Infrared excesses in stars with and without planets using revised WISE photometry

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ABSTRACT

We present an analysis on the potential prevalence of mid infrared excesses in stars with and without planetary companions. Based on an extended database of stars detected with the WISE satellite, we studied two stellar samples: one with 236 planet hosts and another with 986 objects for which planets have been searched but not found. We determined the presence of an excess over the photosphere by comparing the observed flux ratio at 22 µm and 12 µm ($f_{22}/f_{12}$) with the corresponding synthetic value, derived from results of classical model photospheres. We found a detection rate of 0.85% at 22 µm (2 excesses) in the sample of stars with planets and 0.1% (1 detection) for the stars without planets. The difference of the detection rate between the two samples is not statistically significant, a result that is independent of the different approaches found in the literature to define an excess in the wavelength range covered by WISE observations. As an additional result, we found that the WISE fluxes required a normalisation procedure to make them compatible with synthetic data, probably pointing out a revision of the WISE data calibration.

Key words: Stars: circumstellar matter – planetary systems – infrared: stars

1 INTRODUCTION

Discs and rings are common products of the evolution of different astronomical systems at different size scales, from galaxies to stars and planets. Circumstellar discs are found around stars at different evolutionary stages and they are commonly detected as an infrared (IR) excess over the photospheric value, produced by their thermal emission. Debris discs represent the final stage of disc evolution, they may orbit mature systems and can coexist with a fully-formed planetary system, as in our solar case. They are formed by second-generation solid material, ranging from sub-mm dust particles to sub-planetary bodies, and, in a few cases, a small amount of gas has also been observed (e.g., Kós pál et al. 2013). The grain size distribution is determined by the simultaneous processes that form (e.g., collisional grinding) or remove (e.g. Poynting-Robertson and stellar wind drag) solid particles (Wyatt et al. 2011). Thus, this kind of disc continues to evolve collisionally and dynamically.

In the past decade, several surveys have explored debris discs around stars of spectral types from A to M in the mid- and far-IR, probing dust at different locations, due to the positive correlation between the wavelength of the peak of the dust emission and the distance from the star1 (e.g., Wyatt 2008). The most relevant surveys are FEPS2 (Rieke et al. 2005), using the Spitzer observatory, DEBRIS (Sibthorpe et al. 2013) and DUNES3 (Eiroa et al. 2013), carried out with the Herschel satellite. Matthews et al. (2014) made a comparison of detection rates of debris discs among the different surveys and found that, for A stars, the detection rates are 33% and 25% at 70 µm and 100 µm, respectively, while for solar type stars (FGK) it ranges from 10%, in the case of FEPS survey, to 17%, reported in the DEBRIS survey. DUNES increased the detection rate up to 20% (Eiroa et al. 2013), while the recent work by Montesinos et al. (2016) gives a value of 22%. Trilling et al. (2008) interpreted the apparent decrease of ex-

1 For a solar luminosity star, observations at 10 µm detect dust at a distance of ~1 au, at 22 µm the distance is about 4.5 au, at 60 µm the distance increases to ~33 au, while at 100 µm observations probe dust at about 90 au. These distances scale as the square root of the star luminosity.

2 Formation and Evolution of Planetary Systems.

3 DUst around NEarby Stars.
cess rates from A to K spectral types as due to an age effect, as expected by circumstellar disc evolution.

A new kind of discs was detected thanks to extensive surveys in the Mid-IR regime. These objects are called warm debris discs and the emission in excess found at wavelengths between 5 µm and 35 µm suggests the presence of material close to the star. Chen et al. (2005), Uzpen et al. (2007), and Hales et al. (2009) used Spitzer data, from 8 to 70 µm, to identify a significant number of flux excesses attributable to the presence of circumstellar warm dust. More recent studies, that used Wide Infrared Survey Explorer (WISE) data, have found stars with IR excesses in the Mid-IR regime (Kennedy & Wyatt 2012; Cruz-Saenz de Miera et al. 2012; Patel et al. 2014; Kuchner et al. 2016; Costa et al. 2016). We might expect that the presence of planets at few au from the stars (in the “terrestrial” zone) and warm debris discs are correlated, since planets are the final stage of agglomeration of planetesimals and the dust in warm debris discs is also formed from planetesimals. In this work we want to assess if the correlation between the Mid-IR excesses and planets does exist or not. In this context, the work presented here complements previous analyses, in particular those of Krivov et al. (2011) and Morales et al. (2012), who looked for IR excesses using, respectively, a preliminary WISE release and the All-Sky WISE catalogue. While Krivov et al. (2011) found no evidence for IR excesses in 52 transiting exoplanetary systems, Morales et al. (2012) found a prevalence of 2.6% in a large sample (591) of planetary systems around both main sequence (MS) and evolved stars; the incidence decreases to 1% if only MS stars are considered. At longer wavelengths (100 µm), Moro-Martín et al. (2015) did not find significant difference in the occurrence of dust around stars hosting planets in selected samples of DUNES and DEBRIS objects.

