Callisto, that gets as far as $618''$ from Jupiter and could accommodate calibration observations at shorter wavelengths. One must, as with any surface object, be careful about calibrating spectral emissivity features, particularly those that are functions of longitude and, therefore, rotational phase.

The ultimate goal of the calibration system is, in fact, to be capable of deriving spectral flux values that are trustworthy to 1% or better on an absolute scale, commensurate with or better than the current level of confidence in the stellar standard system. A highly accurate system could be derived from a systematic cross-calibration of planetary and stellar sources where the stellar sources are bright enough to be routinely calibrated against solar-system objects. Such a system would also assemble the best aspects of all of the sources reviewed in order to provide a check on the accuracy and consistency of each of its components.

The underpinning of such a system would be the rigorous cross-calibration, from ground-based (submillimetre and mid-infrared) and spacecraft instruments of the spectra of the bodies from which substantial diurnal variations are not expected - Venus, Uranus and possibly Neptune. This can be coupled with an effort to provide increased precision in the mid-infrared spectra of Uranus and Neptune, to evaluate long-term time variability, diurnal variability, and to increase the accuracy of the 17–24 μm spectra. Such observations would also tie Uranus and Neptune more closely with the stellar standard system. In

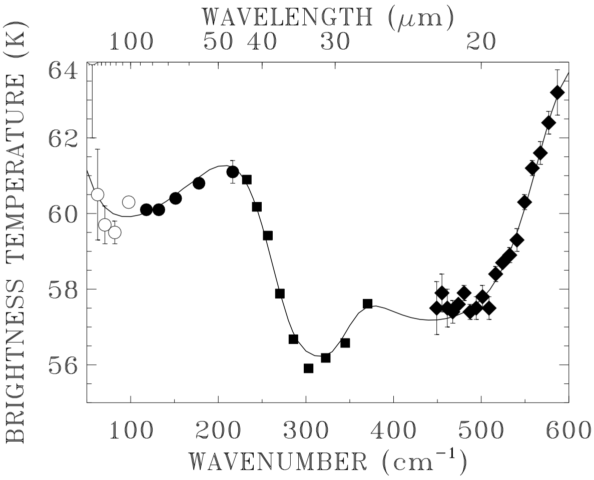

Figure 5. Brightness temperature spectrum of Neptune, also dominated by the collision-induced opacity of H_2. Filled and open circles represent LWS photometric results calibrated against a standard Uranus model. Squares represent SWS spectra averaged and calibrated for consistency with the Voyager IRIS whole-disk spectrum of Neptune. Diamonds illustrate the spectrum observed by Orton et al. (1990) whose radiances are uncertain by $\pm$12%. The curved line represents the spectrum of one of the models best fitting the data.

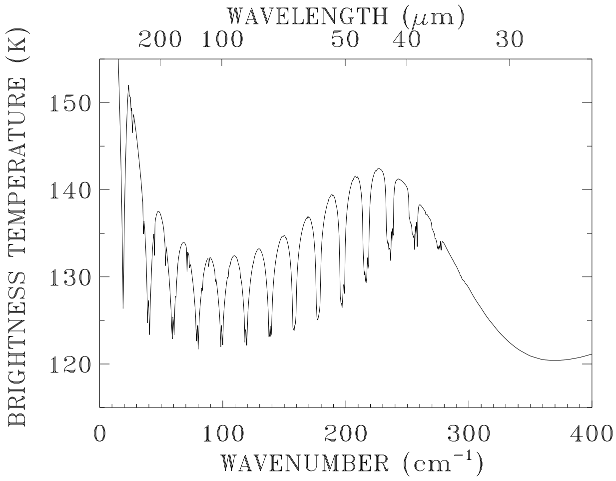

Figure 6. Brightness temperature spectrum of Jupiter's disk, influenced by the collision-induced opacity of H_2, but also containing absorption signatures of NH_3 and PH_3.

turn, all these models can be referenced to Mars, using simultaneous observations, as well as an updated version of the current thermophysical model (Rudy et al. 1987) that incorporates the rich and detailed results of Mars Global Surveyor.

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