HERSCHEL AND SPITZER OBSERVATIONS OF SLOWLY ROTATING, NEARBY ISOLATED NEUTRON STARS

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ABSTRACT

Supernova fallback disks around neutron stars have been suspected to influence the evolution of the diverse neutron star populations. Slowly rotating neutron stars are the most promising places to find such disks. Searching for the cold and warm debris of old fallback disks, we carried out Herschel PACS (70 μm, 160 μm) and Spitzer IRAC (3.6 μm, 4.5 μm) observations of eight slowly rotating (P ≈ 3–11 s) nearby (<1 kpc) isolated neutron stars. Herschel detected 160 μm emission (>5σ) at locations consistent with the positions of the neutron stars RX J0806.4–4123 and RX J2143.0+0654. No other significant infrared emission was detected from the eight neutron stars. We estimate probabilities of 63%, 33%, and 3% that, respectively, none, one, or both Herschel PACS 160 μm detections are unrelated excess sources due to background source confusion or an interstellar cirrus. If the 160 μm emission is indeed related to cold (10–22 K) dust around the neutron stars, this dust is absorbing and re-emitting ~10% to ~20% of the neutron stars’ X-rays. Such high efficiencies would be at least three orders of magnitude larger than the efficiencies of debris disks around nondegenerate stars. While thin dusty disks around the neutron stars can be excluded as counterparts of the 160 μm emission, dusty asteroid belts constitute a viable option.

Key words: pulsars: individual (RX J0420.0–5022, RXJ0720.4–3125, RXJ0806.4–4123, RXJ1308.6+2127, RXJ1605.3+3249, RXJ1856.5–3754, PSRJ1848-1952, RXJ2143.0+0654) – stars: neutron

Online-only material: color figures

1. INTRODUCTION

During the last decade, sensitive X-ray observations have revealed a rather surprising diversity of neutron stars (NSs); for a review see, e.g., Kaspi (2010). While most of the currently known ∼2000 NSs are rotation-powered radio pulsars, there are also rotating radio transients, central compact objects (CCOs) in supernova remnants, X-ray thermal isolated NSs (XTINSs), and magnetars. The group of magnetars, consisting of the Anomalous X-ray Pulsars (AXPs) and the Soft Gamma-ray Repeater (SGRs), posed particular challenges to the simplistic NS model as a rotating magnetic dipole that converts rotational energy into electromagnetic pulsar emission. Magnetar quiescent emission and the occasionally observed huge magnetar flares require an additional energy source. The prevailing model for magnetars is that of young, isolated NSs powered by the decay of very high magnetic fields. These recent results imply that fallback disks currently cannot be excluded as crucial ingredients in the NS evolution. In fact, such disks are a general prediction of supernova models (Michel & Dessler 1981; Chevalier 1989); however, observationally, they have remained rather elusive; for a review about searches for disks around NSs, see Wang (2014). There is so far only one example of a likely fallback disk around the 3.9 kpc distant AXP 4U 0142+61, detected with Spitzer IRAC (Wang et al. 2006; Ertan & Çaliskan 2007). According to Eksi & Alpar (2005), fallback disks are expected to be rare because they are likely to be disrupted when the newly born NS spins rapidly through the propeller stage, at which inflowing matter would be expelled instead of being accreted. The fallback disks can survive if the initial NS spin is slow enough (P0 ⩾ 40 ms at a magnetic moment of μ = 1030 G cm3). The presence of disks around highly magnetized NSs today is therefore, in principle, related to the initial birth parameters of these NSs, in particular, to the origin of the strong fields in highly magnetized NSs. It is important to obtain more comprehensive observational constraints on the presence of supernova fallback disks around the different NS classes. Slowly rotating NSs, such as the magnetars and the XTINSs, appear to be the most promising to find such disks.

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2. SAMPLE SELECTION AND WORKING HYPOTHESES

In the framework of the fallback disk model, Alpar (2001, 2007) suggested that different initial disk masses lead to the different NS classes. In this picture, magnetars are expected to have the most massive disks, followed by those of the XTINSs, while rotation-powered radio pulsars have negligible or no disks. Trümper et al. (2010) suggested that XTINSs may be more evolved versions of AXPs with fallback disks. It is interesting to note that in the \( P - \dot{P} \) diagram the XTINSs are located together with a few high-\( B \) pulsars between the separated groups of magnetars and radio pulsars (see, e.g., Figure 2 in Kaspi 2010). Thus, these NSs may constitute a key population to unify the different NS classes.

Of the 26 currently known magnetars and magnetar candidates, only 5 have been investigated at infrared wavelengths (Olausen & Kaspi 2013). Apart from the detections of AXPs 4U 0142+61 (Wang et al. 2006) and 1E 2259+586 (Kaplan et al. 2009), the shallow mid-IR \textit{Spitzer} searches of three other magnetars were not very constraining (Wang et al. 2007b). It is difficult to constrain the disk emission around magnetars because most of these NSs are far away. The median distance of magnetars with known distances is 8.5 kpc (Olausen & Kaspi 2013).\(^4\) The XTINSs, however, are all expected to be within 1 kpc based on parallaxes and the interstellar absorption of their soft X-ray spectra (e.g., Kaplan et al. 2009; Posselt et al. 2007). Such distances enable constraining searches for fallback disks for the whole known XTINS population. We selected all known slowly rotating (\( P > 3 \) s) NSs within 1 kpc. Our sample includes all seven known XTINSs and the nearby high-\( B \) radio pulsar PSR J1848–1952, which has similar spin-down properties (e.g., Kaplan et al. 2009).

In the framework of the fallback disk model, potential XTINS disks likely have smaller masses than magnetar disks, are likely older than them, and are likely passive, i.e., without significant ongoing accretion on the NS. The latter property can be concluded from the very stable X-ray emission of the XTINSs with the notable exception of RX J0720.4–3125 (e.g., Haberl 2007; van Kerkwijk et al. 2007; Hohle et al. 2012).

The composition and evolution of fallback disks are unknown. Dust grain evolution was shown to decouple from gas evolution in nearby all (protoplanetary) disk configurations if the initial dust-to-gas ratio is larger than 0.03 (Pinte & Laibe 2014). Given the supernova origin, one can reasonably assume metal-rich disk material, i.e., a decoupled dust evolution in the disk. Gas is easier removed from the disks than dust grains by the pulsar wind and the interstellar ram pressure. We will therefore assume dust-rich disks as a working hypothesis for potential residual XTINS fallback disks. In comparison to other stars, the potential XTINS disks may more likely resemble transitional or debris disks—such as those around main-sequence stars (e.g., Wyatt 2008, and references therein), central stars in planetary nebulae (e.g., Su et al. 2007), or white dwarfs (e.g., Debes et al. 2012, and references therein)—than protostellar/protoplanetary disks around young stars.

3. OBSERVATIONS

3.1. Herschel Observations

\textit{Herschel} observations of eight isolated NSs were carried out over a period of \( \sim 1 \) yr using the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010). We obtained the images in mini-map mode in the blue (60–85 \( \mu \)m) and red (130–210 \( \mu \)m) bands with the respective PACS bolometer arrays operated in parallel. The mini-map mode is a particular case of the scan-map mode, where two observations (scan and cross-scan) are carried out that have scan angles in array coordinates along the two array diagonal directions, 70° and 110°. An individual scan-map observation has a pattern of parallel, overlapping scan lines connected by turnaround loops. The mini-map mode provides a good point-source sensitivity with a relatively large homogeneous coverage (about 50° in diameter).\(^5\) Our observations were performed with medium scan speed (20° s\(^{-1}\)), and the mapping parameters were 10 scan legs with scan lengths of 3′ with a separation of 4′′ between them. A repetition factor of 12 was chosen to reach point-source sensitivities close to the expected confusion noise (for a details about the confusion noise in the PACS bands and its estimation, see, e.g., the Herschel Observers’ Manual,\(^6\) Chapter 4.3, and the HERSCHEL-HSC-DOC-08867 document by C. Kiss). Our observations are listed in Table 1. Overall, each Astronomical Observation Request (AOR) was 7 ks. The beam sizes FWHM of the blue and red band at medium speed are 5′.5 × 5′.8 and 10′.5 × 12′.0, respectively (Poglitsch et al. 2010).

3.2. \textit{Spitzer} Observations

We observed RX J0720.4–3125 with the \textit{Spitzer Space Telescope}\(^7\) (Werner et al. 2004) during the post-cryogenic mission in 2011 January (PI: Posselt). The observations were done with the Infrared Array Camera (IRAC; Fazio et al. 2004) at 3.6 \( \mu \)m and 4.5 \( \mu \)m. We used a frame time of 100 s and 31 dither positions in each band. We also consider here some of the NS observations of another \textit{Spitzer} program (PI: Wachter), which searched for fallback disks around a large number of nearby pulsars using the IRAC 4.5 \( \mu \)m channel. Those observations were performed from 2011 September to 2012 December. In each observation, a 100 s frame time and 30 dither positions were used. The \textit{Spitzer} observations discussed in this paper are listed in Table 2. The IRAC field of view is 5′.2 × 5′.2, the native IRAC pixel size is 1′′2, and the FWHM of the point-spread function at 3.6 \( \mu \)m and 4.5 \( \mu \)m is 1′′66 and 1′′72, respectively (Fazio et al. 2004).

\begin{table}[h]
\centering
\begin{tabular}{llll}
\hline
Object & Date & ObsIDs & PointAcca \\
\hline
RX J0420.0–5022 & 2012 Jan 7 & 1342236938 & 1′1 \\
RX J0720.4–3125 & 2011 Nov 10 & 1342232218/9 & 1′1 \\
RX J0806.4–4123 & 2011 Oct 29 & 1342231572/3 & 1′1 \\
RX J1138.6+2127 & 2011 Jul 11 & 1342229581/2 & 1′5 \\
RX J1605.3+3249 & 2011 Jul 20 & 1342224846/7 & 1′5 \\
RX J1856.5−3754 & 2011 Mar 15 & 1342216058/9 & 2′4 \\
PSR J1848−1952 & 2012 Mar 13 & 1342241353/4 & 1′1 \\
RX J2143.0+0654 & 2012 Apr 23 & 1342244870/1 & 1′1 \\
\hline
\end{tabular}
\caption{List of Herschel Observations}
\end{table}

\begin{notes}
1. absolute pointing accuracy; see Section 4.1.
5. PACS Observer’s Manual, Chapter 5.2, herschel.esac.esa.int/Docs/PACS/html/pacs_om.html
6. herschel.esac.esa.int/Docs/Herschel/html/Observatory.html
7. herschel.esac.esa.int/Docs/HCNE/pdf/HCNE_ScienceDoc.pdf
8. irsa.ipac.caltech.edu/data/SPITZER/docs/spitzermission/}

\(^{a}\) McGill SGR/AXP online catalog (2014 March):
\url{www.physics.mcgill.ca/~pulsar/magnetar/main.html}
4. DATA REDUCTION AND FLUX MEASUREMENT PROCEDURE

4.1. Herschel Observations

Using the Herschel Interactive Processing Environment (HIPE), v9.0, we reduced the data based on the deep-survey scan-map pipeline scripts of the PACS photometer pipeline. The PACS calibration file set PACS_CAL_41_010 was applied. We reprocessed the data from the Level 0 to the final maps (Level 2.5) applying the usual processing steps outlined in Poglitsch et al. (2010) and Lutz et al. (2011).

