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Discovery of the Fomalhaut C debris disc

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ABSTRACT

Fomalhaut is one of the most interesting and well-studied nearby stars, hosting at least one planet, a spectacular debris ring and two distant low-mass stellar companions (TW PsA and LP 876−10, a.k.a. Fomalhaut B and C). We observed both companions with *Herschel*, and while no disc was detected around the secondary, TW PsA, we have discovered the second debris disc in the Fomalhaut system, around LP 876−10. This detection is only the second case of two debris discs seen in a multiple system, both of which are relatively wide ($\gtrsim$3000 au for HD 223352/40 and 158 kau [0.77 pc] for Fomalhaut/LP 876−10). The disc is cool (24 K) and relatively bright, with a fractional luminosity $L_{\rm disc}/L_\star = 1.2 \times 10^{-4}$, and represents the rare observation of a debris disc around an M dwarf. Further work should attempt to find if the presence of two discs in the Fomalhaut system is coincidental, perhaps simply due to the relatively young system age of 440 Myr, or if the stellar components have dynamically interacted and the system is even more complex than it currently appears.

Key words: binaries: general – circumstellar matter – stars: individual: AT Mic – stars: individual: Fomalhaut – stars: individual: LP 876−10 – stars: individual: TW PsA.

1 INTRODUCTION

Fomalhaut is perhaps the most interesting nearby stellar and planetary system outside our own. The primary hosts inner and outer dust belts with temperatures similar to the Solar system's Asteroid and Kuiper belts (Su et al. 2013), and in addition hosts an enigmatic exoplanet, Fomalhaut b (Kalas et al. 2008). The system also contains two additional stars, a secondary TW PsA (Fomalhaut B; Barrado y Navascues et al. 1997; Mamajek 2012) and a tertiary LP 876−10 (Fomalhaut C; Mamajek et al. 2013). At only a few dozen light years from Earth, this remarkable system provides a unique laboratory in which to observe one outcome of star and planet formation in detail (see Kalas et al. 2013; Mamajek et al. 2013, for reviews of the Fomalhaut planetary and stellar systems).

The *Herschel* (Pilbratt et al. 2010)[1] DEBRIS Key Programme observed an unbiased sample of nearby stars with the goal of discovering and characterizing the extrasolar Kuiper belt analogues known as 'debris discs' around hundreds of nearby stars (e.g. Matthews et al. 2010). The sample comprises the nearest ∼90 each of A, F, G, K and M spectral types that are not confused by proximity to the Galactic plane (Phillips et al. 2010), and includes TW PsA and LP 876−10 (both at 7.6 pc). Fomalhaut itself was observed as part of a guaranteed time programme (Acke et al. 2012).

M dwarfs are rarely observed to have excesses at any IR or millimetre wavelength (e.g. Lestrade et al. 2006, 2009; Gautier et al. 2007; Plavchan et al. 2009), so the detection of an IR excess around LP 876−10 is interesting as the discovery of a rarely seen object. However, given that the Fomalhaut system is already known to host

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

Table 1. *Herschel* observations of TW PsA and LP 876−10. PACS observes at 70 or 100 μm, and always at 160 μm. Each ObsID represents a single scan direction, and the two differ by 40°. The duration is for a single ObsID.

Target	ObsID	Date	Instrument	Time (s)
TW PsA	1342211140/1	13-12-2010	PACS100	445
LP 876−10	1342211142/3	13-12-2010	PACS100	445
LP 876−10	1342220645	8-5-2011	SPIRE	721
LP 876−10	1342231937/8	6-11-2011	PACS70	1345

a debris disc and at least one planet, this detection of yet another planetary system component is particularly exciting. For example, a possible origin of the eccentric ring and planet around Fomalhaut A is a previous encounter with LP 876−10, and the LP 876−10 disc may show signs of such an encounter. Below, we describe the *Herschel* observations and describe some basic properties of the debris disc around LP 876−10 and quantify the non-detection of debris around TW PsA, noting some possible implications of this discovery for the overall system status and evolution.

2 OBSERVATIONS

TW PsA and LP 876−10 were observed using the *Herschel* Photodetector and Array Camera & Spectrometer (PACS; Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) instruments (see Table 1). The PACS observations used the standard 'mini scan-map', which comprises two sets of parallel scan legs, each taken with a 40° difference in scan direction. The SPIRE observations were taken using a single standard 'small map', with two scans at near-90° angles. The raw timelines were projected on to a grid of pixels (i.e. turned into images) using a near-standard HIPE pipeline (Ott 2010).

