The disk around HD 142527 attracts a great amount of attention compared to others because of its resolved (sub-)millimeter dust continuum that is concentrated into the shape of a horseshoe toward the north of the star. In this Letter we present spatially resolved ALMA detections of the HCN $J = 4–3$ and CS $J = 7–6$ emission lines. These lines give us a deeper view into the disk compared to the (optically thicker) CO isotopes. This is the first detection of CS $J = 7–6$ coming from a protoplanetary disk. Both emission lines are azimuthally asymmetric and are suppressed under the horseshoe-shaped continuum emission peak. A possible mechanism for explaining the decrease under the horseshoe-shaped continuum is the increased opacity coming from the higher dust concentration at the continuum peak. Lower dust and/or gas temperatures and an optically thick radio-continuum reduce line emission by freezing out and shielding emission from the far side of the disk.

Key words: circumstellar matter – protoplanetary disks – stars: individual (HD 142527) – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

High-resolution spatially resolved observations of protoplanetary disks with a gap or central hole, i.e., transitional disks, show that these disks are often rich in azimuthal structure. These asymmetries can be divided in two groups that either trace the disk surface or the disk mid-plane. Scattered light (e.g., Fukagawa et al. 2006) and 12CO molecular line observations, e.g., spiral arms (Christiaens et al. 2014), trace the disk surface. Radio continuum observations trace the bulk of the dust mass in the disk mid-plane. Asymmetries in the latter are interpreted as a clustering of larger (millimeter-sized) dust particles (e.g., LkHa 330, SR 21, and HD 135344B; Brown et al. 2009; Pérez et al. 2014), HD 142527 (Casassus et al. 2013) and IRS 48 (van der Marel et al. 2013) and can be explained by the presence of local pressure maxima which “trap” the dust (see, e.g., Lyra & Lin 2013, and references therein for an overview). In theory, these dust traps would correspond to the local minima of the gas-to-dust ratio. Such an atypical physical environment represents an interesting laboratory for gas chemistry.

The disk with the best studied dust trap can currently be found around HD 142527, a nearby (145 pc; Acke & van den Ancker 2004) Herbig Ae/Be star of spectral type F6III. This star is surrounded by a large disk with an inclination estimated to be between $\approx 20^\circ$ (Verhoeff et al. 2011) and $28^\circ \pm 5^\circ$ (Pérez et al. 2014) and a position angle (P.A.) of $160^\circ$. For the analysis presented in this Letter we adopt the latter value of the disk inclination. A large opacity gap seen in continuum emission both in scattered light and (sub-)millimeter emission separates the inner ($\approx 10$ au; van Boekel et al. 2004) and outer disks ($\approx 140$ au; Fukagawa et al. 2006). The outer disk is rich in spiral structure when imaged in scattered light (Fukagawa et al. 2006; Casassus et al. 2012; Rameau et al. 2012; Canovas et al. 2013; Avenhaus et al. 2014) and, at larger scales, CO rotational lines (Christiaens et al. 2014). Using ALMA at 870 $\mu$m, the outer disk is resolved into a horseshoe-shaped dust continuum that peaks at a P.A. of 35$^\circ$ at a radial distance of $\approx 1''$ (Casassus et al. 2013; Fukagawa et al. 2013) with a surface intensity contrast ratio of $\approx 30$ compared to the minimum of the continuum emission at a similar radius on the other side of the star. Various $J = 3–2$ and $J = 2–1$ CO isotopes have been detected coming from the outer disk but also from within the gap, and HCO$^+$ $J = 4–3$ emission is seen from the outer disk with a decrement coincident with the horseshoe-shaped dust continuum and in two gap-crossing filaments (Casassus et al. 2013).

