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WATER VAPOR CORRECTIONS TO MID-INFRARED PHOTOMETRY

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RESUMEN

En este artículo exploramos la posibilidad de corregir la absorción producida por el vapor de agua atmosférico en las mediciones realizadas con el sistema fotométrico en el mediano infrarrojo CID de San Pedro Mártir. El contenido de vapor de agua se obtiene de mediciones de la opacidad atmosférica a través de un radiómetro a 210 GHz. Utilizando los resultados del modelo ATM se propone una relación lineal entre la opacidad a esta frecuencia y el contenido de vapor de agua. Esta relación nos permite así determinar el contenido de vapor de agua a partir de estas mediciones. También obtenemos una relación similar en el mediano infrarrojo utilizando el modelo MODTRAN 3. De estas dos relaciones se puede entonces encontrar una correlación entre la opacidad en el mediano infrarrojo y la opacidad en la región milimétrica, válida para cielos despejados. Esta relación ha sido comprobada con mediciones de estas dos opacidades en San Pedro Mártir.

ABSTRACT

We explore water vapor corrections for the San Pedro Mártir mid-infrared photometric system CID. Atmosphere opacity is measured by a 210 GHz radiometer. By using the results of the ATM code, we propose a linear relationship between 210 GHz opacity and water vapor content. This relation allows us to determine the water vapor content in the atmosphere from opacity measurements at the radiometer frequency. We also obtain a relation between water vapor content and mid-infrared opacity by using the MODTRAN 3 atmospheric model. Thus, through the water vapor we obtain a relation that connects millimeter opacity to mid-infrared opacity under clear sky conditions. We tested this relation with measurements made at San Pedro Mártir of these two opacities.

Key Words: **ATMOSPHERIC EFFECTS — SITE TESTING — TECHNIQUES: PHOTOMETRIC**

1. INTRODUCTION

The CID (Camara Infrarroja Doble) or Dual Infrared Camera, was designed for the 2.1-m telescope of the Observatorio Astronómico Nacional at Sierra San Pedro Mártir, Baja California (México). The system consists of a separated camera and camera/spectrograph that operates in two regions of the infrared spectrum: the CID-BIB for the mid-infrared (MIR, 6-28 μm) and the CID-InSb for the near-infrared (1-5 μm). A detailed description of the two CID instrumental setups is presented in Salas et al. (2003).

The San Pedro Mártir radiometer at 210 GHz (Hiriart et al. 1997) determines the sky opacity at that frequency by fitting a parallel atmosphere model to the skydips it obtains. A large archive of atmospheric opacity measurements at millimetric wavelength for Sierra San Pedro Mártir has been accumulating since 1992. Results have been published for the years of 1992 (Hiriart et al. 1997) and 1999 (Hiriart 2003a). A compilation for eight years of opacity measurements at millimetric wavelengths appears in Hiriart (2003b).

By using a model of the physical parameters, it is possible to determine the precipitable water vapor (PWV) from the opacity at 210 GHz. Thus, this measurement may be used to remove the effects