2.1 LP 876−10 (Fomalhaut C)

LP 876−10 was first observed at 100 and 160 μm in 2010 December, and showed the presence of a probable IR excess so additional PACS 70 and 160 μm and SPIRE 250, 350 and 500 μm observations were also obtained. Compact emission from the expected position of LP 876−10 was detected in the 100 and 160 μm PACS images, but not at 70 μm or in the SPIRE images. The PACS images are shown in Fig. 1, with emission clearly detected at 160 μm, marginally detected at 100 μm, and not detected at 70 μm. The detection positions are consistent with the expected star position given the 2 arcsec at 1σ pointing uncertainty of *Herschel*. Fitting the emission with observations of the calibration target, γ Dra as a model point spread function (PSF) shows that the emission is consistent with that from a point source. Some structure is seen to the NW at 100 μm, though after PSF subtraction this emission is only 1–2σ significant.

We measured the PACS source fluxes using both PSF fitting and aperture photometry, for which the results were consistent. The final PACS flux measurements are 3.3 ± 1.5 mJy at 70 μm (i.e. formally a non-detection), 7.8 ± 1.9 mJy at 100 μm and 15.5 ± 2.8 mJy at 160 μm. The SPIRE non-detections are largely limited by confusion noise, for which the 3σ limits at 250, 350 and 500 μm are 15.9, 18.9 and 20.4 mJy (see SPIRE Observer's Manual). Emission of about 10 mJy beam^{-1} is present at the expected stellar location in the 250 μm image, though the significance is sufficiently low that the emission does not appear point-like, and we cannot be sure that it is associated with LP 876−10 and not due to the background. We therefore set the 3σ limit in this band to 25.9 mJy.

Fig. 2 shows the spectral energy distribution (SED) for LP 876−10. The stellar photosphere is derived by fitting AMES-Cond atmosphere models to 2MASS, *AKARI* and *WISE* (Skrutskie et al. 2006; Ishihara et al. 2010; Wright et al. 2010) photometry from 1.2–22 μm via least-squares minimization. The best-fitting model has effective temperature $T_{\rm eff}$ = 3200 ± 140 K and luminosity 0.0049 ± 0.0004 $L_\odot$, consistent with values derived by Mamajek et al. (2013). The photospheric fluxes are 2.2, 1.1 and 0.4 mJy at 70, 100 and 160 μm. Fig. 2 includes the PACS photometry and SPIRE upper limits, showing clear (>3σ) far-IR excess emission at 100 and 160 μm. To estimate the temperature of this emission, we fitted a simple blackbody model, finding a temperature of 24 ± 5 K. We have 'modified' the blackbody disc spectrum, multiplying by (λ_0/λ) beyond $\lambda_0 = 210$ μm (Wyatt 2008), to account for inefficient long-wavelength emission by small grains and ensure a more realistic prediction of the sub-mm disc brightness. This modification is not required by the SPIRE limits however, and the true spectrum beyond 160 μm is uncertain. This model has a fractional luminosity $L_{\rm disc}/L_\star \equiv f = 1.2 \times 10^{-4}$, relatively bright for a debris disc, and very similar to the brightness of the disc around Fomalhaut itself ($f = 8 \times 10^{-5}$). For our stellar luminosity, assuming grains that

