Searching for Debris Disks around Isolated Pulsars

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Abstract

Different pieces of observational evidence suggest the existence of disks around isolated neutron stars. Such disks could be formed from supernova fallback when neutron stars are born in core-collapse supernova explosions. Efforts have been made to search for disks around different classes of pulsars, which include millisecond pulsars, young neutron star classes (magnetars, central compact objects, and X-ray dim isolated neutron stars), and regular radio pulsars. We review the main results from observations at wavelengths of from optical to sub-millimeter/millimeter.

Keywords: Pulsars, Debris Disks, Infrared

1. Introduction

It has long been suggested that isolated pulsars (PSRs) might have disks and the existence of disks would affect evolution of pulsars and help explain some observed features in pulsars [Michel and Dessler, 1981]. The discovery of a planetary system around PSR B1257+12 (Wolszczan and Frail, 1992), which actually was the first discovered extrasolar planetary system, motivated numerous studies about how such a planetary system could be formed. The proposed formation mechanisms more or less involved the existence of an accretion/debris disk around the neutron star (see Miller and Hamilton, 2001 and references therein). To date, two additional pulsars, B1620−26 and J1719−1438, have been found with planetary systems, although the first is a triple system in the globular cluster M4 likely having been formed from a dynamical exchange interaction (Sigurdsson et al., 2003 and references therein),
and in the second the planet-mass companion is probably the leftover of a
carbon white dwarf having lost most its mass during the phase of low-mass
X-ray binary evolution (Bailes et al., 2011). In addition to these three pul-
sars, Shannon et al. (2013) recently have shown that the observed, long-term
timing variations for PSR B1937+21 are possibly explained by considering
an asteroid belt around the pulsar.

The above neutron stars are old (ages > $10^8$ yrs), so-called recycled pul-
sars with fast, millisecond spin periods. For regular pulsars formed from
core-collapse supernovae for $10^3$–$10^6$ yrs, rotational spin noise (i.e., timing
noise) in them is several orders of magnitude larger than that in millise-
ccond pulsars (MSPs) (e.g., Shannon and Cordes 2010). It is thus difficult to
detect planetary bodies around them from pulsar timing. However certain
phenomena have been seen hinting the existence of accretion/debris disks.
Cordes and Shannon (2008) summarize four types of pulsar pulse emission
variations: nulling, transient pulse emitting from so-called rotating radio
transients (RRATs; McLaughlin et al. 2006), subpulse drifting, and emission
mode changing, and consider that these phenomena are caused by migration
def circumpulsar debris material into the magnetospheres of pulsars. In in-
dividual pulsars, for example, the recent measurement of the second period
derivative of the spin of PSR J1734−3333 suggests that the magnetic field of
this pulsar is increasing (Espinoza et al., 2011), or alternatively its spin prop-
eties might be affected by having an accretion disk (Çalisko et al., 2013).
It has also been suggested that because jets are generally associated with
accretion disks, young pulsars seen with jets might harbor accretion disks
(Blackman and Perna, 2004).

While it is not very clear how disks around MSPs would be formed
(e.g., Shannon et al. 2013), particularly for the planetary system case around
B1257+12 (Miller and Hamilton, 2001), young pulsars are believed to possibly
have disks due to supernova fallback (Chevalier, 1989). During a core-
collapse supernova explosion, part of ejected material may fallback and if the
material has sufficient angular momentum, a disk might be formed around
the newly born neutron star (Lin, Woosley and Bodenheimer, 1991). The
existence of fallback disks has been suggested to be the cause of the diver-
sity of young neutron stars (Alpar 2001, Alpar, Çalisko and Ertan, 2013 and
references therein). Unlike what was once thought—young radio pulsars like
those in the Crab and Vela supernova remnants were prototypical of new-
born neutron stars, it has been realized that there are classes of magnetars
(Woods and Thompson, 2006), central compact objects (CCOs) in young
supernova remnants (Pavlov, Sanwal and Teter, 2004; de Luca, 2008), and X-ray dim isolated neutron stars (XDINSs; Turolla 2009; Mereghetti 2011). The latter three classes of young neutron stars are rather ‘quiet’ at multiple wavelength regions from optical to radio: they generally do not have strong non-thermal emission and are not surrounded by any bright, pulsar-wind powered nebulae.