In this Letter we present the detection of the HCN $J = 4–3$ and CS $J = 7–6$ emission lines at rest frequencies of 354.50547 and 342.88286 GHz, respectively, from the disk around HD 142527. HCN is a molecule commonly detected from disks (e.g., Dutrey et al. 1997; Thi et al. 2004; Kastner et al. 2008; Fuente et al. 2010; Öberg et al. 2010, 2011). The $J = 4–3$ transition has a critical density $n_{\text{crit}}$ of $8.5 \times 10^6$ cm$^{-3}$ (Thi et al. 2004). Its dominant destruction mechanisms in disks are accretion onto dust grains, charge transfer reactions with H*, the ion–molecule reaction with C*, protonation reactions with H$_2$C*, HCO*, and H3O* and, higher up in the disk at $\approx 1.5$–2 scale heights, photodissociation by stellar UV photons (Semenov & Wiebe 2011).

CS emission has been detected coming from a few disks (e.g., CS $J = 5–4$ and $J = 3–2$; Dutrey et al. 1997; Fuente et al. 2010; Guilloteau et al. 2012). The $J = 7–6$ line presented in this work is the first detection of this rotational transition from a disk. CS is a gas-phase reservoir for sulfur and its higher rotational transitions especially appear to be good tracers for dense gas because of their relatively high critical densities ($n_{\text{crit}} = 2.9 \times 10^6$ cm$^{-3}$ for $J = 7–6$; Thi et al. 2004). CS destruction pathways are photodissociation in the disk atmosphere, depletion onto dust grains, slow endothermic oxidation reaction

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Figure 1. CS $J = 7–6$ (top row) and HCN $J = 4–3$ (bottom row) integrated intensity (left), velocity centroid $v_\circ$ (middle), and peak intensity $I_{\text{peak}}$ (right). The $v_\circ$ and $I_{\text{peak}}$ maps have been created using the maximum intensity of the spectrum at each location providing a $>3\sigma$ signal. Overplotted on the integrated intensity map are intensity contours spaced at three times the noise level of this map (0.014 and 0.018 Jy km s$^{-1}$ beam$^{-1}$ for CS $J = 7–6$ and HCN $J = 4–3$, respectively). The $v_\circ$ and $I_{\text{peak}}$ maps are obtained using all signal above three times the rms as determined from individual channels not containing line emission. The x- and y-axes are labeled in arcseconds; north is up and east is to the left. The position of the star is given by a plus sign and the beam is shown in the bottom left. We show the dust continuum emission at 30% of its maximum with a black line. For clarity, we mark the near and far sides of the disk in the velocity centroid map of the HCN 4–3 emission.

(A color version of this figure is available in the online journal.)

Figure 2. Selected channel maps showing three channels of the HCN 4–3 emission within the gap near the systemic velocity of 3.6 km s$^{-1}$. The black contour denotes $0.2 \times$ the peak intensity of the moment 8 map. Notation is similar to that in Figure 1.

(A color version of this figure is available in the online journal.)

(For $CS + O \rightarrow CO + S$), charge transfer with ionized hydrogen atoms, and ion–molecule reactions with primal ions, e.g., HCO$^+$, H$_3$O$^+$, and H$^+_3$ (Semenov & Wiebe 2011).

2. OBSERVATIONS AND DATA REDUCTION

For the observing strategy and data reduction, we refer to Casassus et al. (2013). In short summary, imaging of the CS and HCN lines was performed using the CLEAN task in CASA (Hogbom 1974). The data presented in this Letter are binned in spectral channels of 0.214 km s$^{-1}$ in width and CLEANed to an rms noise level of 12 mJy channel$^{-1}$ with a synthesized beam size of $0.56 \times 0.35$ and a P.A. of $67^\circ$.