A critical step in the data processing is the removal of the 1/ν noise, the heavy flicker noise of the PACS readout system. In the case of a point-source observation, a high-pass filter along the time line of the observation allows one to remove most of the 1/ν noise, which increases the sensitivity of the observation. The effects of the high-pass filter on the PACS point-spread function and the noise, the resulting flux removal, and mask strategies to avoid the former are discussed in detail by Popesso et al. (2012). According to this study, the high-pass filter most efficiently removes noise in the case of high data redundancy, i.e., large repetition factors. Flux losses of point sources are reduced best by putting circular mask patches on prior source positions. The filter width and patch sizes need to be carefully chosen since their influences dominate the global and local noise in the PACS maps. In our data processing, we checked maps produced with a masking technique where only sources above a certain threshold are masked before the combined map is produced. This method can be expected to have the highest sensitivity for faint point-source identification. However, not all observations show a PACS source near the isolated neutron star (INS) position. Aiming to reduce flux losses in our flux (limit) estimates, we therefore masked a region with radius 10′ around each expected INS position for our final map productions.

The pixel noise of individual pixels in a PACS photometer map is correlated due to the 1/ν noise and due to the applied drizzle projection method by Fruchter & Hook (2002) during the map creation process. Popesso et al. (2012) calculated the individual noise contributions in dependence of the high-pass filter width, the output pixel size, and the pixel drop fraction used in the drizzle method. In general, the noise level is lower in the high data redundancy case compared to the low data redundancy case, and smaller pixel sizes and smaller pixel drop fractions can be chosen in the former case to achieve the same noise limit. We checked different sets of parameters. As a good final choice for all our maps, we used pixel sizes of 1′′ in the blue band, 2′′ in the red band, a pixel drop fraction of 0.04 in both bands, and high-pass filter widths of 15 readouts in the blue band and 25 readouts in the red band.

The expected positions of the INSs at the time of the Herschel observations were calculated from positions and proper motions (if known) in the literature, and they are listed in Table 3. Position errors are usually below 1′′. We comment on individual INS uncertainties in Section 5 and Appendix A if there are close neighbor sources in the Herschel images. The Herschel absolute pointing error ranges from 1′′ to 2′′ for our earliest Herschel observation (RX J1856) to 1′′ to 1′′ for our latest Herschel observations, according to the Herschel calibration and HIPE teams. The pointing errors are listed in Table 1.

We use apertures with sky annuli to measure source fluxes and apply the corresponding aperture corrections using the respective HIPE tasks. The calibration study by Popesso et al. (2012) provided a method to calculate aperture flux errors from the coverage of individual map pixels by considering the chosen data reduction parameters. First, the coverage-error

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**Table 2**

List of Spitzer Observations

| Object  | Date          | Channels | AOR       |
|---------|---------------|----------|-----------|
| RX J0420 | 2011 Sep 17   | 4.5 μm   | 42478336  |
| RX J0720 | 2011 Nov 21   | 3.6 & 4.5 μm | 39947264 |
| RX J0806 | 2012 Apr 30   | 4.5 μm   | 42478592  |
| RX J1308 | 2011 Jul 24   | 4.5 μm   | 42478848  |
| RX J1605 | 2012 May 1    | 4.5 μm   | 42479016  |
| RX J1856 | 2011 Nov 12   | 4.5 μm   | 42479360  |
| RX J2143 | 2012 Dec 31   | 4.5 μm   | 42479872  |

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**Table 3**

Positions and Proper Motions of the Eight Neutron Stars

| Object  | R.A. (h m s) | Decl. (d m s) | PosErra (%) | Epoch (MJD) | Ref. c | μα cos δa (mas yr−1) | μδ a (mas yr−1) | Ref. c | PosErrHb (%) |
|---------|--------------|---------------|-------------|------------|------|----------------------|----------------|------|-------------|
| RX J0420 | 04 20 01.94  | −50 22 47.8   | 1.1 (90%)   | 54122      | 1    | < 123 (2σ)          | 49 ± 5 (1σ)    | 3    | 1.2         |
| RX J0720 | 07 20 24.93  | −31 25 49.78  | 0.02, 0.02 (1σ) | 54477      | 3    | −93 ± 5 (1σ)        | 49 ± 5 (1σ)    | 3    | 0.06       |
| RX J0806 | 08 06 23.40  | −41 22 30.9   | 0.6 (90%)   | 52326      | 4    | < 86 (2σ)           | 84 ± 20 (2σ)   | 2    | 0.9        |
| RX J1308 | 13 08 48.27  | +21 27 06.8   | 0.6 (90%)   | 51719      | 5    | −207 ± 20 (2σ)      | 84 ± 20 (2σ)   | 2    | 0.7        |
| RX J1605 | 16 05 18.52  | +32 49 18.0   | 0.3, 0.3 (1σ) | 52111      | 6    | 25 ± 16 (90%)       | 142 ± 15 (90%) | 7    | 0.7        |
| RX J1856 | 18 56 35.79  | −37 54 35.54  | 0.1 (90%)b  | 52868      | 8    | 326.6 ± 0.5 (1σ)    | −61.9 ± 0.4 (1σ) | 8    | 0.1        |
| PSR J1848 | 18 48 18.04  | −19 52 31     | 0.6, 7 (2σ) | 48695      | 9    | 39 ± 157 (2σ)       | −1200 ± 1900 (2σ) | 9    | 3.19        |
| RX J2143 | 21 43 03.4    | +06 54 17.5   | 0.2,0.2 (1σ) | 54388      | 10   | < 700 (90%)         | twf             | 3.2  |             |

Notes.

a Uncertainty levels as quoted in the respective papers. One value instead of two indicates the radial error.

b Positional radial error (90% confidence level) of the NS position at the epoch of the respective Herschel observation, calculated using the Rayleigh distribution. In the case of different (position, proper motion) error values in R.A. and decl., we use the larger error for our estimate.

c References: (1) Mignani et al. 2009; (2) Motch et al. 2009; (3) Eisenbeiss et al. 2010; (4) Haberl et al. 2004; (5) Kaplan et al. 2002; (6) Kaplan et al. 2003; (7) Motch et al. 2005; (8) Walter et al. 2010; (9) Hobbs et al. 2004; (10) Schwope et al. 2009.

d Absolute positional error not listed in Walter et al. (2010); we assume a reasonable value of 0′′.1 (90% confidence).

e Individual errors in R.A. and decl.; see discussion in Appendix A.6.

1 This work; see Section 5.2.
the case. We list 5\ apertures in nearby source-free regions and found this to be corrected fluxes, we apply the aperture correction factor to the correlation noise, the projection itself, and the residual 1 correlation correction factor accounts for both components in Finally, the cross-correlation factor is applied. This cross-correlation correction factor accounts for both components in the correlation noise, the projection itself, and the residual \( 1/f \) noise not removed by the high-pass filter. Since we give aperture-corrected fluxes, we apply the aperture correction factor to the estimated error as well. We checked whether the determined final error was of the same order as the variance of background apertures in nearby source-free regions and found this to be the case. We list 5\( \sigma \) errors for the aperture-corrected fluxes in Table 5.

If there is no source at the INS position, we consider several apertures to measure the standard deviation of the background in the central, source-free region of the map (close to the INS) where the exposure coverage is reasonably homogeneous. Depending on how crowded the field is, we usually obtain results from 7 to 15 apertures with radii of 5'' or 7''. We list 5\( \sigma \) values for the flux limits in Table 5.

We neglect the PACS photometer color corrections (for estimates of the monochromatic flux densities for different spectral shapes) because they are close to one for a wide range of expected disk temperatures (30–1000 K). However, if highly accurate fluxes for a particular disk model are desired, we refer to the respective Herschel PACS Technical Note PICC-ME-TN-038.12

### 4.2. Spitzer Observations

For the data reduction of the Spitzer IRAC data, we used Spitzer’s MOsaicker and Point source Extractor package, MOPEX.13 v.18.5.6. In the following, we give an exemplary description of the data reduction for the IRAC data of RX J0720.4–3125 (two bands). The data reduction for the 4.5 \( \mu \)m data of the other INSs is performed following the same procedures.

In each case, we start from the artifact-corrected basic calibrated data (cBCD) frames. We removed one cBCD frame from the 3.6 \( \mu \)m data set of RX J0720.4–3125 because it had a bad column at the target position. From the respective 4.5 \( \mu \)m data set, we removed five frames due to artifacts, possibly the so-called column pull-up, at or close to the source position. Using the mosaic task, we obtained a combined image with a pixel size of 0.6''. We checked the alignment of the IRAC mosaic astrometry with the 2MASS Point Source Catalog (Skrutskie et al. 2006) using 114 2MASS sources with the highest quality flag AAA in the field. The astrometric accuracy of the 3.6 \( \mu \)m and the 4.5 \( \mu \)m mosaics of RX J0720.4–3125 are 0/27 and 0/28, respectively. Similar astrometric accuracies are found for the other INS Spitzer mosaics. The expected INS positions were calculated for the times of the respective Spitzer observations using known positions and proper motions as described for Herschel in Section 4.1.

