Dust filtration at gap edges: implications for the spectral energy distributions of discs with embedded planets

W. K. M. Rice,1* Philip J. Armitage,2,3 Kenneth Wood4 and G. Lodato5

1SUPA,† Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ
2JILA, Campus Box 440, University of Colorado, Boulder, CO 80309, USA
3Department of Astrophysical and Planetary Sciences, University of Colorado, Boulder, CO 80309, USA
4SUPA,† School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews, Fife KY16 9SS
5Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

ABSTRACT
The spectral energy distributions (SEDs) of some T Tauri stars display a deficit of near-infrared flux that could be a consequence of an embedded Jupiter-mass planet partially clearing an inner hole in the circumstellar disc. Here, we use two-dimensional numerical simulations of the planet–disc interaction, in concert with simple models for the dust dynamics, to quantify how a planet influences the dust at different radii within the disc. We show that pressure gradients at the outer edge of the gap cleared by the planet act as a filter – letting particles smaller than a critical size through to the inner disc while holding back larger particles in the outer disc. The critical particle size depends on the disc properties, but is typically of the order of 10 μm. This filtration process will lead to discontinuous grain populations across the planet’s orbital radius, with small grains in the inner disc and an outer population of larger grains. We show that this type of dust population is qualitatively consistent with SED modelling of systems that have optically thin inner holes in their circumstellar discs. This process can also produce a very large gas-to-dust ratio in the inner disc, potentially explaining those systems with optically thin inner cavities that still have relatively high accretion rates.

Key words: planets and satellites: formation – Solar system: formation – planetary systems: formation.

1 INTRODUCTION
A fraction of T Tauri stars, including TW Hya (Calvet et al. 2002; Uchida et al. 2004), GM Aur (Marsh & Mahoney 1992; Koerner, Sargent & Beckwith 1993; Rice et al. 2003), CoKu Tau/4 (Forrest et al. 2004; Quillen et al. 2004; D’Alessio et al. 2005) and DM Tau (Calvet et al. 2005), present spectral energy distributions (SEDs) that combine little excess flux (above the photospheric level) at near-infrared (near-IR) wavelengths with robust excesses at λ ≳ 10 μm. A similar effect is seen in at least one Herbig Ae/Be star, HD 100546 (Bouwman et al. 2003; Grady et al. 2005). Since circumstellar discs are generally most optically thick in the inner, hottest regions, this observation is noteworthy and indicative of some processes that can create an optically thin inner cavity within the disc. One interesting possibility is that the cavity arises from the tidal truncation of the inner disc by a massive planet (Goldreich & Tremaine 1980; Lin & Papaloizou 1986), in which case the SED observations provide unique constraints on the time-scale and frequency of giant planet formation. However, non-planetary explanations are also possible. Dust can grow rapidly to form solid bodies that contribute negligible opacity in any observed waveband, while larger bodies may themselves suffer destructive collisions or rapid orbital decay due to aerodynamic drag against the gaseous disc (Weidenschilling 1977). Photoevaporation of the outer disc by ionizing stellar radiation can also starve the inner disc of gas, yielding a short inner hole phase even in the absence of a planet (Alexander, Clarke & Pringle 2006). Protoplanetary disc models that include some or all these effects (Takeuchi & Artymowicz 2001; Kenyon & Bromley 2004; Dullemond & Dominik 2005; Takeuchi, Clarke & Lin 2005) admit the formation of dusty rings and inner holes, even in the absence of planets and gas. As improved SEDs and spectra from Spitzer become available, more detailed theoretical study of both classes of model (pure disc and disc plus embedded planet) is warranted in order to determine whether these models can be distinguished without direct imaging data.