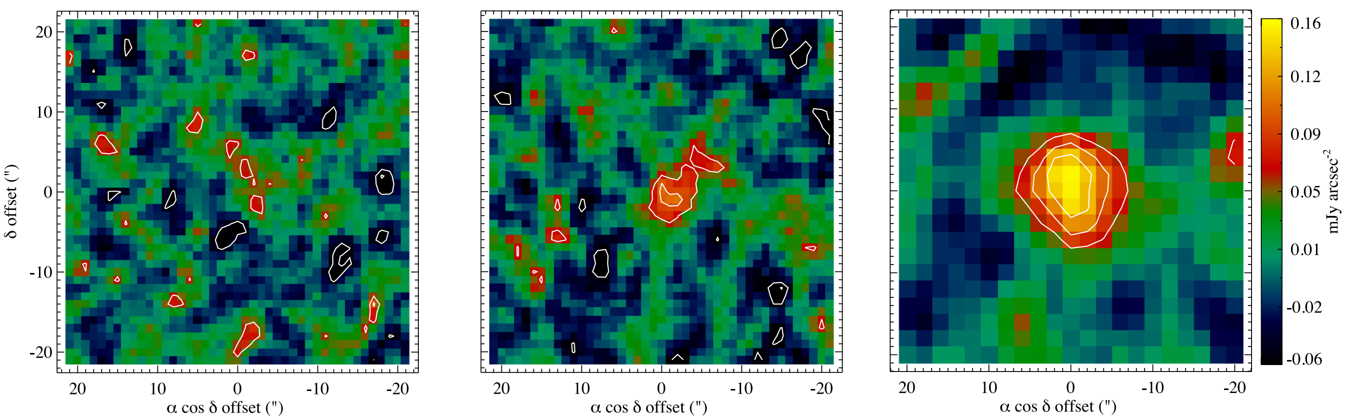

Figure 1. *Herschel* PACS images of LP 876−10, at 70, 100 and 160 μm from left to right. The expected 2010 December source position of $\alpha = 22^{\rm h}48^{\rm m}4\overset{\rm s}{.}7$, $\delta = -24° \, 22' 9\overset{''}{.}9$ is at the centre of the images, and the PACS pointing accuracy for these observations is about 2 arcsec at 1σ. Contours are drawn at intervals of ±2, 3 and 4σ.

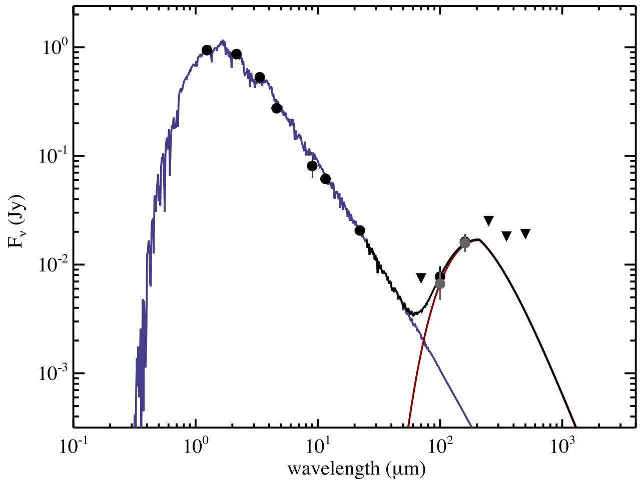

Figure 2. SED for LP 876−10. Dots are fluxes and triangles 3σ upper limits. Black symbols are measured fluxes and grey symbols are star-subtracted (i.e. disc) fluxes. The 3200 K stellar photosphere model is shown in blue, the 24 K blackbody disc model in red, and the star+disc spectrum in black.

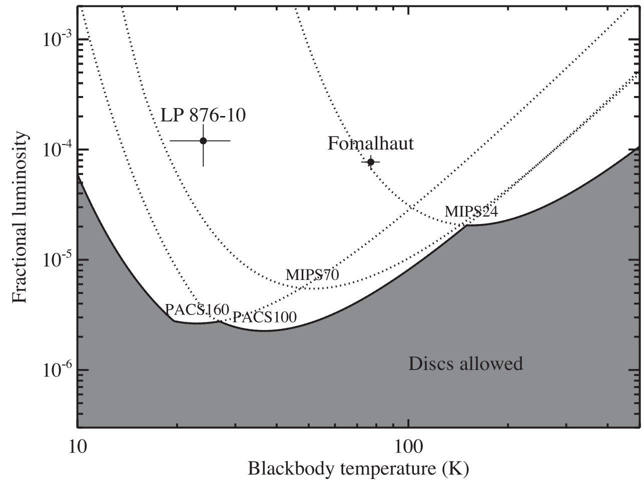

Figure 3. Disc detection limits for TW PsA (Fomalhaut B). Dotted lines show upper detection limits for discs from different observations (as labelled), and the grey region shows where discs are allowed given the non-detection of excess by all observations. Dots show the locations of the Fomalhaut and LP 876−10 (Fomalhaut C) blackbody disc models and 1σ uncertainties. Because they lie in the white region, discs with these temperatures and fractional luminosities would have been easily detected around TW PsA.

absorb and emit as blackbodies, this temperature corresponds to dust at a radial distance of about 10 au.