The IRAC Point Response Function (PRF) is essentially the convolution of a box the size of the image pixel, with the point-spread function (e.g., MOPEX user guide, chapter 8.914). To consider a PRF that is variable in the field of view, one uses the so-called PRF maps, which are provided by the Spitzer

| Object | \( F_{\text{IRAC1}}^{4.5 \mu \text{m}} \) (\( \mu \)Jy) | \( F_{\text{blue}} \) (\( \mu \)Jy) | \( F_{\text{red}} \) (\( \mu \)Jy) | \( M_{\text{20 K}}^{\text{dust}} \) (\( M_\odot \)) | \( M_{\text{100 K}}^{\text{dust}} \) (\( M_\odot \)) |
|--------|-------------------|-----------------|-----------------|-----------------|-----------------|
| RX J0420 | \(< 2.1\) | \(< 4.5\) | \(< 7.0\) | \(< 1.0\) | \(< 0.2\) |
| RX J0720\(^a\) | \(< 3.5\) | \(< 5.2\) | \(< 9.4\) | \(< 1.4\) | \(< 0.2\) |
| RX J0806 | \(< 11.4^{\text{PD,CN}}\) | \(< 4.9\) | \(10 \pm 5^{\text{CN}}\) | \(0.72 \pm 0.36\) | \(0.012 \pm 0.006\) |
| RX J1308 | \(< 1.2\) | \(< 1.7\) | \(< 5.2\) | \(< 1.5\) | \(< 0.2\) |
| RX J1605 | \(< 2.7\) | \(< 6.1\) | \(< 12.2\) | \(< 2.2\) | \(< 0.04\) |
| RX J1856 | \(< 8.9^{\text{CN}}\) | \(< 7.7\) | \(< 7.8\) | \(< 0.2\) | \(< 0.004\) |
| PSR J1848 | \(\cdots\) | \(< 3.6\) | \(< 5.9\) | \(< 6.2\) | \(< 0.1\) |
| RX J2143 | \(< 2.3\) | \(< 5.0\) | \(7.8 \pm 4.8^{\text{CN}}\) | \(1.7 \pm 1.0\) | \(0.03 \pm 0.02\) |

Notes. The results of the following bands are listed: Spitzer IRAC2 (4.5 \( \mu \)m), and the Herschel PACS blue band (60–85 \( \mu \)m) and red band (130–210 \( \mu \)m). For Spitzer data, the color corrections for a \( T = 200 \) K blackbody are applied, but note the general remarks regarding color corrections in Section 4. The superscript\(^{PD}\) indicates a potential (weak) detection, and \(^{\text{CN}}\) indicates confusing neighbor sources. Dust masses are calculated using Equation (1) for dust temperatures of 20 K and 100 K, the Herschel PACS red band measurements, and the distances as listed by Kaplan \& van Kerkwijk (2009). All limits and errors are 5\( \sigma \) values.

\(^{a}\) RX J0720 also has a Spitzer IRAC1 (3.6 \( \mu \)m) limit, \( F_{\text{IRAC1}}^{3.6 \mu \text{m}} < 3.2 \mu \)Jy (color-corrected for \( T = 200 \) K).

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Table 4

| Object | \( 3.4 \mu \text{m} \) (mag) | \( 4.6 \mu \text{m} \) (mag) | \( 12 \mu \text{m} \) (mag) | \( W1 \) for a BB with \( T = 200 \) K \( (\mu \text{Jy}) \) | \( W2 \) \( (\mu \text{Jy}) \) | \( W3 \) \( (\mu \text{Jy}) \) |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| RX J0420 | 18.4 | 17.0 | 12.8 | 6 | 20 | 220 |
| RX J0720 | 17.2 | 15.7 | 11.4 | 21 | 67 | 837 |
| RX J0806 | 17.5 | 16.3 | 12.2 | 15 | 38 | 383 |
| RX J1308 | 17.3 | 15.9 | 11.7 | 18 | 56 | 595 |
| RX J1605 | 17.7 | 16.2 | 12.1 | 12 | 41 | 435 |
| RX J1856 | 17.0 | 15.5 | 11.2 | 24 | 80 | 952 |
| PSR J1848 | 15.3 | 14.3 | 11.0 | 110 | 240 | 1145 |
| RX J2143 | 17.3 | 15.8 | 11.6 | 18 | 61 | 690 |

Notes. Vega magnitude limits in the field of the NSs considering WISE detections with an S/N > 5. The last three columns show the color-corrected WISE fluxes if a 200 K blackbody emitter is assumed for the spectral shape.
Science Center\textsuperscript{15} for the IRAC channels. The PRF is required for point-source fitting photometry, which we performed with the \textit{apex multi-frame} task on each individual cBCD frame. Applying then the \textit{apex-qa} task, we subtracted the fitted point sources from the individual cBCD frame to obtain a residual mosaic. Such residual mosaics are useful if neighboring sources contaminate the flux at the source position.

We use aperture photometry to determine IRAC fluxes and flux limits. We apply aperture radii of 2 native IRAC pixels, corresponding to 4 mosaic pixels, and aperture correction factors of 1.21 and 1.22 for the 3.6 $\mu$m and the 4.5 $\mu$m measurements, respectively (Reach et al. 2005). To obtain an upper limit, we determine not only the source aperture flux, $F_{\text{SRC}}$, but also the background level, $F_{\text{BG}}$, and the standard deviation, $\sigma$, of several (usually 8\textendash10) source-free apertures close to the source position. If necessary and possible, we use the residual mosaics for these measurements. In the case of a non-detection, we define the upper flux limit $F_{\text{UL}} = F_{\text{SRC}} - F_{\text{BG}} + 5\sigma$.

The derived IRAC fluxes are in Jy and correspond nominally to those fluxes one expects to measure in the respective IRAC channel for a source with $F_{\nu} \propto \nu^{-1}$. Sources with different spectral shapes and, in particular, very red sources, require a color correction. The IRAC Instrument Handbook\textsuperscript{16} (Section 4.4) lists color corrections for different power law indices and blackbody temperatures. In Sections 5.1 and 5.2, and Appendices A.1\textendashA.6, we give the aperture-corrected flux values without color correction, while in Table 5 we exemplarily apply the color corrections for a $T = 200 \text{ K}$ blackbody as an approximation for the spectral shape of potential warm disk emission.

### 4.3. Complementary WISE Data

The \textit{Wide-field Infrared Survey Explorer} (WISE; Wright et al. 2010) mapped the sky in 2010 at 3.4 (W1), 4.6 (W2), 12 (W3), and 22 (W4) $\mu$m with an angular resolution of 6\textquoteleft 1, 6\textquoteleft 4, 6\textquoteleft 5, and 12\textquoteleft, respectively. We use the all-sky atlas images and the WISE \textit{Source Catalog} to investigate the regions of our INSs. We cross-checked for astrometric shifts between the positions of known 2MASS sources or sources in our previous \textit{H}band VLT observations and source positions in WISE bands, as well as for noticeable astrometric shifts between WISE sources and the \textit{Herschel} sources. While the astrometric calibrations of the first three WISE bands generally agree well with NIR astrometry, there are often noticeable shifts in the fourth band that are most easily seen when comparing the last two WISE bands. Astrometric biases in the WISE all-sky atlas images are discussed on the IPAC Web page.\textsuperscript{17} While we suspect a shifted W4 astrometry for several of our fields, we do not attempt to improve the W4 astrometric calibration because the scarcity, faintness, and spatial extent of the W4 sources hinder a good, unique astrometric calibration. We ignore the W4 band in the following.

We searched for potential WISE counterparts of the INSs or neighboring Herschel sources in the remaining bands and discuss our findings in the respective subsections. In Table 4 we provide the WISE field limits measured in Vega magnitudes. The limits correspond to the requirement that the IR sources have signal-to-noise ratios $(S/N) \geq 5$ in the respective band. To obtain these limits, we considered all WISE sources in a box area $1\degree \times 1\degree$ around the INS (usually around 20,000 sources). Sources with $S/N = 5$ usually have a magnitude uncertainty of $\approx 0.22$ mag.

To convert the Vega magnitudes into flux density units such as Jy, one has to know and account for the source spectrum in the respective WISE band by applying a color correction. Due to the wide WISE bands, these color corrections can be very different for stars and much cooler blackbody-like sources (asteroids, disks); see, e.g., Cutri et al. (2012), Section IV.4.h, and Wright et al. (2010). As an example, we give fluxes for a $T = 200 \text{ K}$ blackbody additionally to the Vega magnitudes in Table 4, but caution that flux limits should in principle be more carefully calculated for any specific (disk) models under investigation.

### 5. RESULTS

There is no significant emission in the \textit{WISE}, \textit{Spitzer}, and \textit{Herschel} bands for six of the eight investigated NSs. In Sections 5.1 and 5.2, we present detailed results for the two NSs where significant \textit{Herschel} red band emission was detected near the location of the NS. Appendix A includes finding charts and measurement details on the six NSs with only upper limits. We summarize our \textit{Herschel} and color-corrected \textit{Spitzer} flux (limit) results in Table 5, and the WISE field magnitude limits in Table 4.

#### 5.1. RX J0806.4\textendash4123

The \textit{Spitzer} IRAC2 (4.5 $\mu$m) observation of RX J0806.4\textendash4123 is well aligned with previous NIR observations (e.g., 2MASS point sources), with a 1$\sigma$ astrometric accuracy of 0.2$\arcsec$ (using 196 AAA 2MASS sources). Posselt et al. (2009) investigated VLT ISAAC H-band images of this region. Figure 1 shows that the major H-band sources correspond well to the \textit{Spitzer} sources. The \textit{Chandra} X-ray position of RX J0806.4\textendash4123 has a positional uncertainty of 0\arcsec 6 (90\% confidence; Haberl et al. 2004). Together with the upper limit on the INS proper motion at the time of the \textit{Spitzer} observation (0\arcsec 88 (2$\sigma$); Motch et al. 2009), the overall positional uncertainty of the expected

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\textsuperscript{15} irsa.ipac.caltech.edu/data/SPITZER/docs/irac/calibrationfiles/psprf/  
\textsuperscript{16} irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/18/  
\textsuperscript{17} wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec2_3g.html
RX J0806.4–4123 position in IRAC2 is about 0.9′ (90% confidence level) in the worst case.

There appears to be faint emission in the 4.5 μm band within this range in the northwest direction of the nominal INS position; see source A in Figure 1. The emission is so faint that we were not able to detect it with the MOPEX PRF-fitting methods. It may be spurious emission; however, there are similarly faint sources that correspond to known NIR sources (e.g., source C in Figure 1). We were not able to produce a reasonable apex–qa residual mosaic in which the brighter sources would be reliably subtracted. As the H-band contours show, the IRAC2 emission may contain several IR sources that are not recognized by the PRF fit. For example, it would be useful to subtract source B, but this source is not even recognized as an individual source in our PRF fits. If we do flux aperture measurements at the INS position (with a radius of 2 native IRAC pixels), we nominally obtain an aperture-corrected flux of $F_{\text{5.8}}^{\text{IRAC}} = 5.2 \pm 1.9 (1\sigma) \mu$Jy. Since one can argue about the reliability of such 2.8σ emission, we also estimated the aperture-corrected upper flux limit $F_{\text{5.8}}^{\text{upper}} = 14.7 \mu$Jy. We note that there is a very faint NIR source at the INS position in the 2004 VLT H-band data too, but the NIR emission is below the 3σ significance level as well (Posselt et al. 2009).