A sufficiently massive planet (or brown dwarf) can probably create an inner cavity in which both the gas and the dust surface densities are extremely low. However, out of the four aforementioned T Tauri stars – around which inner disc ‘holes’ are inferred from the lack of near-IR emission – only CoKu Tau/4 appears to be entirely devoid of...
2 GAS-DUST DYNAMICS

The disc gas and the embedded dust particles interact via a drag force (Whipple 1972; Weidenschilling 1977) that is a consequence of the different gas and dust orbital velocities. The Keplerian velocity, \( V_K \), at a radius, \( r \), around a star of mass \( M_* \) is

\[
V_K^2 = \frac{GM_*}{r}.
\]  

If \( P \) is the gas pressure and if \( \rho \) is the gas density, the azimuthal component of the gas velocity, \( v_\phi \), in centrifugal equilibrium differs from the Keplerian velocity due to the influence of the gas pressure gradient and is given by

\[
\frac{v_\phi^2}{r} = \frac{V_K^2}{r} + \frac{1}{\rho} \frac{dP}{dr}.
\]  

The dust particles, on the other hand, are not influenced by pressure forces and, in centrifugal equilibrium, orbit at the Keplerian velocity, \( V_K \).

The effect of the drag force depends on the size of the dust particles relative to the mean free path of the gas molecules. If we assume that the gas is primarily molecular hydrogen, the mean free path, \( \lambda \), is

\[
\lambda = \frac{m_H}{\rho A} \approx \frac{4 \times 10^{-9}}{\rho} \text{ cm},
\]

where \( m_H \) is the mass of the hydrogen molecule and \( A \) is its cross-section \((A = \pi a_0^2 \approx 7 \times 10^{-16} \text{ cm}^2)\). The drag force, \( F_D \), is then

\[
F_D = -\frac{1}{2} C_D \pi a_0^2 \rho \lambda^2 \dot{u},
\]

where \( \dot{u} \) is the relative velocity between the gas and dust particles, \( \dot{u} = |\dot{u}|, \dot{u} = u/u, a \) is the mean radius of the dust grains and \( C_D \) is the drag coefficient, given by

\[
C_D = \begin{cases} 
\frac{8}{3} c_s, & a < 9\lambda/4 \\
24R_e^{-1}, & R_e < 1 \\
24R_e^{-0.6}, & 1 < R_e < 800 \\
0.44, & R_e > 800.
\end{cases}
\]

In equation (5), \( R_e \) is the Reynolds number which can be shown to be given by (see e.g. Rice et al. 2004):

\[
R_e = 4 \left( \frac{a}{\lambda} \right) \left( \frac{\dot{u}}{c_s} \right).
\]

In general, the gas pressure in protoplanetary discs decreases with increasing radius. The pressure gradient is therefore negative and the gas velocity is sub-Keplerian. The drag force then acts to slow the dust particles down causing them to spiral in towards the central star. One can then determine the radial drift velocity of dust particles by self-consistently solving the radial and azimuthal components of the momentum equation as outlined in Weidenschilling (1977). Fig. 1 shows an example of the inward radial velocity \((\dot{r}/dr)\) against particle radius at 5 au in disc with a density of \( \rho(r) = 10^{-11} \left( r/5 \text{ au} \right)^{-2.75} \text{ g cm}^{-3} \) and a temperature of \( T(r) = 125 \left( r/5 \text{ au} \right)^{-0.5} \text{ K} \). The radial velocity is clearly strongly dependent on the particle size, and can reach values of ~10\(^{-4}\) cm s\(^{-1}\).

The inward migration of dust particles, however, only occurs if the pressure in the disc decreases monotonically with increasing
radius. If there are any regions of the disc where the gas pressure increases with increasing radius, the gas velocity will become super-Keplerian, and the drag force will cause dust particles to move outwards towards the pressure maxima. This could occur in the presence of self-gravitating spiral structures (Haghighipour & Boss 2003; Rice et al. 2004), in the presence of vortices (Klahr & Bodenheimer 2003), or if an embedded planet has opened a gap in the disc (Paardekooper & Mellema 2004, 2006). At the outer edge of a gap opened by a planet, the drag force will cause dust particles to migrate up the gap edge, away from the star. If, however, there is still gas accretion through the gap, which is expected for Jupiter-mass companions around solar-like stars, then dust particles moving too slowly up the gap edge will be dragged by the gas into the gap. The gap edge will therefore act like a filter, allowing only particles of a certain size through into the inner disc. Even if the inner gas disc has not drained on to the central star, there could still be a substantial difference between the dust populations in the inner and outer discs, and this could have a notable effect on the disc SED.

