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The companion candidate near Fomalhaut – a background neutron star?

R. Neuhäuser,[1⋆] M. M. Hohle,[1,2] C. Ginski,[1,3] J. G. Schmidt,[1] V. V. Hambaryan[1] and T. O. B. Schmidt[1,4]

[1]*Astrophysikalisches Institut und Universitäts-Sternwarte Jena, Schillergässchen 2-3, D-07745 Jena, Germany*
[2]*Graduate School of Quantitative Biosciences Munich, Genecenter of the LMU, Feodor-Lynen-Str. 25, D-81377 Munich, Germany*
[3]*Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*
[4]*Hamburger Sternwarte, Gojenbergsweg 112, D-21029 Hamburg, Germany*

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ABSTRACT

The directly detected planetary mass companion candidate close to the young, nearby star Fomalhaut is a subject of intense discussion. While the detection of common proper motion led to the interpretation as Jovian-mass companion, later non-detections in the infrared raised doubts. Recent astrometric measurements indicate a belt crossing or highly eccentric orbit for the object, if a companion, making the planetary interpretation potentially even more problematic. In this study we discuss the possibility of Fomalhaut b being a background object with a high proper motion. By analysing the available photometric and astrometric data of the object, we show that they are fully consistent with a neutron star: neutron stars are faint, hot (blue), and fast moving. Neutron stars with an effective temperature of the whole surface area being 112 000–126 500 K (with small to negligible extinction) at a distance of roughly 11 pc (best fit) would be consistent with all observables, namely with the photometric detections in the optical, with the upper limits in the infrared and X-rays, as well as with the astrometry (consistent with a distances of 11 pc or more and high proper motion as typical for neutron stars) and non-detection of pulsation (not beamed). We consider the probability of finding an unrelated object or even a neutron star nearby and mostly co-aligned in proper motion with Fomalhaut A and come to the conclusion that this is definitely well possible.

Key words: stars: individual: Fomalhaut – stars: neutron – planetary systems.

1 INTRODUCTION

The direct detection of a possibly planetary mass object near the star Fomalhaut by Kalas et al. (2008) was widely regarded as a great success for the direct imaging detection method. The separation between Fomalhaut A and b is some 100 au or 13 arcsec. In addition to this published planetary mass companion candidate (called Fomalhaut b), Fomalhaut A (the central star) is surrounded by a well-resolved dust belt, which was most recently studied with *Herschel* (Acke et al. 2012) and Atacama Large Millimeter/submillimeter Array (ALMA; Boley et al. 2012). The projected position of the tentative companion was interpreted to indicate that it had cleared the gap in this belt. The presence of the belt close to the companion candidate constrained the upper mass limit of the companion candidate to a few Jupiter masses (Kalas et al. 2008).

The star Fomalhaut[1] (Fomalhaut A) has the following relevant properties (all for the star A):

(i) Position J2000.0: $\alpha = 22^{\rm h}57^{\rm m}39^{\rm s}$ and $\delta = -29^\circ37'20''$ (*Hipparcos*; van Leeuwen 2007).

(ii) The distance as measured by *Hipparcos* is 7.70 ± 0.03 pc (van Leeuwen 2007).

(iii) Proper motion as also measured by *Hipparcos* is $\mu_\alpha = 328.95 \pm 0.50$ mas yr^{-1} and $\mu_\delta = -164.67 \pm 0.35$ mas yr^{-1} (van Leeuwen 2007).

(iv) The spectral type is A4V as obtained by an optical spectrum (Gray et al. 2006); given this spectral type, the colour index is close to zero, e.g. $B - V = 0.09$ mag (e.g. Ducati 2002).

(v) The optical brightness is $V = 1.16$ mag (e.g. Ducati 2002).

(vi) The age was recently determined to be 440 ± 40 Myr by kinematic membership to the young Castor Moving Group (Barrado y Navascues 1998; Mamajek 2012).

The companion was originally discovered in the optical bands of the *Hubble Space Telescope* (*HST*) Advanced Camera for Survey (ACS; Ford et al. 1998). However, several attempts to detect the object in the near- and mid-infrared (IR; see e.g. Kalas et al. 2008; Janson et al. 2012) failed (see Table 1). This was most troublesome, given that a (few hundred Myr) young cooling Jovian-mass object should be much brighter in the IR than in the optical. Furthermore, the latest astrometric measurements by Kalas et al. (2013) indicate

⋆E-mail: rne@astro.uni-jena.de

[1]This star is also called α PsA, i.e. the brightest star in the Southern Fish, the name *Fomalhaut* comes from the Arabic *fam al-hūt al-janūbī* meaning *mouth of the southern fish* (Kunitzsch & Smart 1986).

Table 1. Photometric observation epochs and analysis by various authors of Fomalhaut b.

Date	Telescope	Instrument	Filter	Ref.	Det.?	App. magnitude/ upper limit (mag)	Flux (erg cm^{-2} s^{-1} Å^{-1})
2004 Sep. 26	*HST*	ACS/HRC	*F606W*	Currie et al. (2012)	Yes	24.92 ± 0.10	$3.14 \pm 0.29 \times 10^{-19}$
2004 Oct. 25	*HST*	ACS/HRC	*F606W*	Kalas et al. (2008)	Yes	24.43 ± 0.09	$4.93 \pm 0.41 \times 10^{-19}$
2004 Oct. 26	*HST*	ACS/HRC	*F606W*	Kalas et al. (2008)	Yes	24.29 ± 0.08	$5.61 \pm 0.41 \times 10^{-19}$
2005 July 21	Keck II	NIRC2	*H*	Kalas et al. (2008)	No	$\geq$22.9	$\leq 8.28 \times 10^{-20}$
2005 Oct. 21	Keck II	NIRC2	CH_4S	Kalas et al. (2008)	No	$\geq$20.6	
2006 July 14–20	*HST*	ACS/HRC	*F435W*	Kalas et al. (2008)	No	$\geq$24.7	$\leq 8.36 \times 10^{-19}$
2006 July 14–20	*HST*	ACS/HRC	*F435W*	Currie et al. (2012)	Yes	25.22 ± 0.18	$5.18 \pm 0.86 \times 10^{-19}$
2006 July 14–20	*HST*	ACS/HRC	*F606W*	Kalas et al. (2008)	Yes	25.13 ± 0.09	$2.59 \pm 0.21 \times 10^{-19}$
2006 July 14–20	*HST*	ACS/HRC	*F606W*	Currie et al. (2012)	Yes	24.97 ± 0.09	$3.00 \pm 0.25 \times 10^{-19}$
2006 July 14–20	*HST*	ACS/HRC	*F814W*	Kalas et al. (2008)	Yes	24.55 ± 0.13	$1.69 \pm 0.20 \times 10^{-19}$
2006 July 14–20	*HST*	ACS/HRC	*F814W*	Currie et al. (2012)	Yes	24.91 ± 0.20	$1.21 \pm 0.22 \times 10^{-19}$
2008 Sep. 17–18	Gemini-North	NIRI	*L′*	Kalas et al. (2008)	No	$\geq$16.6	$\leq 1.22 \times 10^{-18}$
2009 Aug. 16	Subaru	IRCS	*J*	Currie et al. (2012)	No	$\geq$22.22	$\leq 4.01 \times 10^{-19}$
2010 Aug. 8–2011 July 23	*Spitzer*	IRAC	4.5 μm	Janson et al. (2012)	No	$\geq$16.7	$\leq 5.71 \times 10^{-19}$

that the object would either cross the dust belt or that it would be on a highly eccentric orbit which is not in alignment with the belt at all. These two facts together have prompted us to seek for an alternative explanation which might explain all the observations and finally resolve some of the apparent contradictions. In the following we will first briefly discuss the various scenarios that have been proposed so far and will then present our own considerations.

In this paper, we first review the observations of Fomalhaut b (Section 2) and the interpretations as Jupiter-mass planet (Section 2.1), as super-Earth (Section 2.2), and as dust cloud (Section 2.3). Then, we consider the background hypothesis as either a white dwarf (Section 3.1) or neutron star (NS; Section 3.2); we discuss the astrometry, the X-ray data, and the optical and IR photometry, to constrain the NS properties (to be consistent with all observables). In Section 3.2.5, we also discuss the probability to find a background object or even a NS close to a star like Fomalhaut. We conclude in Section 4.

2 FOMALHAUT b AS A GRAVITATIONALLY BOUND OBJECT

2.1 Fomalhaut b as a Jupiter-mass planet

The first interpretation of the available data by Kalas et al. (2008) led to the conclusion that the object may be a giant planet. From stability considerations of the dust belt, Kalas et al. (2008) and Chiang et al. (2009) inferred that the mass of the object should be $\leq 3\ M_J$. Larger masses would lead to either smaller orbits than could be inferred from the astrometry, or higher belt eccentricities than are observed. Kalas et al. (2008) concluded that if the flux in the optical wavelength range originates in the photosphere of a cooling planet, then the object needs to be cooler than 400 K. Otherwise too much flux would be produced at 1.6 μm. They suspected that their non-detections at 1.6 and 3.8 μm might be due to model uncertainties. However, Marengo et al. (2009) and Janson et al. (2012) present *Spitzer* Infrared Array Camera (IRAC) upper detection limits at 4.5 μm, which puts additional constraints on the mass of a possible giant planet. Janson et al. (2012) conclude that the optical flux cannot stem from a planet's photosphere, especially since the flux at 0.6 μm is 20–40 times brighter than expected for an object with $\sim 3\ M_J$ and a few hundred Myr (Burrows, Sudarsky & Lunine 2003; Fortney et al. 2008). On the contrary, Currie et al. (2012) and Galicher et al. (2013) argue that a 0.5–1 M_J object would not have been detected at 4.5 μm (using models by Baraffe et al. 2003; Spiegel & Burrows 2012). In addition, Galicher et al. (2013) present upper detection limits at 1.1 μm, which are consistent with this upper mass limit. However, there is a general agreement in all aforementioned studies that the flux in the optical wavelength range cannot stem completely (or at all) from a planet's photosphere.

In addition to the discussed overluminosity in the optical wavelength range, Kalas et al. (2008) and Janson et al. (2012) report significant (5–8σ) variability of the flux at 0.6 μm, which could not be explained by a thermal emission from a planet's photosphere. Kalas et al. (2008) propose that there might be a 20–40 R_J accretion disc around the assumed planet. The disc would reflect light from the primary star, which explains the optical excess flux. Furthermore, they argue that the variability could then be explained by accretion-driven Hα emission. Janson et al. (2012) strongly disagree, stating that at the high system age moons should have formed in a possible accretion disc, and thus the reflective surface should be reduced. Also, they think it is unlikely that accretion-driven Hα emission can explain the variability, because the accretion rate would have to be similar to young T Tauri stars. Currie et al. (2012) and Galicher et al. (2013) re-analysed the same optical data and did not detect any significant variability at 0.6 μm. Thus, they are not excluding a dust disc around a Jupiter-mass planet.

The most recent study by Kalas et al. (2013) incorporates new astrometric measurements taken with the *HST* Space Telescope Imaging Spectrograph (STIS; Woodgate et al. 1998) in 2010 and 2012. They find that the object is most likely on a ring-crossing orbit with a high semimajor axis and eccentricity. One explanation, assuming Fomalhaut b is a planet, would be that it had a close encounter with a further-in massive planet and was scattered out. However, Kenworthy et al. (2013) performed deep coronagraphic imaging and can rule out further-in objects with 12–20 M_J at 4–10 au. They state that this effectively rules out scattering scenarios, which makes the orbit elements recovered by Kalas et al. (2013) somewhat peculiar.