In the Herschel PACS blue band, there is no significant emission around the position of RX J0806.4–4123. Using apertures in different source-free regions and at the target position, we determined the 5σ upper flux limit for the INS as $F_{\text{5.8}}^{\text{blue}} = 4.9 \mu$Jy. There is, however, emission around the INS position in the Herschel PACS red band; see Figure 2. We use the X-ray position of RX J0806.4–4123 from Haberl et al. (2004). This position has an uncertainty of 0.6′ (90% confidence). In addition, an uncertainty of 0.8′′ needs to be considered due to the 2σ upper limit on the proper motion, 86 mas yr⁻¹. In the Herschel field of view, there is only one unambiguous point source in common with other infrared data, e.g., VLT H-band or WISE. The positions of this point source agree well. Comparing the extended emission with the WISE data, we conclude that the nominal Herschel PACS pointing accuracy of $1\sigma \approx 1.1′′$ can be assumed. The PACS red emission around the INS could either consist of several point sources or include extended emission. The peak closest to the INS has a spatial separation of $\approx 2.9′′$ from the X-ray position. We use a 5′′ aperture for the flux measurement and 10 other apertures on source-free regions to measure the background. Using an aperture correction of 3.4, we estimate a flux of $F_{\text{red}} \approx 10 \pm 5 (5\sigma) \mu$Jy at the position of the INS. In Section 6.1, we discuss the likelihood of the Herschel PACS red band emission being not associated with the NS.

We use the previous H-band image for cross-checks with the WISE W1–W3 data; see Figure 3. There is no noticeable astrometric shift between these bands. There is no apparent counterpart in the WISE data to the emission in the Herschel PACS red band. Higher spatial resolution is required to investigate the Herschel emission around the INS position.

### 5.2. RX J2143.0+0654

The position of RX J2143.0+0654 is known with an accuracy of 0.2′ from optical observations (Schwope et al. 2009), but its proper motion is unknown. Comparing the Chandra, XMM-Newton, and optical positions from different epochs as shown by Schwake et al. (2009), one can infer that the proper motion must be smaller than 700 mas yr⁻¹. Thus, at the time of the Herschel and Spitzer observations, the INS could have moved from the optical position by $<3.2′′$ and $<3.7′′$, respectively.

There is no emission at the position of RX J2143.0+0654 in the Spitzer IRAC 4.5μm mosaic image; see Figure 4. There are, however, four Spitzer sources within $<3.7′′$ of the nominal NS position. Since the same sources were detected as faint H-band sources in the 2003 VLT observations by Posselt et al. (2009), none of them can be the NS counterpart. The

![Figure 2](image1.png)  
**Figure 2.** Herschel PACS maps around RX J0806.4–4123. The blue (60–85 μm) and red (130–210 μm) bands are shown in the left and right panels, respectively. Each map is 1′3 × 1′3; north is up, east is to the left. The circle with a radius of 10′ shows the NS position. The white square marks a common source in Herschel PACS, WISE, and VLT ISAAC images.

![Figure 3](image2.png)  
**Figure 3.** WISE W1 (3.6 μm) and W3 (12 μm) maps around the position of RX J0806.4–4123. The same field of view is shown as in the Herschel PACS maps of Figure 2. The white contours in the W1 image are from the VLT ISAAC H-band image (Posselt et al. 2009). The white square marks a common source in Herschel PACS, WISE, and VLT ISAAC images.
Figure 4. Spitzer IRAC2 (4.5 μm) map around the position of RX J2143.0+0654. The white contour highlights sources in the H-band (Posselt et al. 2009). The black circle with a radius of 2″ marks the INS position, the square marks a bright source common in the Herschel PACS, WISE W1 and W2, and H bands.

Figure 5. Herschel PACS maps around RX J2143.0+0654. The blue (60–85 μm) and red (130–210 μm) bands are shown in the left and right panels, respectively. Each map is 2′5 × 2′; north is up, east is to the left. The circle with a radius of 10″ marks the INS position, and the white squares mark bright sources common in the Herschel PACS, WISE W1 and W2, and H bands.

Aperture-corrected 5σ upper flux limit at the nominal NS position is $F_{5\sigma}^{4.5\mu m} = 3.0 \, \mu$Jy.

The field around RX J2143.0+0654 is densely populated in the infrared and includes several common sources in the Herschel PACS bands, Spitzer IRAC, the WISE W1 and W2 bands, and in the VLT ISAAC H-band observations of Posselt et al. (2009); see Figures 4–6. This allows us to confirm that the absolute pointing error of the Herschel observation is not larger than the expected value of 1′/1.

There is emission in the red PACS band at the position of the INS, consisting of a blend of at least one southern and one brighter northern source (see Figure 5; the southern source is marked with a box and was also detected by WISE). In the blue PACS band, there is very faint emission northwest of the INS. The peak position of the 160 μm emission is 3′7 north of the optical INS position, about 2′6 from the closest N(IR) source. Considering the unknown NS proper motion, we cannot rule out the possibility that this source is the counterpart of the INS. However, it appears unlikely that RX J2143.0+0654 has the implied large proper motion (>0.6 yr⁻¹). While the INS distance is unknown, it is expected to be larger than 300 pc (Posselt et al. 2007). For comparison, the closest of the XTINSs, RX J1856.5–3754 ($D = 140$ pc), also has the largest proper motion (330 mas yr⁻¹) of those four of the XTINSs for which proper-motion measurements or limits were reported.

Part of the red band emission at the INS position is likely to come from the bright infrared southwestern source that is seen in several bands. Given the proximity of the sources, their faintness, and the FWHM in the red band of 10′5 × 12′0, it is not possible to remove sources with the necessary accuracy to search for residual 160 μm emission at the optical position of the INS. We used an aperture with radius of 5″ at the position of the INS to measure the flux at this position. The aperture-corrected flux is $F_{5\sigma}^{red} = 7.8 \pm 4.8 (5\sigma) \, mJy$. Due to the surrounding sources, this value must be regarded with caution and it can be an overestimate of any actual flux from the INS position. In Section 6.1, we discuss the likelihood of the Herschel PACS red band emission not being associated with the NS.

In the blue band, there is no prominent source emission at the INS position. Using apertures in different source-free regions and at the target position, we determined the 5σ upper limit for RX J2143.0+0654 flux to be $F_{5\sigma}^{blue} = 5.0 \, mJy$.

We used the VLT ISAAC H-band image by Posselt et al. (2009), Spitzer, and 2MASS point sources for cross-checks with the WISE W1–W3 data; see Figures 4 and 6. There is no noticeable astrometric shift between these bands. The W1 emission west of the INS position is probably related to the southwestern sources seen with Spitzer, and no enhanced emission is detected at the INS position. In W3, there is no emission peak at the INS position, although there is an eastern source at ≈8″ and a faint southern source at ≈5″ from the nominal NS position. Since the astrometry of sources in these WISE images agree well with those of N(IR) sources, we conclude that RX J2143.0+0654 is undetected in the WISE W1–W3 data.

6. DISCUSSION

6.1. The Likelihood for the Herschel Emission to be Associated with Field Sources

In Sections 5.1 and 5.2, we reported on Herschel red band emission at or near the positions of RX J0806.4–4123 and RX J2143.0+0654. How likely is the emission in the Herschel PACS red band to be associated with a source different from the INS? Confusion from faint Galactic stars is negligible for the PACS red band.18 The main two components of sky background confusion noise in the long-wavelength bands of Herschel are extragalactic sources and interstellar cirri. Sibthorpe et al. (2013) showed that, for a given Herschel PACS flux level, results from typical extragalactic fields can be used to estimate the background source numbers in typical debris disk surveys. They used the results from the PACS Extragalactic Probe (Berta et al. 2011; Lutz et al. 2011) to estimate the expected background source number density for given flux and flux uncertainty levels. Following the approach by Sibthorpe et al. (2013), we

18 herschel.esa.esa.int/Docs/HCNE/pdf/HCNE_ScienceDoc.pdf
estimate the chance probability of detecting an \( F_{\text{red}} \approx 10 \, \text{mJy} \) extragalactic source in a circle with a radius of \( r = 5'' \) as 0.5%. For RX J2143.0+0654, we estimate the respective chance probability of detecting an \( F_{\text{red}} = 7.8 \, \text{mJy} \) extragalactic source in a circle with a radius of \( r = 5'' \) as 0.7%. Given these chance probabilities, the binomial probability that we detect background sources in two of eight overall XTINS fields is at maximum 1% for 7.8 mJy sources, but the probability of detecting one background galaxy at one of the eight XTINS positions is already 5%.

Gáspár & Rieke (2014) argued that Sibthorpe et al. (2013) underestimate the confusion noise probabilities, mainly because galaxies fainter than a considered flux limit may also contribute to the overall confusion noise. We used the Monte Carlo Code by Gáspár & Rieke (2014) to estimate the probabilities for \( N_{\text{excess}} \) unrelated “excess sources” in the photometry apertures of our eight NSs. We realized \( 10^6 \) data sets of eight sources with our detection requirement of \( \geq 5 \sigma \) (Table 5, i.e., 5 mJy for RX J0806.4–4123) in a \( r = 5'' \) photometry aperture. In a nutshell, the code by Gáspár & Rieke (2014) simulates background sources in a single large field (0.5 deg\(^2\)), then properties for eight random positions from this field are estimated \( 10^6 \) times. The latter step includes the consideration of noise from interstellar cirrus using a probability distribution with standard deviation \( \sigma_{\text{cirrus}} \), which is calculated from the observed far-infrared interstellar medium (ISM) flux background. For details on the code and the assessment of its statistical performance, we refer to Gáspár & Rieke (2014). For our simulations, we used a cirrus noise value of \( \sigma_{\text{cirrus}} = 0.84 \, \text{mJy} \), which corresponds to the median value of the ISM background flux of 11.74 MJy sr\(^{-1}\), as estimated by using Hspot\(^{19}\) for the observing dates and positions of our eight NSs. The resulting probability plot is shown in Figure 7. The probability to detect no one, or two excess source(s) among our eight NSs is 86%, 13%, and 1%, respectively. Thus, it seems unlikely that both our detections are excess sources.