To investigate this further, we need an approximation for the pressure gradient at the outer edge of a gap opened by an embedded planet. We therefore perform two-dimensional simulations of gaseous discs with embedded planets to determine the approximate disc structure.

3 PLANET–DISC SIMULATIONS

We simulate a planet embedded in a gaseous disc using the ZEUS code (Stone & Norman 1992). We use two-dimensional coordinates (r, φ) and a resolution of n_r = 400, n_φ = 400. The computational domain extends, in code units, from r_in = 0.5 to r_out = 5, and we impose outflow boundary conditions at both r_in and r_out.

We assume that the disc is isothermal with a radially dependent sound speed given by \( c_s (r) = 0.05 r^{-1/2} \). We adopt units in which \( G = 1 \) and the sum of the masses of the central star and embedded planet is \( M_1 + M_\text{pl} = 1 \). Since the disc thickness \( h/r \) is related to the sound speed through \( h/r \approx c_s/V_K \), we have a disc thickness of 0.05 at \( r = 1 \).

We model angular momentum transport using a kinematic viscosity, \( \nu \), that operates only on the azimuthal component of the momentum equation (Papaloizou & Stanley 1986). The initial disc surface density, \( \Sigma \), is taken to have a radial dependence of \( \Sigma (r) \propto r^{-1} \). Since \( M \propto \nu \Sigma (r) \) and since we would expect \( M \) to be constant, we assume that, \( \nu (r) \propto r \). We normalize the viscosity using the standard alpha formalism, \( \nu = \alpha c_s h \) (Shakura & Sunyaev 1973), and assume that at \( r = 1, \alpha = 10^{-3} \).

The planet is located at \( r = 1 \) and we consider planet masses of \( M_\text{pl} = 5 \times 10^{-4}, 10^{-3} \) and \( 5 \times 10^{-3} \). The simulations are evolved for approximately 1000 planetary orbital periods. Fig. 2 shows the surface density structure of the simulation with \( M_\text{pl} = 10^{-3} \) and illustrates that the inner regions of the disc have been significantly depleted. Fig. 3 shows the surface density profiles for the three different planet masses. Also shown (dashed line) is an empirical fit to the gap edge. The surface density is normalized such that the total disc mass within \( r = 100 \) would be \( 10^{-2} \) in code units. It appears that the chosen function is a reasonable fit to the gap edge, especially where the surface density is steepest, which is the region that would have the largest pressure gradient and hence would be the region where the drag force would have the largest influence on the embedded dust particles. From Fig. 3, a general form for the function representing the gap edge would be

\[
\Sigma_{\text{edge}} = \Sigma_0 r^{-\alpha} \left\{ 1 - \exp \left( \frac{-(r - r_{\text{gap}})^2}{d_{\text{gap}}^2} \right) \right\}^3,
\]

where \( r_{\text{gap}} \) is the inner radius of the gap edge, and \( d_{\text{gap}} \) is the gap scalelength. From the fits in Fig. 3, the gap scalelength is somewhat greater for \( M_\text{pl} = 5 \times 10^{-3} \) than for the lower planet masses, but we assume in general that \( d_{\text{gap}} = r_{\text{gap}}/5 \). The gap depth itself depends on the value of the coefficient \( f \). A large \( f \) value results in a deeper gap with a wider edge, and would correspond to a more massive planet. If we use Fig. 3 as a guide, \( f \approx 0.6 \) would correspond to a planet mass of \( M_\text{pl} = 5 \times 10^{-4} \), while \( f \approx 0.9 \) would correspond to a planet mass of \( M_\text{pl} = 5 \times 10^{-3} \). These simulations have all been performed in scale-free code units. To convert to real units, we simply need to introduce length- and mass-scales. For the problem we are considering here, we will generally assume a mass-scale of \( 1 M_\odot \) giving a total disc mass of \( 10^{-2} M_\odot \) and planet masses of about 0.5, 1 and 5\( M_\oplus \). The length-scale we introduce depends on the assumed semimajor axis of the planet. In the rest of this paper, we will assume a length-scale of 4 au, resulting in a semimajor axis of 4 au and, from Fig. 3, an outer gap edge at \( \sim 6 \) au.

