THE ASTROPHYSICAL JOURNAL, 658:569–583, 2007 March 20

TRANSIENCE OF HOT DUST AROUND SUN-LIKE STARS

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Received 2006 July 16; accepted 2006 October 3

ABSTRACT

In this paper a simple model for the steady state evolution of debris disks due to collisions is developed and confronted with the properties of the emerging population of seven Sun-like stars that have hot dust at <10 AU. The model shows that there is a maximum possible disk mass at a given age, since more massive primordial disks process their mass faster. The corresponding maximum dust luminosity is $f_{max} = 0.16 \times 10^{-3} r^{7/3} t_{age}^{-1}$, where r is disk radius in AU and t_{age} is system age in Myr. The majority (4/7) of the hot disks exceed this limit by $\gg 1000$ and so cannot be the products of massive asteroid belts; rather, the following systems must be undergoing transient events characterized by an unusually high dust content near the star: η Corvi, HD 69830, HD 72905, and BD +20 307. It is also shown that the hot dust cannot originate in a recent collision in an asteroid belt, since there is also a maximum rate at which collisions of sufficient magnitude to reproduce a given dust luminosity can occur. The planetesimal belt feeding the dust in these systems must be located farther from the star than the dust, typically at $\gg 2$ AU. Other notable properties of the four hot dust systems are as follows: two also have a planetesimal belt at >10 AU (η Corvi and HD 72905); one has three Neptune mass planets at <1 AU (HD 69830); all exhibit strong mid-IR silicate features. We consider the most likely origin for this transient dust to be a dynamical instability that scattered planetesimals inward from a more distant planetesimal belt in an event akin to the late heavy bombardment in our own system, the dust being released from such planetesimals in collisions and sublimation.

Subject headings: circumstellar matter — planetary systems: formation

1. INTRODUCTION

Planetesimal belts appear to be a common feature of planetary systems. There are two main belts in the solar system: the asteroid belt and the Kuiper Belt. These belts inhabit the regions of the solar system where planetesimal orbits can remain stable over the 4.5 Gyr age of our system (Lecar et al. 2001). The larger planetesimals in the belts are continually grinding down, feeding the smaller bodies in a process known as a collisional cascade, which is slowly eroding the belts (Bottke et al. 2005). The smallest dust in the asteroid belt is acted on by radiation forces; Poynting-Robertson (P-R) drag makes the dust spiral in toward the Sun, making a disk known as the zodiacal cloud that the Earth sits in the middle of (Leinert & Grün 1990). A dust cloud is also predicted to arise from collisions among Kuiper Belt objects (Liou & Zook 1999), although our information on this population is sparse (Landgraf et al. 2002) because its emission is masked by the zodiacal emission (Backman et al. 1995) and few dust grains make it into the inner solar system (Moro-Martín & Malhotra 2003).

Many extrasolar systems also have such planetesimal belts, known as debris disks. These have been detected from their dust content (Aumann et al. 1984), from which it has been inferred that larger planetesimals must exist to replenish the dust disks because of the short lifetime of this dust (Backman & Paresce 1993). The collisional cascade scenario is supported by modeling of the emission spectrum of the dust, which shows a size distribution similar to that expected for dust coming from a collisional cascade (Wyatt & Dent 2002, hereafter WD02). However, the issue of how these disks evolve has recently come under close scrutiny.

From a theoretical point of view, Dominik & Decin (2003, hereafter DD03) showed that if P-R drag is not important, then a planetesimal belt evolving in quasi–steady state would lose mass due to collisional grinding down giving a disk mass (and dust luminosity) that falls off $\propto t^{-1}$. This is in broad agreement with the observed properties of debris disks: the mean dust luminosity at a given age falls off $\propto t^{-1.8}$ (Spangler et al. 2001); the mass inferred from detection statistics falls off $\propto t^{-0.5}$ (Greaves & Wyatt 2003), while the mass of the detected disks falls off $\propto t^{-1}$ (Najita & Williams 2005); the upper limit in luminosity of the detected disks also falls off $\propto t^{-1}$ (Rieke et al. 2005). While these trends can be viewed as a success of the steady state model, it has yet to be proved that a steady state evolution model fits the data in more than just general terms (Meyer et al. 2006). Several puzzling observations also remain to be explained.

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Decin et al. (2003) noted that the maximum fractional luminosity of debris disks remains constant at $f = L_{\rm IR}/L_\star \approx 10^{-3}$ up to the oldest stars, where $L_{\rm IR}$ and $L_\star$ are the disk and stellar luminosities, respectively (see also Table 4 in the Appendix for definitions of the parameters used in the text), and this was explained by DD03 as a consequence of delayed stirring. A delay in the ignition of a collisional cascade is expected if it is the formation of Pluto-sized objects that triggers the cascade, since such massive bodies take longer, up to several Gyr, to form farther from the star (Kenyon & Bromley 2002). However, that interpretation predicts that the radius of the belts should increase with stellar age, and this is not observed (Najita & Williams 2005). There is also recent evidence that the dust content of some systems is transient. The discovery of a population of dust grains around Vega in the process of removal by radiation pressure indicates that this system cannot have remained in steady state for the full 350 Myr age of the star (Su et al. 2005). Rieke et al. (2005) used their statistics on A stars, which showed a wide variety of properties among the debris disks, to suggest that much of the dust we see is produced episodically in collisions between large planetesimals. There is also an emerging population of debris disks detected around Sun-like stars with dust at a few AU (Gaidos 1999; Beichman et al. 2005; Song et al. 2005; R. Smith et al. 2007, in preparation). There is debate over whether these are atypically massive asteroid belts or the consequence of a rare transient event (e.g., Beichman et al. 2005).

A stochastic element to the evolution of debris disks would fit with our understanding of the evolution of the dust content of the inner solar system. This is believed to have been significantly enhanced for timescales of a few Myr following collisions between objects $\sim$100 km in size in the asteroid belt (Nesvorný et al. 2003; Farley et al. 2006). However, it is not known whether the aftermath of individual collisions would be detectable in a debris disk, or indeed whether such events would happen frequently enough to explain the statistics (WD02; Telesco et al. 2005). Such events have a dramatic effect on the amount of dust in the solar system because there is relatively little around during the quiescent periods. Planetesimal belts of equivalent mass to those in the solar system would not have been detected in the current debris disk surveys. However, there is evidence to suggest that both belts were $\sim$200 times more massive in the past (e.g., Stern 1996; Bottke et al. 2005). Periods analogous to the heavy bombardment experienced in the solar system up to $\sim$700 Myr after its formation have also been invoked to explain the fact that debris disks are most often detected around stars <400 Myr old (Habing et al. 1999).

In the light of this controversy we revisit a simple analytical model for the steady state collisional evolution of planetesimal belts that was originally explored in DD03. The model we derive for that evolution is given in § 2 and differs in a subtle but important way from that of DD03, since it affects the dust production as a function of collision velocity. This model shows that there is a maximum possible disk mass (and dust luminosity) at any given age. In § 3 confrontation with the few hot planetesimal belts discovered recently shows that the majority of these cannot be explained as massive asteroid belts; rather, these must be systems undergoing a transient event. The possibility that these are caused by a recent collision within a planetesimal belt is also discussed, as is the possibility that the dust originates in a planetesimal belt in the terrestrial planet region. The implications of these results are discussed in § 4. Application of the model to the statistics of detected debris disks will be considered in a later paper (Wyatt et al. 2007).

2. ANALYTICAL COLLISIONAL EVOLUTION MODEL

In this section a simple analytical model is developed for the evolution of a planetesimal belt due to collisions among its members. The parameters used in this model are summarized in Table 4, which also gives the units assumed for these parameters throughout the paper.

2.1. *The Planetesimal Belt Size Distribution*

The planetesimal belt is assumed to be in collisional equilibrium with a size distribution defined by

$$n(D) = KD^{2-3q}, \tag{1}$$

where $q = 11/6$ in an infinite collisional cascade (Dohnanyi 1969) and the scaling parameter K is called f_a by DD03. That distribution is assumed to hold from the largest planetesimal in the disk, of diameter D_c, down to the size below which particles are blown out by radiation pressure as soon as they are created, $D_{\rm bl}$. If we assume that q is in the range from 5/3 to 2, then most of the mass is in the largest planetesimals while the cross-sectional area is in the smallest particles such that

$$\sigma_{\rm tot} = 3.5 \times 10^{-17} K (3q-5)^{-1} \left(10^{-9} D_{\rm bl}\right)^{5-3q}, \tag{2}$$

$$M_{\rm tot} = 8.8 \times 10^{-17} K \rho (6-3q)^{-1} D_c^{6-3q} \tag{3}$$

$$= 2.5 \times 10^{-9} \left(\frac{3q-5}{6-3q}\right) \rho \sigma_{\rm tot} D_{\rm bl} \left(\frac{10^9 D_c}{D_{\rm bl}}\right)^{6-3q}, \tag{4}$$

where spherical particles of density ρ have been assumed and $M_{\rm tot}$ is in $M_\oplus$ if the units of Table 4 are used for the other parameters.

The planetesimal belt is assumed to be at a radius r and to have a width dr (in AU). One of the observable properties of a planetesimal belt is its fractional luminosity, $f = L_{\rm IR}/L_\star$, i.e., the infrared luminosity from the disk divided by the stellar luminosity. Assuming that the grains act like blackbodies and so absorb all the radiation they intercept, we can write

$$f = \sigma_{\rm tot} / \left(4\pi r^2\right). \tag{5}$$

In other words, in this model $\sigma_{\rm tot}$, $M_{\rm tot}$, and f are all proportional to each other and just one is needed to define the scaling factor K in equation (1). Assuming that the particles act like blackbodies also allows us to derive the following relation:

$$D_{\rm bl} = 0.8 (L_\star / M_\star)(2700/\rho), \tag{6}$$

where $D_{\rm bl}$ is in μm, $L_\star$ and $M_\star$ are in solar units, and ρ is in kg m^{-3}.

Relaxing the blackbody assumption is easily achieved (e.g., WD02). However, this would result in relatively small changes in the way f scales with $M_{\rm tot}$, and so for its heuristic simplicity we keep this assumption throughout this paper. Probably the most important simplification within this model is that of the continuous size distribution. For example, we know that the cutoff in the size distribution at $D_{\rm bl}$ would cause a wave in the size distribution at sizes just larger than this (Thébault et al. 2003), that large quantities of blowout grains can also affect the distribution of small-size particles (Krivov et al. 2000), and that the dependence of planetesimal strength on size can result in $q \neq 11/6$, as well as a wave in the distribution at large sizes (Durda et al. 1998; O'Brien & Greenberg 2003). Also, since the largest planetesimals would not be in collisional equilibrium at the start of the evolution, their initial distribution may not be the same as that of a collisional cascade, although distributions with $q \approx 11/6$ have been reported from planet formation models (e.g., Stern & Colwell 1997; Davis & Farinella 1997; Kenyon & Luu 1999), meaning that this is a reasonable starting assumption. Despite these simplifications, we believe that this model is adequate to explore to first order the evolution of planetesimal belts, which can later be studied in more depth.

