Tracing the Water Snowline in Protoplanetary disks with the ngVLA

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1. Introduction

Water is believed to be the most crucial molecule for the habitability of planetary systems (van Dishoeck et al. 2014). Its abundance and distribution in a protoplanetary disk greatly affect the atmospheric and core composition of giant planets (Öberg et al. 2011b) and the surface water content of terrestrial planets (Raymond et al. 2007).

The most critical location in the water distribution is where water vapor condenses into ices, the so-called, \textit{water snowline}. In the Solar Nebula, the water snowline appears to be the critical boundary that separates the formation of terrestrial planets and giant planets (Hayashi 1981).

Theoretical models predict the water snowline is a pivotal location for planetary architecture, as two important physical changes occur at this transition (see Figure 1). The first one is an enhancement in the surface density of solids–as water accounts for about 50% of the total condensible mass, its condensation will significantly increase the solid mass beyond the snowline and accelerate the planetesimal formation (Stevenson & Lunine 1988; Pollack et al. 1996). The second change is the dust size distribution. Icy aggregates are significantly more resistant to compaction than bare silicate aggregates and thus icy aggregates can readily grow to a much larger size (Ros & Johansen 2013; Zhang et al. 2015). Once a critical decimeter-sized pebble population is formed, streaming instabilities can readily drive the creation of km-sized or larger planetesimals (Johansen et al. 2014). On the other hand, the sintering effect may break aggregates and leads to a pile-up of smaller particles in the region slightly outside the snowline (Okuzumi et al. 2016). Therefore the water snowline may play an important role in regulating the formation and chemical composition of planetesimals, and ultimately the formation of planets and their bulk composition.

Despite the importance of the water snowline, it is challenging to pinpoint its location and to quantitatively study its role in planetesimal formation. First of all, planetesimal formation occurs at the dust-rich mid-plane of the disk, while water forms quite readily in disk surface layers (Bethell & Bergin 2009). Thus water line observations can only constrain the surface snowline (Zhang et al. 2013; Blevins et al. 2016). Second,
Figure 1. (a) The sharp discontinuity in the surface density of solids across the water snowline, based on Hayashi’s minimum mass Solar Nebula model. The Figure is adapted from Armitage (2013). (b) An illustrative example of the sharp discontinuity in spectral index \( \alpha \) across the water snowline, as a result of the change in dust particle size distribution. The dust emission is assumed to be optically thin. The figure is from Banzatti et al. (2015).

the water snowline in an accreting protoplanetary disk is around 1-10 AU (Kennedy & Kenyon 2008; Notsu et al. 2016, 2017). At these radii, the dust emission at relevant line frequencies of water or its isotopologues (\( \geq 100 \) GHz) is largely optically thick and thereby hindering a direct detection of the snowline.

2. Tracing the water snowline with ngVLA

Alternatively, the water snowline maybe traced through the sharp changes of physical properties (surface density and dust size distribution) or through the snowlines of other molecules that sublimate co-spatially with water. In both approaches, observations are needed to be taken at frequencies where dust emission is optically thin and with a sufficient spatial resolution to resolve the region inside the snowline. The ngVLA is the only facility that can provide these capabilities.

2.1. Tracing the water snowline through dust property changes

A sharp change of dust properties across a water snowline may have been seen in recent ALMA observations of the V883 Ori system (Cieza et al. 2016). V883 Ori is an FU Ori type source that is undergoing a large outburst in luminosity arising from a temporary increase in the accretion rate. The luminosity outburst warms the disk and pushes the water snowline to a large radius where the dust emission is less optically thick. The 230 GHz continuum emission of the V883 Ori disk shows an intensity break due to an abrupt change in the optical depth at about 42 AU, where the disk temperature is close to the water condensation temperature. Furthermore, the spectral index across the snowline is consistent with predictions from numerical simulations that include the coagulation, fragmentation and radial drift of dust grains (Banzatti et al. 2015).

