OUTWARD TRANSPORT OF HIGH-TEMPERATURE MINERALS IN PROTOPLANETARY DISKS: A CRITICAL EXAMINATION OF THE MERIDIONAL CIRCULATION.

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Introduction: The discovery of chondrule debris and minute calcium-aluminum-rich inclusions in Wild 2 samples [1], and more generally the abundance of crystalline silicates in comets constitute evidence for efficient outward transport of material processed in the inner solar system to the periphery of the protoplanetary disk.

While outward transport was a prediction of the X-wind model [2], the relevance of this model for the processing and launching of solids is fraught with several difficulties regarding the very survival of those solids [3], so that most of the recent literature has focused on transport within the disk because of turbulent motions of the gas (e.g. [4-16]).

The source of turbulence in the disk is still the subject of on-going studies. Beside gravitational instability which may dominate at early stages (e.g. [4]), a leading contender is the magneto-rotational instability (MRI; [17]), which however may be suppressed over a large range of heliocentric distances because of insufficient ionization of the gas [18]. Regardless of the physical ingredients included, modelers need to resort to numerical simulations to study the properties of turbulence. However, the simulations modelling the disk on a global scale, typically run for a few centuries, would be prohibitively expensive to extend over several Ma to study the transport of embedded solids. Calculations of the transport of solids in the literature ([4-16]) must thus make assumptions on the statistical properties of turbulence averaged over long timescales, rather than really "recreating" this turbulence *ab initio*.

A widespread such prescription is to treat turbulence exactly like a viscosity ([19-21], [15], [6], [7]). In a protoplanetary disk context, this leads to a mean flow profile (after averaging over turbulent fluctuations) with typically outward flows around the disk midplane and inward flows at high altitude above and below it, even if the net, vertically integrated flow is inward (i.e. accretion toward the Sun). This flow profile is known as the *meridional circulation*. The outward flows at the midplane have been proposed to account for outward transport of high-temperature minerals to comet-forming regions ([6-7]).

However, while a "turbulent viscosity" may yield qualitatively sensible results on global scales e.g. regarding the radial redistribution of the gas in the disk (see e.g. [22]), it is by no means obvious that its smaller-scale consequences should be trusted literally. In fact, recent global simulations of MRI-turbulent disks show no evidence of meridional circulation [23-24]. Whether meridional circulation exists at all may at least depend on the nature of the locally active turbulence (MRI-driven, hydrodynamical…).

But how critical is this ambiguity for the net (vertically integrated) radial transport of solids in the disk? What are its most important determinants? This is what I have set out to investigate [25].

Methods: In this analytical study, I have considered two prescriptions for the *Maxwell-Reynolds tensor*, i.e. the correlations between velocity and magnetic field fluctuations on which the average radial velocity of the gas depend: (i) the "viscous" prescription mentioned above and (ii) a "MHD prescription" inspired by MHD simulations (e.g. [23-24]). The resulting turbulence-averaged velocities of the *gas* as a function of altitude above the midplane are plotted in Fig. 1.

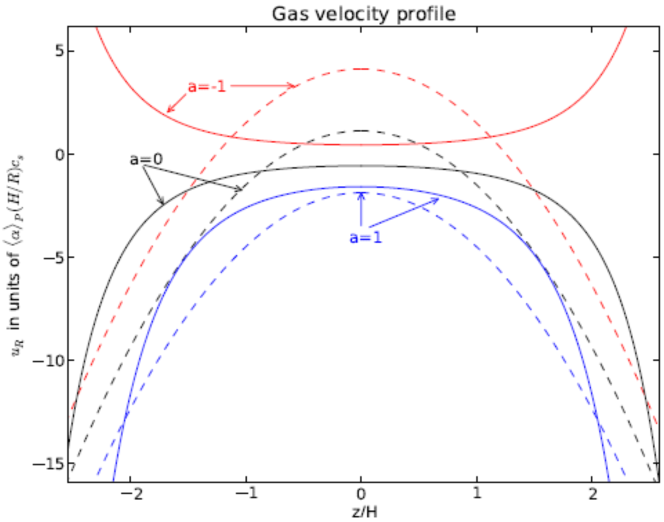

Figure 1: *Mean radial velocity of the gas as a function of altitude z (in units of the pressure scale height H), for the viscous (dashed) and the MHD (solid) prescriptions. (We assume that the midplane turbulence parameter α is proportional to* R^a*, with R the heliocentric distance and a a constant exponent.) The viscous prescription gives rise to the meridional circulation with outward flows around the midplane and inward flows away from it, unlike the MHD prescription.*