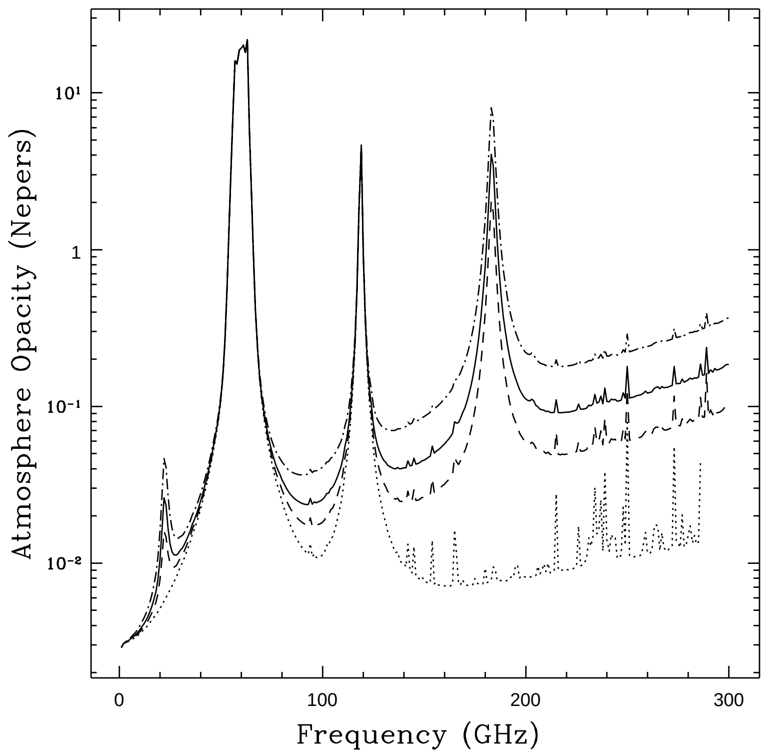

Fig. 1. The zenith opacity on the 0 to 300 GHz window for the atmosphere above San Pedro Mártir with Precipitable Water Vapor of 1.0 (dashed line), 2.0 (solid line), and 4.0 mm (dot-dashed line) as modeled using ATM. The opacity of a dry atmosphere is also included (dotted line).

produced by the atmospheric water vapor from the mid-infrared telescope data.

The determination of the atmospheric opacity above San Pedro Mártir is critical for the calibration of astronomical data from the CID. Precise measurements of the zenith sky opacity must be obtained frequently to ensure proper calibration of astronomical data.

In this paper, we report on results collected at the San Pedro Mártir Observatory of a comparison of the measurements of absorption in the mid-infrared with measurements of PWV obtained concurrently.

2. MODELING THE ATMOSPHERE ABOVE SAN PEDRO MÁRTIR

Under clear-sky conditions, the transparency of the atmosphere above San Pedro Mártir allows observations in the optical, mid-infrared, and millimetric spectral regions. The main contributors to the atmospheric opacity at the mid-infrared and millimetric spectral regions are water vapor, molecular oxygen, and ozone. There are also significant absorptions in certain bands in the near-infrared due to CO_2 and CH_4. On the other hand, liquid water droplets in clouds and in rain will scatter and absorb millimeter waves. The attenuation due to cirrus ice clouds is very small in the millimetric region, since the dielectric constant of ice is much lower than that of liquid water. However, in the mid-infrared the size of ice particles is similar to the wavelength and produces higher attenuation and dispersion. Therefore, we should remark that the comparison presented in this paper is only valid when all the water in the atmosphere is in gaseous phase.

TABLE 1

INPUT PARAMETERS FOR ATM ATMOSPHERIC MODEL OF THE SUMMIT OF SAN PEDRO MÁRTIR

Ground temperature	273.00 K
Ground pressure	625.00 mBar
Site Alt.	2.83 km
Max Alt. Atmosph.	48.00 km
PWV scale height	2.00 km
Lapse Rate	-5.60 K km^{-1}
Pressure Step	10.00 mBar

TABLE 2

ATM MODEL PREDICTIONS OF SKY OPACITY FOR SAN PEDRO MÁRTIR OBSERVATORY

PWV (mm)	H_2O lines	H_2O Opacity	H_2O Opacity	O_2 Opacity	Dry Cont.	Minor Comp.	Total Opacity
0.001	0.00000	0.00000	0.00000	0.00009	0.00834	0.00039	0.00883
0.25	0.00428	0.00581	0.00004	0.00009	0.00834	0.00039	0.01896
0.5	0.00857	0.01162	0.00018	0.00009	0.00834	0.00039	0.02919
1.0	0.01717	0.02323	0.00072	0.00009	0.00834	0.00039	0.04994
2.0	0.03442	0.04644	0.00287	0.00009	0.00833	0.00039	0.09255
3.0	0.05176	0.06961	0.00646	0.00009	0.00833	0.00039	0.13664
4.0	0.06918	0.09276	0.01149	0.00009	0.00832	0.00039	0.18223
5.0	0.06918	0.09276	0.01149	0.00009	0.00832	0.00039	0.18223
6.0	0.06918	0.09276	0.01149	0.00009	0.00832	0.00039	0.18223
7.0	0.12193	0.16203	0.03519	0.00010	0.00830	0.00039	0.32794
8.0	0.13968	0.18506	0.04597	0.00010	0.00830	0.00039	0.37949
9.0	0.15751	0.20806	0.05818	0.00010	0.00829	0.00039	0.43253
10.0	0.17543	0.23104	0.07182	0.00010	0.00829	0.00039	0.48707

Notes: all opacities in neper units.