The V883 Ori study was possible thanks to its large snowline during the luminosity outburst. For the majority of protoplanetary disks, their snowlines are only at 1-10 AU, where the dust emission is highly optically thick at all ALMA bands. Furthermore, even in the V883 Ori case, the region inside the snowline (42 AU) appears to be optically thick at 230 GHz and thus hinders constraints on the dust size distribution. Therefore,
to study the dust size change across a snowline in a large number of disks, observations need to be carried out at much lower frequencies where the dust emission is optically thin. In addition, a higher spatial resolution is needed to spatially resolve the region inside the snowline. Only the proposed ngVLA facility has sufficient sensitivity and resolution to carry out this type of observations.

To resolve a 5 AU water snowline in a disk at a distance of 100 pc, an angular resolution ≤50 mas is needed and a maximum recoverable scale of ≥500 mas is needed to compare regions inside and outside the snowline. To meet the combination of resolution and low dust optical depth, the ideal wavelengths for this experiment is at 30 GHz. The spectral index can be measured across a bandwidth of 20 GHz. For a fiducial disk, the emission is predicted to be strong and a sensitivity of 5 μJy/beam would be sufficient. Higher frequency ALMA observations at a comparable spatial resolution can provide complementary measurements on the dust temperature through optically thick emission, which helps distinguish dust property changes caused by other mechanisms. Through these spectral index observations, we can study whether dust grains grow faster in regions beyond the water snowline and quantitatively constrain the size distribution and surface density of solids across the snowline.

The ngVLA observations will provide the critical measurement of the water snowline locations in disks of different ages and stellar properties. The water snowline locations can be compared to snowlines of other abundant volatiles, such as the CO snowline measured by ALMA (Qi et al. 2013; Zhang et al. 2017). The snowlines of major volatiles set the rough boundaries of planetesimals with different elemental compositions, which further determine the bulk composition of terrestrial planets and cores of gas or ice giants (Öberg et al. 2011b). The spectral index measurements will constrain the dust size distribution and surface density changes across the snowline. These will shed crucial insight into our understanding of the planetesimal formation and the birth locations of giant planets.

2.2. Tracing the water snowline through a proxy: the NH$_3$ snowline

Ammonia (NH$_3$) is a known major constituent of interstellar ices (~5%, Öberg et al. 2011a) and an important tracer of nitrogen chemistry in protoplanetary disks. Laboratory work of ice evaporation has shown at least a portion, or perhaps all of the NH$_3$ ice releases co-spatially with water (Martín-Doménech et al. 2014). Furthermore, NH$_3$ has inversion transitions at cm wavelengths where the dust continuum emission is less optically thick. Given these two advantages, NH$_3$ is the best proxy candidate to trace the water snowline in protoplanetary disks.

To resolve the NH$_3$ snowline, we can either spatially resolve the NH$_3$ emission inside its snowline or obtain high S/N spectra to constrain the gas emitting area through Keplerian velocity field in the disk as well as the centroid of the emission. As the lines are predicted to be faint (see below), the latter case is a more practical approach.

To explore detectability, we assume a minimal model – one that sets limits for how faint NH$_3$ emission would be in the most stringent case. This model assumes no NH$_3$ ice is provided from the ISM and NH$_3$ is made solely by the disk. We then use the model of TW Hya that matches water vapor emission (Du et al. 2015) to predict emission in the 1,1 and 2,2 inversion transitions around 23 GHz. This predicted channel map emission from this model is shown in Figure 2) for TW Hya. This needs to be scaled by one order of magnitude as most disk sources lie a factor of 3 more distant than TW Hya. In the future, we can perform additional calculations that assume interstellar
ices are present and where sublimation would raise the gas phase abundance and hence emission levels. For a NH$_3$ emission detection, we find that a 10σ detection of ammonia 1,1 transition towards TW Hya requires 0.25 mJy in 0.2 km/s channels. To survey NH$_3$ reliably in hundreds of disk systems we need to be able to detect this line at 150 pc at the same level, requiring 25 µJy in 0.2 km/s channels (10σ). However, since lower velocity resolution can be used for detections, a sensitivity of 120 µJy in 1.0 km/s channels (5σ) would be sufficient for a survey.