Neutron stars generally have non-thermal emission radiated from their magnetospheres, and sometimes a thermal component arising from their hot surfaces may be seen (e.g., Becker 2009; note that the thermal emission can be dominant in some cases). The non-thermal emission can be described by a power law with flux decreasing from X-ray to optical/IR wavelengths, while because of their $\sim 10^6$ K surface temperature, the thermal component’s Rayleigh-Jeans tail may be detectable at ultraviolet/optical wavelengths (e.g., Kaplan et al. 2011). As a result, among $\sim 2000$ known neutron stars (Manchester et al., 2005), only over 20 neutron stars have been detected at optical/IR wavelengths. For a comparison, a disk would have thermal-like emission, and depending on temperature, which is often assumed to be a function of disk radius, the disk would be generally bright at optical/IR wavelengths (Perna et al. 2000). Emission from putative disks would thus be distinguishable from that of neutron stars. In addition, if a debris disk consists of cold, $\leq 100$ K dust, it would also possibly be detectable at submillimeter (submm) and millimeter (mm) wavelengths (Phillips and Chandler, 1994).

Given all these reasons, searches for disks around neutron stars have been carried out with different telescopes. The goal of the searches is to find thermal-like emission from neutron stars at wavelengths of from optical to submm/mm, which is not expected to be radiated from neutron stars themselves. In this paper, we review the current status of searches and provide a summary of the main results. It should be note that since young neutron stars (for example the magnetars that are covered in this paper) may exhibit strong variability (e.g., Kaspi 2007), and hence (nearly) simultaneous observations at multiple wavelengths are often required in order to identify the source of emission.
2. Searches for Disks around Different Classes of Neutron Stars

2.1. Millisecond pulsars

Motivated by the discovery of planets around B1257+12, searches for debris disks (particularly) around similar old pulsars were made (e.g., van Buren and Terebey 1993; Foster and Fischer 1996; Koch-Miramond et al. 2002; Lazio and Fischer 2004). The observations were carried out with either first generation infrared space telescopes (namely the Infrared Astronomical Satellite and the Infrared Space Observatory) or ground-based telescopes, and sensitivities were very limited, generally around 100 mJy at mid-infrared (MIR) wavelengths of \( \sim 10–100 \, \mu \text{m} \). With simplified assumptions for dust grains and pulsar-wind heating of dust, the estimated surrounding dust mass would be lower than 30 \( M_\oplus \), for example, for the case of B1257+12 (Foster and Fischer, 1996).

Launched in 2003, Spitzer Space Telescope provided observing capabilities of imaging and spectroscopy at MIR wavelengths with sensitivities of from \( \mu \text{Jy} \) to mJy. Bryden et al. (2006) reported their search for debris material around B1257+12 with Spitzer MIPS observations. The sensitivities were improved by 3 orders of magnitude comparing to those of the previous searches. No IR emission was detected and they concluded that an asteroid belt of 0.01 \( M_\oplus \), similar to that in the solar system, cannot be ruled out.

Efforts were also made at submm/mm wavelengths (Phillips and Chandler, 1994; Greaves and Holland, 2000; Löhmer et al., 2004), but comparing to those at IR wavelengths with temperature \( T \geq 300 \, \text{K} \) dust as the targets, the searches aimed to detect colder, \( T \sim 30 \, \text{K} \) dust material around nearby MSPs. The typical sensitivities reached were \( \sim 5 \, \text{mJy} \) at bands within 0.8–3.0 mm, and mass limits of \( \leq 10 \, M_\oplus \) were obtained. Since the dust is optically thin at submm/mm, the mass limits are rather certain, not depending on disk structures which have to be assumed in optically thick disk cases.

