CONTRASTS ON THE PRESENCE OF SiO GAS IN THE DEBRIS DISK OF HD 172555

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ABSTRACT

We have carried out two sets of observations to quantify the properties of SiO gas in the unusual HD 172555 debris disk: (1) a search for the J = 8–7 rotational transition from the vibrational ground state, carried out with the Atacama Pathfinder EXperiment (APEX) submillimeter telescope and heterodyne receiver at 863 μm and (2) a search at 8.3 μm for the P(17) ro-vibrational transition of gas phase SiO, carried out with the Very Large Telescope (VLT)/VISIR with a resolution, λ/Δλ, of 30,000. The APEX measurement resulted in a 3.3σ detection of an interstellar feature, but only an upper limit to emission at the radial velocity and line width expected from HD 172555. The VLT/VISIR result was also an upper limit. These were used to provide limits for the abundance of gas phase SiO for a range of temperatures. The upper limit from our APEX detection, assuming an 8000 K primary star photospheric excitation, falls more than an order of magnitude below the self-shielding stability threshold derived by Johnson et al. (2012). Our results thus favor a solid-state origin for the 8.3 μm feature seen in the Spitzer IRS spectrum of the circumstellar excess emission and the production of circumstellar OI and SiI by SiO UV photolysis. The implications of these estimates are explored in the framework of models of the HD 172555 circumstellar disk.

Key words: circumstellar matter – stars: individual (HD 172555) – submillimeter: planetary systems – techniques: spectroscopic

1. INTRODUCTION

The occurrence rate of debris disks containing hot dust around Sun-like stars is very low, ~2% (Bryden et al. 2006a, 2006b; Chen et al. 2006). Recent work suggests that the hot dust around most mature Sun-like stars is transiently regenerated since it is found to be present in quantities far in excess of that expected to arise from sublimation of comets (Beichman et al. 2005) or slow collisional grinding of asteroids left over from the era of planet formation (Wyatt et al. 2007). Terrestrial planets are thought to grow by accumulation of smaller objects, through the process of collisional accretion (Kenyon & Bromley 2004, 2006) on timescales of 10–100 Myr (see Wetherill 1990; Yin et al. 2002; Chambers 2004, and references therein).

As we will discuss, HD 172555, located at a distance of 29.3 pc and belonging to the β Pic Moving Group, is an unusual debris disk system. At an age of more than 15 Myr (Manajek et al. 2014; Bell & Manajek 2015), it is at a stage of development where the dusty primordial disk should have dissipated and giant planets formed (terrestrial planets form in the 10–100 Myr time frame, and HD 172555 is 15 Myr old), yet HD 172555 has been identified as a source with pronounced mid-IR excess emission (Schütz et al. 2005; Chen et al. 2006), which is a signpost of thermally radiating circumstellar dust. Dust and gas present at this late stage of disk evolution is likely secondary, i.e., produced from bodies already aggregated, via impacts and cometary outgassing, forming a debris disk. Collisions of planet-sized objects in debris disks may be distinguished from slow, collisional grinding since the giant collisions produce much larger masses of warm dust than that expected from steady-state collisional evolution (Wyatt et al. 2007, 2011). Unlike most young debris disks, and debris disks in general, the dust surrounding the primary star of HD 172555 is peculiar. Lisse et al. (2009) took Spitzer/IRS spectra with λ/Δλ = 90, covering wavelengths λ = 5–35 μm and combined these results with additional IR photometry to determine the spectral energy distribution from 5 to 100 μm. They showed that a large amount of fine dust with a temperature of 245 K was at 5.8 ± 0.6 au from the primary (Lisse et al. 2007), consistent with the later measurements of Pantin & di Folco (2011) using “Lucky Imaging,” and Smith et al. (2012) using VLT/MIDI interferometry that showed that the circumstellar dust emission arises from an axisymmetric torus of radius 1–8 au (Smith et al. 2012) (0″2 at 29.3 pc). The dust mineralogy is composed primarily of highly refractory, nonequilibrium materials, with approximately three quarters of the Si atoms in silica (SiO2) species. Tektite and obsidian laboratory thermal emission spectra (nonequilibrium glassy silicas found in impact and magmatic systems) are required to fit the data (Lisse et al. 2009). The best-fit model size distribution for the observed fine dust is a number-size distribution of

\[ dn/da = a^{-3.95 ± 0.10}. \]