Though uncertain, the disc diameter implied by blackbody grains is therefore 20 au. The disc is probably larger than this estimate however; low-mass stars such as LP 876−10 and GJ 581 are unable to remove small grains with radiation pressure (e.g. Lestrade et al. 2012), and due to inefficient long-wavelength emission, small grains are hotter than blackbodies. The ratio of actual to blackbody size, Γ, has been derived for many discs, and varies from near unity for early A-type stars, to values of 3–4 for Sun-like stars (e.g. Rodriguez & Zuckerman 2012; Booth et al. 2013; Morales et al. 2013). The paucity of debris discs around M-types means that this ratio has only been measured for GJ 581 ($\Gamma = 9$; Lestrade et al. 2012) and AU Mic ($\Gamma \approx 3$; Rebull et al. 2008; Wilner et al. 2012). For LP 876−10, using a simple face-on uniformly bright ring model, we found that disc radii larger than about 40 au were inconsistent with the images, suggesting a limit of $\Gamma < 4$. This simple ratio is of course subject to uncertainty if the disc does not lie in a narrow ring or the observed structure varies with wavelength, but with a sufficient number of objects over a wide range of stellar luminosities it will be an important future diagnostic of grain properties in debris discs.

2.2 TW PsA (Fomalhaut B)

TW PsA was observed in 2010 December. The images have relatively low S/N, but appear consistent with unresolved emission. We obtained fluxes of 10.1 ± 1.9 and 7.2 ± 3.8 mJy at 100 and 160 μm, respectively. The best-fitting photospheric model has $T_{\rm eff} = 4600 \pm 10$ K and $L_\star = 0.187 \pm 0.002\,{\rm L}_\odot$, with photospheric fluxes of 12.8 and 4.9 mJy at 100 and 160 μm, respectively. The observed fluxes are not significantly different from the photospheric values, so no excess is detected and we did not observe this target again. Fig. 3 shows the limits on the fractional luminosity of a disc around TW PsA given these observations, combined with limits also set at 24 and 70 μm by the Multiband Imaging Photometer for Spitzer (MIPS; Carpenter et al. 2008). Discs as bright as those around Fomalhaut and LP 876−10 would easily have been detected around TW PsA, and any disc around TW PsA that has a similar temperature must be more than an order of magnitude fainter than those discs.

2.3 Confusion?

It is possible that the observed *Herschel* excess emission arises from chance alignment of LP 876−10 with a background galaxy. The chance of a 15.5 mJy or brighter background source appearing within 5 arcsec (the *Herschel* pointing accuracy is about 2 arcsec at 1σ) at 160 μm is about 1 per cent (Sibthorpe et al. 2013). This estimate is conservative; a background galaxy randomly placed within a 5 arcsec radius of some position is more likely to be at the outer edge of this circle, and the emission was twice observed to be within 2 arcsec of the expected position.

Given the 89 M dwarfs observed by DEBRIS, one would expect ∼1 case of background galaxy alignment among these stars. However, that LP 876−10 is among the M dwarfs observed by DEBRIS is a red-herring for the confusion estimate; this discovery could have been made by anyone with an interest in LP 876−10 and access to the *Herschel* archive, in which case the DEBRIS sample would not have been considered for the confusion analysis. Of course, LP 876−10 is also among the sample of all stars that were observed by *Herschel* (i.e. background confusion is independent of stellar properties and observing programmes). This study was motivated by the recent discovery by Mamajek et al. (2013) that LP 876−10 has a kinematic association with Fomalhaut, a property that, aside from the age of the Fomalhaut system, is independent of the presence of a debris disc. Therefore, we estimate an ∼1 per cent chance of confusion of LP 876−10.

Another consideration is of system plausibility, in essence consideration of priors that influence the likelihood of the LP 876−10 excess being due to a debris disc. The main property of interest is stellar age; if LP 876−10 were a field M dwarf with a random age between 0 and 10 Gyr, the chance of a disc detection would be low, but given the prevalence of debris around young stars, the association of this star with 440 Myr-old Fomalhaut makes the chance of disc detection more likely and less surprising. Considering binarity, the eccentricity of the debris ring and planet around Fomalhaut itself are both suggestive of possible interactions with another star, for which LP 876−10 is a probable candidate. Such an interaction would also stir up material around LP 876−10, again making the detection of a disc more likely.