In this paper we analyze a sample of stars with planets and another comparison sample of stars where planets have been searched for but not found. Infrared data of the four WISE bands is used to search for IR excesses at 22 µm by comparing the observed and expected photospheric flux ratio \(f_{22}/f^\ast\). Furthermore, we also explored the issue by analysing different procedures used by other authors to obtain more results on the existence (or not) of a correlation between planets and warm debris discs (Morales et al. 2012; Kennedy & Wyatt 2012; Patel et al. 2014; Cruz-Saenz de Miera 2012).

2 WISE

WISE was a NASA mission (2009-2011) whose main objective was to map the entire sky in four Mid-IR passbands at 3.4 µm (W1), 4.6 µm (W2), 12 µm (W3) and 22 µm (W4). It consisted of a cryogenically cooled 40 cm aperture telescope. It used four focal planes that simultaneously took images of a 47×47 arcmin field of view. The full-width-at-half-maximum (FWHM) of the point spread function (PSF) were 6.1″ for W1, 6.4″ for W2, 6.5″ for W3 and 12.0″ for W4. WISE photometry of point sources was conducted using PSF profile fitting and the background level was estimated in a ring at a fixed distance (form 50 to 70′′) from the source. Two comprehensive photometric catalogues have been delivered. The first one, called All-Sky (Cutri & et al. 2012), covered more than 90% of the sky. The second data release, named AllWISE (Cutri & et al. 2013), was delivered in November 2013 and included combined data of previous epochs of WISE, such as NEOWISE, which also provided photometry measurements of asteroids and comets, and Cryogenic WISE, which obtained data before their cooling systems ended operations. Taking into account these combinations, the sensitivity and the photometric precision was improved as compared to the previous All-Sky catalogue.

WISE achieved sensitivities of 5σ for point sources with flux of 0.08, 0.11, 1 and 6 mJy (16.5, 15.5, 11.2 and 7.9 Vega magnitudes, respectively) in the four bands, from W1 to W4. This allowed to detect, in W1, faint objects that do not appear in the 2MASS Ks survey, while at 12 µm and 25 µm the WISE survey is ~100 times more sensitive than IRAS (Neugebauer et al. 1984).

3 HOMOGENEOISING WISE AND SYNTHETIC PHOTOMETRY.

Prior to the search of IR excesses, we tested the agreement between the observed WISE fluxes, provided by the AllWISE catalogue, and the ATLAS9 theoretical photospheric flux (Castelli & Kurucz 2003) that we used as reference, using a very large sample of stars.

3.1 The sample selection.

We selected stars with spectral types from A0 to K9 and luminosity classes V, IV, or IV/V from the SIMBAD Astronomical Database4. The Johnson V magnitude of these stars ranges from 5 to 12, which make them prone to have a good signal-to-noise ratio (S/N ≥ 5) in the WISE band W4. We then discarded all objects in multiple systems and pre-main sequence stars (T-Tauri, Ae/Be Herbig). We assembled an initial sample of 53349 objects.

We collected their WISE magnitudes from the AllWISE catalogue, considering only objects that comply the following constraints: a) they must have a S/N≥5 in W4 band; b) their W1, W2, W3 and W4 photometry must include an uncertainty measurement; c) they must be free from any artifact or contamination by nearby objects (i.e. we excluded those sources considered as spurious detections or contaminated by diffraction spikes, scattered light halos or optical ghosts produced by a bright star on the same image, according to the criteria of allWISE catalogue); d) the saturation in W3 and W4 must be zero.

We also extracted the J, H, and Ks magnitudes from the 2MASS All-Sky catalogue. The restrictions applied on this catalogue are as follows: a) J, H and Ks photometry must be accompanied by the corresponding uncertainties; b) the quality flag of the photometry must be A or B, with a S/N≥10 and S/N≥7, respectively. Finally, we obtained the B and V photometry from SIMBAD. After applying the previous criteria, we obtained a sample of 24,117 stars.