While IR photometry of the system has remained stable since the 1983 IRAS mission, this steep size distribution, with abundant micron-sized particles, argues for a fresh source of material within the last 0.1 Myr (Lisse et al. 2009; Johnson et al. 2012).

In a re-analysis of the HD 172555 data, Johnson et al. (2012) argued that the 8.4 au torus containing the ~1017 molecules of gas phase SiO reported by Lisse et al. (2009) would have to be optically thick in the UV to provide self-shielding stability over decades for any circumstellar SiO gas, while being optically...
thin in the IR to allow detection by Spitzer but reducing any radiation pressure forces on the dust. In addition, from blended 8 μm features, Lisse et al. (2009) reported that 10^{47} SiO molecules were present in the gas phase and proposed that the most likely source of the fine dust and gas phase SiO was a massive hypervelocity impact between two rocky planetoids which liberated huge amounts of melted and reformed ejecta. Such a torus should also contain an abundance of silicon and oxygen atoms. Johnson et al. (2012) found that about 10^{48} atoms of Si and O vapor would be needed to prevent the radiation pressure forces on the dust. In addition, from blended doublet lines, possibly associated with falling evaporating molecules were present in the gas phase and proposed that the vibrational ground state: one at 303.93 GHz and the other at 347.33 GHz. At that frequency, the full width to half-power (∆ν) of the center of the spectrometer band is 0.7 km s⁻¹. The excitation temperature, T_{ex}, characterizes the populations of the upper and lower levels:

\[ \frac{n_u}{n_l} = \frac{g_u}{g_1} e^{(-E/T_{ex})}, \]

where \( n_u \) is the population of the upper level, \( n_l \) is the population of the lower level, and \( E \) is the energy of \( n_u \) above \( n_l \) in K. For the 863 μm line, we can simplify Equation (1) with an off-source integration time in the position-switching mode, with an off-source position 10′ from the source position. Calibration was made using the chopper wheel procedure (see, e.g., Dumke & Mac-Auliffe 2010; Wilson et al. 2013). The GILDAS software package with CLASS commands was used for reducing and adding data from all scans, performing baseline subtraction, and fitting a Gaussian to the flux at the line position. The final spectrum is shown in Figure 1 and line parameters in Table 1.

2.2. VLT

The P(17) transition from the (ν = 1, J = 17) to the (ν = 0, J = 18) energy level of SiO gas lies in the mid-IR with a rest wavelength of λ = 8.305 μm, or ν = 3.61 × 10^{13} Hz. Usable VLT/VISIR data were taken on 2010 August 19 and 20, from Paranal in fair weather. The VISIR spectrometer was used in the high resolution cross-dispersed chopping mode, with a resolution of \( \nu/\Delta\nu = 3 \times 10^4 \), so each channel has a width of 10 km s⁻¹. At 8.3 μm, the diffraction limited FWHM beam size is 0.″72. The total integration time was 3220 s. The bandpass correction for telluric lines was determined from measurements of α Cen. The offset from zero level in the VLT data from chopping was set equal to the flux density from the broadband Spitzer spectrum for this wavelength, 1.47 Jy, to establish the calibration (see Figure 1 of Johnson et al. 2012). The VISIR data were reduced using a suite of IDL routines built to optimize the standard VISIR data reduction of the ESO Recipe Execution Tool (EsoRex, version 3.9.0) as described in Banzatti et al. (2014). The final spectrum is shown in Figure 2, and the results are discussed further in Section 3.