Therefore, while follow-up observations are warranted, we conclude based on the above discussion that the LP 876−10 excess is most likely associated with the star itself, and interpret this emission as arising from dust in a debris disc.

3 DISCUSSION

The discovery of a debris disc around LP 876−10 is remarkable for several reasons: (i) debris discs are rarely detected around late-type stars, (ii) the Fomalhaut system is only the second case where two debris discs have been found in a stellar system and (iii) the primary is host to both a bright debris disc and an exoplanet whose eccentricities may be related to interaction(s) with one or both of the wide companions. We now briefly explore each of these aspects.

Currently, the lowest mass nearby star thought to host a debris disc is the M4V star AT Mic, a member of the β Pictoris Moving Group (Zuckerman et al. 2001; Plavchan et al. 2009). Excesses have also been detected for low-mass stars in young clusters (e.g. M5V ID10 in the 154 pc distant, 50 Myr old IC 2391; Siegler et al. 2007), though these systems are less well characterized due to their greater distance. We attempted to verify the AT Mic 24 μm excess reported by Plavchan et al. (2009), but found a greater photospheric 24 μm flux (144 versus 114 mJy). This higher flux agrees with the observed value (when colour corrected for the stellar spectrum) of 143 mJy, and thus we find no IR excess for AT Mic. The most likely reason for the difference is that we used the more recent AMES-Cond PHOENIX models (Brott & Hauschildt 2005), though we also included more mid-IR photometry (from *WISE* and *AKARI*) in fitting our atmosphere model. Given difficulties with modelling M dwarf photospheres, and a lack of excess detection by Rebull et al. (2008) and Riviere-Marichalar et al. (in preparation), we do not consider the excess for this star to be robust. Thus, LP 876−10, also with a spectral type of M4V, is one of the lowest mass stars thought to host a debris disc, and as a bright nearby star will be an important object for future M dwarf debris disc work.

While debris discs are rarely detected around late-type stars, the most probable reason is that due to the low luminosity of their host stars, their discs are cool and faint and only emit significantly at far-IR wavelengths. Sensitivity at these wavelengths is poor relative to the photospheric level, so only the brightest discs can be detected (e.g. see Plavchan et al. 2009, fig. 2). In addition, the LP 876−10 disc does not emit strongly at 70 μm, so would probably not have been detected even if it had been observed at this wavelength by *Spitzer*. With ∼100 late-type stars observed by *Spitzer* and *Herschel*, the disc around LP 876−10 therefore lies among the brightest few per cent of M dwarf debris discs. The fractional luminosity of $f = 1.2 \times 10^{-4}$ is not extreme enough to exclude the standard picture of a debris disc born at the same time as the star however (e.g. Wyatt 2008). At the system age of 440 Myr (Mamajek 2012), collisional grinding is expected to have reduced the disc mass and luminosity, with fractional luminosities above roughly 10^{-4}–10^{-3} excluded by collisional mass-loss for this disc radius and age (Wyatt et al. 2007a). Thus, while the disc may have originated in a protoplanetary disc that was more massive than average, a scenario where the disc was created more recently is not required (but as noted below is of course possible).

Of the three stars in the Fomalhaut system, both the primary and tertiary are now known to have debris discs. Debris discs around multiple components of multiple stellar systems are rare, with the only other example being the HD 223352 system, with a circumbinary disc around an A0V + K-type close binary, and a second disc around the third object, the K1V star HD 223340 (Phillips 2011). At 75 arcsec from the primary and with a system distance of 42 pc, HD 223340 is at least 3000 au from the primary. The Fomalhaut system is even more loosely bound, with LP 876−10 at 0.77 pc from the primary (158 kau; Mamajek et al. 2013). This rarity is perhaps surprising given that multiple stellar systems with multiple protoplanetary discs are relatively common (e.g. Monin et al. 2007), though may in part be due to the later companion spectral types.

The detection of two discs in these systems might be attributed to their young ages; debris discs are observed to become fainter over time (e.g. Decin et al. 2003), a result of collisional evolution (e.g. Dominik & Decin 2003; Wyatt et al. 2007b), so their discovery is more likely if the host stars are young. HD 223352/40 belongs to the ∼70 Myr old AB Doradus moving group (Zuckerman et al. 2011) so the detection of two discs is perhaps not surprising. The Fomalhaut system is about 440 Myr old, which is young relative to randomly selected M-type stars, whose ages will be evenly distributed up to ∼10 Gyr. Therefore, LP 876−10 is among the youngest ∼5 per cent of M dwarfs, which may explain the presence of a bright debris disc despite detections generally being rare. Many young stars are not seen to have debris however, so the lack of a bright disc around TW PsA may simply mean that the disc around this star had a smaller radius and has evolved to obscurity by more rapid collisional evolution, or that it was initially lower in mass than the other two.