4 http://simbad.u-strasbg.fr/simbad/
Table 1. Zero magnitude flux density for B, V (Bessell 1979), J, H, Ks (from http://ipac.caltech.edu/2mass), W1, W2, W3, W4 (from http://wise2.ipac.caltech.edu) bands.

| Band | $F_0$ (Jy) |
|------|-------------|
| B (Johnson) | 4266.7 |
| V (Johnson) | 3836.3 |
| J (2MASS) | 1594.0 |
| H (2MASS) | 1024.0 |
| Ks (2MASS) | 666.7 |
| W1 (WISEg) | 306.7 |
| W2 (WISEg) | 170.7 |
| W3 (WISEg) | 29.0 |
| W4 (WISEg) | 8.3 |

3.2 Correction for extinction and magnitude to flux conversion

Due to their brightness range, we expect most of the stars in our sample to be nearby objects; however, we considered appropriate to apply a flux correction for those objects that show a considerable colour excess $E(B-V)$. Correction for interstellar extinction will reduce systematic errors in the determination of stellar parameters for which we use optical and near-IR photometry.

We first obtained the intrinsic colour $(B - V)_0$ for each object, based on its spectral type, from the colour calibration of Pecaut et al. (2012), and derived the colour excess $E(B - V)$. We computed the mean $\mu_{E(B-V)}$ and the standard deviation $\sigma_{E(B-V)}$ of the $(B - V)$ distribution, after applying a $3\sigma$-clipping to the data. We only applied a reddening correction, to all wavelength bands considered in this work, for the stars with $E(B - V) > \mu_{E(B-V)} + 1\sigma_{E(B-V)} = 0.078$ mag. The mean value of the colour excess distribution is 0.026 mag. A total of 9230 stars were corrected for reddening through the equation:

$$f_\lambda = f_0 10^{0.4(-A_V)}$$

that also allows to convert apparent magnitudes $m_\lambda$ to fluxes $f_\lambda$. We used the zero magnitude flux $f_0$ in the Vega scale reported in Table 1 and the $A_V$ values provided by the Rieke & Lebofsky (1985) extinction curve. No colour correction was applied to WISE data, since the reddening at micron wavelengths is negligible.

3.3 Photospheric fitting and synthetic photometry

Since the search of IR excesses requires a good estimation of the photospheric contribution of each star, synthetic spectra are needed. In the near and mid IR, the choice of a specific model atmosphere library is not critical: Sinclair et al. (2010) found that ATLAS9 (Castelli & Kurucz 2003) and MARCS (Gustafsson et al. 2008) present discrepancies smaller than 2% at 24 $\mu$m for FGK stars, and Cruz-Saenz de Miera (2012) obtain similar figures comparing ATLAS9 and NEXTGEN SEDs. The stellar spectra in the selected parameter space of the sample are well reproduced by the LTE plane-parallel, low resolution ATLAS9 model atmospheres (see, e.g., Bertone et al. 2004; Martins & Coelho 2007). In order to compute the synthetic photometry that we needed to determine the photospheric fluxes, we first estimated the atmospheric parameters of each star through a match with a grid of ATLAS9 library.

We derive the effective temperature ($T_{eff}$) by identifying the theoretical spectrum that best match the observed B, V, J, H, and $K_s$ fluxes\(^5\), that we assume as purely photospheric, using the MPFIT $\chi^2$ minimization algorithm (Markwardt 2009). The procedure also provides the multiplying factor $c_i$ that takes into account the flux density dependence on distance. Since the surface gravity ($\log g$) and overall metallicity ([M/H]) generate small flux changes in the Rayleigh-Jeans regime (see Cruz-Saenz de Miera 2012), we fixed their values to log $g=4.0$ for main sequence (MS) A and F stars and for stars with luminosity class IV or IV-V, and log $g=4.5$ for MS G and K stars. We assumed solar metallicity in all cases.

