INFERRING THE GAS-TO-DUST RATIO IN THE MAIN PLANET-FORMING REGION OF DISKS
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ABSTRACT
Measuring the amount of gas and dust in protoplanetary disks is a key challenge in planet formation studies. Here we provide a new set of dust depletion factors and relative mass surface densities of gas and dust for the innermost regions of a sample of protoplanetary disks. We do this by combining stellar theory with observed refractory element abundances in both disk hosts and open cluster stars. Our results are independent of, and complementary to, those obtained from spatially resolved disk observations.

INTRODUCTION
Frequently, the dust surface density in protoplanetary disks is measured by spatially resolving its thermal emission and assuming it is optically thin. This assumption is often valid, but not in the inner disk, up to tens of au from the star. This measurement is also insensitive to particles significantly larger than the emission wavelength (typically 0.1 < λ < 10 mm). The gas surface density is mainly estimated via one of two methods (Bergin & Williams 2018): either observations of the rare but rotationally emissive H$_2$ isotopolog, HD (Bergin et al. 2013; McClure et al. 2016; Trapman et al. 2017; Kama et al. 2020) or of optically thin $^{12}$CO isotopologs (Miotello et al. 2016; Williams & McPartland 2016; Zhang et al. 2019; Ruaud et al. 2022). Both of the above require “upscaling” number abundances to that of H$_2$ using assumed isotope ratios and elemental abundances, with uncertainties from chemical networks and volatile element depletion particularly in the case of CO. The gas-to-dust mass ratio (Δ$_{g/d}$) in disks is thus dependent on two quantities whose values are rather uncertain, especially in the inner disk.

Fortunately, for young stars with a mass $\gtrsim$1.4 M$_\odot$ (Herbig Ae/Be stars), a combination of slow internal mixing and high accretion rate leads to the photospheric elemental composition being dominated by recently accreted disk material. This makes the stellar spectrum a direct probe of the gas-to-dust mass ratio in the inner disk where the accretion originates. Indeed, the surface abundance of rock-forming elements (Fe, Mg, Si, etc.) in Herbig Ae/Be stars whose disks have a large dust-depleted inner region (a dust cavity extending outside the nominal dust sublimation front) is lower than the abundance in stars whose disks are “full” i.e., where the dust can freely accrete onto the star (Kama et al. 2015).

METHODS
To accurately use the stellar surface abundances as a probe of the relative ratio of volatile gas to refractory dust in the inner disk, we need the stellar elemental composition for a sample of disk hosts, a stellar mixing model, and a reference composition to anchor the dust depletion factor to.

To explain our approach we focus on iron. To start with, we assume that the stars formed with an iron abundance comparable to that in a sample of non-accreting field stars, and that the bulk of each accreting star has this abundance (X$_{Fe,\text{bulk}}$). In each accreting star, some fraction $f_{\text{acc}}$ of the photospheric material comes from the accretion stream and has composition X$_{Fe,\text{acc}}$. We calculate this using the CAMstars formalism (Jermyn & Kama 2018), which accounts for a variety of stellar mixing processes to match the accretion rate with the rate of mixing between the photosphere and the bulk of the star. The observed photospheric abundance X$_{Fe,\text{obs}}$ is then related to the bulk composition by

$$X_{Fe,\text{obs}} = f_{\text{acc}}X_{Fe,\text{acc}} + (1 - f_{\text{acc}})X_{Fe,\text{bulk}}.$$ (1)
See section 2.4 of Kama et al. (2019) for further discussion of this approach, which is related to those by Turcotte (2002); Turcotte & Charbonneau (1993); Charbonneau & Michaud (1991) and references therein.

We further assume that the accretion stream comes from the circumstellar disk, and that this disk formed with the same composition as the star. As a refractory element, iron is locked in dust in the accretion stream, and so differences between $X_{\text{Fe, acc}}$ and $X_{\text{Fe, bulk}}$ reflect a change in the gas-to-dust ratio due to e.g. dust traps or gas accretion onto planets. We thus define the dust enhancement factor

$$\delta \equiv \frac{X_{\text{Fe, acc}}}{X_{\text{Fe, bulk}}}. \tag{2}$$

This is what we aim to infer.

