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SEARCH FOR PROTOPLANETARY AND DEBRIS DISKS AROUND MILLISECOND PULSARS

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ABSTRACT

The identification of planetary companions around the nearby millisecond radio pulsar PSR B1257+12 implies that planetary formation has occurred in the past evolutionary history of this system. If planetary formation is common around millisecond pulsars and if it occurs by coalescence of small dust particles within a protoplanetary disk, as is thought to have occurred during the formation of the solar system, then it may be possible to detect the presence of protoplanetary dust or a remnant debris disk via thermal infrared emission. We summarize an attempt to detect this emission via a series of 10 μm observations made toward PSR B1257+12 and four other nearby millisecond pulsars using the National Aeronautics and Space Administration (NASA) Infrared Telescope Facility (IRTF) 3 m telescope and the facility bolometer. We also present a simple model for thermal emission from a protoplanetary disk containing grains heated from the pulsar spin-down luminosity. Further, we describe upcoming space-based far-infrared observations that can substantially improve observational limits from the emission of dust that may radiate in the two order of magnitude gap between ground-based accessible mid-infrared and millimeter spectral regions.

Subject headings: circumstellar matter — infrared: stars — planetary systems — pulsars: general

1. INTRODUCTION

The initial identification of two Earth mass planetary companions around the millisecond pulsar PSR B1257+12 by Wolszczan & Frail (1992), and confirmed through independent observations by Backer, Sallmen, & Foster (1992), indicate that planetary formation has occurred in this system. More than 3 yr of follow-up radio pulse timing observations (Wolszczan 1994) reveal that there are at least three planetary bodies in orbit around the neutron star. The two larger masses are locked in a 3:2 tidal resonance with an estimated liberation period of 5.56 yr (Rasia et al. 1992; Malhotra et al. 1992; and Peale 1993). These observations provide the first convincing evidence of an extrasolar planetary system. The discovery of planetary bodies around a millisecond pulsar indicates that planetary formation is not unique to the solar system and has occurred in the past around at least one millisecond pulsar.

The discovery of numerous millisecond radio pulsars in the galactic field (e.g., Camilo 1994) has provided an empirical basis for the idea that an abundant galactic population of old neutron stars exists (e.g., Kulkarni & Narayan 1988). The discovery of nearby millisecond or recycled pulsars at high galactic latitudes (Wolszczan 1991) and the subsequent finding of other such objects by recent pulsar searches have substantially strengthened the evidence for the existence of a sizable population of observable old neutron stars in the solar neighborhood (e.g., Camilo, Nice, & Taylor 1993; Foster, Wolszczan, & Camilo 1993; Johnston et al. 1993; Nice, Taylor, & Fruchter 1993; Thorsett et al. 1993; Bailes et al. 1994; Camilo 1994, 1995; Lorimar et al. 1995; Lundgren, Zepka, & Cordes 1995; Ray et al. 1995; Ray 1995). So far at least one pulsar system of the more than 706 known radio pulsars (Taylor et al. 1995) has planets around it. The frequency of this phenomenon remains to be investigated.

The formation of planets around millisecond pulsars is certainly one of the more surprising developments in the first decade since the discovery of millisecond pulsars (Backer 1992). Since millisecond pulsars are thought to have evolved from pulsars that have been "recycled" through mass accretion from a binary companion (e.g., Bhattacharya & van den Heuvel 1991), it is unlikely that the observed millisecond pulsar planets survived the destructive phase of millisecond pulsar formation (Podsiadlowski 1993, 1995; Phinney & Hansen 1993).

There are a number of suggested mechanisms whereby binary companions of millisecond pulsars can aid in the process of planetary formation (e.g., Benz et al. 1990; Tavani & Brookshaw 1992). Observational and theoretical arguments (e.g., Kluzniak et al. 1988) indicate that some millisecond pulsars are able to evaporate their low-mass stellar companions on a 10^8 yr timescale. Perhaps under certain conditions a small fraction of this ablated material enters into orbit around the neutron star and forms a protoplanetary disk from which planets such as those discovered around PSR B1257+12 may form. Whatever the actual method of planetary formation is, for some period of time a disk of material surrounds planetary millisecond pulsars. The disk needs to last long enough to either coalesce into planets or to be cleared away, leaving just an isolated millisecond pulsar.