2.1. *Microwave Modeling*

In order to investigate the effects of the water vapor content on the opacity in the millimetric region, we used a radiative transfer model known as Atmospheric Transmission Model (ATM) (Pardo, Cernicharo, & Serabyn 2001). This model includes the contributions of water vapor, molecular oxygen, ozone, and other minor constituents. The model includes all the spectroscopy data available for these species covering the range from 0 to 10 THz.

Figure 1 presents the zenith atmosphere opacity above San Pedro Mártir (SPM) from 0 to 300 GHz for different amounts of precipitable water vapor (PWV). At the operating frequency of the San Pedro Mártir radiometer, 210 GHz, atmosphere opacity is dominated by the precipitable water vapor. The total opacity at this frequency, τ_{210}, may be written as

$$\tau_{210} = \tau(H_20) + \tau(O_2) + \tau(minors) \; , \qquad (1)$$

where, $\tau(H_2O)$, $\tau(O_2)$, and $\tau(minors)$ are the opacities of the water vapor, molecular oxygen, and minor components of the atmosphere, including ozone, respectively.

Using ATM, a theoretical value for τ_{210} has been determined for a range of values of precipitable water vapor. Table 1 shows the parameter values used in the San Pedro Mártir simulations. Table 2 shows the results. At 210 GHz, the minor components have a constant contribution of 0.00039 nepers (Np) for all the values of PWV. The contribution of molecular oxygen to the opacity is constant for values ranging from 0.001 to 6.0 mm of PWV. Columns in Table 2 represent: (1) Precipitable Water Vapor and then

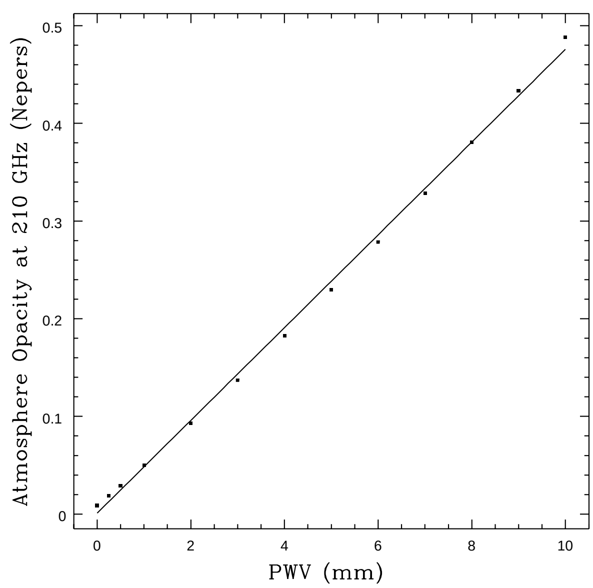

Fig. 2. Theoretical relation between the sky opacity at 210 GHz, in nepers, and the amount of Precipitable Water Vapor, in mm, for the atmosphere above San Pedro Mártir. The dots represent the opacity calculated with ATM code. The solid line represents the best linear fit to the calculated opacities.