We note that the default continuum subtraction scheme in the visibility domain left residuals that stand out as extended negatives following the horseshoe shape of the continuum in the spectral vicinity of the CS $J = 7–6$ line. We found no continuum subtraction artifacts in the spectral vicinity of the HCN $J = 4–3$ line. We correct for this by sampling an average continuum subtraction artifact from the spectral channels within 7 km s$^{-1}$ on either side of the affected line between $-6$ and 1 km s$^{-1}$ and 6 and 13 km s$^{-1}$, respectively. We subtract this average from all spectral channels used in our analysis of the CS $J = 7–6$ line. Removing these negatives increased the integrated CS $J = 7–6$ line flux by 38%.

3. RESULTS

We detect HCN $J = 4–3$ and CS $J = 7–6$ emission from the outer disk around HD 142527. We show the CS $J = 7–6$ and HCN $J = 4–3$ integrated intensity, velocity, and peak intensity maps in Figure 1, selected channel maps of the HCN $J = 4–3$ emission in Figure 2, the integrated emission lines in Figure 3, and the azimuthal brightness variation in Figure 4.
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3. DISCUSSION

3.2. HCN J = 4–3

The integrated HCN J = 4–3 line shape is similar to that of the CS line, but only shows the red peak. The line FWHM is 2.52 ± 0.21 km s⁻¹ and has an integrated flux of 1.73 ± 0.05 Jy km s⁻¹ (1σ ignoring calibration uncertainties). The CS emission traces the outer disk, and there is a strong asymmetry between the near and far side of the disk. In the outer disk, the emission is strongest toward the southwest (P.A. = 200°–240°), while there is only faint emission coming from the region co-spatial to the peak continuum emission. We show the radial intensity cuts in the direction of the peak molecular and peak continuum emission in the right panel of Figure 5.

The segmented appearance of the peak intensity maps is caused by the discretization of the velocity field in channel-averaged visibilities, and is discussed in Christiaens et al. (2014). Both emission lines vary as a function of azimuth and are suppressed in regions with strong continuum emission. The HCN J = 4–3 line originates from radii smaller than the CS J = 7–6 emission at all azimuths. In the outer disk, CS J = 7–6 and HCN J = 4–3 emission is detected beyond the horseshoe, and HCN J = 4–3 marginally on its inside as well. The emission for both lines is strongest close to where the continuum emission is weakest (see Figure 5).

We see no counterpart for the CS and HCN emission with the spiral structure seen in scattered light and CO rotational lines. We discuss the CS and HCN emission in detail in Sections 3.1 and 3.2, respectively.

3.1. CS J = 7–6

The integrated CS J = 7–6 line shows a double-peaked line profile with a FWHM of 2.71 ± 0.21 km s⁻¹ and an integrated flux of 1.67 ± 0.08 Jy km s⁻¹ (1σ ignoring calibration uncertainties). The CS emission traces the outer disk, and there is a strong asymmetry between the near and far side of the disk. In the outer disk, the emission is strongest toward the southwest (P.A. = 200°–240°), while there is only faint emission coming from the region co-spatial to the peak continuum emission. We show the radial intensity cuts in the direction of the peak molecular and peak continuum emission in the right panel of Figure 5.

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3.2. HCN J = 4–3

The integrated HCN J = 4–3 line shape is similar to that of the CS line, but only shows the red peak. The line FWHM is 2.52 ± 0.21 km s⁻¹ and has an integrated flux of 1.73 ± 0.05 Jy km s⁻¹ (1σ ignoring calibration uncertainties). Compared to the CS J = 7–6 line, it traces the disk up to about the same outer radius but a smaller inner radius. The radially integrated emission is strongest toward the southwest (between 200° and 240°), and is weakest where the continuum emission peaks. Emission inside the disk gap is detected at 4σ and 6σ confidence levels to the east and west of the star, respectively, in individual channel maps between 3 and 3.4 km s⁻¹ (see Figure 2), at similar velocities and locations as the gap-crossing streams visible in the HCO+ J = 4–3 reported in Casassus et al. (2013). The radial intensity cuts in the direction of the peak molecular and peak continuum emission are shown in Figure 5.