2.2. Young neutron-star classes

2.2.1. Magnetars

Magnetars are considered to be young neutron stars with ultra-high, \( \sim 10^{14} \) to \( 10^{15} \) Gauss surface magnetic fields, although recent studies of the magnetars SGR 0418+5729 and J1822.3−1606, the surface magnetic fields of which were shown to be in the range of regular young radio pulsars \( 10^{12}–10^{13} \) Gauss), challenge the conventional view (Rea et al., 2010, 2012). Around the year 2000, detailed theoretical studies of fallback disks around young neutron stars, particularly around magnetars and CCOs given their quietness at
multiple wavelength regions, strongly suggested possible detections of them at optical and IR wavelengths (Chatterjee, Hernquist and Narayan, 2000; Perna, Hernquist and Narayan, 2000; Menou, Perna and Hernquist, 2001). A disk would be bright due to either internal viscous heating or irradiation by X-rays from the central neutron star. The discovery of the optical and near-IR (NIR) counterpart to the magnetar 4U 0142+61 by Hulleman, van Kerkwijk and Kulkarni (2000) seemed to have matched the theoretical expectations. However, follow-up optical timing of this magnetar by Kern and Martin (2002) found that its optical emission is pulsed at its spin period with 27% pulsed fraction. Such highly pulsed emission, when considering 4%–14% pulsed fraction in the magnetar’s X-ray emission (Gonzalez et al., 2010), is unlikely to originate from a disk.

Figure 1: Optical and IR broad-band and Spitzer IRS spectrum of the magnetar 4U 0142+61 (Wang, Chakrabarty and Kaplan, 2008b). The squares are the optical, near-IR, Spitzer IRAC 4.5/8.0 μm broadband fluxes (dereddened with $A_V = 3.5$ mag), showing that the optical spectrum is consistent with being a power law (dotted line), $F_\nu \propto \nu^{0.3}$, and the IR spectrum can be fit with an X-ray irradiated dust disk model (dash-dotted curve). The diamonds are the dereddened IRS flux measurements, which appear as a bump when compared to the dust disk model SED and can be fit with a silicate emission feature (dashed curve; Sloan et al. 2003). The Spitzer MIPS 24 μm upper limit is also included in the figure.
In their systematic, deep search for disks around several magnetars and CCOs with the ground-based Magellan telescopes at optical and NIR wavelengths and Spitzer at MIR wavelengths, the magnetar 4U 0142+61 was detected by Wang, Chakrabarty and Kaplan (2006) at Spitzer 4.5 and 8.0 µm bands. Combined with the previous optical and NIR measurements, the spectral energy distribution (SED) of this magnetar from optical to MIR wavelengths was constructed and it likely contains two components: one a power-law spectrum over optical VRI and NIR J-bands, probably arising from the magnetosphere of the pulsar, and one thermal blackbody-like over the 2.2–8 µm range, arising from a debris disk (Wang, Chakrabarty and Kaplan 2006; see also Figure 1). The disk should probably have a size of 2.8 $R_\odot$ to 7.5 $R_\odot$, estimated from fitting the IR component with an X-ray irradiated dust disk model. Followup Spitzer spectroscopy at 7.5–14 µm detected the magnetar with very low signal-to-noise ratios but imaging at 24 µm did not, and the results from the both observations are consistent with the dust disk model (Wang, Chakrabarty and Kaplan 2008b; Figure 1).

The magnetars are sources located at the Galactic plane, and thus extinctions to them are large, making optical detections of them difficult. The magnetar 1E 2259+586 was the second one found with an NIR counterpart but only at $K_s$ band (2.1 µm; Hulleman et al. 2001). After an X-ray outburst of the source in 2002, its $K_s$ flux was observed to have an initial increase and then decrease in concert with the X-ray flux (Tam et al., 2004). On the basis of the results, Tam et al. (2004) suggested a neutron star magnetosphere origin for NIR emission, but it should be noted that the existence of a disk could also be the link for such correlated flux variations, which was pointed out and tested on 4U 0142+61 by Wang and Kaspi (2008). Deep Spitzer MIR imaging detected the counterpart to 1E 2259+586 at 4.5 µm band, and on the basis of the two detections, overall IR emission from the magnetar was determined to be similar to that from 4U 0142+61, suggesting the possible existence of a debris disk (Kaplan et al., 2009).