Given that five astrometric data points are available only for four different epochs separated by a few years, any orbit fits with periods of hundreds of years (Kalas et al. 2013) suffer from high uncertainties anyway. Given the large separation between the two

objects (star and presumable planet), even if bound, other planet detection techniques like the radial velocity or transit technique cannot be applied.

Given the various and sometimes contradictory arguments, the existence of a giant planet at the position of Fomalhaut b is still possible, but seems increasingly problematic.

2.2 Fomalhaut b as a super-Earth

If there is a central object associated with the source Fomalhaut b, then Janson et al. (2012) state that its mass should be limited to $\leq$10 $M_\oplus$ if there is a ring-crossing orbit, which the astrometry suggests. This is in order to prevent the object from significantly influencing the observed belt geometry (see also Kennedy & Wyatt 2011). For such an object to exhibit the observed fluxes in the optical wavelength range, the object would need to be significantly hotter than a cooling planet of that mass. Janson et al. (2012) propose a scenario where the object had undergone an intense bombardment of planetesimals within the time-scale of $\sim 10^4$ yr. However, they recognize that the observation of such an event seems improbable due to the short time-scale, as compared to the age of the system. In addition, this scenario is not entirely compatible with the high flux at 0.6 μm.

Another scenario proposed by Janson et al. (2012) is a 10 $M_\oplus$ object with a cloud of planetesimals which are producing the dust that reflects the starlight. However, this scenario would not explain the aforementioned variability at 0.6 μm which was detected by two independent studies. It is also questionable why the orbit of such an object would exhibit a high semimajor axis and eccentricity as found by Kalas et al. (2013) if scattering scenarios can be ruled out (Kenworthy et al. 2013).

In general, while a smaller planetary mass object does not exhibit the same problems with the IR detection limits as a more massive object, the orbit of such a low-mass companion still seems peculiar. In addition, it is still challenging to explain the optical flux in such a scenario.

2.3 Fomalhaut b as a dust cloud

Kalas et al. (2008) originally discussed the possibility that there might not be a central object associated with the source Fomalhaut b, but that it is rather a dust cloud produced by the recent collision of two planetesimals. They reject this possibility because they think it is improbable to observe such a collision at the location of Fomalhaut b, due to the low density of planetesimals outside the dust belt. In addition, they state that a dust cloud would not account for the variability at 0.6 μm. Janson et al. (2012) note that the observation of such a dust cloud might not be as improbable as Kalas et al. (2008) state. They argue that such collisions should indeed happen more frequently inside the dust belt, but are not observable at this location due to the speckle-like nature of such sources. Thus the probability of observing one such collision outside the dust belt is not negligible. Galicher et al. (2013) argue that their detection of Fomalhaut b at 0.4 μm would fit well with a dust cloud younger than 500 yr composed of water ice or refractory carbonaceous small grains, as originally proposed by Kalas et al. (2008). Furthermore, Galicher et al. (2013) do not detect the variability at 0.6 μm, which was one of the main arguments against this scenario by Kalas et al. (2008). However, Currie et al, (2012) contend that the observation of an unbound dust cloud should be unlikely because Keplerian shear would spread out such a cloud. This small time frame as compared to the system age would make the observation of such a cloud implausible. We want to note that the study by Galicher et al. (2013) finds that the object Fomalhaut b can be fitted slightly better with an extended source (0.58 au) than with a point source. This is, however, on a very low significance level, and other studies have not mentioned the possible resolved nature of the source.

Overall the dust cloud scenario may appear to be a possible scenario if Fomalhaut b is extended and gravitationally bound to Fomalhaut A.

3 FOMALHAUT b AS A BACKGROUND OBJECT

When evaluating the background hypothesis compared to the possibility of a gravitational bound companion, usually a non-moving background object is assumed: One first tests the hypothesis of a bound companion with the null hypothesis that both the central star and the companion candidate have identical proper motion; then one tests the background hypothesis with the null hypothesis that the central star has its finite (known) proper motion and that the companion candidate proper motion is zero.[2] However, this method may fail if the object of interest is a moving background object with a considerable proper motion. Therefore, we discuss the possibility that Fomalhaut b could be a moving background object, unrelated to the primary star.

The *HST* magnitudes of Fomalhaut b point to a flat spectral energy distribution (SED; Kalas et al. 2008; Currie et al. 2012) that rules out any ordinary star given the faint magnitudes. Since the position of Fomalhaut b changes only slightly over years with respect to the primary star, its proper motion should be roughly that of the primary star. Only a white dwarf or a NS is fast moving and dim enough to match these constrains.

3.1 Fomalhaut b as a white dwarf

The absolute visible magnitude of white dwarfs ranges from 10 to 15 mag (Wood & Oswald 1998), Fomalhaut b has an apparent visible magnitude of $\sim$25 mag (Table 1). Even taking visual absorption caused by the interstellar medium (ISM) into account, the putative white dwarf would have a distance of at least 0.5 kpc, but up to 5 kpc (brightest white dwarf; no absorption). From these estimates, the object would have a projected spatial velocity (2D) of 900–9000 km s^{-1} (applying Fomalhaut's proper motion). In addition the putative white dwarf would have an unknown radial velocity component that would raise the spatial velocity (3D) to even larger values. These numbers are rather unrealistic, since the fastest known white dwarf moves with 450 km s^{-1} (Wood & Oswald 1998; Oppenheimer et al. 2001). Hence, a white dwarf as a putative background object is very unlikely.

3.2 Fomalhaut b as a neutron star

Young (1 Myr), hot (1 MK), and closeby ($\leq$500 pc) NSs have visual magnitudes ranging from 25 to 27 mag (see e.g. Kaplan et al. 2011 for a compilation), i.e. as faint as Fomalhaut b, but more distant. These objects are not necessarily radio pulsars and therefore

[2]Even if both objects have common proper motion, this is not yet a proof that they orbit each other. Even the detection of curvature in the motion of the companion may not yet be a proof that they orbit each other, if the curvature would also be consistent with a hyperbolic orbit of a recently ejected object. The detection of curvature in a form that is not consistent with a hyperbolic orbit would be a proof that both objects orbit each other.

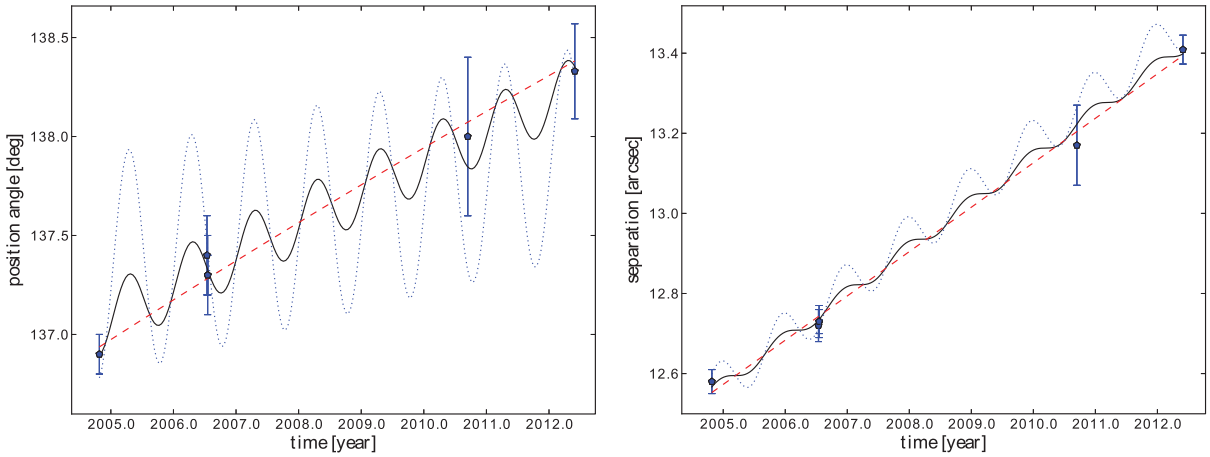

Figure 1. Change in position angle (left) and separation (right) with time: the five astrometric data points for the object called Fomalhaut b are shown (epochs as listed in Table 1) in order to try to measure its own proper motion and parallax. Differential proper motion and differential parallactic fits to the relative astrometric measurements of Fomalhaut A and b. The solid (black) line shows our best fit of a differential proper motion of -50.4 mas yr^{-1} in RA and 107.8 mas yr^{-1} in Dec. as well as a *differential* parallax of 39.1 mas, yielding a total distance of 11 pc for Fomalhaut b. For comparison, we also show a fits with no differential parallax (dashed red line) and with the maximum possible differential parallax of 129.8 mas (dotted blue line), corresponding to a distance estimate of 8 pc in the first case and any (larger) distance in the second case. A differential parallax between Fomalhaut A and b that is equal to the measured absolute parallax of Fomalhaut A implies no measurable parallax of Fomalhaut b. Then, Fomalhaut b could be located at any (larger) distance. In the first (more likely) case the differential motion in RA and Dec. is -42.8 and 110.9 mas yr^{-1}, respectively. In the second case it would be -68.1 and 100.5 mas yr^{-1}, respectively. The relative change in position of Fomalhaut A and b can be due to different distances. The best fit shown results in $\sim$11 pc as distance for the companion candidate, but it is not significant. Within $\geq 2\sigma$ error bars, any other larger distance is also possible.

Fomalhaut b (if a NS) could have remained undetected. Indeed, the radio-quiet X-ray emitting NS RXJ 1856.4−3754, the first such object not powered by rotation, has $V = 25.6$ mag, and it was discovered by coincidence by Walter, Wolk & Neuhäuser (1996) as they actually searched for T Tauri stars. Because of the supernova (SN) kick, the spatial velocities of NSs are on average much larger than those of e.g. white dwarfs and peak at $\sim$400 km s^{-1}, the fastest known NS moves with 1500 km s^{-1} (Hobbs et al. 2005).

3.2.1 *Astrometry: proper motion and parallax*

Since the companion candidate to Fomalhaut (i.e. object b) was found to be (at least nearly) comoving to Fomalhaut A, both Fomalhaut A and b have very similar proper motions. We can therefore estimate the motion of Fomalhaut b by using the proper motion of Fomalhaut A: $\mu_\alpha = 328.95 \pm 0.50$ mas yr^{-1} and $\mu_\delta = -164.67 \pm 0.35$ mas yr^{-1} (*Hipparcos*). The proper motion of both Fomalhaut A and b are then $\sim$368 mas yr^{-1}. This proper motion of Fomalhaut b would then be equivalent to a tangential (2D) velocity of $\sim$30 km s^{-1} for 11 pc distance (i.e. background to Fomalhaut A), or 170 km s^{-1} for 100 pc distance. Such velocities are fully consistent with NS velocities.

Since Fomalhaut A is a very nearby star (7.7 pc), its parallactic motion (wobble) is large (a parallax of 130 mas). Since very precise astrometry for both Fomalhaut A and b are available (which were used to show their common proper motion), one can check whether some differential parallactic motion between the star and the companion candidate are detectable: if the presumable companion candidate would be in the distant background, one would not detect any significant parallactic motion for the companion, but of course still large parallactic motion for the star Fomalhaut A.