2.2. *Collisional Evolution*

In a collisional cascade material in a bin with a given size range D to $D + dD$ is replaced by fragments from the destruction of larger objects at the same rate that it is destroyed in collisions with other members of the cascade. The long-timescale evolution is thus determined by the removal of mass from the top end of the cascade. In this model the scaling factor K (and so the total mass and fractional luminosity, etc.) decreases as the number of planetesimals of size D_c decreases. The loss rate of such planetesimals is determined by their collisional lifetime, which in the terminology of WD02 is given by

$$t_c = \sqrt{r^3/M_\star}(r\,dr/\sigma_{\rm tot})[2I/f(e,I)]/f_{\rm cc}, \tag{7}$$

where maintaining the units used previously gives t_c in yr, I is the mean inclination of the particles' orbits (which determines the torus height), $f(e, I)$ is the ratio of the relative velocity of collisions to the Keplerian velocity ($=v_{\rm rel}/v_k$, also called ν by DD03), and $f_{\rm cc}$ is the fraction of the total cross-sectional area in the belt that is seen by planetesimals of size D_c as potentially causing a catastrophic collision.

From here on we use the assumption that $f(e, I) = (1.25e^2 + I^2)^{1/2}$, where e is the mean eccentricity of the particles, which is valid for Rayleigh distributions of e and I (Lissauer & Stewart 1993; Wetherill & Stewart 1993). An expression for $f_{\rm cc}$ was given in WD02; however, here we ignore the gravitational focusing effect, which is important in the accumulation phase but not during the destruction phase of a planetesimal belt (see § 3.2), and so derive an expression that is the same as that given in Wyatt et al. (1999):

$$f_{\rm cc} = \left(10^{-9}D_{\rm bl}/D_c\right)^{3q-5}G(q, X_c), \tag{8}$$

where $X_c = D_{\rm cc}/D_c$, $D_{\rm cc}$ is the smallest planetesimal that has enough energy to catastrophically destroy a planetesimal of size D_c (which is called ϵ in DD03), and

$$G(q, X_c) = \Big[\left(X_c^{5-3q} - 1\right) + (6q-10)(3q-4)^{-1}\left(X_c^{4-3q} - 1\right) + (3q-5)(3q-3)^{-1}\left(X_c^{3-3q} - 1\right)\Big]. \tag{9}$$

The factor X_c can be worked out from the dispersal threshold, $Q_D^\star$, defined as the specific incident energy required to catastrophically destroy a particle such that (WD02)

$$X_c = \left(2Q_D^\star/v_{\rm rel}^2\right)^{1/3} \tag{10}$$

$$= 1.3 \times 10^{-3}\left[Q_D^\star r M_\star^{-1} f(e,I)^{-2}\right]^{1/3}, \tag{11}$$

where $Q_D^\star$ is in J kg^{-1} (called S in DD03[2]).

[2] Equation (25) in DD03 differs from our eq. (10) because we define $Q_D^\star$ to be the specific incident kinetic energy so that $0.5M_2v_{\rm rel}^2 = M_1Q_D^\star$, whereas DD03 define S to be the specific binding energy of the two objects (giving their eq. [24]). In the limit of $S \ll v_{\rm rel}^2/8$ the two equations are the same, since $X_c \ll 1$.

Combining the above equations gives for the collisional lifetime of the planetesimals of size D_c

$$t_c = \left(\frac{r^{2.5}\,dr}{M_\star^{0.5}\sigma_{\rm tot}}\right)\left\{\frac{2\left[1+1.25(e/I)^2\right]^{-0.5}}{G(q, X_c)}\right\}\left(\frac{10^{-9}D_{\rm bl}}{D_c}\right)^{5-3q} \tag{12}$$

$$= \left(\frac{3.8\rho r^{2.5}\,dr D_c}{M_\star^{0.5}M_{\rm tot}}\right)\left\{\frac{(12q-20)\left[1+1.25(e/I)^2\right]^{-0.5}}{(18-9q)G(q, X_c)}\right\}. \tag{13}$$

Assuming that collisions are the only cause of mass loss in the belt, the evolution of the disk mass $M_{\rm tot}(t)$ (or equivalently of K, $\sigma_{\rm tot}$, or f) can be worked out by solving $dM_{\rm tot}/dt = -M_{\rm tot}/t_c$ to give

$$M_{\rm tot}(t) = M_{\rm tot}(0)/[1 + t/t_c(0)], \tag{14}$$

where $M_{\rm tot}(0)$ is the initial disk mass and $t_c(0)$ is the collisional lifetime at that initial epoch; this solution is valid as long as mass is the only parameter of the planetesimal belt that changes with time. This results in a disk mass that is constant at $M_{\rm tot}(0)$ for $t \ll t_c(0)$, but which falls off $\propto 1/t$ for $t \gg t_c(0)$ (as noted, e.g., in DD03).

However, another interesting property of this evolution is that, since the expression for $t_c(0)$ includes a dependence on $M_{\rm tot}(0)$, the disk mass at late times is independent of initial disk mass. This is because more massive disks process their mass faster. This means that for any given age, $t_{\rm age}$, there is a maximum disk mass $M_{\rm max}$ (and also infrared luminosity, $f_{\rm max}$) that can remain due to collisional processing:

$$M_{\rm max} = \left[\frac{3.8\times10^{-6}\rho r^{3.5}(dr/r)D_c}{M_\star^{0.5}t_{\rm age}}\right] \times \left\{\frac{(12q-20)\left[1+1.25(e/I)^2\right]^{-0.5}}{(18-9q)G(q, X_c)}\right\}, \tag{15}$$

$$f_{\rm max} = \left[\frac{10^{-6}r^{1.5}(dr/r)}{4\pi M_\star^{0.5}t_{\rm age}}\right]\left(\frac{10^{-9}D_{\rm bl}}{D_c}\right)^{5-3q} \times \left\{\frac{2\left[1+1.25(e/I)^2\right]^{-0.5}}{G(q, X_c)}\right\}. \tag{16}$$

In this model, the present-day disk mass (or luminosity) is expected to be equal to this "maximum" disk mass (or luminosity) for disks in which the largest planetesimals are in collisional equilibrium. This corresponds to disks around stars that are older than the collisional lifetime of those planetesimals given in equation (13).

For example, with the further assumptions that $q = 11/6$, $e \approx I$, and $\rho = 2700$ kg m^{-3}, we find

$$M_{\rm max} = 0.009r^{3.5}(dr/r)D_cM_\star^{-0.5}t_{\rm age}^{-1}/G(11/6, X_c), \tag{17}$$

$$f_{\rm max} = 0.004r^{1.5}(dr/r)D_c^{0.5}L_\star^{-0.5}t_{\rm age}^{-1}/G(11/6, X_c), \tag{18}$$

where $M_{\rm max}$ is in $M_\oplus$, r in AU, D_c in km, $t_{\rm age}$ in Myr, and $G(11/6, X_c) = X_c^{-0.5} + 0.67X_c^{-1.5} + 0.2X_c^{-2.5} - 1.87$, with $X_c = 10^{-3}(rQ_D^\star/e^2)^{1/3}$ ($Q_D^\star$ is in J kg^{-1}).

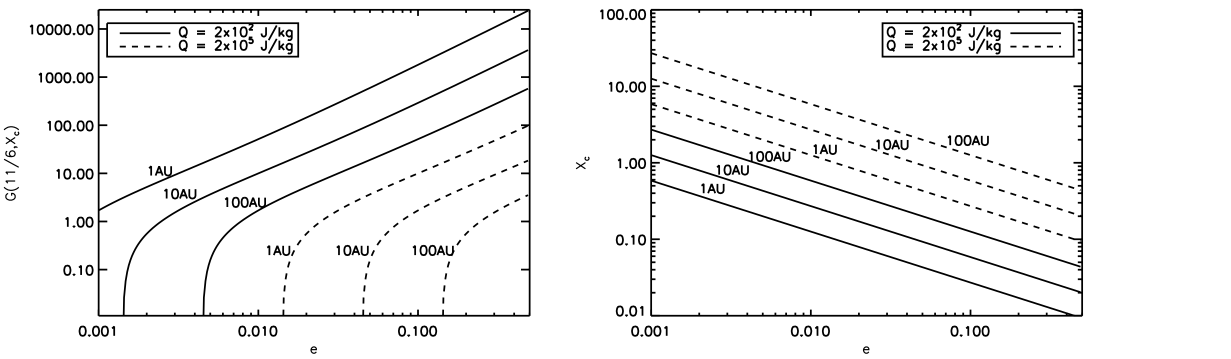

FIG. 1.—Dependence of $G(11/6, X_c)$ (*left*) and X_c (*right*) on planetesimal eccentricity (e) for planetesimals of different strengths ($Q_D^\star$) and at different distances from the star (r).

Plots of $G(11/6, X_c)$ and X_c for typical planetesimal belts are shown in Figure 1. However, for many disks the approximation that $X_c \ll 1$ is valid, and so $G(11/6, X_c) \approx 0.2X_c^{-2.5} = 6.3 \times 10^6 r^{-5/6} Q_D^{\star -5/6} e^{5/3} M_\star^{5/6}$, giving

$$M_{\rm max} = 1.4 \times 10^{-9} r^{13/3} (dr/r) D_c Q_D^{\star 5/6} e^{-5/3} M_\star^{-4/3} t_{\rm age}^{-1}, \quad (19)$$

$$f_{\rm max} = 0.58 \times 10^{-9} r^{7/3} (dr/r) D_c^{0.5} Q_D^{\star 5/6} e^{-5/3} M_\star^{-5/6} L_\star^{-0.5} t_{\rm age}^{-1}. \quad (20)$$

2.3. *Comparison with DD03*

Since DD03 produced a very similar analytical model, our results were compared with those of DD03. The results of disk evolution for a planetesimal belt close to their nominal model were computed using the following parameters: $r = 43$ AU, $dr = 15$ AU, $D_c = 2$ km, $\rho = 2700$ kg m^{-3}, $f(e, I) = 0.1$, $e/I = 1$, $Q_D^\star = 200$ J kg^{-1}, $M_{\rm tot}(0) = 10\ M_\oplus$, A0 star (for which $L_\star = 54\ L_\odot$, $M_\star = 2.9\ M_\odot$, $D_{\rm bl} = 15\ \mu$m). Each of the parameters $M_{\rm tot}(0)$, r, $f(e, I)$, D_c, and spectral type were also varied to make the plots shown in Figure 2, which are equivalent to Figures 1*b*–1*f* of DD03.

The results are very similar in most regards: more massive disks start out with higher f, but the turnover from constant to $1/t$ evolution is later for lower mass disks, meaning that at late times all disks converge to the same maximum value (Fig. 2, *top left panel*); putting the same mass at larger distances reduces the initial dust luminosity f, but the resulting lower surface density and longer orbital timescales there combine to make the turnover happen later, which means that at late times more distant belts are more massive (Fig. 2, *top right panel*); putting the same mass into larger planetesimals reduces the cross-sectional area of dust (eq. [4]) and thus the initial dust luminosity f but increases the collisional lifetime of those planetesimals (eq. [13]), which means that at late times belts with larger planetesimals retain their mass for longer (Fig. 2, *middle right panel*); later spectral types have higher starting dust luminosities because the cascade extends down to smaller sizes (eq. [6]), and the longer orbital times mean that they keep their mass for longer (Fig. 2, *bottom left panel*).

