Debris disc candidates in systems with transiting planets

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ABSTRACT
Debris discs are known to exist around many planet-host stars, but no debris dust has been found so far in systems with transiting planets. Using publicly available catalogues, we searched for infrared excesses in such systems. In the recently published Wide-field Infrared Survey Explorer catalogue, we found 52 stars with transiting planets. Two systems with one transiting ‘hot Jupiter’ each, TrES-2 and XO-5, exhibit small excesses both at 12 and at 22 μm at a >3σ level. Provided that one or both of these detections are real, the frequency of warm excesses in systems with transiting planets of 2–4 per cent is comparable to that around solar-type stars probed at similar wavelengths with Spitzer’s MIPS and IRS instruments. Modelling suggests that the observed excesses would stem from dust rings with radii of several au. The inferred amount of dust is close to the maximum expected theoretically from a collisional cascade in asteroid belt analogues. If confirmed, the presence of debris discs in systems with transiting planets may put important constraints on the scenario of formation and migration of hot Jupiters.

Key words: circumstellar matter – stars: individual: XO-5 – stars: individual: HAT-P-5 – stars: individual: TrES-2 parent star – stars: individual: CoRoT-8 – planetary systems.

1 INTRODUCTION
Many debris discs have been found in systems with known radial velocity (RV) planets (e.g. Beichman et al. 2005a; Moro-Martín et al. 2007; Trilling et al. 2008; Bryden et al. 2009; Kospál et al. 2009), and a few systems with debris discs and directly imaged planetary candidates are known (Kalas et al. 2008; Marois et al. 2008; Lagrange et al. 2010). However, debris dust has not been found yet in systems with planets detected by transits.

In this Letter, we search for debris dust in systems with transiting planets, using publicly available catalogues of transiting planets and several infrared (IR) surveys. The motivation is obvious. A successful search would extend the list of known ‘full’ planetary systems that harbour both planets and asteroid or Kuiper belt analogues. Furthermore, it is the transit technique that allows determination of many planetary parameters, such as masses, radii and densities, and can provide insights into properties of planetary atmospheres and interiors. Finally, transiting planets are on the average even closer to their parent stars than those discovered by the RV method, which might be related to somewhat different formation circumstances. Therefore, systems with transiting planets are of special interest. Detection of planetesimal belts, which are leftovers of planet formation, could help constraining various formation and evolution scenarios of those planets, and, conversely, precise knowledge of planetary parameters could put constraints on the properties of the planetesimal belts. For instance, accurate masses and orbits of planets would result in tighter constraints on dynamical stability zones and thus on the location of planetesimal belts.

2 SEARCH FOR DUST
A list of 93 currently known systems with transiting planets were taken from exoplanets.org (Wright et al. 2011).1 This list was compared with target lists of several IR missions, IRAS (Neugebauer et al. 1984), ISO (Kessler et al. 1996), Spitzer (Werner et al. 2004), AKARI (Murakami et al. 2007) and WISE (Wright et al. 2010), which we accessed through the IRSA, the NASA/IPAC Infrared Science Archive at http://irsa.ipac.caltech.edu.

2.1 IRAS, ISO, Spitzer and AKARI
Nearly all of the transit planet-host stars are located at hundreds of parsecs from the Sun and are thus faint. Accordingly, we had not expected to find them in older, and shallower, IRAS and ISO catalogues and indeed, have not found any. For example, out of 93 systems with transiting planets listed in exoplanets.org, only five are within 50 pc. These are GJ 436, GJ 1214, HAT-P-11, HD 189733 and HD 209458. None of them appears in the IRAS, ISO and WISE catalogues. Three of them, GJ 436, HD 189733 and HD 209458, have been probed by Spitzer/MIPS at 24 and 70 μm, yielding no excess detection (Bryden et al. 2009). We found an entry for the latter star in the AKARI catalogue, reporting a detection at
9 μm, which is consistent with the photospheric level. Note that HD 209458b was the first exoplanet found to transit the disc of its parent star (Charbonneau et al. 2000).