4 DUST MIGRATION AT GAP EDGES

To determine how gas drag influences dust particles at the edge of a gap opened by an embedded planet, we need to know the gas pressure gradient. Equation (7) gives an approximate form for the surface density structure at the edge of a gap. The volume density is then, \( \rho = \Sigma / h \), where \( h = c_s r / V_K \). The sound speed, \( c_s = \sqrt{k T / \mu m_\text{H}} \), where \( \mu = 2.4 \) is the mean molecular weight, \( k \) is Boltzmann’s constant and the temperature, \( T = 280 (\text{au} / r)^{1/2} M_\odot / M_\odot \) (Hayashi 1981) with \( M_\star = 1 M_\odot \). The pressure is then \( P = \rho c_s^2 \) and the pressure gradient at the gap edge can be determined exactly since we have a fully analytic form for the pressure as a function of radius. We should, however, note that since the discs we consider here have optically thin inner regions, the outer edge of the gap will intercept more stellar flux and will be hotter than if the inner disc were optically thick (Dullemond & Dominik 2004; Akeson et al. 2005). A higher temperature will produce a larger pressure gradient. This temperature increase will, however, decay very quickly within the gap edge.
Figure 3. Disc surface density profiles for the three planet masses considered in the gasdynamic simulations. As expected, the gap depth increases as the planet mass increases. The dotted line also shows an approximate analytic fit to the profile of the gap edge which can be used to determine how the presence of a planet influences the interaction between the disc gas and the embedded solid particles.

and so may not be significant at the location where the pressure gradient is largest. Even if the temperature is slightly enhanced, a steeper temperature gradient will act to reduce the effect of the increased temperature. Overall, we would not expect the effect of the increased temperature at the edge of the gap to be particularly significant. Once the pressure gradient is calculated, the technique described in Section 2 can then be used to determine the radial velocity of solid particles at any point on the edge of the gap.

The radial velocity of the solid particles will vary considerably along the edge of the gap. This is illustrated in Fig. 4 which shows the radial velocity against particle size at the edge of a gap in which, \( r = r_{\text{gap}} + 0.2 \) au. As \( r \) increases beyond this point (dash–dot–dot–dotted line), the curves move to the right-hand side (i.e. the particle size at which the radial velocity is maximal increases), and the maximum radial velocity decreases. The radial velocity for all particles smaller than the particle with the largest radial velocity therefore decreases as \( r \) increases. Beyond the peak of the gap edge, the gradient changes sign, the radial velocity changes sign, and solid particles will drift inwards, rather than outwards.

What we wish to determine is the maximum outward radial velocity for particles that would contribute to the SED (e.g. \( a < \sim 0.1 \) cm). This can be determined by simply varying \( r \) until these particles achieve their maximum velocity. In Fig. 4, this would correspond to the dash–dotted line (\( r = r_{\text{gap}} + 0.2 \) au). The two panels in Fig. 5 show the maximum outward radial velocity as a function of particle size for two different surface densities and for three different \( f \) values. In the upper panel, the total disc mass within 100 au would be 0.05 M\(_{\odot}\), while in the lower panel the total mass would be 0.01 M\(_{\odot}\). In both figures, \( r_{\text{gap}} = 4 \) au and \( d_{\text{gap}} = 0.8 \) au. The three curves in each figure correspond to \( f = 0.6, 0.8 \) and 0.9. Based on the simulation results shown in Fig. 3, these could correspond to planet masses of 0.5, 1 and 5M\(_{\oplus}\).