Kaplan et al. (2011) investigated RX J0806.4–4123 with the Hubble Space Telescope (HST) and found no source other than the NS within 2\(^\circ\) of the INS position using the Advanced Camera for Surveys, Wide Field Channel/Filter F475W down to an ST magnitude of 27.92 ± 0.22. Considering the HST pointing accuracy (1\(\'\), Section 5.1) and its large FWHM (\(\approx 11''\) for the red band), there are, however, several HST sources that currently cannot be excluded as potential Herschel background galaxy counterparts.

There is also another alternative explanation for the Herschel PACS red band source: interstellar cirrus. In fact, the ISM background flux in the direction of RX J0806.4–4123 is estimated by Hspot to be about a factor of 10 higher than the median value of the remaining seven NS fields. Illustrating the higher ISM background, the recent 3D maps of the local ISM distribution by Lallement et al. (2014) show a local ISM cloud clump in the direction of RX J0806.4–4123. A typical interstellar cirrus has been found to have temperatures of about \(\sim 20 \, \text{K} \) with a range of about 4 K around this value (Veneziani et al. 2013; see also Gáspár & Rieke 2014)—a temperature range very reminiscent of the one inferred for our Herschel detection around RX J0806.4–4123 (see Section 6.2). If we consider explicitly the higher ISM background flux for this one source in the Monte Carlo simulation by Gáspár & Rieke (2014), we obtain 63%, 33%, and 3% as the probabilities for detecting no, one, or two excess source(s) among our eight NSs, respectively. The probability of one excess source among the eight NSs has nearly tripled, but the probability for no excess sources in the sample is still a factor of 2 higher.

In the case of RX J2143.0+0654, the HST observations are not constrained with respect to excluding obviously present galaxies as counterparts to the faint Herschel emission either. Regarding interstellar cirrus, the ISM background flux in the direction of RX J2143.0+0654 is nearly the same as the median value for the seven NS fields (excluding RX J0806.4–4123). Thus, the probability for an excess source due to an ISM cirrus is less than in the case of RX J0806.4–4123.

**6.2. Multi-wavelength Constraints on the Dust Emission**

In the following, we assume that the detected Herschel emission originated from dust associated with the XTINS. We summarize the Herschel and Spitzer results of the previous subsections in Table 5. Assuming the emitting dust to be optically thin at submillimeter wavelengths, we can use the Herschel 160 \(\mu\)m measurements to calculate the dust mass, assuming a single temperature for all dust grains:

\[
M_d = \frac{F_\nu D^2}{B_\nu(T_d)\kappa_d^\nu},
\]

where \(\nu = 1.9\times10^{12} \, \text{Hz} \) is the frequency, \(F_\nu\) is the measured flux density (limit), \(D\) is the distance, \(B_\nu(T_d)\) is the Planck function at a dust temperature \(T_d\), and \(\kappa_d^\nu\) is the dust mass absorption coefficient. We use \(\kappa_d^{160\mu\text{m}} = 13 \, \text{cm}^2 \, \text{g}^{-1}\) for the PACS red band, which we calculated from the optical constants by Dorschner et al. (1995), assuming dust grains consisting of amorphous magnesium silicate with a grain density \(\rho_g = 2.7 \, \text{g} \, \text{cm}^{-3}\). The dust composition and, therefore, the dust mass absorption coefficient is in general highly uncertain (by a factor of three

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\(^{19}\) The Herschel tools are available at herschel.esac.esa.int/Tools.shtml.
Posselt et al.

RX J0420.0–5022

Figure 8. Measured values and upper limits for the IR/submillimeter to X-ray flux ratios for six XTINSs. The X-ray fluxes are for the energy range 0.1–2.4 keV and are taken from Haberl (2013). Note that the XTINSs show only very soft thermal X-ray emission. The infrared/submillimeter limits/values are taken from Tables 4 and 5 and the measurements by Posselt et al. (2010, 2009). For Spitzer and WISE data, exemplary color corrections for a $T = 200$ K blackbody are applied, but note the general remarks regarding color corrections in Section 4. No extinction correction has been applied since the XTINSs have very small absorbing hydrogen column densities ($N_H \approx 10^{20} \text{ cm}^{-2}$), corresponding to negligible extinction corrections in the infrared ($A_H \approx 0.01$, $A_{3.6\mu m} \approx 0.004$; following the extinction relations by Vuong et al. 2003 and Indebetouw et al. 2005). The dashed lines show upper limits on the emission of dust with a temperature $T_d = 20$ K according to Equation (2). The solid line in the case of RX J2143.0+0654 indicates the respective constraints from the measured Herschel aperture flux.

to five, e.g., Posselt et al. 2010). Additionally, the dust likely has a temperature distribution, not a single temperature. The composition and dimensions of a fallback disk around a $\sim 1$ Myr old NS are unknown, too. Thus, the derived dust masses in Table 5 and Figure 9 are only crude estimates.

In Figures 8 and 9, we show the ratios of the IR/submillimeter fluxes (limits) to the X-ray fluxes of the XTINSs. The obtained flux ratios (limits) are usually in the range $10^{-4}$ to $10^{-3}$ for the $H$-band and the Spitzer 4.5 $\mu$m data, but 0.01 to 0.1 for the Herschel data. For comparison, we refer to similar plots of three CCOs by Wang et al. (2007a, for optical and IR fluxes only). At the Spitzer wavelengths, flux ratio limits of $10^{-2}$ to $10^{-4}$ were reached for the CCOs, but no disks were detected. Wang et al. (2007a) also showed a comparison plot for the only magnetar where a disk is thought to be detected—4U 0142+61 (Wang et al. 2006). For this magnetar, the flux ratio at Spitzer IRAC wavelengths is $\approx 6 \times 10^{-5}$. This comparison might indicate that our limits are simply not deep enough. On the other hand, the single object 4U 0142+61 might not be defining for all potential NS disks. Our Herschel detections of emission around RX J0806.4–4123 and RX J2143.0+0654 could indicate predominantly cold dust around these (older) NSs. Spitzer 4.5 $\mu$m observations are not sensitive enough to detect such cold dust.

Dust emission at long wavelengths can be described in the Rayleigh limit if $\lambda > \max (2\pi a, \lambda_{\text{Res}})$, where $a$ is the (spherical) grain size radius, and $\lambda_{\text{Res}}$ is the largest resonance wavelength of the complex refractive index as tabulated in the DOCCD. If this condition is fulfilled, the flux density $F_\nu \propto \nu^2$ (see Appendix B), and assuming optically thin conditions for the grain as well as the overall medium (e.g., dusty disk or cloud), we can write

$$F_\nu = B_{\nu}(T_d) \left( \frac{\nu}{\nu_0} \right)^2 F_{\nu_0}, \quad (2)$$

where $\nu_0 \ll 10^{13}$ Hz is the reference frequency. Here, we choose the Herschel red band ($\nu_0 = 1874$ GHz) as reference band and show the constraints on the expected dust fluxes at long wavelengths in Figures 8 and 9. In the former, we use an exemplary temperature $T_d = 20$ K, and in the latter, we illustrate the effect of choosing different temperatures.

In the wavelength regime of W1–W3, Spitzer IRAC, and the $H$ band, the dust absorption and emission properties are highly non-monotonic functions of $\lambda$ (see, e.g., the laboratory absorption coefficient measurements of dust grains by

\[ \text{Database of optical constants for cosmic dust: www.astro.uni-jena.de/Laboratory/OCDB/index.html.} \]
Dorschner et al. 1995), and the dust medium is in general not 
optically thin for (its own) emission at such wavelengths. Re-
alistic flux models would require the application of the Mie 
theory for the radiation transport calculation for a distribution 
of dust grains. Given that we deal only with flux limits at these 
wavelengths, such modeling is beyond the scope of this paper.
To estimate at least the maximal upper limits on the luminosity 
oratios, we assume blackbody emission. For blackbody emission, 
the dust luminosity limits, \( L_{\text{dust}}(T_d) \), are related to the 
measured flux density limits, \( F_{\nu} \),
\[
F_{\nu} = \frac{B_{\nu}(T_d)L_{\text{dust}}}{4D^2\sigma_{\text{SB}} T_d^4},
\]
where \( \sigma_{\text{SB}} \) is the Stefan–Boltzmann constant. The right plot in 
Figure 9 shows the blackbody luminosity constraints for 
RX J0806.4–4123.

For \( h\nu_0 \gg 2.8kT \), optically thin dust conditions, and uniform 
properties of the dust grains as well as a uniform temperature, we 
derive for the total luminosity of the dust:
\[
L_{\text{dust}}(T_d) = \frac{160}{21}\pi^2 \left( \frac{kT_d}{h\nu_0} \right)^2 \frac{k}{\kappa_{\text{d}}} M_d \sigma_{\text{SB}} T_d^4
= F_{\nu} D^2 \frac{160}{21}\pi^2 \left( \frac{k}{h\nu} \right)^2 \frac{2}{\alpha_{\text{SB}}} \frac{B_{\nu}(T_d)}{B_{\nu}(T_d)} T_d^4.
\]
where \( k \) is the Boltzmann constant and \( h \) is the Planck 
constant. The middle plot of Figure 9 shows the constraints on 
\( L_{\text{dust}}(T_d)/L_X^{N5} \) from the Herschel red band value and blue band 
limit. We see that only low dust temperatures (\( T_d \ll 25 \) K) 
are allowed considering the detection and non-detection in the red 
and blue band, respectively.

6.3. Constraints on a Potential Dusty Disk or Torus

In the previous section, we discussed only in general the 
constraints on the dust associated with the XTINSs. Here, we 
discuss constraints on different properties of potential disks 
assuming that the detected Herschel fluxes are indeed due to 
emission from dust around the NSs. Bryden et al. (2006) noted 
that only the brightest debris disks detected with Spitzer have 
\( L_{\text{dust}}/L_{\text{bol, s}} \ll 10^{-4} \). The recent Herschel DUNES survey by 
Eiroa et al. (2013) reported \( L_{\text{dust}}/L_{\text{bol, s}} \) ranging from \( 10^{-6} \) to 
\( 3 \times 10^{-4} \) for Herschel debris disk candidates around solar-type stars. If the Herschel 160 \( \mu \)m detections for two XTINSs and 
the marginal Spitzer 4.5 \( \mu \)m and H-band detections of emission 
around RX J0806.4–4123 are confirmed to come from disks, the 
luminosity ratios would be two to three orders of magnitudes 
higher than the values seen for non-degenerate stars. The implied 
large absorption cross section of the disk appears questionable.