To investigate whether the relative astrometry between Fomalhaut A and b would be consistent with Fomalhaut b being a background object, we tried to fit the data points with a differential proper motion and differential parallax. Results are shown in Fig. 1. In principle, our best fit in terms of reduced χ^2 (0.16) yields a differential parallax of 39.1 mas and a differential proper motion of -50.4 mas yr^{-1} in RA and 107.8 mas yr^{-1} in Dec. This corresponds to Fomalhaut b being in the background behind Fomalhaut A at a total distance of 11 pc. However, as indicated by the small reduced χ^2, this result is not significant due to the low number of data points and their uncertainties. We also fit differential motion to the data points without any differential parallax. The resulting linear fit has only a marginally worse reduced χ^2 (0.33) as compared to the best fit and is also fully consistent with all measurements. Finally, we repeated the same fitting procedure but with the maximum possible differential parallax of 129.8 mas. The resulting fit is consistent with all measurements but the one taken in 2010. However, this measurement has the highest uncertainty of all astrometric data points and lies still within 2σ of the fit and thus also for this scenario a reasonable reduced χ^2 of 1.41 was calculated.

This analysis shows that the astrometry is in principle compatible with Fomalhaut b being a background object at any distance (behind Fomalhaut A), although a distance of 11 pc is slightly favoured. However, as pointed out, we cannot exclude that Fomalhaut b is at the same distance as Fomalhaut A.

Fomalhaut is located at a galactic latitude of $-64.^\circ9$, i.e. south of the Galactic plane. The proper motion of both the star Fomalhaut A and its companion candidate (or the nearby NS) is moving (in both equatorial and galactic coordinates) towards the south–south-east, i.e. away from the Galactic plane. This would be consistent with a young NS which was recently born in the Galactic plane. Since the Sun is currently 26 ± 3 pc north of the Galactic plane (Majaess, Turner & Lane 2009), and since Fomalhaut is 7.70 ± 0.03 pc away from the Sun (mostly towards the galactic south), Fomalhaut (and its companion candidate) are currently 33.7 ± 3 pc south of the Galactic plane. For the largest one-dimensional velocity known for a NS (1285 km s^{-1} for PSR B2011+38; Hobbs et al. 2005), our object would have needed (at least) 2.6 ± 0.2 kyr to travel from the

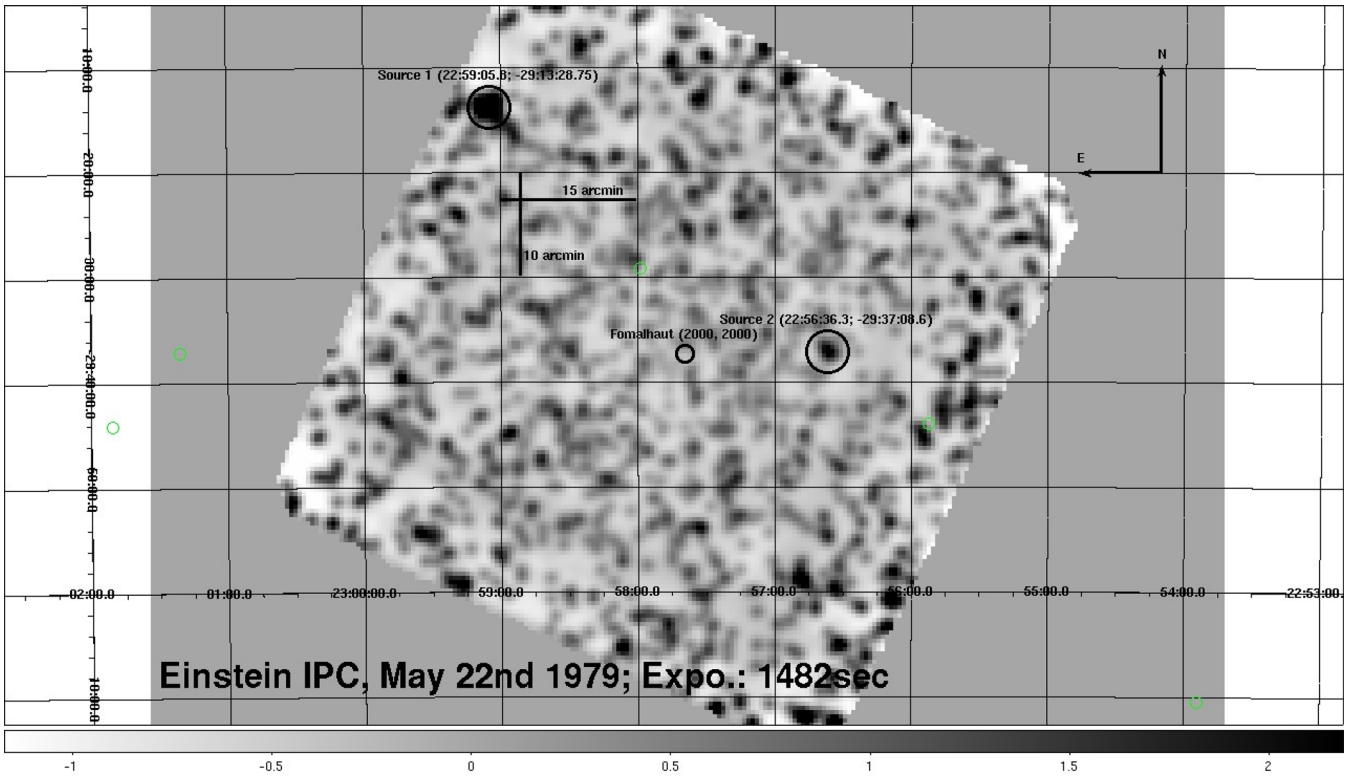

Figure 2. X-ray observation with *Einstein*: a 1.5 ks *Einstein* IPC pointing exhibits numerous artefacts and two potential X-ray sources. However, there is no evidence for X-ray emission at Fomalhaut's former position (1979) in the centre of this image.

Galactic plane to its current position; for the mean one-dimensional NS velocity ($133 \pm 8\,\mathrm{km\,s^{-1}}$; Hobbs et al. 2005), it would have needed 248 ± 37 kyr. Of course, it could have formed outside of the Galactic plane, or it may have oscillated around the plane one or several times (and/or have orbited the Galactic Centre one or more times). Its current position south of the Galactic plane together with its motion away from the plane would be consistent with a young NS.

3.2.2 *X-ray data*

Young and nearby NSs are detectable as bright X-ray sources (e.g. Walter et al, 1996; Haberl et al. 1997; Haberl 2007, for a review). Therefore, we checked the X-ray archives whether there is a source located at the position of Fomalhaut b. Only one 1.5 ks *Einstein* Imaging Proportional Counter (IPC; Miller et al. 1978) pointing from the year 1979 and a 6.2 ks Position Sensitive Proportional Counter (PSPC) exposure with *ROSAT* (Trümper 1983) from 1996 January are available in the archive (in addition to a 170-s exposure from the *ROSAT* All-Sky-Survey), see Figs 2 and 3. The *Einstein* IPC observation shows many artefacts that mimic sources, but there is no evidence of X-ray emission at the current or past position of Fomalhaut b (Fig. 2). Two potential X-ray sources (denoted as 'source 1' and 'source 2', respectively) in Fig. 2 are too distant from Fomalhaut b's past position, considering its proper motion, to be identified with Fomalhaut b.

Also the *ROSAT* PSPC data give no evidence of X-ray emission at the position of Fomalhaut b. Furthermore, 'source 1' (out of view) and 'source 2' detected in the *Einstein* IPC pointing are also not visible, suggesting that the latter is an artefact or a variable source (Fig. 3).

Based on these non-detections of Fomalhaut b in the X-ray images, one can put rough constraints on the properties of the putative NS. In the 6.2 ks *ROSAT* exposure obtained with the boron filter (which blocks about 90 per cent of the soft flux below 0.3 keV), an upper limit count rate of $\leq$0.00066 counts $\mathrm{s^{-1}}$ was determined (Schmitt 1997); while this upper limit was determined for the star Fomalhaut A, it should also apply to Fomalhaut b given the small separation (see also Fig. 3, where no source is detected).

The isolated NS RXJ 1856.4−3754 appears as bright source with pure blackbody emission (therefore often serves as calibration target; see Mereghetti et al. 2012) in the X-ray energies with a *ROSAT* PSPC count rate of 3.67 counts $\mathrm{s^{-1}}$ in the 0.11–2.4 keV band. Hence, RXJ 1856.4−3754 is at least 556 times brighter than Fomalhaut b in the *ROSAT* PSPC energy band (having taken into account that RXJ 1856.4−3754 was observed without boron filter, while Fomalhaut was observed with boron filter). According to the most recent parallax measurements by Walter et al. (2010), RXJ 1856.4−3754 has a distance of $\sim$123 pc, yielding an emitting area of $\sim$4.4 km as origin of the X-ray radiation. Assuming that Fomalhaut b emits as blackbody, too, the temperature T_∞ of its X-ray emitting area must be below 380 000 K, if its radiation would have the same normalization[3] of $N = (4.4\,\mathrm{km}/123\,\mathrm{pc})^2$ as RXJ 1856.4−3754, or its luminosity must scale with $f < (4.4\,\mathrm{km}/123\,\mathrm{pc})^2 \times (10^6\,\mathrm{K})^4$ (Trümper 2003; Trümper et al. 2004; Walter et al. 2010) to obey the upper limit derived from the *ROSAT* data.

[3]Because of high gravity and curved space around a NS, an observer at infinity measures temperature $T_\infty = T\sqrt{1 - r_\mathrm{s}/R}$ and radius $R_\infty = R/\sqrt{1 - r_\mathrm{s}/R}$, where r_s is the Schwarzschild radius.