The curves in Fig. 5 show that as \( f \), or planet mass, increases, the peak radial velocity moves to smaller particle sizes. All particles smaller than the peak particle size then have increased radial velocities. The radial velocities in Fig. 5 are, however, measured in the frame in which the gas radial velocity is zero. If there is no accretion (i.e. the radial gas velocity is zero relative to the central
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The surface densities (upper panel) in Fig. 5 and 5 cm s\(^{-1}\) for the lower of the surface densities (lower panel) in Fig. 5. If the mass transfer through the gap edge is unaffected by the planet, the radial gas velocity should then increase as the surface density decreases. When \(f = 0.6\), the surface density when the radial velocity of the particles maximizes is approximately seven times lower than that at the peak of the gap edge. The radial gas velocity should then be approximately seven times higher, which for the upper panel of Fig. 5, and for the mass-transfer rate assumed above, would give \(v_r \sim 7\) cm s\(^{-1}\). This means that only particles smaller than \(\sim 10\) \(\mu\)m will be swept into the gap by the radial motion of the gas since these particles have outward radial velocities less than \(\sim 7\) cm s\(^{-1}\). For \(f = 0.9\), the surface density changes by a factor of 860 and, if the same applies, then the radial gas velocity would then be \(\sim 860\) cm s\(^{-1}\). The maximum particle size that can populate the inner disc is then \(\sim 5\) \(\mu\)m, comparable to that obtained when \(f = 0.6\). An equivalent result is obtained if we consider the lower panel in Fig. 5. The surface density being five times smaller than that in the upper panel results in the particles’ radial velocities also increasing by a factor of 5. For a given mass-accretion rate, however, the radial gas velocity also increases by a factor of 5 and hence the size of particles that would be swept into the gap is roughly independent of the assumed surface density.

On the other hand, numerical simulations by Lubow et al. (1999) suggest that the mass-accretion rate through a gap actually decreases with increasing planet mass, at least for planets with masses in excess of 1\(M_J\). In this case, the gravitational torques from the planet act to inhibit flow through the gap (Lubow & D’Angelo 2006). The rate of decrease with mass appears to be exponential, with the mass-accretion rate decreasing by almost an order of magnitude as the planet mass increases from 1 to 6\(M_J\). If this is indeed the case, then the size of particles that will be swept into the gap by gas accretion should decrease with increasing planet mass. Again considering the upper panel of Fig. 5, if the three curves correspond to planet masses of \(\sim 0.5\), \(\sim 1\) and \(\sim 5\)\(M_J\), then we may expect the gas radial velocity to decrease by an order of magnitude as \(f\) varies from 0.6 to 0.9. The maximum particle size swept into the gap would then decrease by an order of magnitude. For the gas radial velocities considered above, we might expect the maximum particle size to decrease from \(\sim 10\) \(\mu\)m to a few tenths of a micrometre as \(f\) increases from 0.6 to 0.9 corresponding to the planet mass increasing from 0.5 to 5\(M_J\).

Since the above process results in only the smallest dust grains being swept into the gap, we would expect the dust-to-gas mass ratio to be different in the inner disc, compared to the outer disc. It is, however, difficult to make an independent measurement of the gas and dust masses, and hence determining the different dust to gas mass ratios is probably not possible. The presence of a silicate feature in protostellar disc SEDs does, however, depend on the grain size distribution. The presence of large grains tends to wash out the silicate feature. As we will discuss in the next section, SED modelling of those systems with near-IR deficits suggests that the grain size distribution in the inner disc differs from that in the outer disc in a way that is consistent with dust filtration at a gap edge.

5 DISCUSSION

Although the suggestion that the observed near-IR deficits in some T Tauri SEDs could result from an embedded Jupiter-like planet clearing the inner disc is exciting, there is, as yet, no clear evidence that this is indeed the case. Other non-planetary possibilities, for
example, rapid grain growth, could also result in optically thin regions that may produce SEDs largely consistent with that observed.