Where the models differ is in the exact way $M_{\rm tot}$ is used to get f and t_c and in the way the evolution is affected by changing $v_{\rm rel}/v_k$ (Fig. 2, *middle left panel*). This is because the models make different assumptions. Here we assume that the size distribution is continuous between D_c and $D_{\rm bl}$, whereas in DD03 the large planetesimals feeding the cascade are seen as separate from the cascade. This means that for us $M_{\rm tot}$ gives a direct estimate of K (eq. [3]) and thus the amount of dust f, while for DD03 they equate the mass flow through the cascade with the mass input from the breakup of planetesimals, meaning that while their scaling parameter is proportional to $M_{\rm tot}$ (as is ours), it also includes a dependence on the parameter we call X_c, which affects the mass flow rate in the cascade. This explains all of the differences: the details of the scaling explain the slightly different initial f-values in all the figures, and the fact that for us planetesimals of size D_c are destroyed by planetesimals down to size $X_c D_c$ means that our collisional lifetimes are always shorter than those in DD03, since they assume that planetesimals only collide with same-size planetesimals. For us changing $v_{\rm rel}/v_k$ does not affect the initial f parameter as described above, but it does affect the collisional lifetime of the largest planetesimals, which can survive longer if $v_{\rm rel}/v_k$ is reduced (since this means that fewer planetesimals in the cascade cause destruction on impact). The opposite is the case for the DD03 model: changing $v_{\rm rel}/v_k$ does not affect the collisional lifetime of the largest planetesimals, since they only collide with each other, but a lower collision velocity does increase the initial dust luminosity because the cascade must have more mass in it to result in a mass flow rate sufficient to remove mass introduced by the large planetesimals. While the difference is subtle, it is important, since $v_{\rm rel}/v_k$ may be important in determining the presence of dust at late times (DD03; § 3).

On the face of it, it seems that our model provides a more accurate description of the disk. The reason is that in a collisional cascade the mass flow does not need to be taken into account, since it results in the $q = 11/6$ size distribution (Tanaka et al. 1996). In other words, the dependence of the scaling of the cascade with X_c found by DD03 should have been removed if the largest planetesimals had been allowed to collide with smaller planetesimals (since increasing X_c would have both restricted mass flow within the cascade and slowed down the mass input from the destruction of large planetesimals). However, it is also true that the $q = 11/6$ distribution only applies in an infinite cascade, and since both models have truncated the size distribution at D_c, this would affect the evolution. Also, the effect of the variation of $Q_D^\star$ with D on the size distribution and its evolution are not yet clear, and neither is the evolution of the size distribution while the collisional cascade is being set up. These issues are discussed only briefly in this paper, in which the simple evolution model described above is applied to some of the latest observational results on debris disks.

3. APPLICATION TO RARE SYSTEMS WITH HOT DUST

Very few main-sequence stars exhibit hot dust within ~10 AU, i.e., in the region where we expect planets may have formed. Four

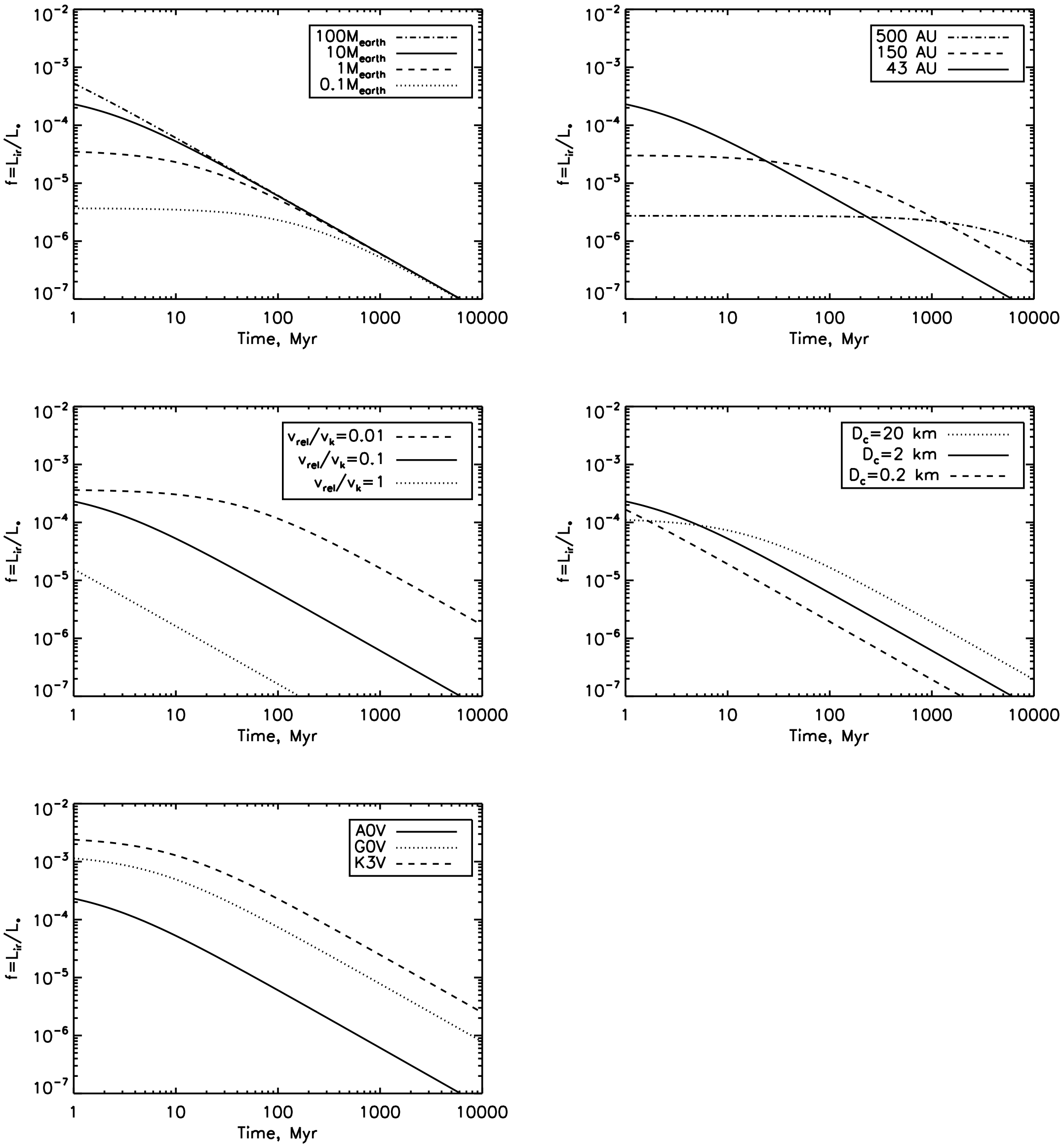

FIG. 2.—Collisional evolution of a planetesimal belt with parameters similar to the nominal model of DD03 [$r = 43$ AU, $dr = 15$ AU, $D_c = 2$ km, $\rho = 2700$ kg m^{-3}, $f(e, I) = 0.1$, $e/I = 1$, $Q_D^* = 200$ J kg^{-1}, $M_{\rm tot}(0) = 10\ M_\oplus$, A0 star] showing the effect of changing the following parameters: starting disk mass $M_{\rm tot}(0)$ (*top left*), disk radius r (*top right*), collision velocity $v_{\rm rel}/v_k$ (*middle left*), maximum planetesimal size D_c (*middle right*), and stellar spectral type (*bottom left*). These plots can be directly compared to Figs. 1*b*–1*f* of DD03.

surveys have searched for hot dust around Sun-like stars (main-sequence F, G, or K stars) by looking for a 25 μm flux in excess of photospheric levels using the *Infrared Astronomical Satellite* (*IRAS*; Gaidos 1999), the *Infrared Space Observatory* (*ISO*; Laureijs et al. 2002), and *Spitzer* (Hines et al. 2006; Bryden et al. 2006). All concluded that only 2% $\pm$ 2% of these stars have hot dust with infrared luminosities $f = L_{\rm IR}/L_\star > 10^{-4}$, finding a total of three candidates. Other hot dust candidates exist in the literature; however, some *IRAS* excess fluxes have turned out to arise from chance alignments with background objects (e.g., Lisse et al. 2002), including the candidate HD 128400 from the hot dust survey of Gaidos (1999) (B. Zuckerman 2006, private communication). Thus, confirmation of the presence of dust centered on the star using ground- and space-based mid-IR imaging is vitally important (R. Smith et al. 2007, in preparation). The tally of confirmed hot dust sources now stands at seven, and these are summarized in Table 1, which also gives the estimated radial location of the dust based on fitting of the spectral energy distribution (SED) of the excess emission; for all stars the dust is predicted to lie at <10 AU.

While the frequency of the presence of such emission is low, there is as yet no adequate explanation for its origin and why it occurs in so few systems. Analogy with the solar system suggests that these are systems in which we are witnessing the collisional grinding down of atypically massive asteroid belts. However, other scenarios have also been proposed in which the dust is transient, having been produced in some stochastic process. Such a process could be a recent collision between two massive protoplanets in an asteroid belt (Song et al. 2005), the sublimation of one supercomet (Beichman et al. 2005), or the sublimation of a swarm of comets, possibly scattered in from several tens of AU in an episode analogous to the period of late heavy bombardment (LHB) in the solar system (Gomes et al. 2005).

TABLE 1

Main-Sequence Sun-like (F, G, and K) Stars in the Literature with Evidence for Hot Dust at <10 AU

Star Name	Spectral Type	Age (Myr)	Radius (AU)	$f_{obs} = L_{IR}/L_\star$	f_{max}	Transient?	References
HD 98800[a]	K4/5 V	~10	2.2	220×10^{-3}	270×10^{-6}	Not required	Low et al. (2005)
HD 113766[a,b]	F3 V	16	3	2.1×10^{-3}	45×10^{-6}	Not required	Chen et al. (2005)
HD 12039	G3/5 V	30	4–6	0.1×10^{-3}	200×10^{-6}	Not required	Hines et al. (2006)
BD +20 307[b]	G0 V	300	1	40×10^{-3}	0.36×10^{-6}	Yes	Song et al. (2005)
HD 72905[b]	G1.5 V	400	0.23[c]	0.1×10^{-3}	0.011×10^{-6}	Yes	Beichman et al. (2006)
η Corvi[b]	F2 V	1000	1–2[c]	0.5×10^{-3}	0.15×10^{-6}	Yes	Wyatt et al. (2005)
HD 69830[b]	K0 V	2000	1	0.2×10^{-3}	0.13×10^{-6}	Yes	Beichman et al. (2005)

[a] Binary star.
[b] Infrared silicate feature.
[c] Also has cool dust component at >10 AU.

