Self-Stirring of Debris Discs by Planetesimals Formed by Pebble Concentration

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ABSTRACT

When a protoplanetary disc loses gas, it leaves behind planets and one or more planetesimal belts. The belts get dynamically excited, either by planets (“planet stirring”) or by embedded big planetesimals (“self-stirring”). Collisions between planetesimals become destructive and start to produce dust, creating an observable debris disc. Following Kenyon & Bromley (2008), it is often assumed that self-stirring starts to operate as soon as the first ∼1000 km-sized embedded “Plutos” have formed. However, state-of-the-art pebble concentration models robustly predict planetesimals between a few km and ∼200 km in size to form in protoplanetary discs rapidly, before then slowly growing into Pluto-sized bodies. We show that the timescale, on which these planetesimals excite the disc sufficiently for fragmentation, is shorter than the formation timescale of Plutos. Using an analytic model based on the Ida & Makino (1993) theory, we find the excitation timescale to be

\[ T_{\text{excite}} \approx 100 x_m^{-1} M_*^{-3/2} a^3 \text{Myr}, \]

where \( x_m \) is the total mass of a protoplanetary disc progenitor in the units of the Minimum-Mass Solar Nebula, \( a \) its radius in the units of 100 AU, and \( M_* \) is the stellar mass in solar masses. These results are applied to a set of 23 debris discs that have been well resolved with ALMA or SMA. We find that the majority of these discs are consistent with being self-stirred. However, three large discs around young early-type stars do require planets as stirrers. These are 49 Cet, HD 95086, and HR 8799, of which the latter two are already known to have planets.

Key words: planetary systems – protoplanetary discs – comets: general – circumstellar matter – submillimetre: planetary systems – stars: individual: 49 Cet, HD 95086, HR 8799

1 INTRODUCTION

Debris discs around main-sequence stars are belts of planetesimals that have not grown to full-size planets (Wyatt 2008; Krivov 2010; Matthews et al. 2014; Hughes et al. 2018; Wyatt 2018). They are commonly observed through the thermal emission of the dust that these small bodies release in collisions. To be able to produce that dust, planetesimal populations must be sufficiently stirred, i.e., planetesimals must have relative velocities high enough for collisions to be destructive. Since the initial orbits of planetesimals formed in the protoplanetary phase are expected to be nearly circular and concentrate in the midplane of the disc, some mechanism is required to dynamically excite the planetesimal belts left after the gas dispersal. Which stirring mechanism is at work is a matter of debate. Two main possibilities have been proposed: planetary stirring, i.e., stirring by planets orbiting the star interior or exterior to the planetesimal belt (Mustill & Wyatt 2009) and self-stirring, i.e., excitation of small, field planetesimals by big planetesimals (or dwarf planets) embedded in the belt (Kenyon & Bromley 2010; Kennedy & Wyatt 2010).

This paper deals with the latter mechanism. The timescale on which the relative velocities of small planetesimals get sufficiently large for fragmentation, allowing them to start producing visible dust in collisions, is a sum of two timescales:

\[ T_{\text{stir}} = T_{\text{form}} + T_{\text{excite}}, \]

where \( T_{\text{form}} \) is the formation timescale of big planetesimals and \( T_{\text{excite}} \) is the time it takes for these big stirrers to pump the random eccentricities and inclinations of field planetesimals to the values sufficient for fragmentation.

Formation of Pluto-sized bodies (∼1000 km in radius) is normally considered sufficient to trigger the cascade, although Kenyon & Bromley (2001) inferred that 500 km-sized bodies may suffice. Kenyon & Bromley (2008) simulated the
growth of big planetesimals in a disc, starting from km-sized seeds, in the runaway and oligarchic regimes, and found a convenient analytic formula for the timescale on which the first “Plutos” emerge. Assuming a standard Minimum-Mass Solar Nebula (MMSN) with a solid surface density of \( \sim 1 M_\odot \text{AU}^{-2} (r/\text{AU})^{-3/2} \) around a solar-mass star, such objects would form on a timescale

\[ T_{\text{form}} \approx T_{1000} \sim 400 (r/80 \text{AU})^3 \text{Myr}. \]  

(2)

Since bodies as big as 1000 km would excite the surrounding population of small planetesimals promptly, the second term in Eq. (1) can be safely neglected, resulting in

\[ T_{\text{stir}} \approx T_{\text{form}}. \]  

(3)

This model suggests that young and large debris discs cannot be excited by self-stirring. For instance, discs 110 AU in radius (which is close to the average radius of resolved debris discs, see Pawellek et al. 2014) cannot be self-stirred in systems younger than \( \sim 1 \text{Gyr} \). This has been used to argue that as yet undiscovered planets must be responsible for triggering the collisional cascade in such systems, suggesting them as potential targets for planet searches (e.g., Kennedy & Wyatt 2010; Moór et al. 2015).