We used the theoretical photospheric SED of each star to compute the WISE synthetic photometry\(^6\). In Fig. 1 we plot the results in the form of the flux ratio between the observed and the photospheric value as a function of the flux value for W1, W2, W3, and W4 bands for all 24,117 stars. We note a significant discrepancy in all cases. It is smaller for the W1 band and it decreases towards brighter objects, apart for the case of W2 band, where it steeply increases with increasing flux. To quantify this discrepancy, we divided the sample in flux bins of 0.1 Jy or wider, when the number of objects per bin fell short of 40; we then computed the median flux ratio for each bin and we estimated its uncertainty as half the difference between the 25% and 75% quartiles. We used these data to search for the best linear fit using the MPFIT algorithm, with the slope $m$ and the constant $b$ as free parameters in the linear equation $f_i_{obs}/f_i_{syn} = m f_i_{obs} + b$, where $i$ indicates the WISE band. The use of the median value minimizes the impact of the objects with a real IR excess on the fit, that therefore should be representative of the majority of stars whose flux emerges from the photosphere. The results, reported in Table 2, show a similar behavior of the two redder bands: they have a 10% flux overestimation over the synthetic value at low fluxes and this discrepancy gradually diminishes for the brighter objects. Conversely, for the case of the W2 band, the theoretical and observed flux match well for the faint objects, but increases to about a 40% overestimation at the brightest end.

Since, this discrepancy may significantly affect the determination of IR excesses, we decided to transform the WISE observed fluxes to the theoretical system, by means of the following equation:

$$f_i'_{obs} = \frac{f_i_{obs}}{m f_i_{obs} + b}$$

where $f_i'_{obs}$ is the transformed flux that we use to explore the WISE database in search of IR excesses in stars with and without planets.

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\(^5\) We extract filter transmission functions from http://voservices.net/filter/ and http://www.ipac.caltech.edu/2mass.

\(^6\) http://wise2.ipac.caltech.edu/docs/release/allsky/expsup
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Figure 1. Flux ratio $f_{W_i,\text{obs}}/f_{W_i,\text{syn}}$ vs. $f_{W_i,\text{obs}}$ for all 24,117 stars (dots). The starred symbols represent the median for each flux bin with their respective uncertainty, the thick line shows the best linear fit while the dashed line indicates the reference flux ratio equal to one.

Table 2. Linear fit parameters.

| WISE band | $m$       | $b$       |
|-----------|-----------|-----------|
| W1        | -0.008±0.004 | 1.045±0.009 |
| W2        | 0.105±0.012  | 1.017±0.010 |
| W3        | -0.145±0.045 | 1.098±0.008 |
| W4        | -0.672±0.206 | 1.107±0.016 |

4 SEARCHING FOR IR EXCESS IN STARS WITH AND WITHOUT PLANETS

4.1 Sample of stars with and without planets

We constructed the sample of stars hosting planets from “The Extrasolar Planet Encyclopedia” web page\(^7\). As of November 2016, the database included 2609 stars with confirmed planets. We applied to this sample the same criteria, on WISE and 2MASS photometry, described in Sec. 3.1 and we obtained a final sample of 236 objects. In order to avoid the inclusion of spurious detections, we also proceeded to perform a careful visual inspection of the W4 images of all these stars. We should mention that some well known sources hosting debris discs like Fomalhaut and $\beta$ Pic were not considered in the sample because these stars are very bright sources and presented saturated photometry, thus they could not pass the selection criteria defined in section 3.1.

To build a comparison sample of stars without planets, we considered objects that were included in planet-search projects but for which no planetary companions were found. We considered the works by Sousa et al. (2008, 2011); Adibekyan et al. (2012); Santos et al. (2011); Bertran de Lis et al. (2015), that used the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph, the sample of Valenti & Fischer (2005), that made use of observations with the Keck, the Anglo-Australian and the Lick telescopes, and the study of Wittenmyer et al. (2011), who

\(^7\) http://exoplanet.eu
also used the Anglo-Australian telescope as part of the Pan-Pacific Planet Search programme. We eliminated the duplicate entries and those stars for which a planet has been discovered after the date of publication. To this initial list of 1850 objects we also applied the same selection criteria as before and the sample of stars without planets ended with 986 stars.