3.1. *Are These Massive Asteroid Belts?*

Here we consider the possibility that these are atypically massive asteroid belts and show that for the majority of the known systems this is unlikely to be the case. The reason is that given in § 2.2, which is that more massive asteroid belts are not necessarily more dusty at late times, and there is a maximum dust luminosity we can expect for a belt of a given age, given its radial location (eqs. [15]–[20]). To arrive at a rough estimate of the maximum possible f_{max}, we assume the following parameters: the largest possible planetesimal is $D_c = 2000$ km, since this is above the largest members of the asteroid belt and Kuiper Belt and fits with the expectation that planetesimal growth is halted once the largest planetesimals reach this size due to the resulting gravitational perturbations (Kenyon & Bromley 2002); belt width is $dr = 0.5r$; planetesimal strength is $Q_D^\star = 200$ J kg^{-1}, the canonical value used in DD03, although gravity strengthening can give rise to higher values for planetesimals larger than ~1 km (see § 3.2); planetesimal eccentricity is $e = 0.05$, typical for planetesimal belts like the asteroid belt that are undergoing a collisional cascade, and close to that expected from stirring by 2000 km planetesimals within such a belt.[3] Substituting these nominal values into equation (20) and approximating $M_\star = L_\star = 1$ gives

$$f_{max} = 0.16 \times 10^{-3} r^{7/3} t_{age}^{-1}. \quad (21)$$

Plots analogous to those in Figure 2 are presented in Figure 3, which shows the evolution for a planetesimal belt with the nominal parameters described above [and with a nominal starting mass of $M_{tot}(0) = 1\ M_\oplus$] along with the consequence for the evolution of changing any of those parameters. Note that it is most appropriate to refer to Figure 3, rather than Figure 2, when considering the evolution of planetesimal belts close to Sun-like stars.

The value of f_{max} is quoted in Table 1 under the assumption that the planetesimal belt has the same age as the star. The quoted value for each star is that from equation (18) for its spectral type but is within a factor of 3 of that given in equation (21), indicating that this equation may be readily applied to observed belts in the future. The four oldest systems (BD +20 307, HD 72905, η Corvi, and HD 69830) have $f_{obs} \gg 10^3 f_{max}$. We show in § 3.2 that even with a change in parameters it is not possible to devise asteroid belts in these systems that could survive to the age of the stars giving rise to the observed dust luminosities. Thus, we conclude that this period of high dust luminosity started relatively recently. The timescale over which a belt can last above a given luminosity, f_{obs}, is $t_{age} f_{max}/f_{obs}$, since collisions would grind a belt down to this level on such a timescale. This implies that belts this luminous only last between a few thousand years (BD +20 307 and HD 72905) and a few Myr (η Corvi and HD 69830). However, the true duration of this level of dust luminosity depends on the details of the process causing it, and moreover there is still up to 2 orders of magnitude uncertainty in f_{max} (see § 3.2). Thus, this calculation should not yet be used to infer from the ~2% of systems with hot dust that, e.g., every Sun-like star must undergo 10–1000 such events in its lifetime (or fewer systems must undergo even more events). For now the conclusion is that these systems cannot be planetesimal belts that have been evolving in a collisional cascade for the full age of the star.

This leaves open the possibility that the collisional cascade in these systems was initiated much more recently, perhaps because a long timescale was required to form the 2000–3000 km sized planetesimals necessary to stir the planetesimal belt and cause the switch from accretion to collisional cascade (Kenyon & Bromley 2004). However, we consider this to be unlikely because the timescale for the formation of objects of this size at 1 AU from a solar mass star was given in Kenyon & Bromley (2004) to be $\sim 0.6\, dr/M_{tot}$ Myr, where M_{tot} is the mass of material in an annulus of width dr, just as in the rest of the paper. This means that the cascade can only be delayed for 100–1000 Myr at 1 AU for planetesimal belts of very low mass, which would also be expected to have low dust luminosities when the cascade was eventually ignited. For example, a delay of >500 Myr would require $< 0.6 \times 10^{-3}\ M_\oplus$ in the annulus at 1 AU of 0.5 AU width, a mass that corresponds to a fractional luminosity of $< 5 \times 10^{-6}$ (eqs. [4] and [5] with $\rho = 2700$ kg m^{-3} and $q = 11/6$), much lower than that observed in all systems. One can also consider the same argument in the following way: the observed luminosity f_{obs} implies a planetesimal belt mass that current planet formation theories indicate would result in the growth of 2000 km planetesimals that would ignite a collisional cascade on a timescale of $3 \times 10^{-3}(dr/r)/f_{obs}$ Myr if this was placed at 1 AU from a solar mass star. The conclusion at the end of the last paragraph also considers the collisional cascade to evolve in quasi–steady state, and it is possible that collisions between large members of the cascade may have recently introduced large quantities of small dust; that possibility is discussed in § 3.3.

For the three youngest systems the conclusions are less clear. The dust luminosities of HD 12039 and HD 113766 are, respectively, close to and 50 times higher than the maximum allowed value for collisionally evolved planetesimal belts. However, given the uncertainties in the parameters in the model (described in § 3.2), we conclude that it is not possible to say that these could not be massive asteroid belts. The main reason that firm

[3] Equating the velocity dispersion in the belt with the escape velocity of a planetesimal of size D_c gives $e \approx 2.6 \times 10^{-7} \rho^{0.5} r^{0.5} M_\star^{-0.5} D_c$.

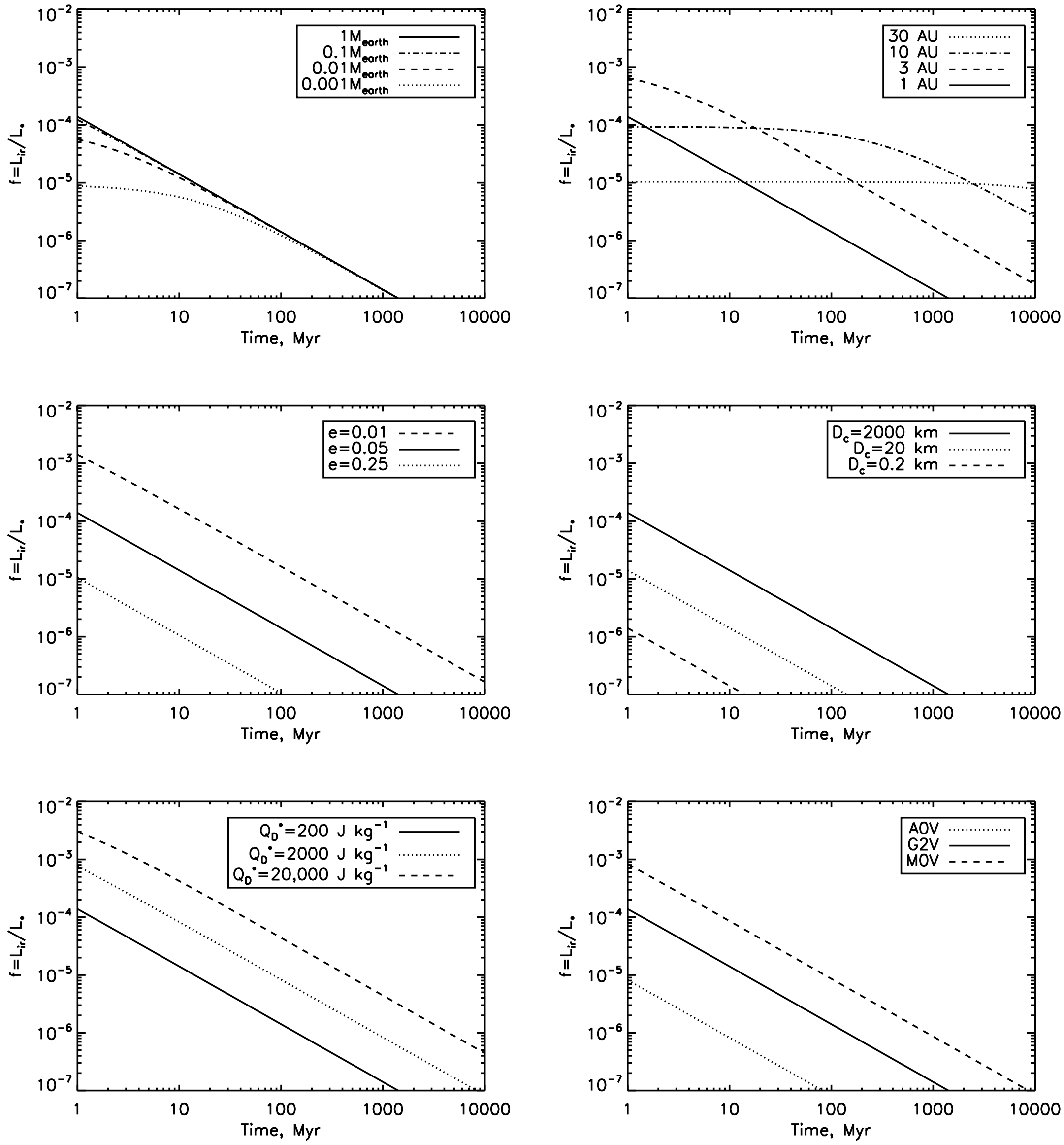

FIG. 3.—Collisional evolution of a planetesimal belt at $r = 1$ AU around a Sun-like star ($L_\star = M_\star = 1$) of initial mass $M_{\rm tot}(0) = 1\ M_\oplus$ assuming that that belt can be described by the parameters used in § 3.1 (i.e., $dr/r = 0.5$, $D_c = 2000$ km, $\rho = 2700$ kg m^{-3}, $e = 0.05$, $e/I = 1$, $Q_D^\star = 200$ J kg^{-1}). All panels show dust luminosity $f = L_{\rm IR}/L_\star$ as a function of time, and the evolution with the above nominal parameters is shown by a solid line. The different panels show the effect of changing the following parameters: starting disk mass $M_{\rm tot}(0)$ (*top left*), disk radius r (*top right*), planetesimal eccentricity e (*middle left*), maximum planetesimal size D_c (*middle right*), planetesimal strength $Q_D^\star$ (*bottom left*), and stellar spectral type (*bottom right*).

conclusions cannot be drawn is the large radial location of the dust at >2 AU. The strong dependence of $f_{\rm max}$ on r means that it is easiest to constrain the nature of belts within a few AU that evolve very rapidly. For the youngest system (HD 98800), while its dust luminosity lies a factor of 800 above the maximum for the age of the star, we do not infer that this must be transient, since the high dust luminosity and low age imply that this system is in a transitional phase and the collisional cascade in this debris disk is likely to have only recently been ignited. Rather, we note that this model implies that, due to collisional processing, this debris disk cannot maintain this level of dust emission beyond the next ∼10,000 yr (albeit with an additional 2 orders of magnitude uncertainty; § 3.2).