The line parameters are listed in Table 1. Our estimates of the number of SiO molecules in the gas phase are derived in Section 3 below.
Further, we have $T_{\text{MB}} = T_{\text{ex}} r$, $A_{ul} = 2.2 \times 10^{-3} \text{ s}^{-1}$, $g_l = 15$, $g_u = 17$, and $\nu = 347.333 \text{ GHz}$. Then the column density in the $J = 7$ level is given by:

$$N_7 = 1.0 \cdot 10^{11} \cdot T_{\text{MB}} \Delta V.$$  \hfill (4)

The parameters are given in Table 1. A radial velocity of $-22 \text{ km s}^{-1}$ is consistent with the interstellar lines of sodium and calcium found by Kiefer et al. (2014) when observing in the direction of HD 172555. With the detection of a single line, however, no detailed analysis is possible on this potential ISM source.

In the following, we restrict our analysis to the SiO emission assumed to arise from circumstellar material in the HD172555 system. This should have a $V_{\text{LSR}} = 1 \text{ km s}^{-1}$ and an FWHM of $33 \text{ km s}^{-1}$ (Gontcharov 2006; Kiefer et al. 2014). Qualitatively, from a perusal of Figure 1, no line seems to be present above the noise at this relative velocity. Quantitatively, we employed a Gaussian fit, using $V_{\text{LSR}} = 1 \text{ km s}^{-1}$ and an FWHM of $33 \text{ km s}^{-1}$, and find an upper limit of $T_A^* = 2.3 \text{ mK}$ with an rms spectral noise of $T_A^* = 4.63 \text{ mK}$. This is an underestimate of the upper limit to any signal, so we have used the 3 rms noise limit, $T_A^* = 13.9 \text{ mK}$ in the following. From this limit to $T_A^*$ and the assumed line width, we determined the number of SiO molecules in the $J = 7$ rotational level of the vibrational ground state. This is

$$N_7 \leq 5.5 \times 10^{10} \text{ cm}^{-2}.$$  \hfill (5)

In the following equations we use equal signs, although this is an upper limit. The total number of SiO molecules in all rotational and vibrational levels depends on temperature. This number is estimated using the following analysis. The total column density in the ground vibrational state is related to the total column density in all rotational levels in the vibrational ground state, $N(\text{total}, \nu = 0)$, by:

$$N(\text{total}, \nu = 0) = \frac{N_l}{8} \times e^{(E_l/T_{\text{mb}})} \times \left( \sum_j g_j e^{E_{ul}/T} \right).$$  \hfill (6)

where $R_e = 1.05 \text{ K}$ (the molecular constants of SiO are to be found in Barton et al. 2013). Here these are expressed in temperature units. The sum can be replaced by an integral for
Equation (1) if $h \nu \ll kT_{\text{ex}}$. Using \( \zeta \), the spontaneous emission coefficient in the equation of radiative transfer, the Einstein $A$ coefficient between the upper level, $J = 18$, $v = 1$, and lower level, $J = 17$, $v = 0$ is:

$$\zeta_{ul} = \frac{h \nu}{4 \pi} A_{ul} N$$

(9)

where $N$ is the column density in units of cm$^{-2}$ and $h$ is Planck’s constant.

$$F = \int S_\nu d\nu = \frac{h \nu}{4 \pi} A_{ul} N \Delta \Omega$$

(10)

where $N$ is the column density in the upper level (ul). The total number of molecules is estimated from the fraction in the observed level. For this, the summation (Equation (6)) cannot be replaced by an integral. For the VLT, the area subtended by the FWHP of the diffraction beam is $6 \times 10^{27}$ cm$^{-2}$ for a distance of 29.3 pc. The 3\( \sigma \) limit for the flux density in the 8.3 \( \mu \) line is $\lesssim 0.48$ Jy in a 10 km s$^{-1}$ wide channel. The other parameters are $v = 1$, $J_0 = 17$, $J_1 = 18$, and $A_{ul} = 3.44 \times 10^{-11}$ from the Barton et al. (2013) molecular data.