In contrast to the luminosities of main sequence stars, most of 
the XTINSs' luminosity is emitted in soft X-rays (<1 keV). In 
contrast to other wavelengths, soft X-ray photons are very 
efficiently absorbed and re-emitted by all dust grains (\( \approx 100\% \) 
of each incident soft X-ray photon; e.g., Dwek & Smith 1996). The 
absorption cross section of a putative disk cannot, however, be 
larger than the geometric cross section of that disk. Hence, even 
if one accounts for an exceptionally high dust heating efficiency, 
geometric arguments exclude a thin flared disk from gobbling up 
20\% of the stellar luminosity. The implied geometric shape 
for an assembly of dust grains surrounding the NS would be 
rather a dusty torus or an envelope.

We use the Rayleigh approximation to estimate the possible 
location of the dust around the NS. As outlined in Appendix B, 
the temperature distribution, \( T_d(r) \), of amorphous magnesium silicate dust grains with sizes \( a \) can be calculated as:
\[
T_d(r) = 39 \left( \frac{L_{\text{bol, 30} \mu \text{m}}}{a_{\text{30} \mu \text{m}}} \right)^{1/6} \left( \frac{1}{r_{\text{d}}} \right)^{1/3} \text{K},
\]
where the NS luminosity, \( L_{\text{bol, 30} \mu \text{m}} \), is normalized to \( 10^{30} \) erg 
\( s^{-1} \), and the distance, \( r_{\text{d}} \), between the NS and the grain 
is normalized to \( 10^{14} \) cm. Note that this equation is only valid for 
\( T < \text{min}(96 \text{K}, 23000 \mu \text{m}^{-1} \text{K}) \).

As shown in Section 6.2 and Figure 9, the inferred temperature 
for potential circumstellar dust around, e.g., RX J0806.4–4123, 
is in the range of 10–22 K. A dust grain with such temperatures 
would be expected at radii of \( r_d = 2.3 \times 10^{14} a_{30 \mu \text{m}}^{-1/2} \text{cm} \) to 
\( 2.2 \times 10^{15} a_{30 \mu \text{m}}^{-1/2} \text{cm} \), corresponding to \( 1600 a_{30 \mu \text{m}}^{-1/2} \text{AU} \) and

Figure 9. Measured values and upper limits for the IR/submillimeter to X-ray flux ratios for RX J0806.4–4123 (left panel) and constraints on the luminosity and temperature of dust around it (middle and right panel). The flux ratios are from this paper and the literature as described in Figure 8. The luminosity ratios are derived with respect to the bolometric luminosity (which is basically the X-ray luminosity), and the mass is calculated using a distance of 250 pc, which is based on the X-ray absorption (Kaplan & van Kerkwijk 2009; Posselt et al. 2007). The middle panel shows the luminosity constraints for dust emission according to Equation (4). The blue area marks the luminosity ratio range implied by the Herschel 160 \( \mu \)m measurement (white line) and its 5\% uncertainty, and the dashed area indicates the excluded dust luminosities according to our Herschel blue band observations. The red solid and dashed lines show the inferred mass constraints from the Herschel 160 \( \mu \)m measurement. The right panel shows the upper limit on the luminosity ratios as implied for blackbody emitters under optically thin conditions. The shaded area indicates the excluded region for blackbody emitters. Similarly, the hatched area shows the allowed range for the marginal 1.9\% Spitzer 4.5 \( \mu \)m detection; see Section 5.1. Realistic dust disk models require the application of the Mie theory and would result in lower limits in the right panel (see the text). (A color version of this figure is available in the online journal.)
150 $a_{\text{m}}^{-1/2}$ AU, respectively. At a distance of $\approx 250$ pc, this translates into angular sizes of about 6” and 1”, i.e., the source would be still unresolved in the Herschel red band, which is consistent with the observations. Thus, we cannot rule out such temperatures based on the expected emission extension for RX J0806.4–4123. For RX J2143.0+0654, the inferred radii would be a factor of 2.8 larger due to its higher X-ray luminosity, although the angular scales are probably similar because of the likely larger distance of this XTINS. The implied orbital radii of the 22 K dust grains with sizes $a \lesssim 1 \mu m$ are larger than the radii commonly considered for (young and gas-rich) fallback disks, $R_{\text{FD}} \approx 10^{0.8}–10^{1.4}$ cm (e.g., Perna et al. 2014). After removal of the gas in the possible disks around the relatively old INSs, however, the dust is difficult to remove by ISM drag (see also below), and a pure dust or debris disk could, in principle, expand to larger radii. Looking at our own solar system, there are the following reminiscent large structures: the Kuiper Belt and the Oort Cloud with radii from $10^4–10^5$ A.U. (e.g., Dones et al. 2004). The formation of the Kuiper Belt and the Oort Cloud are not fully understood, but in general it is believed that gravitational interactions of belt/cloud objects with the newly formed giant planets were of major importance (Morbidelli et al. 2008; Dones et al. 2004). Survival or formation of giant planets around an NS are unlikely, and a mechanism for the extension of an initial compact fallback disk would be needed if the emitting dust grains are smaller than $10 \mu m$. Constraints on the emitting grain size could be obtained by additional investigations at submillimeter wavelengths.

The smallest grains are the hottest and contribute most to the observed dust luminosity. If, in the case of cicumstellar dust, already $\approx 20\%$ of the NS luminosity is re-emitted by cold dust, but the upper limit at Spitzer wavelengths is less than 1% (because of blackbody assumption; see Figure 9), it follows that there are no significant amounts of small hot dust grains around RX J0806.4–4123. An explanation for this finding could be the effect of the Poynting–Robertson (P-R) drag (Phillips & Chandler 1994). In Figure 10, we plot lines corresponding to the P-R drag and different dust temperatures (for the latter we use Equation (5)). The black line corresponds to the P-R drag limit for a putative disk around an NS with radius of $R_{\text{NS}} = 10$ km and a disk age of 0.5 Myr. Dust grains below that line are removed for the respective radius in a putative disk. We see that small grains close to the NS are effectively eliminated. Dust grains with size $\sim 1 \mu m$ can exist only at radii $r > 3 \times 10^{13}$ cm. In Figure 10, we also plot the effects of the ISM drag experienced by the dust grains when they move together with the NS disk/belt through the ISM (Phillips & Chandler 1994). The ISM drag depends on the inclination of the putative disk/belt with respect to the direction of proper motion. We use different inclination angles. If the putative disk moves edge-on in the direction of the proper motion, the inclination angle is $0\degree$. This assumption allows us to obtain an upper limit for the smallest grain size, represented by the red line in Figure 10. An inclination angle of $89\degree$ corresponds to the putative disk moving nearly face-on in the direction of the proper motion. This scenario is more likely because many NSs have a spin-velocity alignment and angles $< 10\degree$ are most probable. In Figure 10, this scenario is represented by the green line. We assumed a disk age of 0.5 Myr, an NS velocity of 100 km s$^{-1}$, a number density of ISM gas particles $1 \text{ cm}^{-3}$, and a dust grain density of $3 \text{ g cm}^{-3}$ for our calculations. The ISM drag is the dominating force on the dust grains at large distances. Similar to the P-R line, grains below the ISM drag lines in Figure 10 would be removed. In the case of face-on disk motion, this mechanism would remove grains smaller than $\sim 1 \mu m$ at all distances. Overall, it appears likely that any dust around RX J0806.4–4123 consists of predominantly large, $a > 1 \mu m$, grains—if the Herschel emission indeed comes from a dusty torus around the XTINS.

![Figure 10](image.png)

**Figure 10.** Distribution of spherical grains with radius $a$ in $\mu m$ over the distance from the NS, $r$ in cm, for different temperatures and dust removal effects. The blue, cyan, and magenta (all with triangles) lines indicate the temperature a dust grain would have if Equation (5) is applied. The open triangle symbols indicate the region left of which the conditions for Equation (5) are not met. The black line indicates the removal of grains due to the Poynting–Robertson drag. Grains below the black line are expected to be removed at the assumed disk age of 0.5 Myr. Similarly, the green and red lines indicate the effect of the ISM drag that the dust grains experience when they move together with the NS disk through the ISM (Phillips & Chandler 1994); see also the text. (A color version of this figure is available in the online journal.)

### 7. CONCLUSIONS

Using Herschel PACS, we detected 160 $\mu$m emission close to positions of two out of the eight investigated NSs. Herschel PACS 70 $\mu$m, WISE, and Spitzer IRAC observations resulted only in upper flux limits for the positions of the eight NSs. The ratios of the 160 $\mu$m band luminosity to the bolometric luminosity of the respective XTINSs are between 5% and 20%. If these detections are associated with the NSs, they would imply cold ($T_d \approx 20$ K) dusty tori/belts around the NSs. For RX J0806.4–4123, the implied belt radius would be within the range discussed for fallback disks if only large ($a > 10 \mu m$) dust grains are present. The implied dust torus radius is larger for smaller grains (e.g., $r \approx 10^{15}$ cm for $a = 1 \mu m$), raising questions about the formation mechanism of such a dust belt. The higher X-ray luminosity of RX J2143.0+0654 would even imply a factor of three larger torus radius.

There is a 3% probability that both Herschel PACS red band detections are unrelated to the XTINSs, and there is a 33% probability that one of the two is unrelated to the respective XTINS. The relatively large offset of the faint Herschel emission in the case of RX J2143.0+0654 and the possibility of a galaxy counterpart suggest that this detection may be associated with a background galaxy. For RX J0806.4–4123, an interstellar cirrus is an alternative to the dusty-torus hypothesis. Deeper
observations at shorter and longer wavelengths with better spatial resolution could probe whether or not the Herschel 160 μm is associated with the NS.

For the six other NSs, we do not find any significant warm or cold dust emission. The reached flux ratio limits come close to those of bright debris disks around non-degenerate stars considering the warm dust, but for cold dust the Herschel observations are still not sensitive enough to exclude cold disks. In principle, our observations are still consistent with the presence of cold dusty disks around the NSs if one relies on the flux ratios found for other debris disks, which are at least two orders of magnitude smaller than what we achieved here. There is, of course, the other possibility that the XTINSs do not harbor disks, either because they never had them or because they lost them due to the composition of the dust in the disk (e.g., only small dust grains close to the NS). Currently, we cannot differentiate between the cold-disk and no-disk scenarios. Future submillimeter interferometer observations provide an opportunity to test whether or not cold disks are present around these fascinating NSs.