In Fig. 2 we plot the distribution of the two samples with respect to spectral type, distance, apparent V magnitude and metallicity ([Fe/H]). We applied a two-sample Kolmogorov Smirnov (KS) test to evaluate whether the samples of stars with and without planets share the same parent population, considering a confidence level threshold of 99% (Massey 1952). This hypothesis was verified in the case of the spectral type and V magnitude distributions, while discarded in the distance and metallicity cases. As far as the distance is concerned, the distribution of Fig. 2 shows that the sample of stars without planets is composed on average by more nearby stars with a mean of 50 pc while the other sample has a mean distance of 75 pc. The cut at the larger distance is due to the photometry criteria that we imposed. In the case of the metallicity, the discrepancy between the two samples is more evident: the average metallicity of the stars without planets is [Fe/H] = -0.09, in agreement with the typical value in the solar vicinity (e.g., Casagrande et al. 2011; Haywood 2001), while the stars with planets are more metal-rich, with an average [Fe/H] = +0.04. This results concords with the positive correlation that exists between the presence of giant planets and the metal content of the host stars (e.g., Gonzalez 1997; Fischer & Valenti 2005). Since about 60% of stars in our sample have planets with mass \( \geq 1 \) M, we expected to find this metal abundance difference in our samples.

4.2 Looking for IR excesses.

In this section, we describe the method we devised for identifying stars with IR excess from the AllWISE data. To date, there have been several works that used WISE data with the same goal. They differ from our work and among them in the definition of IR excess. We therefore considered convenient to also incorporate the procedures used by Cruz-Saenz de Miera et al. (2014), Kennedy & Wyatt (2012), Morales et al. (2012) and Patel et al. (2014) in order to understand how their differences affect the number of detected IR excesses.

4.2.1 Excess definition 1: this work.

We define a IR excess value \( E \) as the difference of the \( f_{22}/f_{12} \) observed flux ratio and the respective stellar photospheric ratio, divided by the associated uncertainty:

\[
E = \frac{(f_{22}/f_{12})_{\text{obs}} - (f_{22}/f_{12})_{\text{syn}}}{\sigma_{\text{tot}}}, \quad \sigma_{\text{tot}} = \sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{cal}}^2 + \sigma_{\text{syn}}^2},
\]

where \( (f_{22}/f_{12})_{\text{obs}} \) is the observed flux ratio between W4 and W3 bands, \( (f_{22}/f_{12})_{\text{syn}} \) is the synthetic flux ratio. \( \sigma_{\text{tot}} \) is the quadratic sum of the observed photometric uncertainty \( \sigma_{\text{obs}} \), obtained from the WISE catalogue; 2) the calibration uncertainty of WISE bands \( \sigma_{\text{cal}} \); and 3) the uncertainty due to the stellar parameters \( \sigma_{\text{syn}} \). This latter value is obtained by first constructing a family of synthetic spectra, whose parameters were a combination of \( T_{\text{eff}} \pm \sigma_{\text{eff}} \) and \( \log g \pm \sigma_{\log g} \). Then, the synthetic flux is calculated for each spectrum and the standard deviation of the flux distribution is considered as \( \sigma_{\text{syn}} \). An infrared excess is considered significant when \( E \) is larger than a chosen threshold.

We adopted the \( f_{22}/f_{12} \) ratio because these 2 bands show a quite similar trend in the flux ratio between observed and photospheric flux (see Fig. 1). However, this choice may affect the detection of the hotter discs, if they emit a non negligible amount of flux at 12 \( \mu \)m.

4.2.2 Excess definition 2: Cruz-Saenz de Miera et al. (2014).

The authors searched for IR excesses in a sample of dwarf stars brighter than \( V=15 \) mag, using the WISE All-Sky survey database for over 9000 sources. They compared the observed \( f_{22}/f_{4.6} \) flux ratio with the expected photospheric level and identified 197 significant excesses at 22 \( \mu \)m. Assuming that the excess is caused by thermal emission of a circumstellar dust disc, they found more than 80% of the sample with dust temperatures higher than 120 K. The definitions of flux excess and its error used by Cruz-Saenz de Miera et al. (2014) is the same as those adopted in this work, with the only difference that the flux ratio they considered is \( f_{22}/f_{4.6} \).

4.2.3 Excess definition 3: Kennedy & Wyatt (2012).

They analyzed 180,000 stars observed by WISE in the Kepler field. After carefully taking into account contamination by background sources, they identify only one bona fide excess at 22 \( \mu \)m due to a debris disc around the A-type star KIC7345479. They defined an excess as the difference of the observed flux in any WISE band and the correspondent photospheric flux, divided by the total error:

\[
E = \frac{f_{\text{obs}} - f_{\text{syn}}}{\sigma_{\text{tot}}}
\]

where \( \sigma_{\text{tot}} \) is the quadratic sum of the observed photometric uncertainty \( \sigma_{\text{obs}} \) and the uncertainty of the expected stellar flux, equivalent to the error produced by the uncertainty on stellar parameters \( \sigma_{\text{syn}} \). They adopted a 4\( \sigma \) threshold.