Examination of the *Infrared Astronomy Satellite* (*IRAS*) database at the position of the pulsar B1257+12 resulted in no detectable sources above background. The 3 σ *IRAS* flux density limits at 12 μm from co-adding scans is 0.18 Jy. In the longer *IRAS* bands the limits for PSR B1257+12 are 0.20, 0.14, 0.53 Jy at 25, 60, and 100 μm, respectively. Other pulsars have also been checked for significant IR emission in the *IRAS* data set. Van Buren & Terebey (1993) compared the positions of 478 pulsars (Taylor, Manchester, &

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Lyne, 1993) with the *IRAS* Point Source Catalog and found 13 sources within the estimated *IRAS* error boxes. They concluded that 13 "detections" did not represent an increase over the number expected from random chance, although the 13 IR/pulsar associations appeared to systematically select pulsars with supernova remnant associations and pulsars in globular clusters. Even if these statistics hold up and there is a trend toward excess IR emission from young pulsars, it is not clear whether the emission is actually from the circumstellar material or from other matter associated with the regions.

The problem of planetary formation in the environment of a neutron star appears to be difficult to resolve with limited observational data. Are planets created out of dust via a slow particle growth mechanism, eventually accumulating into planetary bodies, as is thought for the solar system, or do they form as a result of the breakup of a binary companion, or perhaps some other process? Direct detection of the planets themselves is not possible with present technology. However, detection of infrared radiation from dust grains, possibly heated by energy derived from the spin-down of the neutron star, would offer a means for associating these systems with planetary formation independent of radio timing measurements. Phillips & Chandler (1993) used 99 GHz and 380 GHz observations with the Owens Valley millimeter array and the James Clark Maxwell Telescope to search for circumstellar disks around five neutron stars including three millisecond pulsars. In this paper we describe ground-based infrared observations of a small sample of nearby millisecond pulsars aimed at the detection of warm dust grains in these systems. There is a two order of magnitude gap between 10 μm and 1 mm where additional observations would help constrain our models. Future space-based far-infrared observations may help to fill this gap.

2. OBSERVATIONS

To improve the mid-infrared flux limits toward PSR B1257+12 and other nearby millisecond pulsars, we obtained additional ground-based observations toward five nearby millisecond pulsars. We selected all of our infrared targets from known millisecond pulsars closer than 2 kpc in distance using the Taylor & Cordes (1993) distance model. Included in our sample is the object PSR B1957+20 known to be presently ablating its companion (Fruchter, Stinebring, & Taylor 1988). The observations were carried out at the National Aeronautics and Space Administration (NASA) Infrared Telescope Facility (IRTF) 3 m telescope located at an altitude of 4100 m on Mauna Kea, Hawaii, on two separate nights, 1992 August 16 and 1993 June 15. We used the IRTF bolometer equipped with the N-band filter ($\lambda_0 = 10.1$ μm, $\Delta\lambda = 5.1$ μm) and a 6″ (3 mm) aperture, a 13 Hz chopper frequency, and a 10″ north–south throw.

Several N-band standard stars were used as both primary flux calibrators and as position offset references to guarantee positional pointing accuracy. Guide stars were selected from the *Hubble Space Telescope* star catalog and used for continuous tracking on the pulsar positions during the observations for PSR B1257+12, PSR B1534+12, PSR J1713+0747, PSR B1957+20, PSR J2317+1439. The observations of PSR B1257+12 were made in the late afternoon of 1992 August 16. The other sources were observed during the late evening hours of 1993 June 15. The telescope position was peaked up on a known infrared source every 5 minutes during afternoon observations and every 20 minutes during the night time observations. Tracking was maintained to better than 1″ during the observations.

