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Letter to the Editor

A search for debris disks in the *Herschel*-ATLAS[⋆]

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ABSTRACT

Aims. We aim to demonstrate that the *Herschel*-ATLAS (H-ATLAS) is suitable for a blind and unbiased survey for debris disks by identifying candidate debris disks associated with main sequence stars in the initial science demonstration field of the survey. We show that H-ATLAS reveals a population of far-infrared/sub-mm sources that are associated with stars or star-like objects on the SDSS main-sequence locus. We validate our approach by comparing the properties of the most likely candidate disks to those of the known population.

Methods. We use a photometric selection technique to identify main sequence stars in the SDSS DR7 catalogue and a Bayesian Likelihood Ratio method to identify H-ATLAS catalogue sources associated with these main sequence stars. Following this photometric selection we apply distance cuts to identify the most likely candidate debris disks and rule out the presence of contaminating galaxies using UKIDSS LAS *K*-band images.

Results. We identify 78 H-ATLAS sources associated with SDSS point sources on the main-sequence locus, of which two are the most likely debris disk candidates: H-ATLAS J090315.8 and H-ATLAS J090240.2. We show that they are plausible candidates by comparing their properties to the known population of debris disks. Our initial results indicate that bright debris disks are rare, with only 2 candidates identified in a search sample of 851 stars. We also show that H-ATLAS can derive useful upper limits for debris disks associated with Hipparcos stars in the field and outline the future prospects for our debris disk search programme.

Key words. circumstellar matter – submillimeter: stars – submillimeter: planetary systems

1. Introduction

The *Herschel*-ATLAS or H-ATLAS (Eales et al. 2010) is the largest open time key programme on the *Herschel* Space Observatory (Pilbratt et al. 2010), and will ultimately map over 500 square degrees with both the PACS and SPIRE instruments (Poglitsch et al. 2010; Griffin et al. 2010). H-ATLAS is designed to revolutionise our view of dust and dust-obscured star formation by detecting ~250 000 galaxies in the far-infrared. The primary goal of the H-ATLAS is to study galaxy formation and evolution (see the other H-ATLAS articles in this volume), however the unrivalled sensitivity and wide-area coverage means that H-ATLAS can also reveal dust in a range of more local (i.e. within the Milky Way) environments. At the sensitivity limits of H-ATLAS (a 5σ threshold of 33 mJy at 250 μm measured from the science demonstration data, Pasquale et al. 2010; Rigby et al. 2010) this implies the potential to detect analogues of the well-known debris disks (e.g. Holland et al. 1998; Greaves et al. 1998) out to distances of between 20 and 150 pc.

A search for debris disks in H-ATLAS offers a powerful complement to those deeper and more targeted studies that are currently being undertaken with *Herschel* (DUNES, DEBRIS and GASPS – see publications in this volume), are set to be carried out with SCUBA-2 (SUNS: Matthews et al. 2007) and have been perfomed by *Spitzer* (thoroughly described in Carpenter et al. 2009, and references therein). With its wide areal coverage H-ATLAS is a shallower tier to these studies, but a tier with the potential to search a much larger number of stars for bright debris disks and with a large body of supporting high quality optical and infrared legacy data (Eales et al. 2010). The H-ATLAS fields are covered by SDSS DR7 in *ugriz* (Abazajian et al. 2009) and UKIDSS Large Area Survey in *YJHK* (Lawrence et al. 2007) with forthcoming deeper INT and VST KIDS optical data, VISTA VIKING in the near-infrared, WISE in the mid-infrared and GMRT radio continuum. The supporting optical and infrared data allows straightforward selection of main sequence stars in the H-ATLAS fields via the main sequence colour locus (Covey et al. 2007) and the use of techniques to exclude contaminating background galaxies, such as the inspection of deep *K*-band images for extended objects and the use of the FIR-radio correlation (Carilli & Yun 1999). Finally, a debris disk search in H-ATLAS is completely serendipitous and carried out in parallel with the primary science programme.