However, this analysis comes with some caveats. First, formation of bodies smaller than 1000 km may already be sufficient to induce relative velocities above the fragmentation threshold, which would shorten \( T_{\text{form}} \). Second, Eq. (2) is only valid for a classical formation scenario, in which gravity-assisted collisions starting from km-sized seeds lead to slow, incremental growth of planetesimals (e.g., Kenyon & Lau 1999; Kenyon & Bromley 2008; Kobayashi et al. 2010, 2016). However, in recent years alternative formation pathways for planetesimals have been identified, most notably efficient low-mass solar nebula (MMSN) with a solid surface density of \( \sim 1 M_\odot \text{AU}^{-2} (r/\text{AU})^{-3/2} \) around a solar-mass star, such objects would form on a timescale.

Section 3 gives the resulting formulae for the ‘slow growth’ scenario.

2.1 Small field planetesimals and large stirrers

To describe how planetesimals of mass \( m \) are stirred by those of mass \( M \), we use the analytic theory of Ida (1990) and Ida & Makino (1993). In this section, we assume small planetesimals to be test particles, i.e., set \( m = 0 \). In that case, both stirring of small planetesimals by themselves and dynamical friction are absent, and Eq. (4.1) of Ida & Makino (1993) gives

\[ \frac{\text{d} \epsilon_m}{\text{d} t} = \frac{\epsilon_m + \epsilon_M}{T_{\text{stir}}^2}, \]  

(5)

where \( \epsilon_m = \langle \epsilon_m^2 \rangle \) and \( \epsilon_M = \langle \epsilon_M^2 \rangle \) are the mean squares of orbital eccentricities of small planetesimals, \( \epsilon_m = \langle \epsilon_m^2 \rangle \) are those of large ones, and \( T_{\text{stir}}^2 \) is the viscous stirring timescale specified below. We can assume the big planetesimals to move in circular orbits (\( \epsilon_M = 0 \)), so that Eq. (5) simplifies to

\[ \frac{\text{d} \epsilon_m}{\text{d} t} = \frac{T^{-1}}{\epsilon_m}. \]  

(6)

Assuming that the small planetesimals are in the dispersion-dominated regime, the reciprocal of \( T \) is given by Eq. (4.2) of Ida & Makino (1993):

\[ T^{-1} = C_e \Omega a^2 \left( \frac{M}{M_\star} \right)^2 n_M, \]  

(7)

where \( C_e \approx 40 \) is a numerical factor, \( \Omega \) is the mean motion, \( M_\star \) the mass of the central star, and \( n_M \) the surface number density of big planetesimals with mass \( M \) in the ring of total mass \( M_{\text{disc}} \):

\[ n_M = \frac{M_{\text{disc}}}{M} \frac{1}{2 \pi a \Delta a}, \]  

(8)

so that

\[ T^{-1} = \frac{1}{2 \pi} C_e \Omega \left( \frac{a}{\Delta a} \right) \left( \frac{M}{M_\star} \right)^2 \left( \frac{M_{\text{disc}}}{M} \right)^2. \]  

(9)

The solution to Eq. (6) is

\[ \sqrt{\langle \epsilon_m^2 \rangle} = (2 \pi T)^{1/4}. \]  

(10)

Similar equations hold for the orbital inclinations: \( \epsilon_n = \langle \epsilon_n^2 \rangle \) and \( \epsilon_M = \langle \epsilon_M^2 \rangle \) are replaced by \( \epsilon_n = \langle \epsilon_n^2 \rangle \) and \( \epsilon_M = \langle \epsilon_M^2 \rangle \), whereas the factor \( C_e \) is replaced by \( C_I \approx 2 \). Since \( C_I < C_e \), the eccentricities grow much faster than the inclinations, so that the contribution of the inclinations to the relative velocities between small planetesimals can be neglected:

\[ v_{\text{rel}} \approx v_K \sqrt{\langle \epsilon_m^2 \rangle}, \]  

(11)

where \( v_K \) is the circular Keplerian speed at a distance \( a \) from the star.

If the mean relative velocity of small planetesimals increases to a certain value \( v_{\text{frag}} \) sufficient for fragmentation, the disc gets sufficiently stirred to trigger the collisional cascade and to become a debris disc. Denoting

\[ \epsilon_{\text{frag}} = v_{\text{frag}}/v_K, \]  

(12)
Mean random eccentricity of field planetesimals

\[ \Delta = a_{\text{M}}(\text{lowing "reference case}). We assumed a solar-mass central 
\]

\[ C \equiv 100 M_{\oplus}, \text{ and large stirrers of mass } \]

\[ \rho = 1.0 \text{ g cm}^{-3} \). For this setup, condition (17) is fulfilled.