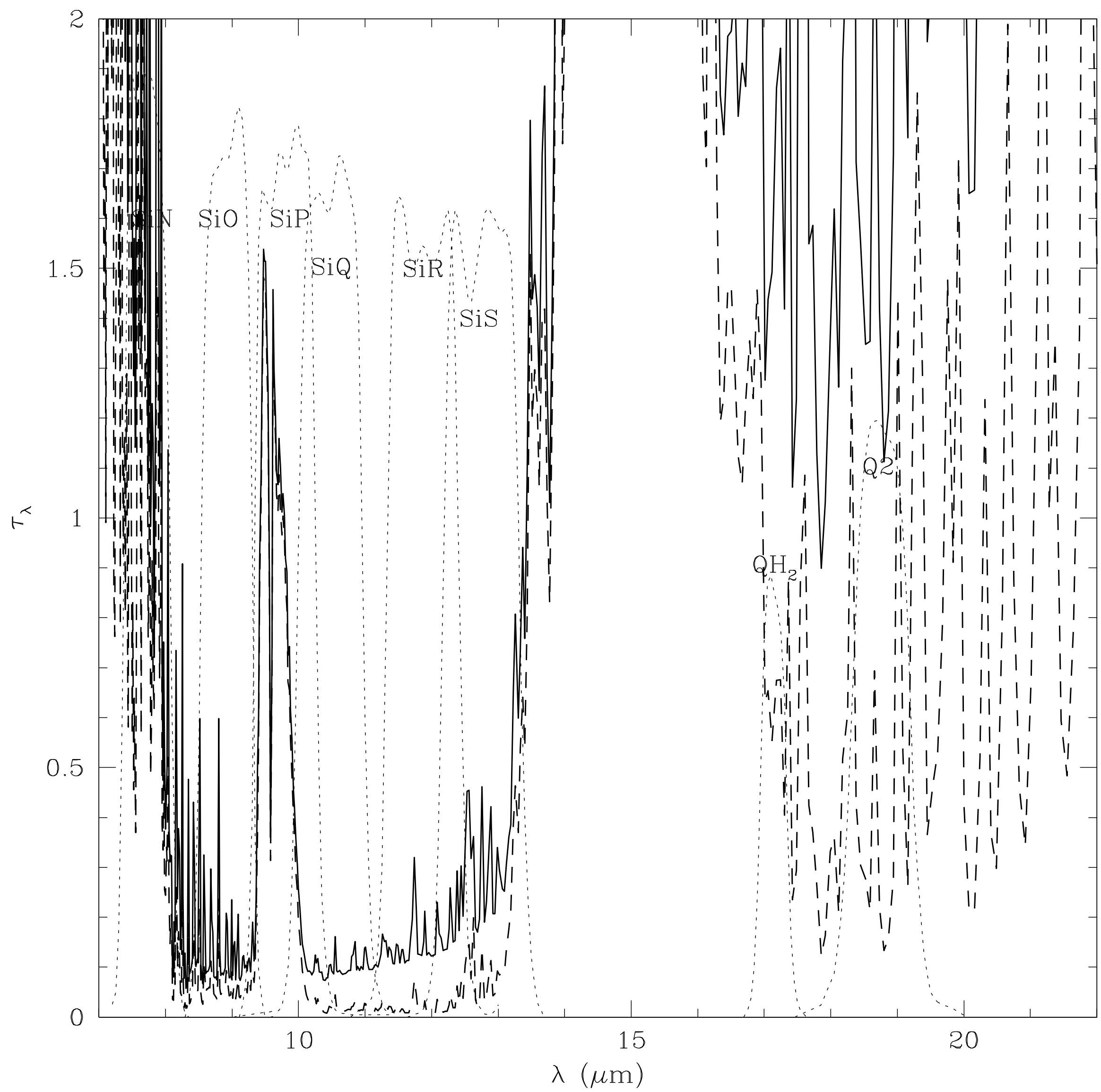

Fig. 3. The optical depth, τ_λ, of the 7-22 μm window for the atmosphere above San Pedro Mártir with water vapor column abundances of 1 (dashed line) and 5 mm (solid line) as modeled using MODTRAN 3. The figure also shows the transmission curve of the CID filters (dotted lines). The transmission curve of the broadband filter N is not shown.

the contribution to the opacity by (2) water vapor lines; (3) water vapor opacity at the continuum (first order); (4) water vapor opacity at the continuum (second order); (5) molecular oxygen contribution; (6) dry component; (7) minor component contribution; and (8) the total opacity (from adding columns 2 to 7).