4.2.4 Excess definition 4: (Morales et al. 2012).

This work explored exoplanet-host stars in searching for the presence of warm dust. They analyzed a sample of 591 stars from the Extrasolar Planet Encyclopedia (January 2012) and found 9 planet-bearing stars with excesses at 12 \( \mu \)m and 22 \( \mu \)m in young MS and giant stars.

To detect IR excess, after obtaining the synthetic spectrum that better fit the photosphere, they calculated the significance of the excess using the total signal-to-noise ratio \( (S/N) \) defined as:

\[
(S/N) = \frac{f_{\text{obs}}}{\sigma} = \left( \frac{S}{N} \right)_{\text{syn}} + \left( \frac{S}{N} \right)_{\text{d}}, \quad \sigma = \sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{cal}}^2}.
\]
with \( f_{\text{obs}} = f_{\text{syn}} + f_d \), where \( f_{\text{syn}} \) is the stellar synthetic flux of the best fit, \( W_d \) is the flux of a debris disc in any of the WISE bands, and \( \sigma \) takes into account the uncertainty of the WISE photometry (\( \sigma_{\text{obs}} \) and calibration (\( \sigma_{\text{cal}} \)). The authors considered an infrared excess when \((S/N)_d \geq 3\).

### 4.2.5 Excess definition 5: (Patel et al. 2014)

The last work we analyzed is Patel et al. (2014), where they searched for excesses, in the WISE database at 12 \( \mu \)m and 22 \( \mu \)m, of Hipparcos MS stars within 75 pc from the Sun. Since they were dealing with many bright objects, they apply corrections for properly handling with saturated objects in W1 and W2 bands. They found 379 stars with flux excesses at 22 \( \mu \)m.

The procedure they devised for detecting infrared excesses is quite different than the previous ones. Patel et al. (2014) based their searching process on empirical relations found in colour-colour diagrams of Tycho-2 \( B-V \) vs. \((W_i - W_j)\), with \( i, j \) representing two different WISE bands. They did not carry out a fitting on the star SED like the previous methods to determine the photospheric flux level, however, they fit the star SED to confirm the validity of the detected excesses.

The authors have calibrated the relations \( W_i - W_j \) vs. \( B-V \) by iteratively removing the largest colours \( W_i - W_j \), for each \( B-V \) bin of 0.1 mag, until half of the data points in the bin are rejected. The different relations \( W_i - W_j \) vs. \( B-V \) are traced in steps of 0.02 mag in \( B-V \). Thus, the mean \( W_i - W_j \) corresponding to a certain \( B-V \) colour is referred as \( W_{ij}(B-V) \). The list of the mean \( W_{ij}(B-V) \), with its respective standard error, for all colour combinations is given also in Patel et al. (2014). Taking into account the colour dependency, an excess \( E[W_i - W_j] \) in the colour \( W_i - W_j \) for a certain \( B-V \) is defined as:

\[
E[W_i - W_j] = W_i - W_j - W_{ij}(B-V),
\]

while, the S/N of this excess is:

\[
\frac{S}{N} = \frac{E[W_i - W_j]}{\sigma_{ij}} = \frac{W_i - W_j - W_{ij}(B-V)}{\sigma_{ij}}
\]

where \( \sigma_{ij} \) is the propagation of the photometric uncertainties of \( W_i \) and \( W_j \), together with the standard error \( W_{ij}(B-V) \);

\[
\sigma_{ij} = \sqrt{\sigma_{W_i}^2 + \sigma_{W_j}^2 + \sigma_{W_{ij}}^2}.
\]

They calculated the ratio of detecting false positives (FPR) by using the empirical S/N distribution and defined FPR as the number of stars beyond the threshold in which the outliers were considered as reliable excesses. This enabled to detect excesses as a function of the threshold beyond which the redder objects can be considered as reliable excesses. Nevertheless, it was not possible to determine empirically the FPR beyond the limit where the number of false positives drops to zero; for this, an upper limit was needed.
To define this limit, the distributions of S/N, which involved W4 as $W_J$, were constructed and the threshold was located between 99.8% and 99.9% for considering a possible excess.