In Table 1 we present 3 σ upper limits on the N-band emission toward these objects, based on observations with exposure times that ranged from 990 to 3400 s. The distance estimates listed in Table 1 are accurate to within a factor of 25% (Taylor & Cordes 1993). The distance toward PSR J1713+0747 is from Camilo, Foster, & Wolszczan (1994). We applied a weighting correction for the varying airmass as a function of zenith angle. The airmass corrections resulted in slightly higher upper limits than previously reported without the corrections (Foster et al. 1994). Light cirrus clouds were occasionally present during the observations on 1993 August 16. Earlier observations using the same telescope and the same bolometer by Zuckerman (1993) placed similar limits on the 10 μm emission from PSR B1257+12.

The flux density limits have been converted into luminosities in the N-band filter, $L_N = 4\pi d^2 f_N \Delta\nu$, where f_N is the N-band flux density, $\Delta\nu$ is the filter bandpass, and d is the nominal distance of the millisecond pulsars. The best limit on 10 μm luminosity is $7.3 \times 10^{32} d_{620}^2$ ergs s^{-1} ($0.19 d_{620}^2$ $L_\odot$) toward PSR 1257+12 (see Table 1), where d_{620} is the pulsar distance in units of 620 pc. The total spin-down luminosity, $L_{\rm SD} = 4\pi^2 I\dot{P}/P^3$, for this system is 2.0×10^{34} ergs s^{-1} (5.2 $L_\odot$), where I is the moment of inertia for a neutron star, assumed to be 10^{45} g cm^2. P is the pulsar period, $\dot{P}$ is the pulsar period derivative. No more than $3.7 d_{620}^2$% of the total spin-down energy from PSR B1257+12 is observed as N-band emission from protoplanetary or remnant dust. Similar constraints limit the N-band emission from PSR B1957+20 to less than $3.1 d_{1530}^2$% of the total energy available from the "spin-down" luminosity, where d_{1530} is the pulsar distance in units of 1530 pc.

3. DISCUSSION

How do we interpret the upper limits on dust emission around millisecond pulsars obtained in this work and previous works, and what exploratory work remains to be done? Though the radiative energy available to heat grains is relatively small, the pulsar spin-down energy loss may be

TABLE 1

10 μm INFRARED FLUX DENSITY LIMITS TOWARDS MILLISECOND PULSARS

Source	Integration Time (s)	Distance (pc)	Flux Density 3 σ Upper Limit (mJy)	IR Luminosity 3 σ Upper Limit ($L_\odot$)	Spin-Down Luminosity ($L_\odot$)	$L_{\rm IR}/L_{\rm SD}$
PSR B1257+12	3400	620	≤ 27	≤ 0.19	5.2	≤ 0.037
PSR B1534+12	990	680	≤ 32	≤ 0.26	0.47	≤ 0.57
PSR J1713+0747	1730	1100	≤ 45	≤ 1.0	0.92	≤ 1.1
PSR B1957+20	1300	1530	≤ 34	≤ 1.3	42	≤ 0.031
PSR J2317+1439	1500	1890	≤ 47	≤ 3.3	1.2	≤ 2.8

as large as 40 solar luminosities (see Table 1). High-energy photons beamed from the millisecond pulsar's 10^{8-9} G magnetic field or interaction of the magnetic field with the gaseous component of the disk might act as a source for heating dust grains surrounding the neutron star. The detection of infrared emission from a millisecond pulsar system would provide a means to estimate the dust temperatures, grain size distribution, and total dust mass of the emitting material, and the efficiency with which the spin-down energy is converted into thermal energy. Knowledge of the grain size distribution could help constrain the evolutionary origin of the dust, and thus shed light on the planetary formation process.