The black solid line in Fig. 1 depicts the time evolution of \( \sqrt{\langle e_{\text{in}}^2 \rangle} \) in this reference case, as predicted by Eqs. (9)–(10). We also show two typical eccentricity values with horizontal straight lines. The lowest line at \( \sqrt{\langle e_{\text{in}}^2 \rangle} = 2h_{\text{M}} \) is a boundary between the shear-dominated and dispersion-dominated regimes (Ida & Makino 1993). The uppermost line is the rms eccentricity that corresponds to the relative velocities of \( v_{\text{frag}} = 30 \text{ m s}^{-1} \). This is roughly the minimum impact velocity needed to disrupt kilometre-sized planetesimals kept together by gravity (e.g., Benz & Asphaug 1999).

As soon as this line is crossed, which happens in \( \lesssim 10 \text{ Myr} \) in the reference case, we consider the disc to be sufficiently stirred for fragmentation to occur.

We tested the analytic model with numerical integrations, using the Mercury6 package with the Bulirsch-Stoer integrator (Chambers 1999). The setup was the same as in Sect. III.2 of Ida & Makino (1993). As in their runs, we took a central star of mass \( M_{\star} = M_{\odot} \), a ring of radius \( a = 1 \text{ AU} \) and width \( \Delta a = 2 \times 17.4h_{\text{M}} = 0.11 \text{ AU} \), and one stirrer with \( M = 0.035M_{\odot} \). That stirrer was placed in a nearly circular, non-inclined orbit with \( \varepsilon_{\text{M}} = \varepsilon_{\odot} = 0.01h_{\text{M}} = 3.2 \times 10^{-5} \). As Ida & Makino (1993), we traced 800 field planetesimals, each having the mass of \( 0.01M_{\oplus} \). We were able to closely reproduce their results (Figs. 3 to 5 in their paper). We then re-scaled the timescale of this setup to the reference one by means of Eq. (9), multiplying the timescale of that test by a factor of

\[ \left( \frac{d_{\text{ref}}}{a_{\text{M}}} \right)^{3/2} \left( \frac{\Delta a_{\text{ref}}}{\Delta a_{\text{M}}} \right) \left( \frac{M_{\text{ref}}}{M_{\text{M}}} \right)^{-1} \left( \frac{M'_{\text{ref}}}{M'_{\text{M}}} \right)^{-1} \approx 3200, \]

where the superscripts “ref” and “IM” stand for the parameter values of the reference case and the Ida & Makino numerical setup, respectively. The numerical result is overplotted in Fig. 1 with a red solid line. A comparison with the analytic curve demonstrates a reasonable match between the numerics and analytics and the validity of scalings. Besides, the numerical result proves that the field planetesimals get into the dispersion-dominated regime pretty quickly, in \( \ll 1 \text{ Myr} \), even if they start from initially circular orbits. This ensures that Eq. (7) is valid.

Since the Ida & Makino (1993) setup described above is very far from the configurations typical of debris discs we are interested in here, we performed a few additional Mercury6 runs. In those runs, we varied the orbital radius \( a \) of the perturber and its mass \( M \). We also tried setting the mass of small planetesimals to zero. Again, the results of each run were re-scaled to the reference case with the aid of Eq. (9). In all the cases the analytics and numerics agreed to each other within a factor of two, which we deem sufficient for our purposes.

2.2 Planetesimals with a mass distribution

We now assume planetesimals in the ring to have a power-law size distribution from some minimum radius \( a \) (or mass \( m \)) to a maximum radius \( s_{\text{max}} \) (or mass \( M_{\text{max}} \)). The exact
values of \( s \) (or \( m \)) are unimportant: it is only required that \( s \ll S_{\text{max}} \) (or \( m \ll M_{\text{max}} \)).

Denoting by \( \varepsilon(m) \) the mean squares of orbital eccentricities of planetesimals with mass \( m \), by \( n(m)/dm \) the surface number density of planetesimals with masses in \([m,m+dm]\), Eqs. (5) and (7) generalise to

\[
\frac{d\varepsilon(m)}{dt} = C_\varepsilon \Delta a^2 \int_m^{M_{\text{max}}} \left( \frac{M}{M_*} \right)^2 n(M) \varepsilon(m) + \varepsilon(M) \frac{M}{C_\varepsilon(m)} dM. \tag{19}
\]