5 RESULTS

We applied all five procedures described in the previous section to the search for IR excess in our two stellar samples of stars with and without planets, using the AllWISE catalogue (Cutri & et al. 2013). We present the results in Table 3, for sake of homogeneity, we used the same threshold for all methods and we assumed both $3\sigma$ and $4\sigma$ as detection limits. We report the number and percentage of significant IR excesses detected using both the modified WISE flux (as explained in Sec. 3), in columns 2–3 and 6–7, and the original AllWISE photometry, in columns 4–5 and 8–9.

The flux homogenization between observed and theoretical fluxes (Sec. 3) decreases the number of detected IR excesses in those cases where the excess is defined through a difference between observed and photospheric value, as in Kennedy & Wyatt (2012) and Morales et al. (2012). It has a lower effect on the other methods, based on colours, and, even though the significance of the IR excess changes, it is not enough to modify the number of objects whose excess surpasses the detection threshold.

In Table 3, we also report the identification of the stars with IR excess detected with each definition. The one adopted in this work allowed to detect 2 excesses over the photosphere at 22 μm in stars with planets (0.85% of the sample) and just 1 excess (0.1%) in stars that do not harbour a detected planet, assuming a $3\sigma$ threshold. The excess definition of Cruz-Sañez de Miera et al. (2014) provides even lower numbers, while the results from the method by Patel et al. (2014) include all objects detected with the other definitions (with a detection rate of 1.27% and 0.51% in stars with and without planets, respectively) and adds two unique stars (BD-10 3166 and HD11938), if the lower significance threshold of $3\sigma$ is considered.

In Fig. 3 , we show the flux ratio diagram using the 2MASS J and K, fluxes for the 1,222 stars with and without planets used in this work and the WISE fluxes at 12 μm and 22 μm. We highlight the 8 stars with Mid-IR excess reported in Table 3 with circles.

The SED of all 8 objects found by the method of Patel et al. (2014), using a $3\sigma$ threshold, are depicted in Figs. 4 and 5. Spitzer photometry (Chen et al. 2005) confirms the presence of an IR excess for 5 stars $^a$HD106906, $^b$HD218396 (HR8799), $^c$HD85301, $^d$HD107146, $^e$HD60491, with a clear indication that the flux peak is located at wavelengths longer than 22 μm. In fact, apart from the case of HD106906 and HD60491, Spitzer data indicate that the W4 band coincides with the wavelength range where the IR excess begins to appear above the photosphere, with a $>3\sigma$ significance, according to the blackbody modeling by Chen et al. (2014).

The excess definitions used in this work, in Cruz-Sañez de Miera et al. (2014) and in Morales et al. (2012) provide the lower number of detections, which do not include all objects whose excesses are supported by Spitzer observations. These are the only approaches that include the WISE flux calibration error in the computation of the uncertainty. As an example, in Fig. 6 we illustrate the impact that this source has on the total uncertainty on the flux ratio $f_{22}/f_{12}$ for the 1,222 stars with and without planets: calibration error is dominant for objects with $f_{22} \gtrsim 20$ mJy, which is the case for all stars with Spitzer data. This fact seems to point out that the WISE calibration error may be overestimated.

In general, the stars which present IR excess in this work share similarities. In the case of HD218396 (HR8799), a well known planetary system with 5 planets, a debris disc with a cold and warm component is found (Ballering et al. 2013). The same happens to the stars without planets HD85301 and recently to HD107146, where MacGregor et al. (2016) add a cold component (30K) to its disc, in agreement to the Spitzer photometry that also shows the excesses for these stars (Chen et al. 2005). Some other debris disc were already found by Patel et al. (2014) (HD136544, HD60491, HD11938) where discs within 95K and 190 K are modeled. HD106906 is a spectroscopic binary, in the Lower Centaurus Crux stellar association, that hosts a well known debris disc, recently observed with adaptive optics systems (Wu et al. 2016; Lagrange et al. 2016). Its strong excess in the W4 band is in perfect agreement with the Spitzer photometry of Chen et al. (2005), whose blackbody fit of the excess provides a temperature of 90 K (Chen et al. 2005). Only BD-10 3166 is not catalogued previously as a debris disc host. Furthermore, Lodieu et al. (2014) report this star with a M5 star as a large proper motion companion.

We performed a Welch’s t-test (Welch 1947), suitable for data populations with different variance, to quantify the statistical significance of the difference in the number of IR excess detections between the two sample of stars, with or without planets. We consider the results obtained by the five excess definitions analyzed in this work, using the “corrected” WISE photometry. We also take into account two detection thresholds of $3\sigma$ and $4\sigma$. In no case the test indicates that the difference in the percentage of IR excess detections is statistically significant, assuming a confidence level of 95%. Our analysis therefore indicates that the presence of warm debris disks (assuming that all detected excesses are caused by such an object) are not correlated to the presence of planets.