A sufficiently massive planet does, however, have a real effect on the structure of the gaseous disc which may influence the distribution of solid particles. This effect could, in turn, influence the nature of the resulting SED. A ~1M_\text{J} planet should open a gap in the disc, the inner region of which could clear to form an inner hole. The outer edge of this gap (or hole) will have a pressure that increases with increasing radius, increasing the net outward force on the gas and resulting in super-Keplerian gas velocities. The resulting drag force on the solid particles then results in these particles drifting up the gap edge, away from the central star. If, however, there is still some gas accretion on to the gap – which is expected for ~1M_\text{J} planets (Lubow et al. 1999) – solid particles with radial velocities smaller than the radial gas velocity will populate the inner region of the disc. For disc properties appropriate for T Tauri stars, the radial velocity increases with particle size for particles smaller than ~1 cm. This means that only the smallest particles will have outward radial velocities small enough to be dragged into the gap by the accreting gas.

Gas accretion through the gap edge therefore acts to filter solid particles, with only the smallest particles making it into the gap. The exact size range that is influenced by the gas depends on the properties of the gas disc and on the radial gas velocity. Assuming a functional form for the gap edge (motivated by two-dimensional, hydrodynamic simulations of embedded Jupiter-like planets), we show that if the inward gas velocity is ~1–10 cm s^{-1}, only ~1 \mu m and smaller grains will be able to populate the inner disc. If the gas-accretion rate is modified by sufficiently massive planets, as suggested by simulations (Lubow et al. 1999), the size of particles that may populate the inner disc should decrease with increasing planet mass. Systems, such as CoKu Tau/4, that appear to have almost no material in the inner disc may indicate the presence of a massive companion while those, such as GM Aur and TW Hya, that appear to still have some material in the inner disc, may have a companion with a mass that allows some material to continually replenish the inner disc.

What is attractive about this possibility is that SED modelling suggests that systems with near-IR deficits do indeed have two populations of dust particles. This spatial segregation of dust within discs has been observed in the TW Hya disc (Calvet et al. 2002), and radiation transfer models of new Spitzer Space Telescope IRS spectra of the CoKu Tau 4, GM Aur and DM Tau discs also require inner holes with small grains in the inner disc, and a larger grain population in the outer disc (Calvet et al. 2005; D’Alessio et al. 2005). The silicate feature present in the IRS spectra provides the clues that the dust grains in the inner disc are smaller than that in the outer disc. As more data come in from Spitzer, the number of disc systems showing evidence for inner holes is increasing (Lada et al. 2006; Muzerolle et al. 2006). To date, most candidates have IRAC and MIPS photometry, so only the presence of inner disc clearing can be inferred. Follow-up observations with IRS will enable us to determine whether the spatial segregation of dust sizes is a common feature and thereby further test our dynamical models for disc–planet interactions and dust filtration.

The SED modelling of systems like GM Aur and DM Tau not only require a population of small grains in the inner disc, but also require that the mass, or surface density, is also low enough for the inner disc to be optically thin. Accretion onto a planet can reduce the amount of mass reaching the inner disc by up to 90 per cent (Lubow & D’Angelo 2006), but this is probably insufficient to produce an optically thin inner disc. Typically, the optical depth will need to be reduced by a factor of ~10^4, a factor of 1000 more than that which can be produced by the planet alone. If solid particles are filtered at the gap edge, the amount of mass reaching the inner disc will depend on the size distribution of the solid particles. Interstellar medium (ISM) grains are generally assumed to have sizes between 0.005 and 1 \mu m and a size distribution of n(r) \propto r^{-3.5} (Mathis, Rumpl & Nordsiek 1977). Grain growth can, however, change this distribution quite significantly. If there is constant replenishment of the ISM grains, this can steepen to n(r) \propto r^{-4} (Mizuno, Markiewicz & Voelk 1988), in which case most of the mass will be in small grains. If, however, there is no source of ISM grains, the final size distribution can be much flatter, approaching n(r) \propto r^{-2}. A relatively shallow size distribution (e.g. \propto r^{-3}) will already have a reduced opacity, independent of the presence of a planet, but, as shown below (see also Fig. 7), a further reduction is needed to match the observed SEDs. Such a reduction can be obtained through the filtration process described here.