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APPENDIX A

ADDITIONAL RESULTS ON INDIVIDUAL SOURCES

The following subsections present detailed results from the WISE, Spitzer, and Herschel observations for the NSs without any significant IR detections. In contrast to Table 5, no color correction has been applied to the quoted flux limits. The figures have different (manually tweaked) color scales and smoothing (only in the case of Spitzer; usually Gaussian with a kernel radius of 3 pixels), optimized to emphasize faint fluxes in the surrounding of the NS position. Circles in the pictures do not represent error circles. In the case of Spitzer, r = 2′′ (2 native IRAC pixel), the circle has the size of the used photometry aperture. In the case of Herschel and WISE, r = 10′′, they merely indicate the NS position. For an overview about the instrumental FWHM in each individual observing band, we refer to Sections 3 and 4.3. Position uncertainties of the targets and instrumental pointing errors are discussed in Section 3 as well as below if necessary.

A.1. RX J0420.0–5022

There is no IR emission at the position of RX J0420.0–5022 in the Spitzer 4.5 μm IRAC image; see Figure 11. The aperture-corrected 5σ upper limit is \( F_{5\sigma}^{4.5\mu m} = 2.8 \mu Jy \).

At the position of RX J0420.0–5022, we detect no source in the Herschel blue and red band (see Figure 12). Using apertures in different source-free regions and at the target position, we determined the 5σ upper flux limits at the INS position as \( F_{5\sigma}^{blue} = 4.5 \) mJy and \( F_{5\sigma}^{red} = 7 \) mJy. There are several common sources in the Herschel bands and WISE bands W1 to W3. There is no noticeable astrometric shift between these bands. The W1 and W3 images for the field around RX J0420.0–5022 are shown in Figure 13. There is very faint emission east and northwest of the INS in the W3 band, but no entry in the WISE source catalog at these positions. Slightly enhanced emission at the same positions might be suspected in the red band (Figure 12). However, these potential W3 sources are separated by at least 5′′8 from the expected INS position and are therefore unassociated with the INS.

A.2. RX J0720.4–3125

We first consider the Spitzer observations. The IRAC mosaics are very crowded, and there appears to be a faint source close to...
the position of RX J0720.4–3125 (Figure 14). The expected position of the INS at the time of the Spitzer observation, MJD 55582, is $\alpha = 7^h20^m24^s$; $\delta = -31^\circ 25'49''$. It is calculated using the latest, MJD = 54477, optical position of the NS and its proper motion, $\mu_\alpha = -93.2 \pm 5.4$ mas yr$^{-1}$ and $\mu_\delta = 48.6 \pm 5.1$ mas yr$^{-1}$, listed by Eisenbeiss et al. (2010).

The radial positional uncertainty of the expected INS position at the time of the Spitzer observation is 62 mas (90% confidence level). The 1σ astrometric accuracy of the 3.6 $\mu$m and 4.5 $\mu$m mosaics is 0'.27 and 0'.28, respectively (Section 4.2). The faint IRAC 3.6 $\mu$m source closest to RX J0720.4–3125 seems to be a blended source and has a spatial separation of at least 1'.3.

From our previous VLT ISAAC H-band observations (Posselt et al. 2009), two individual NIR sources are known close to the position of the faint IRAC source(s). From the spatial separation and the NIR identification of the faint IRAC source(s), we conclude that the IRAC source is not the counterpart of the INS. Thus, RX J0720.4–3125 is undetected at 3.6 $\mu$m and 4.5 $\mu$m.

To obtain an upper limit, we determine the background level and the standard deviation of 10 source-free apertures close to the source position. We use the residual mosaics (Section 4.2) for these measurements. We chose apex-qa task parameters, which result in a good removal of point sources in the immediate surrounding of the INS. The northern part of the faint blended source close to the INS is detected as individual point sources and removed in both IRAC channels. A small flux enhancement remains in both channels at the position of the southern ISAAC source and slightly increases the derived upper limits, which are computed by the measured source aperture flux above the background plus five times the standard deviation of the 10 source-free apertures (Section 4.2). The aperture-corrected 3.6 $\mu$m and the 4.5 $\mu$m upper flux limits at the position of RX J0720.4–3125 are $F_{3.6\mu m}^{\Upsilon} = 4.9$ mJy and $F_{4.5\mu m}^{\Upsilon} = 4.5$ mJy, respectively.

There is no obvious infrared source in the Herschel blue and red band at the position of RX J0720.4–3125 (see Figure 15). The closest possible source in the red band is at least 6' from the INS position. Using apertures in different source-free regions and at the target position, we determine the 5σ upper flux limits for the INS to be $F_{3.5\mu m}^{\text{red}} = 5.2$ mJy and $F_{4.5\mu m}^{\text{red}} = 9.4$ mJy.

The spatial resolution and sensitivity of the two Spitzer IRAC images are superior to the first two channels of the WISE data, but the W3 and W4 band provide new wavelength coverage. Nothing is seen in W3 or W4 at the position of the INS. Because of the uncertainty in the W4 astrometry, only W3 is shown in Figure 15. The closest, very faint 12 $\mu$m source to the east of the INS has a spatial separation from the INS of ~5'. Given the good astrometric compliance of major W3 sources with...
Spitzer IRAC sources, this faint source is unlikely to be the INS counterpart.

A.3. RX J1308.6+2127

There is no IR emission at the position of RX J1308.6+2127 in the Spitzer 4.5 μm IRAC image; see Figure 18. The aperture-corrected 5σ upper limit is $F_{5σ}^{4.5μm} = 1.6$ μJy.

In the Herschel PACS blue band, there is no significant emission around the position of RX J1308.6+2127; see Figure 17. Using apertures in different source-free regions and at the target position, we determine the 5σ upper flux limit for the INS as $F_{5σ}^{blue} = 1.7$ mJy. In the Herschel PACS red band, there is no significant emission at the position of RX J1308.6+2127, but there is faint emission southwest and west of it (Figure 17). The spatial separation of this faint emission and the XTINS position is 10′. The positional uncertainty of the NS at the 90% confidence level in the Herschel observation is smaller than 0′′7, accounting for the uncertainty of the Chandra position (Kaplan et al. 2002; Hambaryan et al. 2002) and the uncertainty of the proper motion (Motch et al. 2009). We checked for common sources in the Herschel observation, 2MASS point-source catalog, and Spitzer IRAC 4.5 μm data. Based on this comparison, we confirm that the absolute Herschel pointing accuracy is better than 1′′5 for this observation, as expected from the works by the Herschel calibration and HIPE teams (see above). Thus, all the faint sources in the Herschel PACS red band can be excluded as INS counterparts. Using apertures in different source-free regions and at the target position, we determine the 5σ upper flux limit in the red band for the INS as $F_{5σ}^{red} = 5.2$ mJy.

We compared the WISE W1–W3 data to the Spitzer IRAC 4.5 μm data. There is no noticeable astrometric shift between Spitzer IRAC 4.5 μm and WISE W1 and W2. For WISE W3, there are only few clear common sources, and three of them are 2MASS point sources. There is no noticeable astrometric shift for these sources. Interestingly, there is faint emission in WISE W3 at a position consistent with the INS position within positional accuracy; see Figure 18. There is no source reported in the WISE All-Sky Source Catalog at this position, and no such emission is seen in any other WISE band, the Spitzer IRAC 4.5 μm, or the Herschel PACS bands. Due to its faintness, the W3 emission can be a noise feature. Confirmation by similar observations is necessary before any conclusions regarding the INS can be drawn. In principle, emission at such wavelengths is particularly interesting, because—if real—it could indicate potential silicate emission in the 8–12 μm region reminiscent of white dwarf debris disks (e.g., in the case of the spectacularly debris-polluted white dwarf GD 362, one-third of the debris disk emission is carried by a strong 10 μm silicate emission feature; Jura et al. 2007).

A.4. RX J1605.3+3249

There is very faint IR emission at the position of RX J1605.3+3249 in the Spitzer 4.5 μm IRAC image; see Figure 19. However, the INS position is located between two IR sources whose PRFs affect any measured flux at the INS position. We found that the faint 4.5 μm emission has a significance of only 1.3σ if we employ PRF subtraction of the two sources in the vicinity (2.9σ otherwise). Hence, there is no significant emission at 4.5 μm from the INS. The aperture-corrected 5σ upper limit is $F_{5σ}^{4.5μm} = 3.6$ μJy.

There are several common sources in the Herschel bands and WISE bands W1–W3. There is no noticeable astrometric shift between these bands. There is no source in the Herschel blue and red bands at the position of RX J1605.3+3249 (see Figure 20). North of the INS, there is a faint source in the red band that is at least 5′′6 separated from the expected INS position and is therefore unassociated with the INS. Using apertures in different source-free regions and at the target position, we determine the 5σ upper limits as $F_{5σ}^{blue} = 6.1$ mJy and $F_{5σ}^{red} = 12.2$ mJy.
of the determined positions are better than 0.1\′. The astrometry of the Spitzer IRAC2 (4.5 μm) image of RX J1856.5–3754 is well aligned with the astrometry of previous H-band observations (Figure 22). There is no prominent emission centered at the expected INS position, but there is strong IR emission north of RX J1856.5–3754, starting at \approx 1′′ from the INS. From the NIR, we know this source consists of at least four individual sources that are, however, not discernible with Spitzer. We were not able to completely remove the IR emission of these northern sources by PRF fitting. Thus, our subsequently derived aperture-corrected 5σ upper limit for RX J1856.5–3754, \( F_{\text{5σ}}^{4.5 \text{μm}} = 11.6 \text{ mJy} \), is a very conservative estimate.

Comparing Herschel PACS and WISE sources, we were not able to identify enough unique common sources to check the astrometry of the Herschel observations. Therefore, we assume the astrometric error to be the absolute pointing error of \approx 2′.4. This value was listed by the Herschel calibration team as the average value for a time window that includes our observations.\(^{21}\) In the Herschel blue band, there is very faint emission at \approx 4′.6 northeast from the INS position. In the Herschel red band, the INS position is located within a larger faint emission region that probably consists of several sources and extends to the northeast and north (see Figure 23). We cannot exclude that the INS contributes to the faint PACS 160 μm band emission. However, it appears likely that most of that emission actually comes from the same NIR sources that are also detected by Spitzer. We measured the flux at the INS position in an aperture with radius 5″. The aperture-corrected flux is \( F_{\text{ap}}^{\text{red}} = 3.1 \text{ mJy} \), which corresponds to \approx 3σ above the background. The nominal 5σ flux limit for the position of RX J1856.5–3754 in the red band is \( F_{\text{5σ}}^{\text{red}} = 7.8 \text{ mJy} \). In the blue band, we used apertures in different source-free regions and at the target position to determine the 5σ upper flux limit at the INS position as \( F_{\text{5σ}}^{\text{blue}} = 7.7 \text{ mJy} \).

