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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.

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 of its mass during the phase of low-mass X-ray binary evolution (Bailes et al., 2011). In addition to these three pulsars, 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), the so-called recycled pulsars 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 millisecond 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 the 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 of circumpulsar debris material into the magnetospheres of pulsars. In individual 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 properties might be affected by having an accretion disk (Çalişkan 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 et al., 1991). The existence of fallback disks has been suggested to be the cause of the diversity of young neutron stars (Alpar, 2001; Alpar et al., 2013 and references therein). Unlike what was once thought—young radio pulsars like those in the Crab and Vela supernova remnants were prototypical of newborn 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

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et al., 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, ≤ 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 ~ 10–$100\ \mu$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). Note that since approximately more than 60% known MSPs are in a binary system (Manchester et al., 2005), binary MSPs quite often were also included as the targets in the searches.

Launched in 2003, *Spitzer Space Telescope* provided observing capabilities of imaging and spectroscopy at MIR wavelengths with sensitivities of from μJy to mJy. Bryden et al. (2006) reported their search for debris material around B1257+12 with *Spitzer* MIPS observations. The sensitivities were improved by three 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; Lohmer et al., 2004), but comparing to those at IR wavelengths with temperature $T \geq 300$ K dust as the targets, the searches aimed to detect colder, $T \sim 30$ K dust material around nearby MSPs. The typical sensitivities reached were $\sim$5 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, $\sim 10^{14}$–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 et al., 2000; Perna et al., 2000; Menou et al., 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 et al. (2000) seemed to have matched the theoretical expectations. However, followup 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.

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 et al. (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 *V RI* 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 et al., 2006; see also Fig. 1). The disk should probably have a size of $2.8 R_\odot$–$7.5 R_\odot$, 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 both observations are consistent with the dust disk model (Wang et al., 2008b; Fig. 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, 2004). On the basis of the results, Tam (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