We note that Öberg et al. (2011) report a 2σ upper limit of 0.77 Jy km s⁻¹ on the HCN J = 3–2 emission line. Assuming that the HCN J = 4–3 and J = 3–2 emission lines are emitted from the same region, optically thin and in LTE, the HCN J = 3–2 2σ upper limit is consistent with the HCN J = 4–3 detection if the excitation temperature is $T_{ex} \geq 30$ K.

4. DISCUSSION

The brightness of the eastern side of the disk in thermal mid-IR emission (Fujiwara et al. 2006; Verhoeef et al. 2011) and the trailing spiral arm toward the west (Fukagawa et al. 2006; Casassus et al. 2012; Christiaens et al. 2014) suggest that the far face of the disk is located toward east-northeast. This orientation and the fact that the CS emission originates from distances larger than the inner rim (see Figure 5) rule out...
emission from the inner rim of the outer disk inclined into the line-of-sight as the source for the brightness asymmetry most clearly seen in the CS emission.

In the following discussion, we assume that the horseshoe-shaped continuum emission from the disk around HD 142527 is caused by dust being trapped, e.g., in a vortex, which leads to a locally enhanced dust-to-gas ratio and a different dust size distribution (Birnstiel et al. 2013). The lack of CS and HCN emission under the horseshoe can be qualitatively understood when considering the implications of these different local dust properties on the presence of gas-phase CS and HCN molecules in the dust trap. The dust provides an extra surface for surface-chemistry reactions and modiﬁes the local temperature and radiation ﬁeld. Additionally, the dust trap may be optically thick even in the sub-millimeter continuum and have a noticeable effect on the molecular emission line.

4.1. Temperature and Chemistry

Within the dust trap, a pressure maximum preferentially traps larger grains. This size sorting has the effect of increasing the local average grain size which in turn drives a lower dust temperature because the ratio of the mass opacity $k_{\nu}$ in the optical and far-IR is lower for larger grains (Miyake & Nakagawa 1993). The impact of an increased dust-to-gas ratio on gas temperature is not straightforward to quantify. Dust inﬂuences the gas temperature both through cooling by thermal accommodation and through heating by photoelectric heating. Increased dust-to-gas ratios better thermalize the gas which can decrease the reservoir of thermally decoupled gas, and also play a role in the chemistry balance. Higher dust abundances provide increased attenuation of the UV radiation ﬁeld and thus shielding against photodissociation and photodesorption. An enhanced dust abundance furthermore provides an extra surface for chemical processes such as the freeze-out of CO, H$_2$O, CS, and HCN molecules. Modelling the effect of a dust trap on the local gas temperature is beyond the scope of this Letter. For a discussion on the effect of increasing the dust-to-gas ratio on the gas temperature, see chapter 6 of van der Plas (2010), who ﬁnd that increasing the dust-to-gas mass ratio with a factor of 10 led to a decrease in gas temperature and reduced the amount of thermally decoupled (from the dust, i.e., gas that is possibly contributing to line emission) CO gas by a factor of three.

Observations that support this interpretation are the local minima observed in the $^{13}$CO and $^{18}$O J = 2–1 isotopologues co-spatial to the horseshoe-shaped dust continuum emission (Perez et al. 2014), which can be interpreted as a lower temperature at the line-forming region or the freeze-out of CO molecules. Abundant crystalline water ice has also been detected from the outer disk (Malfait et al. 1999; Honda et al. 2009). CS and HCN in disks both freeze out at temperatures of $\sim$50–60 K (Garrod & Herbst 2006), between the condensation temperatures of CO and H$_2$O. Based on the peak of the spectral energy distribution at 60 $\mu$m in the Infrared Space Observatory spectrum published by Malfait et al. (1999), we estimate the dust temperature inside the dust trap, which emits the bulk of the (sub-)millimeter emission, to be $\sim$21 K.