Figure 2 presents the relation between the sky opacity at τ_{210} obtained from ATM as a function of the Precipitable Water Vapor. The graph shows that the values of τ_{210} vary linearly with the PWV. Thus, the ATM model predicts a total opacity at 210 GHz of

$$\tau_{210} = (0.0475 \pm 0.0006)PWV + (0.0009 \pm 0.0032)\,, \quad (2)$$

for San Pedro Mártir, where, τ_{210} is given in Np, and PWV in mm. Thus, the column abundance of the water vapor can be expressed as a function of the opacity at 210 GHz as

$$PWV = 20.48 * \tau_{210} - 0.327\,. \quad (3)$$

TABLE 3

MODTRAN 3 OPACITIES FOR CID FILTERS

PWV (mm)	SiN $7.8\mu m$	SiO $8.9\mu m$	SiP $9.9\mu m$	SiQ $10.5\mu m$	SiR $11.9\mu m$	SiS $12.7\mu m$	N 8-$13\mu m$	QH2 $17.1\mu m$	Q2 $18.7\mu m$
0.00	0.515	0.052	0.572	0.040	0.008	0.086	0.195	0.381	0.013
0.25	0.638	0.059	0.573	0.042	0.011	0.096	0.202	0.510	0.192
0.50	0.721	0.065	0.574	0.043	0.014	0.105	0.208	0.583	0.300
1.00	0.857	0.075	0.577	0.047	0.022	0.121	0.219	0.709	0.486
2.00	1.084	0.092	0.585	0.059	0.044	0.157	0.242	0.953	0.832
3.00	1.291	0.110	0.597	0.076	0.073	0.201	0.270	1.207	1.186
4.00	1.487	0.129	0.613	0.098	0.111	0.255	0.304	1.482	1.567
5.00	1.676	0.150	0.633	0.125	0.158	0.320	0.344	1.780	1.982
6.00	1.859	0.173	0.656	0.158	0.213	0.397	0.390	2.104	2.435
7.00	2.039	0.198	0.684	0.196	0.277	0.484	0.443	2.456	2.927
8.00	2.215	0.225	0.715	0.240	0.350	0.584	0.503	2.837	3.463
9.00	2.398	0.255	0.751	0.289	0.431	0.694	0.570	3.248	4.031
10.00	2.570	0.288	0.790	0.344	0.522	0.817	0.643	3.689	4.781

Notes: all opacities in nepers units.

2.2. *Mid-infrared Modeling*

Mid-infrared opacity at San Pedro Mártir Observatory may be calculated by using the Moderate Resolution Transmittance code (MODTRAN 3 Version 1.3) (Berk, Bernstein, & Robertson 1989). MODTRAN 3 calculates atmospheric transmittance and radiance from 0 to 50,000 cm^{-1} at moderate (2 cm-1) spectral resolution. A tenfold increase in resolution is provided by a newer version of MODTRAN 5 (Berk et al. 2005). The new version does a better job of computing the continuum by use of the LBL algorithm, in a way similar to the CKD or MT-CKD models that the Atmospheric and Environmental Research group has put together (Clough et al. 2005). However, since we will be interested in the integral over relatively wide bandpasses, high resolution is not required. Figure 3 presents the atmospheric opacity in the region from 7-22 μm obtained by MODTRAN 3 for the SPM site.

The total opacity at the mid-infrared (MIR) region may be expressed as

$$\tau_{MIR} = \tau(H_2 0) + \tau(O_3) + \tau(minors) \ , \quad (4)$$

where τ_λ is the opacity at wavelength λ, $\tau(H_2O)$ is the water vapor opacity, $\tau(O_3)$ is the ozone opacity with a strong absorption at 9.7 μm, and $\tau(minors)$ is the opacity due to other minor constituents.

The mid-infrared radiation present at the detector will depend on the convolution of the atmosphere transmittance and filter response. Therefore, we define the total integrated opacity $< \tau_\lambda >$ as

$$< \tau_\lambda > = \frac{\int_{\Delta\lambda} \tau(\lambda) f(\lambda) d\lambda}{\int_{\Delta\lambda} f(\lambda) d\lambda} \ , \quad (5)$$

where $\tau(\lambda)$ and $f(\lambda)$ are the atmosphere opacity and the response of the filter at wavelength λ, respectively; $\Delta\lambda$ is the bandwidth of the filter. The response of the filters for the CID system are shown in Figure 3.