To estimate the detectability of circumstellar dust around millisecond pulsars, we developed a simple model following Dwek & Werner (1981). Our model assumed that the emissivity is inversely proportional to the square of the wavelength, becoming optically thick when $\lambda = \lambda_0 = 2\pi a$, where a is the grain radius. Equating the heating of the dust grains to their radiative cooling yields an equation from which we estimate the temperature of the dust grains:

$$fL_{\mathrm{SD}} = N_d 4\pi a^2 \sigma T^4 Q_0(a, T) , \tag{1}$$

where

$$Q_0(a, T) = \frac{1}{\sigma T^4} \int_0^\infty \pi B_\nu(T) Q_\nu(a) d\nu , \tag{2}$$

$B_\nu(T)$ is the Planck blackbody function, σ is the Stefan-Boltzmann constant, f is the fraction of the spin-down energy L_{SD} $(L_\odot)$ of the pulsar converted into thermal energy, and N_d is the number of dust grains of radius a (μm). For temperatures under consideration here, Q_0 can be approximated as $Q_0 = 18.8 x_0^{-2}$, for $x_0 = 1.44 \times 10^4 (\lambda_0 T)^{-1}$. Using a grain density of 3 g cm^{-3} and a total mass in dust of M_d in units of Earth masses, the number of grains is $N_d = 4.8 \times 10^{38} (M_d / a^3)$, and we derive a temperature of $T = 2.08 \times 10^{-4} (fL_{\mathrm{SD}} / a M_d)^{1/6}$ K. The infrared flux density is then given (in units of Jy $= 10^{-26}$ W m^{-2} Hz^{-1}) by

$$F_\lambda(\mathrm{Jy}) = 5.33 \times 10^{-13} \frac{M_d}{d_{\mathrm{kpc}}^2 a} \pi B_\lambda(\mathrm{Jy}) \quad \text{for } \lambda \le \lambda_0 \tag{3}$$

and

$$F_\lambda(\mathrm{Jy}) = 5.33 \times 10^{-13} \frac{M_d}{d_{\mathrm{kpc}}^2 a} \pi B_\lambda(\mathrm{Jy}) \left(\frac{\lambda_0}{\lambda}\right)^2 \quad \text{for } \lambda \ge \lambda_0 , \tag{4}$$

where d_{kpc} is the distance in units of kpc, and $B_\lambda(\mathrm{Jy}) = (3.97 \times 10^{19}) / \lambda^3 (e^{1.44 \times 10^4 / \lambda T} - 1)$.

We show two illustrative examples in Figure 1 using the distance and luminosity values for PSR B1257+12 ($d = 620$ pc and $L_{\mathrm{SD}} = 5.2$ $L_\odot$). For model 1 we assume 300 Earth masses of dust grains with a radius of 0.1 μm. Model 2 assumes a total mass of 30 Earth masses and grains with a radius of 100 μm. The systems in both models are powered by the pulsar spin-down luminosity which we estimated to be 2×10^{34} ergs s^{-1}, with a 1% efficiency in heating the dust grains. We selected a 1% efficiency as a reasonable upper limit to the amount of energy that might be absorbed by a thick dust disk. For the first model the derived dust temperature is 21 K, and the peak disk emission is 35 mJy at 130 μm. For the second model the derived dust temperature is 10 K and the peak emission is longward of 250 μm. The temperature of the dust and the wavelength of the peak emission are dependent on the assumed model parameters. For simplicity, we have selected a single size grain population rather than a grain size distribution as would most likely exist in a true physical system. These simple models illustrate that with a range of reasonable parameters, circumstellar dust around nearby pulsars is detectable with the long-wavelength filters of the ISOPHOT photometer on the *Infrared Space Observatory* (*ISO*) launched by the European Space Agency (ESA) in late 1995.