To keep the problem solvable analytically, we choose to eliminate \( \varepsilon(M) \) from the integrand. Assuming that \( \varepsilon(M) \leq \varepsilon(m) \), which is natural to expect from the dynamical friction, there are two obvious possibilities to do that. The first is to set \( \varepsilon(M) = \varepsilon(m) \), which would result in a slower growth of \( \varepsilon(m) \) than it actually is, and thus in an upper limit on the stirring timescale. The second one is to set \( \varepsilon(M) > \varepsilon(m) \), i.e., to neglect the eccentricity of the stirrers (which are all bodies with mass \( > m \)). This would have the opposite effect, overpredicting the growth rate of \( \varepsilon(m) \) and resulting in the lower limit on the stirring timescale. The exact solution would be between these two limiting cases. Thus we rewrite Eq. (19) as

\[
\frac{d\varepsilon(m)}{dt} = T_{\text{stir}}^{-1} \varepsilon(m), \tag{20}
\]

with

\[
T_{\text{stir}}^{-1}(m) = C_\varepsilon \Delta a^2 \int_m^{M_{\text{max}}} \left( \frac{M}{M_*} \right)^2 n(M) dM, \tag{21}
\]

where \( 1 \leq \gamma \leq 2 \). Eqs. (20) and (21) generalise Eqs. (6) and (7), respectively, to the continuous distribution of planetesimals.

For the surface number density of planetesimals, we assume a power law

\[
n = C(M/M_{\text{max}})^{-\alpha}, \tag{22}
\]

where the normalisation factor \( C \) can be determined from the total ring mass, \( M_{\text{disc}} \). Using

\[
M_{\text{disc}} = 2\pi a \Delta a \int_m^{M_{\text{max}}} M(n(M) dM \tag{23}
\]

results in

\[
C \approx \frac{M_{\text{disc}}}{M_{\text{max}}^2} \frac{2 - \alpha}{2\pi \Delta a}. \tag{24}
\]

Evaluating the integral in Eq. (21) gives

\[
T_{\text{stir}}^{-1} = \frac{1}{2\pi} C_\varepsilon \Omega \left( \frac{a}{\Delta a} \right) \left( \frac{M_{\text{max}}}{M_*} \right)^{2 - \alpha} \left( \frac{M_{\text{disc}}}{M_*} \right)^{3 - \alpha}. \tag{25}
\]

which is independent of \( m \) and only differs from Eq. (9) by the last term containing the power law index \( \alpha \).

The solution to Eq. (20) is

\[
\sqrt{\left( \varepsilon^2 \right)} = \left( \frac{T_{\text{stir}} T}{2\pi} \right)^{1/4}, \tag{26}
\]

and Eq. (13) for the stirring timescale is replaced by

\[
T_{\text{stir}} = \frac{T}{2\pi} T_{\text{frag}}, \tag{27}
\]

Eqs. (22) and (23) show that for \( \alpha \leq 2 \) stirring comes from the largest planetesimals, i.e., those of mass close to \( M_{\text{max}} \).

3 STIRRING TIMESCALES

3.1 Timescales expressed through disc mass

The stirring timescale (27) can be reformulated to show its dependence on all the model parameters:

\[
T_{\text{stir}} = 9.3 \text{ Myr} \times \left( \frac{1}{\gamma} \right) \left( \frac{\rho}{1 \text{ g cm}^{-3}} \right)^{-1} \left( \frac{V_{\text{frag}}}{30 \text{ m s}^{-1}} \right)^{4} \left( \frac{S_{\text{max}}}{200 \text{ km}} \right)^{-3} \times \left( \frac{M_*}{M_\odot} \right)^{-1/2} \left( \frac{a}{100 \text{ AU}} \right)^{7/2} \left( \frac{\Delta a/a}{0.1} \right) \left( \frac{M_{\text{disc}}}{100 M_\odot} \right)^{-1}. \tag{28}
\]

where we assumed \( \alpha = 1.6 \). This is justified by the fact that the models by Johansen et al. (2015) and Simon et al. (2016, 2017) independently and robustly predict \( \alpha = 1.6 \pm 0.1 \). We also note that the stirring timescale depends on \( \alpha \) only weakly, see Eq. (25).