We have also identified two more distant transit planet-host stars that were observed by Spitzer/MIPS: HD 80606 and HD 149026. No excess at 24 and 70 μm was found for HD 189733 (Bryden et al. 2009). For HD 80606, the result is ambiguous due to pointing problems (Carpenter et al. 2008). AKARI has observed one more transit planet-host star, too: HD 149026. It has been detected at 9 μm, showing no excess.

2.2 WISE

The search in the WISE Preliminary Source Catalog was more successful. This is perhaps not a surprise, given the broad sky coverage (57 per cent) of the catalogue, excellent sensitivity of the instrument and thus a huge number of sources observed (257 million). The WISE catalogue provides measured magnitudes in four bands \( W_i \) (\( i = 1, \ldots, 4 \)), which are centred at 3.4, 4.6, 12, and 22 μm, respectively. Out of 93 systems with transiting planet candidates listed in exoplanets.org, we found 53 with entries in the WISE catalogue. One source – CoRoT-14 – is irretrievably contaminated by ghost images in the bands \( W_3 \) and \( W_4 \), and was excluded from further analysis.

To select possible IR-excess candidates from amongst the remaining 52 sources, we first converted the observed magnitudes in the four bands into spectral flux densities. Since no excesses are expected in the bands \( W_1 \) and \( W_2 \), we made simple photospheric predictions for \( W_3 \) and \( W_4 \) from the \( W_1 \) and \( W_2 \) fluxes. At first, we roughly corrected the \( W_1 \) and \( W_2 \) fluxes for an expected average level of interstellar extinction. Considering that systems in our sample are typically at a few hundreds parsecs, we set \( A_V \) to 0.5 mag, which translates into \( A(W_1) = 0.029 \) mag and \( A(W_2) = 0.012 \) mag (Rieke & Lebofsky 1985). We then fitted the corrected \( W_1 \) and \( W_2 \) fluxes with a power law \( F_\text{phot} = F_\text{phot}^{\lambda_a+b} \), with \( a \) and \( b \) being the fitting parameters. Subtracting the expected photospheric flux from the observed one, we derived the ‘excess flux’ \( F = F_\text{obs} - F_\text{phot} \) in the bands \( W_3 \) and \( W_4 \). The net uncertainty of a photometric point for a given star in the band \( W_3 \) or \( W_4 \) was computed as \( \sigma = \sqrt{\sigma_\text{phot}^2 + \sigma_\text{obs}^2 + \sigma_\text{cal}^2} \). Here, \( \sigma_\text{phot} \) is the photospheric uncertainty, which we estimated from the combined uncertainties of the measurements in the bands \( W_1 \) and \( W_2 \), given in the WISE catalogue. Next, \( \sigma_\text{obs} \) is the measurement uncertainty in the bands of interest, \( W_3 \) and \( W_4 \), also taken from the WISE catalogue. Finally, \( \sigma_\text{cal} \) is the absolute calibration uncertainty of the WISE instrument (2.4, 2.8, 4.5 and 5.7 per cent for the bands from \( W_1 \) to \( W_3 \)). The significance of an excess can now be defined as \( \chi = F/\sigma \).

The distributions of \( \chi \) values in the sample are shown in Fig. 1 for the bands \( W_3 \) (top panel) and \( W_4 \) (bottom panel). The \( W_3 \) histogram appears close to Gaussian, without any obvious outliers. However, the \( W_4 \) histogram uncovers a bin containing four systems with \( \chi > 1.75\sigma \), clearly separated from the Gaussian bulk. These are XO-5, HAT-P-5, TrES-2 and CoRoT-8. These four excess candidates will be checked in Section 3 more thoroughly, including an in-depth photospheric analysis and more accurate uncertainty estimates.