In Sect. 2 we show that the full H-ATLAS survey will allow us to search ~10 000 main sequence stars for the presence of bright debris disks analogous to Beta Pictoris and ~1000 stars for Fomalhaut analogues. This large search sample means that H-ATLAS will be much more sensitive to rarities in the debris disk population than targeted surveys, leading to stringent tests

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[⋆] *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

of stochastic disk evolution models (Wyatt 2008) and potentially uncovering bright and/or cold disks that may have undergone recent disruptive events (e.g. Lisse et al. 2007). H-ATLAS will allow us to answer questions such as how frequent are bright systems such as Beta Pictoris or HR 4796 and is there an upper limit to the amount of debris formed during disk evolution?

2. Photometric selection of main sequence stars in the H-ATLAS science demonstration field

The H-ATLAS science demonstration (SD) field occupies roughly 16 square degrees and is centred at 09:05:30.0 +00:30:00 (J2000). Descriptions of the PACS and SPIRE images obtained in parallel mode and the data reduction procedure used can be found in Ibar et al. (2010) and Pasquale et al. (2010) respectively. Point sources were identified within the images using a combination of PSF filtering, Gaussian fitting and aperture photometry (Rigby et al. 2010). The median 5σ noise values (including confusion noise) in the SPIRE 250, 350 and 500 μm maps are 33, 36 and 45 mJy/beam respectively. The PACS images are roughly a factor 2 noiser than predicted with 5σ noise levels of 105 and 138 mJy/beam at 100 and 160 μm respectively. The H-ATLAS source catalogue for the SD field (Rigby et al. 2010) contains 6878 band-merged sources with flux density $>5\sigma$ in at least one of the 5 H-ATLAS bands (100, 160, 250, 350, 500 μm). The catalogue excludes higher noise regions at the edge of the map and thus covers an effective area of 14.5 square degrees. Each source in the H-ATLAS catalogue has been matched to the corresponding most likely SDSS DR7 object within a $10''$ search radius. This matching process is described further in Smith et al. (2010) and is an implementation of the Bayesian likelihood ratio technique of Sutherland & Saunders (1992).

In order to search for debris disks in this catalogue, we must first identify a sample of main sequence stars. We use the main sequence colour locus identified by Covey et al. (2007), which constrains the location of main sequence stars in SDSS colour space. This approach allows us to maximise our search sample by going to faint magnitudes and takes advantage of the well-calibrated and well-understood SDSS optical photometry. We use a 4-dimensional main sequence locus as described in Kimball et al. (2009) rather than the full 7-dimensional SDSS+2MASS locus of Covey et al. (2007). The infrared excess of a warm debris disk at *K*-band can move our target stars away from the nominal locus, and as our aim is to identify stars that are potential debris disk hosts, we thus do not use 2MASS or UKIDSS colours in our photometric selection.

Figure 1 shows a colour–magnitude diagram of the 180 000 star like objects (selected with "probPSF=1") detected by SDSS DR7 in the H-ATLAS SD field. The general population are shown by red dots and those falling within 2 "units" of the 4-dimensional main sequence color locus defined by Kimball et al. (2009) are shown in blue. Note that the colour locus is 4-dimensional and Fig. 1 shows only a 1D cut through the locus. Figure 1 shows that the bulk of the main sequence stellar population detected by SDSS is comprised of faint and likely distant halo stars. However, there are a substantial number of relatively bright ($11 < i < 17$) and hence likely nearby stars for which it is possible that H-ATLAS could detect associated debris disks.