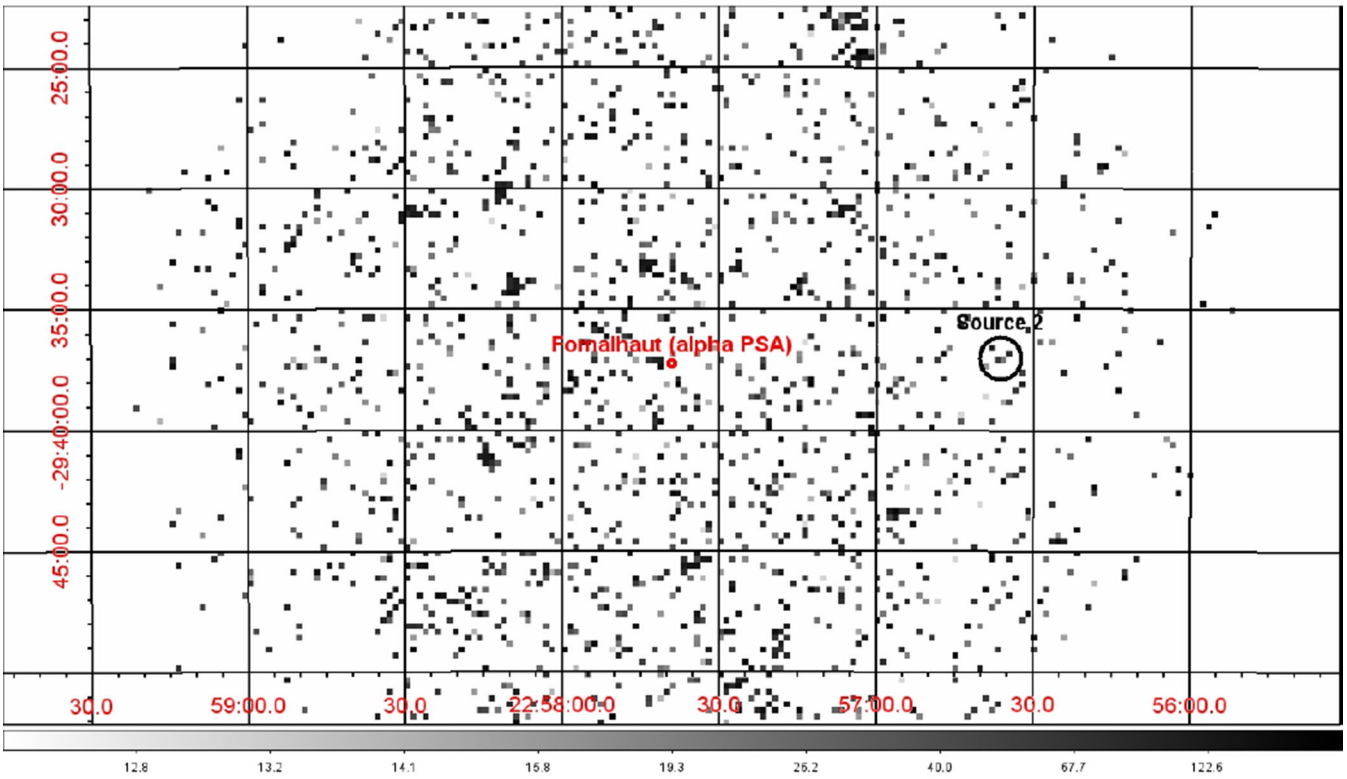

Figure 3. X-ray observation with *ROSAT*: data from *ROSAT* PSPC (6283 s, 0.11–2.4 keV, 1996 Jan 19) do not show X-ray emission near Fomalhaut (α PsA). Fomalhaut b is 13 arcsec north-west of Fomalhaut A, there is neither a source nor more background photons. 'Source 1' from Fig. 2 is not in the field of view and 'source 2' is not detected even though the exposure time is larger.

The non-detection of Fomalhaut b as NS is consistent with a NS with at least a few Myr age – even if only slightly background to Fomalhaut A, see below. This also applies, if it would be a NS of a different kind, i.e. other than RXJ 1856.4−3754 and RXJ 0720.4−3125. The latter two have kinematic ages of 0.5–1 Myr (Table 4), while the X-ray non-detection constraint applies to all NSs older than $\sim 10^{5.5}$ yr (Section 3.2.4).

The fact that Fomalhaut A (spectral type A4) is not detected in X-rays is not surprising, since A stars do not have strong hot winds nor a corona. However, some A4V stars exhibit X-ray luminosities that would correspond to about 50 times the detection limit of Fomalhaut A (Schröder & Schmitt 2007). Many of those (if not all) X-ray detected A-type stars are considered to host a very close stellar companion; this is not the case for Fomalhaut A; there are, however, Fomalhaut B as a wide K4-type stellar companion (0.3 pc away; Mamajek 2012) and Fomalhaut C (LP 876−10) as second wide M4-type stellar companion (0.77 pc away; Mamajek et al. 2013).

3.2.3 *Photometry and SED*

Absorption/extinction caused by the ISM must be taken into account (note that according to Löhne et al. 2012a,b, extinction caused by the disc around Fomalhaut is negligible). We use the average Galactic extinction curve provided by Fitzpatrick & Massa (2007). They fitted this extinction curve with a spline function based on several anchor points that were calculated by comparing model spectra with measured data from individual reference stars. The fit errors are in the order of several mmag, whereas we stress that the extinction curves for individual stars (hence, individual directions) can deviate significantly (Fitzpatrick & Massa 2007).

Taking blackbody normalization, temperature (of the optically emitting area), and A_V as free input parameters, the resulting magnitudes have to fit those measured by Currie et al. (2012) and Kalas et al. (2008).[4] As an estimate for the fit quality, we introduce the factor[5] $q^2 = 1/k^2 \sum_{\rm i}^{k} (m_i - \bar{m}_i)^2$, where m_i are the measured magnitudes (Kalas et al. 2008; Currie et al. 2012) and $\bar{m}_i$ the fitted magnitudes in the filter i. Since Fomalhaut b is only detected in three filters, the total number of different magnitudes is $k = 3$. Distance, temperature (of the optically emitting area), and extinction are free fit parameters, the radius was assumed to be 17 km.

Currie et al. (2012) and Kalas et al. (2008) list magnitude errors in the order of 0.1–0.2 mag for the *HST* photometry (see Table 1). However, the magnitudes of the same filter differ by 0.5 mag for different measurements and by different authors, suggesting that the systematic errors are much larger than the statistical errors. We calibrated the modelled blackbody flux to the Vega magnitude system (our results were checked with the average Vega flux densities in the different *HST* filters as listed in the *HST* handbook), since Currie et al. (2012) and Kalas et al. (2008) give Fomalhaut b's magnitudes in the Vega system, and corrected for non-infinite aperture (see *HST* handbook), see Table 1. Furthermore, we calculated the *HST* magnitudes of the two optically detected isolated NSs with known

[4] We have tested and verified the fit procedure with the optical data of RXJ 1856.4−3754, its optical magnitudes, the distance 123 pc, a radius of 17 km, and negligible extinction.

[5] The low number of data points prevent a fit quality estimate in terms of reduced χ^2.

Table 2. Photometry of two brightest known isolated NSs as measured with *HST* (Kaplan et al. 2011).

Wavelength (Å)	Width (Å)	Flux F_λ (erg cm^{-2} s^{-1} Å^{-1})
	RXJ 1856.4−3754	
1707.4	515.2	$1.50 \pm 0.13 \times 10^{-17}$
2960.5	877.3	$2.34 \pm 0.14 \times 10^{-18}$
4444.1	1210.5	$4.63 \pm 0.24 \times 10^{-19}$
4739.1	1186.4	$3.84 \pm 0.50 \times 10^{-19}$
5734.4	2178.2	$1.51 \pm 0.47 \times 10^{-19}$
	RXJ 0720.4−3125	
1370	320	$7.94 \pm 1.34 \times 10^{-18}$
1480	280	$5.92 \pm 0.57 \times 10^{-18}$
2320	1010	$1.07 \pm 0.13 \times 10^{-18}$
4739.1	1186.4	$1.13 \pm 1.45 \times 10^{-19}$
5850	4410	$7.73 \pm 0.68 \times 10^{-20}$

Table 3. 10 allowed parameter combinations consistent with the photometry of Fomalhaut b. We list magnitudes, effective temperature (T_∞; of the optical emitting area) as seen from an observer at infinity, predicted distance to the Sun (D), and interstellar extinction A_V.

F435W (mag)	*F606W* (mag)	*F814W* (mag)	T_∞ (K)	D (pc)	A_V (mag)	q
25.13	25.07	24.87	19 360	6.2	0.53	0.045
25.15	25.09	24.87	37 890	9.0	0.85	0.048
25.12	25.02	24.81	14 320	4.9	0.33	0.050
25.12	25.08	24.87	45 710	10.1	0.86	0.051
25.22	25.11	24.84	54 190	10.5	1.04	0.052
25.24	25.12	24.87	23 840	6.8	0.77	0.053
25.07	25.02	24.86	13 960	5.1	0.22	0.054
25.20	25.13	24.89	55 520	11.1	0.97	0.054
25.09	25.09	24.92	62 010	12.4	0.85	0.058
25.11	25.03	24.79	53 960	10.4	0.98	0.059

distance, see Table 2, and compared our results to those given by Kaplan et al. (2011) in ST the magnitude system as an additional check.

We can find blackbody SED which fit the observed data, they are in the parameter range of $T_\infty = 6810$–$126\,500$ K, $D = 1.6$–33 pc, and $A_V < 2.5$ mag (but not all combinations in the parameter ranges are possible). In Table 3, we show the 10 allowed combinations as examples. The resulting effective temperatures (of the optical emitting area) yield ages of at least $\sim 10^{5.5}$ yr for the putative NS according to cooling curves in Aguilera, Pons & Miralles (2008) and Page et al. (2009); however, since NSs cool very rapidly for effective temperatures (of the optical and/or X-ray emitting area) of $\leq$100 000 K and ages above at around that age, a precise age estimate from the temperature is not well possible. X-ray non-detection would not be surprising for Fomalhaut b being a relatively old NS. We would like to point out that we assume just one (effective) temperature for both the optical and X-ray emitting area, i.e. the whole NS surface. This temperature fits the optical magnitudes known and agrees with the X-ray upper limit as observed. It is of course possible that the polar caps are hotter than the remaining surface area, so that the object as NS would show pulses, even if not yet detected.

A more realistic model of the emission of a young NS is a two-component model: a cool ($T_\infty \approx 300\,000$–$400\,000$ K) blackbody emitting in the optical (representing the major part of the NS surface) and a hot ($T_\infty \approx 10^5$–10^6 K) blackbody, visible at X-ray energies, caused by the hotspot(s) at the magnetic poles (Kaplan et al. 2011). However, this would mean fitting three magnitudes with five parameters (A_V, D or $R_{1\infty}$, $R_{2\infty}$, $T_{1\infty}$, $T_{2\infty}$) and – as expected – did not lead to useful results: e.g. any high effective temperature value (of the optical and X-ray emitting area, i.e. the whole surface) can be compensated by large A_V values flattening the SED. To put constraints on the two-blackbody model it is necessary to derive more data points for the SED, in particular at ultraviolet (UV) energies.

3.2.4 *Constraining the neutron star properties*

Given the observed astrometry and photometry, we can now try to constrain the properties of Fomalhaut b, if it would be a NS, in particular its distance and age range. We assume for most part of this section that Fomalhaut b as NS would have the typical radius of NSs, ∼10–17 km. First, we assumed ∼17 km radius for the optically emitting area and ∼4.4 km as radius of the X-ray emitting area in our spectral fits; these are values similar as for RXJ 1856.4−3754 (and maybe RXJ 0720.4−3125). Afterwards, we compare the object called Fomalhaut b with other NSs, which have smaller and/or hotter polar caps than RXJ 1856.4−3754 and RXJ 0720.4−3125. At the very end of this subsection, we also consider even smaller emitting areas (and smaller radii) like in strange (quark) stars.

The non-detection of a SN remnant places a lower limit to the age of a NS to roughly 10^5 yr, a SN remnant has diffused and faded away. In such a case, one would regard this NS (Fomalhaut b) as middle-aged, isolated NS (*isolated* means that there is neither a companion nor a SN remnant). Given the small distance of Fomalhaut b (even as NS), ∼11 pc being our best fit, see above, the SN remnant would have a large extend on sky: the Vela remnant at a distance of ∼290 pc (Caraveo et al. 2001; Dodson et al. 2003) and an age of ∼11 kyr (Dodson, McCulloch & Lewis 2002), both measured for the Vela pulsar, has an apparent size of 255 arcmin (Green 2009). A SN remnant some ∼26 times closer would have a size of ∼111°. Even at such a large size, it might have been noticed in the *ROSAT* All-Sky Survey, but no such (large) remnant was detected (in particular not at that position), see e.g. Busser (1998) and Schaudel et al. (2002).

If such a large remnant would not have been detectable, Fomalhaut b as NS would still not be a young NS, because it would then be bright in X-rays (if young), which is not the case. Hence, if a NS, Fomalhaut b is most likely middle aged or old.

If Fomalhaut b as NS would be related to the Local Bubble (∼50 Myr old), a volume around the Sun with very low interstellar medium density, then it might be possible that its SN did not form a detectable remnant; in this case, the NS might be younger than 50 Myr (but still older than $\sim 10^{5.5}$ yr due to X-ray non-detection).