Outside of the dust trap, lower opacities in the UV lead to a higher sublimation and photodissociation rate and temperature deeper in the disk. CS molecules can form at low scale heights in those regions of the disk where water freezes out and CO does not ($T$ between $\approx$20 and 100 K for a typical disk). Water ice traps gas-phase oxygen atoms and prevents the formation of CO, which in turn frees up carbon atoms to form reduced species such as CH and CH$_2$. These molecules can react with sulfur atoms to form CS. HCN molecules have less stringent formation conditions and can reach detectable concentrations higher up in the disk and closer to the star compared to CS molecules (Walsh et al. 2010).

4.2. Optically Thick Continuum

Continuum opacity effects—a (partially) optically thick outer disk—are an alternative explanation for the attenuated molecular emission under the dust trap. HD 142527 is extremely bright in the sub-millimeter and to fit the observed (sub-)millimeter emission a dust mass of $1.0 \times 10^{-3} M_\odot$ is required. This model has a maximum opacity at 850 $\mu$m of $\tau = 2.76$ at the inner rim of the outer disk (M. Min 2014, private communication; Verhoeff et al. 2011). Given the peak ﬂux of 0.36 Jy beam$^{-1}$ and beam size of 0.51 $\times$ 0.33 (Casassus et al. 2013), the Rayleigh–Jeans equivalent brightness temperature of the peak dust emission is $\approx 20$ K and similar to our estimate of the dust temperature. The band 7 continuum is of similar size of the beam and, if radially unresolved, likely to be optically thick.

To check whether shadowing by such an axisymmetric inclined optically thick ring can produce asymmetric features caused by the interception of molecular line emission from the far side of the disk in the line-of-sight toward the observer such as, e.g., the near/far asymmetry as seen in the CS emission maps, we use the radiative transfer model code MCFOST (Pinte et al. 2006, 2009). With a disk model resembling the disk architecture of HD 142527 (the same disk inclination, P.A., and mass, consisting of an inner disk, a disk gap, and an outer disk), we explore a range of models for which, in the inner rim of the outer disk, we vary the dust mass $m_{\text{dust}}$, the CS abundance $\epsilon_{\text{CS}}$, and the dust-to-gas ratio $\delta$. Within a parameter space where we vary $m_{\text{dust}}$ in the inner rim (between 5 and 30 au wide) between $6.6 \times 4 \times M_\odot$ and 4.5 $\times$ 2 $\times M_\odot$, $\epsilon_{\text{CS}}$ between 3.5 e-9 and 3.5 e-11, and $\delta$ between 1 and 100, we fail to reproduce emission maps in which the near side of the inner edge of the outer disk is brighter than the far side. The local concentration of dust particles in a dust trap instead of in an axisymmetric ring enhances the local optical depth further, which in turn can be invoked to explain the horseshoe-shaped decrement observed in the HCN and HCO+/ J = 4–3 and the CO J = 2–1 lines. The emission on the far side of the optically thick regions is absorbed, while only excess temperature relative to the cold background leads to emission on the near side. Thus, an optically thick horseshoe will impart a similarly shaped decrement in line emission maps seen face-on, with some modulation depending on the vertical temperature structure and on the vertical location of the $\tau = 1$ surface.

5. CONCLUSIONS

We report the detection of HCN J = 4–3 and CS J = 7–6 emission from the disk around HD 142527. The emission of both molecules is azimuthally asymmetric, peaks toward the southwest of the disk, and is suppressed in those regions with strong continuum emission. We discard a line-of-sight projection of the inner rim of the outer disk as origin of this asymmetry. We suggest two possible mechanisms that can drive this asymmetry related to the presence of a dust trap: (1) the flatter dust size distribution which drives a lower dust temperature. This in turn can lower the gas temperature and thus emissivity, and promote freeze out of CS and HCN molecules. (2) A
higher (possibly optically thick in sub-millimeter wavelengths) continuum optical depth associated with increased dust concentrations which quenches line emission.

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