We estimate the maximum distance to which H-ATLAS could be sensitive to debris disks by scaling from the *Spitzer* MIPS and SCUBA SEDs of known examples (Beta Pictoris, Rebull et al. 2008; Epsilon Eridani, Backman et al. 2009; HR 8799, Lisse et al. 2007; Fomalhaut, Stapelfeldt et al. 2004, Vega & HR 4796, Sheret et al. 2004). The most sensitive wavelength of H-ATLAS is 250 μm (at which the stellar photospheric contribution is minimal) and we find that the maximum distances for these debris disk analogues are: HR 4796 <200 pc, Beta Pictoris <150 pc, Fomalhaut <80 pc, Vega/HR 8799 <50 pc and Epsilon Eridani <20 pc. We indicate the colour−magnitude region in which main sequence dwarf stars at a distance of 4–200 pc should lie in Fig. 1 by a grey shaded box, calculated using the distance modulus and the M_i vs. $(i - z)$ photometric parallax relation for dwarf stars from Davenport et al. (2006). Note that late M and L dwarfs follow a shallower relation for $(i - z) > 1.26$ (West et al. 2005), and also that we have extrapolated the Davenport et al. (2006) relation to $(i - z) < 0.2$ to account for the bluer stars in the sample.

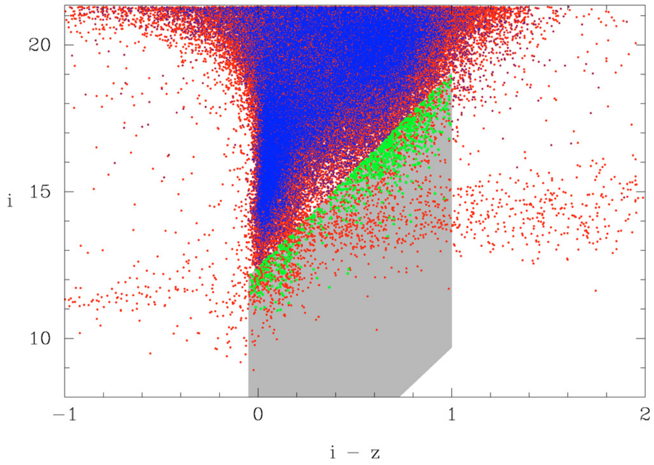

Fig. 1. SDSS i vs. $i-z$ colour magnitude diagram of SDSS point sources (i.e. with probPSF = 1) in the H-ATLAS SD field. A magnitude cut of $i < 21.3$ has been applied to exclude sources with large photometric error. Dots indicate field SDSS point sources (red) and point sources within the main sequence stellar locus (blue). The grey shaded polygon indicates the colour-magnitude region occupied by main sequence stars between distances of 4 and 200 pc (calculated using the Davenport et al. (2006) photometric parallax relation). Stars within the main sequence locus that fall into this box are shown as larger green points for clarity.

In the H-ATLAS SD field for maximum distances of 200, 150, 80 and 50 pc (i.e. sensitive to HR 4796, Beta Pictoris, Fomalhaut and Vega analogues) we find a total of 851, 340, 31 and 9 stars respectively on the main sequence locus. There are no stars on this locus nearer than 20 pc in the SD field, which is likely an effect of the SDSS becoming saturated for near, bright stars. Such stars can be obtained from the Tycho-2 & Hipparcos catalogues (Høg et al. 2000; van Leeuwen 2007), although in this paper we focus upon the larger and better selected SDSS sample of main sequence stars. Assuming similar stellar densities in the remaining 550 square degrees that will be mapped in the full survey, H-ATLAS will thus encompass a search sample on the order of 10 000 main sequence stars for the brightest debris disks (HR 4796 and Beta Pictoris analogues) and on the order of 300−1000 stars for Fomalhaut and Vega analogues.

3. Candidate debris disks in the H-ATLAS SD field

We identify candidate debris disks by taking a sample of H-ATLAS sources from the catalogue that have a high reliability match (>80% reliability) to SDSS DR7 catalogued sources (Smith et al. 2010). There are 2334 sources that pass this criterion. We then filter this list to only include SDSS point sources ("probPSF=1") and identify point sources on the 4-dimensional main sequence colour locus described in the previous section. We find a total of 204 H-ATLAS sources matched to SDSS sources with "probPSF=1", of which 78 sources fall

Table 1. FIR and stellar properties of the candidate disks and their associated stars.