The non-detection of radio pulsations may simply be due to the fact that the pulses are not beamed towards Earth; otherwise, they place a lower limit to the age of a NS to roughly 10^8 yr, the so-called death-line or graveyard of radio pulsars: Most known pulsating NSs are younger than 10^8 yr given their (characteristic) spin-down age (Gyr old millisecond pulsars recycled by mass transfer from their (former) companion are exceptions). In such a case, one would regard this NS (Fomalhaut b) as middle aged to old.

The proper motion is definitely in the possible range for NSs. The astrometry (parallactic motion) would be well consistent with ∼11 pc (best fit), but also much larger distances are not excluded (Fig. 1).

In principle, the colour of Fomalhaut b could also be compared to the NSs RXJ 1856.4−3754 and RXJ 0720.4−3125; however,

Kalas et al. (2008) and Currie et al. (2012) do not agree well on the magnitudes and the differences and error bars in their values are on the order or larger than the colours, and also, while Fomalhaut b was detected by *HST* with *F606W*, *F435W*, and *F814W*, neither RXJ 1856.4−3754 nor RXJ 0720.4−3125 was observed with *F435W* or *F814W* (but detected in *F606W*). We have re-reduced the *HST* photometry and arrived at values close to those of Kalas et al. (2008) and Currie et al. (2012), but also our photometry error bars are comparable to the error bars and absolute differences between the results in Kalas et al. (2008) and Currie et al. (2012).

The optical detections and the upper limits in the IR and X-rays allow good fits for a range in effective temperature (of the optical and X-ray emitting area) of up to roughly ∼100 000 K with small to negligible extinction (see Table 3 for a few examples); this is compatible with the more conservative X-ray temperature upper limit (up to 380 000 K) For a NS, this would then yield a distance of up to 33 pc and an age of at least $\sim 10^{5.5}$ yr (according to the cooling curves in Aguilera et al. 2008; Page et al. 2009), NSs start to cool very rapidly for temperatures ≤100 000 K (of the optical and X-ray emitting area) at ages somewhere between $10^{5.5}$ and $10^{6.5}$ yr, so that a precise age estimate from the temperature (of the optical and X-ray emitting area) is hardly possible in this regime.

The non-detection in X-rays (Figs 2 and 3) can place limits on temperature (of the X-ray emitting area) and distance by comparison with other middle-aged isolated NSs (all without SN remnant), namely the NSs RXJ 1856.4−3754 and RXJ 0720.4−3125, which are middle aged, isolated, and which have a known distance; in Table 4, we list their *ROSAT* PSPC count rates, distances, ages, and *V*-band magnitudes – to be used to scale to Fomalhaut b (we assume negligible extinction for Fomalhaut b and the NSs here).

Given that RXJ 1856.4−3754 and Fomalhaut b have very similar optical photometric magnitudes (Tables 1 and 2), we can relate distances d and temperatures T (since flux scales with T^4 and d^{-2}). If the temperature ratio between RXJ 1856.4−3754 (380 000 K) and Fomalhaut b (say 100 000–150 000 K) is the same for the warm surface responsible for the optical emission as for the hot polar spots responsible for X-ray emission, then we can scale from the temperature ratio and the distance ratio (123 pc for RXJ 1856.4−3754 and, say, 11 pc for Fomalhaut b as NS) as well as the X-ray count rate of RXJ 1856.4−3754 (3.67 counts s^{-1}, Table 4) also to the expected X-ray count rate of Fomalhaut: with the PIMMS software, we obtain ∼0.00066 counts s^{-1} for *ROSAT* PSPC with boron filter for 112 000–126 500 K at ∼11 pc; this is exactly the upper limit count rate obtained for Fomalhaut (A and b): 0.00066 counts s^{-1} (Schmitt 1997). Hence, for a distance range of 11 pc (best fit obtained from the astrometry), a NS would need to have a temperature (of the X-ray emitting area) of 112 000–126 500 K to obey the X-ray upper limit. The X-ray non-detection of Fomalhaut b is then consistent with being a NS. Indeed, the temperature of 380 000 K is both the upper limit on the temperature of the X-ray emitting region (based on the comparison with RXJ 1856.4−3754, above), and it is also close to the temperature of the optical emitting region of RXJ 1856.4−3754 (see e.g. Kaplan et al. 2011).

In Figs 4 and 5, we show the available photometry and upper limits of the object known as Fomalhaut b, compared to the NSs RXJ 1856.4−3754 (380 000 K) and RXJ 0720.4−3125 (112 000 K) as well as compared to several blackbodies with temperatures of 112 000–126 500 K (for the X-ray emitting area), as well as a typical model atmosphere for 400 K (as should be expected for a planet; Kalas et al. 2008). The blackbodies of 380 000–112 000 K do fit the Fomalhaut b data. For the comparison with RXJ 0720.4−3125, one should keep in mind that Kaplan et al. (2011) showed that a Rayleigh–Jeans tail with a temperature of 112 000 K would not fit the spectrum without an additional power-law component. For RXJ 1856.4−3754, however, there is no evidence for a deviation from a blackbody.

The constraints from optical data and X-ray non-detection are also consistent with an age above $\sim 10^5$ yr as derived from the non-detection of a SN remnant or even $\sim 10^8$ yr as derived from the non-detection of radio pulsations (if beaming towards us). By comparison with RXJ 1856.4−3754 and RXJ 0720.4−3125 (i.e. same temperature and area of the emitting polar caps), Fomalhaut b as NS would be $\sim 10^{5.5}$ yr (or older) as derived from the non-detection of X-rays, but see below.

Let us now also compare the object called Fomalhaut b with NSs other than RXJ 1856.4−3754 and RXJ 0720.4−3125, namely with NSs with smaller and/or hotter emitting areas (polar caps). For example the radio pulsars PSR J0108−1431, PSR B1929+10, and PSR B0950+08 are detected in X-rays at large distance; the existence of radio-silent NS with hot and/or small emitting regions is possible. According to recent X-ray observations with *Chandra* and *XMM*, the relevant parameters are known.

PSR J0108−1431 can be fitted with a blackbody with $kT = 0.28$ keV and an X-ray emitting area of 53^{+32}_{-21} m^2, or a power law with $\gamma = 2$ (Pavlov et al. 2009), it has an age of ∼160 Myr and a distance of ∼210 pc (Taylor & Cordes 1993). Then, using the PIMMS software, we expect 0.045 counts s^{-1} (0.027–0.072 for full 1σ error range) with *ROSAT* PSPC with boron filter (same set-up as used in the observation of Fomalhaut), if such a NS would be at ∼11 pc distance only. This is more than the *ROSAT* PSPC Fomalhaut upper limit being 0.00066 counts s^{-1} (Schmitt 1997). According to Posselt et al. (2012), this NS has an energy of $kT = 0.11$ keV with the radius of the X-ray emitting area being 43 m. Then, we would obtain with PIMMS a *ROSAT* PSPC count rate of 0.0047 counts s^{-1} with boron filter, again at 11 pc, again larger

Table 4. Properties of two isolated NSs. We list both the kinematic age from tracing back the motion of the object to its presumable birth place inside an OB association as well as its characteristic (spin-down) age τ_{ch}, which is to be considered an upper limit to the true age; the kinematic ages fit better with cooling curves than spin-down ages (Tetzlaff et al. 2010).

NS name	X-ray (counts s^{-1})	Ref	Distance (pc)	Ref	Age (Myr) τ_{ch}	Ref	Kin.	Ref	*F606W* (mag)	Ref
RXJ 1856	3.67	Wal96	123^{+15}_{-11}	Wal10	3.8	vKK08	∼0.5	Tet10	25.6	vKK01
RXJ 0720	1.65	Hab97	280^{+210}_{-85}	Eis10	1.9	Kap05	0.7–1.0	Tet11	26.8	Eis10

Notes. Ref: Wal96 – Walter et al. (1996); Wal10 – Walter et al. (2010); vKK08 – van Kerkwijk & Kaplan (2008); vKK01 – van Kerkwijk & Kulkarni (2001); Tet10 – Tetzlaff et al. (2010); Hab97 – Haberl et al. (1997); Eis10 – Eisenbeiss (2010); Kap05 – Kaplan & van Kerkwijk (2005); Tet11 – Tetzlaff et al. (2011).

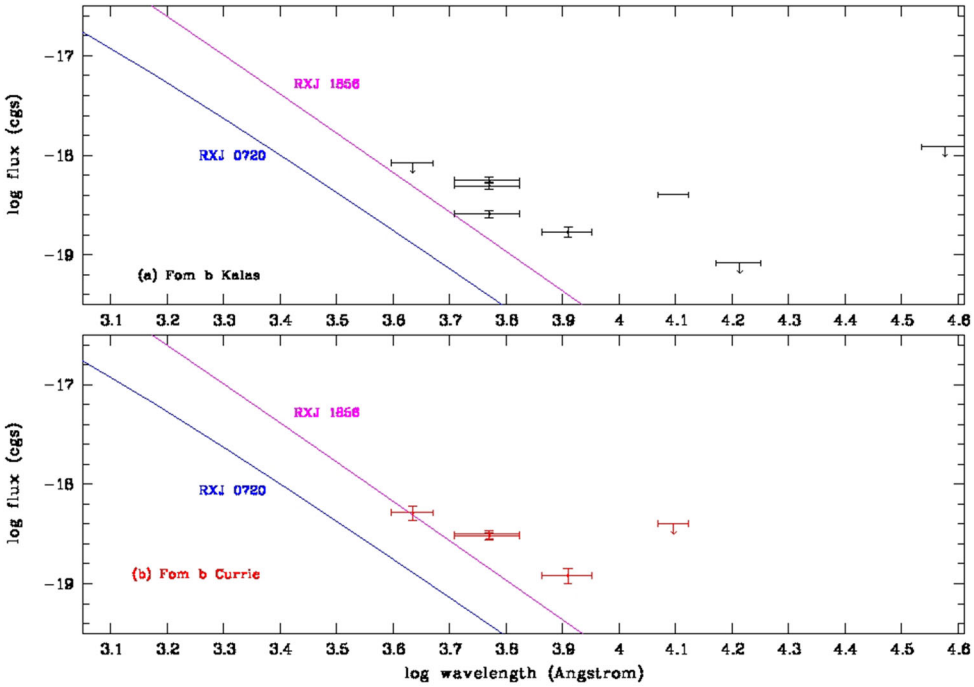

Figure 4. Optical photometry for the object called Fomalhaut b compared to two NSs: (a, top) in black (Kalas et al. 2008) and (b, bottom) in red (Currie et al. 2012) with IR upper limits as arrows (band width indicated), data from Table 1. The optical emission from RXJ 1856.4−3754 can well be fitted with a 380 000 K blackbody, the emission from RXJ 0720.4−3125 is consistent with 112 000 K (both assumed to be unabsorbed); we show their SED (Planck functions for 112 000 and 125 500 K) as pink and blue line, respectively. See also Fig. 5.

than the upper limit. A NS like PSR J0108−1431 would have been detected up to 0.00066 counts s^{-1} up to a distance of 90–120 pc, but is not detected at the position of what is called Fomalhaut b.