3 ANALYSIS OF EXCESS CANDIDATES

For the excess candidates, we have collected stellar data (Table 1) as well as optical and near-IR photometry. In the visual, we used the USNO-B1.0 Catalog (Monet et al. 2003), the Guide Star Catalog, the 2MASS catalogue (Skrutskie et al. 2006). For transforming the \( J \), \( H \), \( K \) magnitudes into units of flux density (Jy), we used the Johnson calibration system (Cohen, Wheaton & Megeath 2003) calibration.

In the first step, this photometry was corrected for interstellar extinction. Since for distances considered here the latter is known to correlate with distance only weakly, we used colour indices from Kenyon & Hartmann (1995) and the spectral type as given in Table 1 to derive the best-fitting \( A_V \) from multiple colours and then \( A_j/A_V \) ratios of Rieke & Lebofsky (1985) to compute extinction for the wavelengths of all photometry points. The derived \( A_V \) values are within 0.1 mag for non-CoRoT stars, but as large as 1.3 ± 0.2 mag for CoRoT-8. The extinction in the \( W_3 \) and \( W_4 \) bands does not exceed 0.04 mag (CoRoT-8).

In the second step, we performed a minimum \( \chi^2 \) fitting of the extinction-corrected stellar photospheric fluxes by NextGen models (Hauschildt, Allard & Baron 1999), only to data points between 1 and 5 μm. This is because those wavelengths are short enough not to expect any excess emission, but are long enough for interstellar extinction to be small. The interval from 1 to 5 μm includes three 2MASS points (\( J, H, K \)) and two WISE points (3.4 and 4.6 μm), all of which were given equal weights. Since the surface gravity of our stars (log g between 4.33 and 4.61) and their metallicity ([Fe/H]) from −0.2 to +0.31 deviate from the solar values only slightly (see Table 1 for references), we assumed a log g of 4.5 and the solar
metallicity. Using \( T_{\text{eff}} \) and \( d \) listed in Table 1 as starting values, we varied the temperature by \( \pm 400 \) K in 200 K steps and the distance from the star within \( \pm 30 \) per cent in 5 per cent steps to derive best-fitting values of these two parameters. This yielded deviations from the starting values of up to 8 per cent in \( T_{\text{eff}} \) and up to 20 per cent in \( d \) (Table 1). The results with the photometric points overplotted are shown in Fig. 2. Importantly, TrES-2 and XO-5 and possibly also HAT-P-5 reveal small excesses in the band \( W_3 \) as well, which were not seen in Fig. 1 (top panel).

We now come to a detailed analysis of the fluxes and their uncertainties. Let us denote the observed flux by \( F_{\text{obs}} \), the extinction-corrected one by \( F_{\text{obs}}^{\text{phot}} \), the predicted extinction-corrected photospheric flux by \( F_{\text{phot}} \) and the excess flux by \( F \equiv F_{\text{obs}} - F_{\text{phot}} \). As in Section 2, the net uncertainty of \( F \) for a given star in the band \( W_i \) or \( W_j \) is computed as \( \sigma = \sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{cal}}^2 + \sigma_{\text{ext}}^2} \). The measurement uncertainty \( \sigma_{\text{obs}} \) and the calibration uncertainty \( \sigma_{\text{cal}} \) are included as described before. However, the photospheric uncertainty \( \sigma_{\text{phot}} \) is now a by-product of the fitting procedure. It is dominated by a scatter in \( J, H, K_s \), \( W_1 \) and \( W_2 \) points (the error bars of the points themselves as well as the uncertainty of the extinction correction are much smaller). All the quantities above, and the resulting excess significance \( \chi = F / \sigma \), are listed in Table 2. Nearly all excesses are at an \( \approx 2 \sigma \) level, whereas usually a \( 3 \sigma \) excess is treated as a significant detection. However, in the cases of TrES-2, XO-5 and HAT-P-5, the excess is detected in two bands. The combined multiband (\( W_1 \) and \( W_2 \)) Gaussian statistics suggest the significance level for these sources of 3.28, 3.23 and 2.82, respectively. This finally selects two systems, TrES-2 and XO-5, as \( > 3 \sigma \) significant and thus the best excess candidates. The binomial probability that one of these two detections is false is only 6.4 per cent, and the probability that both are false is as low as 0.2 per cent. The expected number of false detections at a \( > 3 \sigma \) level is just 0.14; we detected two excesses at that level.