It is natural to compare these results to the Kenyon & Bromley model (2008) timescales (see their Eq. 41):

\[
T_{\text{stir}} \approx 145 \text{ Myr} \times \left( \frac{a}{80 \text{ AU}} \right)^3 \left( \frac{2 M_\odot}{M_*} \right)^{3/2}, \tag{29}
\]

where \( x_m \) can be expressed through the debris ring mass, location, and width (see their Eq. 27):

\[
x_m = \left( \frac{\Sigma}{\Sigma_0} \right) \left( \frac{a}{a_0} \right)^{3/2}, \tag{30}
\]

with \( a_0 = 30 \text{ AU} \), \( \Sigma_0 = 0.18 \text{ g cm}^{-2}(M_\odot/M_*) \), and \( \Sigma = M_{\text{disc}}/(2\pi a \Delta a) \). These formulae can be brought to the same form as Eq. (28):

\[
T_{\text{stir}} \approx 39 \text{ Myr} \times \left( \frac{M_*}{M_\odot} \right)^{-0.35} \left( \frac{a}{100 \text{ AU}} \right)^{3.575} \left( \frac{\Delta a/a}{0.1} \right)^{1.15} \left( \frac{M_{\text{disc}}}{100 M_\odot} \right)^{-1.15}. \tag{31}
\]

Some typical results obtained with Eq. (28) are shown in Fig. 2. Kenyon & Bromley’s timescales given by Eq. (31) are overplotted for comparison. As a caveat, Kenyon & Bromley (2008) find the above formulae as a fit to their results for the range \( x_m \in [1/3, 3] \) only. The models with \( M_{\text{disc}} = 100 M_\odot \) and \( 1 M_\odot \) would correspond to \( x_m = 13.8 \) and 0.14, respectively. However, another case also shown in the figure, \( M_{\text{disc}} = 10 M_\odot \), has \( x_m = 1.4 \), for which the Kenyon & Bromley (2008) model is valid.

Figure 2 provides a justification to Eqs. (3) and (4). Indeed, for the pebble concentration scenario, it shows that the planetesimal formation timescale is negligible compared to the disc excitation timescale, i.e., \( T_{\text{form}} \ll T_{\text{excite}} \). And conversely, for the slow growth scenario, formation of Pluto-sized objects takes much longer than the disc excitation by Pluto after their formation, i.e., \( T_{\text{form}} \gg T_{\text{excite}} \). To draw the latter conclusion, we use the fact that the excitation timescales determined in this work are independent of the assumed planetesimal formation scenario and so also apply to the slow growth model.

Most importantly, Fig. 2 demonstrates that the disc stirring by planetesimals of 100s kilometres in radius formed by pebble concentration occurs more rapidly than stirring by Pluto grown in the classical accretion scenario. At the same time, we see that the timescales we predict are still long enough to be taken into account.
dependent of the debris ring width $x$. This is because the parameter $(34)$ predict a stronger dependence on the stellar mass than on other parameters is different. For instance, Eqs. (33)–(34) are in-

$$T_{\mathrm{stir}} = \frac{129 \text{ Myr}}{x_m} \times \left( \frac{\rho}{1 \text{ g cm}^{-3}} \right)^{-1} \left( \frac{v_{\text{frag}}}{30 \text{ m s}^{-1}} \right)^4 \left( \frac{S_{\text{max}}}{200 \text{ km}} \right)^{-3} \left( \frac{M_*}{M_\odot} \right)^{-3/2} \left( \frac{a}{100 \text{ AU}} \right)^3$$

and

$$T_{\mathrm{KB}} = \frac{801 \text{ Myr}}{x_m^{1.5}} \left( \frac{M_*}{M_\odot} \right)^{-3/2} \left( \frac{a}{100 \text{ AU}} \right)^3.$$  

Unlike Eqs. (28) and (31), Eqs. (33) and (34) are independent of the debris ring width $\Delta$ and the dependence on other parameters is different. For instance, Eqs. (33)–(34) predict a stronger dependence on the stellar mass than Eqs. (28) and (31). This is because the parameter $x_m$, as defined by Kenyon & Bromley (2008), includes $M_*$. A physical basis for their definition is that the protoplanetary disc masses are known to be roughly proportional to the stellar masses (e.g., Williams & Cieza 2011), so that an “MMSN” of a lower-mass star has a lower mass than the one around a higher-mass star.

### 4 APPLICATIONS

We now apply the results to a handful of prominent debris discs to see which of them can and which cannot be self-stirred over their full radial extent. We took a sample of discs resolved by ALMA or SMA from Matrà et al. (2018). Marginally resolved discs (marked with an asterisk in their Table 1) were excluded. The resulting list includes 23 discs with a broad coverage of radii and ages around stars from early to late types.

Figure 3 compares the ages and radial extent of the discs in this sample with the predictions of the self-stirring models, both Kenyon & Bromley’s and the one developed in this work. It demonstrates that all discs can be classified into three groups:

(i) Some discs (including the majority of discs around stars later than G0) can be stirred in both scenarios (e.g., Fomalhaut, $\eta$ Crv, HD 377, 61 Vir, $\tau$ Cet, $\iota$ Eri, AU Mic).