H-ATLAS ID	SDSS ID	Sp. type	Distance (pc)	F_{250} (mJy)	F_{350} (mJy)	F_{500} (mJy)	T (K)	Dust mass ($M_{\oplus}$)
J090315.8+015758	J090315.91+015800.9	K2	90–130	51 ± 14	53 ± 14	19 ± 9	65	0.06–0.13
J090240.2−014351	J090240.10-014349.7	G5	190–290	86 ± 12	48 ± 7	17 ± 9	60	0.5–1.3

Notes. Spectral types are estimated from the $(g-i)$ colour relation of Covey et al. (2007) and distances from the photometric parallax from Davenport et al. (2006). Temperatures are estimated by a greybody fit to the 250, 350 and 500 μm fluxes and the upper limits of 140 mJy at 160 μm, and 105 mJy at 110 μm with a fixed $\beta = 0.5$ (Wyatt et al. 2005). Masses are calculated using the standard technique with a mass absorption coefficient $\kappa = 1.7$ cm^2 g^{-1} at 850 μm (Sheret et al. 2004).

within the main sequence locus (see Fig. 2). Within this sample we expect considerable contamination from dust obscured QSOs or unresolved galaxies whose optical colours are reddened into the main sequence locus (Ivezić et al. 2002). Indeed, the sample have a median r-band magnitude of 19.8, fainter than the value at which galaxies dominate over stars (Covey et al. 2007). Unsurprisingly due to their optical colours, none of the H-ATLAS main sequence locus objects have measured SDSS spectroscopic redshifts which would allow us to select out QSOs and unresolved galaxies. The inclusion of UKIDSS near-IR colours in the selection would aid in this discrimination (Ivezić et al. 2002), but as we mention in the previous section, would also select against possible K-band excess in debris disk stars.

To identify candidate disks in our sample we apply a photometric distance cut to select the brightest and nearest objects that are least likely to be QSOs or unresolved galaxies and the most likely to be debris disks. We apply an initial photometric distance cut of 200 pc to select the most likely candidate disks, though Fig. 2 shows that there are a further 7 objects at 200−400 pc distance that could be massive or luminous disk candidates. The candidates that pass the main sequence colour locus and photometric distance tests are then finally subject to a detailed inspection of SDSS DR7 *ugriz* and UKIDSS LAS *YJHK* images to reject the presence of possible contaminating galaxies, and the wider field of the H-ATLAS SPIRE images to search for contaminating cirrus. We stress that our search technique reveals *candidate* disks. Spectroscopic confirmation of the host star spectral types, more accurate spectrophotometric distances, higher resolution PACS or SCUBA-2/ALMA imaging, or scattered light imaging are required to confirm these objects as debris disks and to better constrain their physical properties such as temperature and mass.

We focus our following discussion on the two closest candidate disks found within a photometric distance cut of 200 pc: H-ATLAS J090315.8+015758 and H-ATLAS J090240.2−014351. As we will show, the physical properties of these objects are within the spectrum of known debris disks and the H-ATLAS detections are thus consistent with a debris disk hypothesis. We summarise the FIR and stellar properties of H-ATLAS J090315.8 and H-ATLAS J090240.2 in Table 1 and present three colour images of the disks in Fig. 3. The $g-i$ colours of the host stars imply spectral types of K2 and G5 respectively (Covey et al. 2007). Their 2MASS colours or brightnesses are inconsistent with those of giant stars ($J-H$ and $H-K_s$ for both stars is <0.3 and ≤ 0.1 respectively). The photospheric flux of these stars at 250 μm is of the order of a few μJy and so we can be confident that the 250 μm emission is a genuine excess over the stellar spectrum. Both disks are unresolved at 250 μm, although H-ATLAS J090315.8 shows a marginal extension to the West. H-ATLAS J090240.2 on the other hand is compact and centred on the star's position to within the pointing accuracy of *Herschel*. Inspection of UKIDSS K-band images shows that background galaxy contamination is unlikely.