4 PRESUMED DUST BELTS

In what follows, we estimate the parameters of dust that would produce the excesses in the best candidate systems, TrES-2 and XO-5, provided these are real. Since the excesses are of low significance and the data are limited to two photometry points, a detailed spectral energy distribution (SED) modelling based on various assumptions about the size distribution and composition of dust is not warranted.

Instead, we used a pure blackbody (BB) and a modified BB emission model. In the latter case, we assumed a single grain size \( s_0 \) and the opacity index \( q = -2 \) beyond \( \lambda = 2 \pi s_0 \). The effective grain size \( s_0 \) was chosen in the following way. Assuming a power-law size distribution with the index \( q = 3.5 \) and the lower cut-off radius \( s_{\text{min}} \) of twice the radiation pressure blowout limit \( s_{\text{blow}} \) (see e.g.

\[
\sigma_{\text{obs}} \equiv \sigma_{\text{phot}} = \sigma_{\text{cal}} = \sigma_{\text{ext}}
\]



\[
\chi = \frac{F}{\sigma} = \frac{F_{\text{obs}} - F_{\text{phot}}}{\sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{cal}}^2 + \sigma_{\text{ext}}^2}}
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\[
\sigma_{\text{phot}} = \frac{F_{\text{obs}} - F_{\text{phot}}}{\sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{cal}}^2 + \sigma_{\text{ext}}^2}}
\]

Figure 2. SEDs of four selected stars. Grey solid line: predicted extinction-corrected photosphere. Diamonds and open circles: visual and near-IR photometry data before and after correction for interstellar extinction, respectively. Filled circles: extinction-corrected \( \text{WISE} \) data (errors bars are \( \sigma_{\text{obs}} \)). Black dashed line: modified BB model.

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Krivov, Löhne & Sremčević 2006; Thébault & Augereau 2007), we have equated the emission of a disc of grains having such a size distribution and the emission of a disc composed of equal-sized grains of radius $s_0$:

$$\int_{\lambda_{\min}}^{\infty} Q_{\text{abs}}(\lambda, s_0) B_\lambda(\lambda, T_d(r_d, s))s^{2-q} \, ds$$

$$= Q_{\text{abs}}(\lambda, s_0) B_\lambda(\lambda, T_d(r_d, s_0))s_0^2\int_{\lambda_{\min}}^{\infty}s^{-q} \, ds,$$

(1)

where $r_d$ is the distance from the star, $\lambda$ is the wavelength where excess emission is observed, $B_\lambda$ is the Planck intensity, $Q_{\text{abs}}(\lambda, s)$ is the grain absorption efficiency and $T_d$ is the grain temperature. In calculating $s_{\text{low}}$, we assumed the unit radiation pressure efficiency and the bulk density of 3 g cm$^{-3}$ and took the stellar parameters from Table 1. Equation (1) was solved for $s_{\text{low}}$.

We then sought pure BB and modified BB curves that reproduce $F(12 \mu m)$ and $F(22 \mu m)$. This has yielded estimates of the temperature, location, mass and fractional luminosity of the emitting dust (Table 3). When deriving the dust mass, we converted the temperature, location, mass and fractional luminosity of the emitting dust (Table 3). When deriving the dust mass, we converted the temperature, location, mass and fractional luminosity of the emitting dust (Table 3). When deriving the dust mass, we converted the temperature, location, mass and fractional luminosity of the emitting dust (Table 3). When deriving the dust mass, we converted the temperature, location, mass and fractional luminosity of the emitting dust (Table 3). When deriving the dust mass, we converted the temperature, location, mass and fractional luminosity of the emitting dust (Table 3). When deriving the dust mass, we converted the temperature, location, mass and fractional luminosity of the emitting dust (Table 3).