The magnetar 1E 1048.1−5937 was the third one discovered with an NIR counterpart (Wang and Chakrabarty, 2002), and the initial detection was likely associated with an X-ray flare of this magnetar in 2002 (Israel et al., 2002; Durant and van Kerkwijk, 2005). No MIR counterparts were found with Spitzer imaging at 4.5, 8.0, and 24 µm, although the derived flux upper limits were not very constraining (Wang, Kaspi and Higdon, 2007b). In 2007, another X-ray flare was found occurring, with the X-ray flux approximately 3 times higher than that when the source was in the quiescent state (Tam et al.)
Deep optical, NIR, and MIR observations during this flare revealed that the optical and NIR fluxes were correlated with the X-ray flux, but no MIR emission was detected (Wang et al., 2008a). The MIR flux upper limit at 4.5 $\mu$m was sufficiently deep that similar MIR emission to that from 4U 0142+61 was excluded.

Magnetars are characterized by occasional high-energy outbursts or flares (e.g., Kaspi 2007), and new members have thus been discovered. Optical and NIR observations were often carried out once such outbursts/flares were identified by X-ray space telescopes. Among 21 confirmed magnetars (Mcgill SGR/AXP Online Catalog; Olausen and Kaspi 2013), three other magnetars were confirmed with NIR counterparts during their outbursts: SGR 0501+4516 (Dhillon et al., 2011), SGR 1806−20 (Israel et al., 2005), and XTE J1810−197 (Camilo et al., 2007; Testa et al., 2008). The NIR detections benefited from their emission brightening during outbursts, and for SGR 0501+4516 a possible 20% pulsed emission at $K$ band was detected (Dhillon et al., 2011). The nature of the NIR emission is not clearly understood. In addition, the magnetars 1RXS J170849.0−400910 and XTE J1810−197 were also searched for their MIR counterparts with Spitzer, but the observations were not sufficiently deep and sub-mJy flux upper limits at 4.5 $\mu$m, 8.0 $\mu$m, and 24 $\mu$m were obtained (see Figure 2; Wang, Kaspi and Higdon 2007b).

2.2.2. CCOs

CCOs were probably the best neutron star candidates to be searched for fallback disks. They appear to have no non-thermal magnetospheric emission, no pulsar wind nebulae, and be radio quiet, drastically different from Crab-pulsar–like young radio pulsars (see Gotthelf, Halpern and Alford 2013 and references therein). Deep optical and IR observations are therefore not interfered by strong emission such as that from the Crab pulsar and its nebula, and are sensitive. In addition, since they are located near the centers of young (∼10³ yr) supernova remnants (SNRs), their ages and distances are relatively certain. However deep searches have failed to detect optical/IR counterparts in any of them (Fesen et al., 2006; Wang et al., 2007a; Mignani et al., 2007, 2008, 2009; de Luca et al., 2011). The obtained optical and NIR upper limits of 26–28 mag and 21-24 mag, respectively, generally rule out the existence of accretion disks, if considering X-ray emission from CCOs is powered by accreting from them (Wang et al., 2007a; Mignani et al., 2008; de Luca et al., 2011).
Figure 2: Upper limits on the Spitzer/IRAC 4.5 µm to X-ray (in the 2–10 keV range) flux ratios of the magnetars 1E 1048.1−5937, 1RXS J170849.0−400910, and XTE J1810−197. Fluxes of them are unabsorbed, and $A_V = 5.6, 7.7,$ and 3.6 are used for dereddening the 4.5 µm flux upper limits of the three magnetars, respectively. The error bar near 1E 1048.1−5937 indicates the uncertainty on its upper limit due to its X-ray variability. The upper limits are above the dashed line, which indicates the flux ratio of the magnetar 4U 0142+61, suggesting that the observations were not sufficiently deep.