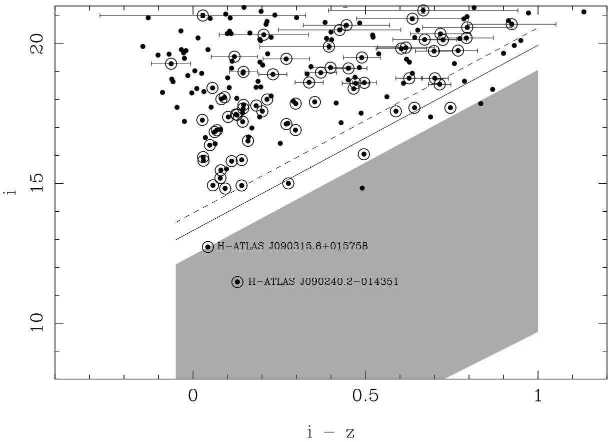

Fig. 2. SDSS i vs. $i-z$ colour magnitude diagram of SDSS point sources with high reliability matches to H-ATLAS catalogue sources. Objects whose SDSS colours place them on the stellar locus are identified by open circles. Three grey shaded region indicates the colour-magnitude region occupied by stars between 4 and 200 pc as in Fig. 1. Solid and dashed lines indicate distances of 300 and 400 pc respectively. The two candidate debris disks are identified by their H-ATLAS catalogue ID.

Both candidate disks are detected in the 250 and 350 μm SPIRE bands, but not at 100, 160 or 500 μm (both disks have emission significant at the 2σ level at 500 μm). With only two flux points it is difficult to constrain either the fractional luminosity or the temperature of the disk. We estimate temperature by fitting a fixed $\beta = 0.5$ modified blackbody (e.g. Wyatt et al. 2005) to the 110, 160 μm upper limits and 250, 350 and 500 μm flux measurements. As the 110 and 160 μm flux are only an upper limit the derived temperatures should be considered as strict upper limits. We note that as our photometric distance estimates are only good to within ~50% (Davenport et al. 2006), the error in derived disk mass is largely dominated by distance rather than temperature. Using the standard techniques outlined in Holland et al. (1998) and Sheret et al. (2004) we derive masses for the two candidate disks of 0.06−0.13 $M_{\oplus}$ and 0.5−1.3 $M_{\oplus}$ for H-ATLAS J090315.8 and H-ATLAS J090240.2 respectively. The mass of both candidate disks is within the observed range of known disks (Wyatt 2008; Lisse et al. 2007; Sheret et al. 2004), comparing specifically to HD 12167 with a mass of 1 $M_{\oplus}$ and β Pic with a mass of 0.1 $M_{\oplus}$. (Sheret et al. 2004)

4. Conclusions and future prospects for H-ATLAS debris disk searches

We have described a search method for debris disks in the H-ATLAS and present the two most likely candidate disks in the H-ATLAS SD field: H-ATLAS J090315.8 and H-ATLAS J090240.2, ~0.1 and 1 $M_{\oplus}$ mass candidate disks around K0 and G5 stars respectively. We also identify a further population of 76 SDSS point sources that are associated with FIR/sub-mm emission and whose optical colours place them on the main sequence locus. The majority of these objects are likely to be dust-obscured QSOs or unresolved galaxies (e.g. Ivezić et al. 2002),