Considering how the LP 876−10 debris disc fits within the greater context of the Fomalhaut system, the properties of note are the large separations of TW PsA and LP 876−10, the spectacular offset debris ring (Kalas, Graham & Clampin 2005), and the high-eccentricity planet, Fomalhaut b (Kalas et al. 2013). That LP 876−10 lies along the same position angle as the Fomalhaut disc major axis, which is only 24° from edge-on, may be a hint that both currently orbit in the same plane (Kalas et al. 2013), though the LP 876−10 plane will vary over time due to Galactic tides (see below). A key question is whether the companions ever come very close to the primary (i.e. have small pericentre distances) or each other, which could influence the observed properties of the debris discs. There seem to be two formation scenarios for this wide multiple system, each with differences in the expected companion orbital evolution; relatively gentle multiple system formation during cluster evaporation (e.g. Kouwenhoven et al. 2010; Moeckel & Clarke 2011), and dynamical interactions in a triple system where hardening of an inner binary results in a wider companion (e.g. Reipurth & Mikkola 2012).

If the Fomalhaut system was originally more compact overall and LP 876−10 dynamically thrown to a much larger orbit, it would have a highly eccentric orbit and the two debris discs could be related. However, this formation scenario relies on the hardening of an inner binary, and TW PsA is itself probably too well separated from Fomalhaut to be the cause (Reipurth & Mikkola 2012). It is also very unlikely that Fomalhaut is itself a close binary (e.g. Kenworthy et al. 2013) so the inner binary hardening scenario seems unlikely here.

If the Fomalhaut system formed essentially by chance when momentarily bound stars in a cluster became a permanent system, then their inclinations should be random, and their eccentricities are expected to be weighted towards higher values (a median e of about 0.7; Kouwenhoven et al. 2010). It is therefore unlikely, though possible, that either TW PsA or LP 876−10 would initially have an eccentricity sufficient to come very close to Fomalhaut (within 500 au, or $e > 0.98$, say). This eccentricity may evolve however, due to interactions between the companions (e.g. Kozai 1962), and/or the effect of Galactic tides (e.g. Heisler & Tremaine 1986). The time-scale for the eccentricity of TW PsA to vary due to Kozai cycles depends on the companions' orbits, which are unknown, but for circular orbits at their known separation is ∼2.7 Gyr (e.g. Beust & Dutrey 2006), meaning that this mechanism may not have had time to cause this companion to interact strongly with the primary unless the initial eccentricity was already very high. Such a scenario also provides no link between the Fomalhaut and LP 876−10 discs. Galactic tides however, become stronger for wider orbits, and the time-scale estimate given by Heisler & Tremaine (1986) suggests that the companion orbits will vary on time-scales similar to the orbital periods (∼10–100 Myr). With the caveat that the system must also remain stable for the system age of ∼440 Myr, the effects of Galactic tides may dominate the dynamics of the companions, and thus may also have led to sufficiently close encounters of either companion with the primary (see also Kaib, Raymond & Duncan 2013).

Whether there is any link between the discs around Fomalhaut and LP 876−10 is unclear. If the stars have always remained well separated, the evolution of the two bright debris discs should be no different to random single stars, and their detection in the Fomalhaut system would be attributed to the relative youth of the system (in particular LP 876−10). Alternatively, the wide separation of the companions may lead to complex dynamics; the bright debris discs and eccentric planet may have a common cause due to a past interaction between Fomalhaut and LP 876−10, which stirred up their debris discs, perhaps igniting a collisional cascade in a previously quiescent disc (e.g. Kenyon & Bromley 2002), or provoking an instability in the planetary system (e.g. Malmberg, Davies & Heggie 2011) that later stirs the disc. Such scenarios are of course speculation, but motivate detailed observations of all system components. It may be that high-resolution observations of the LP 876−10 disc will reveal evidence of dynamical perturbations, a signature of yet another planet (e.g. Fomalhaut Cb) or a highly eccentric stellar orbit that periodically brings it closer to Fomalhaut or TW PsA.

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