PSR B1929+10 is ∼3 Myr old at ∼361 pc distance with hot polar caps (∼0.3 keV or $\sim 3.5 \times 10^6$ K, with a projected emitting area of ∼3000 m for the two X-ray emitting polar caps together, i.e. a radius of the X-ray emitting area of ∼21.5 m each for two circular polar caps), resulting in an X-ray luminosity (or the polar caps) of $\sim 1.7 \times 10^{30}$ erg s^{-1} in the 0.3–10 keV band; see e.g. Misanovic, Pavlov & Garmire (2008) or Slowikowska, Kuiper & Hernsen (2005) as well as references therein. Again using PIMMS, we would expect a *ROSAT* PSPC count rate of 3.47 counts s^{-1} with the boron filter at 11 pc, so that a NS like PSR B1929+10 would be detectable until ∼800 pc at 0.00666 counts s^{-1} (but is not detected at the Fomalhaut b position).

PSR B0950+08 is ∼17 Myr old at ∼262 pc distance with hot polar caps ($kT = 0.086$ keV or $\sim 10^6$ K with ∼250 m radius of the X-ray emitting caps), resulting in an X-ray luminosity of $\sim 3 \times 10^{29}$ erg s^{-1} from the polar caps; see e.g. Zavlin & Pavlov (2004) or Becker et al. (2004) as well as references therein. Again using PIMMS, we would expect a *ROSAT* PSPC count rate of 1.097 counts s^{-1} with the boron filter at 11 pc, so that a NS like PSR B1929+10 would be detectable until ∼450 pc at 0.00666 counts s^{-1} (but is not detected at the Fomalhaut b position).

By comparison with RXJ 1856.4−3754 (X-ray luminosity of 3.8×10^{31} erg s^{-1} at 120 pc; Burwitz et al. 2003), PSR B1929+10 would be detectable at up to five times larger distances than RXJ 1856.4−3754, and PSR B0950+08 would be detectable at up to 11 times larger distances than RXJ 1856.4−3754. PSR J0108−1431, PSR B1929+10, and PSR B0950+08 would have been detectable in X-rays at a distance of only ∼11 pc (best fit for Fomalhaut b) – even given the short exposure time of the *ROSAT* pointing. The astrometry of Fomalhaut b does not exclude larger distances, where those two NSs would also have been detectable.

Hence, if Fomalhaut b as NS would be similar to PSR J0108−1431, PSR B1929+10, or PSR B0950+08 in both temperature and radius of both the X-ray emitting area as well as age, than it would be detectable at 11 pc. Or, putting it another way around, Fomalhaut b as NS would need to be older than the previously given lower limit of $\sim 10^{5.5}$ yr. On the other hand, the available optical photometry of Fomalhaut b allows good fits only for blackbody temperatures (of the optically emitting areas) from 112 000 to 126 500 K, which may be too small for PSR B1929+10 and PSR B0950+08.

If Fomalhaut A is a member of the several hundred Myr (440 ± 40 Myr) old Castor Moving Group (Barrado y Navascues 1998), it might well be possible that Fomalhaut b as NS (and/or its progenitor) also belongs to this Moving Group – given that Fomalhaut b (even as NS) and Fomalhaut A have a similar proper motion (as most members of Moving Group have a similar proper motion).

The Castor Moving Group has 26 known members (plus the two stellar companions to Fomalhaut A, being Fomalhaut B and C with K4 and M6) with at least eight A-type stars, four stars with A0-2 (Barrado y Navascues 1998), so that it is not impossible that there was originally also one early B-type star in this group (the progenitor of Fomalhaut b as NS): we have converted the known spectral types of the Castor Moving Group members (Barrado y Navascues 1998; Mamajek 2012; Mamajek et al. 2013) to main-sequence masses to investigate the present mass function; extrapolating from the bin with the largest masses (a bin with stars above 1 $M_\odot$) by using the exponent $N \simeq 2.7 \pm 0.7$ from the Kroupa, Tout & Gilmore (1993) initial mass function to even larger masses, we can estimate the expectation number for core-collapse SN progenitors (with at least

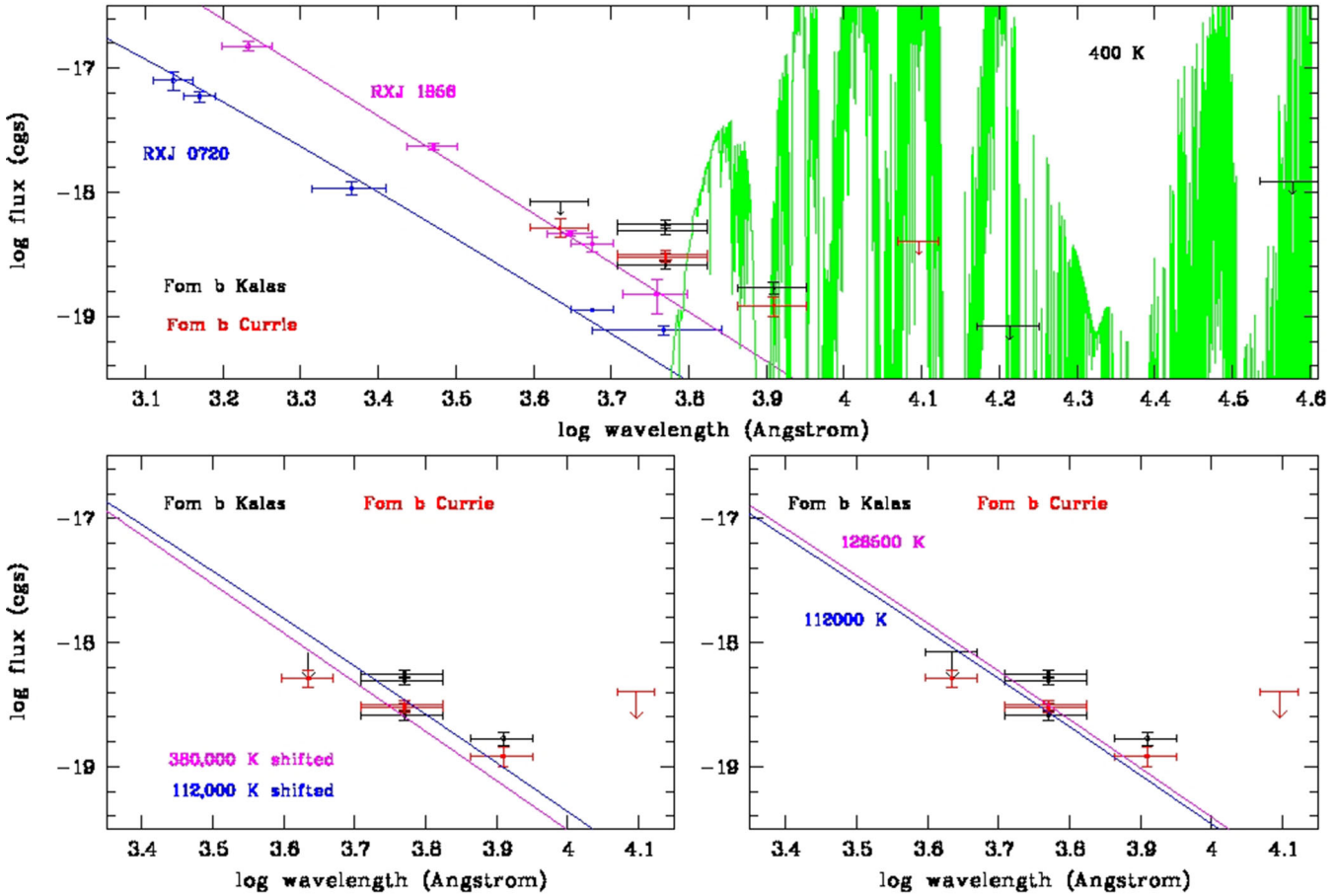

Figure 5. Fomalhaut b photometry compared to typical hot NSs and a typical cold planet. The available optical photometry for the object called Fomalhaut b in red (Currie et al. 2012) and black (Kalas et al. 2008) with IR upper limits as arrows (bandwidth indicated), data from Table 1, as also plotted in Fig. 4. We also show the optical data points for the two well-known isolated middle-aged NSs RXJ 1856.4−3754 and RXJ 0720.4−3125 in pink and blue, respectively (data from Table 2). The optical emission from RXJ 1856.4−3754 can well be fitted with a 380 000 K blackbody, the emission from RXJ 0720.4−3125 is consistent with 112 000 K (both assumed to be unabsorbed). The model atmosphere for 400 K in green (here from AMES COND for $\log g = 4.0$ (Chabrier et al. 2000; Allard et al. 2001) for a few hundred Myr planet, from phoenix.ens-lyon.fr/Grids/AMES-Cond/SPECTRA, as an example (similar for other models), scaled in *y*-axis as far down as possible to still fit the optical data points does not fit the Fomalhaut b data as known before – it is inconsistent with the IR non-detection. We show all data in the upper panel and then again (for clarity) in the lower panels the Fomalhaut b data with Planck functions for 380 000 and 112 000 K (bottom left) and with Planck functions for 112 000 and 125 500 K (bottom right), which do fit (fits with 17 km radius as RXJ 1856.4−3754). The *y*-axis (flux) ranges are identical, the *x*-axis (wavelength) ranges differ slightly.

8 $M_\odot$) in the Castor Moving Group to be $0.2^{+0.6}_{-0.4}$ within 2σ error bars. Hence, it may appear unlikely, but possible.

If the progenitor of Fomalhaut b as NS would indeed have been a member of the Castor Moving Group, then Fomalhaut b as NS would now have an age only slightly below the age of the Castor Moving Group (given the short lifetime of its progenitor), so that it would have an age of a few hundred Myr. Such an age is fully consistent with the cooling curves of NSs given its brightness in the optical and its non-detection in the X-rays. [The proper motion of the two presumable stellar companions Fomalhaut B and C being comoving with Fomalhaut A can be interpreted either that they form a triple stellar system (with undetected orbital motion around the common centre-of-mass) or that all three stars are (independent) members of the same Moving Group.] The proper motion of Fomalhaut A and b would be equivalent to a tangential (2D) velocity of $\sim$30 km s^{-1} for $\sim$11 pc distance, which is a low, but a possible velocity for a NS. The unknown radial velocity has to be added. Only if Fomalhaut b (as NS) got a very small kick in its SN, then its velocity can now still be similar to the velocity of the progenitor star, i.e. the typical Castor velocity; a small velocity would be consistent with a small SN kick.

We would like to stress that, for our interpretation of Fomalhaut b as NS, it is not essential that it would be a member of the Castor Moving Group.

At an age of 440 ± 40 Myr (or, say, hundreds of Myr), detections of radioisotopes on the Earth due to the very nearby SN explosion are also very difficult: At the proper motion and current distance of the Fomalhaut companion candidate, it would have moved $\sim$16 kpc in 440 Myr (the space velocity used considers only the known 2D motion, not its unknown radial velocity); it would have orbited the Galactic Centre almost twice, so that it is not possible to constrain well the location of the SN; hence, it is also completely unknown, whether the SN took place within a few tens or hundreds of pc around the Earth. Also, Firestone (2014) had to restrict their study to SNe (in radioisotopes) within the last 300 kyr given also the half-life and measurement precision of relevant radionuclides.

Could Fomalhaut b as NS be just $\sim$2 Myr young ? It is at least $\sim$10 times closer than RXJ 0720.4−3125 (at $\sim$280 pc; Eisenbeiss

2010), so that it would be expected to be at least ∼100 times brighter, if at the same age (∼1 Myr, Table 2) and with the same temperature of the emitting area (Figs 4 and 5), and radius (∼17 km; Eisenbeiss 2010). In fact, it is only ∼3 times brighter in the optical than RXJ 0720.4−3125 (∼1 Myr, Tables 1, 2, and 4). If Fomalhaut b as NS would be 2–3 times smaller than RXJ 0720.4−3125, it would be 4–9 times fainter. The remaining factor could easily be obtained by a slightly different temperature of the emitting area (luminosity scaling with the forth power of the temperature), even if at the same radius; also, cooling tracks at that age are highly uncertain. Hence, from these considerations, Fomalhaut b as NS could be as young as ∼2 Myr.