Comparing sources in the WISE W1–W3 band images with H-band sources from a deep VLT observation (Posselt et al. 2009), there is no apparent astrometric shift between these bands (see Figure 24). The IR sources observed with W1 and W2 correspond to the ones seen with Spitzer IRAC 4.5 μm. Nothing is detected around the INS position in W3.

\(^{21}\) herschel.esac.esa.int/twiki/bin/view/Public/SummaryPointing
The position of PSR J1848–1952 at MJD 48695 is known with a 2σ accuracy of 0.6 arcmin in right ascension, but 7″ in declination (Hobbs et al. 2004). The proper motion is unknown for this pulsar. PSR J1848–1952 was recently observed for 38 ks with XMM-Newton (ObsId: 0653300101, PI: Kaspi). Unfortunately, the pulsar was not detected (Olausen et al. 2013), and the closest X-ray source to the pulsar radio position has an angular separation of ≈1.65. Thus, the X-ray observations cannot be used to determine the current position of PSR J1848–1952 with higher accuracy. Hobbs et al. (2004) gave the following proper motion values: $\mu_\alpha\cos\delta = 39(157)$ mas year$^{-1}$ and $\mu_\delta = -1200$ (1900) mas year$^{-1}$. While the error in declination is too large to be used for a reasonable upper limit on the expected pulsar proper motion, we use the error in right ascension to determine the maximal angular separation of the possible pulsar position in this direction at the time of the Herschel observation as 3′ (2σ). The mean 2D speed of pulsars is $\approx 250$ km s$^{-1}$, and PSR B2224+64 has the highest inferred 2D speed of $\approx 1600$ km s$^{-1}$ (Hobbs et al. 2005). We assume this most extreme 2D speed to determine the maximal expected shift in declination for PSR J1848–1952. Its DM = 18.23 cm$^{-3}$ pc translates to a distance of 750 pc using the NE2001 model for the Galactic distribution of free electrons (Cordes & Lazio 2002). We estimate the upper limit of the proper motion of PSR J1848–1952 as 0.045 yr$^{-1}$. Thus, at the time of the Herschel observation, the maximal expected shift is 9″. We assume this value as the upper limit on the proper motion in the direction of declination.

The sky region around PSR J1848–1952 is densely populated with infrared sources. Comparing 2MASS, WISE, and our Herschel observation, it is difficult to pin down common sources. However, we found at least three common sources between these bands. From the comparison of their positions, the expected absolute pointing error of 1′′1 for the Herschel observation seems to be a reasonable estimate. There is no source in the Herschel blue and red band at the position of RX J1848–1952 (see Figure 25). There is a faint southern source that is inside the box of proper motion upper limits. However, this source has a counterpart in other bands, in particular in 2MASS. Therefore, it is not the counterpart of the pulsar. Using apertures in different source-free regions and at the target position, we determine the 5σ upper flux limits at the INS position as $F_{\text{blue}}^\text{5σ} = 3.6$ mJy and $F_{\text{red}}^\text{5σ} = 5.9$ mJy.

The WISE W1 and W3 images for the field around PSR J1848–1952 are shown in Figure 26. Except for the southern 2MASS source, there is no WISE point source detected in the region of PSR J1848–1952.

### APPENDIX B

#### TEMPERATURE DISTRIBUTION OF DUST AROUND A NEUTRON STAR

We know from X-ray and UV observations of XTINSs that their radiation can be approximately described as blackbody radiation with temperatures $kT_{\text{NS}} = 40–100$ eV (i.e., $T_{\text{NS}} = 0.5–1.2 \times 10^6$ K; see, e.g., Haberl 2007). This radiation heats the dust grains around a XTINS. If collisions of a grain with surrounding particles can be neglected, its temperature $T_g$ is determined by the balance between the radiative heating and cooling (e.g., Backman & Paresce 1993):

$$\left(\frac{R_{\text{NS}}}{r}\right)^2 \int_0^\infty \epsilon_v^\text{abs}(a)\pi B_v(T_{\text{NS}}) \, dv = 4 \int_0^\infty \epsilon_v^\text{em}(a)\pi B_v(T_g) \, dv,$$

where $R_{\text{NS}}$ is the stellar radius; $r$ is the distance of the spherical grain with radius $a$ to the NS; $B_v(T)$ is the Planck function in dependence on the NS surface temperature, $T_{\text{NS}}$, or the grain temperature $T_g$; and $\epsilon_v^\text{abs}(a)$ and $\epsilon_v^\text{em}(a)$ are the grain’s absorption and emission efficiencies, which depend on the radiation wavelength (frequency), the grain size, and the properties of grain material.

If the grain radius $a$ is much larger than the wavelength of the heating radiation (e.g., $a \gg 0.03$ μm for $T_{\text{NS}} = 0.5 \times 10^6$ K),

![Figure 24](image_url) WISE W1 (3.6 μm) and W3 (12 μm) maps around the position of RX J1856.5–3754. The same field of view is shown as in the Herschel PACS maps of Figure 23. The white contours in the W1 image are from the VLT ISAAC H-band image (Posselt et al. 2009).

![Figure 25](image_url) Herschel PACS maps around PSR J1848–1952. The blue (60–85 μm) and red (130–210 μm) bands are shown in the left and right panels, respectively. Each map is $2' \times 2'$; north is up and east is to the left. The circle with a radius of 10″ marks the pulsar position, and the $7'4 \times 32''$ box shows the upper limits of the unknown proper motion together with the radio position uncertainty (see the text).

![Figure 26](image_url) WISE W1 (3.6 μm) and W3 (12 μm) maps around the position of PSR J1848–1952. The same field of view is shown as in the Herschel PACS maps of Figure 25. The white boxes in W1 mark the positions of the 2MASS point sources. The circle with a radius of 10" marks the pulsar position, and the $7'4 \times 32''$ box shows the upper limits of the unknown proper motion together with the radio position uncertainty (see the text).
the absorption efficiency can be approximated as \( \varepsilon_v^\text{abs} \approx 1 \), i.e., the grains are nearly perfect absorbers. For the UV and soft X-rays considered here, this approximation is consistent with the detailed calculations by, e.g., Dwek & Smith (1996). At large distances from the XTINS, we expect cold dust grains, which emit long-wavelength radiation and are inefficient emitters. In the Rayleigh limit, \( \lambda \gg 2\pi a \) (or \( \nu \ll c/(2\pi a) \)), the emission efficiency of a dielectric grain is (e.g., Seki & Yamamoto 1980)

\[
\varepsilon_v^\text{em} \approx \frac{8\pi a v}{c} \Im \left[ \frac{\varepsilon_v - 1}{\varepsilon_v + 2} \right] = \frac{2\pi a v}{c} \left( \frac{2n_v k_v}{(n_v^2 - k_v^2 + 2)^2 + 4n_v^2 k_v^2} \right) \ll 1, \tag{B2}
\]

where \( \varepsilon_v = (n_v + ik_v)^2 \) is the dielectric constant and \( k_v \) and \( n_v \) are the imaginary and real parts of the complex refractive coefficient of the grain material. The quantities \( n_v \) and \( k_v \) depend on the grain’s chemical composition, and their dependence on \( \nu \) can be quite complex, including resonances at some frequencies/wavelengths (e.g., at \( \lambda \approx 10 \) and \( \approx 20 \mu m \) for silicate grains; see Dorschner et al. 1995). However, at wavelengths well above the resonance wavelength, \( k_v \) and \( n_v \) show a universal frequency dependence:

\[
n_v = n, \quad k_v = k_0(v/\nu_0) \ll n, \quad \text{at} \quad \nu < \nu_0, \tag{B3}
\]

where \( \nu_0 \) is a frequency below the lowest resonance frequency, and \( k_0 \) is a constant that depends on the grain composition. Using these expressions for \( k_v \) and \( n_v \), it is convenient to parameterize the long-wavelength emission efficiency as follows:

\[
\varepsilon_v^\text{em} = \varepsilon_0 (v/\nu_0)^2 \tag{B4}
\]

where

\[
\nu_0 = \left( \frac{\nu_0 c}{2\pi a} \right)^{1/2}, \quad \varepsilon_0 = \frac{2n}{(n^2 + 2)^2} k_0 \tag{B5}
\]

(the last equation takes into account that \( k_v \ll n \) in this limit). Substituting the above equations for \( \varepsilon_v^\text{abs} \) and \( \varepsilon_v^\text{em} \) into Equation B1, we obtain

\[
T_g = \left[ \frac{21}{640\pi^3} \frac{L_{\text{NS}}}{\sigma_{\text{SB}}^2 v_0} \left( \frac{h v_0}{k} \right)^2 \right]^{1/6} = \left[ \frac{21}{640\pi^3} \frac{L_{\text{NS}}}{\sigma_{\text{SB}}^2 v_0^2} \frac{h^2 c v_0}{2\pi k^2 a} \right]^{1/6}, \tag{B6}
\]

where \( \sigma_{\text{SB}} \) is the Stefan–Boltzmann constant and \( L_{\text{NS}} = 4\pi R_{\text{NS}}^2 \sigma_{\text{SB}} T_{\text{NS}}^4 \) is the star’s bolometric luminosity. These equations are applicable when three conditions are fulfilled: \( \varepsilon_v < 1 \), \( \nu < \nu_0 \), and \( \nu < c/(2\pi a) \), where \( \nu \sim 3kT/h \). The quantities \( \varepsilon_0 \) and \( \nu_0 \) in Equation (B6) can be evaluated from measurements of optical properties of grain material for a chosen \( \nu_0 \). Using measurements for amorphous magnesium silicate dust grains as listed in the Jena Database of Optical Constants for Cosmic Dust, we obtain \( \varepsilon_0 = 0.36 \) for \( \nu_0 = 6 \times 10^2 \) Hz (corresponding to the Herschel red band wavelength of 160 \( \mu m \)). This gives the following estimate for the temperature at distance \( r \):

\[
T_g = 39 \left( \frac{L_{30}}{r_{14}^2 a} \right)^{1/6} \text{K}, \tag{B7}
\]

where \( L_{30} \) is the bolometric NS luminosity in units of \( 10^{30} \) erg s\(^{-1} \), \( a \) is the grain radius in \( \mu m \), and \( r_{14} \) is the distance from the NS in units of \( 10^{14} \) cm. This equation is valid for \( T < \text{min} (96 \text{ K}, 2300a^{-1/2} \text{K}) \).