We use the same sample of stars as in Kama et al. (2019), see appendix A1 for details. In brief, abundances were taken from Fossati et al. (2011), Folsom et al. (2012), Kama et al. (2016), and Martin et al. (2017).

We use abundances for elements Fe, Mg, Si, Ca, Sc, and Ti in our inference procedure, treating each as we treated iron above and using uniform $\delta$ and $f_{\text{acc}}$ across elements. We then employ the Bayesian Multinest sampling algorithm (Feroz & Hobson 2008; Feroz et al. 2009, 2013) to obtain posterior probability distributions on log $\delta$ for each star individually. To allow for the possibility of either a very strong dust depletion or a dust enhancement up to $\Delta_{g/d} = 1$, we set a uniform prior on log $\delta$ over $[-3,2]$ and simultaneously infer $f_{\text{acc}}$, using a gaussian prior distribution calculated with the mean and variance from our CAMstars calculation. Our likelihood is defined as a Gaussian in log $X$, fitting the observed iron abundance for each star using the field sample and equations (1) and (2). Summary statistics from this inference are reported in Table 1. We additionally report the more familiar gas-to-dust mass ratio: $\Delta_{g/d} = 100 \times \delta^{-1}$, where 100 is the standard value, $\Delta_{g/d} > 100$ characterises dust depletion as in a cavity or gap in the dust disk, and $<100$ means enhancement, perhaps from a large influx of pebbles to the innermost disk region.

RESULTS

The gas-to-dust mass ratios presented in Table 1 reveal both dust-enriched ($\Delta_{g/d} < 100$) and -depleted inner disks ($>100$). For this sample, all systems with dust-enriched inner disks are so-called Group II or “full” dust disks where pebbles are expected to drift into the inner disk relatively unobstructed, while the dust-depleted inner disks all belong to the “transitional” category, which are usually disks with a very prominent dust trap (ring) and an inner cavity. Two of the dust-depleted inner disks, while thought to be “full” on large scales, display dust ring structures on $\approx$ sub-au scales (see Kama et al. 2015, for discussion and references).

As an example, models of the disk around HD 163296 have favoured $\Delta_{g/d} < 100$ for the inner regions (Boneberg et al. 2016), consistent with our inferred value of 81. Similarly favourable comparisons can be made for disk models and our measurements in the case of HD 100546. A thorough cross-analysis is however outside the scope of this Research Note, where we aim to provide our measured $\Delta_{g/d}$ values as an inner boundary condition for any analysis of the gas and dust surface density profile in the disks. In particular, our results characterise the disk material that is accreting onto the star, implying it is characteristic of the innermost few astronomical units where most planets are thought to complete their assembly.

DATA AVAILABILITY

The CAMstars software instrument is available on GitHub. The analysis in this work was performed with the individual_open_cluster_Fe.py script, also in that repository.

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Table 1. Summary statistics for the inferred dust enhancement fac-
tor $\delta$ and photospheric accretion fraction $f_{\text{acc}}$ are shown for the stars
in our accreting sample. Values for each are given as median, $-1\sigma$, and $+1\sigma$. We additionally report the gas-to-dust ratio using the me-
dian log $\delta$, calculated as $\Delta g/d = 100 \times (\log \delta - 1)$.

| Star        | $\Delta g/d$ | $\log \delta$ | $-1\sigma$ | $+1\sigma$ | $-1\sigma$ | $+1\sigma$ |
|-------------|-------------|---------------|------------|------------|------------|------------|
| HD169142    | 5129        | -1.71         | -2.62      | -0.72      | -0.35      | -0.46      | -0.25      |
| HD141569    | 4673        | -1.67         | -2.56      | -0.75      | -0.47      | -0.79      | -0.31      |
| T Ori       | 2890        | -1.46         | -2.51      | -0.50      | -0.41      | -0.57      | -0.27      |
| HD144432    | 1443        | -1.16         | -2.41      | -0.24      | -0.61      | -0.84      | -0.41      |
| HD142666    | 987         | -0.99         | -2.33      | -0.25      | -0.41      | -0.55      | -0.23      |
| HD100546    | 301         | -0.48         | -0.56      | -0.41      | -0.01      | -0.01      | -0.00      |
| HD68695     | 210         | -0.32         | -0.40      | -0.25      | -0.01      | -0.01      | -0.00      |
| HD245185    | 194         | -0.29         | -0.37      | -0.20      | -0.01      | -0.01      | -0.00      |
| HD 278937   | 194         | -0.29         | -0.35      | -0.22      | -0.01      | -0.01      | -0.00      |
| HD101412    | 182         | -0.26         | -0.34      | -0.18      | -0.01      | -0.01      | -0.00      |
| HD139614    | 169         | -0.23         | -0.30      | -0.16      | -0.01      | -0.01      | -0.00      |
| HD179218    | 161         | -0.21         | -0.28      | -0.13      | -0.01      | -0.01      | -0.00      |