(ii) For some others, however, Kenyon & Bromley’s scenario fails, whereas stirring by 200km-sized planetesimals would work (e.g., HD 131835, HD 138813, $\beta$ Pic, HD 145560).

(iii) Still others do require planets (49 Cet, HD 95086, HR 8799). At least the outer parts of their extended planetesimal belts cannot be self-stirred for any reasonable parameter choices in our model.

The three systems that require planets to explain why their debris discs are stirred are all well-known and truly remarkable:

- One is HR 8799, a young (≈30 Myr) system with a planetesimal belt extending from ≈140 AU to as far as ≈440 AU from the star (Booth et al. 2016). In this system, four planets have been discovered by direct imaging (Marois et al. 2008, 2010), and one more has been suggested (Booth...
et al. 2016; Read et al. 2018) (see, however, Wilner et al. 2018).

- Another one is HD 95086, a 17 ± 4 Myr-old (Mroˇz et al. 2013) star with a broad disc extending from 106 ± 6 AU to 320 ± 20 AU (Su et al. 2017; Zapata et al. 2018) and one massive planet (Rameau et al. 2013a,b).

- The third system is 49 Cet, a 40 Myr-old (Zuckerman & Song 2012) star with a large and broad disc (Hughes et al. 2017; Choquet et al. 2017). One peculiarity of this system is that it is currently the oldest one found to harbour molecular gas in copious amounts (see, e.g., Kral et al. 2017). No planets have been discovered so far around 49 Cet, however.

Since 49 Cet is the only system in this group without known planets, it deserves a closer look. Using the Mustill & Wyatt (2009) planet stirring formulae, Mroˇz et al. (2015) made calculations to estimate the parameters of an alleged planet that would stir the entire 49 Cet disc. At the time only low-resolution Herschel data were available and so they used a conservative estimate of 250 AU as the outer edge of the planetesimal belt. From these calculations they found that a low eccentricity (≤ 0.05) planet could only stir out to such a distance if it were massive (> 6Mjup) and close to the inner edge of the disc at 70 AU (see their Fig. 7). Such high mass planets are clearly ruled out by the observational limits of SPHERE observations that range from ~ 3Mjup at 20 AU to ~ 1Mjup at 110 AU (Choquet et al. 2017). For a planet to satisfy these limits, it would need an eccentricity of at least 0.2 to stir out to 250 AU and higher to stir out to the full extent of the disc as now seen by ALMA (~ 300 AU, Hughes et al. 2017). It is possible though that lower planetary masses would suffice if two or more planets were present in the system (e.g., Lazzoni et al. 2018).

Following Matrà et al. (2018), the above has assumed a simplistic model of a smooth disc with a sharp inner and outer edge. Hughes et al. (2017) note an alternative possibility suggested by the observations of a narrow ring located at 110 AU combined with a broad disc, where the emission beyond 110 AU is coming from small (possibly primordial) grains and so the disc only needs to be stirred out to the lo-
culation of the ring (see also a discussion in Krivov et al. 2013). Assuming this is the case, they then show that a planet responsible for this could easily have a mass lower than the observational limits, whilst also having a low eccentricity orbit. However, if the disc only needs to be stirred out to 110 AU, our results show that self-stirring can explain the dust in this system as the self-stirred region of our model extends out to ~ 250 AU for an age of 40 Myr. Nonetheless, further work is necessary to determine the exact source of these grains at large distance and whether they really can be explained without the need for a collisional cascade at large distances.

Coincidentally or not, all three discs in our sample that require planets are those around stars with spectral classes earlier than F0. This may be surprising, as the stirring timescale is shorter around more massive stars (see Eq. 33). However, this is probably a double bias in our disc selection. First, early-type stars are younger on the average, and second, their discs are larger on the average (Matr`a et al. 2018). Obviously, younger and/or larger discs are more difficult to explain by self-stirring.

It is also interesting to compare our analysis with that of Mo`or et al. (2015). They addressed the same question of whether the discs can or cannot be self-stirred, based on a somewhat different sample which included 11 bright discs well-resolved by Herschel. Five of them (49 Cet, HD 21997, β Pic, HD 95086, and HR 8799) are also part of our sample. Their Fig. 6 compares the radii and age estimates of the discs (not exactly the same as adopted here) with the predictions of Kenyon & Bromley (2008) model. For three out of five discs that appear in both samples, our conclusion is the same as theirs: 49 Cet, HD 95086, and HR 8799 cannot be self-stirred. For the other two discs (HD 21997 and β Pic), the conclusion is different: these discs cannot be self-stirred according to their study, but are compatible with being self-stirred in this work. This difference is readily understood by inspecting Fig. 3. It shows that the ages of these two systems are younger than the timescale of disc stirring by Pluto, but older than the stirring timescale by smaller planetesimals formed by pebble concentration. There is one more disc in their sample, HD 16743 with an estimated radius of 157 ± 20 AU and an age of 10-50 Myr, that appears incompatible with self-stirring. Assuming this radius and age, that disc could be self-stirred in our model.