### Table 2. Fluxes (mJy), uncertainties (mJy) and significance of excesses.

| System | Band | $F_{\text{obs}}$ | $F_{\text{cal}}$ | $F_{\text{phot}}$ | $\sigma_{\text{cal}}$ | $\sigma_{\text{phot}}$ | $\sigma_{\text{obs}}$ | $\chi$ | $\chi_{\text{joint}}$ |
|--------|------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----|-----------------|
| TrES-2 | W3   | 3.71            | 3.72            | 3.10            | 0.62            | 0.20            | 0.11            | 0.17| 0.29            | 2.17            | 3.28            |
|        | W4   | 2.22            | 2.22            | 0.93            | 1.29            | 0.12            | 0.58            | 0.13| 0.61            | 2.12            |
| XO-5   | W3   | 2.38            | 2.38            | 1.92            | 0.47            | 0.09            | 0.14            | 0.11| 0.20            | 2.35            | 3.23            |
|        | W4   | 2.16            | 2.16            | 0.58            | 1.58            | 0.08            | 0.85            | 0.12| 0.86            | 1.84            |
| HAT-P-5| W3   | 1.99            | 2.00            | 1.74            | 0.26            | 0.09            | 0.10            | 0.09| 1.65            | 1.58            | 2.82            |
|        | W4   | 1.93            | 1.94            | 0.53            | 1.41            | 0.09            | 0.68            | 0.11| 0.70            | 2.03            |
| CoRoT-8| W4   | 2.17            | 2.24            | 0.24            | 2.00            | 0.09            | 0.96            | 0.13| 0.97            | 2.05            |

**Columns:** observed flux $F_{\text{obs}}$; observed flux after correction for extinction $F_{\text{cal}}$; expected photospheric flux $F_{\text{phot}}$; uncertainty of photospheric flux $\sigma_{\text{phot}}$; observation uncertainty $\sigma_{\text{obs}}$; absolute calibration uncertainty $\sigma_{\text{cal}}$; net uncertainty of the excess flux $\sigma$; excess significance level in a single band $\chi$; and joint (W3 and W4) significance level $\chi_{\text{joint}}$.

### Table 3. Dust parameters inferred from the observed excesses and parameters of transiting planets.

| System | BB | Modified BB | Planet |
|--------|----|-------------|--------|
|        | $T_d$ (K) | $r_d$ (au) | $s_{\text{low}}$ ($\mu$m) | $s_0$ ($\mu$m) | $M_d$ ($M_\oplus$) | $f_d$ | $q_d$ (au) | $\varepsilon_p$ | $\varepsilon_p$ | $M_p$ ($M_{\text{Jup}}$) |
| TrES-2 | 218 | 1.7 | 0.4 | 2.1 | 155 | 5.8 | $5 \times 10^{-5}$ | 3 $\times 10^{-4}$ | 0.037 | 0 (fixed) | 1.28 |
| XO-5 | 181 | 2.2 | 0.4 | 2.0 | 133 | 8.0 | $1 \times 10^{-4}$ | 6 $\times 10^{-4}$ | 0.051 | 0.049 | 1.06 |

**Note:** Planetary parameters are taken from the papers listed in Table 1.

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5 CONCLUSIONS AND DISCUSSION

We have found that two out of 52 systems with transiting planets observed by the WISE reveal warm two-band (12 and 22 $\mu$m) IR excesses at a $\approx 3\sigma$ level. The probability that both excesses are real is 94 per cent and that one of them is real is 99.8 per cent.