Table 3 presents the total $< \tau_\lambda >$ opacity integrated in each of the CID bandpases for different values of the Precipitable Water Vapor. When we subtract from each column the corresponding value at PWV = 0 mm, i.e., $\tau(O_3) + \tau(minors)$, we obtain Figure 4 that presents the relation between $< \tau_\lambda >$, including only water vapor opacity, and PWV. It is observed that $< \tau_\lambda >$ increases as τ_{210} increases, particularly at the SiN, QH2, and Q2 filters, which are the most affected by water absorption lines in the atmosphere, although this same effect is present in all the filters.

3. OBSERVATIONAL CONFIRMATION

To verify the relation between the water vapor opacities in the millimeter and MIR regions, we have observed a set of standard stars in the MIR with the CID instrument and recorded the τ_{210} opacity measured with the radiometer at the time of each observation.

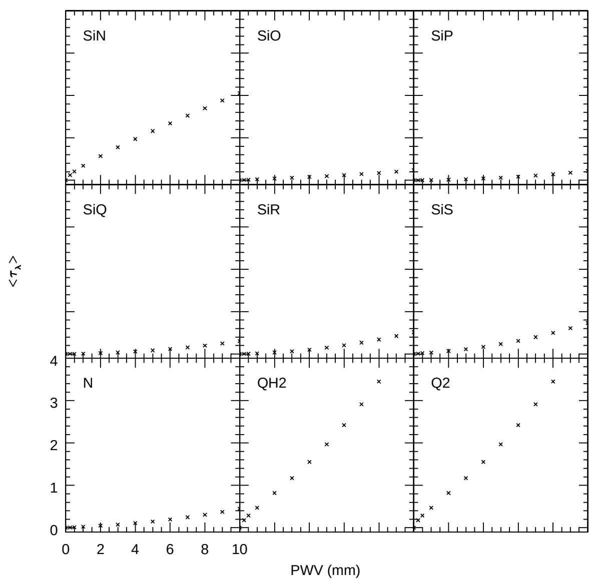

Fig. 4. The total integrated sky opacity, $< \tau >$, on each of the filters of the CID (nepers) and the amount of Precipitable Water Vapor (PWV), in mm, for the atmosphere above San Pedro Mártir. Only water vapor is included in this graph. The crosses represent the opacity calculated with MODTRAN 3 code.

The observations were carried out from November 10 - 13, 2005 under clear sky and excellent photometric conditions using the CID instrument on the 2.1-m telescope at San Pedro Mártir Observatory. Five stars were observed as part of the definition work of the San Pedro Mártir MIR photometric system (Salas, Cruz-González, & Tapia 2006) supplemented by one silicate standard star. All of the stars were observed in each of the 9 CID MIR filters several times (see Table 4) at low air-masses ranging from 1-2.5 and for different values of the 210 GHz opacity which varied from 0.04 - 0.24 nepers.

The observations were reduced as described by Salas et al. (2006), taking into account non-linear air-mass corrections necessary for the compensation of the Forbes effect. However, a single zero point and extinction coefficient were used for all the observing runs in order to explore residual variations as a function of the water vapor opacity. Residual variations, Δmag, were calculated by subtracting each obtained magnitude from the actual magnitude of the standard star. Figure 5 shows these residuals binned as a function of the opacity at 210 GHz, $\tau(210)$ for each CID filter. An arbitrary vertical shift has been applied to each panel to compensate for an overall offset of the mean zero point that was used.

TABLE 4

OBSERVED STARS

Star	Date	Filters	Airmass	$\tau(210)$
αTau	10	sil+Q	1.26	0.21
αTau	11	all	1.20	0.06
αTau	11	all	1.25	0.07
αTau	11	all	1.65	0.06
αTau	11	all	2.06	0.08
αTau	12	all	1.21	0.04
αTau	12	all	1.50	0.04
αTau	12	all	2.50	0.04
αTau	13	all	1.10	0.10
αTau	13	all	1.39	0.09
βAnd	10	sil+N	1.04	0.23
βAnd	11	sil+Q	1.33	0.07
βAnd	11	sil+Q	1.66	0.06
βAnd	11	sil	2.10	0.07
βAnd	12	all	1.04	0.04
βAnd	13	all	1.08	0.08
βPeg	10	all	1.08	0.21
βPeg	10	all	1.37	0.22
βPeg	12	all	1.30	0.04
βPeg	13	all	1.22	0.09
αCMa	11	all	1.58	0.06
αCMa	12	all	1.49	0.05
αCMa	13	sil+N	1.57	0.12
μCep	10	all	1.21	0.20
μCep	11	all	1.15	0.07
μCep	12	all	1.27	0.04
μCep	13	all	1.13	0.08

Notes: filters: sil= silicate series 7.8 to 12.7. Date: UT, November 2005.