I then considered a (single-size) population of solids embedded in the gas, and calculated their net radial velocity integrated over the thickness of the disk at the heliocentric distance of interest. The velocity of the solids differs from that of the gas by a drift term [e.g. 26] due to gas drag in the direction of the pressure gradient (typically inward); the level of decoupling being measured by a “gas-solid decoupling parameter” *S* proportional to particle size [27].

Results and discussion: Sample results are plotted in Fig. 2. It is seen that the curves corresponding to the different prescriptions and parameters differ little, and are well-approximated by the usual 1D approximation “(vertical) average velocity of gas + midplane drift term”, which is generally inward. This is because when $S \ll 1$, particles are tightly coupled to the gas and drift is negligible whereas for $S \gg 1$, the particles are concentrated around the midplane and essentially only the drift there matters.

Still, over a long transport range, a significant difference can arise between the prescriptions. For example, [6] showed simulations of outward transport of crystalline silicates where the crystalline fraction at 10 AU was raised from 17 to 40 % by including meridional circulation, even though, there, the outward transport should be properly attributed to radial diffusion rather than the meridional flow itself (for, as seen in Fig. 2, its vertical average is actually inward; meridional circulation makes it simply slightly less negative and thus a lesser obstacle to outward diffusion). In fact, the difference is within errors of the uncertainty due to the radial *Schmidt number* which ratios the turbulent viscosity to the turbulent diffusivity; only halving the value used by [6] would suffice to retrieve the higher outward transport efficiency in the 1D approximation. A low Schmidt number (that is efficient outward diffusion) ~0.1 was also suggested by [13] to account for the low D/H ratios of water in carbonaceous chondrite and the Earth compared to comets. It however remains to be shown that a low Schmidt number is astrophysically sensible. While it may hold for hydrodynamical turbulence [28], e.g. locally in a dead zone, a wind-driven accretion (e.g. [29]) may imply a *high* effective Schmidt number…

Whatever that may be, the conclusion of this work is that the unsettled question of the 2D flow in the disk has a subordinate effect on the transport of solids. In particular, evidence of outward transport in the early solar system is no evidence for meridional circulation. Only further theoretical studies can shed light on the nature of turbulence and thence the transport conditions of chondrite components in protoplanetary disks.

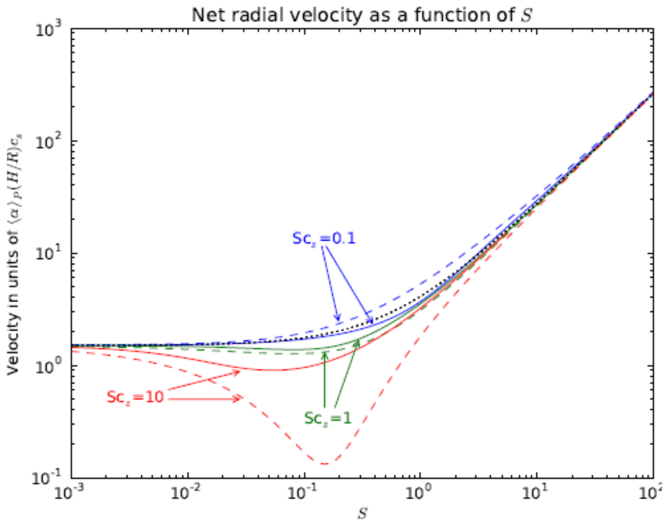

Figure 2: *Vertically averaged (inward-directed) radial velocities of solids as a function of the gas-solid decoupling parameter S, for the viscous (dashed) and the MHD (solid) prescriptions, for various values of the vertical Schmidt number* Sc_z *(the ratio of the turbulent viscosity to the turbulent diffusivity). In general, irrespective of the prescription chosen, the results depart little from the usual 1D approximation (dotted).*

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