Provided that one of the two systems, or both, does possess a warm disc, this would imply the excess incidence rate of 2–4 per cent. For comparison, the Spitzer/MIPS detection rate of 24-\mum excesses around old (~4 Gyr) field stars was found to be 1/69 (1 ± 3 per cent) (Bryden et al. 2006). Another sample of solar-type stars probed by the MIPS at 24 $\mu$m resulted in an ≈4 per cent detection rate, averaged over all ages (Trilling et al. 2008). Lawler et al. (2009) analysed Spitzer/IRS observations of nearby solar-type stars and found excesses around 12 per cent of them in the long-wavelength IRS band (30–34 $\mu$m), but only 1 per cent of the stars have detectable excesses in the short-wavelength band (8.5–12 $\mu$m).

Thus, the frequency of warm excesses around solar-type stars with transiting planets seen in the WISE data may be comparable to that in unbiased samples of similar stars found with Spitzer.

Each of the two systems discussed here hosts one known close-in planet and, if the excesses are real, an asteroid belt-size dust ring well outside the planetary orbit. In both cases, more planets could orbit both inside and outside the belts. Additional planets at $\lesssim 10$ au could be revealed by in-depth RV analyses, by transits or by transit-time variations of already known planets (Maciejewski et al. 2011a). The latter method was used for TrES-2 (Rätz et al. 2009) and XO-5 (Maciejewski et al. 2011b). Non-detection is consistent with the presence of debris belts at several au, which are incompatible with planets in that region. In the case of TrES-2, Rätz et al. (2009) noted a second dip in the light curve, both in their own light curves and those published in the literature. This second dip has been observed several times and then disappeared. In addition to other possible reasons for this effect, discussed by Rätz et al., it could be due to an occultation by the material in the debris disc. Estimates show that a clump of dust produced in a recent collision of two ~100 km sized planetesimals would bear enough cross-section to account for such a dip before it is azimuthally spread into a ring in a few years, although the probability of witnessing such an event is low.

Planets at largest orbital radii ($\gtrsim 10$ au) will be hard to find by the transit technique. Direct imaging and astrometry are not feasible either, since these systems are too old and too distant. It will also be difficult to search for possible Kuiper belt analogues on the
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The periphery of the systems, because they are too faint for far-IR facilities such as Herschel. However, future mid-IR instruments such as JWST/MIRI should have enough sensitivity to study warm dust in great detail, including dust grain spectroscopy. They may also take a closer look at further potential excess candidates, such as HAT-P-5 and CoRoT-8, identified in this study.

The origin and the production mechanisms of the presumed dust are unclear. We have computed the dust mass expected to be produced through a steady-state collisional cascade in a belt of ‘asteroids’ with moderate eccentricities, using the model of Löhne, Krivov & Rodmann (2008) with a velocity-dependent critical fragmentation energy from Stewart & Leinhardt (2009). At ages of \(\sim 1 \text{ Gyr}\), the maximum expected dust mass is \(\sim 10^{-4} \text{M}_\oplus\) at \(r_d = 10 \text{au}\) and \(\sim 10^{-5} \text{M}_\oplus\) at \(r_d = 6 \text{au}\). Comparing with Table 3, we conclude that the amount of dust in our systems is close to, or even somewhat greater than, the theoretical maximum allowed by a steady-state collisional cascade. This means that we might have a similar difficulty that exists in explaining other systems with hot excesses that have been known before, such as HD 69830 (Beichman et al. 2005b). Proposed scenarios for such systems include supply of comets from an outer massive cometary reservoir, possibly following a recent dynamical instability such as the Late Heavy Bombardment; the inward-scattering and disintegration of a large object from such an outer reservoir; and a recent major collision between two large planetesimals (see Payne et al. 2009, and references therein). Finally, the possibility of steady-state collisional dust production can be resuscitated if one allows the asteroids in the belt to have very eccentric orbits (Wyatt et al. 2010). Such a belt could result from shepherding and scattering of an initial planetesimal belt during the inward migration of ‘hot Jupiters’ (Payne et al. 2009).

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