3.2. *Possible Caveats*

Given the large number of assumptions that went into the estimate for $f_{\rm max}$, it is worth pointing out that this model is in excellent agreement with the properties of the asteroid belt in the solar system, since for a 4500 Myr belt at 3 AU the model predicts $M_{\rm max} = 0.4 \times 10^{-3}\ M_\oplus$, which is close to the inferred mass of the asteroid belt of $0.6 \times 10^{-3}\ M_\oplus$ (Krasinsky et al. 2002). The model also predicts $f_{\rm max} = 5 \times 10^{-7}$, which is consistent with the estimate for the zodiacal cloud of $L_{\rm IR}/L_\star = 0.8 \times 10^{-7}$ (Backman & Paresce 1993).[4] It is also necessary to explore if there is any way in which the parameters of the model could be relaxed to increase $f_{\rm max}$ and so change the conclusions about the transience of the hot dust systems. Equation (20) indicates one way in which $f_{\rm max}$ could be increased, which is by either reducing the eccentricities of the

[4] In planetesimal belts as tenuous as the asteroid belt, the effect of P-R drag is important (Wyatt 2005), meaning that the cross-sectional area of dust in the zodiacal cloud is dominated by ∼100 μm sized grains rather than grains of size $D_{\rm bl}$ as assumed in the simple model of § 2.1. Taking this into account would reduce the fractional luminosity predicted by the model by an order of magnitude.

planetesimals, e, or increasing their strength, $Q_D^\star$, both of which could increase X_c and so decrease the rate at which mass is lost from the cascade (e.g., Fig. 3). The other way is to change the size distribution so that a given disk mass results in a significantly larger dust luminosity, e.g., by increasing q.

In fact, Benz & Asphaug (1999) found a value of $Q_D^\star$ that is higher than 2×10^5 J kg^{-1} for planetesimals as large as 2000 km for both ice and basalt compositions. This would result in an increase in $f_{\rm max}$ by a factor of $\sim$170 (e.g., Fig. 3). However, such a high value of $Q_D^\star$ is possible only due to gravity strengthening of large planetesimals, and the dependence in this regime of $Q_D^\star \propto D^{1.3}$ (Benz & Asphaug 1999) would result in an equilibrium size distribution with $q_g \approx 1.68$, since when $Q_D^\star \propto D^s$, $q = (11 + s)/(6 + s)$ (O'Brien & Greenberg 2003). If such a distribution was to hold down to the smallest dust grains, the net result would be a decrease in $f_{\rm max}$ by $\sim$200. This is not the case, however, since objects in the size range $D < D_t = 0.15$ km are in the strength-scaled regime where $Q_D^\star \propto D^{-0.4}$, leading to a size distribution with $q_s = 1.89$ in this range. According to O'Brien & Greenberg (2003), the size distribution of a collisional cascade with a realistic $Q_D^\star$ prescription should have two components (characterized by q_g and q_s), but there is a discontinuity at the transition size D_t with the strength-scaled component shifted down by an appropriate amount x_t (see their Fig. 3*b*). This means that $f_{\rm max}$ should be higher than that derived using equation (16) with $q = q_g$ by a factor $x_t(3q_g - 5)(3q_s - 5)^{-1}(D_{\rm bl}/D_t)^{3(q_g - q_s)}$. Since $x_t < 1$, substituting the values from Benz & Asphaug (1999) given above implies that Table 1 underestimates $f_{\rm max}$ by at most a factor of 50–100 (possibly much less). In other words, we anticipate that by including a more realistic prescription for $Q_D^\star$ and the resulting size distribution, this would change the inferred $f_{\rm max}$ but not upward by an amount more than 2 orders of magnitude. For this reason, transience is only inferred for those systems for which $f_{\rm obs}/f_{\rm max} \gg 100$.

A lower eccentricity is, however, one potential avenue for increasing the amount of dust remaining at late times. Equation (20) shows that since $G(11/6, X_c) \propto e^{5/3}$ (Fig. 1, *left panel*), this means that reducing e from 0.05 to 0.01 or 0.001 gives a decrease in $G(11/6, X_c)$ of 15 or 680 and thus an increase in $f_{\rm max}$ by a corresponding amount (e.g., Fig. 3). In fact, the increase can be much more than this, since when e is reduced to levels below $4.7 \times 10^{-5}\{Q_D^\star r M_\star^{-1}[1.25 + (I/e)^2]^{-1}\}^{1/2}$, $X_c > 1$ (e.g., Fig. 1, *right panel*). In such a regime mutual collisions do not result in the destruction of planetesimals, but rather in their merger and growth. At this point $G(11/6, X_c) < 0$, i.e., $f_{\rm max}$ is infinite since, in this simple model, whatever the starting conditions there is no evolution (although in practice the size distribution would evolve due to planetesimal growth). At $\sim$1 AU, this means that e must be larger than 0.0005 (for $Q_D^\star = 200$ J kg^{-1}, appropriate for $D_c = 0.15$ km) or 0.014 (for $Q_D^\star = 2 \times 10^5$ J kg^{-1}, appropriate for $D_c = 2000$ km) to initiate a collisional cascade, values that are consistent with those quoted by more detailed planet formation models (e.g., Kenyon & Bromley 2002). Such eccentricities would be expected through stirring either by >1000 km planetesimals that formed within the belt or by more massive perturbers that formed outside the belt, both of which can be expected to occur within 10–100 Myr (Kenyon & Bromley 2006). This was considered in § 3.1, where it was shown that the cascade would be initiated following the growth of $\sim$2000 km planetesimals on timescales that are much shorter than the age of the system for the disk masses required to produce a dust luminosity at the observed level.

The only route that could plausibly maintain the hot dust systems in Table 1 in collisional equilibrium over the age of the stars might be to invoke some mechanism that maintains the eccentricity at a level at which the cascade is only just being eroded. However, the left panel of Figure 1 shows that $G(11/6, X_c)$ is a strong function of e when $G(11/6, X_c) < 1$, since the range $G(11/6, X_c) = 0$–1 is covered by a factor of <2 in eccentricity. Thus, we consider it reasonable to assume that the best possible combination of $Q_D^\star$ and e in this regard would result in $G(11/6, X_c) \approx 1$ (corresponding to $X_c = 0.69$); lower values of $G(11/6, X_c)$ are possible, but only within a very narrow range of eccentricity. Since in the above example with a realistic $Q_D^\star$ prescription extending up to 2000 km we assumed $e = 0.05$, which already resulted in $G(q_g, X_c) < 1$, we consider that it is not reasonable to fine-tune the eccentricity further to increase $f_{\rm max}$; e.g., decreasing to $e = 0.03$ results in some disks not evolving and the rest with $f_{\rm max}$ higher than that quoted in Table 1 by a factor of $\sim$150. Thus, we conclude that the estimate given in Table 1 (and, e.g., eq. [16]) underestimates $f_{\rm max}$ by at most a factor of $\sim$100, unless the eccentricity happens to lie within $\pm$10% of a critical value.

It is also worth noting that low levels of eccentricity would result in large gravitational focusing factors for large planetesimals that would enhance $f_{\rm cc}$ and so decrease the time for these planetesimals to be catastrophically destroyed, something that is compounded by the higher collision velocity in gravitationally focused collisions that reduces X_c because collisions with smaller planetesimals can cause catastrophic disruption (e.g., eq. [11]). However, we do not need to account for this here, since gravitational focusing becomes important when $v_{\rm rel} < v_{\rm esc} \approx [(2/3)\pi\rho G]^{1/2}(10^{-3}D)$ and thus when $e < 4 \times 10^{-7}\{\rho r M_\star^{-1}[1.25 + (I/e)^2]^{-1}\}^{1/2} D$ (where D is in km), i.e., when $e < 2 \times 10^{-6}$ for $D = 0.15$ km and $e < 0.027$ for $D = 2000$ km at 1 AU from a 1 $M_\odot$ star, both of which occur close to or below the level at which collisions result in accumulation rather than destruction.

3.3. *Are These the Products of Single Collisions?*

One possible origin for the hot dust that is quoted in the literature is that it is the product of a single collision (Song et al. 2005). Our model can be used to make further predictions for the likelihood of massive collisions occurring within an asteroid belt. The maximum number of parent bodies (i.e., planetesimals) larger than $D_{\rm pb}$ remaining at late times occurs when $M_{\rm tot} = M_{\rm max}$ and so is given by

$$n(D > D_{\rm pb}) = \left[\frac{5.6 \times 10^{10} r^{3.5}(dr/r)}{M_\star^{0.5} D_c^2 t_{\rm age}}\right]\left[\left(\frac{D_c}{D_{\rm pb}}\right)^{3q-3} - 1\right] \times \left\{\frac{(3q-5)\left[1 + 1.25(e/I)^2\right]^{-0.5}}{(3-3q)G(q, X_c)}\right\}. \quad (22)$$

The collision timescale for planetesimals of size $D_{\rm pb}$ is

$$t_c(D_{\rm pb}) = t_c(D_c) f_{\rm cc}(D_c)/f_{\rm cc}(D_{\rm pb}) = 10^6 t_{\rm age}(D_{\rm pb}/D_c)^{3q-5}, \quad (23)$$

noting that the collisional lifetime of the largest planetesimals, $t_c(D_c)$, is the age of the star for a planetesimal belt at maximum luminosity for this age. These can be combined to give the destructive collision rate for planetesimals larger than $D_{\rm pb}$:

$$dN_c(D > D_{\rm pb})/dt = 1000 r^{13/3}(dr/r) t_{\rm age}^{-2} D_c D_{\rm pb}^{-3} \times M_\star^{-4/3} Q_D^{\star 5/6} e^{-5/3}, \quad (24)$$

TABLE 2

Model of the Hot Dust Systems as the Outcome of Single Collisions

Star name	D_{pb} (km)	$N(D > D_{pb})$	$dN_c(D > D_{pb})/dt$ (Myr^{-1})	$t_c(D_{bl})$ (yr)	$P(f > f_{obs})$	Single Collision?
HD 98800	530	200	41	0.36	15×10^{-6}	No
HD 113766	280	890	150	41	6100×10^{-6}	Not impossible
HD 12039	110	77000	12000	2300	27[a]	Not impossible
BD +20 307	320	0.47[a]	0.0039	0.49	0.0019×10^{-6}	No
HD 72905	15	1.4	0.036	22	0.79×10^{-6}	No
η Corvi	110	7.8	0.033	59	2.0×10^{-6}	No
HD 69830	39	19	0.068	110	7.7×10^{-6}	No

Note.—These are the parameters in the model for the hot dust systems of Table 1 used to determine whether the observed dust can be the outcome of a single collision in a massive asteroid belt that is itself not normally bright enough to be detected.

[a] For disks with $P(f > f_{obs}) > 1$, this value indicates the number of collisions at that level we can expect to see in the disk at any one time. Likewise, for disks with $N(D > D_{pb}) < 1$, this value indicates the probability that there is an object of this size remaining in the disk.

in Myr^{-1}, where the assumptions that $q = 11/6$, $e = I$, and $X_c \ll 1$ have been used in deriving this equation.