The amount of material that can reach the inner disc will depend on the maximum size that can accrete through the gap edge, and on the size distribution of the particles in the outer disc. Fig. 6 shows the ratio of the mass of particles smaller than 1 \mu m (solid line) and 10 \mu m (dashed line) to the total mass of solid particles, plotted against the exponent of the power-law size distribution. In this figure, we assume a minimum size of 0.005 \mu m and a maximum size of 1 mm. For steep size distributions, most of the mass is in small grains, and even if the maximum size of filtered particles is 1 \mu m, the inner disc would remain optically thick. It is also likely that in this case, grain coagulation would soon produce large grains in the inner disc (Dullemond & Dominik 2005). From SED modelling, however, we know that systems like GM Aur, TW Hya and DM Tau must have a size distribution that extends to larger sizes in the outer disc and, since these systems are reasonably evolved, there is unlikely to be a significant new source of ISM grains. We might, therefore, expect the size distribution in the outer disc to be flatter than the ISM grain size distribution (Mizuno et al. 1988). It has already been shown that in some systems, flatter grain size distribution [e.g. n(r) \propto r^{-2.5}] provides better fits to the SEDs than ISM size distributions (D’Alessio, Calvet & Hartmann 2001). Fig. 6 shows that a size distribution of n(r) \propto r^{-3} and a maximum filtered size of 1 \mu m,
would reduce the mass of solid material accreting through the gap edge by a factor of $10^3$. If the planet accretes 90 per cent of this material, the amount of solid material reaching the inner disc would be reduced by a factor of $10^4$, sufficient to produce an optically thin inner disc.

This process would also produce a very different dust-to-gas ratio in the inner disc, compared with the outer disc. The fact that systems like GM Aur and DM Tau have optically thin inner discs but are still accreting at $M \gtrsim 10^{-9} M_\odot \text{yr}^{-1}$ suggests that there is still a substantial amount of gas in the inner disc. The optically thin inner disc requires a reduction in solid particles of the order of $10^4$, while the ongoing accretion requires a far smaller reduction in the amount of gas in the inner disc. This is at least qualitatively consistent with the suggestion that the solid particles are filtered at the outer edge of the gap which, together with the subsequent accretion on to the planet reduces the mass of solid particles by a factor of $\sim 10^3$, while at least 10 per cent of the gas is allowed through into the inner disc (Lubow & D’Angelo 2006). Such a reduction in the solid particle surface density in the inner disc also means that subsequent grain coagulation is probably not very important. Dullemond & Dominik (2005), using a relatively simple one-particle model (Safronov 1969), showed that at $\sim 1$ au grain coagulation can produce $\sim 500 \mu m$ particles within a few hundred years for reasonable surface densities. If the mass that can be swept up by a growing particle is then reduced by a factor of $10^4$, one might assume that the maximum size that this particle could achieve is then reduced by a factor of 20 (i.e. a maximum size of $\sim 25 \mu m$). This, however, is a significant overestimate since the amount of mass swept up by a growing particle depends strongly on the size of the particle, or its collision cross-section. In the simple one-particle model, there is almost no grain growth if the surface density is reduced by a factor of $10^4$ from an initial density that would be appropriate for the inner regions of a T Tauri disc. Although this is a fairly simple model, it at least suggests that if the amount of mass reaching the inner disc is reduced significantly, coagulation should not play an important role in the subsequent evolution of these grains.