If Fomalhaut b as NS would be as young as ∼2 Myr, it would have moved ∼61 pc since 2 Myr (the space velocity used considers only the known 2D motion, not its unknown radial velocity). Given its current distance of ∼11 pc (best fit), it had a distance of somewhere with ∼72 pc at birth (i.e. still inside the Local Bubble). A SN that close might have left some effect on the Earth, e.g. a ^{60}Fe signal, such as the one detected at an age of 2 Myr under the Earth ocean crust (Knie et al. 1999; Fields 2004; Bishop et al. 2013). We conclude that, for certain parameter combinations, Fomalhaut b as NS could be 2 Myr young and could be the NS that was born in the nearby SN that left ^{60}Fe on the Earth. However, this is speculative. The true age could be constrained with e.g. an X-ray detection.

If Fomalhaut b as compact, non-planetary object would not have the typical NS radius, nor the same radius as the NSs RXJ 1856.4−3754 or RXJ 0720.4−3125, to which we compared it, but a different radius, also a different distance estimate would apply. Theoretical considerations show that a NS cannot be much larger than RXJ 1856.4−3754 (17 ± 3 km; Trümper et al. 2004; Walter et al. 2010). However, some equations-of-state predict smaller radii such as half the radius, namely for strange (quark) stars. Our considerations above hold in a similar way for both normal NSs and strange stars, with one exception: if strange stars are half a large as normal NSs, then the allowed distance range for Fomalhaut b as strange star would need to be accordingly smaller by a factor of $\sqrt{2}$.

For similar temperatures (of both the X-ray and optical emitting areas), the radius of the emitting area cannot be smaller by more than a factor of 5 than in RXJ 1856.4−3754: a somewhat larger distance of, say, 20 pc – divided by the $\sqrt{5}$ – gives 8 pc, the lowest allowed distance (at or just behind Fomalhaut A).

If Fomalhaut b would be a NS or a strange star, we would not expect photometric variability (except maybe pulsations), and we would not expect the object to be resolved/extended.

3.2.5 *Probability considerations*

From the age of the Galaxy and the core-collapse SN rate of a few events per century (Tammann, Löffler & Schröder 1994), as well as from several other considerations (metallicity of the ISM, pulsar birth rates, ^{26}Al content, etc.), $\sim 10^8$ NSs should have been produced in our Galaxy so far. Of course, only the hottest (i.e. youngest) ones can be detected in the optical: for the bright isolated NS RXJ 1856.4−3754, the optical emission and size indicate a surface temperature (of the optical emitting area) of a few 10^5 K (Trümper 2003; Trümper et al. 2004; Walter et al. 2010). According to several sets of NS cooling curves, and depending on assumption about their interior and their mass (see e.g. cooling curves in Aguilera et al. 2008; Page et al. 2009), NSs with that temperature (of the optical emitting area) might be sufficiently hot and, hence, detectable in the optical (like RXJ 1856.4−3754), until an age of $\sim 10^6$ yr (or a few times $\sim 10^6$ yr). For a constant NS formation rate since $\sim 1.4 \times 10^9$ yr (the age of the Galaxy), there should then be some ∼72 000 detectable (young, hot) NS. Given the velocity distribution of NSs, many of them can leave the Galaxy, but the young ones that we consider here could not leave it, yet. Given their high velocities, NSs are not restricted to the Galactic plane; if they would be distributed uniformly on the sky (4π sr = 41 253 deg^2), then we would expect ∼1.75 detectable NS per deg^2.

To get a rough estimate of the area that was covered by instruments capable of detecting Fomalhaut b, we used the *HST* archived exposure catalogue (provided by Space Telescope Science Institute, STScI, in 2007). This is a sensible approach, since Fomalhaut b has so far only been detected with the *HST*, only in the optical, and the majority of the *HST* measurements of Fomalhaut b including the discovery epoch were taken before 2007. From the catalogue, we extracted all imaging exposures which were taken in bands with a central wavelength shorter than 1 μm and with longer exposure times than 1000 s, i.e. exposures in which objects as faint as Fomalhaut b should have been detected. After removal of duplicate exposures (i.e. exposures with a separation of less than 1 arcmin), we found 862 exposures with ACS/HRC, 2216 exposures with ACS/WFC, and 2900 exposures with Wide Field and Planetary Camera 2 (WFPC2) matching our criteria. Given the fields of view of these instruments, these exposures cover a total area of 11.65 deg^2 on the sky. Thus, ∼20 NSs could be contained in this area. A few well-known middle-aged NSs are indeed optically detected by *HST* (like RXJ 1856.4−3754 and the other the so-called Magnificent Seven NSs; see review in Haberl 2007), namely in deep exposures, some of them at high galactic latitude.

If we restrict this estimate to the Galactic plane ($|b| \leq 20^\circ$), where almost all stars (and most NSs) are located (we deal here with a potential NS in the background to a star with small apparent separation to that star), then we are left with only 1.64 deg^2, so that we would expect ∼3 detectable NSs. Therefore, it is not unlikely to discover a previously unknown NS in one or a few of these exposures.

If we would restrict the estimate to a small area on the sky around a bright nearby star (like Fomalhaut A), we can arrive at a different estimate: Fomalhaut b is some 13 arcsec off Fomalhaut A, so that a circle with 13 arcsec radius is relevant here for a background probability estimate. The probability to find any one of ∼72 000 detectable NSs (as given above) within 13 arcsec around one particular star (on the whole sky) is then only $\sim 7 \times 10^{-3}$. However, several thousand different young and/or nearby stars were surveyed with deep exposures for planetary companions by direct imaging, e.g. the directly imaged planet candidate (or brown dwarf) companion near GQ Lup was first detected in 1999 by the *HST* in an optical imaging snapshot programme (Neuhäuser et al. 2005). Then, the expectation number of background (or foreground) NSs within 13 arcsec around any one of several thousand stars (say 5000 stars) is ∼0.35. This estimate is not significantly different from one object found.

Hence, probability estimates show that it is not very unlikely to find one unrelated object (or even a NS) with deep imaging in the background (or foreground) of one of the surveyed stars.

Above, we have estimated the probability for young, self-luminous NSs only. It is also possible that older NSs get reheated due to Bondi–Hoyle accretion of interstellar material (e.g. Madau & Blaes 1993). However, it may well be that reheating of old NSs is not important, because otherwise many more such reheated NSs should have been detected by e.g. the *ROSAT* All-Sky Survey and other X-ray missions (see e.g. Neuhäuser & Trümper 1999) – such

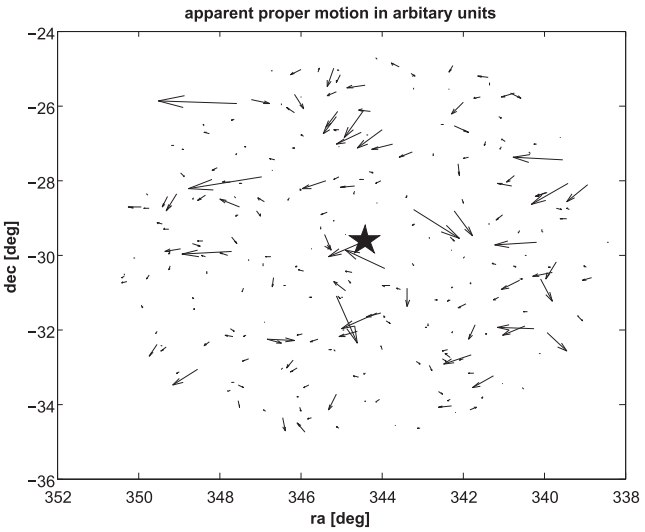

Figure 6. Proper motion (scaled to arbitrary units) of Fomalhaut's neighbouring stars according to the SIMBAD data base. Fomalhaut is marked by the black solid star in the centre.

old accreting NSs were not detected (in particular not in large numbers) probably due to both higher space velocities v (Bondi–Hoyle accretion scales with v^{-3}) and larger magnetic fields (propeller effect) than assumed in Madau & Blaes (1993). On the other hand, with PSR J0108−1431 at ∼160 Myr, there also exists an example of a relatively old NS which is still quite hot – probably due to internal reheating (Tauris et al. 1994; Pavlov et al. 2009; Posselt et al. 2012). If we would add those NSs in our probability estimate, the probability for finding one NS would increase.

Fomalhaut b is not only located close to a bright star (Fomalhaut A), but it also moves with a similar proper motion. We checked the proper motions of all stars (projected) near Fomalhaut, where this quantity is measured, see Fig. 6. Many stars move from north-east to south-west (including Fomalhaut), suggesting a preferred direction of motion of stars in this field. Therefore, an apparently comoving object located a few parsec behind Fomalhaut (in the same Galactic spiral arm) is well possible.

3.2.6 Gamma-ray detection?

Before we conclude let us also check whether the object might have been detected by some γ-ray detector. We have cross-correlated the position of Fomalhaut b with all sources from Burst and Transient Source Experiment (BATSE) and *Fermi*.

We found two positive possible correlations.

Fomalhaut b is located in the positional error ellipse of a BATSE γ-ray burst (GRB) source, namely 0.°34 off the BATSE source 11591a at 2000-02-17T06:54:21, which has a large positional error of 9.°4 and a very low flux of 0.106 photons cm^{-2} s^{-1} (Stern et al. 2001).

Fomalhaut b is also located 0.°96 off the BATSE source named 951022.99 inside its large positional error ellipse (11.°3); this source did not even lead to a follow-up trigger (Kommers et al. 2001).

Given the large error bars of these two BATSE γ-sources, it is unlikely that Fomalhaut b is related to any of them.

Then, we have retrieved the *Fermi* Large Area Telescope (LAT) data ourselves to search for a source near Fomalhaut. We used the data up to 15° around Fomalhaut with a resolution of 0.°1 pixel^{-1} in the energy range from 100 to 300 000 MeV. We detected only the two known sources 2FGL J2258.9−2759 (separation 97.8 arcmin) and 2FGL J2250.8−2808 (separation 126.5 arcmin) near Fomalhaut. Then, we have subtracted those sources from the data, to search again for a faint remaining source, but we could not detect anything near Fomalhaut.

There is no *Fermi* source or even *Fermi* pulsar anywhere near Fomalhaut b.

4 CONCLUSIONS

The faint object near Fomalhaut A (called Fomalhaut b) remains the subject of intense discussion. If one assumes that Fomalhaut b is gravitationally bound to Fomalhaut A, then the most likely hypothesis seems to be an expanding dust cloud without a central source of $\geq$10 M$_\oplus$. We show that the body of observations (optical photometry, proper motion, X-ray non-detection) can in principle be fit with a NS. In particular, we can explain the SED in the optical wavelength range and the non-detections in the near- and mid-IR: The available photometry allows good fits for a blackbody with temperature range from 112 000 to 126 500 K (of the optical emitting area) – for a NS, this temperature range would yield a distance of ∼11 pc to remain undetected in X-rays as observed. While this may appear to be a fine-tuned parameter range, one should also keep in mind that such parameters are consistent with *all* observables, while the planetary interpretation has problems with two observational issues (ring-crossing orbit and non-detection in IR).