Estimates of the total number of SiO molecules in the gas phase, from our data and from Lisse et al. (2009), are plotted in Figure 3 as a function of temperature. Our APEX data in Figure 1 were analyzed using Equations (5), (6), and (8) under the assumption of LTE. For $T = 8000$ K, the curve based on the APEX data is more than a factor of $10^2$ below the value reported by Lisse et al. (2009), while the VLT limit is more than a factor of $10^3$ below the value of Lisse et al. (2009). For $T = 300$ K, the APEX data are more significant, being more than a factor of $10^3$ below the value of Lisse et al. (2009).

4. DISCUSSION

The 2.3 km s$^{-1}$ wide line at $V_{\text{LSR}} = -22$ km s$^{-1}$ arises in the interstellar medium (see, e.g., Kiefer et al. 2014), so is not related to gas in the disk associated with HD 172555. Although weak, the radial velocity is in agreement with the value for the interstellar atomic lines found by Kiefer et al. (2014). We will not discuss this feature in the following, but note that this result shows that the APEX system has functioned satisfactorily during our observations. In the following, we concentrate on the upper limit for SiO at $V_{\text{LSR}} = 0$ km s$^{-1}$.

According to Johnson et al. (2012), the abundance must exceed $10^{17}$ to allow survival against photodissociation of the SiO in the environment of HD 172555. With the re-assessment of the classification of the central star, the amount of SiO is lower, but the VLT data set an upper limit much lower than $10^{27}$ for $T \geq 300$ K, while the APEX limit is below this value for all temperatures considered. Taken together, these results indicate that the abundance based on the feature in the Spitzer spectrum of Lisse et al. (2009) should be reduced. On the basis of the gas disk analysis of Johnson et al. (2012), it is likely that SiO in the gas phase would not survive; instead, any SiO gas produced by a giant hypervelocity impact should be photolyzed into Si + O atoms by the strong UV flux of the A7V primary, producing the O I population detected by Herschel (Riviere-Marichalar et al. 2012). To explain the 8 \( \mu \)m emission feature seen in the Spitzer data, Johnson et al. (2012) suggested an alternative explanation for its source: this would be a shoulder seen from thermal emission produced by fine-grained, amorphous, hydrated silica (i.e., opalescent) smokes, as seen.

3.2. The VLT Data

There is no obvious spectral line in the 8.3 \( \mu \)m VLT/VISIR spectrum, so we have used three times the rms limit in a single spectral channel as the limit. This is $0.48$ Jy in a 10 km s$^{-1}$ channel. For the $P(17)$ transition, the wavelength is 8.380 \( \mu \)m. For the following analysis, we follow the approach used in Lisse et al. (2009). This can be obtained from

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Figure 3. Plot of limits for the total abundance of gas phase SiO in HD172555 as a function of the LTE temperature. For $T \geq 500$ K, the lowest curve is based on our VLT measurement of the ro-vibrational $P(17)$ line at 8.3 \( \mu \)m. The next higher curve is based on our APEX measurement of the $J = 8-7$ rotational transition at 347.33 GHz. The downward arrows indicated that these values are upper limits. The horizontal line shows the abundance of gas phase SiO reported by Lisse et al. (2009) from their Spitzer data.

$E_{\text{rot}}/k$ greater than 5 K. Then for $J = 7$ we have:

$$N(\text{total}, \nu = 0) = \frac{N_f}{15} \times \left( \frac{T}{1.05} \right) \times e^{\left(\frac{E_{\text{rot}}}{T}\right)}$$

(7)