The detection of the snowline via the model provided here appears be challenging as the required sensitivity in sources at 150 pc would be 30 µJy to detect the emission from the line wings at 150 pc (using the model shown in Figure 2). Since this represents a minimal model (a maximum NH$_3$ abundance of $\sim 2\times10^{-6}$), any additional level of ice evaporation will increase the emission at these channels. Furthermore, we likely will need to observe disks surrounding more massive stars such as B and A spectral type. Here we still must use velocity line profiles to reach material at a few AU. Thus, if NH$_3$ was present in the gas at the level of 5% relative to water ice then its emission within the evaporated zone would be substantially increased, at least until the line becomes optically thick. We estimate that the line will become optically thick when the line is about a factor of 10 higher than the current model or at 300 µJy in 0.2 km s$^{-1}$ channels.

3. Conclusion

The water snowline in protoplanetary disks is one of the most pivotal locations for planet formation: it not only sets a critical boundary of chemical composition in the disk, but may also serve as a favorable site of planetesimal growth and planet for-
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formation. The water snowline at the mid-plane cannot be directly traced by water line observations as the dust emission around the water snowline is highly optically thick at these line frequencies.

In this chapter, we discuss two alternative approaches to trace the mid-plane water snowline – by observing sharp transitions in dust properties across the snowline or by using the NH$_3$ snowline as a proxy. Either approach requires observations at cm wavelengths where the dust emission is likely to be optically thin. We found that with the current design of the ngVLA ability, a sharp transition in dust property across the water snowline can be readily traced through measuring the spectral index of continuum emissions of relatively bright disks. The NH$_3$ snowline detection is likely to be challenging under the current design, but the NH$_3$ abundance can be an order of magnitude higher than our conservative model and thus still be detectable. In summary, the proposed ngVLA is the only facility can provide sufficient sensitivity and spatial resolution to trace the evolution of water snowline at the disk mid-plane and reveal its role in the formation of planetesimals and in building the architecture of planetary systems.

References

Armitage, P. J. 2013, Astrophysics of Planet Formation
Banzatti, A., Pinilla, P., Ricci, L., et al. 2015, ApJ, 815, L15
Bethell, T., & Bergin, E. 2009, Science, 326, 1675
Blevins, S. M., Pontoppidan, K. M., Banzatti, A., et al. 2016, ApJ, 818, 22
Cieza, L. A., Casassus, S., Tobin, J., et al. 2016, Nat, 535, 258
Du, F., Bergin, E. A., & Hogerheijde, M. R. 2015, ApJ, 807, L32
Hayashi, C. 1981, PTPS, 70, 35
Johansen, A., Blum, J., Tanaka, H., et al. 2014, Protostars and Planets VI, 547
Kennedy, G. M., & Kenyon, S. J. 2008, ApJ, 673, 502
Martín-Doménech, R., Muñoz Caro, G. M., Bueno, J., & Goesmann, F. 2014, A&A, 564, A8
Notsu, S., Nomura, H., Ishimoto, D., et al. 2016, ApJ, 827, 113
—. 2017, ApJ, 836, 118
Öberg, K. I., Boogert, A. C. A., Pontoppidan, K. M., et al. 2011a, ApJ, 740, 109
Öberg, K. I., Murray-Clay, R., & Bergin, E. A. 2011b, ApJ, 743, L16
Okuzumi, S., Momose, M., Sirono, S.-i., Kobayashi, H., & Tanaka, H. 2016, ApJ, 821, 82
Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, Icarus, 124, 62
Qi, C., Öberg, K. I., Wilner, D. J., et al. 2013, Science, 341, 630
Raymond, S. N., Scalo, J., & Meadows, V. S. 2007, ApJ, 669, 606
Ros, K., & Johansen, A. 2013, A&A, 552, A137
Stevenson, D. J., & Lunine, J. I. 1988, Icarus, 75, 146
van Dishoeck, E. F., Bergin, E. A., Lis, D. C., & Lunine, J. I. 2014, in Protostars and Planets VI, ed. H. Beuther, R. S. Klessen, C. P. Dullemond, & T. Henning, 835
Zhang, K., Bergin, E. A., Blake, G. A., Cleeves, L. I., & Schwarz, K. R. 2017, Nature Astronomy, 1, 0130
Zhang, K., Blake, G. A., & Bergin, E. A. 2015, ApJ, 806, L7
Zhang, K., Pontoppidan, K. M., Salyk, C., & Blake, G. A. 2013, ApJ, 766, 82