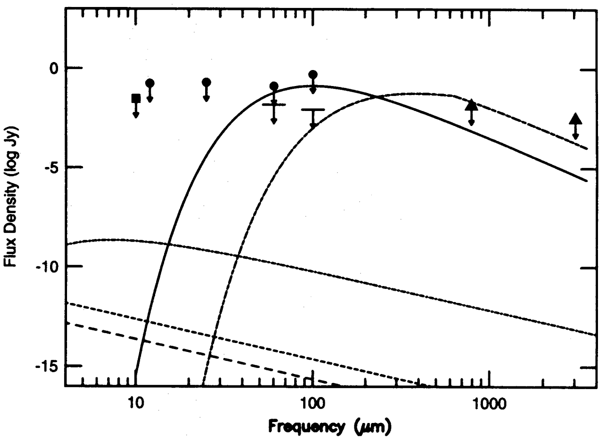

FIG. 1.—Infrared emission expected from (*a*) neutron star with a thermal surface temperature of 10^5 K (*long dashed line*), (*b*) neutron star with a thermal surface temperature of 10^6 K (*short dashed line*), (*c*) an Earth diameter planet with surface temperature of 700 K (*short dashed-dot line*), (*d*) circumstellar dust emission for model 1 parameters (*solid line*), (*e*) circumstellar dust emission for model 2 parameters (*long-short dashed line*), (*f*) the 3 σ limits for PSR B1257+12 from *IRAS* co-added data (*filled circles*) at 12, 25, 60, and 100 μm, (*g*) the 3 σ limits for PSR B1257+12 at 10 μm from the IRTF (*filled square*), (*h*) the expected 3 σ limits from a 1024 s integration with the ISOPHOT photometer on the *Infrared Space Observatory* (*ISO*) at 60 and 95 μm (*horizontal lines*), and (*i*) the 99 and 380 GHz upper limits from Phillips & Chandler (*solid triangles*). All flux densities are based on a nominal distance of 620 pc, the current best estimate of the distance to the planetary millisecond pulsar system PSR B1257+12.

For comparison, Figure 1 shows the expected IR flux from a 10^5 and 10^6 K neutron star surface, plus a 700 K Earth sized planetary surface, all assumed to be at the 620 pc nominal distance of PSR B1257+12. We show upper limits from observations of PSR B1257+12 with the IRTF and *IRAS*. The estimated sensitivity of ISOPHOT for a 1024 s integration at 60 and 95 μm are also shown. Typical upperlimits produced by the 99 and 380 Ghz observations of Phillips & Chandler (1993) are shown as solid triangles in Figure 1. Their observations are at wavelengths nearly 100 times longer than our 10 μm observations, but their measurements do help to constrain thermal emission models. They used a protoplanetary pre-main-sequence disk model to derive limits on the total disk mass of a few percent of solar mass. While both our illustrative models shown in Figure 1 have disk masses below Phillips & Chandler's measured upper limits for the PSR 1257+12 system, their observations constrain possible grain sizes by eliminating or seriously constraining our model 2 with 100 μm diameter grains and derived dust temperatures below 10 K. Figure 1 shows that if dust is present and can be heated efficiently by the spin-down energy of millisecond pulsars, its infrared flux will dominate that of the pulsar or any planets and it may be detected by its far-infrared continuum emission.

4. SUMMARY

Millisecond pulsars are an important class of systems capable of producing planetary size companions, and by inference, systems that may have evolved through a stage of protoplanetary formation. Deep 10 μm bolometric observations toward these millisecond pulsars PSR B1257+12, PSR B1534+12, PSR J1713+0747, PSR B1957+20, and PSR J2317+1439 have produced upper limits to possible mid-infrared emission from heated dust. Pulsar timing observations toward these and other objects generally rule out unknown companion objects larger than asteroids (Thorsett & Phillips 1992). Assuming that the coupling of the spin-down energy to the grains is weak our simple models indicate that the dust, if present, is expected to be relatively cold. Further investigation with improved instrumentation at far-infrared wavelengths is warranted to close the observational gap between the mid-infrared and the millimeter spectral region. We have scheduled ISOPHOT observations to study a number of nearby millisecond pulsars at 60 μm and 95 μm. The detection and characterization of infrared emission from a millisecond pulsar system would help to further our understanding of the planetary formation process in millisecond pulsars.

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