We now assume that we are considering collisions capable of reproducing the observed dust level, f_{obs}, so that the lifetime of the resulting collision products can be estimated from the collisional lifetime of that dust, assumed to be of size D_{bl} (WD02):

$$t_c(D_{bl}) = 0.04 r^{1.5} M_\star^{-0.5} (dr/r) f_{obs}^{-1}, \quad (25)$$

in yr, noting that collisions would remove the dust on a faster timescale than P-R drag (Wyatt 2005; Beichman et al. 2005). Combining equations (24) and (25) gives the fraction of time that collisions are expected to result in dust above a given level of f_{obs}:

$$P(f > f_{obs}) = 4 \times 10^{-5} r^{35/6} (dr/r)^2 t_{age}^{-2} D_c D_{pb}^{-3} \times M_\star^{-11/6} f_{obs}^{-1} Q_D^{\star 5/6} e^{-5/3}. \quad (26)$$

To estimate the minimum size of the parent body, D_{pb}, responsible for this dust, we consider how large a planetesimal must be to reproduce f_{obs} if a destructive collision resulted in one fragment with half the mass of the original planetesimal (i.e., the definition of a destructive collision), with the remaining mass in particles of size D_{bl}:

$$D_{pb} = 890 \left(D_{bl} r^2 f_{obs}\right)^{1/3}. \quad (27)$$

Table 2 lists the parameters for the hot dust systems assuming the canonical parameters of $Q_D^\star = 200$ J kg^{-1}, $D_c = 2000$ km, and $e = 0.05$. To determine whether a system could have been reproduced by a single collision, the final value of $P(f > f_{obs})$ was compared with the statistic that 2% of systems exhibit hot dust (which therefore considers the optimistic case where all stars have planetesimal belts at a few AU). For the systems that were inferred in Table 1 to be transient, all are extremely unlikely (<0.001%) to have been caused by a single collision among planetesimals in a planetesimal belt that has undergone a collisional cascade since the star was born.

While this statistic is subject to the uncertainties in the model parameters described in § 3.2 and so could be in error by around 2 orders of magnitude, it must also be remembered that the most optimistic assumptions were used to arrive at this figure. For example, it is unlikely that the destruction of planetesimals of size D_{pb} would release half of the mass of the planetesimal into dust D_{bl} in size.[5] On the other hand, one might consider that the lifetime of the observed dust, $t_c(D_{bl})$, is an underestimate of the duration of dust at the level of $f > f_{obs}$, since the dust could be replenished from the destruction of larger particles. Indeed, Farley et al. (2006) modeled the destruction of a 150 km planetesimal in the asteroid belt and inferred a dust peak that lasted ~1 Myr, precisely because large fragments produced in the collision replenished the dust population. However, it should be cautioned that the dust peak inferred by Farley et al. (2006) would not have been detectable as an infrared excess since it only caused a factor of ~10 enhancement in the luminosity of the zodiacal cloud (i.e., to $f \approx 0.8 \times 10^{-6}$), and that in the context of our model, invoking a population of larger grains that result from the collision would lead to a larger parent body (i.e., a larger D_{pb}) required to reproduce the observed luminosity f_{obs} and so less frequent collisions; i.e., it may be possible (even desirable) to increase $t_c(D_{bl})$, but only at the expense of decreasing $dN_c(D > D_{pb})/dt$, leading to little change in $P(f > f_{obs})$. We note that $t_c(D_{bl})$ given in Table 2 is sufficiently short that a measurement of the variability of the infrared excess on realistic (few year) timescales could lead to constraints on the size of the grains feeding the observed phenomenon, since if a population of larger grains existed, then the luminosity would fade on much longer timescales.

A further argument against the transient disks being caused by single collisions is the fact that the probability of seeing the outcome of a collision, $P(f > f_{obs})$, falls off $\propto t_{age}^{-2}$, which means that we would expect to see more transient disks around younger stars than around older stars (because young stars have more massive disks with more large planetesimals and so more frequent collisions). There is some evidence from Table 1 that transience is more common around young systems, since none of the transient systems are older than 2 Gyr, whereas Sun-like stars in the solar neighborhood would be expected to have a mean age of ~5 Gyr. However, while the statistics are poor, a t_{age}^{-2} dependence does seem to be ruled out; e.g., we would have expected to have detected 10 times more transient disks caused by single collisions in the age range 50–500 Myr[6] than in the age range 0.5–5 Gyr,

[5] Such an optimistic assumption should not be dismissed out of hand, however, since the large amount of collisional processing that must have taken place means that planetesimals more than a few kilometers would be rubble piles. These would have undergone shattering and reaccumulation numerous times, meaning that they could have deep dusty regolith layers that could be preferentially ejected in a collision.

[6] It is not reasonable to extend the age range to younger systems, since, as noted in § 3.1, it is hard to discern whether or not dust detected in such systems is transient.

whereas two transient disks are known in the younger age bin, and two in the older age bin, which is more consistent with a $t_{\rm age}^{-1}$ dependence.

In fact, within the context of this model, all of the disks that we infer to be transient would also be inferred to not be the product of single collisions. This is evident by substituting $D_{\rm pb}$ from equation (27) and $f_{\rm max}$ from equation (18) into equation (26) to get

$$P(f > f_{\rm obs}) = 0.2 \times 10^6 (f_{\rm max}/f_{\rm obs})^2 \left(M_\star e^2 r^{-1} Q_D^{\star -1}\right)^{5/6}, \quad (28)$$

which reduces to $P(f > f_{\rm obs}) = 16(f_{\rm max}/f_{\rm obs})^2 (M_\star r^{-1})^{5/6}$ for the canonical parameters used before. Since transient disks are defined by $f_{\rm obs}/f_{\rm max} \gg 100$, this means that they cannot also have a high probability of having their origin in single collisions. It would only be inferred that disks with $f_{\rm obs}/f_{\rm max} \ll 100$ could have their origin in single collisions, but since it is also possible that these disks are the result of steady state collisional evolution, there is no need to invoke a single collision to explain their presence, which is why Table 2 simply concluded that it is "not impossible" that the disks of HD 113766 and HD 12039 are the product of single collisions. What equation (28) does indicate, however, is that it is possible for single collisions to cause disks to spend some fraction of their time at a luminosity enhanced above the nominal maximum value $f_{\rm max}$, and that this occurs more readily for disks at smaller radii and around higher mass stars. However, whether single collisions really do achieve an observable increase in luminosity depends on the size distribution of the collisional fragments, for which it must be remembered that equation (28) used an unrealistically optimistic estimate.

3.4. *Are Parent Planetesimals Coincident with Dust?*

For similar reasons to those in § 3.3, it is also possible to show that the parent planetesimals of the dust are extremely unlikely to originate in a planetesimal belt that is coincident with the dust. The reason is that the mass remaining in such a belt would be insufficient to replenish the dust for a length of time commensurate with the statistic that 2% of stars show this phenomenon. The observed dust luminosity, assuming that this is comprised of dust of size $D_{\rm bl}$ that has a lifetime of $t_c(D_{\rm bl})$ (eq. [25]), implies a mass-loss rate due to mutual collisions between the dust grains of

$$dM_{\rm loss}/dt = 1700 f_{\rm obs}^2 r^{0.5} L_\star M_\star^{-0.5} (r/dr), \quad (29)$$

in $M_\oplus$ Myr^{-1}, and this is independent of the collisional evolution model of § 2. However, due to the collisional evolution of a planetesimal belt's largest members, there is a maximum mass that can remain in a belt at the same radius as the dust at this age, and this is given in equation (15). This means that if the observed dust originates in an event that, for whatever reason, is causing planetesimals in a belt at the same radius as the dust to be converted into dust, then this can last a maximum time of $t(f > f_{\rm obs}) = M_{\rm max}/dM_{\rm loss}/dt$ before the planetesimal belt is completely exhausted. These figures are given in Table 3, which shows that the longest the type of transient event observed could be sustained in these systems is under 1 Myr, under the assumptions about the planetesimal belts employed in the rest of the paper.

A maximum duration of 1 Myr is not sufficient to explain the statistic that 2% of Sun-like stars exhibit this phenomenon, since the median age of such stars is 5 Gyr, indicating a typical duration (even if this occurs in multiple, shorter events) of around 100 Myr. Clearly a reservoir of mass is required in excess of that which it is possible to retain so close to the star.

TABLE 3
Constraints on Location of Parent Planetesimal Belts Feeding the Hot Dust

Star Name	$dM_{\rm loss}/dt$ (10^{-6} $M_\oplus$ Myr^{-1})	$M_{\rm max}$ (10^{-6} $M_\oplus$)	$t(f > f_{\rm obs})$ (Myr)	$r_{\rm out}$(100 Myr) (AU)
BD +20 307	8.0×10^6	53	6.7×10^{-6}	45
HD 72905	19	0.072	3.7×10^{-3}	2.4
η Corvi	2500	57	0.023	9.6
HD 69830	64	12	0.18	4.5

Notes.—These are the parameters in the model for the transient hot dust systems of Table 1 used to determine whether the observed dust could originate in the destruction of a planetesimal belt coincident with the dust. Here $dM_{\rm loss}/dt$ is the observed mass-loss rate, $M_{\rm max}$ is the maximum mass of a planetesimal belt that is coincident with the dust given the age of the star, $t(f > f_{\rm obs})$ is the length of time such a planetesimal belt could sustain the observed dust luminosity, and $r_{\rm out}$(100 Myr) is the radius of a planetesimal belt that would still have enough mass to sustain the observed dust luminosity for 100 Myr.

3.5. *Constraints on Parent Planetesimal Belt*

If we assume that the observed mass of hot dust originates in planetesimals that were initially in a belt at a radius $r_{\rm out}$ that has properties like those assumed in the rest of the paper and a fractional luminosity of $f_{\rm out}$, then there are two main constraints on that belt. First, assuming that this belt has been collisionally evolving for the age of the star, this belt cannot have more mass (or luminosity) than the maximum that could possibly remain due to collisional processing, i.e., $f_{\rm out} < f_{\rm max}$ (eq. [16]). Second, it must have sufficient mass remaining to feed the observed mass-loss rate for long enough to reproduce the statistic that 2% of stars exhibit this phenomenon, which implies a total duration of >100 Myr. For a belt to have enough mass to feed the observed hot dust luminosity of $f_{\rm obs}$ at a radius r for a total time of $t_{\rm hot}$ in Myr requires the belt to have a luminosity of

$$f_{\rm out} > 710 t_{\rm hot} f_{\rm obs}^2 r_{\rm out}^{-2} r^{0.5} D_c^{-0.5} L_\star^{0.5} (dr/r)^{-1}, \quad (30)$$

or rather, this is the luminosity it must have had before it was depleted.