We also show that it is not unlikely to find one such faint, but unrelated object (or even one of ∼10^8 Galactic NSs) near one of the many bright stars surveyed with deep imaging for planets. If Fomalhaut b is a NS rather than a planet, then the eccentricity of the dust ring around Fomalhaut A might be explained by either one or more lower mass, as yet undetected planet(s) or possibly by an eccentric stellar companion.

Given our rough distance estimate for Fomalhaut b as NS, it might also be possible that Fomalhaut b is both a NS and a companion in the Fomalhaut system (∼8 pc), i.e. that they orbit around each other – Fomalhaut b as NS currently located some tens to hundreds of au behind (or before) Fomalhaut A. It should be less problematic for a NS component to orbit on an eccentric and/or inclined orbit (than for a planetary companion). In such a case, one might expect Bondi–Hoyle accretion of circumstellar material on to the NS and, hence, variable brightness, but such a variable brightness would be hard to detect for an object as faint as ∼25 mag with large error bars (see Table 1 and Figs 4 and 5).

If the companion candidate to Fomalhaut is indeed a NS at some 11 pc distance, it would be the closest known NS. With a total of some 10^8 NSs in the Galaxy (∼30 kpc diameter, ∼0.6 kpc thickness), we would expect ∼2.2 NSs between 8 and 14 pc (i.e. ±3 pc around the best fit, the lower value being the lowest allowed distance). We may have noticed one of them. If we would restrict this estimate to young (self-luminous) NSs, the expected number would be smaller. If the companion candidate to Fomalhaut is indeed a NS, then it may either be an exception (as self-luminous very nearby NS) – or it may be an old NS reheated by accretion from the interstellar material. For the latter, this NS would need to travel with small velocity v through the interstellar material (Bondi–Hoyle accretion scales with v^{-3}), which is indeed the case: ∼30 km s^{-1} only as 2D velocity from its proper motion at ∼11 pc, respectively, which is slow for NSs.

Our NS hypothesis could be tested by observations in the UV (e.g. with the ACS Solar Blind Camera): if the object is detected and shows a similar flat SED as in the optical, then a planet or dust

cloud be ruled out and a background NS becomes the most likely explanation. If radio, X-ray, or γ-ray pulsations (in the typical range as for NSs, i.e. few ms to $\sim$20 s) could be detected in the Fomalhaut companion candidate in very deep observations, it would certainly be a NS (we would expect pulsations around $\sim$1–$\sim$10 s, rather than below 1 s, because it would need to be a middle-aged to old NS). An X-ray detection would also yield a more stringent constraint on the age. A detection of gravitational waves due to rotation of a non-spherical object would confirm its compactness.

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REFERENCES

Acke B. et al., 2012, A&A, 540, A125
Aguilera D. N., Pons J. A., Miralles J. A., 2008, A&A, 486, 255
Allard F., Hauschildt P. H., Alexander D. R., Tamanai A., Schweitzer A., 2001, ApJ, 556, 357
Baraffe I., Chabrier G., Barman T. S., Allard F., Hauschildt P. H., 2003, A&A, 402, 701
Barrado y Navascues D., 1998, A&A, 339, 831
Becker W., Weisskopf M. C., Tennant A. F., Jessner A., Dykes J., Harding A. K., Zhang S. N., 2004, ApJ, 615, 908
Bishop S. et al., 2013, APS Abstr., XB.00002
Boley A. C., Payne M. J., Corder S., Dent W. R. F., Ford E. B., Shabram M., 2012, ApJ, 750, L21
Burrows A., Sudarsky D., Lunine J. I., 2003, ApJ, 596, 587
Burwitz V., Haberl F., Neuhäuser R., Predehl P., Trümper J., Zavlin V. E., 2003, A&A, 399, 1109
Busser J. U., 1998, PhD thesis, Univ. Munich
Caraveo P. A., De Luca A., Mignani R. P., Bignami G. F., 2001, ApJ, 561, 903
Chabrier G., Baraffe I., Allard F., Hauschildt P., 2000, ApJ, 542, 464
Chiang E., Kite E., Kalas P., Graham J. R., Clampin M., 2009, ApJ, 683, 734
Currie T. et al., 2012, ApJ, 760, L32
Dodson R. G., McCulloch P. M., Lewis D. R., 2002, ApJ, 564, L85
Dodson R., Legge D., Reynolds J. E., McCulloch P. M., 2003, ApJ, 596, 1137
Ducati J. R., 2002, Catalogue of Stellar Photometry in Johnson's 11-Color System, CDS/ADC Collection of Electronic Catalogues, 2237 (http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=II/237)
Eisenbeiss T., 2010, PhD thesis, Univ. Jena
Fields B. D., 2004, New Astron., 48, 119
Firestone R. B., 2014, ApJ, 789, 29
Fitzpatrick E. L., Massa D., 2007, ApJ, 663, 320
Ford H. C. et al., 1998, in Bely P. Y., Breckinridge J. B., eds, Proc. SPIE Vol. 3356, Space Telescopes and Instruments V. SPIE, Bellingham, p. 234
Fortney J. J., Marley M. S., Saumon D., Lodders K., 2008, ApJ, 683, 1104
Galicher R., Marois C., Zuckerman B., Macintosh B., 2013, ApJ, 769, 42
Gray R. O., Corbally C. J., Garrison R. F., McFadden M. T., Bubar E. J., McGahee C. E., O'Donoghue A. A., Knox E. R., 2006, AJ, 132, 161
Green D. A., 2009, Bull. Astron. Soc. India, 37, 45
Haberl F., 2007, Ap&SS, 308, 181
Haberl F., Motch C., Buckley D. A. H., Zickgraf F. J., Pietsch W., 1997, A&A, 326, 662
Hobbs G., Lorimer D. R., Lyne A. G., Kramer M., 2005, MNRAS, 360, 974
Janson M., Carson J. C., Lafrenire D., Spiegel D. S., Bent J. R., Wong P., 2012, ApJ, 747, 116
Kalas P. et al., 2008, Science, 322, 1345
Kalas P., Graham J. R., Fitzgerald M. P., Clampin M., 2013, ApJ, 775, 56
Kaplan D. L., van Kerkwijk M. H., 2005, ApJ, 635, L65
Kaplan D. L., Kamble A., van Kerkwijk M. H., Ho W. C. G., 2011, ApJ, 736, 117
Kennedy G. M., Wyatt M. C., 2011, MNRAS, 412, 2137
Kenworthy M. A., Meshkat T., Quanz S. P., Girard J. H., Meyer M. R., Kasper M., 2013, ApJ, 764, 7
Knie K., Korschinek G., Faestermann T., Wallner C., Schotten J., Hillenbrandt W., 1999, Phys. Rev. Lett., 83, 18
Kommers J. M., Lwin W. H. G., Kouveliotou C., van Paradijs J., Pendleton G. N., Meegan C. A., Fishman G. J., 2001, ApJS, 134, 385
Kroupa P., Tout C. A., Gilmore G., 1993, MNRAS, 262, 545
Kunitzsch P., Smart T., 1986, Short Guide to Modern Star Names and Their Derivations. Otto Harrassowitz, Wiesbaden
Löhne T. et al., 2012a, A&A, 537, A110
Löhne T. et al., 2012b, Astron. Nachr., 333, 441
Madau P., Blaes P., 1993, ApJ, 403, 690
Majaess D. J., Turner D. G., Lane D. J., 2009, MNRAS, 398, 263
Mamajek E. E., 2012, ApJ, 754, L20
Mamajek E. E. et al., 2013, AJ, 146, 154
Marengo M., Stapelfeldt K., Werner M. W., Hora J. L., Fazio G. G., Schuster M. T., Carson J. C., Megeath S. T., 2009, ApJ, 700, 1647
Mereghetti S., Sartore N., Tiengo A., De Luca A., Turolla R., Haberl F., 2012, in Lewandowski W., Maron O., Kijak J., eds, ASP Conf. Ser. Vol. 466, Electromagnetic Radiation from Pulsars and Magnetars. Astron. Soc. Pac., San Francisco, p. 33
Miller R., Austin G., Koch D., Jagoda N., Kirchner T., Dias R., 1978, IEEE Trans. Nucl. Sci., 25, 422
Misanovic Z., Pavlov G. G., Garmire G. P., 2008, ApJ, 685, 1129
Neuhäuser R., Trümper J., 1999, A&A, 343, 151
Neuhäuser R., Guenther E. W., Wuchterl G., Mugrauer M., Bedalov A., Hauschildt P. H., 2005, A&A, 435, L13
Oppenheimer B. R., Hambly N. C., Digby A. P., Hodgkin S. T., Saumon D., 2001, Science, 292, 698
Page D., Lattimer J. M., Prakash M., Steiner A. W., 2009, ApJ, 707, 1131
Pavlov G. G., Kargaltsev O., Wang J. A., Garmire G. P., 2009, ApJ, 691, 458
Posselt B., Arumugasamy P., Pavlov G. G., Manchester R. N., Shannon R. M., Kargaltsev O., 2012, ApJ, 761, 117
Schaudel D., Becker W., Voges W., Aschanbach B., Reich W., Weisskopf M., 2002, in Slane P. O., Gaensler B. M., eds, ASP Conf. Ser. Vol. 271, Neutron Stars in Supernova Remnants. Astron. Soc. Pac., San Francisco, p. 391
Schmitt J. H. M. M., 1997, A&A, 318, 215
Schröder C., Schmitt J. H. M. M., 2007, A&A, 475, 677
Slowikowska A., Kuiper L., Hernsen W., 2005, A&A, 434, 1097
Spiegel D. S., Burrows A., 2012, ApJ, 745, 174
Stern B. E., Tikhomirova Y., Kompaneets D., Svensson R., Poutanen J., 2001, ApJ, 563, 80
Tammann G. A., Löffler W., Schröder A., 1994, ApJS, 92, 487
Tauris T. M. et al., 1994, ApJ, 428, L53
Taylor J. H., Cordes J. M., 1993, ApJ, 411, 674
Tetzlaff N., Neuhäuser R., Hohle M. M., Maciejewski G., 2010, MNRAS, 402, 2369
Tetzlaff N., Eisenbeiss T., Neuhäuser R., Hohle M. M., 2011, MNRAS, 417, 617
Trümper J., 1983, Adv. Space Res., 2, 241

Trümper J., 2003, in van den Heuvel E. P., Kaper L., Rol E., Wijers R. A. M. J., eds, ASP Conf. Ser. Vol. 308, From X-ray Binaries to Gamma-Ray Bursts: Jan van Paradijs Memorial Symposium. Astron. Soc. Pac., San Francisco, p. 183
Trümper J., Burwitz V., Haberl F., Zavlin V. E., 2004, Nucl. Phys. B Proc. Suppl., 132, 560
van Kerkwijk M. H., Kaplan D. L., 2008, ApJ, 673, L163
van Kerkwijk M. H., Kulkarni S. R., 2001, A&A, 378, 986
van Leeuwen F., 2007, A&A, 474, 653
Walter F. M., Wolk S. J., Neuhäuser R., 1996, Nature, 379, 233
Walter F. M., Eisenbeiss T., Lattimer J. M., Kim B., Hambaryan V., Neuhäuser R., 2010, ApJ, 724, 669
Wood M. A., Oswald T. D., 1998, ApJ, 497, 870
Woodgate B. E. et al., 1998, PASP, 110, 1183
Zavlin V. E., Pavlov G. G., 2004, ApJ, 616, 452

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