REFERENCES

Bergin, E. A., & Williams, J. P. 2018, arXiv e-prints, arXiv:1807.09631.  https://arxiv.org/abs/1807.09631
Bergin, E. A., Cleeves, L. I., Gorti, U., et al. 2013, Nature, 493, 644, doi: 10.1038/nature11805
Boneberg, D. M., Panić, O., Haworth, T. J., Clarke, C. J., & Min, M. 2016, MNRAS, 461, 385, doi: 10.1093/mnras/stw1325
Charbonneau, P., & Michaud, G. 1991, ApJ, 370, 693, doi: 10.1086/169853
Feroz, F., & Hobson, M. P. 2008, Monthly Notices of the Royal Astronomical Society, 384, 449, doi: 10.1111/j.1365-2966.2007.12353.x
Feroz, F., Hobson, M. P., & Bridges, M. 2009, Monthly Notices of the Royal Astronomical Society, 398, 1601, doi: 10.1111/j.1365-2966.2009.14548.x
Feroz, F., Hobson, M. P., Cameron, E., & Pettitt, A. N. 2013, Importance Nested Sampling and the MultiNest Algorithm
Folsom, C. P., Bagnulo, S., Wade, G. A., et al. 2012, MNRAS, 422, 2072, doi: 10.1111/j.1365-2966.2012.20718.x
Fossati, L., Folsom, C. P., Bagnulo, S., et al. 2011, MNRAS, 413, 1132, doi: 10.1111/j.1365-2966.2011.18199.x
Jermyn, A. S., & Kama, M. 2018, MNRAS, 476, 4418, doi: 10.1093/mnras/sty429
Kama, M., Folsom, C. P., & Pinilla, P. 2015, A&A, 582, L10, doi: 10.1051/0004-6361/201527094
Kama, M., Shorttle, O., Jermyn, A. S., et al. 2019, ApJ, 885, 114, doi: 10.3847/1538-4357/ab45f8
Kama, M., Bruderer, S., van Dishoeck, E. F., et al. 2016, A&A, 592, A83, doi: 10.1051/0004-6361/201526991
Kama, M., Trapman, L., Fedele, D., et al. 2020, A&A, 634, A88, doi: 10.1051/0004-6361/201937124
Martin, A. J., Stift, M. J., Fossati, L., et al. 2017, MNRAS, 466, 613, doi: 10.1093/mnras/stw3052
McClere, M. K., Bergin, E. A., Cleeves, L. I., et al. 2016, ApJ, 831, 167, doi: 10.3847/0004-637X/831/2/167
Miotello, A., van Dishoeck, E. F., Kama, M., & Bruderer, S. 2016, A&A, 594, A85, doi: 10.1051/0004-6361/201628159
Ruaud, M., Gorti, U., & Hollenbach, D. J. 2022, ApJ, 925, 49, doi: 10.3847/1538-4357/ac3826
Trapman, L., Miotello, A., Kama, M., van Dishoeck, E. F., & Bruderer, S. 2017, A&A, 605, A69, doi: 10.1051/0004-6361/201630308

Turcotte, S. 2002, The Astrophysical Journal, 573, L129, doi: 10.1086/342054

Turcotte, S., & Charbonneau, P. 1993, ApJ, 413, 376, doi: 10.1086/173006

Williams, J. P., & McPartland, C. 2016, ApJ, 830, 32, doi: 10.3847/0004-637X/830/1/32

Zhang, K., Bergin, E. A., Schwarz, K., Krijt, S., & Ciesla, F. 2019, ApJ, 883, 98, doi: 10.3847/1538-4357/ab38b9