Finally, it is important to note that the detection rate of warm debris disks of $\lesssim 1\%$ is much lower than that of cold debris discs, making them a rare phenomena. As Wyatt (2008) mentioned, in fact, the rare finding of warm debris discs in FGK MS stars is due to a combination of their long lifetimes and the short periods of time in which dust is produced by a transient event.

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Table 3. Number and percentage of IR excesses in stars with and without planets, using $3\sigma$ (top) and $4\sigma$ (bottom) threshold.

| IR excess definition | Stars with planets | Stars without planets |
|----------------------|--------------------|-----------------------|
|                      | corrected flux     | AllWISE flux          | corrected flux | AllWISE flux |
|                      | # | % | # | % | # | % | # | % |
| This work            | 2\textsuperscript{a,b} | 0.85 | 2 | 0.85 | 1\textsuperscript{d} | 0.10 | 1 | 0.10 |
| Cruz-Saenz de Miera et al. 2014 | 1\textsuperscript{a} | 0.42 | 1 | 0.42 | 1\textsuperscript{e} | 0.10 | 1 | 0.10 |
| Kennedy & Wyatt 2012  | 2\textsuperscript{a,b} | 0.85 | 6 | 2.54 | 4\textsuperscript{d,e,f,g} | 0.41 | 35 | 3.55 |
| Morales et al. 2012  | 2\textsuperscript{a,b} | 0.85 | 2 | 0.85 | 3\textsuperscript{d,e,f} | 0.30 | 5 | 0.51 |
| Patel et al. 2014     | 3\textsuperscript{a,b,c} | 1.27 | 3 | 1.27 | 5\textsuperscript{d,e,f,g,h} | 0.51 | 5 | 0.51 |

|                      | # | % | # | % | # | % | # | % |
| This work            | 1\textsuperscript{a} | 0.42 | 1 | 0.42 | 0 | 0 | 0 | 0 |
| Cruz-Saenz de Miera et al. 2014 | 1\textsuperscript{a} | 0.42 | 1 | 0.42 | 0 | 0 | 0 | 0 |
| Kennedy & Wyatt 2012  | 2\textsuperscript{a,b} | 0.85 | 2 | 0.85 | 4\textsuperscript{d,e,f,g} | 0.41 | 9 | 0.91 |
| Morales et al. 2012  | 2\textsuperscript{a,b} | 0.42 | 2 | 0.85 | 0 | 0 | 3 | 0.30 |
| Patel et al. 2014     | 2\textsuperscript{a,b} | 0.85 | 2 | 0.85 | 4\textsuperscript{d,e,f,g} | 0.41 | 4 | 0.41 |

\textsuperscript{a}HD106906, \textsuperscript{b}HD218396, \textsuperscript{c}BD-103166, \textsuperscript{d}HD85301, \textsuperscript{e}HD136544, \textsuperscript{f}HD107146, \textsuperscript{g}HD60491, \textsuperscript{h}HD11938

Figure 3. Flux ratio diagram of WISE photometry at 22 $\mu$m and 12 $\mu$m versus the 2MASS J and $K_s$ fluxes for the 1,222 stars with and without planets, as explained in the inset. Objects with IR excess refer to the stars reported in Table 3. The location of HD 106906 is indicated in the upper inset.
Figure 4. SEDs of the stars with planets for which a significant flux excess has been detected in the WISE data. HD106906, HD218396, BD-103166. We show in black dots the WISE photometry while in grey dots optical and Spitzer photometry. Continuous line represents the best atmospheric model fit.

Figure 5. SEDs of the stars without planets for which a significant flux excess has been detected in the WISE data. HD85301, HD136544, HD107146, HD60491, HD11938. We show in black dots the WISE photometry while in grey dots optical and Spitzer photometry. Continuous line represents the best atmospheric model fit.

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Figure 6. Sources of uncertainty in the flux ratio $f_{22}/f_{12}$ as a function of the flux at 22 µm for the complete sample of 1,222 stars with and without planets. The errors due to *WISE* photometry (green dots), flux calibration (red) and uncertainty on the stellar photospheric parameters (blue) are shown separately, along with the total error (yellow).