Comparing this with the maximum mass possible at this age indicates that the parent belt must have a minimum radius of

$$r_{\rm out}(t_{\rm hot}) > 615 t_{\rm hot}^{3/13} t_{\rm age}^{3/13} f_{\rm obs}^{6/13} r^{3/26} (dr/r)^{-6/13} \times D_c^{-3/13} Q_D^{\star -5/26} e^{5/13} L_\star^{3/13} M_\star^{5/26}. \quad (31)$$

Table 3 gives an estimate of the minimum radial location of such a planetesimal belt, under the assumption that the event (or multiple events) of high hot dust luminosity last $t_{\rm hot} = 100$ Myr. These values indicate that the planetesimal belts must be at least a few AU from the star. It must be cautioned that this conclusion is relatively weak in the case of HD 69830, since the uncertainty in the properties of the planetesimals still leaves 2 orders of magnitude uncertainty in the maximum luminosity, $f_{\rm max}$, and hence also in the maximum mass $M_{\rm max}$ (see § 3.2). This means that, with suitable planetesimal belt properties, a belt in this system that is coincident with the dust at 1 AU may be able to replenish the observed phenomenon for 20 Myr. However, we still consider this to be an unlikely scenario, since it would require that the mass of the planetesimal belt is depleted at a constant rate for the full 100 Myr, whereas most conceivable scenarios would result in a mass-loss rate that decreases with time as the planetesimal population is depleted, thus requiring an even larger starting mass.

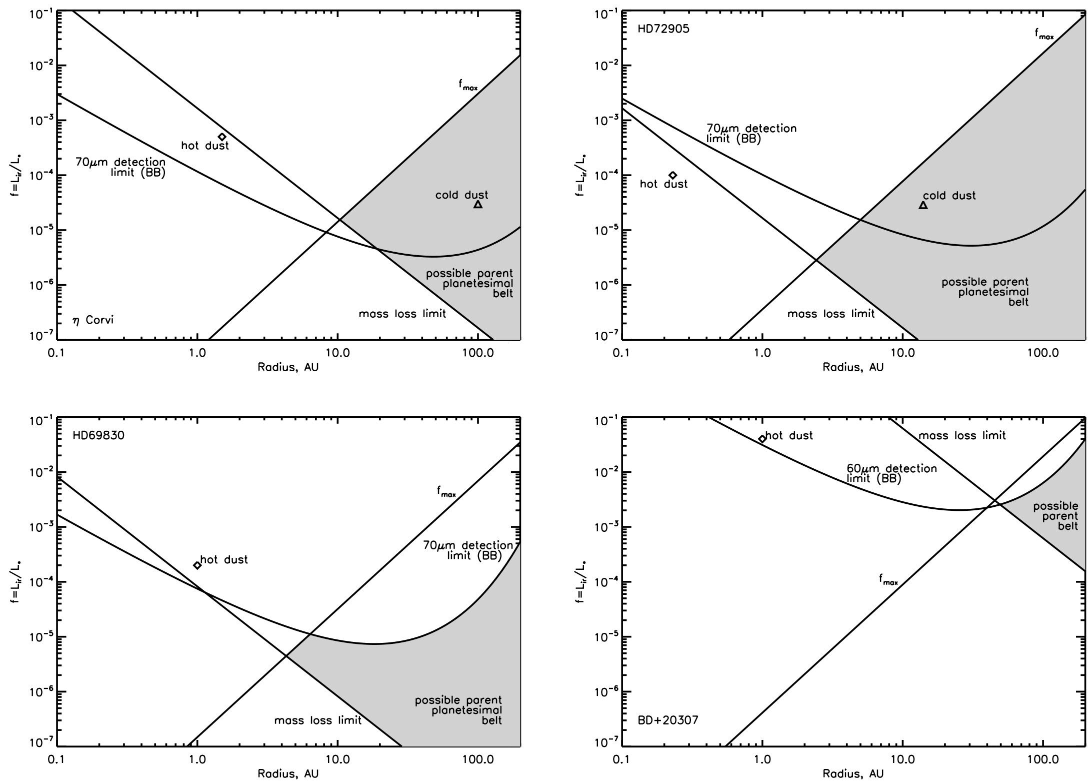

Fig. 4.—Constraints on the fractional luminosity and radius of the planetesimal belt feeding the observed transient hot dust (*shaded region*) for the following systems: η Corvi (*top left*), HD 72905 (*top right*), HD 69830 (*bottom left*), and BD +20 307 (*bottom right*). The solid lines are the constraints imposed by the far-IR detection limits (assuming blackbody emission), the maximum luminosity possible in a belt at this radius due to erosion by collisional processing, and the luminosity from a belt of sufficient mass to feed the observed mass-loss rate for 100 Myr. The properties of the hot dust in these systems are shown by a diamond, and those of the cold dust, where known (the top two panels), are shown by a triangle.

These two constraints are summarized for the four systems with transient hot dust in Figure 4, which shows the shaded region of parameter space in $f_{\rm out}$ and $r_{\rm out}$ where the parent planetesimal belt can lie. This figure also shows the location of the hot dust at $f_{\rm obs}$ and r, illustrating the conclusion of § 3.1 that this lies significantly above $f_{\rm max}$, the maximum fractional luminosity expected for a planetesimal belt at the age of the parent star. Note that the value $r_{\rm out}$(100 Myr) given in Table 3 denotes the intersection of the limits from $f_{\rm max}$ and from equation (30).

A third constraint for the parent planetesimal belt comes from far-IR observations of these systems. For two out of four of the transient dust systems a colder dust component has already been detected: η Corvi has a planetesimal belt with a resolved radius of ~100 AU (Wyatt et al. 2005), and HD 72905 has one inferred to be at ~14 AU (Beichman et al. 2006). In both cases these outer planetesimal belts have been inferred to be at a different spatial location from the hot dust either because of imaging constraints (Wyatt et al. 2005) or from analysis of the SED (Beichman et al. 2006). The properties inferred for these planetesimal belts are indicated in Figure 4 and lie within the shaded region, implying that these planetesimal belts do not have to be transiently regenerated, and they also provide a plausible source population for the hot dust found closer in. However, no such excess emission has been seen toward HD 69830 at either 70 μm (Beichman et al. 2005) or 850 μm (Sheret et al. 2004), indicating a planetesimal belt with a mass at most 5–50 times greater than our own Kuiper Belt. Likewise, BD +20 307 does not have a detectable excess in *IRAS* 60 μm observations (Song et al. 2005).

A low-mass reservoir of planetesimals does not necessarily rule out the presence of an outer planetesimal belt that is feeding the hot dust, for two reasons. First, the shaded region of Figure 4 actually constrains the properties of the planetesimal belt at the time at which depletion started; i.e., this population may have already been severely depleted by the same event that is producing the dust, and we are now nearing the end of the hot dust episode. Second, the constraints imposed by a nondetection in the far-IR do not eliminate the whole of the parameter space in which an outer planetesimal belt can lie. Figure 4 includes the constraints on the outer planetesimal belt imposed by the nondetection of excess in the far-IR, assuming that the dust emits like a blackbody. The resulting detection limit is then given by

$$f_{\rm det} = 3.4 \times 10^9 F_{\rm det}(\lambda) d^2 r_{\rm out}^{-2} / B_\nu(\lambda, T_{\rm bb}), \qquad (32)$$

where $F_{\rm det}$ is the detection limit in Jy, d is the distance to the star in pc, $T_{\rm bb} = 278.3 L_\star^{0.25} r_{\rm out}^{-0.5}$ is the blackbody temperature of dust at $r_{\rm out}$ in K, and $B_\nu(\lambda, T_{\rm bb})$ is in Jy sr^{-1}. For BD +20 307 the nondetection is limited by the sensitivity of *IRAS*, and so lower limits should be achievable with *Spitzer*. For the two systems with nondetections, the shaded region already takes the far-IR constraint into account.

The simplification that the emission comes from blackbody-type grains means that equation (32) underestimates the upper limit from the far-IR fluxes. This is because the majority of the luminosity comes from small grains that emit inefficiently at long wavelengths. Indeed, the blackbody assumption would require the hot dust of HD 69830 and BD +20 307 to have been detected in the far-IR, whereas this is not the case. We modeled the emission from nonporous silicate-organic refractory grains in a collisional cascade size distribution at 1 AU from these stars to find that the blackbody assumption used in equation (32) underestimates the limit by a factor of 3–5, meaning that nondetection of the hot dust in these systems in the far-IR is to be expected. This also means that slightly more luminous outer planetesimal belts than those indicated by the shaded region in Figure 4 may still have escaped detection in the far-IR.

Until now we have not proposed a mechanism that converts the planetesimals into dust. Whereas Beichman et al. (2005) invoke sublimation of comets as the origin of the hot dust and use this to estimate the mass of the parent planetesimal belt, we consider a scenario in which a significant fraction of material of all sizes in the parent planetesimal belt is placed on orbits either entirely coincident with the hot dust or with pericenters at that location. In this scenario the dust is reproduced in collisions and the material maintains a collisional cascade size distribution. Simply moving material from $r_{\rm out}$ to r would result in an increase in fractional luminosity from $f_{\rm out}$ to $f_{\rm out}(r_{\rm out}/r)^2$. This indicates that the parent planetesimal belt responsible for the hot dust could have originally been on the line in Figure 4 traced by $f_{\rm out} = f_{\rm obs}(r/r_{\rm out})^2$. Since this is parallel to the mass-loss limit line (eq. [30]) and for all but HD 69830 the observed hot dust component lies below this line, this indicates that parent planetesimal belts in the shaded region could be responsible for the hot dust observed, as long as a large fraction of their mass is scattered in to the inner regions. However, it is to be expected that only a fraction of the outer planetesimal belt ends up in the hot dust region, and so it is more likely that the parent planetesimal belt started on a line that falls off less steeply than $\propto r_{\rm out}^{-2}$, and this is consistent with the ratio of the hot and cold components of η Corvi and HD 72905, which indicate a dependence of $f_{\rm out} = f_{\rm obs}(r/r_{\rm out})^{0.5\pm0.2}$; it is also interesting to note that both have $r_{\rm out}/r = 60$–70. We defer further consideration of the expected properties of the parent planetesimal belt to a more detailed model of the dynamics of the types of events that could cause such a perturbation, but we simply note here that the existence of an outer planetesimal belt is not ruled out by the current observational constraints in any of the systems.

4. DISCUSSION

A simple model for the steady state evolution of dust luminosity for planetesimal belts evolving due to collisions was described in § 2. This showed how at late times the remaining planetesimal belt mass and hence dust luminosity are independent of the initial mass of the belt. This has important implications for the interpretation of the properties of detected disks. This paper discussed the implications for the population of Sun-like stars with hot dust at <10 AU; the implications for the statistics will be discussed in a forthcoming paper (Wyatt et al. 2007).

It was shown in § 3.1 that for four out of seven of the systems with hot dust their radius and age are incompatible with a planetesimal belt that has been evolving in quasi–steady state over the full age of the star, and in § 3.2 it was shown that this is the case even when uncertainties in the model are taken into account. This implies either that the cascade was started recently (within the last Myr or so) or that the dust arises from some other transient event. Recent ignition of the collisional cascade seems unlikely, since the mass required to feed the observed luminosity would result in the growth of 2000 km planetesimals that would stir the belt and ignite the cascade on timescales much shorter than the age of the stars. Possible origins for the transient event that have been proposed in the literature are as follows: recent collision between massive planetesimals in a planetesimal belt that introduces dust with a size distribution $q \gg 11/6$ and so can be detected above a collisional cascade that is too faint to detect; one supercomet ~2000 km in diameter that was captured into a circular orbit in the inner system replenishing the dust through sublimation (Beichman et al. 2005); and a swarm of comets scattered in from the outer reaches of the system (Beichman et al. 2005). In § 3.3 the collisional model was used to show that the transient disks are very unlikely (<0.001% for the most optimistic estimate for any of the stars compared with a detection probability of 2% for transient hot dust) to have their origin in a recent collision; such collisions occur too infrequently. In § 3.4 it was also shown that the parent planetesimals of the observed dust must originate in a planetesimal belt much farther from the star than the observed dust, typically at ≫2 AU. This is because collisional processing means that the mass that can remain so close to the star at late times is insufficient to feed the observed phenomenon.