Fig. 7 illustrates how the filtration process discussed above may influence the disc SEDs. The SED models in Fig. 7 are computed assuming a 300-au flared disc of total mass 0.01 $M_\odot$ that is passively heated by a star with $T_{\text{dust}} = 4000 K$, and $R_{\text{dust}} = 1 R_\odot$. The disc surface density and scaleheight have radial profiles of $\Sigma \propto r^{-1}$ and $h \propto r^{1/2}$, and the scaleheight is normalized such that $h = 18$ au at $r = 100$ au. The temperature is determined self-consistently by the Monte Carlo radiation transfer calculation. The solid curve is the SED resulting from a dust model with a grain size distribution of $n(r) \propto r^{-3}$ with minimum and maximum grain sizes of $0.005 \mu m$ and 1 mm, respectively (see Wood et al. 2002, table 1 and fig. 3). The other two models simulate the dust filtration discussed above. These models have the large grain model in the outer disc (beyond 5 au) and ISM-like grains (maximum size 1 $\mu m$) inside 5 au. The dashed curve has a depletion factor of $10^4$ for the dust density, while the dotted curve has a depletion factor of $10^6$, still within the possibilities discussed above. Note the near-IR deficit and prominent silicate features at 10 and 20 $\mu m$ for the SED models with ISM-like grains and inner disc depletions. The redistribution of IR excess from short to long wavelengths for discs with optically thin interiors is also apparent as discussed in Rice et al. (2003). These SEDs are not models for any particular system, but demonstrate the observable signatures of the filtration process we have described. In these models, the dust density in the inner disc is significantly reduced by filtration at the gap edge and by accretion on to the planet, while the gas is only influenced by accretion on to the planet. The gas density in the inner disc is therefore reduced by a much smaller amount than the dust density. This extremely small dust-to-gas ratio in the inner disc produces an ‘opacity gap’, while still allowing gas accretion on to the star, in line with observations of many T Tauri stars that exhibit near-IR deficits in their SEDs.

It has, however, also been suggested (Eisner, Chiang & Hillenbrand 2006) that ‘opacity gaps’ and the presence of small grains in the inner disc could actually be evidence for grain growth and subsequent rapid inward migration, rather than inferring the presence of a gap-opening planet. This conclusion was partly because Jupiter-like planets in relatively massive discs should migrate into the central star within the disc lifetime (Eisner et al. 2006). Although this may indeed be the case, the viscous time-scale at 5 au can be $\sim 10^9$ yr for reasonable viscosity values. The observation of such a system is therefore still possible, even if the planet ultimately does not survive the migration process. If near-IR deficits are due to grain growth, there must also be some means of sharply truncating the grain size distribution at $\sim 1 \mu m$ in the inner disc. It is possible that we are seeing a population of planets that form early, and potentially do not actually survive the migration process.

6 CONCLUSION

Although we cannot definitively conclude that near-IR deficits in the SEDs of some T Tauri stars are a consequence of an embedded Jupiter-like planet, that the filtering effect of such a planet – producing a small grain population in the inner disc that differs from the population in the outer disc – is consistent with SED modelling of these systems is suggestive. The SED modelling also requires that the inner disc be optically thin, while ongoing gas accretion requires that the inner disc still have a substantial amount of gas. If the grain size distribution is somewhat flatter than the standard ISM size distribution (Mathis et al. 1977), filtration at the outer gap
edge can significantly reduce the amount of solid material reaching the inner disc, while still allowing sufficient gas through the gap. Although we do not actually know the grain size distribution in the outer discs of those systems that show inner holes, they do show evidence for grain growth. In some cases, flatter size distributions do provide better fits to T Tauri SEDs (D’Alessio et al. 2001), although this has yet to be tested on the systems we consider here. The fact that filtration of solid particles at the outer edge of a gap opened by an embedded Jupiter-like planet can not only produce a population of small grains in the inner disc, but can potentially also make this region optically thin, makes this an attractive possibility.

The filtration process should also lead us to an enhancement of larger particles at the peak of the gap edge. Particles exterior to the gap will continue to drift inwards until they reach the gap edge, at which point the change in the gas pressure gradient will prevent the larger particles from drifting any farther. If the surface density of such particles becomes sufficiently high, further planet formation could occur at this location. Since ‘Hot’ Jupiters are thought to form at modest radii and then migrate inwards via Type II migration to their present locations, one may expect in some cases to find additional lower-mass planets in 2:1 resonances with these ‘Hot’ Jupiters. The presence of even terrestrial mass planets in resonant orbits with ‘Hot’ Jupiters could be detected using transit timing (Agol et al. 2005). Although such a detection would be consistent with the analysis presented here, it has been suggested that this could also occur if low-mass, fast migrating planets (>0.1M_⊕) were resonantly trapped by gap-opening planets (Thommes 2005). In the latter case, however, one may expect the trapped planets to subsequently grow into gas giants (Thommes 2005), while in the former case the planetesimal trapping could occur later when there may only be sufficient time for the newly forming planet to reach a terrestrial-like mass.

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