We can also apply our self-stirring models to other samples. For instance, Holland et al. (2017) reported on outer radii of 16 debris discs resolved in the SONS survey done with the JCMT/SCUBA-2 sub-mm camera (see their Tab. 4). Seven of them are not part of our sample. We computed the self-stirring timescales for these discs by means of Eq. (33) with the same set of parameters as for our sample. We then compared them with the system ages listed in Tab. 1 of Holland et al. (2017). Five of the discs (HD 38585, HD 48682, γ Oph, HD 170773, Vega, and HD 207129) turned out to be compatible with self-stirring. Two other discs (HD 15745 and HD 143894) would require planets as stirrers, at least to explain them over the full radial extent up to the outer edge. These conclusions come with the caveat that the angular resolution of SCUBA2 is lower than that of ALMA and SMA, so that the disc radii given in Holland et al. (2017) are more uncertain than the ones in our sample.

5 DISCUSSION

5.1 Uncertainties of the model

We argue that our model is likely setting an upper limit on the self-stirring timescales, which is to say that in reality the cascade may ignite earlier. There are several reasons to expect this. Firstly, we only considered self-stirring by planetesimals that form “instantaneously” by particle concentration models. Our model does not take into account that these planetesimals, whose sizes are originally smaller than a few 100s of kilometres, may – and most likely will – grow further to Pluto and even gas giant core sizes, either in traditional Kenyon–Bromley–Kobayashi mode or by other mechanisms such as pebble accretion (Lambrechts & Johansen 2012, 2014). Should that subsequent growth proceed faster than the stirring timescales considered here, the cascade will obviously ignite earlier.

Secondly, the stirring timescale drops rapidly with increasing size of the largest planetesimals. Figure 3 assumes $S_{\text{max}} = 200$ km. If the largest bodies are somewhat larger than 200 km, for instance 300 km, which cannot be excluded (Johansen et al. 2015; Simon et al. 2016; Schäfer et al. 2017; Simon et al. 2017), the stirring timescale will shorten by more than a factor of three. Furthermore, the maximum planetesimal size may not be independent of some of the other factors in Eq. (28). For instance, $S_{\text{max}} \propto \alpha^{3/2}$ (Schäfer et al. 2017), meaning that larger planetesimals form farther out from the star. Taking this into account would flatten the dependence of $T_{\text{stir}}$ on $a$, speeding up the stirring in the outer parts of the discs.

Apart from $S_{\text{max}}$, there are a few more poorly known parameters in our model. One is the bulk density $\rho$, which we set to 1 g cm$^{-3}$ in Fig. 3. Using, for instance, 0.53 g cm$^{-3}$ instead, as inferred for the comet 67P/Churyumov-Gerasimenko (Jorda et al. 2016), would double the stirring timescale.

However, most of the uncertainty probably comes from the minimum velocity for fragmentation, $v_{\text{frag}}$. Our choice in the numerical examples above, 30 m sec$^{-1}$, is rather arbitrary. This velocity is directly related to (actually, is roughly a square root of) the critical fragmentation energy $Q_2$, determination of which has been the subject of numerous laboratory impact experiments and hydrocode simulations (see, e.g., Blum & Wurm 2008; Stewart & Leinhardt 2009; Guttler et al. 2010; Leinhardt & Stewart 2012; Blum 2018). The critical fragmentation energy depends on the composition of planetesimals, being quite different for the "pebble piles" predicted by turbulent concentration and streaming instability models and for the "monolithic" bodies formed in traditional slow growth models (see, e.g., Krivov et al. 2018, and references therein). Furthermore, the composition and strength may be different at different distances from the star, and may even change in time during early evolution of the discs. Of course, $Q_2$ and so $v_{\text{frag}}$ are also strong functions of size. Sizes that matter for the stirring calculations are those for which collisional timescales do not exceed the current age of the systems. Thus these vary in time and depend on the distance from the star as well. Another complication arises from the fact that some degree of fragmentation is possible even at velocities insufficient for collisional disruption, through erosive collisions (e.g., Kobayashi et al. 2010). All this makes
choosing the right value for $v_{\text{frag}}$ very difficult. At the same
time, the stirring timescale depends on it very sensitively,
since $T_{\text{stir}} \propto v_{\text{frag}}$. Overall, the resulting timescales we infer
can easily be uncertain to at least one order of magnitude,
perhaps even more.