Deep Spitzer imaging of the CCOs RX J0822.0−4300 (in the SNR Puppis A), 1E 1207.4−5209 (in the SNR PKS 1209−52), and CXOU J232327.8+584842 (in the SNR Cas A) were carried out at 4.5 µm and 8.0 µm bands, with no MIR counterparts detected (Wang et al. 2007a; Kaplan, Chakrabarty and Wang 2013). Comparing to the 4U 0142+61 dust disk case, Wang et al. (2007a) argued that if dust disks exist around them, because their X-ray luminosities are two orders of magnitude lower than that of 4U 0142+61, the non-detection could be due to their relatively weak irradiation fluxes.

2.2.3. XDINSs

There are seven XDINSs discovered by ROSAT all-sky X-ray survey, which have properties characteristic of a class of their own. They are nearby (100–500 pc) and young ($< 1$ Myr), and generally have only thermal emission. Intensive studies of them were conducted, and they are thought, arguably,
to be linked to magnetars as their inferred magnetic fields are of the order of $10^{13}$ G and their luminosities are comparable or even greater than their rotational energy loss rates (so-called spin-down luminosities). For detailed reviews of these neutron stars, see Haberl (2007) and Kaplan (2008).

The ultraviolet/optical counterparts to the seven stars have all been identified. However, the detections indicate that the emission is very likely the Rayleigh-Jeans tail of the surface thermal emission, although detailed properties are not fully understood (e.g., Kaplan et al. 2011). Deep searches for their IR counterparts were carried out, with surrounding disks as the main targets (Lo Curto et al. 2007; Mignani et al. 2008). No counterparts were found and the flux upper limits were 20–23 mag at NIR $H$ or $K_s$ bands. In addition, for the purpose of searching for substellar companions to these neutron stars, Posselt et al. (2009) conducted similar searches and similar upper limits were obtained. Given the low X-ray luminosities of XDINSs ($L_X \sim 10^{31}–10^{32}$ erg s$^{-1}$), Lo Curto et al. (2007) found that a hypothetical accretion disk would be bright due to internal viscous heating by using the fallback disk models given by Perna et al. (2000). The derived upper limits on the inflow rates of the hypothetical disks were $\sim 10^{-10} M_\odot$ yr$^{-1}$. It should be noted that due to their slow rotation and thus possibly large inner disk radii (i.e., equal to either corotation radius or light cylinder radius; Lo Curto et al. 2007), the inflow-rate upper limits are not very constraining. As a comparison, low-mass X-ray binaries known in our Galaxy, which include those that contain accreting neutron stars, have the order of magnitude mass-inflow rates in their accretion disks and their disks are easily detectable at optical wavelengths.

In addition, Posselt et al. (2010) conducted a search for submm emission from RX J1856.5–3754, the brightest and closest member among the seven XDINSs. No counterpart was found. The flux upper limit was 5 mJy, setting an upper limit of a few Earth masses on the cold, optically thin dust or a mass accretion limit of $< 10^{14}$ g s$^{-1}$ on the basis of the disk model given by Perna et al. (2000).

2.3. Regular pulsars

Efforts have also been made to investigate the possible existence of debris disks around regular radio pulsars, the major class among neutron stars thus far known (Manchester et al. 2005). Their main energy output is a pulsar wind which is basically in a form of high-energy particles and whose luminosity is limited by the spin-down luminosity $L_{\text{sd}}$ of a pulsar. As a
result, the interaction would be between the pulsar wind and the surrounding disk. Calculations about the possible interaction processes were given \cite{Foster1996, Jones2007, Jones2008, Cordes2008}.

With the purpose of searching for cold dust disks, several nearby (distances generally lower than 500 pc) regular pulsars were often included along with MSPs as the targets \cite{Phillips1994, Koch-Miramond2002, Lohmer2004}. No counterparts were found, and the obtained flux upper limits and mass limits on putative disks are similar to those given in Section 2.1.