It is observed that the measured mid-infrared radiation diminishes as τ_{210} increases. This effect is particularly pronounced for the SiN, QH2, and Q2 filters which are the most affected by water absorption lines in the atmosphere, although this same effect is present in all the filters. The solid lines represent the combination of the atmospheric models (ATM and MODTRAN 3) used to relate the 210 GHz opacity to the MIR expected attenuation. That is, we use the ATM model to obtain the PWV from the measured τ_{210} and then MODTRAN 3 to calculate the expected attenuation from this PWV in the MIR, as has been described above.

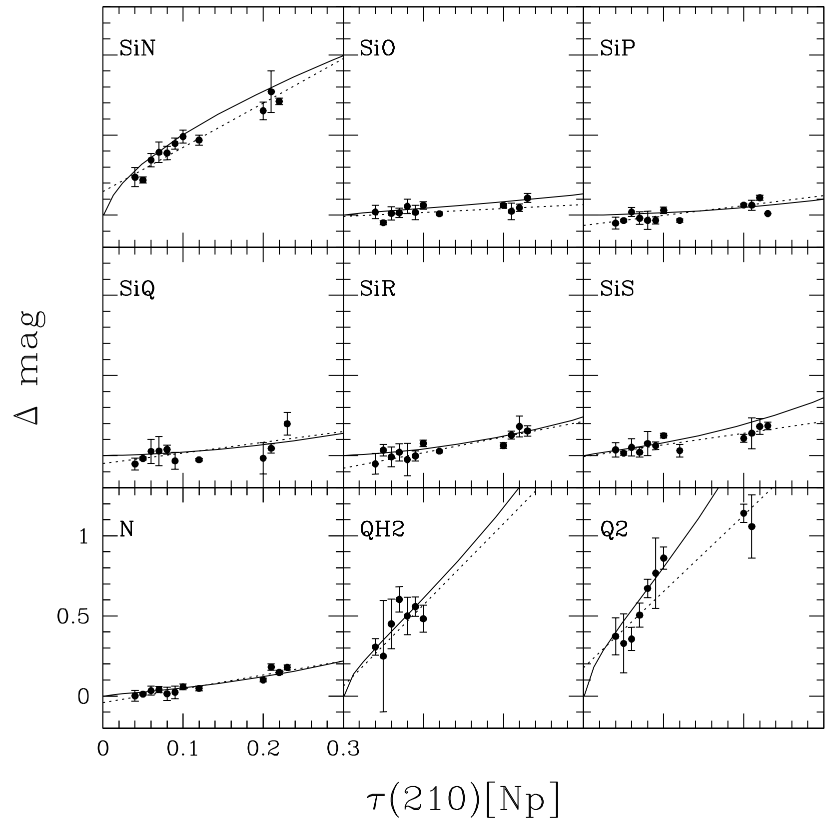

Fig. 5. Magnitude differences, Δ mag, of observed standard stars as a function of the measured atmosphere opacity, $\tau(210)$, at 210 GHz (dots). Error bars are assigned to each point from the variance of the differences binned in 0.01 increments in τ. The solid line represents the predicted relation from ATM and MODTRAN 3 atmospheric models. A linear fit to the data is also presented (doted line) for comparison.

The good fit to the data allows us to conclude that both models conform to reality, and provides us with a way to determine water vapor corrections needed for MIR photometry from radiometer measurements.

4. CONCLUSIONS

Measurements of the column abundance of atmospheric water vapor above San Pedro Mártir obtained with a 210 GHz heterodyne radiometer show a high degree of correlation with the absorption of the water vapor determined for mid-infrared photometric measurements.

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