The total column density is the sum over the populations of the vibrational states, given by:

$$N(\text{total, vibrational}) = \sum_{\nu=0} e^{E_{\text{rot}}/T}$$

(8)

where $E_{\text{rot}} = 1758$ K is the energy of the $\nu = 1$ state above the ground state, in K, and the vibrational levels are very nearly equally spaced by this energy. The column density of SiO molecules, in cm$^{-2}$, is the product of Equations (5), (7), and (8). The total number of SiO molecules is the product of the column density and and the beam area in cm$^2$. The FWHP beam of APEX at the line frequency is 17\(^\circ\)6; taking this as the diameter, the beam area is $4.7 \times 10^{31}$ cm$^2$. The upper limit to the total number of SiO molecules is plotted as a function of temperature in Figure 3. We allow a wide possible range of excitation temperatures since arguments have been made in the literature by Lisse et al. (2009) for the excitation of SiO at 8000 K, the stellar surface temperature, and by Johnson et al. (2012) for an excitation at 245 K by intermixed dust. For two extreme values, 300 K and 8000 K, the 3\( \sigma \) limit for the total number of SiO molecules is $\lesssim 5.5 \times 10^{43}$ and $\lesssim 4.2 \times 10^{45}$, respectively.
in laboratory spectra by Speck et al. (2011) and as detected on the surface of Mars by Ruff et al. (2011) and Sun et al. (2015).

If the abundance of gas phase SiO is close to our limit, there are a number of additional findings. First, the dissociated SiO gas could be a source of the O i detected by Herschel, so we do not require substantial CO (Moór et al. 2011) or CO2 gas to do so. The lifetime against photodestruction for O i is considerably longer than that of gas phase SiO, so the abundance of gas phase SiO would have been larger in the past; thus the presence of O i is consistent with a hypervelocity collision 10^7 years ago (Johnson et al. 2012). Alternatively, Riviere-Marichalar et al. (2012) speculate that the O i may have been produced by the slow destruction of grains, that is, collisions, sublimation, or sputtering, and remained in place since this species is less affected by radiation pressure than SiO. Second, the heating and vaporization of rocky dust material that produces SiO could also produce the CaII and NaI detected by Kiefer et al. (2014) since a process that destroys the SiO lattice of silicate dust should also liberate the associated cations in the matrix.

Our abundance is based on the 3σ upper limits from two non-detections. A reasonable follow-up to go deeper and search for a detection of total SiO abundances down to 10^{42}, while also mapping the system in the dust continuum, could be provided by a short integration (1 hr, including calibration) with the ALMA array using a resolution of 0"/2. SiO abundances in the 10^{42} range are expected if the Kiefer et al. (2014) detection of Ca ii and Na i are due to the destruction of rocky material in-system.

5. CONCLUSIONS

We have a 3.3σ detection of the J = 8–7 rotational line (Figure 1) from the interstellar medium toward HD 172555. For gas associated with HD 172555 itself, we have the 3σ limits for the J = 8–7 rotational line and the P(17) ro-vibration line at 8.3 μm of gas phase SiO, the conclusions are as follows:

1. From the APEX data, our upper limit for 300 K, the limit is 5.3 × 10^{43}. The APEX data are more sensitive to cooler gas, so these results preclude large amounts of cooler gas phase SiO. For T = 8000 K, the total LTE abundance of gas phase SiO is less than 4.4 × 10^{45}.

2. From the VLT data our upper limit for the total LTE is less than 2.7 × 10^{47} at 8000 K. At lower temperatures, the abundance is smaller. See Figure 3 for the dependence of abundance on temperature.

3. The upper limit obtained with APEX, if interpreted as representative of the minimum past SiO gas content of the system, does not exclude SiO as a source of the O i detected with Herschel, so substantial amounts of CO or CO2 gas are not required.

4. The heating and vaporization of rocky dust material that could produce gas phase SiO to the upper limit found with APEX could also produce the Ca ii and Na i detected by Kiefer et al. (2014).

5. With the SiO gas stability analysis of Johnson et al. (2012), revised down to about 5 × 10^{48} molecules for the approximately two times lower UV flux for an A6V type primary star, our upper limit on SiO gas suggests that the feature in the Spitzer spectrum previously attributed to gas phase SiO is caused by an amorphous silica compound.

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