Recently Danilenko et al. \cite{Danilenko2011} have found a candidate IR counterpart to the Vela pulsar from Spitzer imaging at 3.6 and 5.8 \(\mu\)m. If it is confirmed, the IR emission would likely indicate the existence of a debris disk around the middle-aged (spin-down age is 11 kyr) pulsar and provide a certain case for our understanding of the appearance of debris disks around regular radio pulsars. The Vela pulsar has \(L_{sd} = 6.9 \times 10^{36} \text{ erg s}^{-1}\) and \(L_X \approx 5.3 \times 10^{32}\) \cite{Paylov2001} and is at a distance of 287 pc \cite{Dodson2003}, which imply fractions of \(2.4 \times 10^{-8}\) or \(3.2 \times 10^{-4}\) (at 5.8 \(\mu\)m) when its \(L_{sd}\) or X-ray emission is considered, respectively. The value from considering X-ray heating is very similar to that in the 4U 0142+61 case (see Figure 2), suggesting that X-ray heating probably plays the key role in making a debris disk detectable.

Having selected those relatively young (ages of several tens of kyr) and supposedly bright (i.e., high \(L_{sd}/d^2\) values, where \(d\) is the estimated distance for a pulsar) as the targets among the known radio pulsars, Wang et al. \cite{Wang2014} carried out ground-based NIR \(K\)-band imaging of nearly 20 such pulsars. On the basis of the results from \(K\)-band imaging, which helped further select out those pulsars in non-crowded fields as targets since source confusion at IR could be a severe problem for counterpart identification, seven pulsars were imaged with Spitzer at 4.5 and 8.0 \(\mu\)m. No IR counterparts were found. The flux upper limits for PSR J0729−1448 are shown in Figure 3. This pulsar has \(F_{sd} = L_{sd}/(4\pi d^2) = 1.2 \times 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2}\), where \(d = 4.4 \text{ kpc}\) is used, and is taken as a typical example as other pulsar targets have similar properties \cite{Wang2014}. The Wide-field Infrared Survey Explorer (WISE) band 1, 3 and 4 (for WISE observations, see below) flux upper limits are also included. Simply assuming a fraction \(\eta\) of the energy flux from the pulsar would be re-radiated by a disk at the IR bands, \(\eta F_{sd} = \nu F_{\nu}\), where \(F_{\nu}\) is the flux density at a band of frequency \(\nu\), the upper limits reached \(\eta \sim 5 \times 10^{-4}\) at 20 \(\mu\)m and \(\eta \approx 5 \times 10^{-6}\) at 4.5 \(\mu\)m. The first fraction value is nearly as
Figure 3: Observed ground-based $K_s$ (diamond), Spitzer (triangles), and WISE (squares) flux upper limits of PSR J0729−1448. Different fraction values of $F_{sd}$ are indicated by dotted lines. Emission from a debris-disk model is displayed by the dashed curve.

Deep as that for the planetary system PSR B1257+12 obtained from Spitzer MIPS observations (Bryden et al., 2006) and the latter is at least one order of magnitude deeper than that of the disk case of the magnetar 4U 0142+61 ($\eta \sim 10^{-4}$; Figure 2). Cordes and Shannon (2008) have proposed that X-ray emission from a neutron star provides heating of a debris disk. If this is the case, assuming $L_X \approx 10^{-3} L_{sd}$ (Becker and Truemper 1997) the fraction reached at 4.5 $\mu$m would be $5 \times 10^{-3}$, actually not sufficiently deep in comparison with the 4U 0142+61 (or the Vela pulsar) case.