The most likely scenario is thus a recent event that provoked one or more planetesimals to be scattered in from farther out in the disk (Beichman et al. 2005). The observed dust could have been produced from such a scattered planetesimal population through their grinding down in mutual collisions (§ 3.5), although sublimation close to the pericenters of the planetesimals' orbits is a further possible source of dust. More detailed study of the scattering and consequent dust production processes is required to assess these possibilities. However, this scenario is supported by the presence of far-IR emission originating from a colder outer planetesimal belt component in two out of four of the transient dust systems. The constraints on the outer planetesimal belt that is feeding the phenomenon are discussed in § 3.5, showing that the outer planetesimal belts already found in η Corvi and HD 72905 provide a plausible source population for the hot dust found closer in, and that the current nondetection of cold dust around the remaining two systems does not rule out the presence of an outer planetesimal belt capable of feeding the observed hot dust luminosity.

One clue to the origin of the parent planetesimals of the dust may be the composition of that dust. Silicate features have been detected in the mid-IR spectrum of all of the transient hot dust stars (Song et al. 2005; Beichman et al. 2005, 2006; Chen et al. 2006). Detailed modeling of the spectrum of HD 69830 indicates that the mineralogical composition of its dust is substantially different from that of comets; rather, there is a close match to the composition of P- or D-type asteroids found mainly in the 3–5 AU region of the solar system (Lisse et al. 2007). While the radial location at which planetesimals of this composition form in the HD 69830 system will depend on the properties of its protostellar nebula, which may be significantly different from that of the protosolar nebula, as well as on the structure and evolution of its planetary system, evidence for water ice in the dust spectrum indicates that the parent body formed beyond the ice line in this system (Lisse et al. 2007), i.e., beyond 2–5.5 AU (Lecar et al. 2006; Alibert et al. 2006). Thus, the compositional data support the conclusion that the dust is not produced by a planetesimal that formed in situ. However, it is worth noting that the same compositional data also find evidence for differentiation in the parent body (inferred from abundance differences between the dust and the star) and for heating of its rocky material to >900 K (inferred from the absence of amorphous pyroxene), which would also have to be explained in the context of an outer planetesimal belt origin for the dust.

An analogous transient event is thought to have happened in the solar system, resulting in the period known as the LHB when the terrestrial planets were subjected to an abnormally high impact rate from asteroids and comets. This is believed to have been triggered by a dynamical instability in the planetary system resulting from Jupiter and Saturn crossing the 1:2 resonance during their slow migration (inward for Jupiter, outward for Saturn) due to angular momentum exchange with the primordial Kuiper Belt (Gomes et al. 2005). In this scenario both the asteroid belt and Kuiper Belt were depleted with a large fraction of these objects being scattered into the terrestrial planet region during an event that lasted 10–150 Myr (Gomes et al. 2005), i.e., exactly the type of event required to explain the observed hot dust in the scenario proposed here (§ 3.5). Dynamical instabilities in extrasolar planetary systems can also arise from mutual gravitational perturbations between giant planets that formed close together (Lin & Ida 1997; Thommes et al. 1999). In both scenarios slow diffusion of the orbits of the planets means that the dynamical instability can occur up to several Gyr after the formation of the planetary system. The delay to the onset of the instability is determined by the separation of the outer planet from the outer planetesimal belt (Gomes et al. 2005), or from the separation between the planets (Lin & Ida 1997), with larger separations resulting in longer timescales.

Little is known about the planetary systems of four of the hot dust systems. However, three Neptune mass (or Jupiter mass if the system is seen face-on) planets have recently been discovered orbiting the star HD 69830 at <1 AU on nearly circular orbits (Lovis et al. 2006). Dynamical simulations showed that the detected planetary system is stable on timescales of 1 Gyr. This does not, however, rule out the possibility of a dynamical instability having occurred. While no mean motion or secular resonances are immediately identifiable within the detected planetary system that could have been crossed recently, invoking such a catastrophic event, it is possible that the instability arose with another planet farther out that has yet to be detected with longer timescale observations. It is also possible that a fourth planet that existed in the region 0.19–0.63 AU between the planets HD 69830c and HD 69830d has recently been scattered out due to a dynamical instability (e.g., Thommes et al. 1999). The region 0.3–0.5 AU was identified in Lovis et al. (2006) as being marginally stable and, to encompass several mean motion resonances with the outer planet, including the 1:2 resonance at 0.4 AU; i.e., a putative fourth planet could have remained in this region for the past 2 Gyr until the slow migration/diffusion of the outer planet (HD 69830d) caused the 1:2 resonance to coincide with the orbit of the putative planet that was then scattered outward, thus promoting the depletion of an outer planetesimal belt, much of which was scattered into the inner regions of the system. Alibert et al. (2006) considered that the most plausible formation scenario for the planetary system of HD 69830 included the inward migration of the outer planets from beyond the ice line at a few AU. This would put a substantial distance between the outer planet (HD 69830d) and any outer planetesimal belt that favors a delay of 2 Gyr before the onset of the instability. Searches for further planetary companions in this system, and for the relic of its outer planetesimal belt, are clearly necessary to constrain the evolutionary history of this system.

In conclusion, $\sim$2% of Sun-like stars exhibit transient hot dust in the terrestrial planet region; this dust must originate in a planetesimal belt located farther from the star than the dust, typically at $\gg$2 AU. Just four members of this class are currently known, although it seems reasonable to assume that our own solar system would have been placed in this class during the LHB. The frequency of this phenomenon indicates that either all stars are subjected to an epoch of similar duration (lasting $\sim$100 Myr assuming a typical age of 5 Gyr) or a smaller fraction of stars undergo much longer (or multiple) events. The distribution of the ages of the stars in this class indicates that the likelihood of these events occurring falls off roughly inversely proportional to the age of the stars. An origin for these events in a dynamical instability as proposed for the LHB in the solar system is supported by the recent discovery of a multiple-planet system coincident with the dust in one of the systems currently in this class. However, since the LHB in the solar system is thought to have lasted just $\sim$100 Myr, it remains to be seen whether we are to infer that dynamically unstable planetary systems form around all stars, or that the LHB event in other systems lasted much longer than in our own, or perhaps that there is in fact more than one mechanism causing this hot dust signature. Observations that further constrain the planet, planetesimal, and dust complements of the transient hot dust systems are needed to ascertain the similarities and dissimilarities within this population.

We are grateful for support provided by the Royal Society (M. C. W.) and PPARC (R. S.). We are also grateful to Ben Zuckerman, Joseph Rhee, and Inseok Song for pointing out that there is a strong (unrelated) infrared source in the vicinity of HD 128400 that is causing the excess identified by Gaidos (1999).

APPENDIX

SUMMARY OF SYMBOLS

The symbols that are employed in this paper are summarized in Table 4, along with the units assumed throughout the paper.

TABLE 4

Symbols Employed in This Paper and Their Units

Symbol	Units	Meaning
$B_\nu(\lambda, T)$	Jy sr^{-1}	Blackbody emission spectrum
d	pc	Distance to star
$dM_{\rm loss}/dt$	$M_\oplus$ Myr^{-1}	Rate of mass loss assuming observed dust has size $D_{\rm bl}$
dr	AU	Planetesimal belt width
$D_{\rm bl}$	μm	Diameter of smallest dust in cascade
D_c	km	Diameter of largest planetesimal in cascade
$D_{\rm cc}$	km	Smallest planetesimal capable of destroying planetesimals of diameter D_c
$D_{\rm pb}$	km	Minimum diameter of parent body required to produce observed dust
D_t	km	Planetesimal diameter at transition between strength and gravity regimes
e	...	Mean orbital eccentricity of planetesimals
f	...	Fractional luminosity ($=L_{\rm IR}/L_\star$) in model

TABLE 4—*Continued*

Symbol	Units	Meaning
f_{det}	...	Fractional luminosity for emission from belt to be detected
f_{max}	...	Maximum fractional luminosity of cascade after time t_{age}
f_{obs}	...	Fractional luminosity observed
f_{out}	...	Fractional luminosity of putative outer planetesimal belt feeding the dust
$f(e, I)$	...	Ratio of collision velocity to Keplerian velocity
f_{cc}	...	See eq. (8)
$F_{det}(\lambda)$	Jy	Detection limit at wavelength λ
$G(q, X_c)$	...	See eq. (9)
I	rad	Mean orbital inclination of planetesimals
K	...	Scaling factor in size distribution
$L_\star$	$L_\odot$	Stellar luminosity
L_{IR}	$L_\odot$	Infrared luminosity of material in the cascade
$M_\star$	$M_\odot$	Stellar mass
M_{max}	$M_\oplus$	Maximum mass remaining in cascade after time t_{age}
M_{tot}	$M_\oplus$	Total mass of material in cascade
$n(D)$	...	Size distribution of material in the cascade
$n(D > D_{pb})$	...	Number of objects in cascade larger than D_{pb}
$dN_c(D > D_{pb})/dt$	Myr^{-1}	Destructive collision rate for planetesimals larger than D_{pb}
$P(f > f_{obs})$	...	Fraction of time collisions result in $f > f_{obs}$
q	...	Slope of size distribution
q_g	...	Slope of size distribution expected in the gravity regime
q_s	...	Slope of size distribution expected in the strength regime
$Q_D^\star$	J kg^{-1}	Specific incident energy required to catastrophically destroy a planetesimal
r	AU	Planetesimal belt radius, assumed to be coincident with dust
$r_{out}(t_{hot})$	AU	Outer planetesimal belt radius required to maintain f_{obs} for t_{hot}
r_{out}	AU	Radius of putative outer planetesimal belt feeding the dust
s	...	Exponent in relation $Q_D^\star \propto D^s$
$t(f > f_{obs})$	Myr	Time a planetesimal belt at r can sustain $f > f_{obs}$
t_{age}	Myr	Time since cascade initiated (assumed to be stellar age)
t_c	yr	Collisional lifetime of planetesimals of size D_c
$t_c(D)$	yr	Collisional lifetime of material of size D
t_{hot}	Myr	Total duration of hot episodes throughout stellar lifetime
T_{bb}	K	Blackbody temperature of dust at a given distance from the star
v_{rel}	m s^{-1}	Relative velocity of collisions
v_{esc}	m s^{-1}	Escape velocity
v_k	m s^{-1}	Keplerian velocity
x_t	...	Jump in size distribution expected at D_t
X_c	...	$=D_{cc}/D_c$
ρ	kg m^{-3}	Planetesimal density
σ_{tot}	AU^2	Total cross-sectional area of material in cascade

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