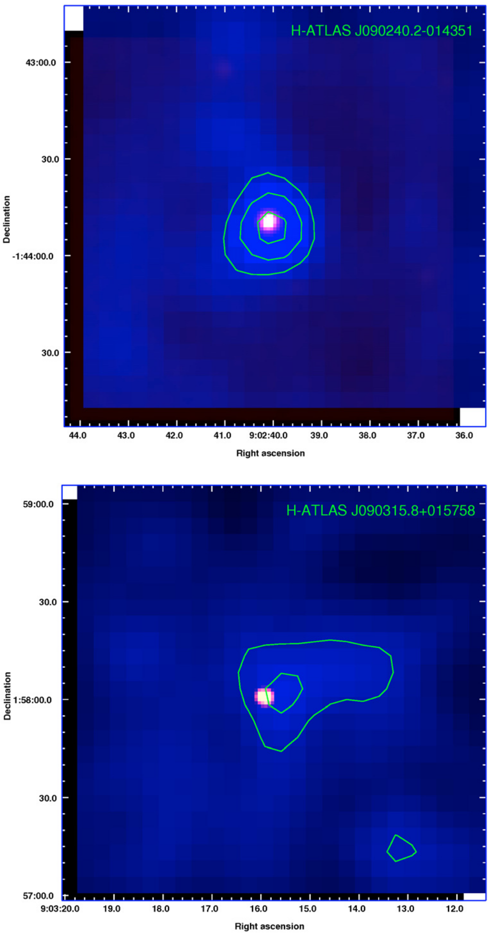

Fig. 3. Three colour images of the two candidate debris disks detected by H-ATLAS. Red and green channels are 2MASS J and K_s respectively. The blue channel is SPIRE 250 μm, smoothed by a 3 pixel Gaussian kernel to increase the signal to noise ratio. Contours are of 250 μm emission starting at 3σ and spaced by 2σ.

although the brighter and nearer (7 objects lie within a photometric distance of 400 pc) may be potentially luminous debris disks. Follow-up spectroscopy is required to investigate these hypotheses. What is clear from the H-ATLAS SD field is that bright disks are rare – we have searched 851 stars within 200 pc for FIR/submm emission and find only two candidate disks brighter than 33 mJy at 250 μm. Our search finds a much lower fraction of candidate debris disks than previous *Spitzer* and SCUBA studies (e.g. Carpenter et al. 2009; Hillenbrand et al. 2008; Wyatt 2008), which typically find a 7−14% disk detection fraction. However we note that direct comparisons between these detection fractions should not be made as H-ATLAS is flux-limited rather than volume-limited and we do not reach the exquisite photospheric signal-to-noise levels of the *Spitzer* studies (Carpenter et al. 2009). Hence H-ATLAS is likely to only detect the bright end of the debris disk population.

The search that we present in this Letter is a forerunner to a much more extensive programme that will be carried out in the future. The full H-ATLAS will contain a search sample of ~10 000 photometrically selected main sequence stars out to 200 pc, allowing us to place more stringent limits upon the frequency of the bright end of the debris disk population. With a large and well-selected sample of main sequence stars covering a range of spectral types we will also be able to carry out a stacking analysis (e.g. Kurczynski & Gawiser 2010) to determine the statistical frequency of disk occurrence as a function of spectral type. We also plan to include bright stars from the Tycho-2 and Hipparcos catalogues, which will extend our search to nearer main sequence stars. A preliminary search of the Tycho-2 catalogue indicates that none of the 569 stars found within the H-ATLAS SD field are associated with detectable debris disks. For the 7 nearest Hipparcos main sequence stars within our field (which lie between 30 and 80 pc) this means that H-ATLAS can place upper limits on their disk masses of 0.01−0.07 $M_\oplus$ (or between 0.8 and 5.7 Lunar masses of dust, assuming $T_{\rm dust} = 40$ K). Finally, H-ATLAS has significant legacy potential for the GAIA mission (Lindegren et al. 2008), which will determine distances and spectral types for all stars brighter than $r = 20$ in the H-ATLAS fields. In combination with GAIA parallaxes, H-ATLAS will be able to determine precise disk mass upper limits for a large sample of stars.

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