One more parameter that strongly affects the predicted
stirring timescales is the total mass of a planetesimal disc.
In all the examples given in this paper, we do not consider
planetesimal discs with mass larger than $100M_\oplus$, because
this would exceed the total mass of solids in protoplanetary
progenitors to debris discs, inferred from (sub-)mm surveys
(e.g., Williams & Cieza 2011). However, Krivov et al. (2018)
have shown that bright discs (such as those considered here)
require higher total masses in planetesimals, up to several
$1000M_\oplus$, to be explained with steady-state collisional mod-els. One possibility is that protoplanetary discs are indeed
more massive ($\sim 0.1$– a few $M_\odot$) and larger ($\sim 100$–1000AU)
than usually assumed (Nixon et al. 2018). Such discs would
obviously become gravitationally unstable and might be able
to build planetesimals pretty early. In this case, the total
(observable) mass of planetesimal rings in the outer sys-
tems might, indeed, be much higher than $\sim 100M_\odot$. This
would dramatically shorten self-stirring timescales, meaning
that even the young and large discs do not necessarily
require planets – which does not, however, exclude the pos-
sibility that these are present, as such massive discs should
also form planets quickly.

5.2 Implications of the model

Notwithstanding the uncertainties, we find that sufficiently
young and large discs are clearly incompatible with self-
stirring. Assuming that discs can only be stirred either by
embedded planetesimals or by planets, this automatically
means that one or more planets must be present in such sys-
tems. Furthermore, the stirring criterion is actually a more
compelling diagnostic of planets than the other ones com-
monly invoked. One of these is the fact that all of the de-
bris discs have inner cavities. Even though these are often
attributed to planets inside the discs (e.g., Shannon et al.
2016; Zheng et al. 2017; Lazzoni et al. 2018; Regaly et al.
2018), planetesimal discs might preferentially form in distinct ra-
dial zones (e.g., Carrera et al. 2017). Similarly, many of the
discs exhibit asymmetries that are also considered signposts
of planets (e.g., Lee & Chiang 2016; Löhne et al. 2017). Yet
here, too, there exist alternative scenarios to explain the asymmetries. These include interactions with the ambient
interstellar medium (Debes et al. 2009), recent giant impacts
(Olofsson et al. 2016), gravitational interactions in a debris
disc-hosting multiple stellar system (Shannon et al. 2014;
Kaib et al. 2018), and combinations of these effects (e.g.
Marzari 2012). While accounting for inner gaps or asymme-
tries, not all of these alternative models and scenarios ex-
plain per se why the planetesimal discs get stirred. Thus it is
the stirring requirement that points to planets more unam-
biguously. A caveat is that stirring mechanisms other than
self-stirring and planetary stirring cannot be completely ex-
cluded. Some of the discs could be excited for instance by
stellar flybys in birth cluster environments (Kenyon & Brom-
ley 2002; Kobayashi & Ida 2001) of by as yet undiscovered
external stellar companions (e.g., Thébault et al. 2010;
Thébault 2012).

6 CONCLUSIONS

In this paper, we investigate the birth stage of debris discs.
Since the planetesimals left over after the gas dissipation
should be in low-eccentricity, low-inclination orbits, some
mechanism is required to dynamically excite them to relative
velocities above the fragmentation threshold, allowing them
to produce observable debris dust in mutual collisions. One
natural mechanism would be “self-stirring”, in which smaller
planetesimals are excited by larger planetesimals embedded
in the disc. Following Kenyon & Bromley (2008), it is com-
nonly assumed that self-stirring comes into play as soon as
the first Pluto-sized objects have formed. We explore the
idea that smaller objects, with radii of $\lesssim 200$km, that are
predicted to form in the disc through pebble concentration
by the time of gas dispersal, may be able to excite the plan-
etesimal disc well before the first Plutos are able to form.

Our main conclusions are as follows:

- We conclude that 1000km-sized objects are, indeed, not
  really necessary to stir debris discs. Planetesimals $\sim 200$km
  in size are sufficient. Although 1000km-sized objects would
  stir a disc promptly, their formation takes longer than the
time it takes for much more rapidly forming 200km-sized
  objects to stir the same disc.

- Applying the model to a suite of debris discs resolved
  in the sub-mm, we show that the majority of them could
  be self-stirred by $\sim 200$km-sized planetesimals. However,
  we have identified three discs (HR 8799, HD 95086, and
  49 Cet) that cannot be explained by self-stirring. Such sys-
tems would be the natural targets to search for planets. In-
deed, we note that planets are already known around two
  of these. Further resolved observations of young discs will
  likely produce more candidates for discs where planet stir-
ring is necessary and so more promising targets for planet
  searches.

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