Launched in 2009 December, WISE mapped the entire sky at 3.4, 4.6, 12, and 22 $\mu$m (called W1, W2, W3, and W4 bands, respectively) in 2010 with FWHMs of 6.1, 6.4, 6.5, and 12.0 arcsec in the four bands, respectively (see Wright et al. 2010 for details). The WISE all-sky images and source catalogue were released in 2012 March. Given its point-source detection limits of $\sim 0.08-6$ mJy at the four bands (Wright et al. 2010), WISE imaging could have provided a sensitive search for debris disks around all known neutron stars, although it suffers from source confusion and contamination, particularly at the Galactic plane, because of its mediocre spatial resolution. Wang
et al. (2014, in preparation) have conducted searches for MIR counterparts to all radio pulsars using WISE images. Preliminary results from the data analysis of the released WISE source catalogue are negative, with no counterparts found. The 4.6 µm flux upper limits, normalized by spin-down fluxes of pulsars, reached \( \sim 10^{-6} \). Detailed image-data analyses for possible detections of MIR objects near pulsars’ positions are underway, and approximately 30 such sources are found. In order to identify them, multiwavelength observations are needed.

3. Discussion and Summary

Sufficient observational evidence has shown that debris disks are ubiquitous around from different main-sequence stars (e.g., see Wyatt 2008 and references therein) to white dwarfs (e.g., Farihi et al. 2009, Xu and Jura 2012 and references therein). In main-sequence stars, debris disks may likely be the remnants of protoplanetary disks at early ages of \( \sim 10 \) Myr and then are replenished by planetesimal collisions. In white dwarfs, which like the neutron stars are also post main-sequence, compact stars, debris disks are thought to be formed from material produced by tidal disruption of planetary bodies (Graham et al. 1990, Jura 2003) that have survived through late phases of stellar evolution (Debes and Sigurdsson 2002). Comparing neutron stars to them, the major uncertainties would be the initial conditions and heating mechanisms if the current scenario of fallback disk formation is believed. For young neutron stars (magnetars, CCOs, and XDINSs) and regular radio pulsars, a debris disk would be the remnant of a fallback disk. The initial mass of the fallback disk and its interaction with a newly-born neutron star are quite uncertain, which would affect subsequent evolution and detectability. While dust grains around normal stars or white dwarfs are nicely heated to 100–1000 K temperature by ultraviolet/optical photons from host stars, revealing their existence, it is not clear how much a pulsar’s particle wind can heat up a disk. Hopefully in the near future, with great capabilities of the next generation telescopes such as the thirty meter telescope and James-Webb Space Telescope, these uncertainties would be cleared out by detections or even sufficiently deep upper limits of a number of different classes of neutron stars.

In summary, deep searches for disks around different types of neutron stars have been carried out. For magnetars, 6 of them were found with NIR emission, which was seen (except for 4U 0142+61) to be related to
magnetars’ outburst activities. Further observations to identify the origin of the NIR emission is needed. Among the 6 magnetars with NIR counterparts, 4U 0142+61 has been found to have a MIR component in its optical and IR broad-band spectrum and it is likely indicative of a dust disk around this X-ray emitting neutron star. Deep MIR imaging of the magnetars 1E 2259+586 and 1E 1048.1−5937 detected the first source at MIR 4.5 µm but did not detect the second one, and the results suggest a similar dust disk to that of 4U 0142+61 around the first source (although only on the basis of the MIR and NIR $K_s$ band detections) and exclude the existence of a similar disk around the second one. For CCOs and XDINSs, the deepest optical and NIR observations were carried out. The non-detections of them rule out accretion (from a disk) as the power source to produce the observed X-ray emission from the CCOs, while the upper limits on the XDINSs are not very constraining due to possibly large inner radii considered for their putative accretion disks. Deep MIR imaging of CCOs was also conducted, but the obtained upper limits can not conclusively determine whether or not dust disks exist. A few millisecond and middle-aged radio pulsars were searched. The discovery of a candidate MIR counterpart to the Vela pulsar, if confirmed, would provide a certain case for our understanding of disk heating and detectability of disks around regular pulsars. Extensive searches using WISE imaging data are underway, and hopefully the results would bring to light the general existence of debris disks and their evolution under pulsars’ extreme environments.

This research was supported by the National Natural Science Foundation of China (11073042, 11373055) and the Strategic Priority Research Program “The Emergence of Cosmological Structures” of the Chinese Academy of Sciences (Grant No. XDB09000000). Z.W. is a Research Fellow of the One-Hundred-Talents project of Chinese Academy of Sciences.

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